Texas Water Development Board
Groundwater Management Report 17-01

Transborder Aquifers:

A Summary of Aquifer Properties, Policies, and Planning Approaches for Texas, Surrounding States, and Mexico

April 2017

by Rima Petrossian, Ph.D., P.G, C.P.G.
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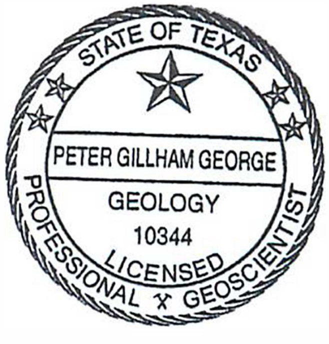

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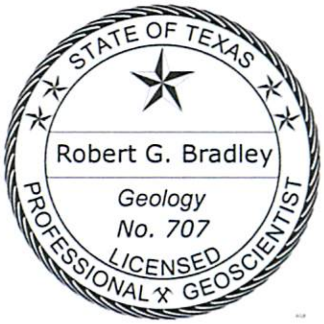

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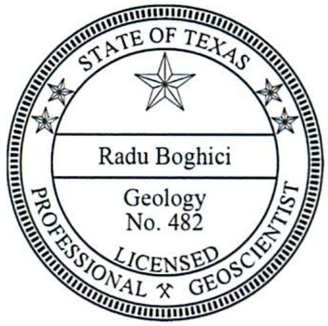

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Texas Water Development Board

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Published and distributed by the

Texas Water Development Board

P.O. Box 13231, Capitol Station

Austin, Texas 78711-3231

April 2017

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1. Executive summary

Groundwater in Texas is a valuable natural resource shared with eight national and international states: New Mexico, Oklahoma, Arkansas, and Louisiana, in the United States; and Tamaulipas, Nuevo León, Coahuila de Zaragoza, and Chihuahua, in Mexico. Of the 30 Texas aquifers that provide groundwater, 23 are shared with one or more other states. Internationally, Mexico and Texas share four major aquifers and three minor aquifers, based on the Texas definition of aquifers (see Appendix A for detailed maps).

Decision makers and stakeholders for these shared groundwater resources have the complicated task for planning for and securing future resources without the commonality of administrative, legal, or policy approaches. Texas recognizes the importance of understanding the legal and legislative frameworks, planning and policy approaches, path-dependent[1] actions, and aquifer characteristics of bordering states. This understanding will aid efforts to manage the development and conservation of groundwater resources in the future.

Legal doctrines that address groundwater management in the study area include prior appropriation, absolute ownership or rule of capture with and without modifications, correlative rights with reasonable use, and federal ownership and control. Groundwater is governed via various water doctrines which each state chooses, so a single aquifer may be subject to numerous conflicting laws, differing water management approaches, and unique public and private interests. Texas and adjacent transborder areas encompass a wide variety of geologic terranes hosting diverse aquifer systems. The western and southern portion of the study area, including New Mexico, Mexico, and west Texas, has geologic features modified by tectonic activity, volcanic deposits, and basin-fill alluvial aquifers. In contrast, much of Texas, Oklahoma, Arkansas, and Louisiana have more regional groundwater systems in extensive sedimentary geologic formations. Another aquifer boundary is the connection between coastal aquifers and Gulf of Mexico seawater.

In 1985, Texas began the initial step of sharing information and establishing conjunctive planning efforts through proposing a multi-state commission to secure Texas' future water supplies (Texas Water Code, Chapter 8). This commission has changed in current Texas statutes, renamed the Southwestern States Water Commission in 2015, and is repurposed to provide a policy development framework for surface water and groundwater.

Groundwater management in Texas occurs primarily on the local level through nearly 100 groundwater conservation districts. After 1949, when Texas adopted legislation allowing locally elected, state-sanctioned entities to regulate groundwater withdrawals, groundwater policy became locally driven. The rule of capture exists mostly unmodified in areas without

[1] Path-dependency is the concept that initial conditions trigger choices or decisions that, once followed, are difficult to undo even as conditions change or evolve with new or better choices. This progression is due in part to social acceptance, familiarity, and investment to support those initial choices and occurs when seemingly insignificant or narrow initial choices dynamically influence and accelerate, magnify, or constrain later conditions or choices.

groundwater conservation districts, but a variety of groundwater management approaches may modify the rule of capture within groundwater conservation districts.

The states that border Texas employ different groundwater management approaches to address their water needs. New Mexico's aquifers provide close to half of all water used in the state, with 75 percent of the public supply and 100 percent of the self-supplied individual households depending on groundwater for drinking. Groundwater and surface water are managed together as waters belonging to the state, based on a landowner's first historic use of the water for beneficial purposes.

Groundwater in Oklahoma provides about 44 percent of water use in the state with the Ogallala Aquifer, in western Oklahoma, being the largest resource. Oklahoma manages and permits uses of both groundwater, based on reasonable use, correlative rights, and allocation, and surface water. Oklahoma plans for groundwater for a minimum aquifer yield of at least 20 years with required 20-year updates on groundwater basin studies and envisions managing all groundwater resources using maximum annual yield.

Arkansas' aquifers account for over 60 percent of the state's water use. Water law in Arkansas is based on the riparian rights law subject to a "reasonable use" doctrine and uses the concept of sustainable yield to quantify the state's groundwater resources.

Groundwater in Louisiana provides only about 15 percent of all water resources. Louisiana manages groundwater based on landowners having absolute ownership and a right to capture and use groundwater if there are no other laws in place affecting use or no injury to others' rights. North-central Louisiana has seen some significant water level declines in the Sparta Aquifer where the state ordered larger well owners to report use type, monthly pumpage values, the static well water level, when possible. The state directed water users to identify alternative potable water sources to help develop a plan to move towards groundwater sustainability for the Sparta Aquifer with local authorities sponsoring a thorough water conservation education and outreach program.

Groundwater in Mexico provides about 50 percent of water used in the four neighboring border states. Water resources in Mexico are property of the federal government, and groundwater is managed on the local or regional level. When the state transfers permission to individuals or entities to withdraw groundwater, that right becomes private property. Aquifer divisions in Mexico are based on watersheds and do not compare directly to Texas aquifer divisions, although the geologic units are usually comparable. Administrative tools are available to the United States and Mexico to help create agreements and resolve disputes about shared surface water resources. One example is the 1944 United States-Mexican Water Treaty that regulates the use of water in the Rio Grande (Rio Bravo) and Colorado rivers, yet does not mention groundwater. However, a treaty section indicates that all the water from Goodenough Spring along the Rio Grande (Rio Bravo), sourced from groundwater, goes to the United States.

States that share groundwater resources without shared management processes will experience unknown and unquantifiable consequences to those future groundwater resources, possibly affecting reliance of the resource. Opportunities exist and continue to emerge for sharing information and planning efforts for this resource that transcend political boundaries. The results of this study are intended to help decision makers and stakeholders understand Texas' and her bordering states current groundwater resources, policies, and approaches to managing those resources and to identify successful steps forward.

2. Introduction

Groundwater is a natural resource shared among Texas and eight bordering national and international states—New Mexico, Oklahoma, Arkansas, and Louisiana in the United States, and Tamaulipas, Nuevo León, Coahuila de Zaragoza, and Chihuahua in Mexico (Figure 2-1). Of the 30 major and minor aquifers recognized by the State of Texas, 23 aquifers are shared with one or more of these states. In 2009, the U.S. Environmental Protection Agency Region 6 evaluated groundwater resources in Arkansas, Louisiana, New Mexico, Oklahoma, and Texas (Todd and others, 2009) and compared the states in terms of water quality, water quantity, population, and groundwater uses. This report extends the federal study by describing the shared transborder aquifers, summarizing groundwater management approaches, and identifying entities participating in natural resource management among these same states and Mexico.

The Southwestern States Water Commission serves as an advisory board to the Texas governor, working with other states including Mexico and may develop compacts to address groundwater. This commission may identify and develop sources and methods of augmenting water supplies on a regional basis after existing water supplies are fully committed. Most recent water resources planning efforts are communicated to neighboring interests through state-assisted regional water planning group activities, publications, and other collaborative local and regional water resource activities.

Texans recognize the need for future collaboration among neighboring states and nations. Many local, regional, state, national, and international entities identified here could serve in future joint planning efforts among Texas and her bordering states. Continued technical updates of groundwater data, such as groundwater availability estimates, will help to improve policy development efforts. These efforts, seeking to maintain good groundwater quality while balancing growth effects by developing reasonable amounts of groundwater, are key in securing water for all residents of the study area and beyond.

Figure 2-1. States within the transborder aquifers study area.

2.1 Study goals

The goal of this study is to describe the shared aquifer resources of Texas, surrounding states, and Mexico. These shared aquifer resources are described in terms of their physical properties, management and planning approaches, related institutions, laws, and legal instruments. The results of this study are intended to help decision makers and stakeholders understand Texas' and bordering states' common groundwater resources and approaches available to manage those resources.

Appendix A includes detailed descriptions of the shared aquifer resources. These descriptions include hydrogeological maps illustrating the shared aquifer boundaries and groundwater properties. Appendix B provides a list of relevant water-related institutions and related web pages if available. Appendix C provides Texas' groundwater availability estimates by county through 2040 for transborder aquifers within Texas.

2.2 Study area features

Several geographic aspects can contribute to understanding aquifers. This section includes discussions about locations studied with projected population changes, physiographic provinces, and climate.

The study area of this report (Figure 2-1) covers Texas, the four U.S. states that border Texas (Arkansas, Louisiana, New Mexico and Oklahoma), and four Mexican states (Chihuahua, Coahuila de Zaragoza, Nuevo León, and Tamaulipas). Texas is the largest of these states, covering an area of 261,797 square miles (Table 2-1), and includes more than 60 percent of the Mexico-United States border, which is approximately 2,066 miles long (Gunning, 1996).

Table 2-1. State size and aquifers shared with Texas.

State	Area (square miles)	Aquifers shared with Texas
Texas	261,797	
Arkansas	52,068	Blossom, Carrizo-Wilcox, Nacatoch, Sparta, Trinity, Woodbine
Louisiana	43,562	Carrizo-Wilcox, Gulf Coast, Queen City, Sparta, Yegua-Jackson
New Mexico	121,356	Bone Spring-Victorio Peak, Capitan Reef, Dockum, Edwards-Trinity (High Plains), Hueco-Mesilla Bolsons, Ogallala, Pecos Valley, Rita Blanca, Rustler
Oklahoma	68,667	Blaine, Blossom, Dockum, Nacatoch, Ogallala, Rita Blanca, Seymour, Trinity, Woodbine
Chihuahua	95,552	Hueco-Mesilla Bolsons, Igneous, West Texas Bolsons
Coahuila de Zaragoza	58,542	Carrizo-Wilcox, Edwards-Trinity (Plateau)
Nuevo León	24,798	Carrizo-Wilcox
Tamaulipas	30,982	Carrizo-Wilcox, Gulf Coast, Yegua-Jackson

Source: U.S. Census Bureau (2000); TWDB (2007); Comisión Nacional del Agua (2011b)

2.3 Population

Mexico and U.S. border populations together are projected to increase substantially by 2030 (Table 2-2). Over the past 60 years, the population in the study area has nearly tripled, growing from 18.2 million people in 1950 to 52.8 million people in 2010. Throughout the study area, populations continue to increase overall, with large population increases in metropolitan areas and steady or declining populations in rural regions. Growth in the United States-Mexico border area is occurring primarily in sister cities—urban areas that lie opposite to each other across the border. Population growth rates in these sister cities are estimated to be more than double the national average in their respective countries (Van Schoik and others, 2004). These areas are also highly industrialized due the numerous maquiladoras along the border.

In Texas, and in all of the U.S. states bordering Texas the populations are projected to increase, from a low of 4.3 percent in Oklahoma to a high of 32.5 percent in Texas by 2030 (U.S. Census

Bureau, 2012). Mexican state populations are all projected to increase, between a low of 18.5 percent in Chihuahua to a high of 29.1 percent in Nuevo León by 2030 (Consejo Nacional de Población, 2012).

Table 2-2. Study area population estimates and projections.

State	1950	2010	2030*	Percent increase, 2010–2030
Texas	7,711,194	25,145,561	33,317,744	32.5
Arkansas	1,909,511	2,915,918	3,240,208	11.1
Louisiana	2,683,516	4,533,372	4,802,633	5.9
New Mexico	681,187	2,059,179	2,099,708	5.8
Oklahoma	2,233,351	3,751,351	3,913,251	4.3
Chihuahua	846,414	3,525,273	4,177,815	18.5
Coahuila de Zaragoza	720,619	2,782,013	3,427,879	23.2
Nuevo León	740,191	4,723,273	6,097,769	29.1
Tamaulipas	718,167	3,334,664	4,069,115	22.0
Total	**18,244,150**	**52,770,604**	**65,146,122**	

Source: Consejo Nacional de Población (2012); Secretaría de Economía (1952); U.S. Census Bureau (1952); U.S. Census Bureau (2005); U.S. Census Bureau (2012). *U.S. projections for 2030 are based on historical data from the 2000 Census.

2.4 Physiographic sections

Three physiographic provinces in five U.S. states share part of nine physiographic sections in the study area (Figure 2-2). These sections include: (1) Edwards Plateau, (2) High Plains, (3) Mexican Highland, (4) Osage Plains, (5) Pecos Valley, (6) Plains Border, (7) Sacramento, (8) Raton, and (9) the West Gulf Coastal Plain (U.S. Geological Survey, 2011a). Four Mexican states are part of five physiographic sections in the study area (Figure 2-2). These sections include: (1) Sierra Madre Occidental, (2) Sierras y Llanuras del Norte, (3) Sierra Madre Oriental, (4) Grandes Llanuras de Norteamérica, and (5) Llanura Costera del Golfo Norte (Instituto Nacional de Estadística Geografía y Informática, 2000). Similar landscape characteristics and geology are shared between northern Mexico and the bordering United States. Physiographic sections sharing characteristics include: (1) the Mexican Highlands, Sierra Madre Occidental, and Sierras y Llanuras del Norte, (2) Edwards Plateau, Sierra Madre Oriental, and Las Grandes Llanuras de Norteamérica, and (3) West Gulf Coastal Plain, Llanura Costera del Golfo Norte, and Las Grande Llanuras de Norteamérica. Elevation varies significantly across the study area and ranges from at or below sea level in the states that border the Gulf of Mexico to over 13,000 feet elevation mean sea level (MSL) in the mountains of New Mexico (Table 2-3).

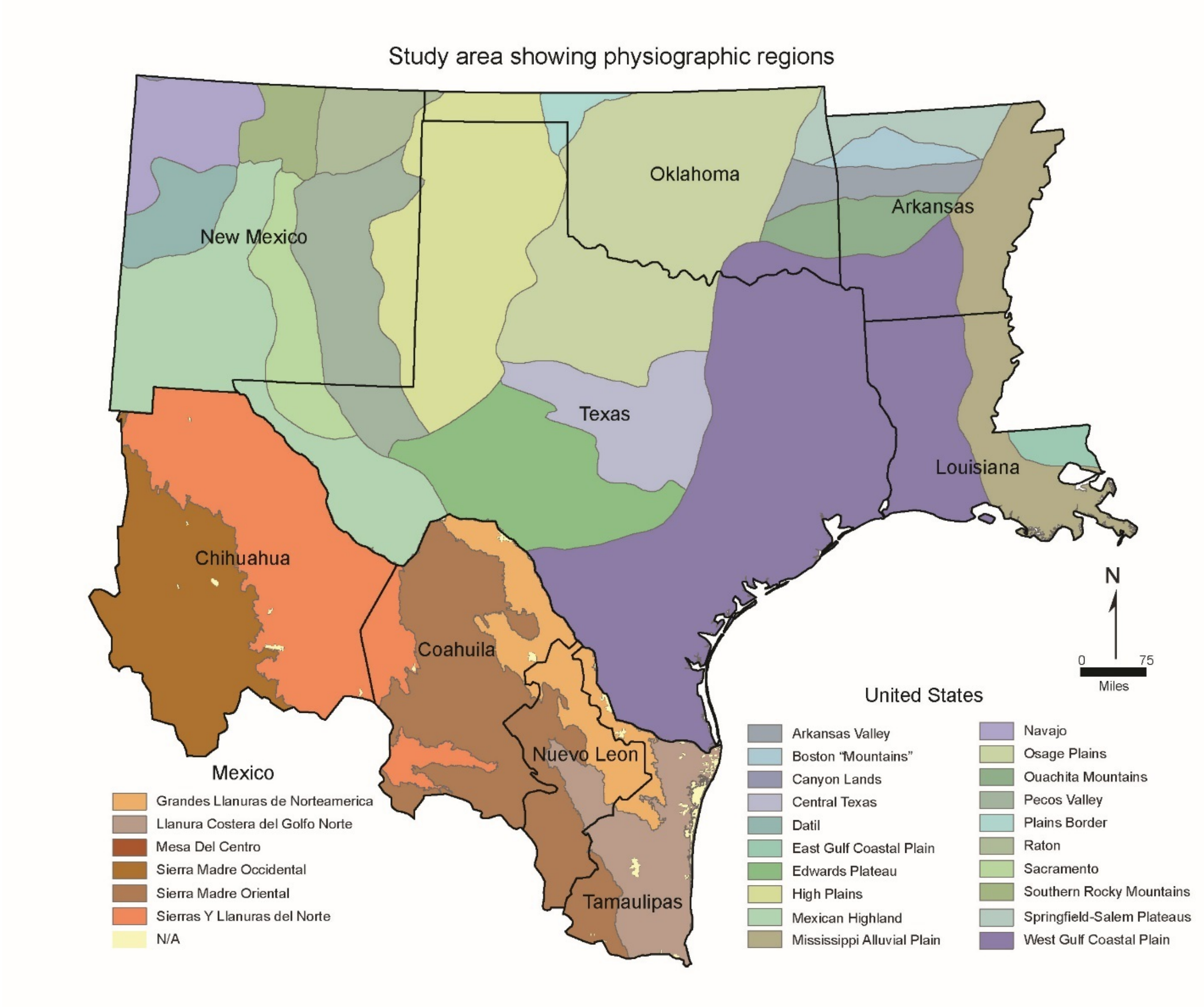

Figure 2-2. Physiographic regions within the study area (Fenneman and Johnson, 1946; INEGI, 2001).

Table 2-3. Range of elevations within the study area.

State	Low elevation (feet above MSL)	High elevation (feet above MSL)
Texas	0 (sea level)	8,749
Arkansas	55	2,753
Louisiana	-8	535
New Mexico	2,842	13,161
Oklahoma	289	4,973
Chihuahua	764	10,778
Coahuila de Zaragoza	-33	11,234
Nuevo León	200	12,195
Tamaulipas	446	12,129

***Source:* U.S. Geological Survey (2001); EROS and others (2008).**

Note: Mexican data converted from meters to feet; MSL is mean sea level.

2.5 Climate

Temperature and precipitation vary significantly across the study area. In the United States, the National Weather Service's Climate Prediction Center defines nine climate regions (National Weather Service Climate Prediction Center, 2004). New Mexico is in the southwest region, and Arkansas, Louisiana, Oklahoma, and Texas are in the southern region. Each of the individual states is subsequently divided into numerous climatic divisions. In the Mexican states, climate is arid to semi-arid in the north and east, and trends to more moderate conditions in southern Chihuahua, central Nuevo León, and southern Tamaulipas.

Precipitation

Generally, both temperature and precipitation vary by elevation (Table 2-3). For example, in the western mountainous areas precipitation in the winter falls as snow. Winter storms bring snow down to the southern parts of Texas and Louisiana in rare occurrences. On the eastern side of the study area, with no significant elevation changes, Louisiana has a subtropical climate (Bucker, 2001), with high amounts of rainfall, high temperatures, and high humidity. Mexico reflects similarities in precipitation due to elevation longitudinally along a north-south axis within about 100 miles of the Texas-Mexico border. Further south in Chihuahua, Nuevo León, and Tamaulipas, inland mountainous landforms modify the precipitation regime. Precipitation in the study area ranges from arid in the west with little rainfall to humid in the east with a high amount of rainfall (Figure 2-3 and Table 2-4). In Texas, precipitation sometimes falls as snow in the winter months in the northern and western parts of the state. In Oklahoma, rainfall is highly variable from the east to the west and also varies by season. Winter precipitation is higher in the western panhandle (Arndt, 2003). In both countries, areas along the Gulf Coast typically receive more precipitation due to large storm systems that originate in the Atlantic Ocean, develop, and track through the Gulf of Mexico.

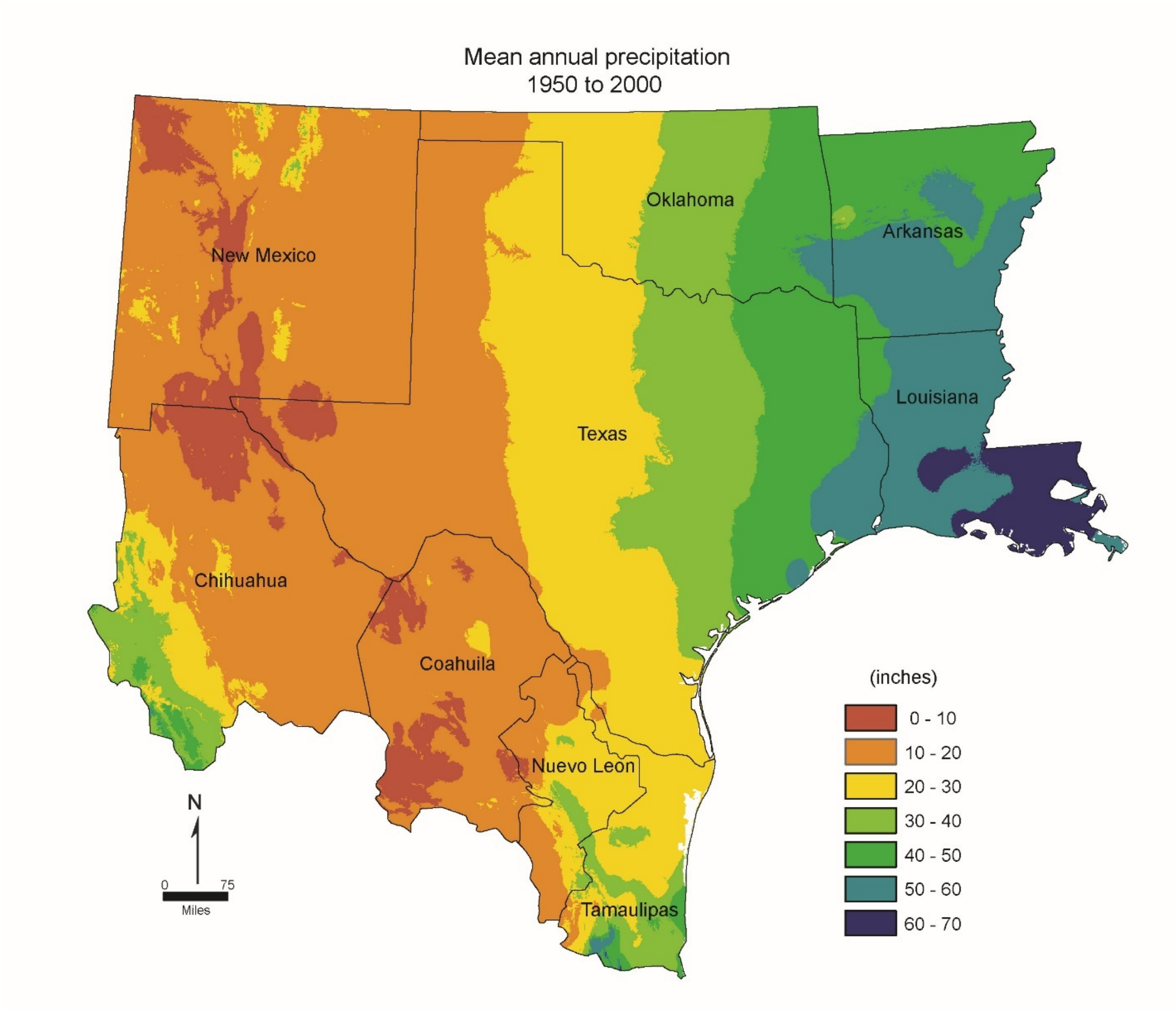

Figure 2-3. Mean annual precipitation 1950 to 2000 (CEC, 2011a).

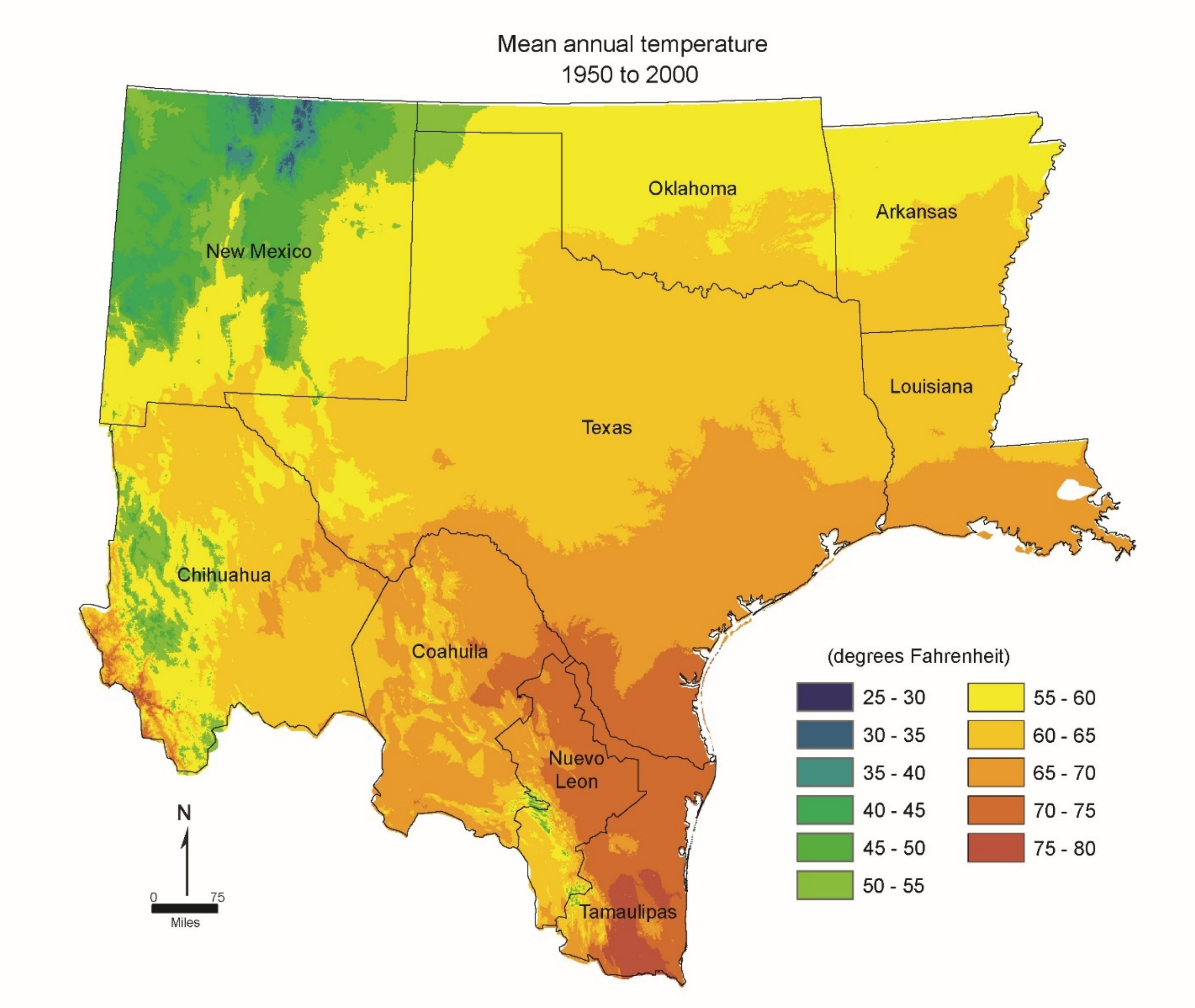

Figure 2-4. Mean annual temperature 1950 to 2000 (CEC, 2011b).

Temperature

In Texas, temperature varies more in the northern and western areas, as distance increases from the Gulf of Mexico. Arkansas has a temperate, mild climate, with the southern part of the state experiencing warmer and more humid conditions. Oklahoma has a temperate climate, with the southern and eastern parts of the state experiencing more humidity and precipitation. The climate of Mexico varies from arid to humid. Two-thirds of the country (including states in the study area) is arid or semi-arid, and the southeastern area is humid (Comisión Nacional del Agua, 2008d). The range of average temperatures (Figure 2-4) increases with proximity to the Gulf Coast in Texas, Louisiana, and Mexico, and south towards central Mexico (Texas Water Development Board, 2007). New Mexico is generally arid, with an alpine-like climate at higher elevations (Western Regional Climate Center, 2009). Table 2-4 lists average precipitation and temperature for the states covered in this report.

Table 2-4. Study area annual mean precipitation and temperature data, 1950-2000.

State	Annual average total precipitation (inches)	Annual average daily temperature (degrees Fahrenheit)
Texas	6 – 58	48 – 74
Arkansas	29 – 59	54 – 63
Louisiana	46 – 67	63 – 68
New Mexico	8 – 38	27 – 64
Oklahoma	15 – 55	52 – 63
Chihuahua	8 – 52	46 – 75
Coahuila de Zaragoza	6 – 32	45 – 73
Nuevo León	8 – 43	45 – 73
Tamaulipas	14 – 64	48 – 79

Source: National Climatic Data Center (2005a, b); Comisión Nacional del Agua (2011b); Comisión Nacional del Agua (2006). Note: Mexican data is converted from Celsius to Fahrenheit.

Texas, New Mexico, Oklahoma, and Mexico have experienced repeated cycles of drought and wetter periods throughout recorded history. The duration of these cycles can range from months to decades to centuries and vary in intensity and location throughout the study area (Cook and others, 2007). As these cycles continue in the future, policy makers will need to recognize these patterns and will be challenged to develop groundwater management approaches that accommodate these changes.

2.6 Study area geology overview

Texas and bordering areas encompass a wide variety of geologic terranes (Figure 2-5) that host diverse local and regional aquifer systems. Geologic processes influence rock type and characteristics, structure, exposure at the land surface, and control most aquifers' hydrologic characteristics. This report describes in detail all shared aquifers, presented by state first (chapters 4–9) and then by individual aquifer (Appendix A).

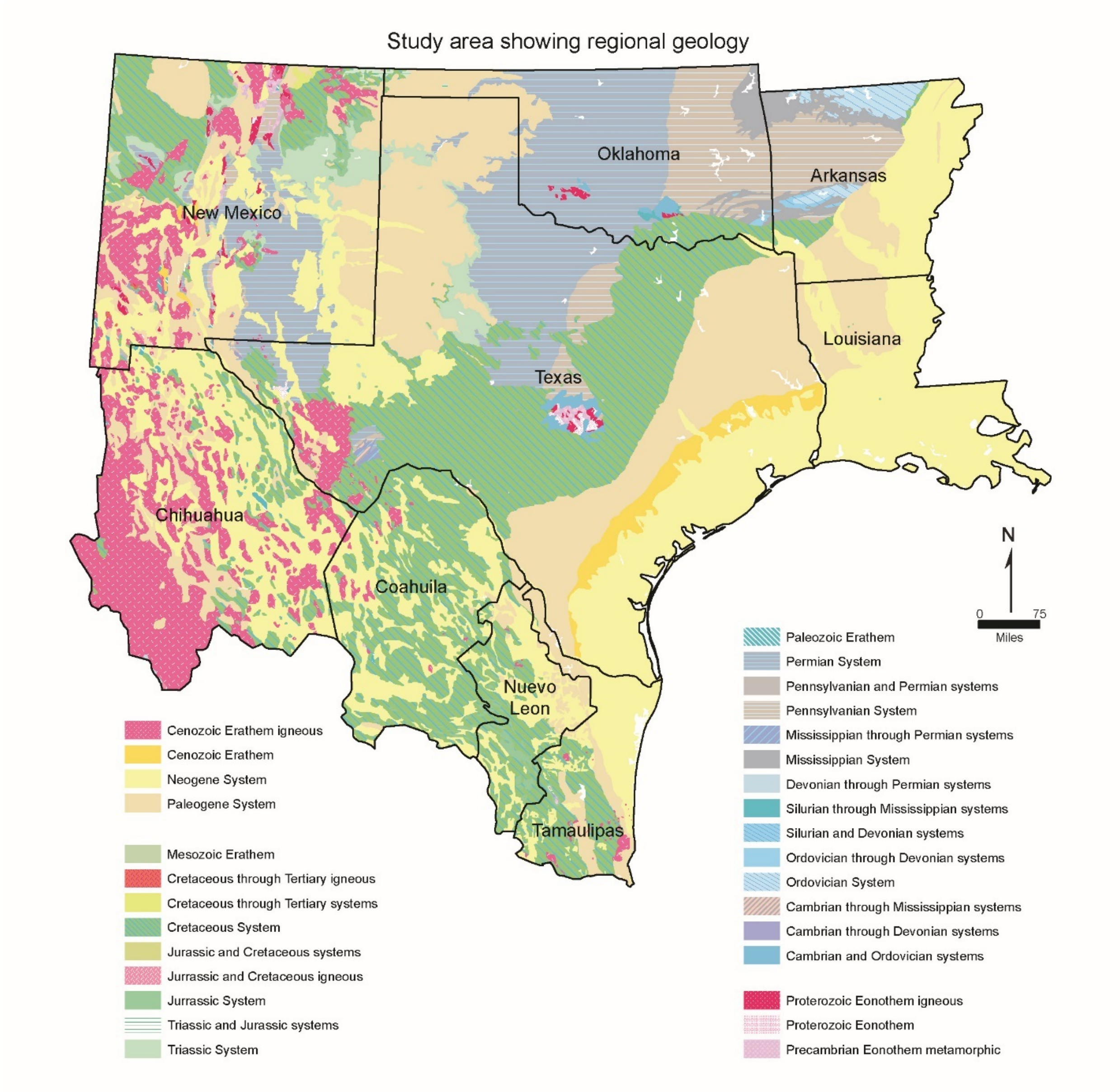

Figure 2-5. Regional geology of Texas and surrounding states in the United States and Mexico (Reed and others, 2004).

In this large study area, hydrologic characteristics vary due to the great extent of most of these shared aquifers and the discontinuities in some aquifer extents. The western portion of the study area (Figure 2-5), including New Mexico, much of Mexico, and west Texas, is characterized by local geologic features modified by tectonic activity (faulting and mountain building) and related development of local volcanic deposits and basin-fill alluvial aquifers. In contrast, much of Texas, Oklahoma, Arkansas, and Louisiana have more extensive, regional geologic features. These features, while containing significant local variations, are often characterized by large-scale groundwater systems within sedimentary rocks that typically include regional hydrologic interactions within and between aquifers. Water quality varies within and between aquifers due to rock type, topography, climate, contamination, and land use, all of which range widely throughout the study area (Reilly and others, 2008).

People primarily use groundwater in large volumes for public or household supply, irrigation, and industrial uses (Reilly and others, 2008). Human uses and extraction rates, which may impact an aquifer through changing natural flow patterns and modifying land uses, also vary tremendously by location and hydrological characteristics. Water quality may be impacted through land use change from natural landscapes to urbanization, deforestation, or crop irrigation which may affect groundwater chemistry. For example, aquifer recharge from urban-sourced surface water or agricultural run-off may contain enhanced concentrations of nitrates, sulfates, and potassium. This is due to rainfall picking up these chemicals, combining with natural decomposition products of organic matter in clay or soil such as ammonium, organic complexes, and carbonic acid, and recharging an aquifer. Increases in carbonic acid in runoff will dissolve carbonates present in the soil and aquifers, which may change the aquifer properties along with the groundwater quality (Schot and van der Wal, 1992).

2.7 Study area aquifers

At the national scale, some of the larger south-central aquifers have slightly different names than what Texas calls major aquifers. None of the Mexican aquifers share an official international designation with Texas or the United States (Figure 2-6). Mexico identifies and evaluates aquifers by lateral and vertical geologic extents and potential production while Texas identifies aquifers based on past water production and quality.

Figure 2-6. Study area showing regional aquifer names and Mexico's basin aquifers (modified from U.S. Geological Survey, 2015).

Eight of Texas' nine major aquifers and 15 of the state's 21 minor aquifers are shared by one or more of the states on its borders (Table 2-5). A few of these, such as the Gulf Coast and Ogallala aquifers, reach across bordering states to as far away as Florida and South Dakota, respectively; this report focuses on only the shared groundwater resources directly bordering Texas.

Table 2-5. Texas aquifers names, designations, and contiguous states.

Texas' shared aquifers	Texas' term	Contiguous states sharing or adjacent to the aquifer
Blaine	Minor	Oklahoma
Blossom	Minor	Arkansas, Oklahoma
Bone Spring-Victorio Peak	Minor	New Mexico
Capitan Reef	Minor	New Mexico
Carrizo-Wilcox	Major	Arkansas, Coahuila, Louisiana, Nuevo León, Tamaulipas
Dockum	Minor	New Mexico, Oklahoma
Edwards-Trinity (High Plains)	Minor	New Mexico
Edwards-Trinity (Plateau)	Major	Coahuila
Gulf Coast	Major	Louisiana, Tamaulipas
Hueco-Mesilla Bolsons	Major	Chihuahua, New Mexico
Nacatoch	Minor	Arkansas, Oklahoma
Igneous	Minor	Chihuahua
Ogallala	Major	New Mexico, Oklahoma
Pecos Valley	Major	New Mexico
Queen City	Minor	Louisiana
Rita Blanca	Minor	New Mexico, Oklahoma
Rustler	Minor	New Mexico
Seymour	Major	Oklahoma
Sparta	Minor	Arkansas, Louisiana
Trinity	Major	Arkansas, Oklahoma
West Texas Bolsons (Presidio-Redford, Green River Valley)	Minor	Chihuahua
Woodbine	Minor	Arkansas, Oklahoma
Yegua-Jackson	Minor	Louisiana, Tamaulipas

Note: In most cases, major aquifers produce a large amount of water over a large area. Minor aquifers yield a small amount of water over a large area or a large amount of water over a small area.

2.8 Groundwater resources overview

Prior to well drilling advancements and increased water use, people tended to settle where surface water supplies could sustain domestic, agricultural, and industrial demands. Surface water was considered a plentiful renewable resource replenished on a short cyclical basis of hours to days when it rained. In the past, groundwater was considered an infinitely renewable resource because the actual or assumed replenishment rate far exceeded the withdrawal rate. Prior to groundwater development, the presence of springs flowing continuously over hundreds or thousands of years seemed to signal an infinite and sustainable resource. However, since the early part of the 20th century—when new technologies made groundwater withdrawals from deep beneath the ground less expensive, and as aquifers became better described and understood—people have demanded more groundwater, in some areas withdrawing groundwater at rates previously not anticipated.

Replenishment or recharge rates studied in 29 aquifer systems across the United States, depending on aquifer properties, range widely from about half an inch of water per year to 47 inches a year (McMahon and others, 2011). Groundwater residence time, the length of time that groundwater travels in an aquifer from recharge to discharge, depends on groundwater velocity through the aquifer and distance from the recharge to discharge point (Reilly and others, 2008).

Generally, residence time estimates range from days to hundreds of years in the Edwards Aquifer to tens of thousands of years in the Ogallala and Dockum aquifers in Texas, New Mexico, and further north (Mehta and others, 2000; Scanlon and others, 2002). Groundwater, which constitutes approximately 30.1 percent of total freshwater on Earth and about 1.7 percent of all water globally, is being withdrawn at a faster rate than it is being replenished in many U.S. aquifers (U.S. Geological Survey, 2016g).

Over the past century, as the south-central and southwestern states have become more densely populated, each state has employed different paths or approaches to managing water resources. Although these paths vary, the need for resource management is commonly driven by water use for agriculture, municipalities, or industry. Surface water and groundwater resources are affected by both contamination and increasing use rates due to population growth. In many places, including parts of Texas, groundwater can be thought of as a finite resource and a common pool resource inseparable from surface water. Aquifers are affected by multiple jurisdictions and by both short-term weather and long-term climate patterns. Because aquifers have specific quantity and quality characteristics and cover areas that rarely match political boundaries, water development may lead to unanticipated changes and aquifer conditions which may affect other natural resources that transcend county, state, and international borders.

Aquifers that cross state or national boundaries are often subject to a range of regulations, none of which may apply across the entire aquifer. Likewise, development pressures and data availability can vary widely within transborder aquifers, making them difficult to understand and manage. In the United States, the responsibilities of groundwater management are generally allocated to state governments, and regulations often vary substantially (Hall, 2004). In addition, state level regulation and management include varying levels of involvement with federal, local, and tribal governments. The U.S. Environmental Protection Agency, responsible for monitoring and protecting water quality, has 10 administrative regions within the United States. The south-central states of Arkansas, Louisiana, New Mexico, Oklahoma, and Texas, which include 66 federally managed tribal lands, comprise U.S. Environmental Protection Agency Region 6. The U.S. Environmental Protection Agency is responsible for designating any sole source aquifers, or aquifers that are the principle source of drinking water within a specified area of the United States, that supply more than 50 percent of the drinking water in the specified area, and that are the only viable source of water available (U.S. Environmental Protection Agency, 2007a). In Region 6 there are six designated sole-source aquifers which receive special protection against projects that might cause contamination (U.S. Environmental Protection Agency, 2007b): (1) Edwards Aquifer—San Antonio area (Texas), (2) Chicot Aquifer System (Texas and Louisiana), (3) Edwards Aquifer—Austin area (Texas), (4) Southern Hills Aquifer System (Louisiana), (5) Arbuckle-Simpson Aquifer (Oklahoma), and (6) Española Basin Aquifer System (New Mexico) (U.S. Environmental Protection Agency, 2008). One of these aquifers, the Chicot Aquifer System, is shared by Texas and Louisiana.

2.9 Gulf of Mexico seawater border

Another type of aquifer boundary is the contact between the coastal aquifers and seawater in the Gulf of Mexico. The Gulf Coast, often called the third coast to differentiate it from the U.S. east and west coasts, is a border for states in the study area including Louisiana, Texas, and Tamaulipas, Mexico. Saltwater intrusion is common along the Gulf Coast due to storm surge, groundwater pumping, groundwater level declines, density differences between fresh and saline water, natural tidal exchanges, and sea level changes (Breier, 2006).

Texas

The Gulf Coast Aquifer has saline groundwater forming in-situ and from seawater intrusion from the Gulf of Mexico (Davidson and Mace, 2006). Seawater intrusion occurs in Texas due to groundwater pumping and the subsequent lowering of the water table (Chowdhury and others, 2006). An estimated twenty percent of groundwater in Texas suitable for desalination occurs in the Gulf Coast Aquifer (Davidson and Mace, 2006). Freshwater can be found down to about 2,000 feet below the surface, with the more extreme occurrences ranging from 2,200 feet below ground near Houston to near the land surface in Duval County (Chowdhury and others, 2006). Groundwater is generally fresher in the outcrop area, and more saline nearer the coast, deeper in the aquifer, near discharge points, and in the central and southern part of the aquifer (Chowdhury and others, 2006). Submarine groundwater discharge along the coast potentially contributes large amounts of groundwater due to the large area of contact between the aquifer and the seawater coastal interface but at a relatively slow rate (Breier, 2006).

Detecting and quantifying these discharge amounts can be difficult due to upwelling and mixing of less-dense, fresher groundwater with saline gulf water at a large number of small-scale occurrences. Mixing of fresher groundwater and saline seawater results in complex chemical and ecological changes in coastal estuaries, some of which are detrimental to the coastal ecosystem, including increased algal bloom occurrences and eutrophication of seawater. Methods used to quantify groundwater advection with seawater include complex algorithm calculations in two and three dimensional groundwater models, seepage metering, and using chemical tracers (Breier, 2006).

Louisiana

In western Louisiana, the coastal lowlands aquifer system is equivalent to the Evangeline Formation in the Texas Gulf Coast Aquifer (Scanlon and others, 2011). In Louisiana, the aquifer names are referenced according to the depth or order of water-bearing sand units such as the 1,200-foot sand unit or permeable zone A and so forth. Permeable zone A includes the equivalent to the Sparta Formation in Texas and Arkansas. Permeable zones C, D, and E occur at depths shallower than around 2,000 feet below ground (Renken, 1998).

The Evangeline Aquifer extends seaward to the edge of the continental shelf and becomes more saline due to dissolution of aquifer minerals and seawater intrusion. Groundwater moves more slowly near the coast and does not cause much flushing of the formation to bring in fresher water. More deeply occurring groundwater is pressurized (Renken, 1998).

The Southern Hill Aquifer system, a sole source aquifer in Louisiana, suffered temporary saltwater intrusion from storm surges most recently documented from hurricanes Katrina and Rita in 2005. Samples from shallow wells (250 to 460 feet below ground) on the north shore of Lake Pontchartrain damaged by the storms showed locally occurring contamination from saltwater. Storm surge occurred over an area with about 1,400 wells, which caused casings and well surface housings to break, allowed seawater to infiltrate, and caused the groundwater to experience elevated specific conductivity, chloride, other naturally occurring constituents, and bacteria counts. Hydrostatic pressure in wells screened in deeper aquifers prevented storm surge water from entering the wells due to water levels pressured above land surface (Tomaszewski and Lovelace, 2007).

Tamaulipas, Mexico

Studies on saltwater intrusion in Mexico indicate more aquifers being affected by saltwater on the Pacific Coast and the Gulf of California and do not include evidence of intrusion from the study area of eastern coastal Mexico on the Gulf of Mexico. Seventeen aquifer basins in Mexico are considered to have saltwater intrusion out of the 653 aquifer basins, primarily in four states on the Gulf of California coast and in Veracruz, the state just south of Tamaulipas (Comisión Nacional del Agua, 2008b; Rhoda and Burton, 2010; Comisión Nacional del Agua, 2014).

In Tamaulipas, Acuífero Bajo Río Bravo extends from near Laredo several hundred miles to the coast bounded by the Rio Grande to the north, varying from about 30 to 70 miles wide. Geologic formations associated with significant groundwater in this aquifer are related to the Gulf Coast Aquifer Goliad and Lissie Formations along with the Reynosa Conglomerate and Rio Grande Holocene alluvium (Comisión Nacional del Agua, 2009a). Groundwater is brackish, averaging from 2,000 parts per million to 2,500 parts per million total dissolved solids. This salinity level is not attributed to saline intrusion but is likely due to groundwater flushing naturally occurring evaporite units in the subsurface. South of Tamaulipas is the state of Veracruz, with two coastal aquifers identified with saline intrusion.

2.10 Management practices governing groundwater

Legal doctrines that states or countries have adopted which address groundwater withdrawals in the study area include prior appropriation, absolute ownership with and without modifications, correlative rights with reasonable use, and federal ownership and control (Houston and others, 2004; Comisión Nacional del Agua, 2014). Water resources management is based on the nature of the water resources, interpretation of legal doctrines, technical information available, and policies enacted and supported by each state or country.

Managing these shared natural resources is becoming increasingly affected by global economic development, public health concerns, and in some areas, political stability. Since 1800, worldwide water use through irrigation increased from close to 20 million acres to approximately 700 million acres (Postel, 1999). In response to increased use, between 1950 and 2000, the per person water supply decreased 59 percent worldwide while population increased from 2.5 billion to 6 billion (Postel and Wolf, 2001). In Texas, available groundwater supplies are projected to decrease 30 percent between 2010 and 2060, while the state’s population is projected to increase approximately 82 percent over the same timeframe (Texas Water Development Board, 2012c).

Past management practices and policies in the United States do not provide a precedent for developing integrated interstate groundwater resource development and management plans. Although nations have been signing treaties and compacts addressing water use for centuries, until recently these have done little to address complex environmental changes or the long-term availability and security of shared groundwater resources. Due to insufficient available data, most water-sharing agreements have failed to address groundwater. Further, groundwater is often closely connected to surface water bodies, and although this may be overlooked by water law, government agencies, and interstate water-sharing agreements, water resources respond to the interconnection (McCaffrey, 2001).

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3. Groundwater legal framework

Groundwater is governed via various water doctrines that each state has chosen to follow or modify to local conditions. This section includes details about historical precedents for several states and countries, briefly describes the U.S. federal framework, summarizes state laws, and introduces international law.

3.1 Background

In 1904, an often-cited Texas legal case about groundwater withdrawals affecting neighboring wells opined that groundwater movement was “mysterious and occult” (Mace and others, 2004). This case, *Houston & Texas Central Railway Co. v. East*, paraphrasing a previous 1861 legal decision from the Ohio Supreme Court (Mace and others, 2004), also referenced a vital basis for Texas groundwater law: the 1843 English case *Acton v. Blundell* (Dellapenna, 2013). In this even earlier case, groundwater is referenced similarly yet less intriguingly as “unknown” (Dellapenna, 2013).

Groundwater is difficult to understand, control, and manage because it is stored unseen throughout fractures and pore space within rocks and sediments rather than in visible surface water streams and lake beds, and because it can move continuously across borders. In the hydrologic cycle, groundwater discharges from underground to streams, is pumped from wells, is recharged by rainfall, and may evaporate if located near land surface. These factors make it difficult to accurately express the exact quantity or quality of water in a given location at a given time. Climate and weather directly affect groundwater in complex ways. For example, in dry or hot weather, water withdrawals may increase at differing rates according to each user’s needs to make up for the lack of rainfall. These withdrawals may cause water level changes to lag behind pumping withdrawals or recharge events. One season of hot weather and low rainfall or conversely several years of wet and cooler summers or any unique series of weather conditions may not necessarily be directly correlated to water level fluctuations. Laws and legal instruments may need to reflect uncertainties generated through inherently imprecise efforts such as groundwater use estimates and projections and quantifying groundwater supplies, as well as irreversible and unpredictable changes to aquifers due to groundwater mining and historical practices.

Political and administrative borders do not follow the boundaries of the shared aquifers in Texas, its bordering states, and Mexico. A single aquifer, therefore, may be subject to numerous conflicting laws, differing water management approaches, and public and private interests. Worldwide, there are at least 263 shared international river basins covering 45 percent of the earth’s continents (Global Water Partnership, 2009). Shared international aquifers are estimated at 608 as defined by the European Union Water Framework Directive. This directive identified four aquifers that are shared across the Texas-Mexico boundary (International Groundwater Resources Assessment Centre, 2014); however, Texas recognizes six such shared aquifers.

Water laws, compacts, and treaties are based on several theories about how to distribute water supplies in shared basins. These theories can be applied at several governance levels to address water resources that are shared by nations, states within nations, communities, or landowners. Several of these doctrines support shared rights and responsibilities in managing water resources (Johnson, 2004). The relevant doctrines that address surface water and groundwater are described below.

3.2 Water resource doctrines

The doctrine of “absolute territorial sovereignty”, sometimes referred to as the Harmon Doctrine, is based on an opinion U.S. Attorney General Judson Harmon prepared in 1895 in response to Mexican protests that the flow of the Rio Grande used by Mexico was being reduced. Harmon held that a sovereign state has absolute freedom to use any water resources within its territory, regardless of negative consequences for other states (Rieu-Clarke and others, 2012). The United States did not act on Harmon’s opinion on international watercourses and subsequently entered into a 1906 treaty with Mexico to apportion water in an ‘equitable and acceptable’ manner (McCaffrey, 1996; Rieu-Clarke and others, 2012). The English common law of absolute ownership and the rule of capture governing groundwater use in Texas follow this same reasoning, but at the level of individual landowners (Eckstein, 2004).

The “absolute territorial integrity” doctrine makes nearly the opposite argument of the Harmon Doctrine, saying that no sovereign state has the right to deprive another sovereign state of its territory and resources (Rieu-Clarke and others, 2012). Following this position, no state would have the right to alter in any way water resources that flow into another state (McCaffrey, 2001). These “absolute” doctrines are more theoretical than practical (McCaffrey, 2001).

The “prior appropriation doctrine”, also known as the Colorado Doctrine, gives the highest priority through allocation to the first user to put a water source to a beneficial use (Eckstein, 2004). While this process does not address who owns the water, everyone who uses the water after the first person is considered a junior user. The last person into the water allocation system may not lose their water right but will be the first to lose their right to capture water if it becomes scarce to a downstream water right (Castle, 1999).

The doctrine of “limited territorial sovereignty” maintains that state sovereignty is restricted by an obligation not to use resources within its territory in a way that will considerably harm other states (McCaffrey, 2001). This is similar to the “reasonable use” doctrine, or the American Rule, under which each party has an equal right to the amount of water necessary for a “reasonable and beneficial” use (Eckstein, 2004). Another closely related term—equitable utilization—is referred to in international legal resolutions. This term refers to the right of all states in a shared water basin to a “reasonable and equitable share in the beneficial uses” of their transborder water resources. Although the term was first used in international law, the idea was based primarily on U.S. law that was formed in U.S. Supreme Court cases on apportioning water between states (McCaffrey, 2001). Each of these ideas emphasizes that a user has a right to resources within its territory but must also acknowledge that neighbors have those same rights.

The doctrine of “community of interests” asserts that water should be treated as the users’ common property within a water basin and cannot be owned. While this idea cannot be used literally in basins where free public access would lead to a quick depletion of the water supply, it can be interpreted as supporting the use and development of water supplies to maximize the benefit to all users. In practice, agreements that reflect this doctrine lead to joint planning and implementation of water development projects and management (McCaffrey, 2001).

Similarly, the “correlative rights” doctrine states that water resources must be shared equitably. Entities within or overlying the water supply and those entities outside the area may use the surplus water if it is not needed by users within the basin. The equitable allocation of water to each user is generally based on the proportion of the basin that is owned or governed by each user (Eckstein, 2004).

Another water doctrine is found in Restatements of (Second) Torts, published by the American Law Institute, which attempts to clarify and improve general principles of common law through expert interpretation (Johnson, 2004). These legal experts considered every state's approach to groundwater law (American Law Institute, 2009) and culled the best approaches to managing groundwater. This approach supported determining reasonable use by comparing the reasonableness of water use of the litigants, but not restricting on-tract uses. Withdrawals that exceed a reasonable share of the annual or total supply of groundwater, or that directly harm owners of surface water rights, could result in a liability imposed, even if surface water and groundwater rights are treated differently in the law. Equitability is reviewed case-by-case rather than by establishing a specific standard amount. In this approach, economic and social values are relevant when deciding about withdrawal parameters but formulaic land size restrictions, such as a given number of acre-feet per acre, are not supported (Johnson, 2004).

Water users may defend or reject these doctrines based on whether the idea supports their own rights—for example, a downstream user that has used water for many years may argue for the prior appropriation doctrine. On the other hand, an upstream user may argue the opposite, citing absolute territorial sovereignty.

Louisiana, Oklahoma, New Mexico, and Texas are home to 66 federally recognized American Indian Tribes (U.S. Environmental Protection Agency, 2013a); therefore, both tribes and states must understand the implications of the water rights resulting through the Winters Doctrine. This doctrine originates from the 1908 U.S. Supreme Court decision in *Winters v. United States* in which the court declared that tribal rights on reservations included natural resources (Williams, 1990). This decision conveys that water rights are reserved based on the date the Indian reservation was established and must satisfy present and future needs (Brooks, 2005). These federal reserved rights[2] retain their validity and seniority regardless of whether tribes established beneficial use of the water (Britton, 2006) and regardless of non-use (Brooks, 2005). In order to quantify reserved rights, rights can be negotiated, settled, and ratified by Congress or adjudicated through court systems (Williams, 1990).

The following section describes water-related legal instruments that may be applied between states within the United States and those that may be used between the United States and other countries. There are federal laws that apply to all of the United States and affect how states manage groundwater. However, within the United States, each state has its own rules and regulations, institutions, infrastructure, and planning tools that largely govern how its

[2] The doctrine of federal reserved water rights implies that there is enough water to satisfy the purposes of the reservation, with the date of the reservation establishing the priority date. The existence and quantity of reserved water rights primarily rely on the reservation's authorizing legislation and the specific purposes for which the land was reserved and applies to all federally reserved public lands, such as national forests, national recreation areas, and national wildlife refuges. Usually state courts address litigation about stream adjudications although the reach of the reserved rights doctrine extends to protect federal reserved rights both from injurious surface and groundwater diversions (U.S. Department of Justice, 2016).

groundwater resources are developed and managed. This section addresses the areas where federal law controls groundwater.

3.2.1 United States federal law

The U.S. federal government has several laws, primarily water-quality oriented, that provide a legal basis for interactions between Texas and its neighbors in the United States. Some of the federal laws that most directly affect the states regarding groundwater management, use, and planning are described below.

The Endangered Species Act (1973) requires the U.S. federal government to seek to conserve endangered species and threatened species. The Endangered Species Act has a significant effect on planning for the distribution and management of water resources because the majority of species at risk of extinction in the United States depend on freshwater supplies (Postel, 1999). The Endangered Species Act can affect groundwater supplies when groundwater inputs are essential to threatened or endangered species—at springs, for example—or in rare cases where the species actually lives within the aquifer (Votteler, 1998).

The Federal Water Pollution Control Act of 1948, commonly known as the Clean Water Act (1977) after major amendments in 1977, is the primary federal law for regulating the quality of surface water in the United States. Under this act, the U.S. Environmental Protection Agency is responsible for setting water quality standards for contaminants and implementing pollution control programs. The Water Quality Act (1987) amended the Clean Water Act by establishing a program to help states develop and implement nonpoint source monitoring, management, and control programs. Federal grant opportunities now exist for states to carry out groundwater protection activities; however, these activities must contribute to a statewide comprehensive nonpoint source pollution control program.

The Safe Drinking Water Act of 1974 established national, enforceable standards for drinking water quality. This act expanded the focus of drinking water programs to include development of standards, contaminant monitoring, and enforcement. To support these goals, the Safe Drinking Water Act (1974) also established the Public Water System Supervision, Underground Injection Control, and Sole Source Aquifers programs (U.S. Environmental Protection Agency, 2013c).

The Ground Water Rule, a National Primary Drinking Water Regulation, implemented by the U.S. Environmental Protection Agency, became effective November 8, 2006. This rule aims to reduce the risk of exposure to and increase protection against microbial pathogens in public water systems that use groundwater. States were required to complete initial surveys of these public water systems by the end of 2012 for most community water systems, and by the end of 2014 for community water systems showing outstanding performance (generally defined as below maximum contaminant levels with no evidence of microbial pathogens, see each state for definitions) and non-community water systems. Groundwater systems that are at risk of fecal contamination are required to take corrective action to reduce exposure (U.S. Environmental Protection Agency, 2013b).

In 2006, Congress passed the United States-Mexico Transboundary Aquifer Assessment Act, authorizing the U.S. Secretary of Interior to work with border states (Arizona, New Mexico, and Texas), Mexico, state-level water resource research institutes, and the International Boundary and Water Commission to characterize, map, and model transborder aquifers (109th United States Congress, 2006). Priority aquifers to study include the Hueco and Mesilla Bolson aquifers, Santa Cruz River Valley Aquifer, and the San Pedro Aquifer (109th United States Congress, 2006). In 2013, the U.S. Geological Survey released an interim report outlining the study framework, objectives, and future efforts planned to assess further the shared aquifers (U.S. Geological Survey, 2013a).

In a similar change, in 2014 the U.S. Department of Agriculture Forest Service released a proposed directive to update previous approaches to addressing groundwater resources on National Forest System land (U.S. Department of Agriculture Forest Service, 2014). These rules were proposed for adoption in 2015 and included addressing groundwater uses, for a variety of purposes, to establish goals and processes for evaluating and approving groundwater withdrawals. Although these rules were withdrawn in 2015, if reconsidered and enacted, decisions would be based on ecosystem viability and human needs while considering water availability and quality (Gurrieri, 2014). A 2014 update to the U.S. Environmental Protection Agency Clean Water Act clarifying the types of waters protected indicated groundwater is not addressed (U.S. Environmental Protection Agency, 2014a).

3.2.2 State laws

Each state approaches groundwater management and regulation differently (Table 3-1). There are five fundamental approaches (described in detail in Section 3.2), usually reflecting path dependency through a combination of the historical social and political frameworks, climate, topography, and geology. This report discusses these frameworks in more detail within each state section.

Table 3-1. Groundwater governance framework.

Important dates in state- and federal-level groundwater governance
Arkansas: correlative rights with reasonable use • 1957 case law included groundwater in the reasonable use doctrine by observing the similarity with surface water • 1973 case law indicated that groundwater could be removed from the originating property as long as the removal did not harm groundwater availability for other users
Louisiana: absolute ownership/rule of capture subject to state regulation in groundwater conservation districts • 1808 Civil Code established absolute ownership • 1963 case law indicated harm to neighbor through dropping water levels in well is not cause for suit; additional case law refers primarily to groundwater contamination • 1972 legislation addressing water well drilling is the first groundwater legislation since statehood in 1812; after severe drought in 1999–2000, legislature established Ground Water Resources Commission and legal structure for groundwater management • 2001 legislation gave the state authority to regulate groundwater withdrawals • 2012 report recognized that managing groundwater and surface water is inextricable, although water resources are managed with two separate doctrinal approaches (Louisiana Ground Water Resources Commission, 2012)
New Mexico: Prior appropriation • 1907 territorial water code and rights established to promote the value of water rights and attract development (Franks, 2014) • 1912 state adjudicated water rights (New Mexico Office of the State Engineer, 2007) • 1931 state water code established prior appropriation of groundwater for a beneficial use through State Engineer proclaiming declared groundwater basins; groundwater rights

Important dates in state- and federal-level groundwater governance
are granted by the State Engineer and unappropriated water belongs to the public (Bushnell, 2012) • 1966 state water code established rules governing wells and groundwater appropriations • 2004 state water code established Active Water Resource Management Tools governing physical distribution of water rights (New Mexico Office of the State Engineer, 2013a)
Oklahoma: Absolute ownership with correlative rights/prior appropriation rights through state sovereignty subject to reasonable regulation and beneficial use • 1890 territorial legislature adopted absolute ownership for underground water not forming a definite stream and that water in the stream may be used on landowners property subject to some restrictions (Oklahoma Water Resources Board, 2015) • 1936 case law indicated that legal recourse for unreasonable use was only legitimate after damage is experienced and established differences between groundwater and underground stream water (Savage, 2002a), rejected absolute ownership in favor of American rule (Couch and Dumars, 2011) • 1949 state legislation established conservation-based Oklahoma groundwater law allocating groundwater with priority system and reasonable use regulation, did not equate land ownership with groundwater use (Couch and Dumars, 2011) • 1963 clarification that water in a definite stream is public water subject to appropriation (Oklahoma Water Resources Board, 2015) • 1967 water law definitions updated to identify water in stream alluvium as groundwater (Oklahoma Water Resources Board, 2015) • 1973 laws totally replaced 1949 laws, changing from conservation to use through the premise of beneficial use (Savage, 2002a) subject to economic development allowing for depletion in permitted cases (OWRB, 2008) and domestic use rights being granted to the surface property owner (Savage, 2002a), tying together groundwater allocation to surface acres owned; directed the OWRB to calculate each groundwater basin's maximum annual yield (Couch and Dumars, 2011)
Texas: Absolute ownership and rule of capture modified by groundwater conservation districts, which are formed through local, state agency, or legislature actions; each groundwater conservation district's rules are voted on locally, subject to state objectives of beneficial use and waste prevention • 1904 case law established rule of capture (Mace and others, 2004) • 1917 Conservation Amendment to the Texas Constitution, supporting conservation of all water, does not articulate groundwater specifically (Horton, 2014) • 1949 legislation established groundwater conservation districts that could make rules addressing spacing and withdrawal (Potter, 2004b) • 2005 legislation established requirements for desired future conditions and modeled available groundwater, which require groundwater conservation districts to make regional policy choices which would specify aquifer conditions over a 50-year period; through groundwater modeling, the Texas Water Development Board provides an amount of groundwater to withdraw that would meet these policy choices (Mace and others, 2008) • 2011 legislation established that a landowner owns the groundwater below the surface of the landowner's land as real property but that does not include the right to capture a specific amount of groundwater or affect the existence of common law or other defenses to liability under the rule of capture; required districts to develop and submit an explanatory report identifying each desired future condition that provided the policy and technical justification for each desired future condition and list other desired future

Important dates in state- and federal-level groundwater governance
conditions considered, if any, and the reasons why those options were not adopted; also included is a list of advisory committee recommendations and relevant public comments that were or were not incorporated into the desired future conditions (Texas Administrative Code Chapter 36) • 2015 legislation clarified that a landowner also has any other right recognized under common law (Texas Administrative Code Chapter 36)
Mexico: Federal constitutional control of water resources • From 1521 to 1821, the King of Spain owned the water and required a royal grant to use water with the rights passing to the Mexican government in 1821 • 1870 Mexican civil code indicated the government owned the water and water users needed a qualified authority to grant a concession to use the water (Garduño, 2005) • 1917, following the 1910 revolution and a rewritten constitution, the government was required to grant water concessions (Garduño, 2005) • 1947 through 1976 a government agency, the Ministry of Water Resources, managed all water (Garduño, 2005) • 1975 first national water plan adopted (Comisión Nacional del Agua, 2014) • 1980s Mexican tax law changes supported water user's paying for water and polluter's paying for damages (Garduño, 2005) • 1992 National Water Law enacted and introduced a reform of federal water policy to allow more regional and local decision-making for groundwater withdrawals; the National Water Commission (Comisión Nacional del Agua) was identified as the sole water authority in Mexico (Garduño, 2005) • 2013 national water plan for 2014–2018 revealed six objectives with multiple strategies based on the underpinnings of water security and sustainability, revisited every two years, and identifies multiple tiers of governance to work together on implementing the plan (Comisión Nacional del Agua, 2014)

3.3 International legal framework

For over a thousand years, between the years 805 and 1984, more than 3,600 international water-related treaties were signed by countries throughout the world (Postel and Wolf, 2001). However, many of these treaties addressed the use of water for navigation; the issue of non-navigational uses of water has only recently become a major source of international dispute (Postel and Wolf, 2001). It was not until the 1966 Helsinki Rules on the Uses of the Waters of International Rivers that an international resolution explicitly included groundwater as part of an international drainage basin (McCaffrey, 2001).

Other notable international resolutions that are applicable to shared groundwater include the Seoul Rules on International Groundwater, adopted by the International Law Association in 1986 (International Law Association, 1986); the Resolution on Confined Transboundary Groundwater, adopted by the International Law Commission in 1994 (International Law Commission, 1994); the Law of the Non-Navigational Uses of International Watercourses, adopted by the United Nations General Assembly in 1997 (International Water Law Project, 1997); and the Resolution on the Law of Transboundary Aquifers, adopted by the United Nations General Assembly in 2008 and updated in 2011 (International Water Law Project, 2011). In addition, the globally applicable Bellagio Draft Agreement concerning the use of transboundary groundwater provides a series of non-binding principles and mechanisms for managing transboundary groundwater resources (Hayton and Utton, 1989) although this non-governmental model agreement is not known to be in place (Mechlem, 2012). International legal instruments differ from interstate legal instruments in that there is no supra-national authority that can enforce adherence to an international law or agreement. If Texas and New Mexico disagree over whether an interstate river compact is being followed, the states can go to the U.S. Supreme Court to come to a final decision. However, if the United States and Mexico disagree over a negotiated water treaty, no higher court or enforceable legal decision can resolve the dispute (Eaton and Eaton, 1996).

In Texas and neighboring U.S. states, sharing surface water resources is addressed through the existing transborder river compacts, outlined in Texas Administrative Code Chapters 41 through 46, for the Rio Grande, Pecos, Canadian, Sabine, and Red river basins. These compacts address all eight bordering states and states containing these rivers by specifying goals. These goals include removing controversy that might arise through shared use, addressing mutual recognition of state-level legislation, judicial and executive decisions, and equitable apportioning of the water.

There are currently no internationally recognized legal instruments or entities that address water quality, pumping, and availability in transborder aquifers. Although there are still international challenges ahead, many aspects of water management in Mexico are progressive. Through the Water Management Modernization Program (PROMMA), Mexico has made significant progress in monitoring water quantity and quality, operating hydraulic infrastructure and dam safety, water planning in river basins, administration of water rights, studies of exploited aquifers, and meteorological forecasting (Asad and Garduño, 2005). The memorandum of understanding between Juarez, Chihuahua, and El Paso, Texas is an example of a joint resolution that has operated for over 10 years (Eckstein and Hardberger, 2008). The agreement supported implementing cross-boundary projects of common interest, developing plans to extend the aquifer life, and supporting efforts to secure future water supplies (PSB and JMAS, 1999). Eckstein and Hardberger (2008) cite this agreement as an example of how international communities can achieve useful and lasting results for sharing limited groundwater resources.

A lack of shared planning and policy approaches for common natural resources may cause disputes among those sharing the resource. Solutions encouraged through The Good Neighbor Environmental Board, an independent advisory committee associated with the U.S. Environmental Protection Agency, include sharing aquifer information in the border area between the Mexico and the U.S. (GNEB, 2005). Collaboration among the south-central and southwestern states can also be facilitated through existing state agencies and Texas' regional water planning groups.

International tools and agreements are used by nations throughout the world that may help states come to mutually agreeable solutions and arrangements on many issues, including shared natural resources. There is little international legal precedent for dealing with disputes over the water in international river basins and even less precedent for dealing with international aquifers (Hall, 2004). According to Hall (2004), management of groundwater resources is a complex and critical issue along the border of Texas and Mexico. Governance is complicated by the lack of international agreements regarding shared aquifer regulation, differences in policy on either side of the border, and the diversity of aquifer types in the region (Hall, 2004).

United States-Mexico agreements

There are several legal tools available specifically to the United States and Mexico to help create agreements and resolve disputes about the two countries' shared water resources. These tools are focused largely on shared surface waters. For example, the 1944 United States-Mexican Water Treaty, fully named the "Treaty Regarding Utilization of Waters of Colorado and Tijuana Rivers and of the Rio Grande", created rules for apportioning, delivering (Gunning, 1996), and constructing infrastructure (McCaffrey, 2001) on the waters of the Colorado, Tijuana, and Rio Grande river basins between the United States and Mexico. In addition, the treaty established the International Boundary and Water Commission (Gunning, 1996). The treaty does not explicitly refer to groundwater (Duckstein and others, 1996), yet refers to Goodenough Spring (International Boundary and Water Commission, 2015). The Edwards-Trinity Aquifer contributes flow to Goodenough Spring (Kamps and Groeger, 2006), one of the measured river tributaries specified in the treaty for allotment to the U.S. portion (International Boundary and Water Commission, 2015) and once the third largest spring in Texas (Brune, 2002). Lake Amistad, filled in 1968, covered the Goodenough Spring outflow point (Brune, 2002).

Since 1944, formally agreed-upon cooperative actions called minutes have been added to the 1944 Treaty (Gunning, 1996). In 1973, Minute 242 of the Treaty set salinity standards for Colorado River water delivered to Mexico (International Boundary and Water Commission, 1973) and provides the International Boundary and Water Commission with limited authority over groundwater and water quality in the border region. It sets a specific limitation, allowing no more than 160,000 acre-feet per year of groundwater pumping within five miles of the boundary between the states of Arizona and Sonora (Waterstone, 1996). The agreement calls for the states to consult with each other before beginning groundwater or surface water development projects that have the potential to negatively affect the other country (McCaffrey, 2001). In 1979, Minute 261 gave the International Boundary and Water Commission authority to deal with transborder water pollution issues (Gunning, 1996).

In 1983, the La Paz Agreement, or the "Border Environment Cooperation Agreement" was created to set a framework for the two countries to cooperate and address transborder environmental problems but was not specifically related to groundwater (Mumme, 2000). The treaty is coordinated by the U.S. Environmental Protection Agency in the United States and by the Secretaría de Desarrollo Social (Ministry of Social Development) in Mexico (Gunning, 1996). These coordinating agencies are responsible for monitoring the implementation of one of the first international environmental agreements and providing their respective governments with an annual report on their activities (Hayton and Utton, 1989). The Treaty defines the United States- Mexico border area as including all territory within 62 miles (100 kilometers) of the 2,066 mile United States-Mexico border (Gunning, 1996).

In Mexico, groundwater management was largely a federal effort until legislation passed in 1992 started a decentralization of water resource management (Hearne, 2004). Managing by river basin and organized user participation are two of the basic principles Mexico articulated in the National Water Program 2007–2012 report. Mexico's Río Bravo hydrological-administrative unit based in Monterrey, Nuevo León, is most closely associated with Texas-Mexico transborder aquifers and is one of 13 such institutions country-wide (Comisión Nacional del Agua, 2008d).

Cooperation between local and state institutions in the use and management of shared groundwater resources is preferable. Collecting and analyzing data through shared efforts helps to avoid, or at least minimize, the overuse and contamination of groundwater resources. In order to manage shared groundwater resources, states must understand how much groundwater is available, how it moves within an aquifer, and how recharge rates and withdrawals have affected and will affect the aquifers. Coordinated management also requires communication among institutions that may not have worked together previously.

Border plans

In 1992, the United States and Mexico entered into the "Integrated Environmental Plan for the Mexican-United States Border Area," or the Border Plan. The plan was meant to strengthen the framework created in the 1983 La Paz Agreement by providing specific goals towards building a comprehensive border management plan and by suggesting what funds would be needed to meet them (Gunning, 1996). The Border Plan was succeeded by the Border XXI Program (1996–2000), which was succeeded in 2002 by the Border 2012 program, and in 2012 by the Border 2020 program (U.S. Environmental Protection Agency, 2014c).

Border 2012 was a 10-year plan to protect the environment and public health, with participants from the 10 United States and Mexican border states and federal agencies in both countries (U.S. Environmental Protection Agency, 2003). The program included four regional workgroups, three border-wide workgroups, three policy forums, and site-specific task forces (U.S. Environmental Protection Agency, 2003). These coordinating bodies facilitated bottom-up participation, which incorporated local governments and communities in the planning process. The plan had six goals, including reducing water contamination, that are considered critical to meeting environmental and health challenges in the region (U.S. Environmental Protection Agency, 2003). One regional issue identified in the Border 2012 program was aquifer overdraft and deteriorating water quality of the Hueco Bolson Aquifer in the Ciudad Juárez-El Paso area (U.S. Environmental Protection Agency, 2003).

One way the recent Border 2020 Program builds on the previous plan is to focus more regionally and locally to set priorities and make decisions where environmental issues are most significant. Establishment of new basic strategies and thematic goals, using new two-year action plans, is critical to encourage completion of projects to meet more ambitious goals over the eight-year effort. Two years was chosen as a timeframe that more easily incorporates resource and priority updates and provides more immediate feedback for unforeseen modifications. Another upgrade to the plan is the higher emphasis placed on communication through two new committees, relevant stakeholder participation, and bottom-up actions (U.S. Environmental Protection Agency, 2014c).

Regional workgroups

Regional workgroups help to identify, consider, and develop these two-year action plans for at least seven general regional issues: (1) air, (2) water, (3) waste, (4) emergency response, (5) compliance assistance, (6) education, and (7) rural. Two taskforces which include Texas address water-related issues, the Texas-New Mexico-Chihuahua Regional Workgroup and the Texas Tamaulipas-Nuevo León-Coahuila Regional Workgroup (U.S. Environmental Protection Agency, 2014b).

A regional workgroup addressing the Chihuahua Desert ecosystem and the Paso del Norte region (around the El Paso area), the second largest metropolitan area on the U.S.-Mexico border includes local, state, national, and tribal representatives from two U.S. states and one Mexican state. In 2013 this group set goals to improve access to clean and safe water. These goals include objectives such as increasing the number of houses connected to adequate water and wastewater infrastructure, implementing sustainable approaches toward reducing operating costs, improving energy efficiency, adapting to climate, and identifying and reducing surface water contamination in transborder water resources (Texas-New Mexico-Chihuahua Regional Workgroup, 2013).

A regional workgroup addressing the most complex border area, due to the size of the area and number of municipalities, includes 29 Mexican municipios and 168 Texas cities and towns. In 2013 this group set goals to improve access to clean and safe water. These goals include objectives and projects such as establishing a desalination plant in Nuevo León using renewable energy, educating the Lower Rio Grande stakeholders through a "Water Awareness Summit," teacher training workshops, efficiency assessments for water and wastewater facilities, assessments of methods and strategies to improve the Rio Grande water quality through joint binational efforts, and other water and wastewater initiatives (Texas-Coahuila-Tampico-Nuevo León Regional Workgroup, 2013).

Regional trade agreements

The North American Free Trade Agreement emerged in 1994 between Canada, Mexico, and the United States. In addition to eliminating trade barriers and linking international markets, this agreement includes several components that address issues of shared water resources. The three countries agreed not to relax health, safety, or environmental standards to encourage capital investment. The countries are also obligated to increase scientific research and technology development relating to environmental issues, complete environmental impact statements, and publish periodic reports on the state of the environment. In addition, the United States and Mexico have agreed on a shared set of sanitation standards for traded products (Gunning, 1996).

Two side agreements to the North American Free Trade Agreement—the North American Agreement on Environmental Cooperation and the U.S.-Mexico Border Environment Cooperation Agreement—resulted in the creation of the Commission for Environmental Cooperation, the Border Environment Cooperation Commission, and the North American Development Bank. In addition, under Article 5 of the North American Agreement on Environmental Cooperation, the three North American countries pledged that government action will be taken to enforce their national environmental laws and regulations. In addition, articles 22–36 provide exact methods for addressing a "persistent" failure to enforce environmental regulations. This addition "represents the first intergovernmental dispute resolution mechanism that links environmental enforcement with trade and other monetary benefits" (Gunning, 1996).

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4. Texas

In Texas, groundwater management occurs primarily on the local level with several state agencies collecting and analyzing groundwater-related information. Locally elected or appointed boards for groundwater conservation districts develop and maintain groundwater monitoring programs that vary according to district size, financial resources, aquifer complexities, and groundwater usage. The Texas Commission on Environmental Quality collects public drinking water supply information and provides some administrative and technical services to groundwater conservation districts (Texas Commission on Environmental Quality and Texas Water Development Board, 2013). The Texas Water Development Board (TWDB) identifies and designates aquifers statewide and develops and maintains groundwater availability models. As part of its data collection mission, the TWDB also maintains a statewide network of real-time water level monitoring wells and deploys field crews to measure water levels and collect groundwater samples for chemical analysis across the state. In addition, the TWDB reviews groundwater conservation district management plans and provides districts, groundwater management areas, and the public with technical information and assistance.

4.1 Groundwater resources

Groundwater provides close to half of all Texas water resources for a variety of uses and the available groundwater is projected to decrease by 2060. This section includes details about Texas aquifers and monitoring.

4.1.1 Aquifers

The TWDB recognizes 9 major and 21 minor aquifers (Table 4-1). Texas' major aquifers (Figure 4-1) include the Carrizo-Wilcox, Edwards (Balcones Fault Zone), Edwards-Trinity (Plateau), Gulf Coast, Hueco-Mesilla Bolsons, Ogallala, Pecos Valley, Seymour, and Trinity aquifers (Texas Water Development Board, 2012c). The Edwards Aquifer—the primary source of drinking water for San Antonio—was the first aquifer to receive the sole source aquifer designation by the U.S. Environmental Protection Agency in 1975 (U.S. Environmental Protection Agency, 2007b). Texas' minor aquifers (Figure 4-2) are often a significant source of water for local communities in the state (Texas Water Development Board, 2012c).

Table 4-1. Aquifer names used in Texas.

Texas Water Development Board Aquifers	U.S. Geological Survey Aquifers
Blaine Aquifer	Blaine Aquifer
Blossom Aquifer	Blossom Aquifer
Bone Spring-Victorio Peak Aquifer	Bone Spring-Victorio Peak Aquifer
Brazos River Alluvium Aquifer	Brazos River Alluvial Aquifer
Capitan Reef Complex Aquifer	Capitan Reef Complex Aquifer
Carrizo-Wilcox Aquifer	Lower Claiborne-Upper Wilcox and Middle Wilcox aquifers, part of the Texas Coastal Uplands Aquifer System in Texas (Mississippi

Texas Water Development Board Aquifers	U.S. Geological Survey Aquifers
	Embayment Aquifer System in Arkansas and Louisiana)
Dockum Aquifer	Dockum Aquifer
Edwards (Balcones Fault Zone) Aquifer	Edwards Aquifer, part of the Edwards-Trinity Aquifer System
Edwards-Trinity (High Plains) Aquifer	Edwards-Trinity (High Plains) Aquifer
Edwards-Trinity (Plateau) Aquifer	Edwards-Trinity Aquifer, part of the Edwards-Trinity Aquifer System
Ellenburger-San Saba Aquifer	Ellenburger-San Saba Aquifer
Gulf Coast Aquifer	Part of the Coastal Lowlands Aquifer System
Hickory Aquifer	Hickory Aquifer
Hueco-Mesilla Bolsons Aquifer	Hueco and Mesilla basin aquifers, part of the Rio Grande Aquifer System
Igneous Aquifer	Igneous Aquifer
Lipan Aquifer	Lipan Aquifer
Marathon Aquifer	Marathon Aquifer
Marble Falls Aquifer	Marble Falls Aquifer
Nacatoch Aquifer	McNairy-Nacatoch Aquifer, part of the Texas Coastal Uplands Aquifer System in Texas (Mississippi Embayment Aquifer System in Arkansas and Louisiana)
Ogallala Aquifer	High Plains Aquifer
Pecos Valley Aquifer	Pecos River Basin Alluvial Aquifer
Queen City Aquifer	Middle Claiborne Aquifer, part of the Texas Coastal Uplands Aquifer System in Texas (Mississippi Embayment Aquifer System in Arkansas and Louisiana)
Rita Blanca Aquifer	Rita Blanca Aquifer
Rustler Aquifer	Rustler Aquifer
Seymour Aquifer	Seymour Aquifer

Texas Water Development Board Aquifers	U.S. Geological Survey Aquifers
Sparta Aquifer	Sparta-Memphis Aquifer, part of the Texas Coastal Uplands Aquifer System in Texas (Mississippi Embayment Aquifer System in Arkansas and Louisiana)
Trinity Aquifer	Trinity Aquifer, part of the Edwards-Trinity Aquifer System
West Texas Bolsons Aquifer	Salt, Eagle, Red Light, and Presidio basin aquifers, part of the Rio Grande Aquifer System
Woodbine Aquifer	Tokio-Woodbine Aquifer
Yegua-Jackson Aquifer	Upper Claiborne Aquifer, part of the Texas Coastal Uplands Aquifer System in Texas (Mississippi Embayment Aquifer System in Arkansas and Louisiana)

Sources: Ryder (1996); TWDB (2007).

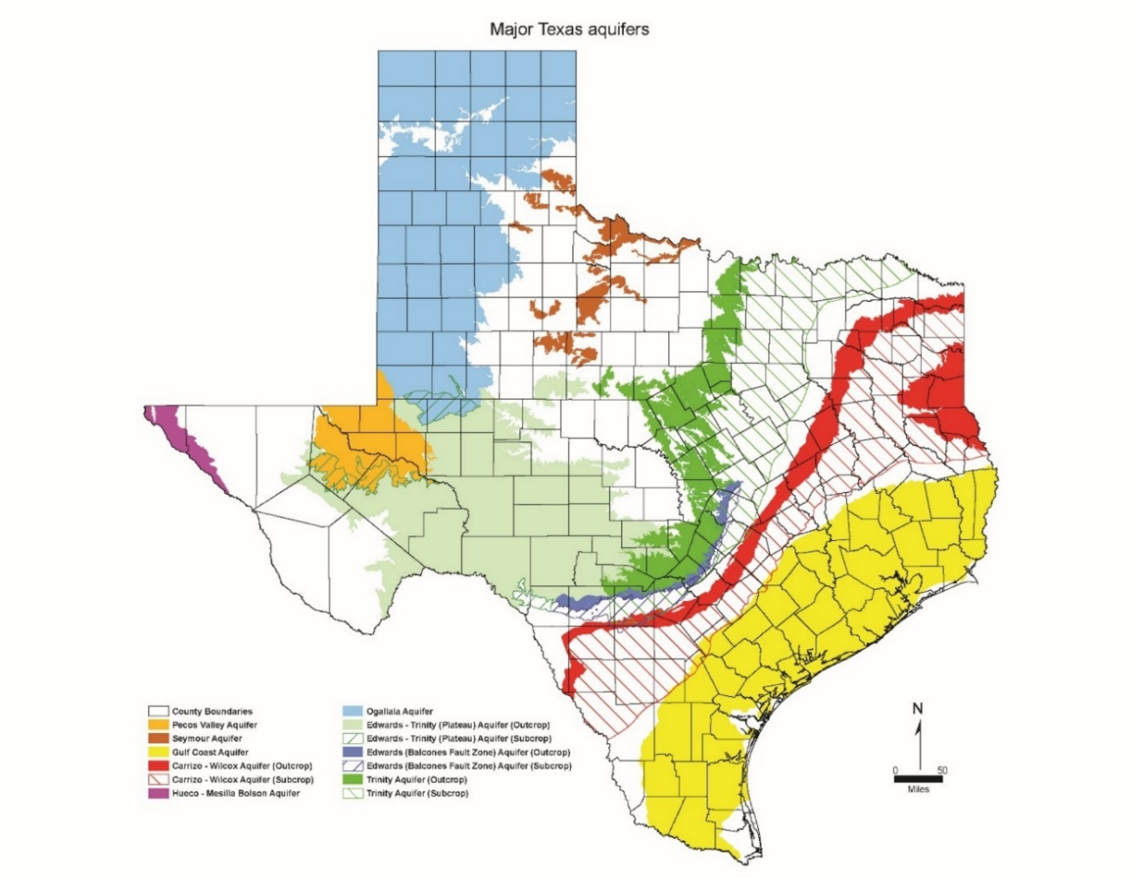

Figure 4-1. **Major aquifers of Texas.**

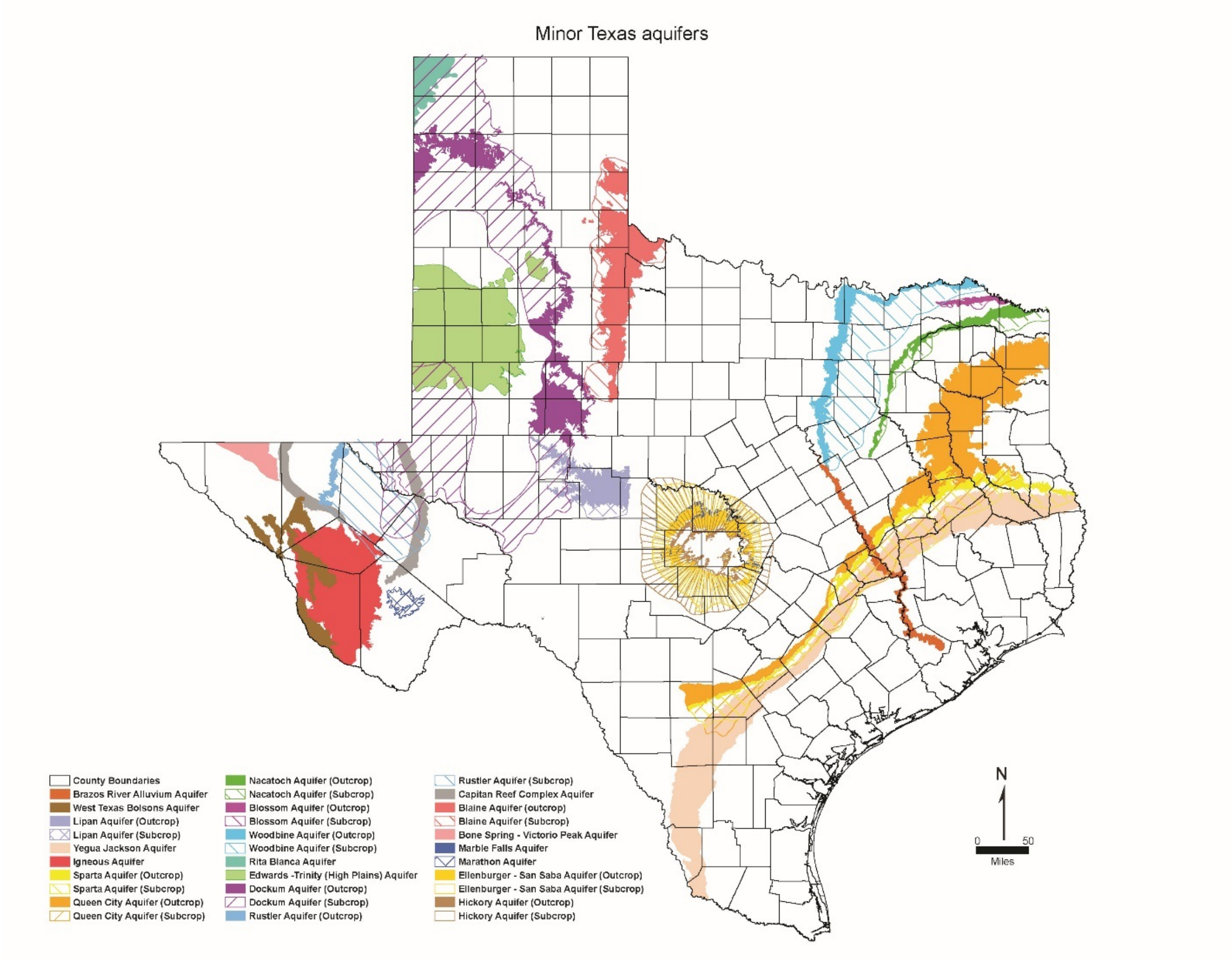

Figure 4-2. Minor aquifers of Texas.

Out of the 16.1 million acre-feet of water used in 2012, approximately 9.7 million acre-feet (60 percent) was groundwater produced from these aquifers. Farmers use approximately 80 percent of the groundwater withdrawn for irrigation (Texas Water Development Board, 2012c). The 2017 State Water plan indicated that in 2020, 7.2 million acre-feet will come from groundwater, about 47 percent of the existing water supply.

Since the onset of groundwater production in the late 1800s, significant groundwater level declines have occurred in some of the state’s aquifers. The largest declines are in the Trinity Aquifer in the proximity of Dallas, Fort Worth, and Waco, where levels have declined as much as 1,000 feet. In the Ogallala Aquifer, water levels have similarly declined more than 300 feet over the last 60 years in many areas, while other areas in the Ogallala and other aquifers have experienced small water level increases. Even relatively small water level declines have had significant effects in the Gulf Coast Aquifer in areas that are susceptible to land subsidence such as Houston (Texas Water Development Board, 2007) .

4.1.2 Groundwater monitoring

There are many entities that monitor groundwater in Texas. The TWDB has monitoring programs for groundwater levels and groundwater quality and maintains a publicly available database of the information collected. TWDB's water level program has developed an "ideal" monitoring network, considered to be the optimal number of wells needed to represent groundwater levels, of approximately 4,000 observation wells. Staff collects over 2,000 measurements annually and receives approximately 12,500 additional measurements—some from observation wells measured more frequently than once-a-year—from cooperators. The TWDB also has an automatic groundwater level recorder program at 191 sites in 87 counties, with other entities providing additional data, which transmit real-time water level data to the agency's website. The TWDB and its cooperators collect water samples from approximately 350 sites annually, with a goal to sample wells in each aquifer once every four years. Constituents analyzed include major ions, trace elements, and nutrients (Texas Water Development Board, 2016).

The Texas Commission on Environmental Quality maintains an ongoing monitoring program for measuring organic and inorganic constituents in public water supply wells. The U.S. Geological Survey collects both water level and water quality data. As of April 2015, the U.S. Geological Survey monitored 827 wells in 52 counties and 16 springs within its Texas Active Groundwater Level Network; over 65 percent of the wells are located in Harris, Fort Bend, and Montgomery counties (U.S. Geological Survey, 2016f).

Many groundwater conservation districts measure water levels to monitor changes within a district and send these data to the TWDB for incorporation into the TWDB groundwater database. Some of the districts have extensive and sophisticated monitoring networks that supplement the TWDB statewide monitoring network. A smaller number of districts also collect water quality data. Additionally, groundwater data are collected by some river authorities.

4.2 Groundwater law, management, planning, and availability

For about one hundred years, groundwater law remained relatively unchanged in Texas. For about half that time, since 1951, Texans in most areas of the state have opted for local control of groundwater through the establishment of groundwater conservation districts. More recently, over the past 11 years, groundwater conservation districts have come together to plan for aquifer conditions for the ensuing 50 years. Planning and managing groundwater includes groundwater modeling efforts to help better understand groundwater movement. Modeling results include amounts of groundwater that could be permitted to arrive at the aquifer conditions as planned for 50 years in the future. Graphs included in this section describe the amounts of modeled available groundwater in shared aquifers. This section includes details about groundwater law, management, modeling, planning, and availability.

4.2.1 Groundwater law

The legal basis for groundwater withdrawals in Texas began with the Texas Supreme Court decision from the 1904 *Houston & Texas Railroad Co. vs. East* case (Potter, 2004a). The Court's opinion supported the rule of capture doctrine, similar to the absolute ownership doctrine, and this remains unchanged. As a result, landowners were allowed to pump as much water as possible, with no liability to their neighbors. However, the doctrine is modified (described in Section 4.2.2) for certain conditions by court rulings and in most areas where groundwater conservation districts exist. In the East case, the Court ruled in favor of the rule of capture partly because it considered groundwater "secret and occult", making legal regulations impractical (Potter, 2004a).

In 1917, a Conservation Amendment was added to the Texas Constitution, which declared the state's natural resources to be public rights and duties and authorized the Legislature to pass laws to conserve them. This was codified in the Texas Constitution Article XVI Section 59 (Potter, 2004a). Other Texas Supreme Court cases in the 20th century reaffirmed the rule of capture and deferred groundwater regulation to the Legislature, including the 1955 *City of Corpus Christi vs. City of Pleasanton* case, the 1978 *Friendswood Development Co. vs. Smith-Southwest Industries* case, and the 1999 *Sipriano vs. Great Spring Waters of America, Inc.* case (Potter, 2004a). The Texas Supreme Court has imposed some judicial limitations to the rule of capture through the outcomes of these cases by prohibiting pumping that causes malicious harm, prohibiting wasteful pumping, and prohibiting pumping groundwater that causes land subsidence on adjoining land (Potter, 2004a).

In 1949, the Texas Groundwater District Act was passed which authorized the establishment of underground water conservation districts and created a process for designating underground water reservoirs (Mace and others, 2008). In the 1950s, districts began to form in the High Plains, far west Texas, and the Edwards Plateau (Texas Commission on Environmental Quality, 2014). Since 1951 the Texas Legislature has updated the Texas Water Code rules to support creation of groundwater conservation districts to manage groundwater withdrawals locally (Caroom and Maxwell, 2004). Chapter 36 of the Texas Water Code addresses the powers and duties of groundwater conservation districts which allow districts to establish local approaches to withdrawing groundwater, well spacing requirements, and exempt well withdrawal limits (Texas 83rd State Legislature, 2013).

In 2012, the Texas Supreme Court supported groundwater ownership in place and allowed for possible compensation to landowners for groundwater conservation district rules that overreach landowner rights to groundwater (Hecht, 2012). Specifically, this case challenged the Edwards Aquifer Authority's practice of limiting groundwater withdrawals through issuing amount-specific permits without compensation when more groundwater was requested, which tested whether land ownership interests include groundwater in place that cannot be taken for public use (Hecht, 2012).

4.2.2 Groundwater management

The state of Texas has a combination of groundwater management approaches. Since 1949 when the state adopted legislation allowing locally elected, state-sanctioned entities to regulate groundwater withdrawals, groundwater policy has become locally driven (Caroom and Maxwell, 2004). The local entities, groundwater conservation districts, are the state's preferred method of managing groundwater (Mace and others, 2008). Groundwater conservation districts are created to conserve, preserve, protect, recharge, and prevent the waste of groundwater, as well as prevent land subsidence (Mace and others, 2008). The rule of capture exists unmodified in areas without groundwater conservation districts, but a variety of groundwater management approaches may modify the rule of capture within groundwater conservation districts (Potter, 2004a). Since the late 1990s, the number of groundwater conservation districts (Figure 4-3) and subsidence districts has grown from about 44 to 99 districts in 2016. The legislature and citizens have established more groundwater districts over the past 26 years than in the 40 years prior to 1990 (Texas Commission on Environmental Quality, 2014). In 2016, groundwater conservation districts regulated groundwater in about 70 percent of the state's land area.

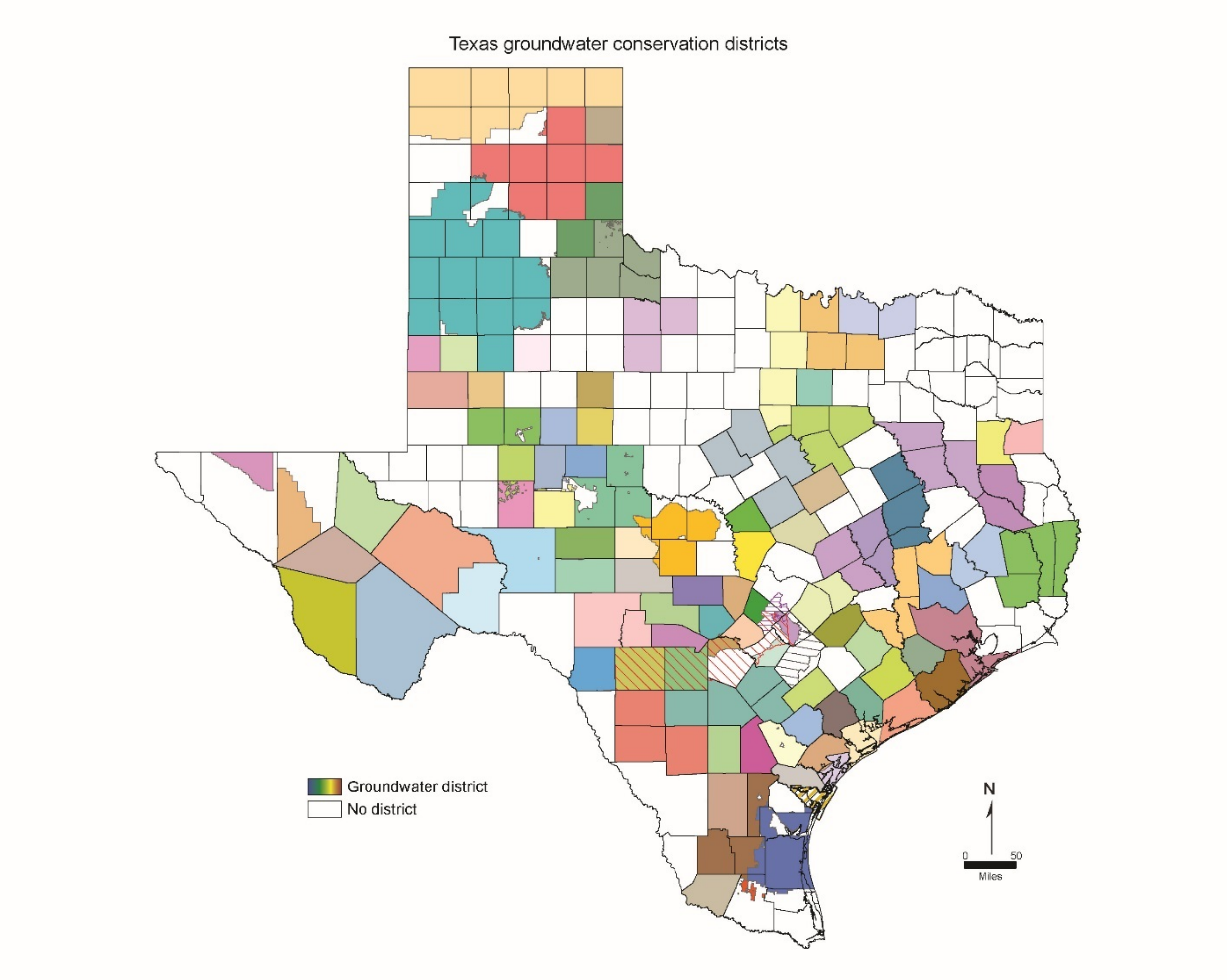

Figure 4-3. Texas groundwater conservation districts, confirmed and unconfirmed, as of April 2017.

***Note*: Areas without colors or patterns do not have groundwater conservation districts.**

In the 1950s, the first several districts were formed through petitions to local Commissioners' Courts and through subsequent court action or petitions to the Texas Board of Water Engineers and by Board order or legislation (TWDB, 2012a). Newer groundwater conservation districts in Texas have been formed through Special Law and subsequent local elections (Texas Natural Resource Conservation Commission, 2001). The Texas Water Code Chapter 35 gives the Texas Commission on Environmental Quality authority to establish groundwater conservation districts through the priority groundwater management area process (Texas Commission on Environmental Quality and Texas Water Development Board, 2013). Priority Groundwater Management Areas are areas that are currently or are expected to experience critical problems with groundwater quality, groundwater quantity, or land subsidence within the next 50 years (Texas Commission on Environmental Quality and Texas Water Development Board, 2013). Before a priority groundwater management area is designated, the Texas Commission on Environmental Quality is charged with conducting a detailed study and compiling a report recommending what direction to take in the establishment of groundwater conservation districts (Texas Commission on Environmental Quality and Texas Water Development Board, 2013).

When a priority groundwater management area is established by the Texas Commission on Environmental Quality, groundwater conservation districts must be formed or the area must be annexed into an existing district within two years (Texas Commission on Environmental Quality and Texas Water Development Board, 2013). Otherwise, the Texas Commission on Environmental Quality may take action to establish a district (Texas Commission on Environmental Quality and Texas Water Development Board, 2013). As of 2016, the Texas Commission on Environmental Quality has designated seven priority groundwater management areas in 35 counties (Texas Commission on Environmental Quality, 2016). Districts created within priority groundwater management areas are expected to address groundwater issues as necessary (Texas Commission on Environmental Quality and Texas Water Development Board, 2013).

Texas Water Code Chapter 36 requires certain duties of groundwater conservation districts, including developing groundwater management plans, maintaining a record of driller logs for water wells, and requiring permits for the drilling and operation of wells (Texas 83rd State Legislature, 2013). Districts are required to exempt certain wells from regulation (Texas 83rd State Legislature, 2013). Exemptions include domestic and livestock wells that are on a tract of land larger than 10 acres and that are unable to produce more than 25,000 gallons a day, water wells for oil and gas exploration, and other wells authorized by the Railroad Commission of Texas (Texas 83rd State Legislature, 2013). District rules may also specify additional wells that are exempt from regulation and decrease or increase the standard 25,000 gallons a day production rate exemption (Texas 83rd State Legislature, 2013).

Texas Water Code Chapter 36 also authorizes groundwater conservation districts to adopt rules using various management approaches to limit groundwater production (Texas 83rd State Legislature, 2013). These rules may include methods such as specifying limits on tract size, well spacing, and priority dates, or historical use requirements in order to prevent land subsidence, water quality degradation, and waste of groundwater (Texas 83rd State Legislature, 2013). Groundwater conservation districts are also authorized under Chapter 36 to buy and sell groundwater or surface water, acquire land by eminent domain, conduct surveys and monitoring programs, require the capping of uncovered wells, and require permits for transferring water out of the district (Texas 83rd State Legislature, 2013).

Texas is divided into 16 groundwater management areas (Figure 4-4), with one area not having any groundwater conservation districts, and 16 regional water planning areas (Figure 4-5) with somewhat similar boundaries (Mace and others, 2008). Groundwater management areas have existed in Texas through investigations beginning in 1987. Texas Water Development Board and the Texas Commission on Environmental Quality delineate these areas together using data collected by both agencies. Until September 2001, the primary purposes of delineating priority groundwater management areas were to allow for the creation of groundwater conservation districts and to identify areas with water quality issues or water elevation declines (Texas Natural Resource Conservation Commission, 1997). After September 2001, the 76th Legislature formulated a new type of groundwater management area differing from a priority groundwater management area; the primary purpose of this new area is to facilitate joint planning in the entire state by groundwater conservation districts (Texas Commission on Environmental Quality and Texas Water Development Board, 2009). Senate Bill 2 (Texas 76th State Legislature, 2001) required the TWDB to delineate groundwater management areas that covered all of the major and minor aquifers in the state using hydrologic and political boundaries. Senate Bill 2 also updated Chapter 36 of the Texas Water Code by requiring groundwater conservation districts to share their management plans with the other districts in the same management area (Texas 76th State Legislature, 2001).

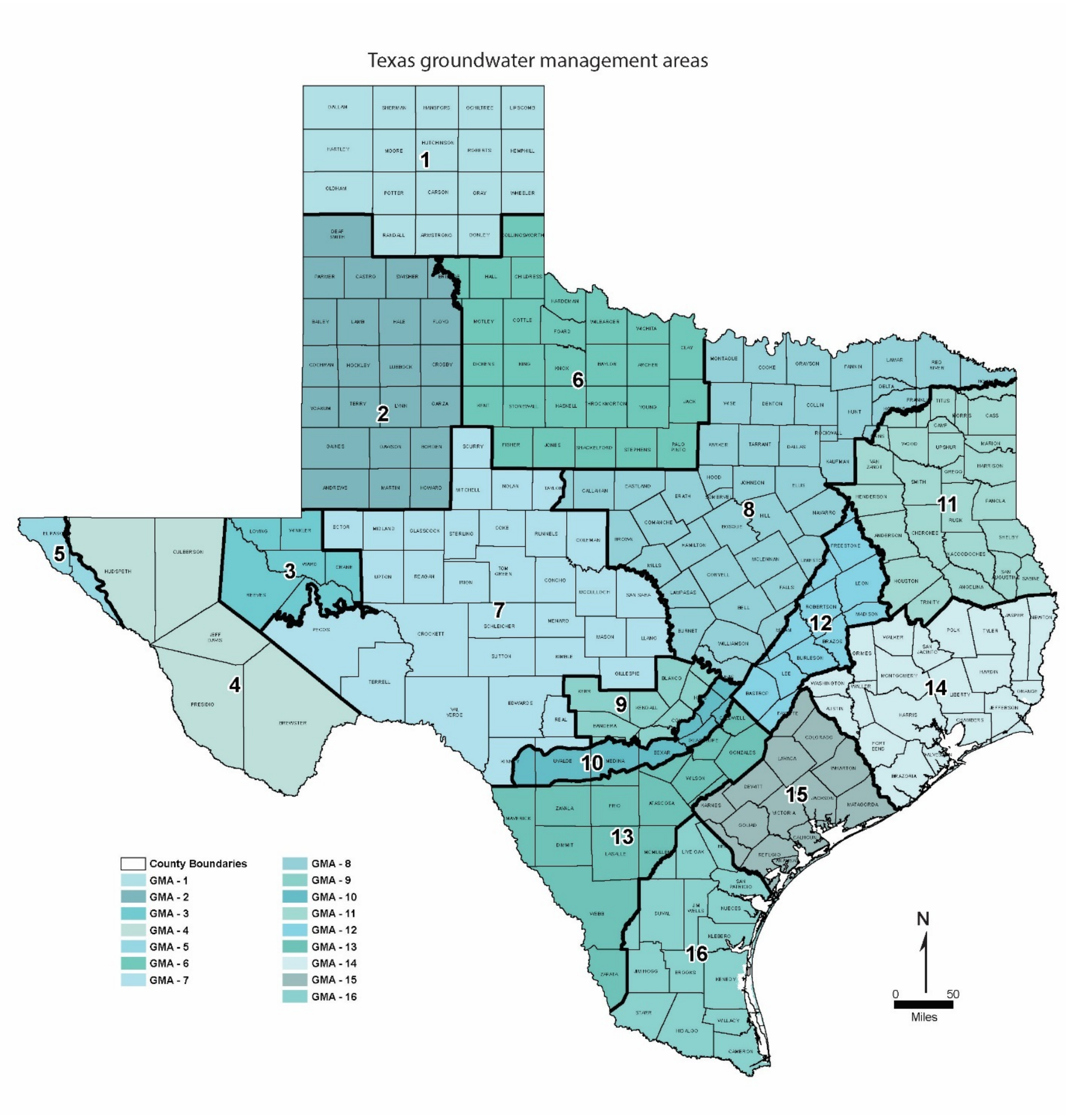

Figure 4-4. Texas groundwater management areas.

4.2.3 Groundwater availability modeling

Groundwater availability models are an essential component of groundwater management in Texas. Groundwater availability models include scientific and technical information on each aquifer, such as recharge (amount of water entering the aquifer), geology, surface water features, water levels, aquifer properties, and pumping.

The TWDB initiates the process of developing groundwater availability models by involving stakeholders. Stakeholders are often concerned with water-level changes due to pumping, future groundwater availability, evaluating groundwater management strategies, and finding local alternative supplies. To address these concerns and bring local understanding of the aquifers into focus, TWDB holds stakeholder advisory forums (SAFs) when developing conceptual model inputs. Meetings are locally publicized and involve targeted invitations to relevant participants. For example, groundwater availability model development for the Presidio-Redford Bolsons—an aquifer system located about two-thirds in Presidio County, Texas and one-third in Chihuahua, Mexico—included stakeholders focused on international and interstate concerns. Groundwater model development stakeholder meetings in Presidio, Texas, included representatives from the International Boundary and Water Commission, Comisión Internacional de Límites y Aguas, City of Presidio, state and federal parks, state agencies, journalists, educators, water suppliers, consultants, landowners, and groundwater conservation districts.

Groundwater conservation districts are required to use information from groundwater availability models (if available) in the development of management plans. Districts also use the models to evaluate possible desired future conditions for aquifers, resulting in values of modeled available groundwater (see section 4.2.5 Groundwater availability). In addition, the models are used by regional planning groups to evaluate the effects of increased pumping and water availability trends. Models cover parts or all of 9 major and 21 minor aquifers, with 8 minor aquifer models in various stages of development. Several models extend outside the state to reach natural boundaries or to a distance considered effective for modeling in Texas. Groundwater availability models are developed by the TWDB or by external contractors or cooperators, such as the Edwards Aquifer Authority, U.S. Geological Survey, El Paso Water Utilities, and Harris-Galveston Coastal Subsidence District, and then adopted by the TWDB Groundwater Availability Modeling program (Texas Water Development Board, 2007).

4.2.4 Water planning

Regional planning groups plan for both groundwater and surface water using information provided by the TWDB and by regional and local entities. Each local groundwater conservation district develops a five-year plan using applicable state-identified goals. The state is divided into 16 areas called groundwater management areas that are comprised of most groundwater conservation districts. Three districts which have some authority over groundwater withdrawals, the Edwards Aquifer Authority, Harris-Galveston Subsidence District, and Fort Bend Subsidence District, are non-voting members in the relevant management areas. Every five years groundwater conservation districts together develop policy statement about aquifers for a 50-year planning process called desired future conditions. These statements are the basis for the TWDB's calculation of groundwater availability amounts, called modeled available groundwater, for inclusion in regional water plans and eventually the state water plan.

Regional water planning

Senate Bill 1, sweeping water legislation passed in 1997, made groundwater conservation district management plans mandatory (Texas Natural Resource Conservation Commission, 2001). The bill also authorized and provided funding to regional water planning groups to develop bottom-up, consensus-based regional plans for surface water and groundwater resources throughout Texas (Texas Groundwater Protection Committee, 2012). Development of this process stemmed from an increased awareness of drought and limitations of the water supply. In 1998 the TWDB delineated 16 regional water planning areas (Figure 4-5) covering the state (Texas Water Development Board, 2002). Planning groups within each area are responsible for developing a regional water plan, and public participation is an important part of the regional planning process (Texas Water Development Board, 2002). Regional water plans aim to address the conservation, development, and management of water supplies; to identify where water shortages will occur during a repeat of the drought of record; and to recommend strategies or conservation methods to meet future water supply needs over a 50-year period (Texas Water Development Board, 2013).

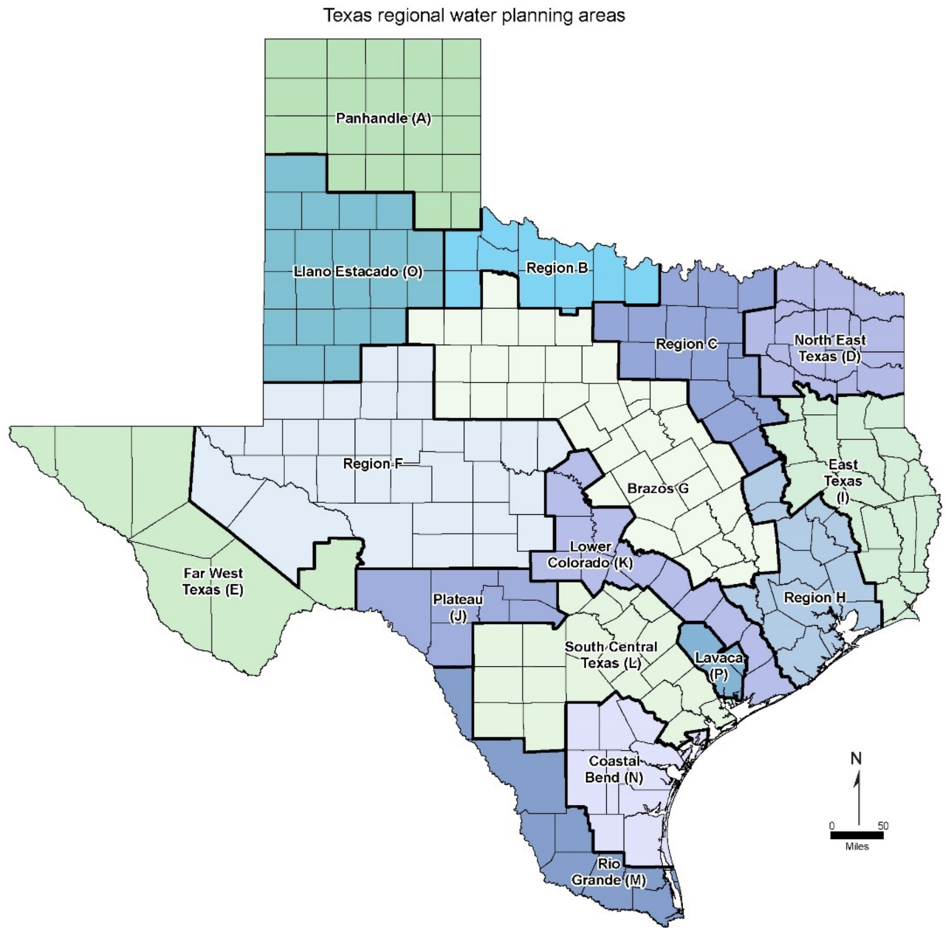

Figure 4-5. **Texas regional water planning areas.**

The regional planning groups are composed of at least 12 specified stakeholder interests: agriculture, counties, electric generating utilities, environmental, industries, municipalities, public, river authority, small business, groundwater management areas, water districts, and water utilities (Texas Water Development Board, 2013). These stakeholders identify both the state's water needs and water management strategies to meet those needs (Texas Water Development Board, 2013).

International coordination

Out of the 16 2016 regional plans, seven regions (A, E, F, I, J, M, and O) acknowledged other states' participation in the planning process or shared groundwater resources. The two largest water planning regions bordering Mexico, regions E and M, discussed water resources with representatives from outside the planning regions in regional water planning meetings and included non-voting members from Mexico on their membership rosters. The Region E Water Planning Group invited representatives from Mexico and New Mexico to attend meetings and to help plan, including one member from the International Boundary and Water Commission, which is a U.S. federal agency, and one member from the Mexican counterpart Comisión Internacional de Limites y Aguas. Region M did likewise, with four non-voting members from the International Boundary and Water Commission, two members from Comisión Nacional del Agua, and one member from Comisión Internacional de Limites y Aguas.

Shared surface water management is addressed specifically through interstate compacts outlined in the Texas Water Code. The Texas Commission on Environmental Quality reported in their Fall 2010 Natural Outlook newsletter article, *If a River Runs through It, Texas Shares the Water,* that managing surface water resources shared by multiple states would be almost impossible without interstate water compacts (Texas Commission on Environmental Quality, 2010). International shared surface water is managed through treaties applied by the International Boundary and Water Commission and the Comisión Internacional de Limites y Aguas, but no such parallel exists specifically for groundwater (Texas Legislature, 2014). For example, groundwater flow from the Edwards-Trinity (Plateau) Aquifer in Texas into the Amistad Aquifer in Mexico contributes to joint United States-Mexico treaty-managed releases to the Rio Grande River, but the groundwater component is quantified as surface water once it flows into the reservoir.

In 1985, the 69th Texas Legislature promulgated Texas Water Code Chapter 8, establishing a state agency called the Multi-State Water Resources Commission to study water resources and create groundwater compacts addressing shared aquifers. However, this commission was not activated until the 84th Texas Legislature in 2015, when it was also renamed the Southwest Regional Water Planning Commission. Along with restating its membership and updating the focus to include discussions with other states and Mexico, a new part of the mission is designating areas where the present and future water supply is not sufficient to meet the future requirements, even after considering water conservation in the projections of future needs. These discussions may address water development, augmenting water supplies on a regional basis after existing water supplies are fully committed in Texas, and possibly establishing compacts with other states and Mexico. The TWDB provides administrative assistance for these tasks. As part of the 2015 legislation, commission membership changed from public representatives to state leadership with three members including the governor, a senator with committee membership in water, and a representative with committee membership natural resources.

4.2.5 Groundwater conservation district joint planning

House Bill 1763, passed in 2005, updated the Texas Water Code Chapter 36 by requiring joint planning within groundwater management areas (Mace and others, 2008). Joint planning requires groundwater conservation districts located within the same management area to meet at least annually, to review district management plans and accomplishments of the management area, and propose to adopt new or amend existing desired future conditions (Mace and others, 2008). The Texas Water Code, Section 36.001, Subsection (30) defines desired future conditions as "…a quantitative description, adopted in accordance with Section 36.108, of the desired condition of the groundwater resources in a management area at one or more specified future times." Joint planning takes place through public meetings within each groundwater management area, and desired future conditions are established for not only areas with groundwater conservation districts but for non-district areas as well (Mace and others, 2008). The deadline for the first round of desired future conditions was September 1, 2010 (Mace and others, 2008), which all groundwater management areas met. Although the conditions must be readopted every five years, they can be readopted as often as the groundwater management area desires (Mace and others, 2008). Groundwater conservation districts also have the option to declare an aquifer or portion of an aquifer as non-relevant, therefore choosing not to establish a desired future condition for that particular aquifer or portion thereof (Texas Water Development Board, 2012b).

In 2011, the Texas 82nd Legislature required groundwater conservation districts to provide official representatives to the appropriate regional water planning groups to help coordinate the regional and statewide groundwater planning efforts (Texas Water Development Board, 2014b). Additional changes to the joint planning process from the 82nd Legislature included a requirement to consider the following factors prior to proposing a desired future condition: aquifer uses, water supply needs and strategies, hydrological conditions, environmental impacts, subsidence, socioeconomic impacts, impacts on private property rights, and the feasibility of achieving the desired future conditions (Texas Water Development Board, 2014a). Changes were also made to strengthen stakeholder involvement, with a requirement for a public comment period and public hearings prior to final adoption of the desired future conditions (Texas 83rd State Legislature, 2013).

In 2013, the Texas 83rd Legislature made changes to the desired future condition appeal process. Prior to September 1, 2015, the TWDB reviewed petitions about the reasonableness of desired future conditions with the new process requiring petitioners to submit a petition directly to a groundwater conservation district. The groundwater conservation district then contracts with the State Office of Administrative Hearings and the TWDB provides an administrative completeness and technical review of a petition.

After final adoption, the groundwater conservation district submits desired future conditions to the TWDB, and TWDB staff calculate modeled available groundwater estimates (see next section, Groundwater availability). After adopting desired future conditions, districts must address their progress in achieving these conditions as part of their management plan goals (Texas 83rd State Legislature, 2013).

4.2.6 Groundwater availability

Groundwater availability in Texas is defined as the amount of groundwater that is available for use from an aquifer, determined by both management policy and the scientific understanding of an aquifer (Mace and others, 2001). The process for determining groundwater availability has undergone a transition in Texas. Since 1997, regional water planning groups determined groundwater availability for planning purposes, and these amounts were reported in regional and state water plans. At the same time, groundwater conservation districts were able to define their own groundwater availability estimates in their management plans, and for permitting purposes, as long as that volume was not less than the regional planning estimates, to implement these plans (Mace and others, 2008).

Since the passage of House Bill 1763 in 2005, groundwater availability is established by groundwater conservation districts through the joint planning process based on a policy choice, the desired future conditions. Once the districts in a groundwater management area adopt final desired future conditions, they are submitted to the TWDB for scientific evaluation. TWDB staff use groundwater availability models or other appropriate methods to calculate modeled available groundwater—the total volume of water that can be pumped to achieve the desired future condition (Mace and others, 2008). Modeled available groundwater is defined in the Texas Water Code, Section 36.001, subsection (25) as "…the amount of water that the executive administrator determines may be produced on an average annual basis to achieve a desired future condition established under Section 36.108". TWDB also provides estimates of groundwater withdrawals exempt from permitting to the groundwater conservation districts for their consideration when quantifying permitted amounts of groundwater available in a district (Texas 83rd State Legislature, 2013). Appendix C lists the most recently adopted desired future conditions the groundwater management areas developed and the resulting groundwater availability from TWDB estimates for aquifers Texas shares with Mexico and surrounding states. Note that in counties or parts of counties without groundwater conservation districts, the desired future conditions are not being managed and are irrelevant except if a groundwater conservation district is formed or for regional and state water planning.

Once the estimated amount of modeled available groundwater is calculated, groundwater conservation districts are required to include these numbers in each management plan and regional water planning groups are required to use the estimates as groundwater availability volumes in their regional plans (Texas 83rd State Legislature, 2013). These groundwater availability values are one of several considerations for permitting in groundwater conservation districts in Texas, according to each district's rules and management plan. Values are compiled from TWDB modeled available groundwater reports listed under each relevant groundwater management area (http://www.twdb.texas.gov/groundwater/management_areas/index.asp).

Each groundwater management area developed policy approaches to determine what relevant aquifers would look like in 50 years. Modeled available groundwater values quantified in acre-feet per year are listed in Appendix C by aquifer, county, and potentially affected states (Table C-2 through Table C-12). Figures 4-6 through 4-39 show graphs of the modeled available groundwater estimates determined through the desired future conditions policy goals in years 2020, 2030, and 2040 generated from the tables in Appendix C. Each graph represents a groundwater management area and aquifer and the affected counties. If the modeled available groundwater is zero, the graph will show a county but with no values.

Due to the deadline for determining desired future conditions and the cycles of the regional water plans, the 2016 regional plans and 2017 State Water Plan include, for the first time, all modeled available groundwater estimates. These estimates listed in the appendix are the from the first five-year cycle desired future condition decision-making process which ended in 2010. The deadline for the second round of planning was not required before May 1, 2016, slightly extending the second five-year cycle. Two areas excluded from the desired future conditions process are the San Antonio Segment of the Edwards (Balcones Fault Zone) Aquifer (Texas Water Development Board, 2014d) and the Hueco-Mesilla Bolsons Aquifer in Groundwater Management Area 5. For the San Antonio Segment of the Edwards (Balcones Fault Zone)

Aquifer, groundwater availability is defined by the Texas Legislature (Texas Water Development Board, 2014d). Because no groundwater conservation districts exist within Groundwater Management Area 5, the joint planning process and establishment of desired future conditions are not applicable (Mace and others, 2008). Groundwater availability for the Hueco-Mesilla Bolsons Aquifer is currently and will continue to be estimated by Region E unless a groundwater conservation district is formed (Mace and others, 2008; Texas Water Development Board, 2014b). Groundwater availability for aquifers or portions of aquifers declared non-relevant by groundwater conservation districts through the joint planning process will also continue to be defined by the regional water planning groups (Mace and others, 2008).

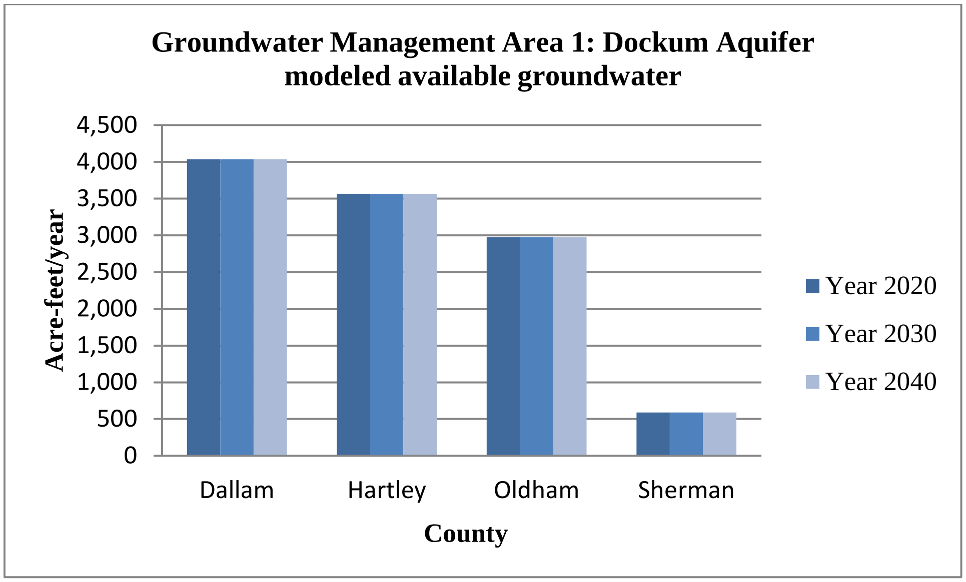

Figure 4-6. **Groundwater availability estimates for Dockum Aquifer Groundwater Management Area 1.**

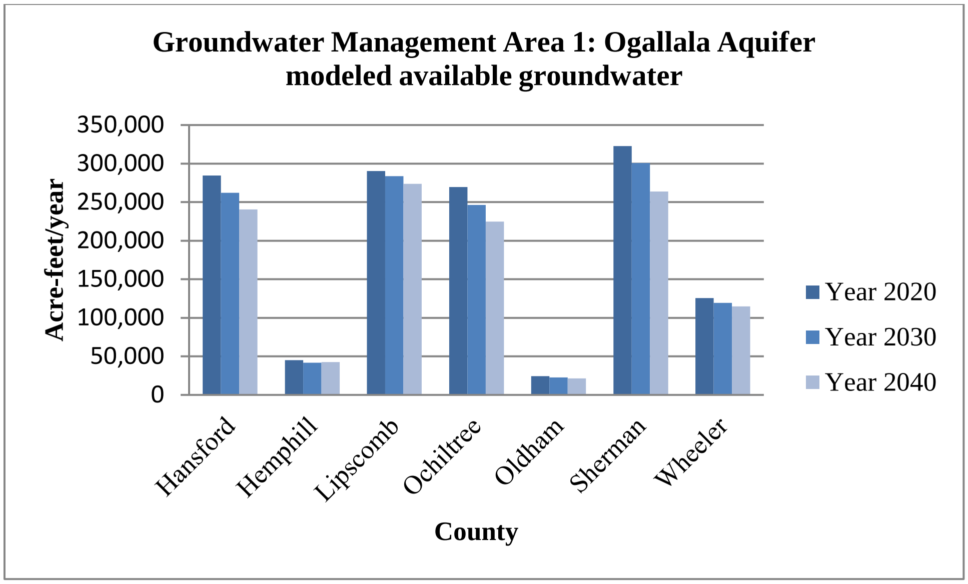

Figure 4-7. **Groundwater availability estimates for Ogallala Aquifer Groundwater Management Area 1.**

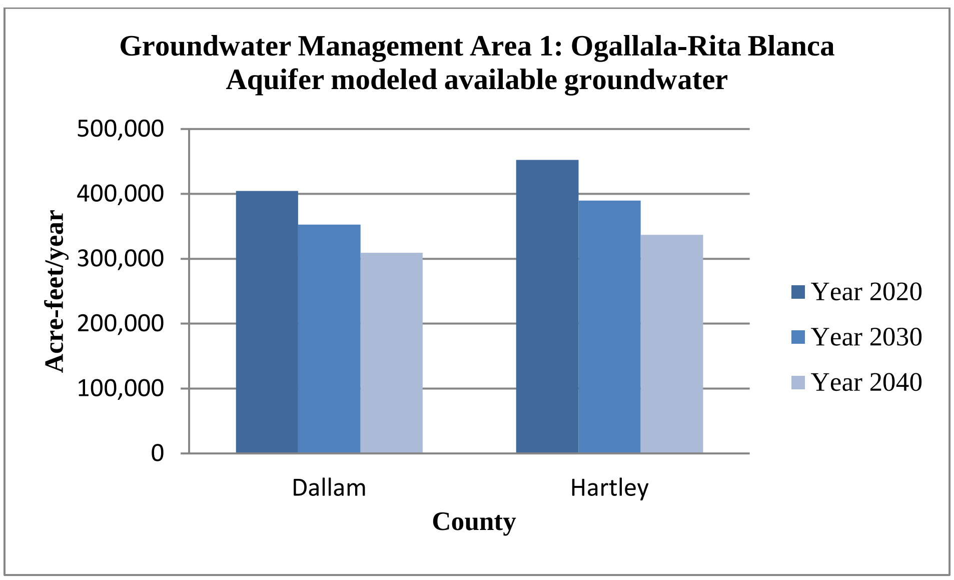

Figure 4-8. **Groundwater availability estimates for Ogallala-Rita Blanca Aquifer Groundwater Management Area 1.**

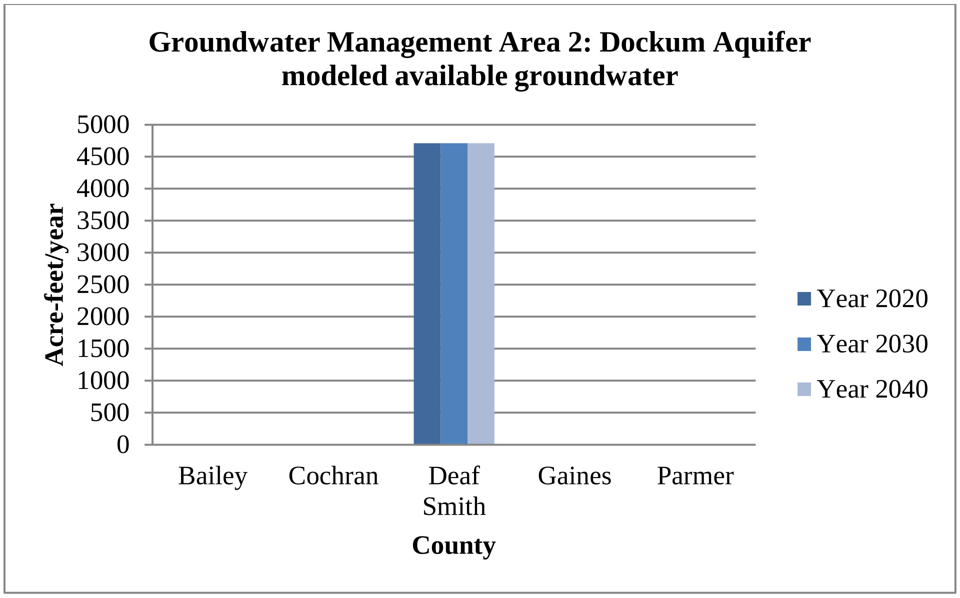

Figure 4-9. **Groundwater availability estimates for Dockum Aquifer Groundwater Management Area 2.**

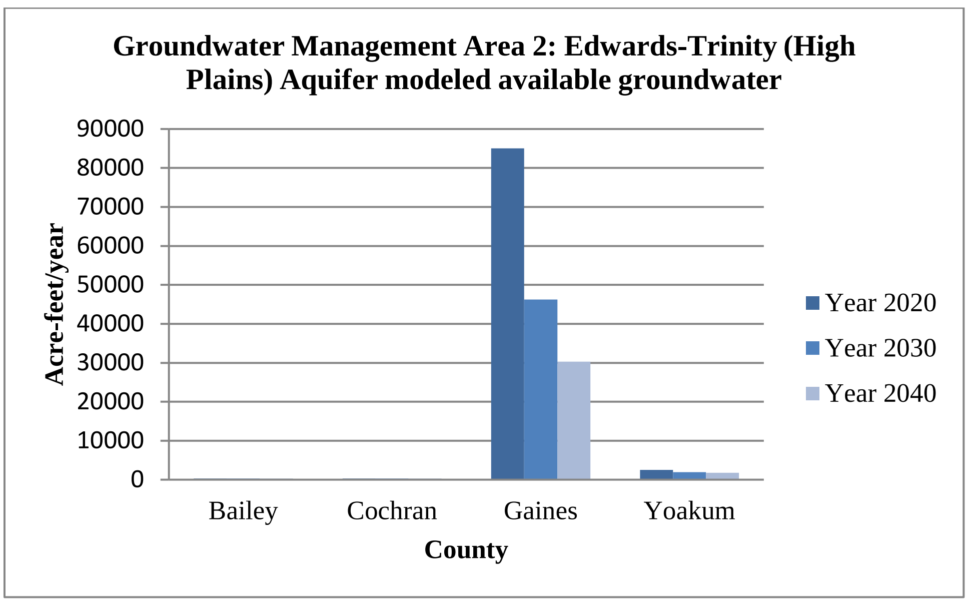

Figure 4-10. **Groundwater availability estimates for Edwards-Trinity (High Plains) Aquifer Groundwater Management Area 2.**

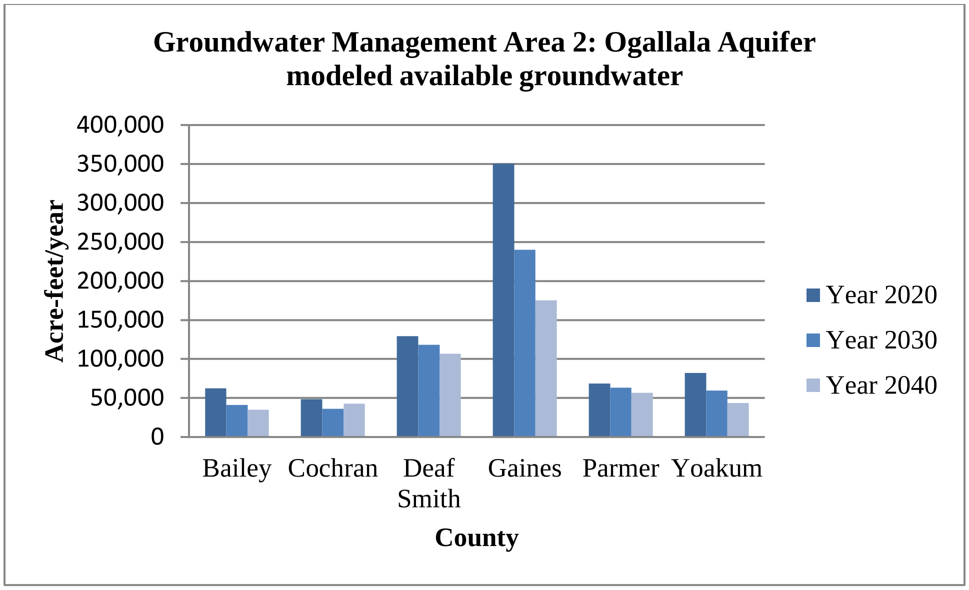

Figure 4-11. Groundwater availability estimates for Ogallala Aquifer Groundwater Management Area 2.

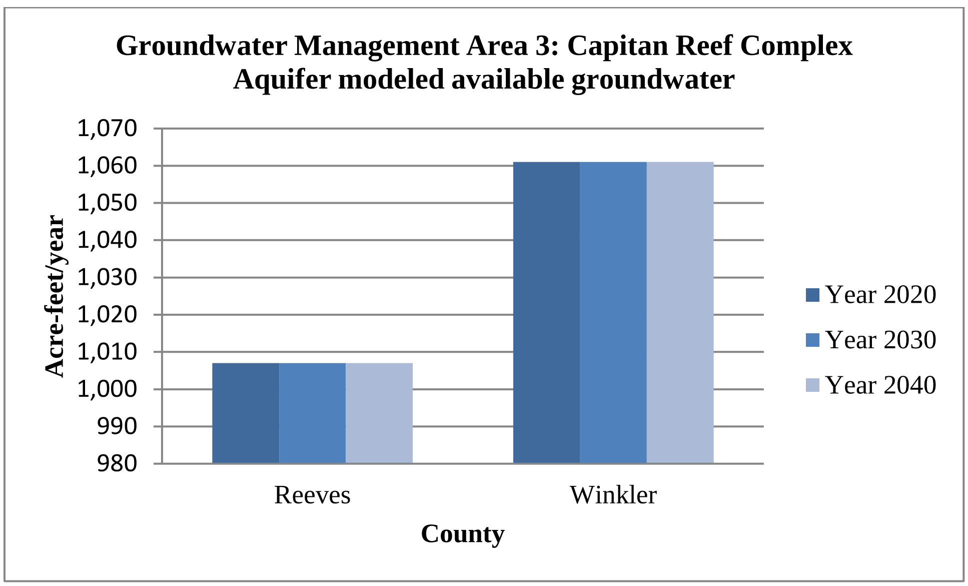

Figure 4-12. Groundwater availability estimates for the Capitan Reef Complex Aquifer Groundwater Management Area 3.

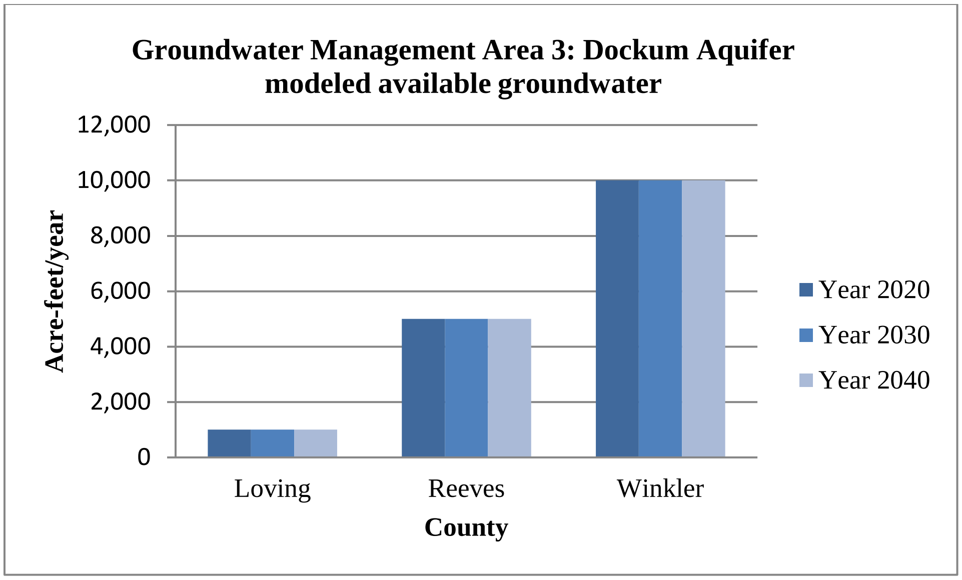

Figure 4-13. **Groundwater availability estimates for Dockum Aquifer Groundwater Management Area 3.**

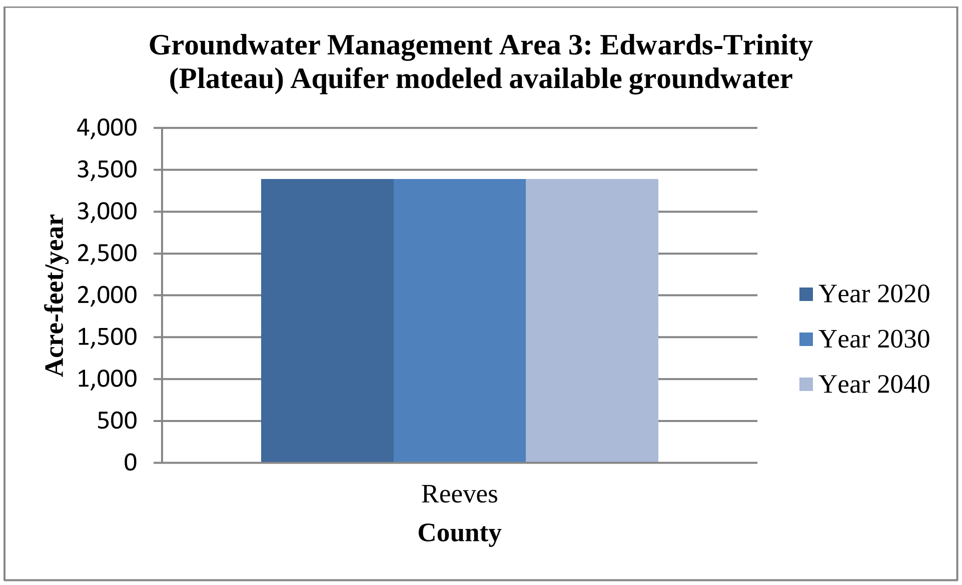

Figure 4-14. **Groundwater availability estimates for Edwards-Trinity (Plateau) Aquifer Groundwater Management Area 3.**

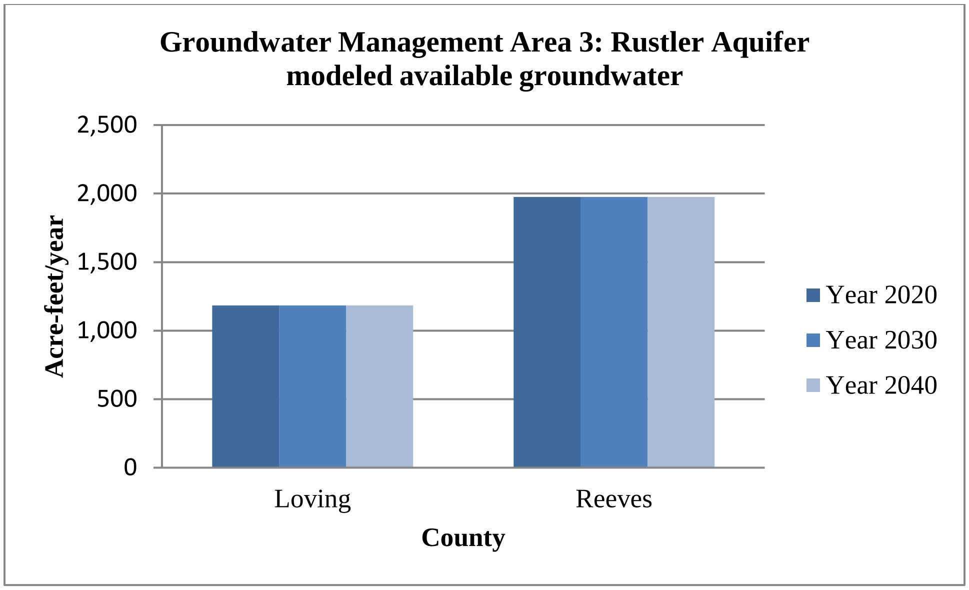

Figure 4-15. **Groundwater availability estimates for Rustler Aquifer Groundwater Management Area 3.**

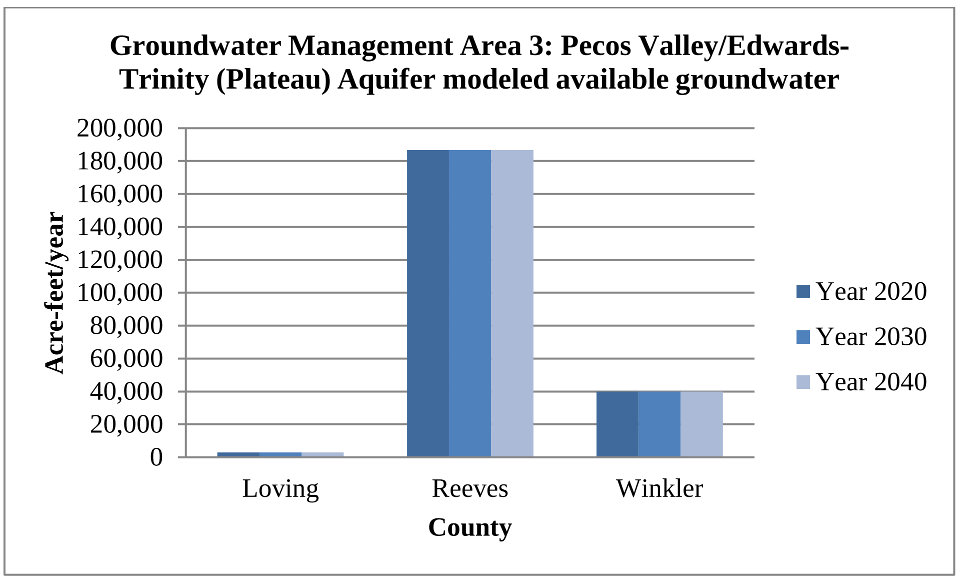

Figure 4-16. **Groundwater availability estimates for Pecos Valley Aquifer Groundwater Management Area 3.**

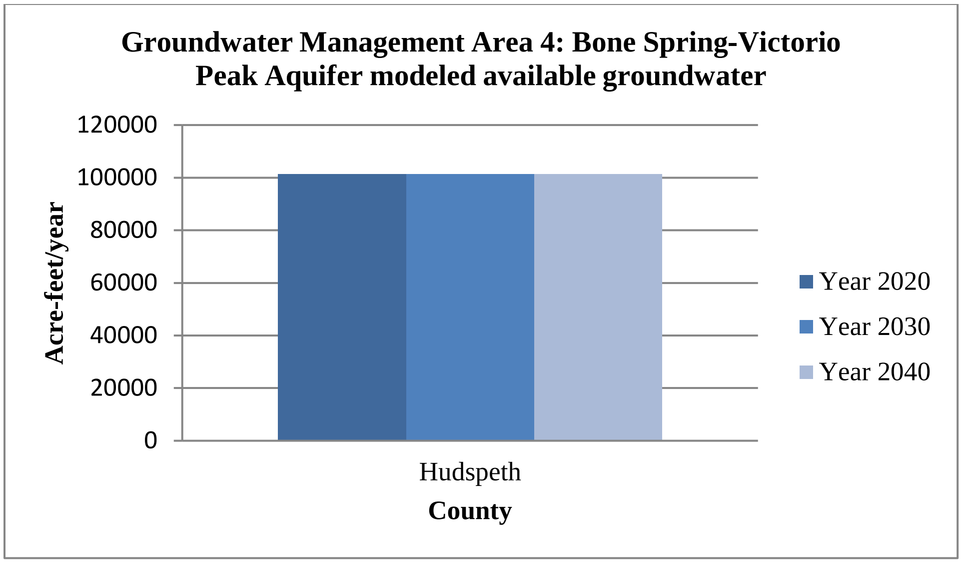

Figure 4-17. **Groundwater availability estimates for Bone Spring-Victorio Peak Aquifer Groundwater Management Area 4.**

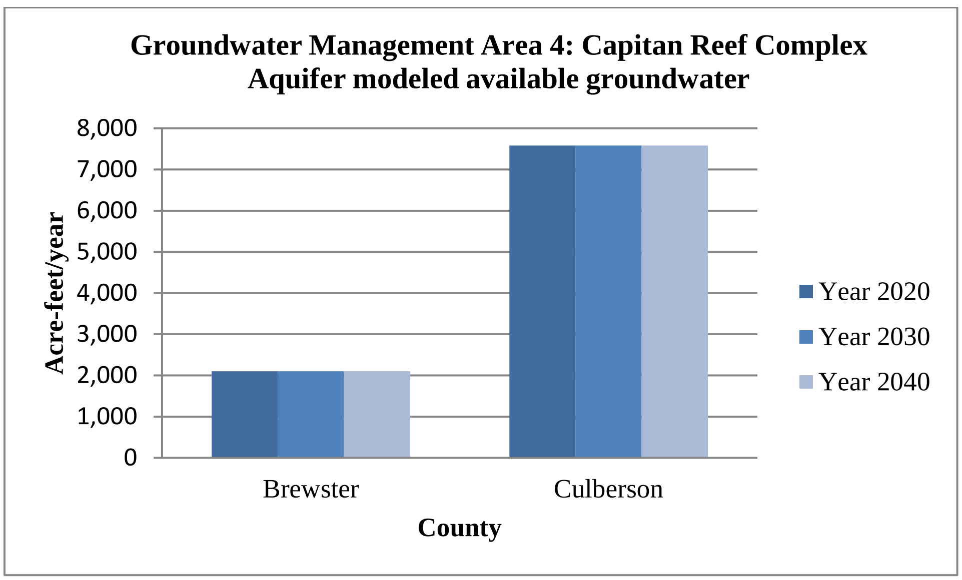

Figure 4-18. **Groundwater availability estimates for Capitan Reef Complex Aquifer Groundwater Management Area 4.**

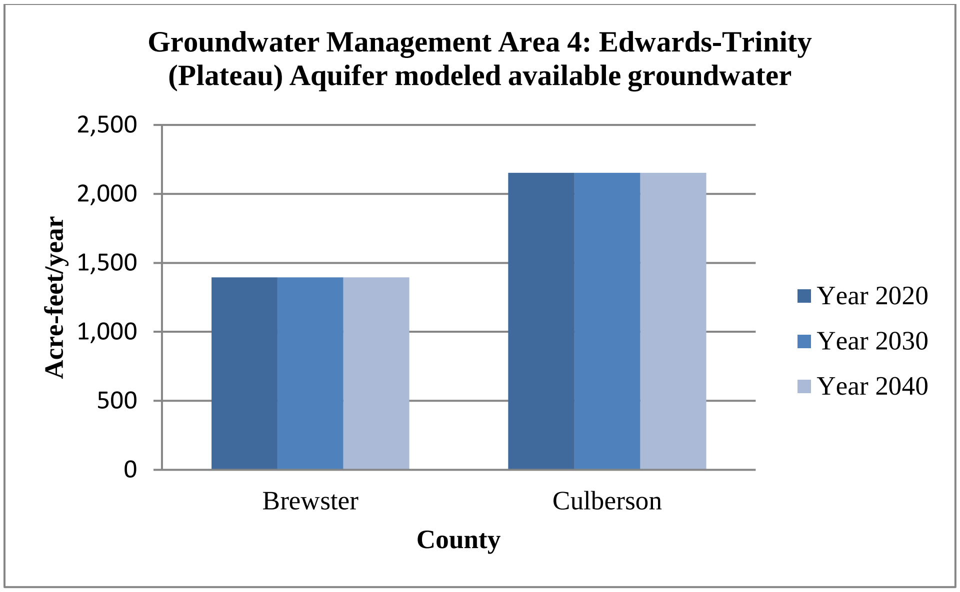

Figure 4-19. Groundwater availability estimates for Edwards-Trinity (Plateau) Aquifer Groundwater Management Area 4.

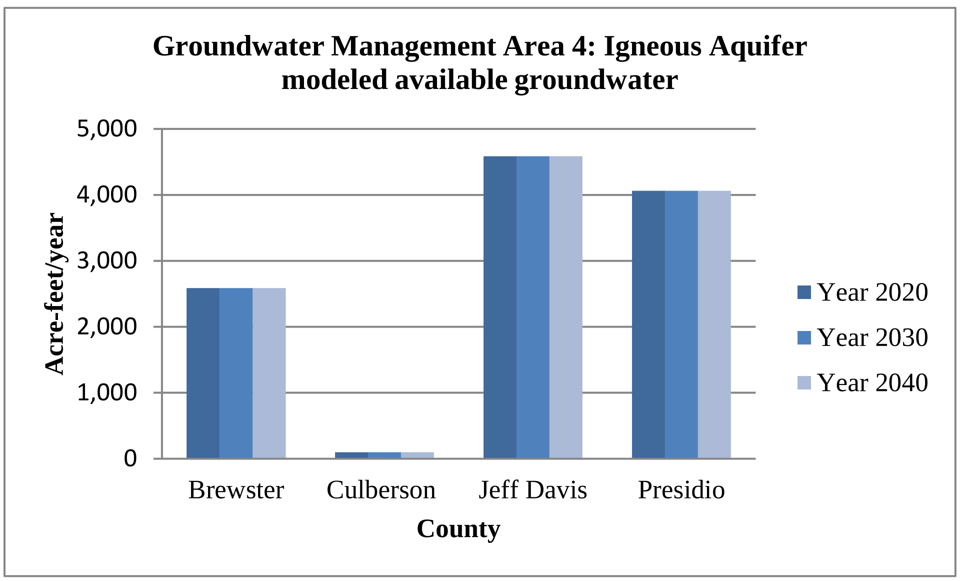

Figure 4-20. Groundwater availability estimates for Igneous Aquifer Groundwater Management Area 4.

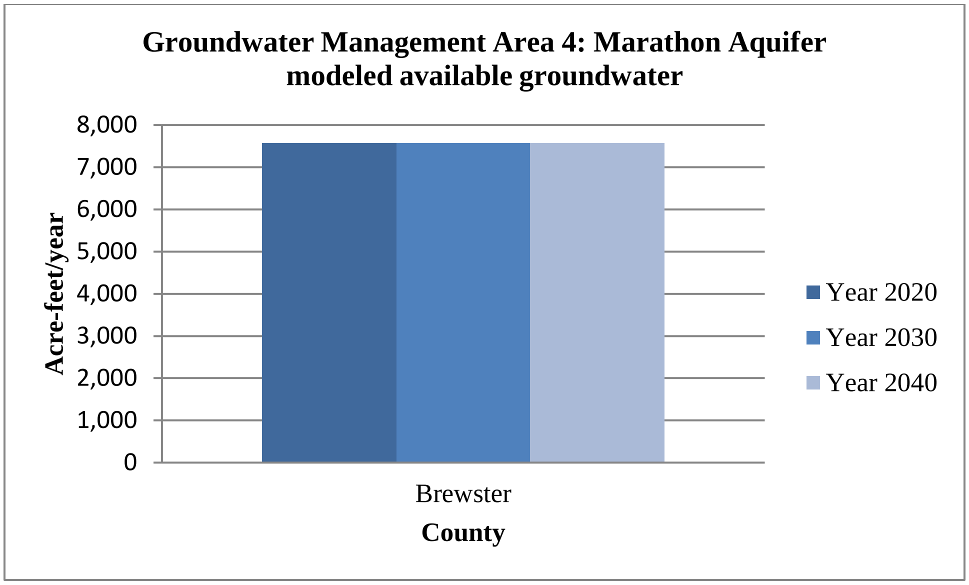

Figure 4-21. **Groundwater availability estimates for Marathon Aquifer Groundwater Management Area 4.**

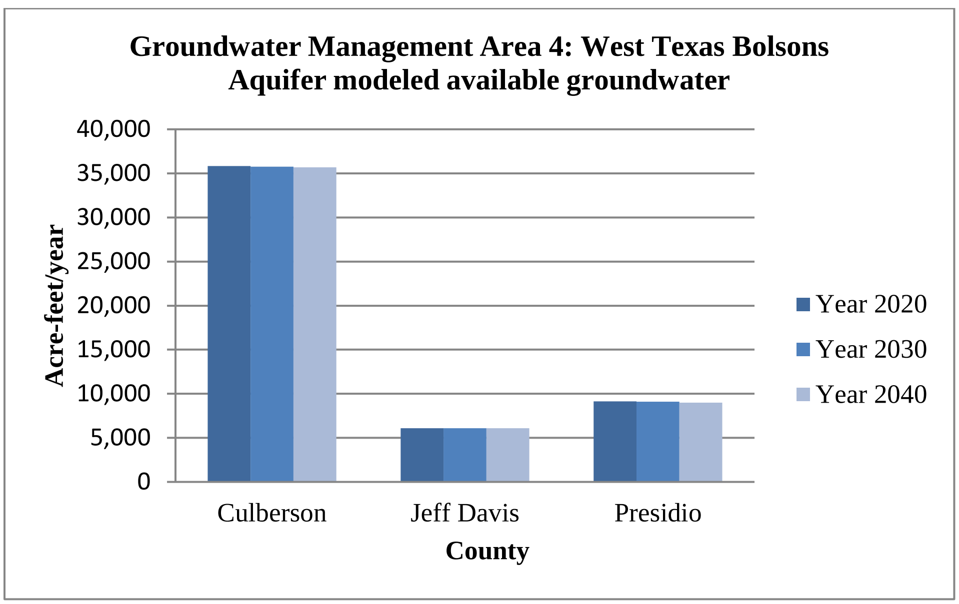

Figure 4-22. **Groundwater availability estimates for West Texas Bolsons Aquifer Groundwater Management Area 4.**

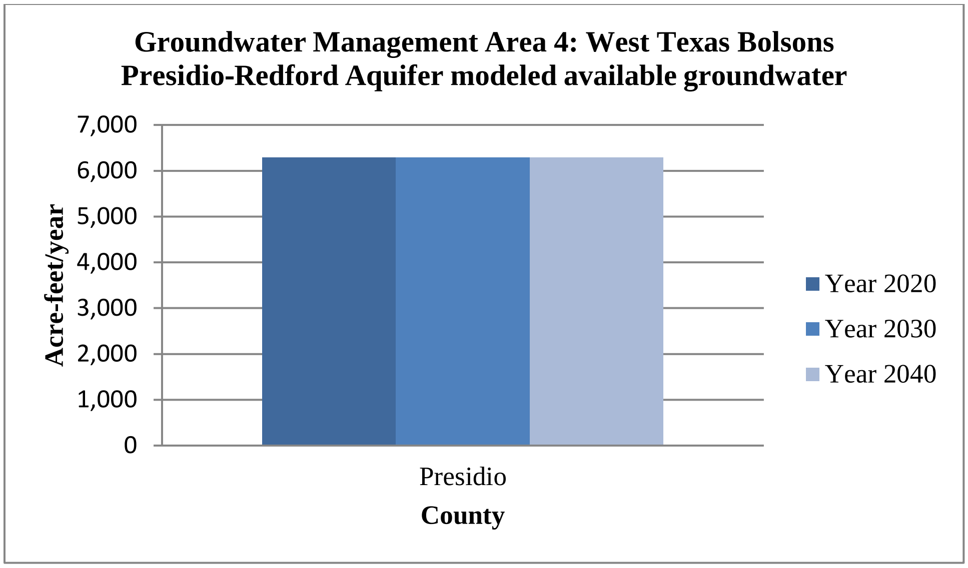

Figure 4-23. **Groundwater availability estimates for Presidio-Redford Aquifer Groundwater Management Area 4.**

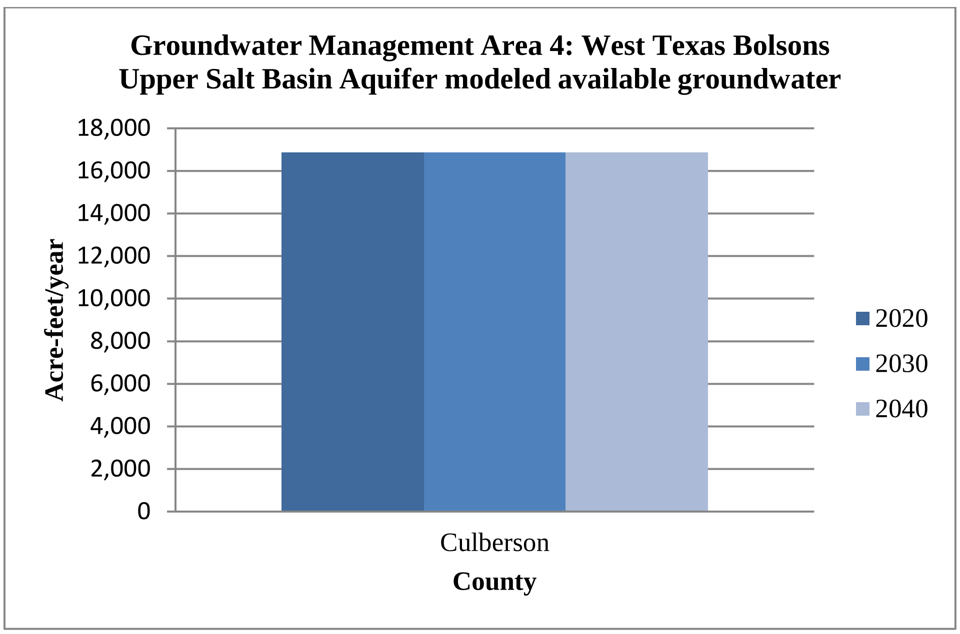

Figure 4-24. **Groundwater availability estimates for Upper Salt Basin Aquifer Groundwater Management Area 4.**

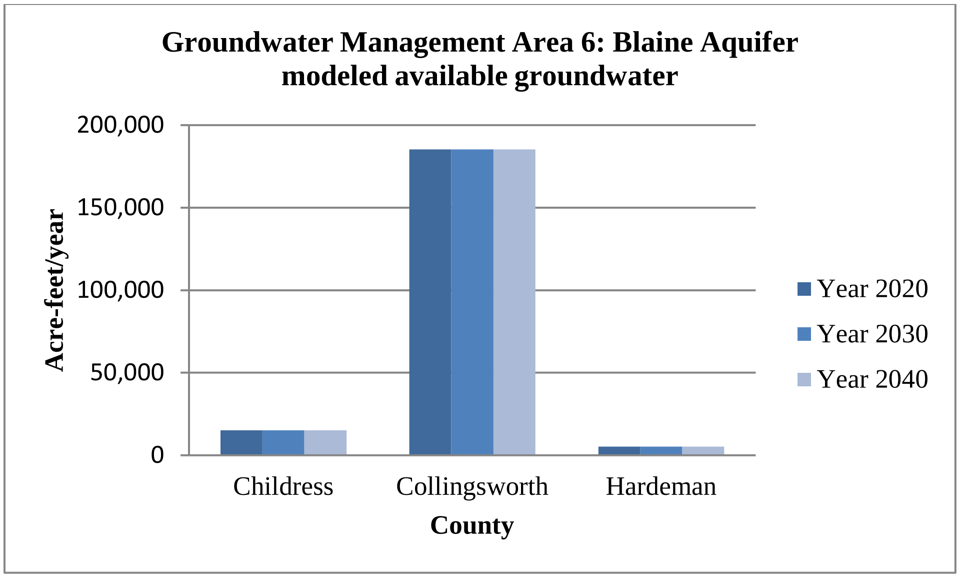

Figure 4-25. **Groundwater availability estimates for Blaine Aquifer Groundwater Management Area 6.**

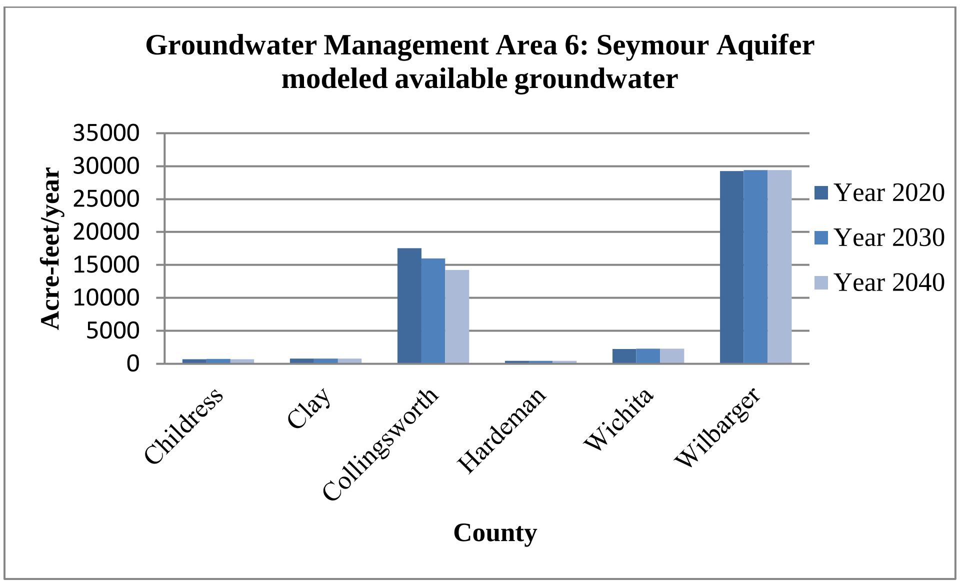

Figure 4-26. **Groundwater availability estimates for Seymour Aquifer Groundwater Management Area 6.**

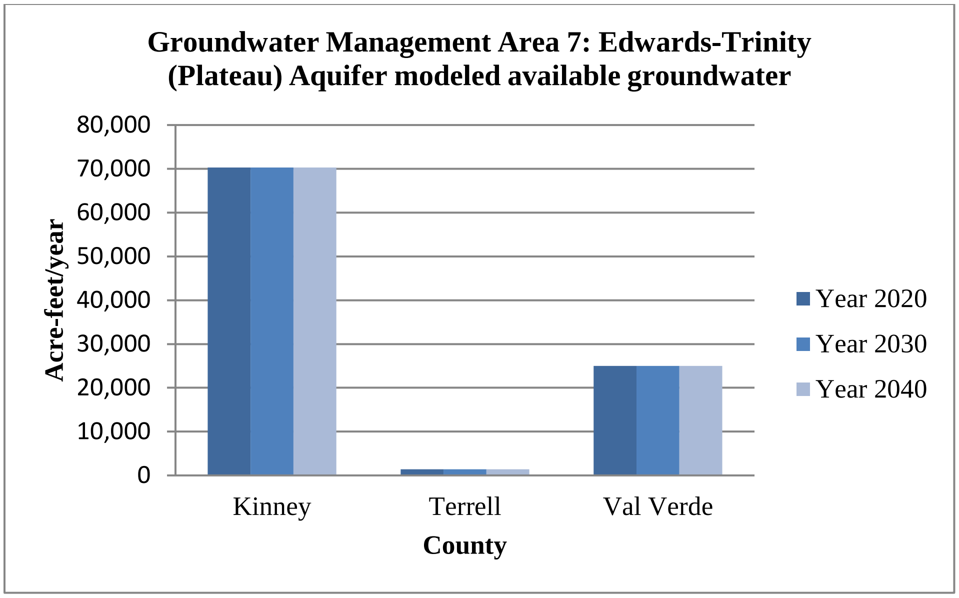

Figure 4-27. **Groundwater availability estimates for Edwards-Trinity (Plateau) Aquifer Groundwater Management Area 7.**

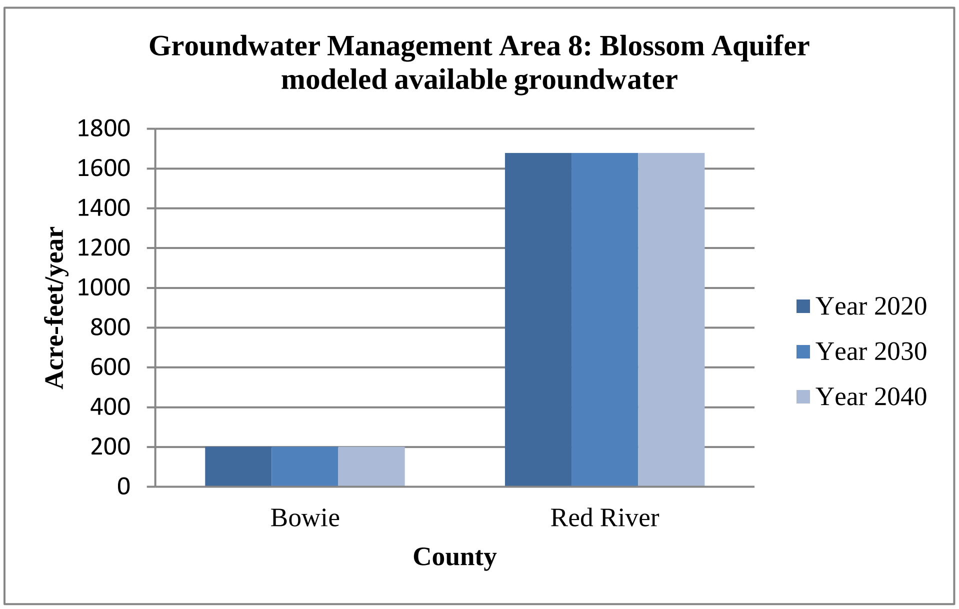

Figure 4-28. **Groundwater availability estimates for Blossom Aquifer Groundwater Management Area 8.**

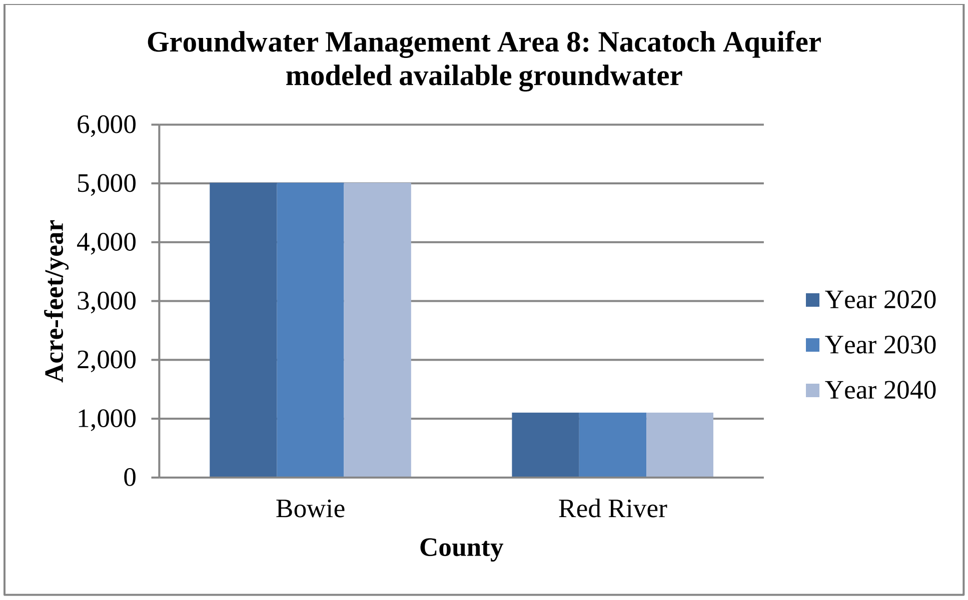

Figure 4-29. Groundwater availability estimates for Nacatoch Aquifer Groundwater Management Area 8.

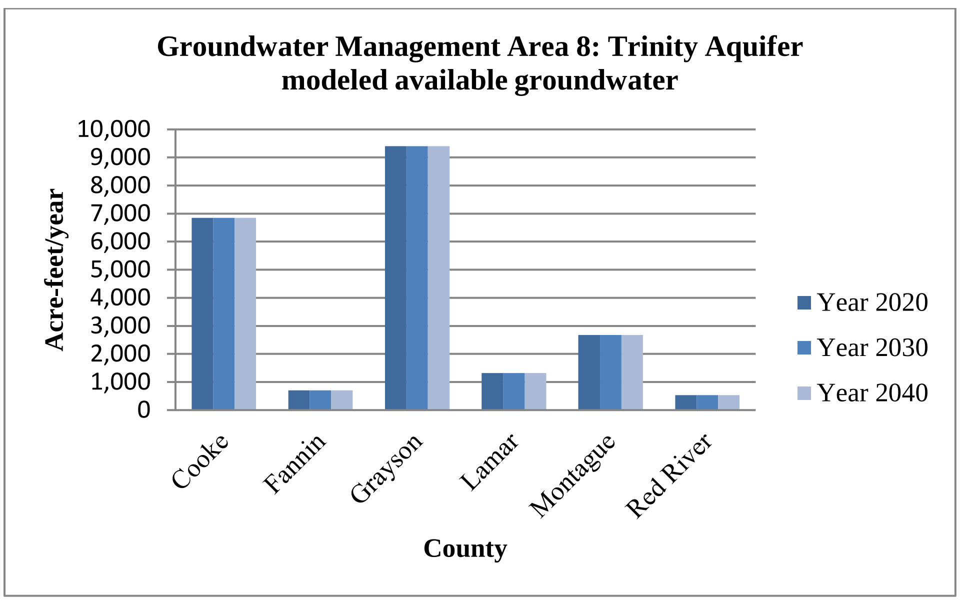

Figure 4-30. Groundwater availability estimates for Trinity Aquifer Groundwater Management Area 8.

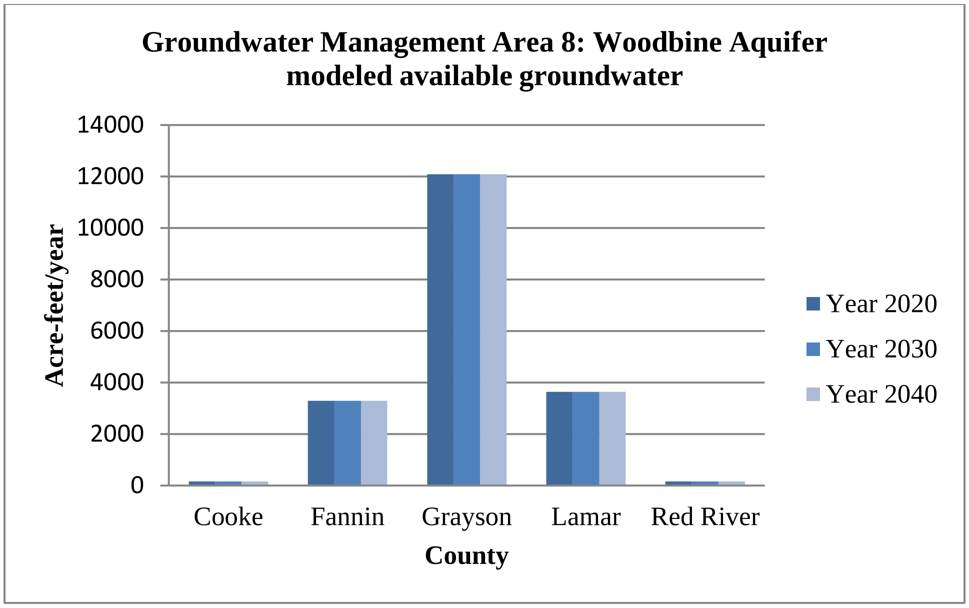

Figure 4-31. **Groundwater availability estimates for Woodbine Aquifer Groundwater Management Area 8.**

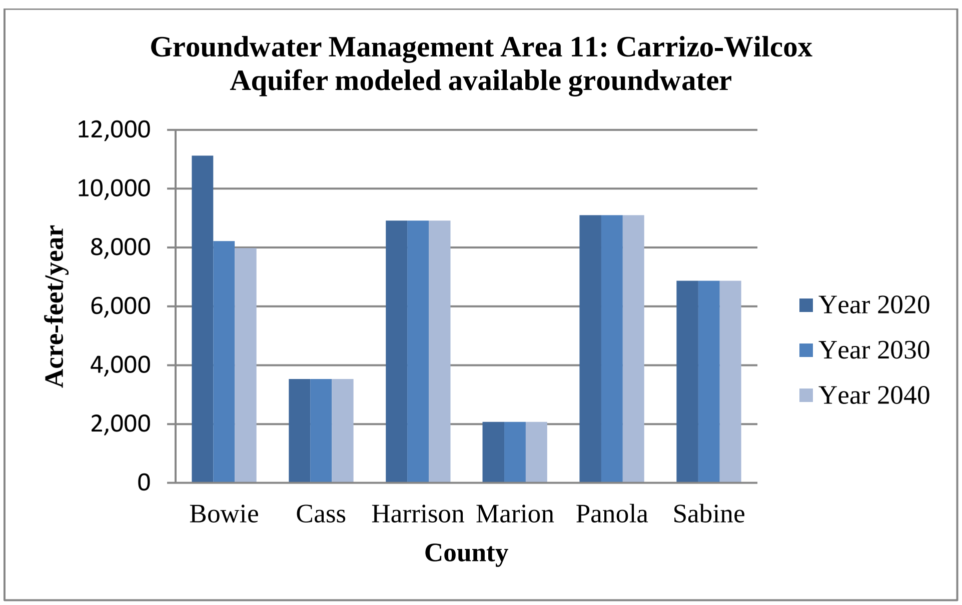

Figure 4-32. **Groundwater availability estimates for Carrizo-Wilcox Aquifer Groundwater Management Area 11.**

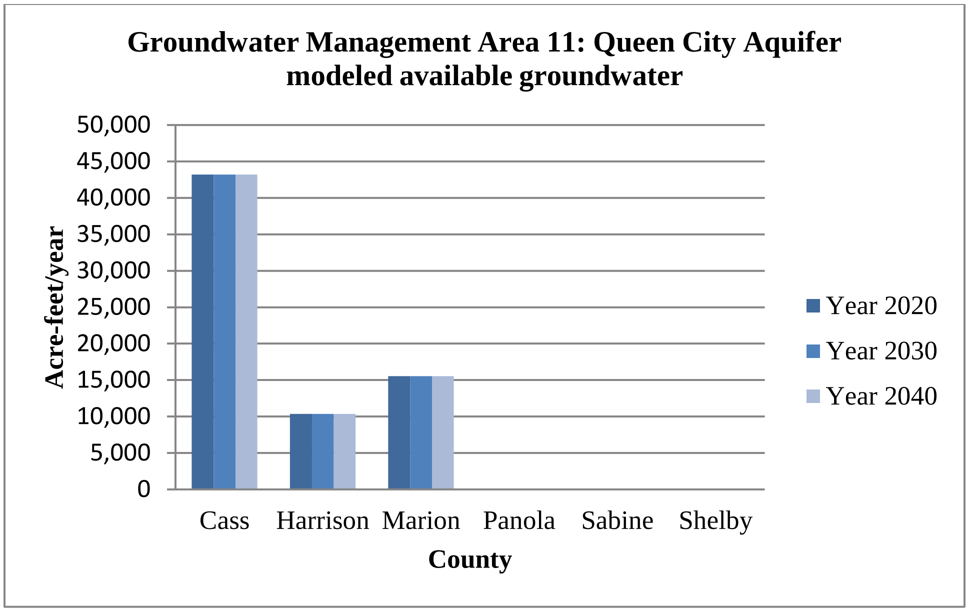

Figure 4-33. **Groundwater availability estimates for Queen City Aquifer Groundwater Management Area 11.**

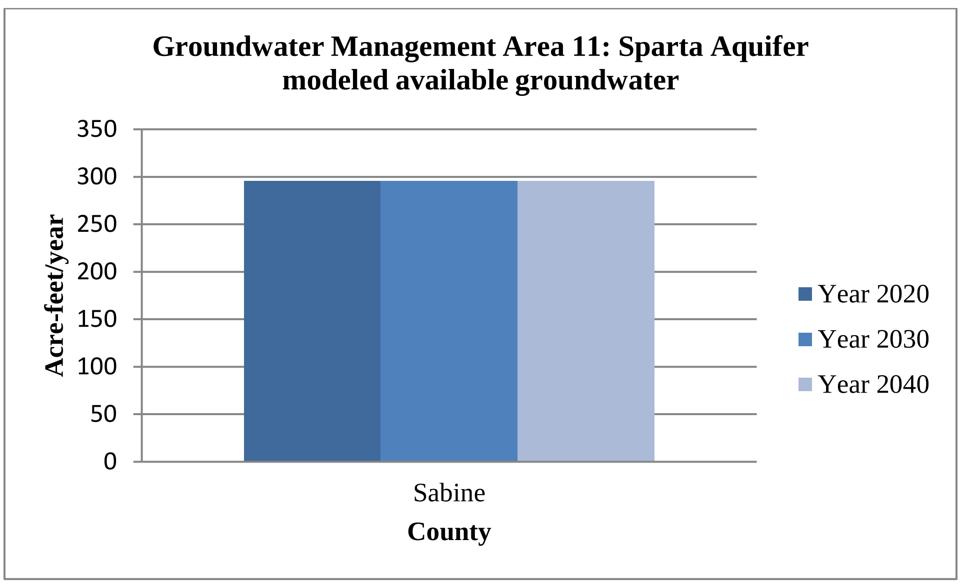

Figure 4-34. **Groundwater availability estimates for Sparta Aquifer Groundwater Management Area 11.**

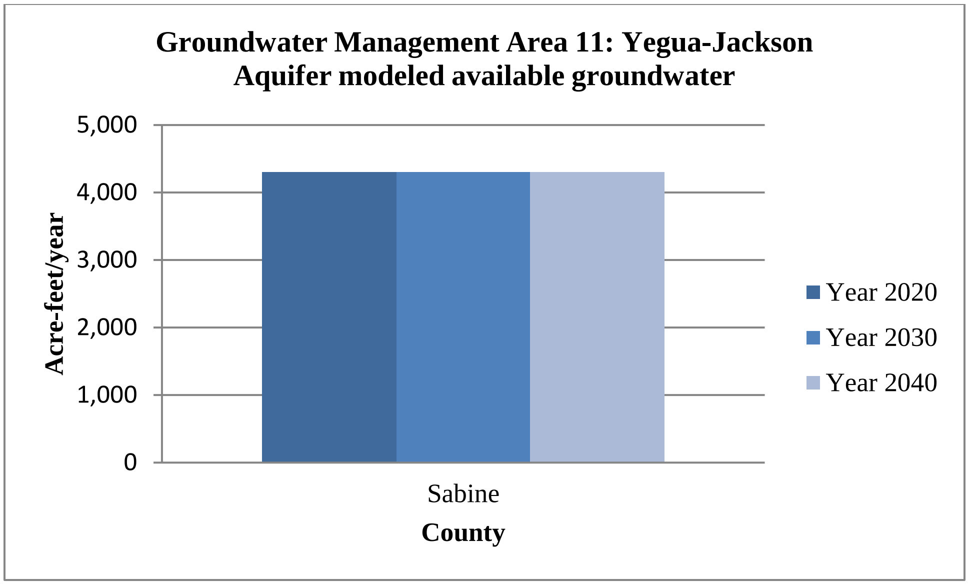

Figure 4-35. **Groundwater availability estimates for Yegua-Jackson Aquifer Groundwater Management Area 11.**

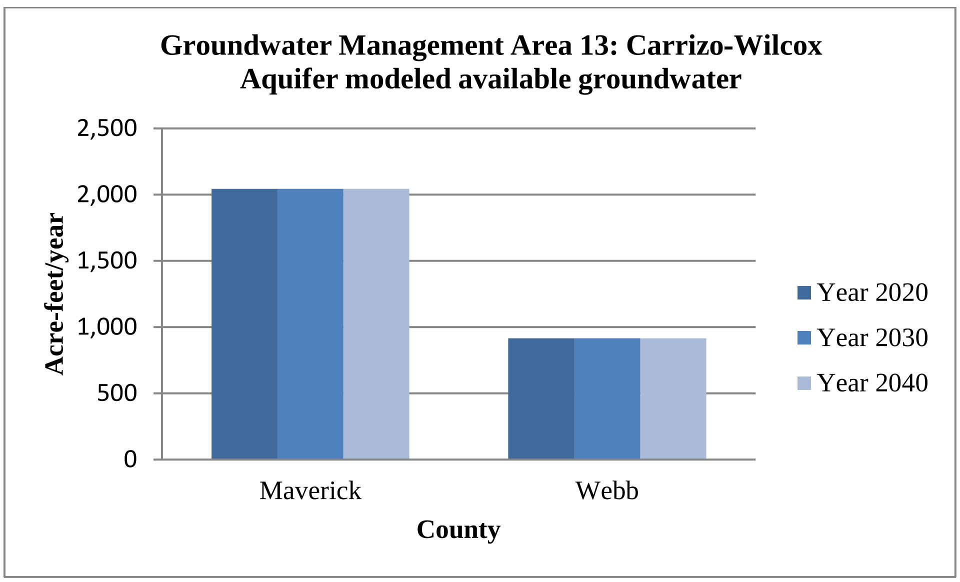

Figure 4-36. **Groundwater availability estimates for Carrizo-Wilcox Aquifer Groundwater Management Area 13.**

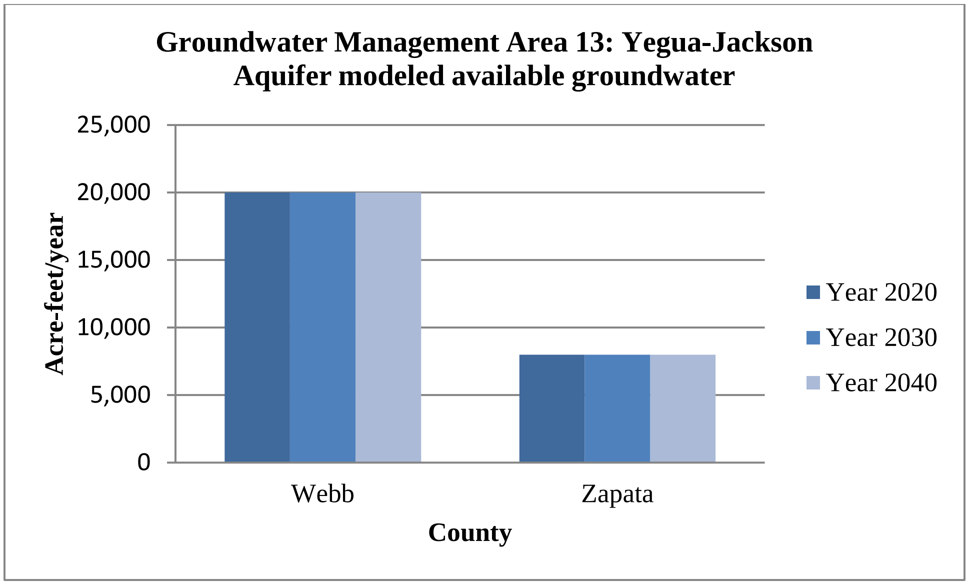

Figure 4-37. **Groundwater availability estimates for Yegua-Jackson Aquifer Groundwater Management Area 13.**

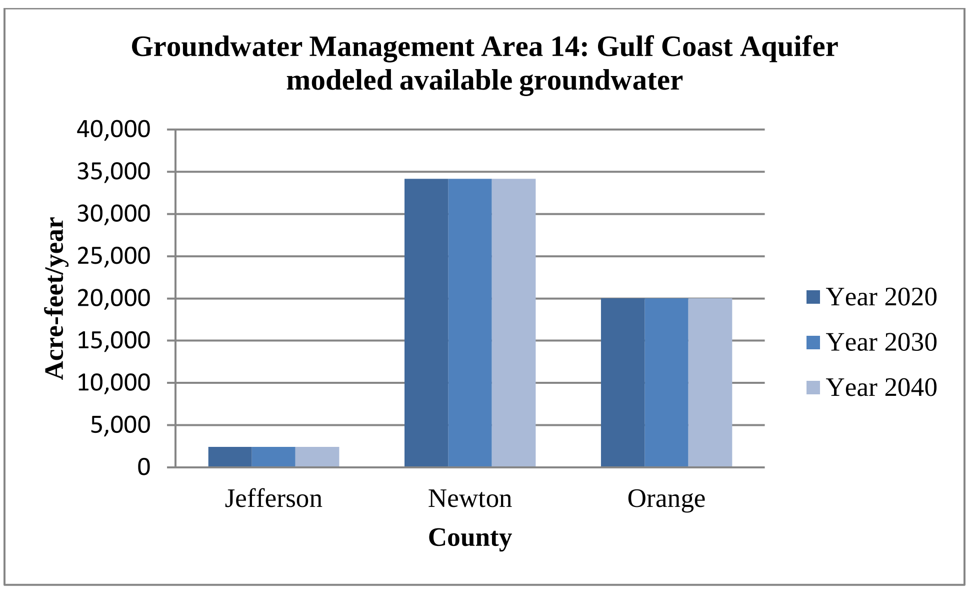

Figure 4-38. **Groundwater availability estimates for Gulf Coast Aquifer Groundwater Management Area 14.**

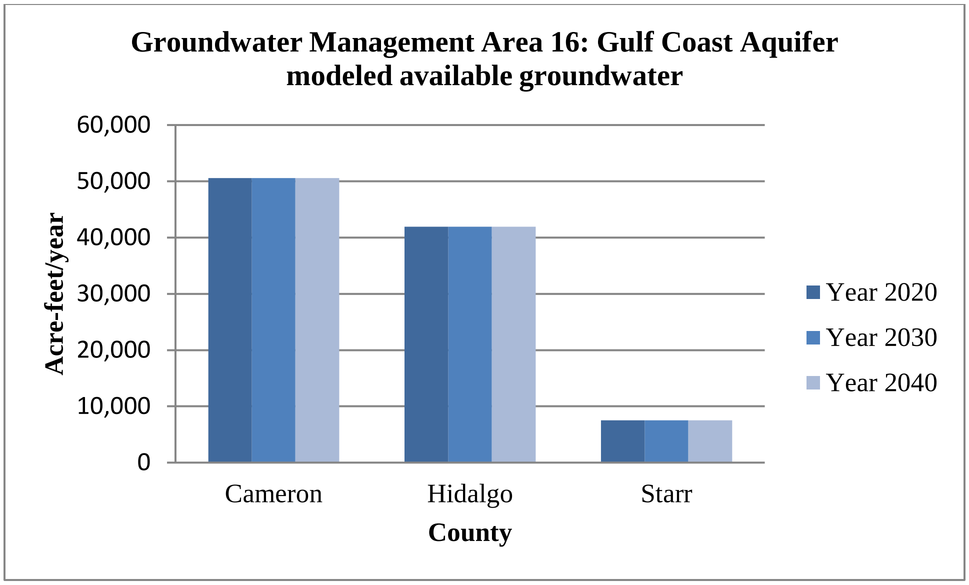

Figure 4-39. Groundwater availability estimates for Gulf Coast Aquifer Groundwater Management Area 16.

4.3 Institutions

A variety of agencies and organizations affect groundwater policy in Texas. This list is not exhaustive. Most entities described actively monitor, study, plan for, or manage groundwater resources in the state and many are governmental agencies that exist in response to governmental legislation.

4.3.1 International, national, and regional institutions

Border Environment Cooperation Commission — The binational Border Environment Cooperation Commission, together with the North American Development Bank, work to plan, finance, and implement environmental and public health infrastructure projects in the United States-Mexico border area. The Border Environment Cooperation Commission provides technical assistance during project development, facilitate stakeholder meetings, certifies projects as technically feasible, identifies the impacts of projects on the environment and public health, and ensures that communities are involved in project development. These interdependent institutions focus on projects that provide potable water treatment and distribution, wastewater collection and treatment, water conservation, and municipal solid waste management.

North American Development Bank — The North American Development Bank is a binational institution that administers the financing for environmental and public health infrastructure projects certified by the Border Environment Cooperation Commission. In addition to funding project implementation through loans and grants, the North American Development Bank provides financial guidance and technical assistance. These interdependent institutions focus on projects that provide potable water treatment and distribution, wastewater collection and treatment, water conservation, and municipal solid waste management.

U.S. Geological Survey — The U.S. Geological Survey collects water-related data and conducts research on water resources throughout the United States. The Texas Water Science Center of the U.S. Geological Survey is involved in many groundwater projects, including studies of Barton Springs and the Edwards Aquifer, land subsidence in the Gulf Coast Aquifer, groundwater quality in the Ogallala Aquifer, and groundwater conditions in the Trinity River Basin. The U.S. Geological Survey monitors water levels in wells throughout the state and maintains monitoring sites at many springs.

U.S. Environmental Protection Agency — The U.S. Environmental Protection Agency is responsible for designating sole source aquifers and establishing baseline water quality and public drinking water standards for groundwater and surface water. In addition, the agency oversees the regulation of several operations that can affect groundwater, including hazardous waste sites, point sources that discharge pollution into surface waters, underground injection wells, underground storage tanks, and solid waste landfills. In Texas, the agency has authorized the Texas Commission on Environmental Quality and the Texas Railroad Commission to implement many of these regulatory functions. Texas is within Region 6 of the U.S. Environmental Protection Agency, which is responsible for implementing and enforcing compliance of water pollution control laws within Arkansas, Louisiana, New Mexico, Oklahoma, and Texas, including the 66 tribal nations in the region. Although the agency does not regulate private groundwater wells, Region 6 provides technical assistance to support groundwater protection. The U.S. Environmental Protection Agency is also a national coordinator of the Border 2020/Frontera 2020 program, a joint effort to improve the environment and protect people’s health, with projects located along United States-Mexico border.

U.S. Fish and Wildlife Service — The U.S. Fish and Wildlife Service is the principal agency that oversees the Endangered Species Act. If an endangered species is recognized as being dependent on groundwater, the groundwater supply can become federally protected. Species endemic to San Marcos, Comal, and Barton springs, all located within the Edwards (Balcones Fault Zone) Aquifer in Central Texas, have been listed as endangered, creating a legal requirement for groundwater management. Lawsuits against allowing takings of the endangered species within the central portion of the Edwards Aquifer resulted in state regulation of groundwater withdrawals. West Texas is also home to several endangered spring fishes.

Natural Resources Conservation Service, U.S. Department of Agriculture — The Natural Resources Conservation Service provides technical and financial assistance to help reduce soil erosion, protect water supplies, promote sustainable agriculture, and monitors and inventories soil and water resources. The agency provides assistance to farmers and ranchers, city planners, watershed groups, and state and local governments, and it partners with the state's 217 soil and water conservation districts. In 2009, the Natural Resources Conservation Service approved funding for a large irrigation efficiency improvement project in an area overlying the Ogallala Aquifer in Texas.

Good Neighbor Environmental Board — The Good Neighbor Environmental Board is a United States-based, independent federal advisory committee, managed by the U.S. Environmental Protection Agency that advises the President of the United States and Congress on United States-Mexico border environmental issues. The group holds meetings in border communities and provides a yearly report with recommendations for environmental and infrastructure issues. Since the publication of the first report in 1995, the group has repeatedly discussed the importance of groundwater quality and quantity to the region and recommended that the two countries develop mechanisms for protecting shared aquifers.

United States-Mexico Border Field Coordinating Committee — As a committee under the U.S. Department of the Interior, the Field Coordinating Committee aims to enhance communication and coordination between Department of Interior bureaus on border environmental and cultural issues. The Field Coordinating Committee has helped establish several memoranda of understanding between the U.S. Department of Interior and the Secretaría de Medio Ambiente y Recursos Naturales in Mexico to protect shared resources and has developed work groups on groundwater and shared water resources.

The U.S. Section of the International Boundary and Water Commission — The U.S. Section of the International Boundary and Water Commission is a federal agency charged with applying treaties between the United States and Mexico that address boundaries and water and settling disputes related to these treaties. The International Boundary and Water Commission helped develop and publish a binational aquifer study and data report on the Tularosa, Hueco Bolson, and Rio Grande aquifers shared by Mexico, New Mexico, and Texas.

Paso del Norte Water Task Force — The Paso del Norte Water Task Force is a regional partnership between Las Cruces, New Mexico; El Paso, Texas; and Ciudad Juárez, Chihuahua that is involved in binational water issues in the Paso del Norte area, which includes parts of the Rio Grande and Hueco-Mesilla Bolson aquifers. The task force consists of water managers, water experts, water users, and citizens. Goals of the task force are to determine priority water issues in the area, promote information sharing, and make policy recommendations to relevant authorities in Mexico and the United States.

Communities Unlimited — This non-profit rural development organization, based in Fayetteville, Arkansas, provides resources for education and guidance programs for rural areas in seven states, including Arkansas, Louisiana, Oklahoma, and Texas. The group provides technical and financial assistance, training, and publications to help provide small communities with safe water supplies and wastewater facilities.

Southeastern Regional Small Public Water Systems Technical Assistance Center —This center, administered by Mississippi State University and funded by the U.S. Environmental Protection Agency, funds training programs, technical assistance, and pilot projects to help small public water systems meet the goals of the Safe Drinking Water Act and protect public health. It serves an 11-state region, including Arkansas, Louisiana, Oklahoma, and Texas.

4.3.2 Statewide institutions

Texas Water Development Board — The TWDB provides financial assistance for water infrastructure and planning, administers water resources planning, conducts research, collects monitoring data on water resources, develops water use estimates, and provides technical assistance. The agency supports 16 regions statewide in developing their regional water plans that are incorporated into a statewide water plan. The agency's Groundwater Division monitors water chemistry and water levels in aquifers, develops and maintains groundwater availability models, conducts studies, and provides information and data about groundwater resources to the public. In addition, the division provides technical and administrative assistance to groundwater conservation districts and is responsible for calculating modeled available groundwater values based on the desired future conditions adopted by groundwater management areas.

As part of the TWDB, the Texas Natural Resources Information System is the state's repository for natural resource information and spatial data. The Texas Natural Resources Information

System also has a Borderlands Information Center, which collects, manages, and distributes geographic data for the area within 100 kilometers of the Texas-Mexico border. Geographic datasets available for Texas describe hydrology, topography, aerial photography, geology, transportation and navigation, land use and vegetation, population distribution, and other variables relevant to water management.

Texas Commission on Environmental Quality — As the state's environmental regulatory agency, the Texas Commission on Environmental Quality is responsible for implementing many federal and state environmental laws. The agency sets state water quality standards, oversees surface water rights, and monitors compliance with water quality standards by all public water systems in the state, including those that provide groundwater. The agency is responsible for enforcing the adoption of groundwater conservation district groundwater management plans and dealing with non-compliance issues. In addition, it is the agency responsible for designating priority groundwater management areas and establishing districts through the priority groundwater management area process or by landowner petitions. The agency also provides a petition process for persons with a legally defined interest in groundwater if a district refuses to participate in the joint planning process; fails to adopt or enforce rules that must be designed to achieve the desired future conditions; fails to update and submit a management plan for TWDB review; fails to follow specified timelines; or has rules that do not adequately protect groundwater.

Texas State Auditor's Office — The Texas State Auditor's Office may audit groundwater conservation districts to determine whether the districts are actively pursuing the goals and objectives of their management plans. An audit may be conducted a year after the first approval of the plan by the TWDB. Further audits may be conducted on a seven-year cycle and are determined on a risk-assessment basis. Reports are posted on the Auditor's website and are reported to the Texas Commission on Environmental Quality and the Legislative Audit Committee.

Texas Department of Licensing and Regulation — The Texas Department of Licensing and Regulation is responsible for regulating the licensing of water well drillers and water well pump installers. The agency provides information to water well drillers on licensing, abandoned wells, and continuing education. The agency coordinates with the TWDB to maintain an online water well driller's report submission and retrieval system.

Railroad Commission of Texas — The Railroad Commission of Texas is responsible for regulating surface mining and the exploration, production, and transportation of oil and gas within the state. Wells drilled to supply water to oil and gas exploration rigs and mining activities are exempt from requirements to obtain a drilling permit from a groundwater conservation district under Chapter 36 of the Texas Water Code, although the well drilling logs are required to be submitted to the state.

Texas Groundwater Protection Committee — The Texas Groundwater Protection Committee was formed to facilitate coordination between nine state agencies that manage aspects of groundwater, the Texas Alliance of Groundwater Districts, and federal agencies. The state entities make up the committee, and their goal is to protect and maintain current and future groundwater supplies and to keep them relatively free of contamination. The Texas Groundwater Protection Committee maintains and implements a state groundwater protection strategy and publishes an annual joint groundwater monitoring and contamination report.

Texas Parks and Wildlife Department — As the state agency responsible for stewardship and management of state-owned park lands, the Texas Parks and Wildlife Department is required to participate in the regional water planning process. This participation reflects the public interest in planning for the state's water resources. The agency may identify any issues associated with designation of river or stream segments of unique ecological value or designation of a site of unique value for reservoir construction. The agency may also fund studies described in Texas Water Code Section 36.160.

Texas State Soil and Water Conservation Board — The Texas State Soil and Water Conservation Board administers the state Soil and Water Conservation Law and coordinates conservation programs, with a focus on nonpoint source pollution from agriculture and forestry. The agency provides technical, financial, and administrative assistance to the 217 soil and water conservation districts within the state.

Texas Water Resources Institute — Located in College Station, the Texas Water Resources Institute is housed at Texas A&M University and is a member of the National Institutes for Water Resources. The Texas Water Resources Institute promotes and manages priority water research projects and provides educational programs throughout the state.

The University of Texas, Bureau of Economic Geology — As a research unit of the University of Texas at Austin, the Bureau of Economic Geology conducts research and provides guidance related to energy and environmental issues and functions as the state geological survey. The Bureau of Economic Geology is involved in many research programs related to groundwater, including studies of vadose-zone hydrology, groundwater recharge, groundwater availability modeling, hydrogeologic characterization using remote sensing and near-surface geophysics, paleoclimate, carbon sequestration, and desalination.

The University of Texas, Center for Research in Water Resources — As a research component of the University of Texas at Austin, the Center for Research in Water Resources designs and implements many advanced research and planning projects in water resources and waste management. The Center for Research in Water Resources houses many technical reports and acts as a regional educational resource. It has previously cooperated with Mexico's Comisión Nacional del Agua to develop a Rio Grande/Rio Bravo water management information system. The two organizations are expanding on this research, along with the Mexican Institute of Water Technology. The tasks include developing a geodatabase for groundwater information for border aquifers.

Texas A&M University, Texas AgriLife Extension Service — As part of the Texas A&M University System, the AgriLife Extension Service provides educational information and services to the public regarding the state's natural resources. The legislature also charged the organization with providing educational programs on water resources in areas designated as priority groundwater management areas.

Texas Tech University, College of Agricultural Sciences and Natural Resources Water Resources Center — This research center is part of Texas Tech University and provides research and education in water resources. Priority research is conducted in the High Plains region and focuses on augmentation, conservation, and the protection of water resources. The College of Agricultural Sciences and Natural Resources Water Resources Center has previously conducted a study on perchlorate in the groundwater of Southern High Plains and is actively involved in the regional water planning effort.

Texas Alliance of Groundwater Districts — The Texas Alliance of Groundwater Districts is a non-profit organization composed of groundwater conservation districts that have authority from Chapter 36 of the Texas Water Code to manage groundwater. The Texas Alliance of Groundwater Districts aims to further the purposes of groundwater conservation and protection activities and provides a method for the exchange of information between districts. Many member districts also serve on various advisory groups to provide information on groundwater management.

Texas Ground Water Association — The Texas Ground Water Association is a non-profit organization that provides continuing education for licensed water well drillers and pump installers and advocates for improvements in wells and pumping, scientific advancement, and communication within the water well industry.

Texas Water Conservation Association — The Texas Water Conservation Association provides leadership and acts as an advocate for water users. The Texas Water Conservation Association advises the Texas Legislature and government agencies on water issues, promotes public awareness of water conservation, and represents the water use interests of groundwater users, irrigators, municipalities, industrial users, river authorities, flood control districts, drainage districts, and utility districts.

Texas Rural Water Association — The Texas Rural Water Association is a non-profit organization that provides training, technical assistance, and educational information for small or local public water and wastewater systems and utilities in Texas. Members include water supply and sewer service corporations, special utility districts, municipal utility districts, water control and improvement districts, and privately owned water utilities.

4.3.3 Local institutions

Groundwater conservation districts — Groundwater conservation districts are local entities with the authority to manage groundwater, are the state's preferred method of groundwater management, and strive to conserve and prevent the waste of groundwater. The 99 confirmed and unconfirmed districts (as of September 2016) have powers granted from Chapter 36 of the Texas Water Code. The enacting legislation of groundwater conservation districts may grant additional powers or restrict the powers of districts. For example, the Edwards Aquifer Authority has a set amount of groundwater it can permit for withdrawal. This limit is set by the Texas Legislature and codified in the Edwards Aquifer Authority Act. Groundwater conservation districts are generally governed by a locally elected board, although in several districts some board members are appointed. The districts are required to develop groundwater management plans and participate in the joint planning process.

Regional water planning groups — Texas is divided into 16 regional water planning areas. Each area has a planning group responsible for developing and adopting a regional water plan for the area every five years. Regional planning group members consist of representatives from the following 12 interest groups: the public, counties, municipalities, industries, agricultural interests, environmental interests, small businesses, electric generating utilities, groundwater management areas, river authorities, water districts, and water utilities. The groups also consist of non-voting members.

Soil and water conservation districts — Soil and water conservation districts are local units of government that promote natural resource management on private and public lands.

Responsibilities include documenting land, soil, and water resources within the district as well as conservation problems, including the causes and possible solutions. Working with the Natural Resources Conservation Service, the districts also provide technical assistance to ranchers and farmers and help them prepare soil and water conservation plans and water quality management plans.

Special purpose districts — Two districts were formed to address land subsidence resulting from groundwater withdrawals. The Harris-Galveston Subsidence District, formed in 1975 through the Texas Legislature, regulates groundwater withdrawals in those two counties. The Harris-Galveston Subsidence District formed rules based on three regulatory areas established in 1999. The Fort Bend Subsidence District, formed in 1989 as a conservation and reclamation district through the Texas Legislature, regulates groundwater withdrawals in one county; it formed rules based on three regulatory areas, established in 2013.

5. Arkansas

In Arkansas, the Arkansas Natural Resources Commission has purview over groundwater resources, including permitting. State policy supports conjunctive use with surface water and where feasible, replacing groundwater use with surface water using tax credit incentives. Several state and federal agencies collaborate to collect groundwater samples and measure groundwater levels. The Arkansas Department of Environmental Quality evaluates the water quality of surface and groundwater resources.

5.1 Groundwater resources

Arkansas borders a small part of the far northeast corner of Texas. Groundwater provides over 60 percent of all Arkansas water resources and is projected to have a shortage, termed a "groundwater gap," by 2050. This section includes details about Arkansas aquifers and monitoring.

5.1.1 Aquifers

The U.S. Geological Survey identifies four principal aquifers and aquifer systems in Arkansas—the Mississippi Embayment Aquifer System, the Mississippi River Valley Alluvial Aquifer, the Ozark Plateaus Aquifer System, and the Edwards-Trinity Aquifer System—and recognizes several other aquifers within these systems (Table 5-1 and Figure 5-1) (Renken, 1998; Reilly and others, 2008). The State of Arkansas Geological Commission recognizes four stratigraphic regions covering the state: the Ozark Plateaus, the Ouachita, the Mississippi Embayment and Gulf Coastal Plain, and the Igneous (McFarland III, 2004). The U.S. Environmental Protection Agency recognizes three corresponding hydrostratigraphic areas: the Mississippi Embayment, the Ozark Plateau, and West Central Arkansas (Todd and others, 2009).

Table 5-1. Aquifers shared by Arkansas and Texas and naming conventions.

Arkansas	Texas	U.S. Geological Survey aquifer names
Trinity Aquifer	Trinity Aquifer	Trinity Aquifer, part of the Edwards-Trinity Aquifer System
Carrizo Aquifer/ Wilcox Aquifer	Carrizo-Wilcox Aquifer	Lower Claiborne-Upper Wilcox and Middle Wilcox Aquifers, part of the Mississippi Embayment Aquifer System (Texas Coastal Uplands Aquifer System in Texas)
Tokio Aquifer	Blossom Aquifer	Tokio-Woodbine Aquifer
Nacatoch Aquifer	Nacatoch Aquifer	McNairy-Nacatoch Aquifer, part of the Mississippi Embayment Aquifer System (Texas Coastal Uplands Aquifer System in Texas)
Cane River Aquifer	Queen City Aquifer	Middle Claiborne Aquifer, part of the Mississippi Embayment Aquifer System (Texas Coastal Uplands Aquifer System in Texas)
Not recognized	Woodbine Aquifer	Tokio-Woodbine Aquifer
Sparta-Memphis Aquifer	Sparta Aquifer	Sparta-Memphis Aquifer, part of the Mississippi Embayment Aquifer System (Texas Coastal Uplands Aquifer System in Texas)
Not recognized	Not recognized	Red River Alluvial Aquifer, part of the Surficial Aquifer System
Cockfield Aquifer	Yegua-Jackson Aquifer	Upper Claiborne Aquifer, part of the Mississippi Embayment Aquifer System (Texas Coastal Uplands Aquifer System in Texas)

Source: Ryder (1996); Renken (1998); TWDB (2007); and ANRC (2010).

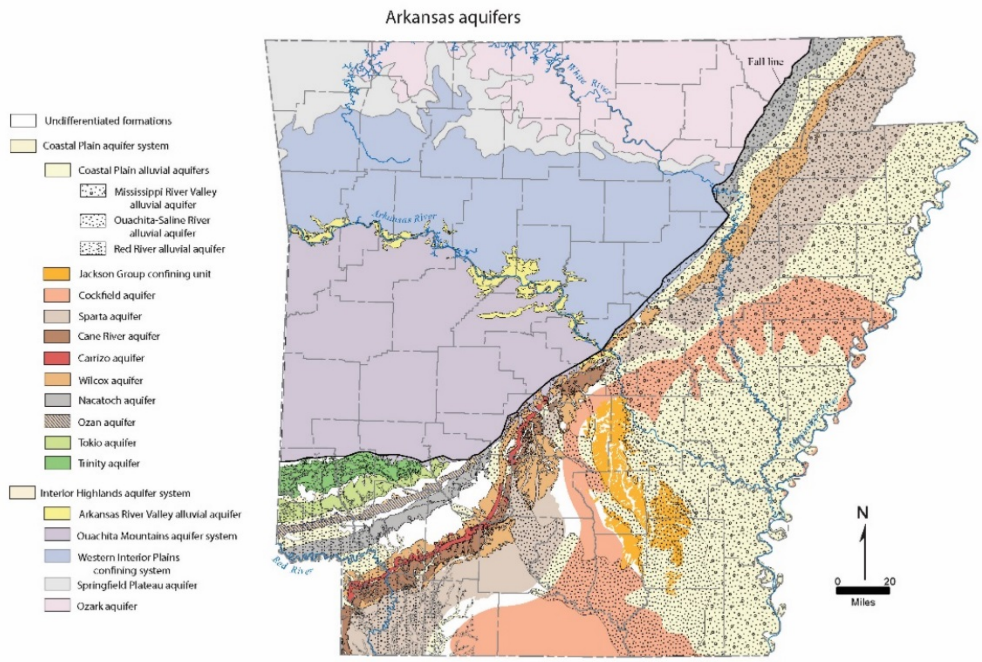

Figure 5-1. Arkansas aquifers map and fall line (from Kresse and others, 2013).

Groundwater accounts for over 60 percent of water use in Arkansas. Around 95 percent of that groundwater is from the Mississippi River Valley Alluvial Aquifer and is used almost exclusively for irrigation (Arkansas Natural Resources Commission, 2010). Measurements from spring 2012 through spring 2013 showed a -1.44 foot average decline throughout the entire aquifer (Arkansas Natural Resources Commission, 2014b).

Statewide concerns include aquifer depletion and water quality degradation (Arkansas Natural Resources Commission, 2014c). Much of the eastern half of the state is within critical groundwater areas, designated by the Arkansas Natural Resources Commission, or is being studied for possible future inclusion in a critical groundwater area. The most significant water level declines have resulted from groundwater withdrawals from the Mississippi River Valley Alluvial and Sparta-Memphis aquifers. Sustainable pumping is defined by the Arkansas Natural Resources Commission as 42 percent of the 2007 pumping in the Mississippi River Valley Alluvial Aquifer and 47 percent of 2007 pumping in the Sparta-Memphis Aquifer (Arkansas Natural Resources Commission, 2010). Water quality concerns include saline water intrusion in critical groundwater areas and shallow groundwater contamination in the Ozark Plateau (Todd and others, 2009; Arkansas Natural Resources Commission, 2010).

5.1.2 Groundwater monitoring

Monitoring of statewide groundwater levels and quality is a cooperative effort of the U.S. Geological Survey, the Arkansas Natural Resources Commission, the Arkansas Geological Commission, and the Natural Resources Conservation Service. The Arkansas Natural Resources Commission and Natural Resources Conservation Service monitor water levels in approximately 700 wells in the Mississippi River Valley Alluvial Aquifer and 350 wells in the Sparta-Memphis Aquifer (Arkansas Natural Resources Commission, 2010). As of September 2016, the U.S. Geological Survey monitors 592 wells and five springs in 47 out of 75 Arkansas counties, primarily in the east and southeast part of the state, as part of its groundwater level network (U.S. Geological Survey, 2016b). The U.S. Geological Survey also works with the Union County Conservation District to monitor water levels and water quality in a network of wells within a critical groundwater area in the Sparta Aquifer in southern Arkansas and northern Louisiana (Freiwald and Johnson, 2007).

The Arkansas Department of Environmental Quality monitors aquifers in nine areas of the state that are under high risk for contamination. Monitoring consists of sampling water quality parameters for targeted contaminants specific to each site. Contamination is mostly characterized as being critical in the shallow aquifers and related to arsenic, nitrate, and bacterial constituents. The Arkansas Department of Health monitors water quality in public water supplies, including 426 public water systems that use groundwater. In addition, the U.S. Environmental Protection Agency has established a nationwide water quality program that includes Arkansas. The agency monitors and samples groundwater in order to determine any trends using biological, chemical, and physical parameters (Todd and others, 2009).

5.2 Groundwater law, management, planning, and availability

Arkansas manages groundwater based on landowner’s having a correlative right to reasonable use of the water. Groundwater is managed on a statewide basis, with most of the groundwater withdrawals coming out of the Mississippi River Valley Alluvial Aquifer. Arkansas uses the concept of sustainable yield to quantify their groundwater resources and reports percent sustainable yield by county. Over half of the groundwater withdrawals in the state are considered unsustainable, based on the sustainable yield values derived from optimization models using 2007 water use data. This section discusses groundwater law, management, planning, and availability.

5.2.1 Groundwater law

Water law in Arkansas is based on the riparian rights law subject to a “reasonable use” doctrine (Bryant, 1997). Although Arkansas courts have not provided a rigid definition of what constitutes reasonable use, court decisions have established that domestic use has priority over other uses (Swaim and others, 2014). Arkansas law specifies groundwater ownership as being part of the public trust, protected by the Arkansas Water and Air Pollution Control Act (Todd and others, 2009). The Arkansas Ground Water Protection and Management Act authorizes the Arkansas Natural Resources Commission to permit or regulate groundwater extraction by delineating spacing requirements, assessing fees, and issuing groundwater rights only in critical groundwater areas (Arkansas Code Annotated §15-22-901). The Arkansas Administrative Code Title IV Section 401, promulgated and revised in 2005, describes groundwater management and protection provisions that exist under the responsibility of the Arkansas Natural Resources Commission.

Several legal cases, articles of legislation, and regulatory programs support the foundation for Arkansas's approach to state groundwater rights (Bryant, 1997; Arkansas Natural Resources Commission and Looney, 2011). In 1930, the Arkansas Supreme Court ruled that landowners could beneficially use water as long as those uses were not causing unreasonable damage to other riparian users in *Merriweather Sand and Gravel Co. v. State* [181 Ark. 216, 26 S.W. 2d 57] (Swaim and others, 2014). In 1955, the Arkansas Supreme Court adopted the reasonable use doctrine for the allocation of surface water in *Harris v. Brooks* [283 S.W.2d 129 (Ark. 1955)] (Arkansas Natural Resources Commission, 2013). In 1957, the court extended their opinion, in *Jones v. Oz-Ark-Val Poultry Co.* [228 Ark. 76, 306 S.W.2d 111], to include groundwater in the reasonable use doctrine by observing that there was no good reason not to do so (Robinson, 1957). This decision opened the door for pumping regulation. The 1957 ruling indicated that Arkansas property owners had "…a common and correlative right," to fully use groundwater, but only if a reasonable share of common supply was sufficient for users not to affect one another. Much later, in the 1975 case of *Lingo v. City of Jacksonville* [258 Ark. 63. 522 S.W.2d 403], the court decided that groundwater could be removed from its originating property as long as the removal did not harm groundwater availability for other users (Holt, 1975).

5.2.2 Groundwater management

Arkansas manages its groundwater through the Arkansas Natural Resources Commission's statewide groundwater protection and management programs. Their stated policy goals are to promote conservation, conjunctive use of surface water and groundwater for current and future water needs, and education (Peralta and Peralta, 1986; ANRC, 2009; Arkansas Natural Resources Commission, 2009). The Commission aims to protect and manage groundwater resources through monitoring water levels and water quality, implementing best management practices to prevent nonpoint source pollution, enforcing water well construction standards, conservation, and education (Fugitt, 2013).

The 2005 Arkansas Natural Resources Commission rules for protection and management of groundwater are in Title 4, Subtitle I, Section 401 through 407. These rules indicate that all groundwater withdrawals must be registered and reported to the state, except for wells used for domestic purposes or wells not capable of withdrawals of more than 50,000 gallons per day. The state charges a $10.00 fee per well for groundwater withdrawals but does not otherwise directly regulate small groundwater withdrawals (Arkansas Natural Resources Commission, 2005). In statute Title 15 Chapter 22 Subchapter 902, the state recognizes that Arkansas must reduce current groundwater use in order to protect future groundwater resources. Arkansas code Subchapter 905 indicates that surface water is preferred as a substitute for groundwater if available in an alluvial aquifer and if not more expensive than well operating costs. In addition, there are unlimited withdrawals for a grandfathered well in a sustaining aquifer unless surface water is available. Subchapter 905 addresses withdrawals where water rights are granted as unlimited if the right holder reduces their use by 20 percent through water conservation means, a change to surface water, or use of a commission-reviewed water conservation plan (Arkansas Code Title 15, Chapter 22, Subchapter 9). The Arkansas General Assembly also recognized that eventually a system of water rights might need to be implemented, and in that eventuality the state supported local control (Mahoney, 1999). Act 1426 of 2001 required that all non-domestic wells that withdraw groundwater from a "sustaining aquifer," defined as all significant aquifers except the Mississippi River Valley alluvial aquifers, maintain a functioning meter for use in reporting annual water use after 2006 (Arkansas Code Title 15, Chapter 22, Subchapter 9).

In 1999 the Arkansas General Assembly passed an act responding to groundwater levels dropping dramatically in the Sparta Aquifer, codified and termed as a water crisis (Mahoney, 1999). The act declared an emergency for the aquifer, authorizing a local agency to install water meters and collect fees from significant groundwater users in order to stem the potentiometric surface declines (Mahoney, 1999). In 2002, a consortium of agencies and consultants began a monitoring program (Yeatts, 2004). Groundwater models developed by the U.S. Geological Survey helped to provide estimates of the amount of groundwater withdrawal reduction necessary for water levels to recover (Yeatts, 2004).

Arkansas designates and monitors what the state terms "critical groundwater areas," defined as areas experiencing water quality issues or groundwater elevation declines, similar to Texas' priority groundwater management areas, without a time constraint to resolve the issues. The critical designation supports potential higher priority for federal funding and participation in conservation programs (Fugitt, 2015). Currently, four areas covering parts or all of 31 counties—much of the eastern half of the state in the Mississippi River Basin—are designated as critical groundwater areas (see Figure 5-2), based on water level elevation declines and water quality degradation using defined aquifer boundaries (Swaim and others, 2014).

The Arkansas Natural Resources Commission is authorized to delegate water management responsibilities to regional water or conservation districts (Arkansas Code Title 15, Chapter 22). Rather than establishing additional state regulation, local entities are encouraged to develop action plans, which could include water conservation programs and using surface water sources. These programs could also include tax incentives, education, and cost-sharing programs (U.S. Geological Survey, 2009). In addition, the Arkansas Ground Water Protection and Management Act of 1991 (Arkansas Code Annotated 15-22-906) authorized the Arkansas Natural Resources Commission to produce an annual report addressing their groundwater protection and conservation programs. In the most recent report from 2013, the Arkansas Natural Resources Commission states that long-term groundwater levels are declining due to unsustainable pumping. Cones of depression occur in the two aquifers supplying over half of the public supply wells, the Sparta/Memphis Aquifer and alluvial aquifers in the Mississippi river valley (Swaim and others, 2014).

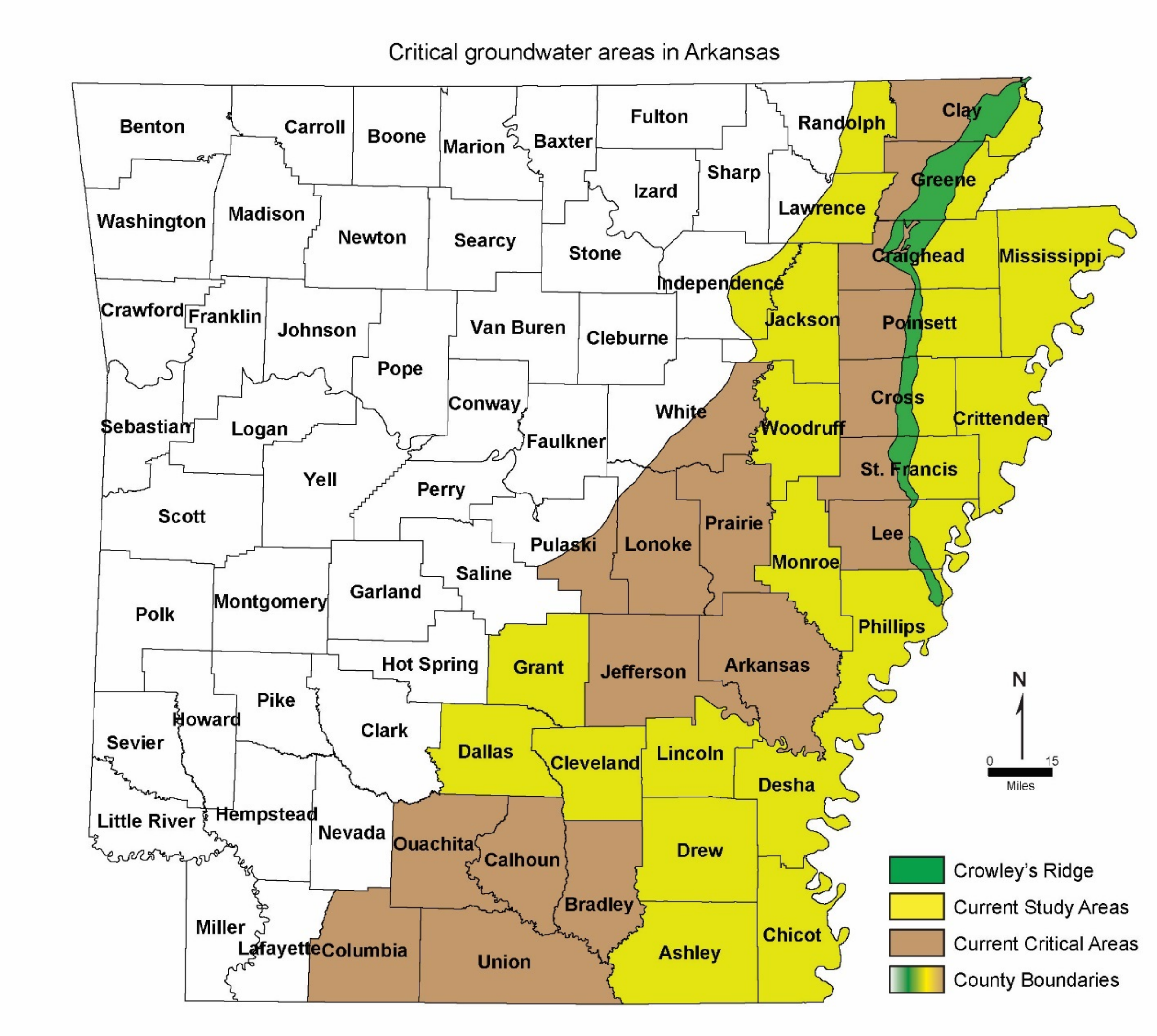

Figure 5-2. Arkansas critical groundwater areas (Fugitt, 2015)**.**

5.2.3 Groundwater planning

The 1969 Arkansas Legislature tasked the Arkansas Natural Resources Commission to be responsible for state water planning and authorized the Commission to develop a state water plan. In 1975, the Commission published the first state water plan addressing specific water-related problems and needs. In 1985, the Arkansas Legislature directed the Arkansas Natural Resources Commission to update the plan and, through examining the state's water resources, determine where needs will become critical over the ensuing 30 years, project the future water needs, and identify if surface water can be put to beneficial use to resolve these needs. This update, completed in 1990, established a comprehensive state water policy. The primary policies supported by the state include conjunctive use, using excess surface water to meet future needs, water conservation, and education (Arkansas Soil and Water Conservation Commission, 1990).

Groundwater planning, which primarily addresses water quality degradation and groundwater elevation changes, exists on a local level with support from state and national agencies. Beginning in 1937, Arkansas became the first state in the United States to pass a federally-mandated state conservation law and create conservation district boards in every county in the state. These districts were authorized to develop groundwater policies and plans inside designated county boundaries, along with other duties (Arkansas Natural Resources Commission, 2014b).

The conservation districts collect well registration fees and provide education and water conservation programs to residents, but currently they provide no regulatory restrictions for pumping. In some critical groundwater areas, well metering might be used to track but not regulate water use. Tax credits in these areas provide an incentive for groundwater conservation. The state projects groundwater shortages of up to 7 million acre-feet per year by 2050 (Arkansas Natural Resources Commission, 2014c).

In 2014 Arkansas released a public review copy of an updated statewide water plan (Arkansas Natural Resources Commission, 2009). This plan specifies Arkansas' vision for managing water resources sustainably and protecting public health and natural resources by employing best management practices with limited regulation and preservation of private property rights. Through this plan the state outlines a comprehensive planning process with a goal of long-term sustainable water use. A projected annual average "groundwater gap", the difference between supply and demand through 2050, is resolved primarily through use of excess surface water supplies. These supplies are developed from four major river basins, although the associated transportation and storage infrastructure are currently not in place (Arkansas Natural Resources Commission, 2014a).

5.2.4 Groundwater availability

The 1990 Arkansas Water Plan defined the safe yield for groundwater as "the amount of water that can be withdrawn from an aquifer on a continuing basis without causing serious depletion effects." It also establishes an optimum withdrawal rate for the Mississippi River Valley Alluvial Aquifer, defined as "the amount of water that will maintain a minimum of 20 feet of saturated thickness of aquifer"(Arkansas Soil and Water Conservation Commission, 1990).

More recently, Arkansas uses the concept of sustainable yield to quantify their groundwater resources. In their annual groundwater protection and management reports, the Arkansas Natural Resources Commission reports percent sustainable yield by county. Sustainable yield is derived from groundwater flow and conjunctive use optimization models developed by the U.S. Geological Survey, based on pumping rates, that provide the percentage sustainable yield and a rate of optimal withdrawal compared to 1997 pumping rates. Using 2007 water use data, over half of the groundwater withdrawals in the state are considered unsustainable (Arkansas Natural Resources Commission, 2010).

Critical groundwater areas are established as a step toward protecting areas experiencing water level declines and degradation of water quality. Each year the Arkansas Soil and Water Conservation Commission monitors and evaluates groundwater statewide to establish if a critical designation may be necessary. The criteria include water level declines at a rate of one foot per year or more, water level declines to below the top of an aquifer formation or below 50 percent saturated thickness in an unconfined aquifer, and water quality degradation. The Arkansas Soil and Water Conservation Commission considers education, tax incentives, development of alternative surface water supplies, and conjunctive use strategies as the most effective tools to address these groundwater issues rather than water use or well drilling regulation (Swaim and others, 2014).

5.3 Institutions

A variety of agencies and organizations actively monitor, study, plan for, or manage groundwater resources in the state. Most are governmental agencies or exist in response to governmental legislation.

5.3.1 National and regional institutions

U.S. Geological Survey —Current and recent groundwater projects conducted by the U.S. Geological Survey in Arkansas include studies of the Sparta-Memphis, Cockfield, and Wilcox aquifers; monitoring water-level recovery in the Sparta Aquifer following a reduction in pumping; a long-term study of the Ozark Plateaus Aquifer System as part of the National Water-Quality Assessment Program; and development of a groundwater flow model in the Mississippi Embayment Aquifer System. The U.S. Geological Survey monitors water levels in wells throughout the state and maintains monitoring sites at several springs in Garland County.

U.S. Environmental Protection Agency —Arkansas is within Region 6 of the U.S. Environmental Protection Agency, which has authorized state agencies, including the Arkansas Department of Environmental Quality, the Arkansas Department of Health, the Arkansas Natural Resources Commission, and the Arkansas Oil and Gas Commission, to implement many of its regulatory functions. Region 6 has a Ground Water Center that provides technical assistance to support groundwater protection.

U.S. Fish and Wildlife Service — The U.S. Fish and Wildlife Service is the principal agency that oversees the Endangered Species Act. If an endangered species is recognized as being dependent on groundwater, the maintenance of the groundwater supply can become federally protected.

Natural Resources Conservation Service, U.S. Department of Agriculture — The Natural Resources Conservation Service provides technical and financial assistance to help reduce soil erosion, protect water supplies, promote sustainable agriculture, and monitors and inventories soil and water resources. The agency is a member of the Arkansas Conservation Partnership.

Communities Unlimited — This non-profit rural development organization, based in Fayetteville, Arkansas, provides resources for education and guidance programs for rural areas in seven states, including Arkansas, Louisiana, Oklahoma, and Texas. The group provides technical and financial assistance, training, and publications to help provide small communities with safe water supplies and wastewater facilities.

Southeastern Regional Small Public Water Systems Technical Assistance Center —This center, administered by Mississippi State University and funded by the U.S. Environmental Protection Agency, funds training programs, technical assistance, and pilot projects to help small public water systems meet the goals of the Safe Drinking Water Act and protect public health. It serves an 11-state region, including Arkansas, Louisiana, Oklahoma, and Texas.

5.3.2 Statewide institutions

Arkansas Natural Resources Commission — The Arkansas Natural Resources Commission is the primary agency responsible for water development and land resource protection in Arkansas. The agency provides financial assistance for water infrastructure, is responsible for state water planning and management, and offers financial and technical support for conservation districts. It is also the agency that enforces rules related to water well construction. In addition, the agency develops and publishes the state water plan, designates critical groundwater areas, monitors groundwater levels and groundwater quality, collects groundwater use data, implements best management practices to prevent nonpoint source pollution, establishes nutrient management rules for supporting water quality goals, and offers technical assistance for groundwater resources. Each year the agency publishes a report summarizing aquifer conditions and water quality.

Arkansas Department of Environmental Quality — The Arkansas Department of Environmental Quality administers programs as required by many state and federal environmental laws. The agency is responsible for protecting all water bodies in the state. The agency develops water quality standards, issues permits and licenses for waste and wastewater, monitors water quality, and is responsible for the clean-up of contaminated sites. The agency also creates and distributes geospatial datasets.

Arkansas Pollution Control and Ecology Commission — The Arkansas Pollution Control and Ecology Commission is a 13-member group representing state agencies and congressional districts that develops environmental policies for the state of Arkansas.

Arkansas Department of Health — The Arkansas Department of Public Health regulates public water suppliers and monitors drinking water quality from public water supplies. The agency also implements the state's Wellhead Protection and Source Water Assessment programs.

Arkansas Geographic Information Office — The Arkansas Geographic Information Office develops and distributes spatial data for the state. Available geospatial datasets provide information about the state's hydrology, soils, topography, regulated sites, land use, administrative boundaries, and other topics related to water management.

Arkansas Water Well Construction Commission — The Arkansas Water Well Construction Commission regulates drilling and pump installation for water wells. The agency licenses contractors and registers drillers and pump installers who install new wells in the state. Drillers submit well reports for new wells to this agency.

Arkansas Oil and Gas Commission — The Arkansas Oil and Gas Commission regulates oil and gas exploration and production. Water wells drilled for oil and gas exploration or production are permitted through this agency.

Arkansas Watershed Advisory Group — The Arkansas Watershed Advisory Group is a consortium of state and federal agency personnel and private citizens that promotes local, voluntary approaches to watershed management and conservation. The group provides training, hosts roundtable discussions and conferences, and provides educational materials.

Arkansas Association of Conservation Districts — The Arkansas Association of Conservation Districts provides support to the 75 soil and water conservation districts in Arkansas.

Arkansas Geological Survey — The Arkansas Geological Survey is the state agency responsible for developing geologic maps; investigating the state's fossil fuels, geohazards, minerals, and hydrology; and providing information to the public. The agency publishes reports about groundwater resources in the state and partners with the U.S. Geological Survey to monitor water levels, streamflow, and water quality.

Arkansas Water Resources Center — Housed at the University of Arkansas in Fayetteville, the Arkansas Water Resources Center monitors water quality and conducts studies related to groundwater and surface water in the state. It also provides analytical laboratory services for a fee to the public for water analyses. The Arkansas Water Resources Center is a member of the National Institutes for Water Resources.

University of Arkansas, Division of Agriculture — Based in Little Rock, the Division of Agriculture at the University of Arkansas houses the Cooperative Extension Service and the Agricultural Experiment Station. The Cooperative Extension Service provides information and educational programs through offices in each county in Arkansas, and it includes a Public Policy Center that has published a series of water fact sheets. The Agricultural Experiment Station, based in Fayetteville, conducts basic and applied research related to agriculture and food production through several academic departments and programs. Areas of expertise within the division include natural resources management, water quality, water conservation, and pesticide application.

Arkansas Rural Water Association — The Arkansas Rural Water Association is a non-profit organization of publicly owned water and wastewater utilities that serve populations of up to 10,000 in Arkansas, and provides on-site technical assistance, training, and additional support for its members.

5.3.3 Local institutions

County conservation districts — Arkansas has 75 conservation districts, which are local units of government that promote natural resource management on private and public lands and develop soil and water conservation policies. These districts work with the Natural Resources Conservation Service to provide technical assistance such as helping to prepare nutrient management plans to ranchers and farmers. In addition, the districts provide tax incentives for water users to reduce groundwater use.

5.4 Interactions with Texas

Arkansas shares a very small portion of its border with Texas, in the southwestern corner, partly based on river flow and partly based on political subdivisions. States have a variety of ways to interact regarding shared water resources. This section includes details about two specific kinds of interactions which may or may not address groundwater.

5.4.1 Interstate compacts

Currently, there are no interstate compacts between Texas and Arkansas that directly address groundwater. However, the 1978 Red River Compact apportions the water of the Red River and its tributaries in Arkansas, Louisiana, Oklahoma, and Texas and provides a means for joint state planning, pollution control, and water conservation in the Red River Basin. The Red River

Compact could potentially impact groundwater resources in these states (Arkansas Code Section 15-23-501).

5.4.2 Interstate commissions

The Red River Compact Commission facilitates negotiations between member states in order to avoid litigation over the waters of the Red River and its tributaries and may address problems concerning the distribution of streamflow, equitable development, and water quality (Oklahoma Water Resources Board, 2014e).

6. Louisiana

In Louisiana, the Ground Water Resources Commission which is part of the Louisiana Department of Natural Resources, has purview over groundwater resources, including permitting. Louisiana manages groundwater based on landowners having a right to capture and use groundwater if there are no other laws in place affecting use or no injury to others' rights. Groundwater is more closely managed on an aquifer basis in state-identified "areas of concern" which are identified as suffering adverse effects from salt water encroachment, water level declines, or subsidence. In critical areas of groundwater concern, aquifer uses cannot be sustained without limitations on groundwater withdrawals. Louisiana plans to expand statewide management of groundwater resources using two key approaches of considering alternative supplies and new technology.

6.1 Groundwater resources

Louisiana borders almost the entire eastern border of Texas. Louisiana's abundant surface water and groundwater resources allow for locally available water resource supply substitution when necessary and a more secure water position (Louisiana Department of Transportation and Development, 2014). Groundwater provides only about 15.5 percent of all water resources for a variety of uses. This section includes details about Louisiana aquifers and monitoring.

6.1.1 Aquifers

The U.S. Geological Survey has identified the following principal regional aquifers in Louisiana (Figure 6-1): the Coastal Lowlands Aquifer System, the Mississippi Embayment Aquifer System, the Mississippi River Valley Alluvial Aquifer, and the Surficial Aquifer System (Renken, 1998; U.S. Geological Survey, 2008). Northern Louisiana and southern Arkansas share a major aquifer, the Sparta Aquifer (C.H. Fenstermaker and Associates Inc. and others, 2002). The U.S. Environmental Protection Agency has designated two sole source aquifers in Louisiana that cover most of the southern half of the state: the Chicot Aquifer System and the Southern Hills Aquifer System (U.S. Environmental Protection Agency, 2007a). Groundwater supplies primarily agriculture, industry, and public supply, while surface water is used primarily for electricity generation followed by industry and commercial entities (C.H. Fenstermaker and Associates Inc. and others, 2002). Major groundwater issues include saltwater intrusion, areas suffering water level declines, and groundwater contamination (C.H. Fenstermaker and Associates Inc. and others, 2002).

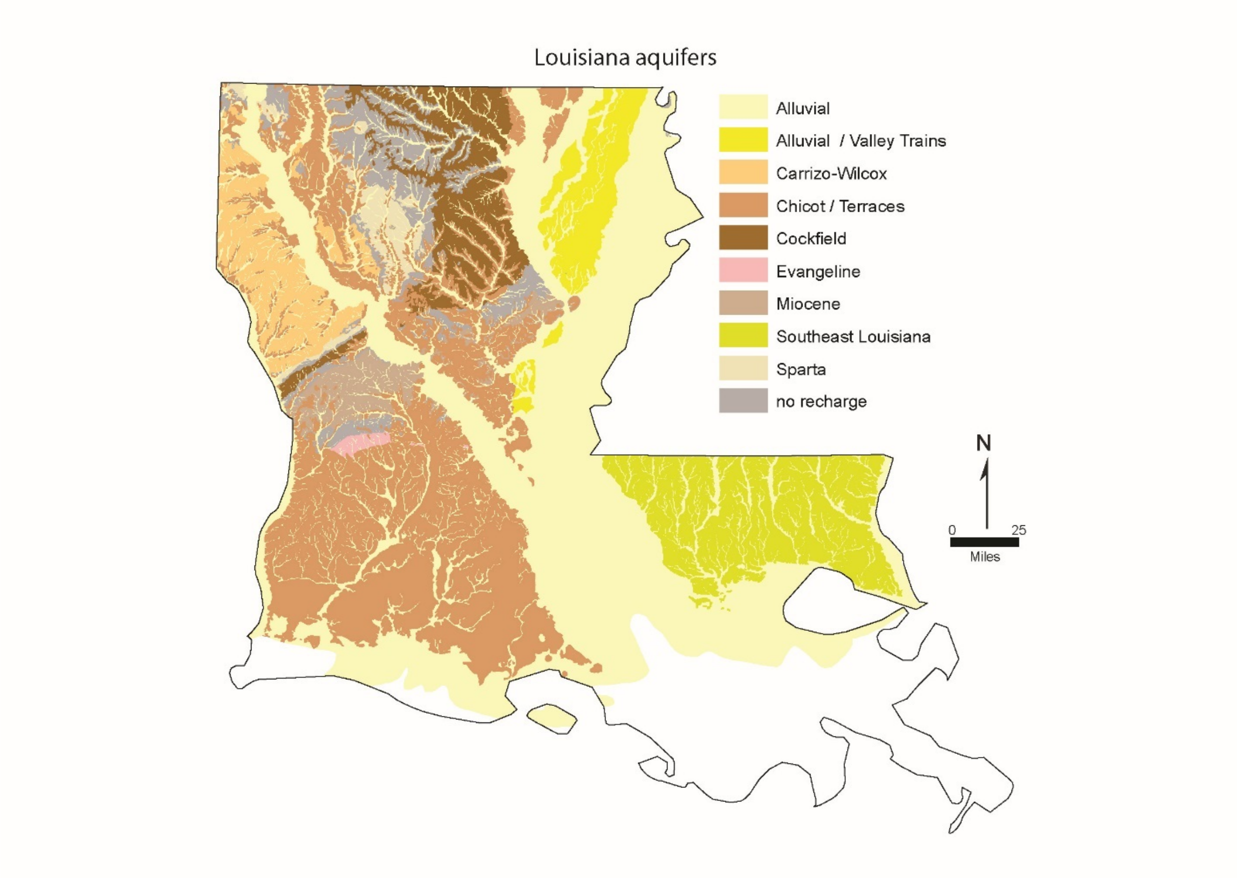

Figure 6-1. **Louisiana aquifer systems from Louisiana Department of Environmental Quality (1999).**

Several aquifers are shared between Texas and Louisiana yet are named differently (Table 6-1). Larger aquifers in east Texas and western Louisiana trend most east and northeast, with smaller alluvial aquifers associated with river basins in Louisiana trending perpendicular at northwest and north (Figure 6.1). The Mississippi River created a north-south trending surficial division among Louisiana aquifers and the Gulf of Mexico creates alluvial aquifers overlying the coastal aquifers.

Table 6-1. Aquifers shared by Louisiana and Texas and naming conventions.

Louisiana	Texas	U.S. Geological Survey aquifer names
Sparta Aquifer System	Sparta Aquifer	Sparta-Memphis Aquifer, part of the Mississippi Embayment Aquifer System (Texas Coastal Uplands Aquifer System in Texas)
Cockfield Aquifer System	Yegua-Jackson Aquifer	Upper Claiborne Aquifer, part of the Mississippi Embayment Aquifer System (Texas Coastal Uplands Aquifer System in Texas)
Carrizo-Wilcox Aquifer System	Carrizo-Wilcox Aquifer	Lower Claiborne-Upper Wilcox and Middle Wilcox aquifers, part of the Mississippi Embayment Aquifer System (Texas Coastal Uplands Aquifer System in Texas)
Part of the Alluvial Aquifer System	Not recognized	Surficial Aquifer System, Coastal Lowlands Aquifer System include parts of this
Chicot/Terraces Aquifer System	Gulf Coast Aquifer (Chicot Aquifer)	part of the Coastal Lowlands Aquifer System
Evangeline Aquifer System	Gulf Coast Aquifer (Evangeline Aquifer)	part of the Coastal Lowlands Aquifer System
Miocene Aquifer System	Gulf Coast Aquifer (Catahoula Aquifer)	part of the Coastal Lowlands Aquifer System
Carnahan Bayou Aquifer	Gulf Coast Aquifer (part of Jasper Aquifer)	part of the Coastal Lowlands Aquifer System
Not recognized	Nacatoch Aquifer	McNairy-Nacatoch Aquifer, part of the Mississippi Embayment Aquifer System (Texas Coastal Uplands Aquifer System in Texas)
Not recognized (Cane River Formation)	Queen City	Middle Claiborne Aquifer, part of the Mississippi Embayment Aquifer System (Texas Coastal Uplands Aquifer System in Texas)
Part of the Alluvial Aquifer System	Not recognized	Red River Alluvial Aquifer, part of the Surficial Aquifer System

Sources: Hosman and Weiss (1991); Ryder (1996); Renken (1998); Louisiana Geological Survey (1999); Johnston and others (2000); and TWDB (2007).

In 2005, groundwater supplied 15.5 percent of the total water supply, a decrease of about 3.7 percent since 2000 (Sargent, 2007). In 2012, irrigation represented 42 percent of groundwater use, followed by public drinking supply at 22 percent, industrial or commercial at 16 percent, livestock or aquaculture at 11 percent, thermoelectric power at 6 percent, and individual household wells at 3 percent, with a negligible amount for mining. In 2012, the state released a report addressing groundwater management concerns that recognized the connection between groundwater and surface water, the need for more monitoring, and the need for more educational efforts supporting conservation awareness (Louisiana Department of Natural Resources, 2012).

6.1.2 Groundwater monitoring

The Louisiana Department of Environmental Quality monitors water quality in approximately 200 groundwater wells in 14 aquifers and aquifer systems every three years (Louisiana Department of Environmental Quality, 2009, 2011b, a). Standard water quality parameters are analyzed and reported, as well as volatile and semi-volatile organics, pesticides, and polychlorinated biphenyls (Louisiana Department of Environmental Quality, 2006). As of September 2016, the U.S. Geological Survey measured water levels in 518 wells (no springs identified as such) in 59 parishes (U.S. Geological Survey, 2016c). The Louisiana Department of Environmental Quality monitors water quality in both surface water and groundwater (Ecology and Environment Inc., 2010). In addition, the Center for Environmental Health Services at the Louisiana Department of Health and Hospitals monitors water quality in public water supplies, including those that use groundwater (Louisiana Department of Health and Hospitals, 2014). The U.S. Environmental Protection Agency also provides assistance in the state's baseline monitoring program for major freshwater aquifers statewide (Louisiana Department of Health and Hospitals, 2014).

6.2 Groundwater law, management, planning, and availability

Louisiana manages groundwater based on a landowner's right to capture water. Groundwater is managed primarily on an aquifer basis. In 2005, the Louisiana Legislature created a groundwater designation called "area of groundwater concern." This new designation added sustainability as an aquifer management goal in an area defined as having unsustainable groundwater use. This section discusses groundwater law, management, planning, and availability.

6.2.1 Groundwater law

Although Louisiana law does not directly address groundwater ownership, the state operates under the rule of capture. Louisiana Civil Code Article 490 states that landowners own everything above and below their property unless otherwise restrained by law or others' rights (Louisiana State Legislature, 2008). Subsequent court case decisions and the Louisiana Mineral Code clarify that the landowner has rights to groundwater only after capturing it for use. The Louisiana Mineral Code indicates that groundwater is a mineral and that all the rules of withdrawals apply to it. More specifically, the Louisiana Mineral Code gives landowners exclusive rights to minerals mined or withdrawn on the property but not to minerals in place (Acts 1974, No. 50, §1, eff. Jan. 1, 1975).

Absolute ownership in Louisiana civil law dates from 1808, although depriving or causing damage to neighboring landowners is prohibited by Louisiana Civil Code Article 667, adopted in 1996 (Louisiana Ground Water Resources Commission, 2012). Unlike some other states, including Texas, current groundwater law did not directly result from Louisiana case law. Most groundwater-related litigation in Louisiana addresses deteriorating groundwater quality and associated oil or natural gas extraction and processing. A 1963 oft-cited court case, *Adams v. Grisby*, upheld the rule of capture by testing this civil code (Louisiana Department of Natural Resources, 2012). The court held that groundwater is a mineral and that a landowner therefore owns groundwater after he or she has pumped it to the surface, thus possessing or capturing it (Louisiana State University, 2001). In 1972, the Louisiana Legislature passed legislation authorizing the Louisiana Department of Transportation and Development to register and track wells extracting over 50,000 gallons per day (Louisiana Sparta Ground Water Commission, 2014b). In 1974, the state-authorized, five-parish Capital Area Groundwater Conservation District became the first district (Figure 6-2) intended to both protect water quality and systematically develop groundwater (Capital Area Ground Water Conservation Commission, 2013). Groundwater in Louisiana was not subject to the considerable legislation that regulates the development of oil, gas, and other mineral resources (Levine, 1984; Bolourchi, 2001) until 2001. At that time, the legislature adopted a Groundwater Management Act creating a commission authorized to establish critical groundwater areas, regulate groundwater use, and to research and develop groundwater laws (Louisiana Department of Natural Resources, July 5, 2016). In 2005, the Louisiana Legislature created a new groundwater designation, called "area of concern," that modified the previous "critical groundwater area" by adding to the definition and including concept of sustainability as an aquifer management goal in an area defined as having unsustainable groundwater use (Louisiana Sparta Ground Water Commission, 2014b).

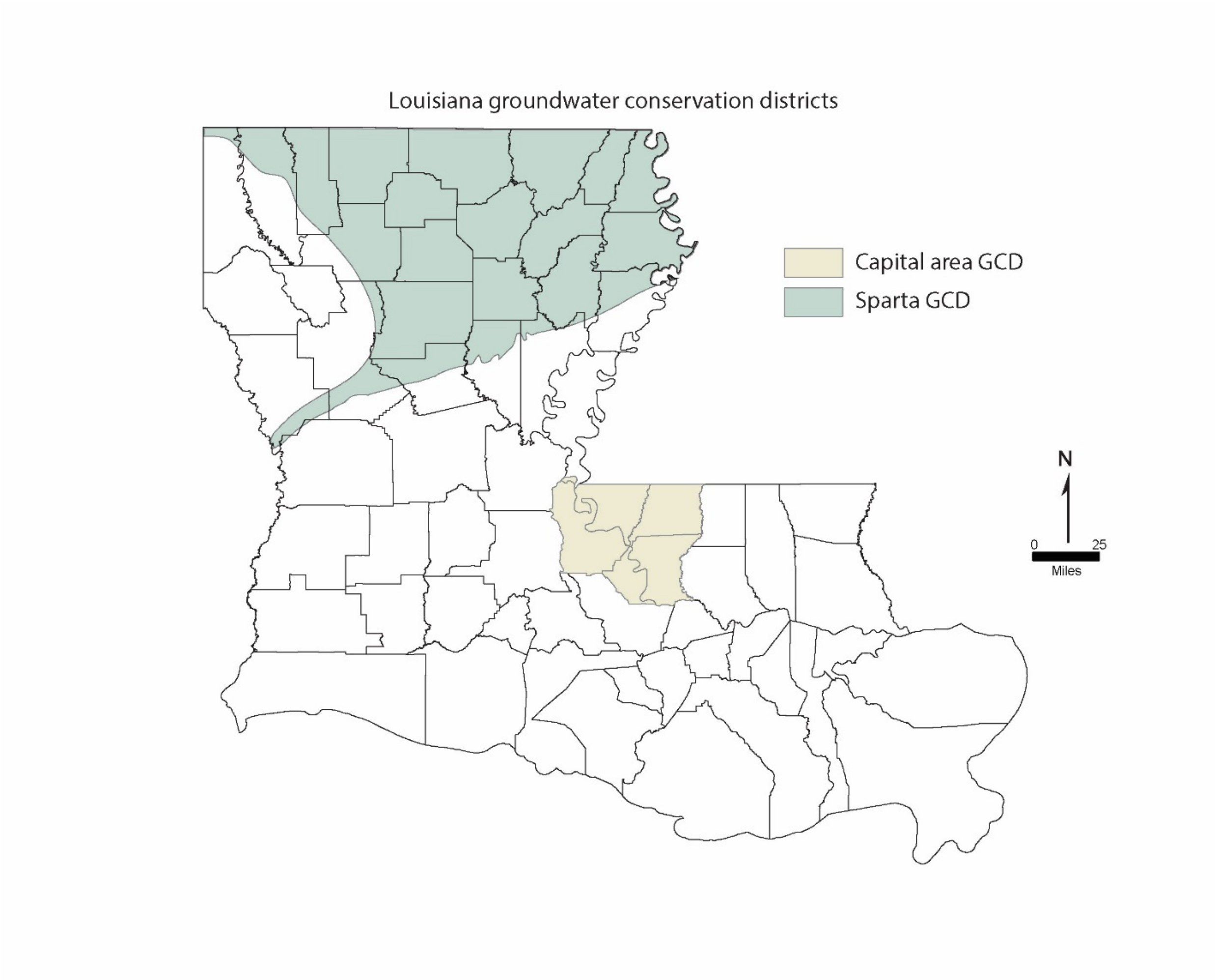

Figure 6-2. Louisiana groundwater conservation districts (from U.S. Geological Survey and Louisiana Department of Natural Resources, 2015).

Statutes passed by the Louisiana Legislature contain language, such as "…that surface and ground water resources within the state be put to beneficial uses to the extent of which they are most reasonably capable," that suggests a reasonable use doctrine. Additionally, in 2001, the Water Resources Study Commission recommended that "public drinking water supply shall be considered the use of first priority" (Bolourchi, 2001). In 2005, James Welsh, Commissioner of Conservation issued a memorandum declaring three areas in the Sparta Aquifer, covering four parishes, as areas of groundwater concern. He ordered remedial actions intended to reduce or reverse groundwater declines and indicated the first priority uses should be human consumption and public safety (Welsh, 2005). The Louisiana Ground Water Commission recognized that Louisiana groundwater management efforts are based on sustaining the resource (Louisiana Ground Water Resources Commission, 2012). However, the state continues to operate under an absolute ownership doctrine, which recognizes no priorities of use in most areas.

6.2.2 Groundwater management

The state registers water wells and enforces well construction standards but does not expressly limit pumping. The Louisiana Administrative Code Title 43 Natural Resources Part VI, Subpart 1, promulgated July 2002, revised June 2004 and February 2009, describes groundwater management provisions existing under the responsibility of the Louisiana Department of Natural Resources (Louisiana State Legislature, 2014). Louisiana's Commissioner of Conservation administers programs and actions through the Office of Conservation, within the Department of Natural Resources, and has authority over groundwater. This authority falls broadly into three categories: (1) areas where the sustainability of an aquifer is threatened, (2) times during which natural forces or human actions cause groundwater to become temporarily unavailable for immediate beneficial use or during drought, and (3) groundwater management.

After a two-year drought, in 2002 the state legislature made rules for establishing critical groundwater areas (Louisiana Sparta Ground Water Commission, 2014a). Louisiana Administrative Code Title 43, Natural Resources Part VI, Subpart I indicated that the Commissioner of Conservation may respond to a petition from any well owner adversely affected in that area by establishing a critical groundwater area. Severe adverse effects, including water level declines, saltwater intrusion, or geologic subsidence, could all serve as support for establishing this designation (Louisiana State Legislature, 2014). A critical groundwater area is defined as an area experiencing one or more of these problems, resulting in unacceptable impacts, "in which the commissioner finds that the sustainability of the aquifer cannot be maintained without withdrawal restrictions" (Title 43, Part VI, Subpart 1, Chapter 1, §103 Definitions). In 2005, the Louisiana Legislature updated the designation definition and name to "critical area of groundwater concern" and added "area of ground water concern" as a lesser designation while maintaining the sustainable use goals of groundwater management in both types of areas (Louisiana Department of Natural Resources, 2009b). In a critical area of groundwater concern, owners of proposed larger wells seeking permits may or may not be ordered to fix production, spacing, or metering, if necessary to reduce extraction rates.

On August 15, 2005, the commissioner named three areas of groundwater concern in four parishes, resulting from the Sparta Ground Water Conservation District filing an application for the Sparta Aquifer. The order language cites this designation as being necessary to insure "the most advantageous use of the state's ground water resources consistent with their protection, conservation, and replenishment". In addition, the order indicated that the groundwater was not being maintained sustainably. The remedy identified three approaches: (1) establishing a groundwater conservation educational program, (2) establishing a mandatory monthly groundwater level report for non-domestic wells, and (3) identifying and securing alternative water resources (Welsh, 2005).

Louisiana manages groundwater mostly by addressing water quality issues primarily through a consortium of agencies. These agencies include the departments of Environmental Quality, Natural Resources, Agriculture and Forestry, Wildlife and Fisheries, Transportation and Development, and Health and Hospitals, and one federal agency, the U.S. Geological Survey (Louisiana Ground Water Resources Commission, 2012). Louisiana's definition of groundwater also includes a water quality component identifying waters that containing less than 10,000 milligrams per liter total dissolved solids concentrations and encompassing both brackish and freshwater designations (Louisiana State Legislature, 2014). Ultimately, the state aims to manage all groundwater resources under one program encompassing complementary supplies and innovative technologies for treating surface water (Louisiana Department of Natural Resources, 2009a).

Extensive environmental damage from hurricanes provides an example of a past and potential future groundwater management issue that threatens groundwater resources. Damage from past hurricanes included destruction of public drinking water supply groundwater wellheads in six parishes and well inundation near Lake Pontchartrain (Louisiana Department of Environmental Quality, 2008). In addition to the direct physical damage, hurricanes increased the threat of groundwater contamination through surface sources, called significant potential sources of potential contamination (Louisiana Department of Environmental Quality, 2008). The Department of Environmental Quality investigated and identified potential contamination from groundwater well inundation by sampling for water quality parameters, dissolved metals, nutrients, volatile organic compounds, and microbiological activity (Louisiana Department of Environmental Quality, 2008).

6.2.3 Groundwater planning

In 2000, Governor Foster signed an executive order establishing a State Water Policy Advisory Task Force. The State Water Policy Advisory Task Force, enabled to reach the objectives of the Louisiana: Vision 2020 master economic plan, identified 22 entities and state offices who were to meet and evaluate water resources and policies (Foster, 2000). Subsequently, in 2002, state legislators recognized the need for groundwater planning by establishing the criteria for critical groundwater management areas (C.H. Fenstermaker and Associates Inc. and others, 2002), which are similar to those in Arkansas. The framework developed in statute for a regional planning approach for groundwater and surface water was similar to those used in Texas and New Mexico. Agencies responsible for establishing and developing groundwater protection programs include the Louisiana's departments of Environmental Quality, Transportation and Development, Human Health, and Natural Resources. In 2010, the state released a preliminary report summarizing Louisiana's water resources, and published a final report in 2012. This preliminary report recognized the interstate connections to recharging Louisiana's aquifers in out-of-state recharge zones and sought to recommend that the state needed to identify mechanisms to cooperate with other states on recharging the aquifers. The final report also indicated that Texas' interest in buying surface water demonstrated some short-term and long-term implications that needed further public vetting (Louisiana Department of Natural Resources, 2012).

In 2014, three agencies agreed to fund studies to assess the state's current and future water supplies related to sustainability and energy production. Areas included in this study are the eastern part of the Chicot Aquifer and surface water basins, the Carrizo-Wilcox Aquifer and surface water basins, and the western part of the Southern Hills Aquifer System and surface water basins. This information will be a resource available for any decision-makers to consult as guidance when developing policies or approaches to reduce costs or conserve energy for water production and delivery (Louisiana Water Resources Commission, 2016).

6.2.4 Groundwater availability

Louisiana does not directly report on groundwater availability. However, the Louisiana Department of Transportation, in collaboration with the U.S. Geological Survey, issues a five-year summary report on water use, including groundwater withdrawals, from 13 aquifers by sector (U.S. Geological Survey, 2011b). This data is updated for 2012 through 2014 in tables listing groundwater production by parish, aquifer, and basin. Eight types of uses are reported, primarily increasing from 2012 to 2014, with rice irrigation withdrawing the most at 557 million gallons per day in 2014, followed by public supply at 349 million gallons per day and aquaculture at 321 million gallons per day (U.S. Geological Survey, 2016a). In 2010, groundwater withdrawals of 1,600 million gallons per day were approximately 18.8 percent of total water use statewide, with 41 percent of that withdrawn from the Chicot Aquifer and 25 percent from the Mississippi River Alluvial Aquifer (Sargent, 2011). Groundwater use increased 1.8 percent from 2005 through 2010 and 2010 use was estimated at less than 20 percent of total water use (Sargent, 2011).

6.3 Institutions

A variety of agencies and organizations affect groundwater policy in Louisiana. This is a condensed list; the entities described here primarily monitor, study, plan for, or manage groundwater resources in the state. Most are governmental agencies or exist in response to governmental legislation.

6.3.1 National and regional institutions

U.S. Geological Survey —The Louisiana Water Science Center of the U.S. Geological Survey is involved in a long-term study of groundwater quality in southern Louisiana as part of the National Water-Quality Assessment Program, a study of the structure of the Carrizo-Wilcox Aquifer, the development of a groundwater flow model to assess saltwater encroachment in Baton Rouge Parish, and publication of fact sheets about water resources in each parish of the state. The U.S. Geological Survey monitors water levels in wells throughout the state.

U.S. Environmental Protection Agency —Louisiana is within Region 6 of the U.S. Environmental Protection Agency, which has authorized the Louisiana Department of Natural Resources and the Louisiana Department of Environmental Quality to implement many of its regulatory functions related to groundwater quality. Although the agency does not regulate private groundwater wells, Region 6 has a Groundwater Center that provides technical assistance to support groundwater protection.

U.S. Fish and Wildlife Service — The U.S. Fish and Wildlife Service is the principal agency that oversees the Endangered Species Act. If an endangered species is recognized as being dependent on groundwater, the maintenance of the groundwater supply can become federally protected.

Natural Resources Conservation Service, U.S. Department of Agriculture — The Natural Resources Conservation Service provides technical and financial assistance to help reduce soil erosion, protect water supplies, and promote sustainable agriculture, and it monitors and inventories soil and water resources. The agency also leads the Louisiana State Technical Committee, coordinated by the State Conservationist, which advises stakeholders on water issues, such as water quality and aquifer overdraft, and identifies and ranks priority natural resource concerns.

Communities Unlimited — This non-profit rural development organization, based in Fayetteville, Arkansas, provides resources for education and guidance programs for rural areas in seven states, including Arkansas, Louisiana, Oklahoma, and Texas. The group provides technical and financial assistance, training, and publications to help provide small communities with safe water supplies and wastewater facilities.

Southeastern Regional Small Public Water Systems Technical Assistance Center — This center, administered by Mississippi State University and funded by the U.S. Environmental Protection Agency, funds training programs, technical assistance, and pilot projects to help small public water systems meet the goals of the Safe Drinking Water Act and protect public health. It serves an 11-state region that includes Arkansas, Louisiana, Oklahoma, and Texas.

6.3.2 Statewide institutions

Louisiana Department of Natural Resources, Office of Conservation — The Office of Conservation of the Louisiana Department of Natural Resources is responsible for regulating and conserving oil, gas, and other natural resources in the state, including groundwater. It houses water well notification forms for exempt and non-exempt water wells and is responsible for designating areas of groundwater concern in the state. The office's Ground Water Resources Program prepares monthly water usage and water level reports for these areas and is currently developing a state groundwater resources management program, focusing on alternative water supplies and technologies.

Louisiana Department of Environmental Quality — As the state's environmental regulatory agency, the Louisiana Department of Environmental Quality is responsible for implementing many federal and state environmental laws and enforces regulations controlling both surface water and groundwater. The agency monitors water chemistry in surface waters and aquifers, issues water and waste permits, handles non-compliance problems, and administers the state Wellhead Protection, Aquifer Sampling and Assessment, Total Maximum Daily Load, National Pollutant Discharge Elimination System, and Source Water Assessment programs.

Louisiana Department of Health and Hospitals, Center for Environmental Health Services — The Center for Environmental Health Services, part of the Louisiana Department of Health and Hospitals, is responsible for enforcing the Louisiana State Sanitary Code. The center monitors public water suppliers and systems, including those that provide groundwater, for compliance with water quality standards. It also provides loans and technical assistance to public water systems.

Louisiana Department of Agriculture and Forestry — Among other duties accomplished by the Department of Agriculture and Forestry, this agency assists the state's 44 soil and water conservation districts with funding, administrative support, centralized guidance, and direction. It also helps landowners plan or build conservation systems and develops programs for coastal wetlands revegetation.

Louisiana Department of Wildlife and Fisheries — Information about natural communities is developed through wildlife action plans, and state wildlife grants programs are administered through Department of Wildlife and Fisheries. Forest management prescriptions, which propose habitat management objectives and efforts, are part of the state's 60 Wildlife Management Areas.

Louisiana Ground Water Resources Commission — A variety of appointed members serve on the Ground Water Resources Commission, organized to be the state's focal point for groundwater data, knowledge, and policy. On March 9, 2009, the Commission passed a resolution recommending the development of a statewide groundwater management plan to the Louisiana Legislature. The Commission released a schedule for implementing and completing the statewide groundwater management plan in 2011. In 2016, the Commission released an updated report on the activities related to earlier recommendations.

Louisiana Geographic Information System Council and Louisiana Geographic Information Center — The Louisiana Geographic Information System (GIS) Council consists of government member agencies and is tasked with facilitating GIS data acquisition, development, and use for the purposes of state policy and planning. To implement these tasks, the council created the Louisiana Geographic Information Center. The Center distributes GIS data for the state, including datasets covering topics useful for water management such as hydrology, soils, topography, regulated sites, land use, administrative boundaries. In addition, these groups provide training and advice to improve GIS capacity in Louisiana.

Louisiana Department of Transportation and Development — The Louisiana Department of Transportation and Development is responsible for transportation and public works systems in Louisiana. The Public Works and Water Resources Division cooperates with the U.S. Geological Survey on several water resources programs, including surface water and groundwater monitoring, hydrologic studies, and the development of water use estimates. In addition, the agency licenses water well drillers, receives water well registration forms for water wells drilled in the state, and maintains an online database of water well registration data.

Ground Water Management Advisory Task Force — The Ground Water Management Advisory Task force represents a range of public and private groups in Louisiana and is responsible for advising the Groundwater Resources Division of the Louisiana Department of Environmental Quality on technical groundwater issues.

Louisiana Association of Conservation Districts — In 1938, the Louisiana Legislature's Act No. 370 established the State Soil and Water Conservation Committee to help farmers to petition for and establish conservation districts. The Louisiana Association of Conservation Districts now consists of 44 soil and water conservation districts. In 1984, Plaquemines Parish was the last part of the state to be organized into a district. The newest district was created in 2003 by the division of a larger district into smaller districts. This group supports activities, meetings, and education about state programs and conservation.

Louisiana State Soil and Water Conservation Commission — The eight-member Louisiana State Soil and Water Conservation Commission develops state policy for soil and water conservation. In addition, the Commission provides financial and administrative assistance, advice, and regulatory oversight for the 44 local conservation districts in the state and facilitates communication between districts.

Louisiana Geological Survey — Part of the Office of Research and Economic Development at Louisiana State University, the Louisiana Geological Survey develops geologic maps and geographic information systems and performs studies of the state's coastlines, fossil fuels, and hydrology. Groundwater research at the survey focuses on aquifer characterization and modeling, and includes studies of groundwater-surface water interactions, groundwater pollution, and effects of storm surges and saltwater intrusion on groundwater.

Louisiana State University, AgCenter Research and Extension — The Agricultural Center at Louisiana State University in Baton Rouge hosts the Louisiana Agricultural Experiment Station and the Louisiana Cooperative Extension Service. The Agricultural Experiment Station conducts research, while the Cooperative Extension Service provides information and outreach through offices in each parish. The AgCenter promotes water conservation and the prevention of water pollution through educational outreach.

Louisiana Water Resources Research Institute — Located in Baton Rouge, the Louisiana Water Resources Research Institute promotes research and education addressing water resources problems. The institute funds research, education, and pilot programs to investigate the state's water resources. It provides outreach through conferences, publications, and online resources and is a member of the National Institutes for Water Resources.

Louisiana Rural Water Association — The Louisiana Rural Water Association is a non-profit organization that provides training and technical assistance for small water and wastewater utility systems. The group's programs focus on on-site assistance, operator certification, and compliance with federal and state regulations.

6.3.3 Local institutions

Levee districts — Levee districts are responsible for operating and maintaining levees, floodgates, floodwalls, relief wells, and other flood control structures. There are 23 levee districts authorized in statute in Louisiana. The Association of Levee Boards of Louisiana includes five smaller levee districts that are part of two larger districts, several freshwater districts, and a representative of the governor's office for a total of 27 members.

Soil and water conservation districts — There are 44 soil and water conservation districts in Louisiana. These districts are local units of government that promote natural resource management on private and public lands. Working with the Natural Resources Conservation Service, the districts also provide technical assistance to ranchers and farmers and help them plan and implement soil and water conservation projects.

Louisiana Sparta Ground Water Commission — In 1999 the Louisiana Legislature created this group to research the Sparta Aquifer and identify potential management issues. In order to preserve its use for future generations, the 19-member commission studies alternative sources of supply and promotes water conservation. State funding, as well as member agencies, industry, and political subdivision funds, support the commission's efforts.

Capital Area Ground Water Conservation Commission — This 15-member board represents industry, public supply, five parishes, state agencies, and the Louisiana Farm Bureau & Cattlemen's Association. Since 1974, their mission has been to promote planned development of groundwater in the parishes surrounding and including Baton Rouge. The commission issues drilling permits, although permits are not required for wells screened less than 400 feet deep, for agricultural use, or capable of producing less than 56 acre-feet per year. In addition, the commission publishes technical studies and a quarterly newsletter.

6.4 Interactions with Texas

Louisiana shares almost its entire western border with Texas, partly based on river flow on the southern half and political subdivisions on the northern portion. States have a variety of ways to interact regarding shared water resources. This section includes details about two specific kinds of interactions which may or may not address groundwater.

6.4.1 Interstate compacts

Currently there are no interstate compacts between Texas and Louisiana that directly address groundwater. However, the 1978 Red River Compact apportions the waters of the Red River and its tributaries in Arkansas, Louisiana, Oklahoma, and Texas and provides a means for joint state planning, pollution control, and water conservation in the Red River Basin. The Red River Compact, addressed in Louisiana statute Title 38 Public Works, Contract, and Improvement, Section 20 in 1978 (Louisiana State Legislature, 1978), could potentially impact groundwater resources due to groundwater-surface water interactions (Oklahoma Water Resources Board, 2014f).

6.4.2 Interstate commissions

The Red River Compact Commission facilitates negotiations between member states in order to avoid litigation over the waters of the Red River and its tributaries. The Red River Compact Commission may address problems concerning the distribution of streamflow, equitable development, and water quality (Oklahoma Water Resources Board, 2014e).

7. New Mexico

Groundwater and surface water are managed together as waters belonging to the state. The Office of the State Engineer declares groundwater basins and issues permits to use groundwater. Seven basins, called active water resource management areas, follow rules designed to achieve three objectives: (1) protect senior water rights, (2) ensure compliance with interstate stream compacts, and (3) prevent waste (New Mexico Office of the State Engineer, 2004). In 2011, groundwater from 39 declared underground water basins supplied slightly less than half of all water used in New Mexico (Bushnell, 2012).

7.1 Groundwater resources

New Mexico borders almost the entire western border of Texas. Groundwater provides close to half of all water resources for a variety of uses. This section includes details about New Mexico's aquifers and monitoring.

7.1.1 Aquifers

According to the 2002 New Mexico Water Resources Atlas (New Mexico Interstate Stream Commission and New Mexico Office of the State Engineer, 2002), major aquifers in the state include the Basin and Range aquifers, Capitan Reef Aquifer, Estancia Valley Fill Aquifer, Gallup and Westwater Canyon aquifers, High Plains Aquifer, Pecos River Basin Alluvial Aquifer, Rio Grande Aquifer, Roswell Artesian Aquifer, Salt Basin Alluvial Aquifer, and the Tularosa Basin Aquifer (Figure 7-1). Bordering Texas are the High Plains, Capitan Reef, Salt Basin Alluvial, and Tularosa Basin aquifers, as well as several other aquifers not formally recognized in New Mexico (Table 7-1).

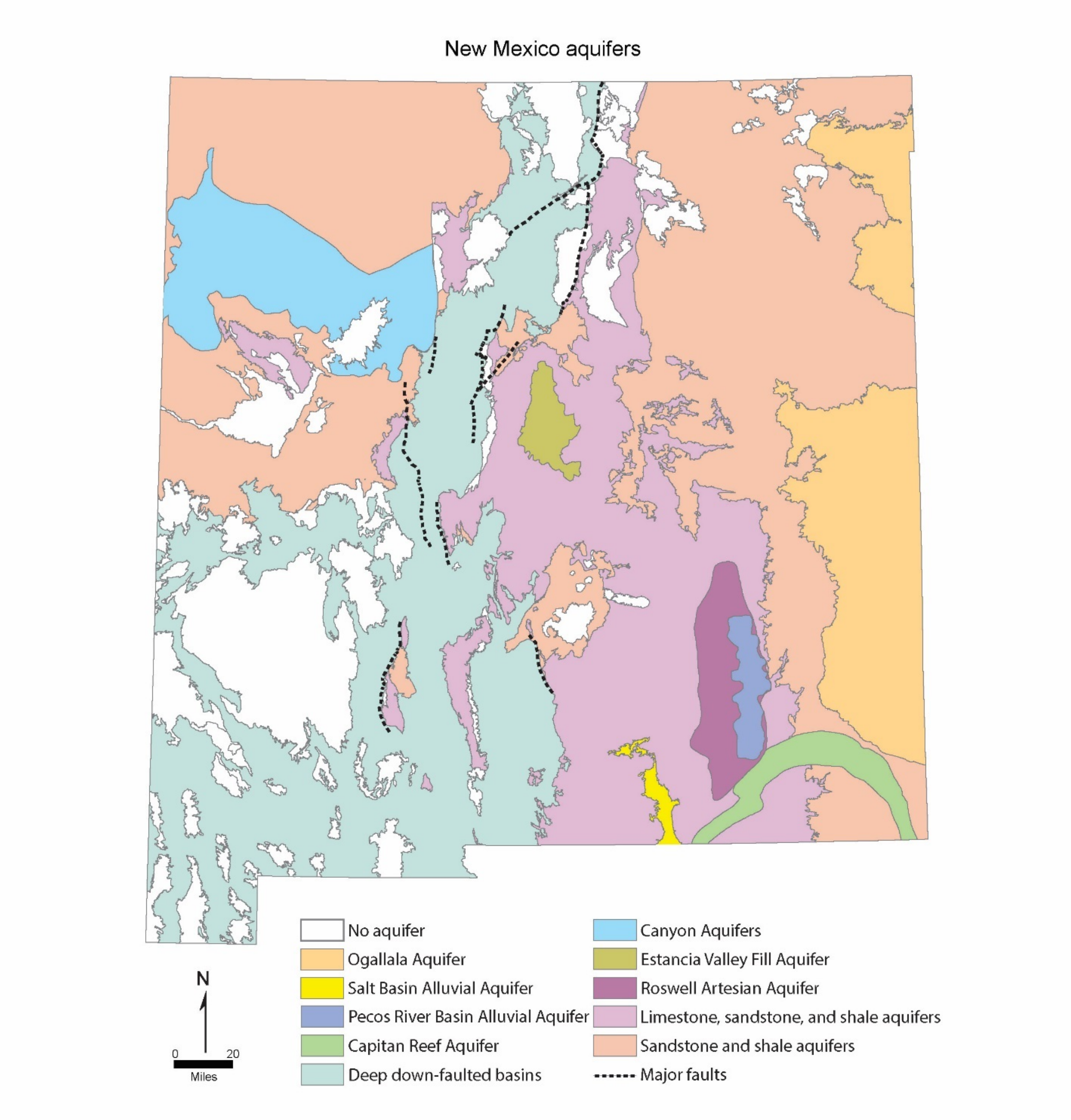

Figure 7-1. **New Mexico aquifers and major faults (modified from New Mexico Office of the State Engineer, 2016).**

Approximately 90 percent of the population in New Mexico depends on groundwater for drinking (New Mexico Office of the State Engineer and New Mexico Interstate Stream Commission, 2003). In 2010, more than 3.8 million acre-feet of water was withdrawn from surface water sources and aquifers in New Mexico, slightly less than in 2005 despite a five percent increase in population (Longworth and others, 2013). In the Canadian and Dry Cimarron river basins of northeastern New Mexico, slightly more than half of water use comes from groundwater. In the Tularosa River Basin, more than two-thirds of water needs are met by groundwater.

Water levels are declining in the High Plains (Ogallala) Aquifer (New Mexico Office of the State Engineer and New Mexico Interstate Stream Commission, 2003), Hueco Bolson Aquifer (New Mexico Office of the State Engineer and New Mexico Interstate Stream Commission, 2004), and other aquifers in New Mexico that are shared with Texas (New Mexico Office of the State Engineer and New Mexico Interstate Stream Commission, 2003). Water use is dominated by irrigation at over 78 percent and less so by public supply at just over 8 percent; all other uses add up to about 6 percent, while evaporation accounts for just over another than 6 percent (Longworth and others, 2013). Groundwater accounts for about 46 percent of withdrawals in all use categories (Longworth and others, 2013). Groundwater supplies 100 percent of self-supplied domestic uses, over 96 percent of commercial uses, over 92 percent of industrial uses, over 91 percent of livestock uses, over 75 percent of public water supply, almost 74 percent of mining uses, almost 46 percent of the water used for irrigated agriculture, and just above 18 percent of power uses (Longworth and others, 2013). In addition, the U.S. Environmental Protection Agency has designated the Española Basin Aquifer System in north-central New Mexico as a sole source aquifer (U.S. Environmental Protection Agency, 2008).

Table 7-1. **Aquifers shared by New Mexico and Texas and naming conventions.**

New Mexico	Texas		U.S. Geological Survey aquifer names
Capitan Reef Aquifer	Capitan Reef Complex Aquifer		Capitan Reef Complex Aquifer
High Plains Aquifer	Ogallala Aquifer		High Plains Aquifer
Salt Basin Alluvial Aquifer	Not recognized in Texas		part of the Rio Grande Aquifer System
Not recognized	Bone Spring-Victorio Peak Aquifer		Not recognized in New Mexico
Tularosa Basin Aquifer	Hueco-Mesilla Bolsons Aquifer		Part of the Rio Grande Aquifer System
Rio Grande Aquifer	Hueco-Mesilla Bolsons Aquifer		Part of the Rio Grande Aquifer System
Not recognized	Pecos Valley Aquifer		Pecos River Basin Alluvial Aquifer
Not recognized	Rita Blanca Aquifer		Not recognized in New Mexico
Not recognized	Dockum Aquifer		Not recognized in New Mexico
Not recognized	Edwards-Trinity (High Plains) Aquifer		Not recognized in New Mexico

Source: Ryder (1996); New Mexico Office of the State Engineer and New Mexico Interstate Stream Commission (2002); and TWDB (2007).

7.1.2 Groundwater monitoring

The New Mexico Hydrology Bureau works with the U.S. Geological Survey to monitor water levels throughout the state (New Mexico Office of the State Engineer and New Mexico Interstate Stream Commission, 2002). As of September 2016, the U.S. Geological Survey monitors 999 wells in 24 counties and one spring as part of its active water level network (U.S. Geological Survey, 2016d). Most of these wells are within the High Plains (Ogallala) Aquifer and the Santa Fe Group/Rio Grande Aquifer System, including large numbers of wells near the Texas-New Mexico border in Curry, Doña Ana, Lea, and Union counties.

7.2 Groundwater law, management, planning, and availability

New Mexico manages groundwater and surface water together, based on landowner’s first historic use of the water for beneficial purposes. Chapter 72 (New Mexico Statutes Annotated) describes state code addressing water. The groundwater code, enacted in 1931, requires permits for groundwater appropriation within 40 declared underground water basins covering the state (The Utton Center, 2013). The State Engineer issues rules and regulations in order to implement the water code (Rose, 2005).Groundwater is managed primarily by declared underground basins

(Figure 7-2), although the state may use conjunctive use practices when determining permitting amounts. New Mexico began delineating underground extents of groundwater as early as 1931 (New Mexico Office of the State Engineer, 2015). The state further defined and extended 16 underground basins (Figure 7-3), most recently in 2005 (New Mexico Office of the State Engineer, 2015). In 2004, the state established a framework for administering priority water rights during drought that includes tools such as water metering, establishing water districts, appointing water masters for each district, and establishing water district rules and regulations (New Mexico Office of the State Engineer, 2005b). This section discusses groundwater law, management, planning, and availability.

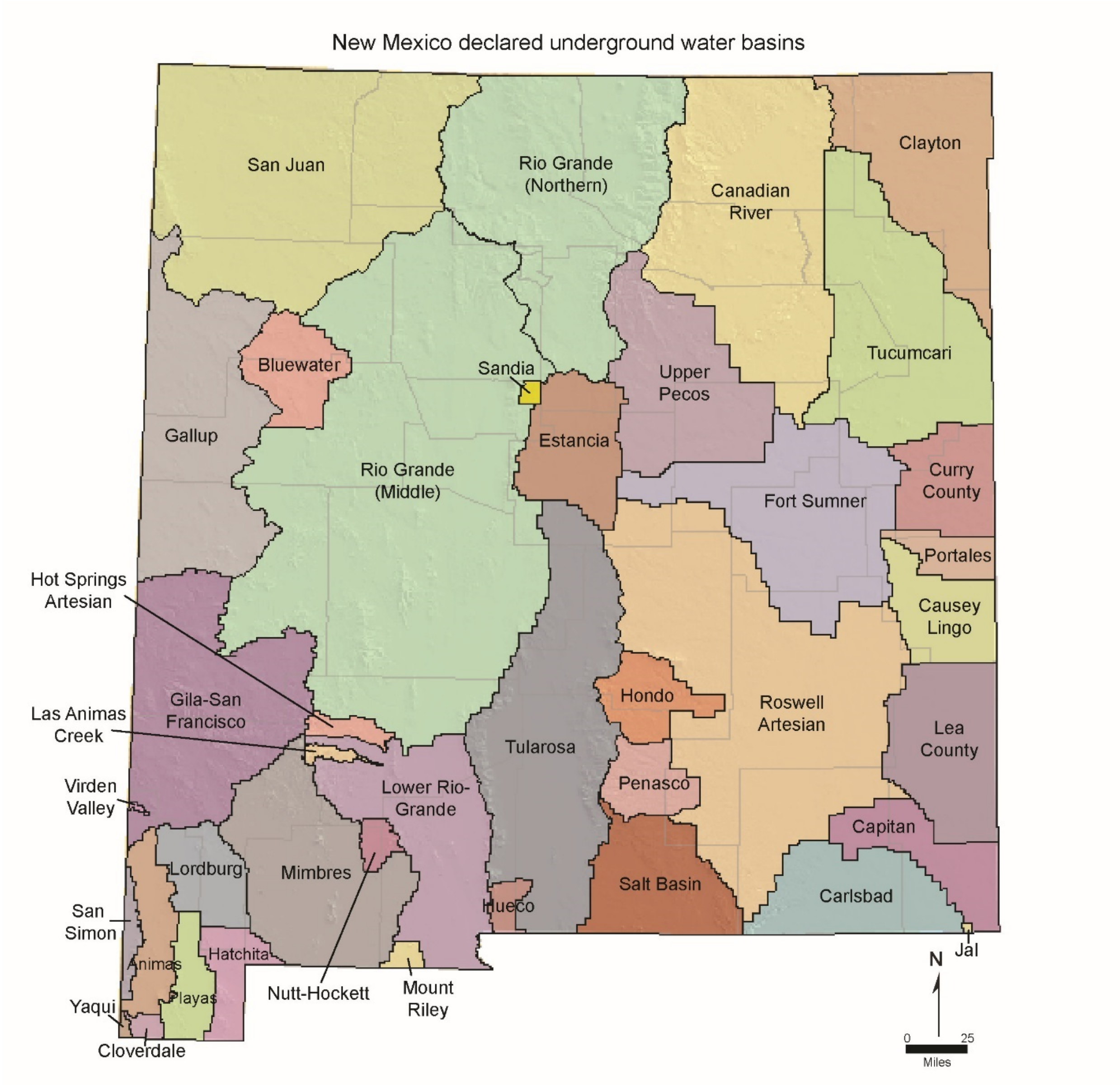

Figure 7-2. **New Mexico declared underground water basins (from Office of the State Engineer, 2015).**

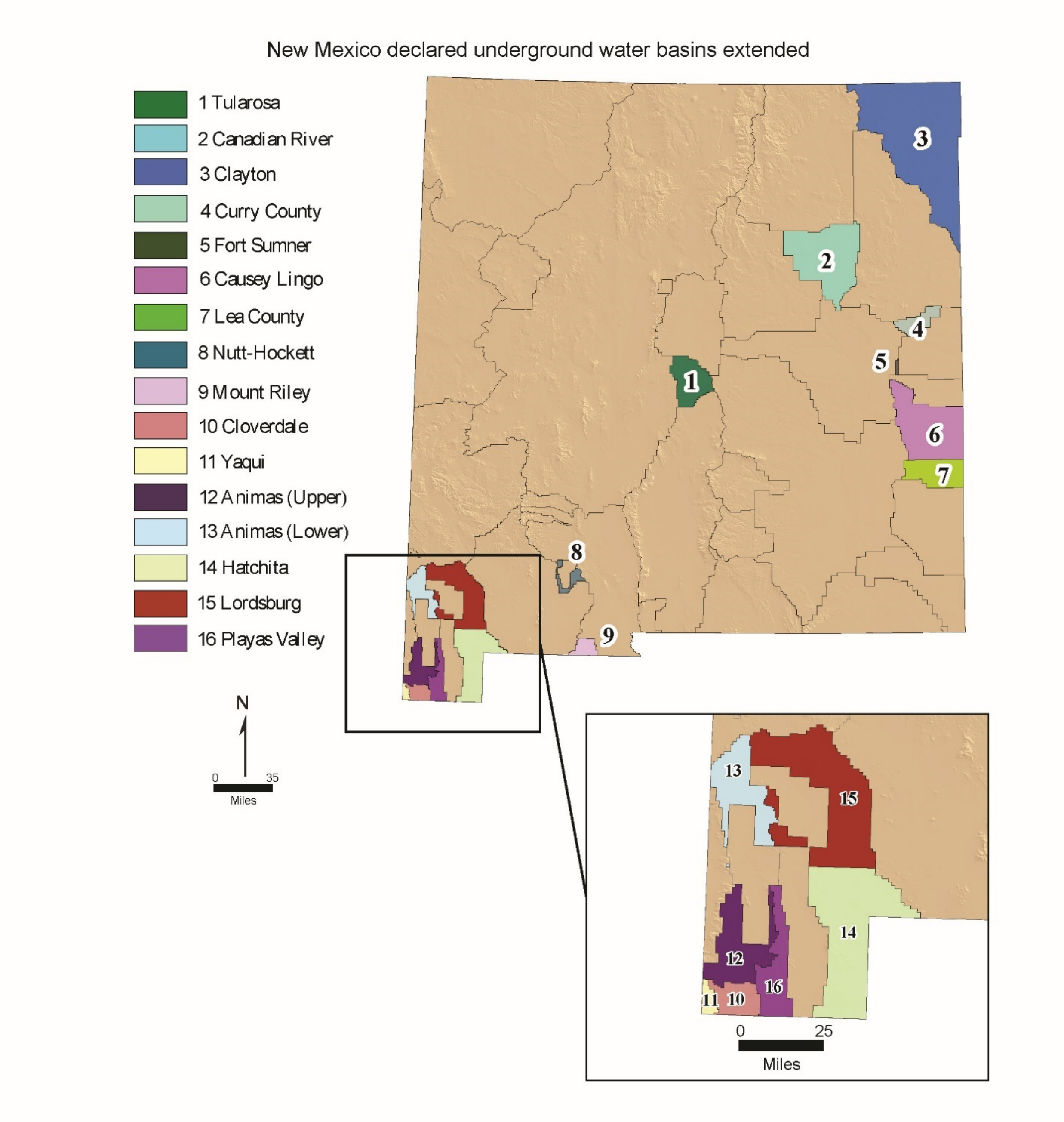

Figure 7-3. New Mexico declared underground water basins extended in 2005 (from the Office of the State Engineer, 2015).

7.2.1 Groundwater law

Surface water rights particularly relevant to irrigation in New Mexico are recognized as early as the 17th century (Maynez, 1978), whereas groundwater development began much later in the 20th century (Barroll, 2003). Unique to New Mexico are a kind of reserved water rights, called pueblo historic use water rights, which include groundwater withdrawals and are not subject to New Mexico's system of prior appropriation (Maynez, 1978).

New Mexico established a territorial water code in 1907, and assigned the courts the responsibility of adjudicating water rights (New Mexico Office of the State Engineer, 2007). Water rights originating prior to March 19, 1907, primarily originating from the Spanish and Mexican governments (Bushnell, 2012), are recognized by the state constitution and were confirmed when the state adopted the constitution (New Mexico Office of the State Engineer, 2011). The foundation for surface water law was established in 1911 by Article XVI of the New Mexico Constitution. This article, called Irrigation and Water Rights, states that rights will follow the rule of prior appropriation and beneficial use (New Mexico Constitution, 1911). The prior appropriation doctrine gives rights to the first person or entity to use the water for a beneficial purpose (Bryner and Purcell, 2003). All unappropriated water belongs to the public and is appropriated by the state (Rose, 2005). The state has the sole authority to grant water rights, which are administered by the Office of the State Engineer (Barroll, 2003).

7.2.2 Groundwater management

New Mexico manages surface and groundwater through an active water resource management strategy. In response to drought, the State Engineer adopted regulations in 2004 to establish a framework for administering priority water rights (New Mexico Office of the State Engineer, 2005a). Tools to implement the active water resource management strategy include metering, establishing water districts, appointing water masters for each district, and establishing water district rules and regulations (New Mexico Office of the State Engineer, 2013a).

New Mexico's legal and administrative institutions recognize conjunctive use—water use that recognizes hydrologic interactions between surface water and groundwater (Bushnell, 2012). As a result, the Office of the State Engineer may require groundwater permit applicants to purchase surface water rights that offset surface water lost due to groundwater pumping (New Mexico Office of the State Engineer and New Mexico Interstate Stream Commission, 2004). To aid in the administration of water rights and groundwater-surface water interaction studies, New Mexico has 17 groundwater flow models (New Mexico Interstate Stream Commission and New Mexico Office of the State Engineer, 2002) created by the Office of the State Engineer, U.S. Geological Survey, and other entities. Models bordering Texas include the Lower Rio Grande, Hueco, Lea, and Curry groundwater flow models (New Mexico Interstate Stream Commission and New Mexico Office of the State Engineer, 2002).

Chapter 72 (New Mexico Statutes Annotated) gives the State Engineer authority to establish underground water basins (Bushnell, 2012). When an underground water basin is declared, regulatory authority over groundwater rights within the basin becomes the responsibility of the State Engineer (New Mexico Office of the State Engineer and New Mexico Interstate Stream Commission, 2002). Within these basins, permits are required for any new wells or changes in water use (New Mexico Office of the State Engineer and New Mexico Interstate Stream Commission, 2002). Existing water users can file declarations to obtain legally recognized water rights if the user can demonstrate the use was for beneficial purposes (New Mexico Office of the State Engineer and New Mexico Interstate Stream Commission, 2002). In 2005, the State Engineer declared six new basins and extended the boundaries of nine existing basins to cover the entire state, bringing the total number of basins to 39 (New Mexico Office of the State Engineer, 2006a). The Capitan, Carlsbad, Causey Lingo, Clayton, Curry County, Hueco, Jal, Lea County, Lower Rio Grande, Portales, Salt Basin, Tucumcari, and Tularosa basins border Texas (Noftsker, 2005).

Underground water basins can have basin-specific administrative guidelines. For example, guidelines in the Mesilla Valley Administrative Area, a sub-region of the Lower Rio Grande Underground Water Basin, restrict streamflow depletions due to groundwater pumping and require surface water rights to be purchased in order to offset streamflow losses over 0.1 acre-feet per year. In addition, groundwater level declines are limited locally to one foot, and locations where the depth to groundwater is less than 100 feet have been defined as high impact areas, specifically because of their potential effects on the flow of the Rio Grande (New Mexico Office of the State Engineer and New Mexico Interstate Stream Commission, 2002). Within basins where groundwater is being pumped faster than it is being recharged, the State Engineer can declare that groundwater in these “mined” basins has been fully appropriated and close the basins for new water use permits. The State Engineer also has the authority to declare Critical Management Areas within mined basins. Critical Management Areas are areas that require additional protection due to significant water level declines and where groundwater is unable to sustain existing appropriations over a 40-year period. These areas may have more stringent restrictions (The Utton Center, 2013).

New Mexico began delineating groundwater basins as early as 1931. The Office of the State Engineer’s rules and regulations concerning groundwater appropriation and use, originally effective in 1966, were updated in 1978, 1985, 1991, 1995, and further revised in 2006 (New Mexico Office of the State Engineer, 2005b). These rules regulate many aspects of water use in the state, including well construction, water use permits, production limitations, metering requirements, transfer of water outside of New Mexico, changing the location of a permitted well, and other aspects of well ownership (New Mexico Office of the State Engineer, 2005b). In 2011, rules addressing use of groundwater specifically for household or domestic use were updated (New Mexico Office of the State Engineer, 2011). All of these actions require approval from the State Engineer, who must take into account existing rights, the effects on water conservation, and the effect on public welfare before granting a permit (Bushnell, 2012). Notices are posted in local newspapers prior to applications being approved for new water rights or changes to wells or water use. The public may file an objection or protest to applications, which in turn subjects the application to a hearing process (New Mexico Office of the State Engineer, 2005b), with most applications being challenged and few licenses to appropriate groundwater being issued (Bushnell, 2012).

In 2006 and 2011, the Office of the State Engineer updated the rules and regulations pertaining to domestic well permits (New Mexico Office of the State Engineer, 2011). A domestic well application may be denied in areas where there is a court restriction on water use, water well drilling, or drilling new wells due to water quality concerns. Permits may be approved with conditions, such as requirements for well construction, minimum well spacing, metering, and compliance. There are no public hearings or means for protesting domestic well permits. The permit limit for new domestic wells is one acre-foot per year for beneficial use (New Mexico Office of the State Engineer, 2011). Applicants that can demonstrate the water use will not impair existing water rights may be permitted to use up to three acre-feet per year (New Mexico Office of the State Engineer, 2011). Wells that serve multiple households are limited to one acre-feet per year per household, and wells that serve three or more households are limited to a combined diversion of up to three acre-feet per year (New Mexico Office of the State Engineer, 2011). The new regulations do not affect existing permits, and some areas of the state have enacted lower permit limits by methods such as court order, county ordinance, or State Engineer guidelines (New Mexico Office of the State Engineer, 2006b).

In 2013, the New Mexico Legislature updated domestic well rules and required developers to provide proof of water supply availability on lands with no irrigation rights and two options to show evidence and ability to provide water to a new subdivision. In one case, the developer would commit to supply water from a water provider. In the other case, the developer must show that permitted water would be provided without using a domestic well. Another specification is that subdivisions with 10 or more parcels containing one or more parcels of less than two acres must provide similar evidence to that described above (Bokum and others, 2014).

In areas where aquifers are hydrologically connected to streams and where pumping could significantly impact surface water rights or the state's obligations under interstate compacts, the State Engineer has the authority to establish domestic well management areas to prevent impairment to existing surface water rights (New Mexico Office of the State Engineer, 2011). The State Engineer must develop guidelines for each area based on hydrologic conditions and existing rights (New Mexico Office of the State Engineer, 2011). New domestic wells for single households in these management areas are limited to 0.25 acre-feet per year (Titus, 2005). Multiple households are allowed 0.25 acre-feet per year per household with a combined total diversion of three acre-feet per year (Titus, 2005). Domestic use for a governmental, commercial, or non-profit entity is not allowed unless there is no alternative water supply (New Mexico Office of the State Engineer, 2011). According to the Office of the State Engineer, over half of all domestic wells in the state are located within five miles of a perennial stream, and about one quarter of the state's domestic wells are located within one mile of a stream (New Mexico Office of the State Engineer, 2006b).

7.2.3 Groundwater planning

New Mexico's current water planning process was developed following a 1987 federal court ruling against the state's prohibition on out-of-state groundwater transfers (New Mexico Interstate Stream Commission, 1994). During this same year, the New Mexico Legislature passed legislation creating a regional water planning program, administered by the Interstate Stream Commission, to ensure there is enough available supply for current and future water demands (New Mexico Office of the State Engineer, 2014d). The state was divided into 16 planning regions and the Interstate Stream Commission provided funding to assist in the development of water plans (New Mexico Office of the State Engineer, 2014d).

The Regional Water Planning Handbook outlines the requirements of regional plans (New Mexico Interstate Stream Commission, 1994). Due to the diversity of previous approaches to regional planning, the Interstate Stream Commission, Office of the State Engineer, and regional water planners worked together to provide a template that includes assumptions and guidelines for developing a plan (New Mexico Interstate Stream Commission, 1994). The handbook stresses the importance of public participation in the planning process to address local concerns. With limited resources, some regions struggled to obtain public participation in the first round of planning (New Mexico Interstate Stream Commission, 1994). The regional plans use a 40-year planning horizon and assess the quantity and quality of water resources, population projections and water demands, and how projected demands can be met through management strategies and conservation (New Mexico Interstate Stream Commission, 1994). Funding for regional water plan development is provided by the Interstate Stream Commission in the form of grants or loans; however, regions must meet certain criteria (New Mexico Interstate Stream Commission, 1994). The Office of the State Engineer and the Interstate Stream Commission must review and accept the plan before it is considered official (New Mexico Interstate Stream Commission, 1999).

The first New Mexico State Water Plan was developed in 2003, as required by the State Water Plan Act. Required contents of the plan, intended to be a tool to promote stewardship of the state's water resources, are set forth in the State Water Plan Act. This plan is developed to protect water rights and public welfare, protect water supply and quality, promote water management strategies, maintain interstate compacts, prioritize infrastructure funding, and provide a statewide water management policy. While the state water plan is meant to integrate the regional water plans, funding and other problems slowed down the regional planning process. As a result, the 2003 State Water Plan reflected only the six regional plans that had been completed at that time (New Mexico Office of the State Engineer and New Mexico Interstate Stream Commission, 2003). Funding was increased from 1999–2006, which lead to the completion of the regional water plans. The 16th and final regional water plan was accepted by the Interstate Stream Commission in 2008. The Office of State Engineer and Interstate Stream Commission are required to collaborate and develop the state plan, as well as to review the plan every five years and update as necessary. The 2003 plan was reviewed in 2008 (New Mexico Office of the State Engineer and New Mexico Interstate Stream Commission, 2008). In 2013, the New Mexico Interstate Stream Commission reviewed the 2003 plan and determined that due to changed circumstances the state plan needed updating through the regional water planning process by December 2015 (New Mexico Office of the State Engineer, 2013b). Additional regional water planning steering committee meetings were held in 2015 through 2016 to gather updated public input to improve the plans (New Mexico Office of the State Engineer/Interstate Stream Commission, 2016).

7.2.4 Groundwater Availability

Water availability in New Mexico is limited by a variety of factors, including physical and institutional constraints, water quality, and the protection of existing water rights. Some underground water basins have additional administrative guidelines that further limit pumping and groundwater level declines (New Mexico Office of the State Engineer and New Mexico Interstate Stream Commission, 2002). The State Water Planning Handbook directs the regional water plans to include a section on sustainable yield of groundwater by aquifer. The 2003 State Water Plan defines "potentially available groundwater" as an estimated volume that must take into account current knowledge of the aquifer, effects of pumping on senior water right holders, water quality, land use regulations, land ownership factors, and economic constraints (New Mexico Office of the State Engineer and New Mexico Interstate Stream Commission, 2003). The 2003 State Water Plan also reports estimates of groundwater in storage for some aquifers (New Mexico Office of the State Engineer and New Mexico Interstate Stream Commission, 2003). The regional water plans report either total groundwater storage or groundwater availability based on water quality parameters acceptable for drinking (Daniel B. Stephens & Associates, 2007). Some regional plans report groundwater budgets, which detail the inflows and outflows of the aquifers (Daniel B. Stephens & Associates, 2007). The Office of the State Engineer also develops a water use report every five years that included groundwater withdrawals by water use category, county, and river basin (New Mexico Office of the State Engineer, 2010).

7.3 Institutions

A variety of agencies and organizations actively monitor, study, plan for, or manage groundwater resources in the state. Most are governmental agencies or exist in response to federal, state, or local rules and legislation.

7.3.1 International, national, and regional institutions

Border Environment Cooperation Commission — The binational Border Environment Cooperation Commission, together with the North American Development Bank, work to plan, finance, and implement environmental and public health infrastructure projects in the United States-Mexico border area. The Border Environment Cooperation Commission provides technical assistance during project development, facilitate stakeholder meetings, certifies projects as technically feasible, identifies the impacts of projects on the environment and public health, and ensures that communities are involved in project development. These interdependent institutions focus on projects that provide potable water treatment and distribution, wastewater collection and treatment, water conservation, and municipal solid waste management.

North American Development Bank — The North American Development Bank is a binational institution that administers the financing for environmental and public health infrastructure projects certified by the Border Environment Cooperation Commission. In addition to funding project implementation through loans and grants, the North American Development Bank provides financial guidance and technical assistance. These interdependent institutions focus on projects that provide potable water treatment and distribution, wastewater collection and treatment, water conservation, and municipal solid waste management.

U.S. Geological Survey —Groundwater projects currently being conducted by the New Mexico Water Science Center of the U.S. Geological Survey include monitoring surface water-groundwater interaction between the Rio Grande and the Santa Fe Group Aquifer System, including the Mesilla Basin Aquifer, and an investigation of salinity in shallow groundwater in the Rincon and Mesilla valleys. The U.S. Geological Survey monitors water levels in wells throughout the state as part of its active groundwater level network.

U.S. Environmental Protection Agency — New Mexico is within Region 6 of the U.S. Environmental Protection Agency, which has authorized the New Mexico Environment Department and the New Mexico Oil Conservation Division to implement many of its regulatory functions. The U.S. Environmental Protection Agency is also a national coordinator of the Border 2020/Frontera 2020 program, a joint effort to improve the environment and protect people's health, with projects located along United States-Mexico border.

U.S. Fish and Wildlife Service — The U.S. Fish and Wildlife Service is the principal agency that oversees the Endangered Species Act. If an endangered species is recognized as being dependent on groundwater, the maintenance of the groundwater supply can become federally protected. The recovery plan for the Rio Grande silvery minnow (*Hybognathus amarus*), an endangered species in New Mexico, states that maintenance of sufficient river flow is necessary for habitat restoration, that increased groundwater withdrawals could cause the river channel to dry, and that conjunctive management of surface water and groundwater may be necessary to provide habitat for the species in some areas.

Natural Resources Conservation Service, U.S. Department of Agriculture — The Natural Resources Conservation Service provides technical and financial assistance to help reduce soil erosion, protect water supplies, promote sustainable agriculture, and monitors and inventories soil and water resources. The agency provides assistance to private landowners, acequia associations, ranchers, dairy farmers, and the state's 47 soil and water conservation districts. In 2009, the Natural Resources Conservation Service approved funding for several irrigation efficiency improvement projects in New Mexico.

U.S. Bureau of Reclamation — The Albuquerque Area Office of the U.S. Bureau of Reclamation, within the U.S. Department of the Interior, includes almost all of New Mexico, the far west region of Texas, and south-central Colorado. The U.S. Bureau of Reclamation is responsible for activities in the Rio Grande, Pecos River, and Canadian River basins and operates several dams and reservoirs in New Mexico. The agency also conducts river maintenance and habitat enhancement projects and offers technical assistance on water issues for tribes, acequia communities, conservancy districts, and cities. In 2007, as part of the Carlsbad Project, the U.S. Bureau of Reclamation conducted an environmental assessment of the impacts of leasing a long-term groundwater right in order to pump the water and release it to the Pecos River to supplement flows for habitat of the federally protected Pecos Bluntnose Shiner.

U.S. Bureau of Indian Affairs — The Bureau of Indian Affairs, part of the U.S. Department of the Interior, is the main federal agency involved in managing Indian affairs. The Bureau of Indian Affairs assists federally recognized tribes through its four offices: the Office of Indian Services, the Office of Justice Services, the Office of Trust Services, and the Office of Field Operations. These offices support general assistance, disaster relief, tribal government, law enforcement and tribal courts, and management of land and resources. The Bureau of Indian Affairs carries out trust responsibilities, and the Department of the Interior helps develop strategies for settling tribal water disputes.

Good Neighbor Environmental Board — The Good Neighbor Environmental Board is a United States-based, independent federal advisory committee, managed by the U.S. Environmental Protection Agency that advises the President of the United States and Congress on United States-Mexico border environmental issues. The Good Neighbor Environmental Board holds meetings in border communities and provides a yearly report with recommendations for environmental and infrastructure issues. Since the publication of its first report in 1995, the Good Neighbor Environmental Board has repeatedly discussed the importance of groundwater quality and quantity to the region and recommended the two countries develop mechanisms for protecting shared aquifers.

United States-Mexico Border Field Coordinating Committee — As a committee under the U.S. Department of the Interior, the Field Coordinating Committee aims to enhance communication and coordination between Department of Interior bureaus on border environmental and cultural issues. The Committee has helped establish several memoranda of understanding between the U.S. Department of Interior and the Secretaría de Medio Ambiente y Recursos Naturales in Mexico in order to protect shared resources (U.S. Department of the Interior, 2008) and has developed work groups on groundwater and shared water resources.

The U.S. Section of the International Boundary and Water Commission — The U.S. Section of the International Boundary and Water Commission is a federal agency charged with applying treaties between the United States and Mexico that address boundaries and water and with settling disputes related to these treaties. The U.S. Section of the International Boundary and Water Commission helped develop and publish a binational aquifer study and data report on the Tularosa, Hueco Bolson, and Rio Grande aquifers shared by Mexico, New Mexico, and Texas.

Southwest Consortium for Environmental Research and Policy (Consorcio de Investigación y Politica Ambiental del Suroeste) **—** The Southwest Consortium for Environmental Research and Policy was a consortium of universities in the United States and Mexico that studied problems in the United States-Mexico border area from 1992-2013. Projects consisted of research, policy development, outreach, education, and community capacity building. Past projects have addressed hydrology, access to drinking water, and transborder water management in the region. The participating university in New Mexico was New Mexico State University.

Paso del Norte Water Task Force — The Paso del Norte Water Task Force is a regional partnership between southern New Mexico, west Texas, and northern Chihuahua that is involved in binational water issues in the Paso del Norte area, which includes parts of the Rio Grande and bolson aquifers. The task force consists of water managers, water experts, water users, and citizens. Goals of this task force are to determine priority water issues in the area, promote information sharing, and make policy recommendations to relevant authorities in Mexico and the United States.

7.3.2 Statewide institutions

New Mexico Office of the State Engineer and the Interstate Stream Commission — The New Mexico Office of the State Engineer and the Interstate Stream Commission jointly administer New Mexico's water resources. The Office of the State Engineer has control over the appropriation, adjudication, supervision, and measurement of surface water and groundwater and water rights in the state. The Interstate Stream Commission oversees water planning and is responsible for ensuring New Mexico's water rights under interstate agreements. As a part of these duties, the agencies study, develop, and work to conserve waters in the state; develop water use estimates; provide permits for eligible water use; and delineate groundwater basins. In addition, the agencies' Hydrology Bureau manages the state groundwater level monitoring program, conducts hydrologic and water availability studies, and develops water resource models. The Office of the State Engineer is also responsible for regulating water well construction, licensing well drillers, and collecting well records and logs for wells drilled in the state.

New Mexico Water Trust Board — Administered by the New Mexico Finance Authority, the purpose of the Water Trust Board is to recommend and prioritize projects to be funded by the Water Project Fund. Funds can be used to support projects that address water conservation, flood prevention, implementation of the Endangered Species Act, water infrastructure improvements, and watershed management and restoration.

New Mexico Environment Department, Ground Water Quality Bureau — The New Mexico Environment Department houses the Ground Water Quality Bureau, whose job it is to implement state and federal law to protect groundwater quality in the state. The Ground Water Quality Bureau issues groundwater discharge permits and groundwater pollution prevention permits; oversees the identification, investigation, and cleanup of contaminated sites, including Superfund and mining sites; develops related rules; and promotes public and industry awareness of the importance of groundwater quality.

New Mexico Environment Department, Water Quality Control Commission — Also a part of the New Mexico Environment Department, the New Mexico Water Quality Control Commission is responsible for controlling surface water and groundwater pollution within New Mexico. It does this through implementing the U.S. Clean Water Act; the Wellhead Protection Program and the Sole Source Aquifer Program; adopting related rules; and administering federal loan and grant programs.

New Mexico Resource Geographic Information System Program — A joint program of the University of New Mexico and the New Mexico Information Technology Commission, the New Mexico Resource Geographic Information System is the state's clearinghouse for geospatial data. The program promotes the use of GIS in policy development, planning, and research. Datasets available describe the state's hydrology, soils, topography, regulated sites, land use, administrative boundaries, and other information relevant to water management.

New Mexico Energy, Minerals and Natural Resources Department, Oil Conservation Division — The Oil Conservation Division of the New Mexico Energy, Minerals and Natural Resources Department regulates the oil, gas, and geothermal industries in New Mexico. Within the Oil Conservation Division, the Environmental Bureau is responsible for developing and enforcing regulations aimed at preventing groundwater contamination.

New Mexico Institute of Mining and Technology, New Mexico Bureau of Geology and Mineral Resources **—** The New Mexico Bureau of Geology and Mineral Resources is a subdivision of the New Mexico Institute of Mining and Technology and serves as the state geological survey. As part of this role, the Bureau of Geology and Mineral Resources is involved in mapping and characterizing water quantity and quality in New Mexico aquifers, with an emphasis on studies that provide relevant and impartial information for decision-makers.

New Mexico State University, College of Agricultural, Consumer and Environmental Sciences — The College of Agricultural, Consumer and Environmental Sciences at New Mexico State University houses the state's Cooperative Extension Service, which cooperates with county governments to provide research-based information through public outreach throughout the state. The college also leads the Water Task Force, a group composed of research and teaching faculty that promotes research and dialogue to address water resources science, policy, management, conservation, and quality.

New Mexico Water Resources Research Institute — The New Mexico Water Resources Research Institute is housed at New Mexico State University in Las Cruces and is a member of the National Institutes for Water Resources. The institute funds research in New Mexico on state, regional, and national water problems, and it cooperates with other groups to address water-related problems along the U.S.-Mexico border.

New Mexico Rural Water Association — The New Mexico Rural Water Association is a non-profit organization that provides training and technical assistance for small public water and wastewater systems and utilities as well as tribes in New Mexico, particularly those in rural areas. Association members include community water cooperatives, small municipal government water utilities, and public water and wastewater sanitation districts.

New Mexico Drought Task Force — The New Mexico Drought Task Force is responsible for updating the New Mexico Drought Plan, providing recommendations for water conservation during periods of drought, and reducing the negative impacts of drought.

New Mexico Acequia Commission — The Acequia Commission is an advisory group consisting of acequia and ditch association members appointed by the Governor. The group advises the state on issues affecting acequia associations and makes recommendations on funding applications for acequia projects. The Acequia Commission also acts as a liaison between the acequia associations and state and federal agencies.

7.3.3 Local institutions

Artesian conservancy districts — Artesian conservancy districts strive to conserve water in artesian basins. The districts are required to develop a plan or program for water conservation. These districts are considered political subdivisions that are governed by a board of directors, have the powers of a public or municipal corporation, and can exercise the right of eminent domain. A required duty of the districts is to prevent wells from leaking or wasting water. Waters covered by the district may also include underground water other than artesian water after a petition, notice, and resolution have been filed. The district must have a certificate from the State Engineer to include non-artesian water.

Regional water planning areas — New Mexico is divided into 16 regional water planning areas, each of which has developed its own water plan. Of these, five include areas that border Texas: the Lea County Planning Area (Region 16), which completed an original plan in 1999 and completed a draft update in 2016; the Lower Pecos Valley Planning Area (Region 10), which completed an original plan in 2007 and completed a draft update in 2016; the Lower Rio Grande Planning Area (Region 11), which completed an original plan in 1999 and a draft update in 2016; the Northeast New Mexico Planning Area (Region 1), which completed an original plan in 2007 and a draft update in 2016; and the Tularosa, Sacramento, and Great Salt Basins Planning Area (Region 5), which completed an original plan in 2004 and a draft update in 2016.

Soil and water conservation districts — New Mexico has 48 soil and water conservation districts, local units of government that promote natural resource management on private and public lands. Working with the Natural Resources Conservation Service, the districts provide technical assistance to ranchers and farmers and help to implement conservation practices.

Acequias — Acequias are ditch irrigation systems managed by communities. These systems are considered political subdivisions of the state, which enables them to receive loans from the Interstate Stream Commission. The Acequia and Community Ditch Fund Act created a fund for the state to provide financial assistance so acequias could obtain technical, legal, and educational services to help conserve water. Acequias may pass bylaws that require changes in the location of water rights by acequia water users to be approved by the acequia commissioners. The State Engineer is subject to taking into consideration acequia rules when approving water rights transfers.

Water user associations — Water user associations consist of land, irrigation ditch, or reservoir owners either in the same or neighboring county that have entered an agreement to build, maintain, and operate reservoirs, dams, or irrigation ditches. Water user associations are often involved in the development of the regional water plans. Along the Texas-New Mexico border, the following water user associations played a key role in developing the regional plans: the Lea County Water Users Association, the Lower Rio Grande Water User Organization, and the Pecos Valley Water User Organization.

7.4 Interactions with Texas

New Mexico shares almost its entire eastern border and over half of its southern border with Texas, based on political subdivision boundaries. States have a variety of ways to interact regarding shared water resources. This section includes details about two specific kinds of interactions which may or may not address groundwater.

7.4.1 Interstate compacts

The state of New Mexico has eight interstate compacts regarding water resources (New Mexico Office of the State Engineer, 2014b). Of these, Texas is also a signatory of the Rio Grande Compact between New Mexico, Texas, and Colorado, signed in 1938 (New Mexico Office of the State Engineer, 2014e); the Pecos River Compact between New Mexico and Texas, signed in 1948 (New Mexico Office of the State Engineer, 2014c); and the Canadian River Compact between New Mexico, Texas, and Oklahoma, signed in 1950 (New Mexico Office of the State Engineer, 2014a). Each of these compacts requires specific amounts of streamflow to reach downstream regions and states and is both a U.S. federal law and a state law in the participating states (Turney, 2001).

Although these compacts address surface water, groundwater resources play a part in the fulfillment of delivery requirements defined by the compacts. Many aquifers are hydrologically connected to streams; if groundwater levels in these aquifers drop, surface water levels will also drop, reducing flow in the rivers (Turney, 2001). A study by the Interstate Stream Commission and the U.S. Army Corps of Engineers found that New Mexico's ability to meet its obligations under the Rio Grande Compact is decreasing, due in part to continued use and development of groundwater (Turney, 2001), and Texas previously threatened to sue New Mexico over compliance issues with the Rio Grande Compact (New Mexico Office of the State Engineer and New Mexico Interstate Stream Commission, 2004). Compliance issues and river releases continue to be a disputed issue between New Mexico and Texas (Clawson, 2014; Hallinan, 2015).

Separate research by the Office of the State Engineer in 2000 estimated that in five interstate rivers subject to interstate compact agreements, domestic groundwater pumping may be causing annual stream depletions of 4,757 to 13,692 acre-feet (New Mexico Office of the State Engineer, 2000). Calculations are based on wells within the floodplain or one-mile radius of the river and the range was determined using 0.35 to 1 acre-foot withdrawals and 45 percent net depletion (New Mexico Office of the State Engineer, 2000).

There is no regulatory framework between Texas and New Mexico that specifically covers groundwater pumping. The New Mexico Interstate Stream Commission has noted the need for cooperation between the two states to successfully manage the quantity and quality of water supplies. For example, the New Mexico Office of the State Engineer and the New Mexico Interstate Stream Commission found that groundwater supplies in New Mexico are being negatively affected by pumping from the Mesilla Bolson Aquifer in and around El Paso, Texas, and Ciudad Juarez, Chihuahua, as well as by pumping from the Ogallala (High Plains) and other aquifers near the state line in northwest Texas (New Mexico Office of the State Engineer and New Mexico Interstate Stream Commission, 2002, 2004).

7.4.2 Interstate commissions

The New Mexico-Texas Water Commission was formed in 1991 following the 1991 El Paso Water Suit Settlement Agreement (New Mexico Office of the State Engineer and New Mexico Interstate Stream Commission, 2004). Its objectives include collaborating on studies of shared water resources, reporting on related legislative and administrative actions in each state, promoting regional participation, reviewing water resource plans affecting the area, and exploring policy changes to help achieve interstate cooperation (New Mexico-Texas Water Commission, 2016). The Commission is also working on the Las Cruces-El Paso Sustainable Water Project, which would divert surface water from the Rio Grande via a pipeline to the El Paso-Las Cruces area for use and store unused water in the Hueco Bolson Aquifer for later use (New Mexico Office of the State Engineer and New Mexico Interstate Stream Commission, 2004).

The Rio Grande Compact Commission consists of representatives from each state in the Rio Grande Compact, as well as a representative from the United States government. The Commission administers the Rio Grande Compact and holds annual meetings. The Pecos River Compact Commission and the Canadian River Compact Commission are similar commissions that administer the Pecos River and Canadian River compacts, respectively (NMOSE, 2014a, c).

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8. Oklahoma

In 2012, Oklahoma passed legislation calling for statewide policy goals such as water efficiency improvement and using alternative sources to support a goal of consuming the same amount of water in 2060 as was used in 2010. Oklahoma identifies reliable water supplies for a 50-year planning window through a statewide plan, most recently published in 2012 and including a one-year implementation review in 2013. In Oklahoma, the Water Resources Board has purview over groundwater resources, including permitting for both groundwater and surface water. Oklahoma manages groundwater based on landowners having a legal right to capture and use groundwater based on land ownership and correlative rights. Groundwater is managed on an aquifer basis with permitted uses generally equaling 2 acre-feet per acre of land annually. Groundwater resources are evaluated for a minimum 20-year lifetime to develop what is called maximum annual yield, an amount considered safe for permitted users to withdraw.

8.1 Groundwater Resources

Oklahoma borders almost the entire northern border of Texas. Groundwater provides close to half of all water resources for a variety of uses. This section includes details about Oklahoma's aquifers and monitoring.

8.1.1 Aquifers

The Oklahoma Water Resources Board recognizes 22 major aquifers and 32 minor aquifers (Figure 8-1) covering almost 80 percent of the state (Oklahoma Water Resources Board, 2016). Of these 54 aquifers, eight extend into Texas (see Table 8-1). Estimates indicate that these aquifers contain about 390 million acre-feet of groundwater storage, although only half is considered to be recoverable (Oklahoma Water Resources Board, 2014c). The Ogallala Aquifer, located in western Oklahoma, serves as the largest groundwater resource, with about 90 million acre-feet (Oklahoma Water Resources Board, 2014c). At a regional scale, the U.S. Geological Survey recognizes the following principal aquifers in Oklahoma: the Ada-Vamoosa Aquifer, the Arbuckle Simpson Aquifer, the Blaine Aquifer, the Central Oklahoma Aquifer, the Edwards-Trinity Aquifer System, the High Plains Aquifer; the Ozark Plateaus Aquifer System, and the Rush Springs Aquifer (Ryder, 1996; Reilly and others, 2008). The U.S. Environmental Protection Agency has designated one aquifer in Oklahoma—the Arbuckle-Simpson Aquifer, in the south-central part of the state—as a sole-source aquifer (U.S. Environmental Protection Agency, 2008).

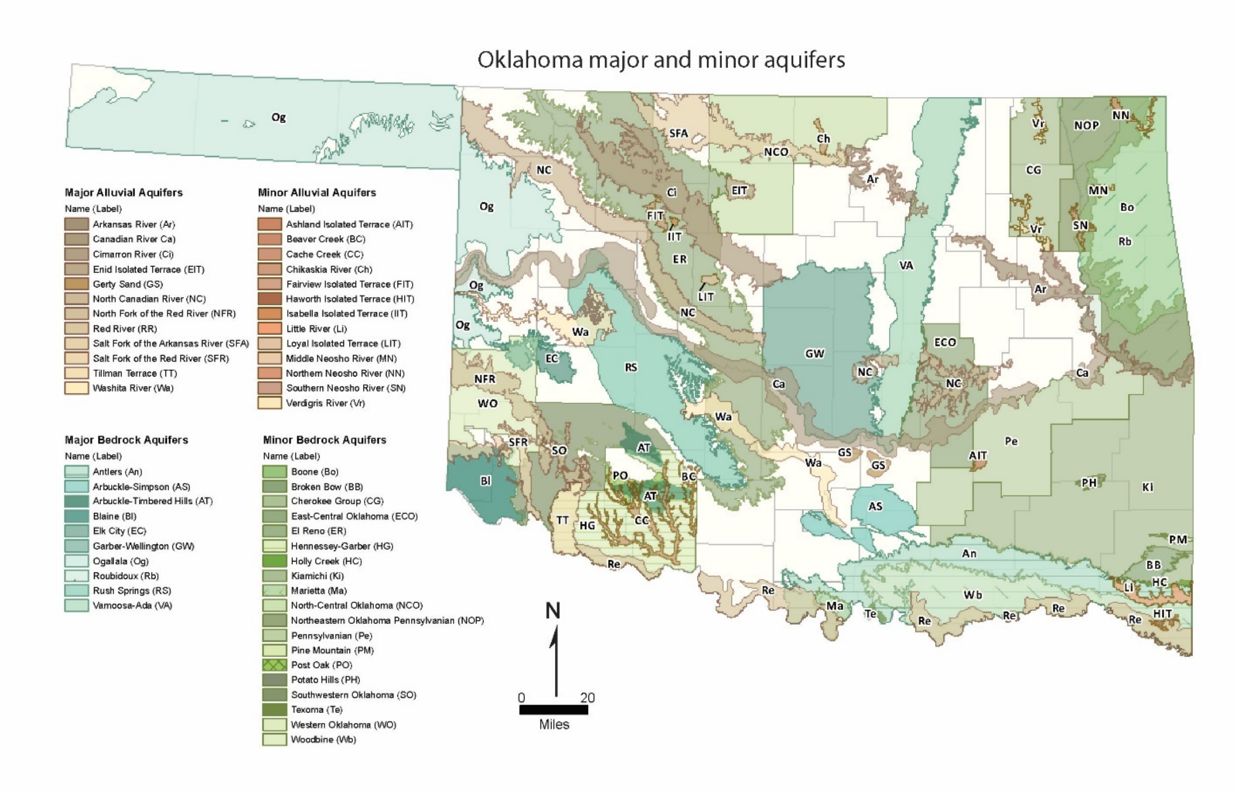

Figure 8-1. **Oklahoma major and minor alluvial and bedrock aquifers (modified from Oklahoma Water Resources Board, 2016).**

In 2007 groundwater was the source of 44 percent of water used in the state, supplying 73 percent of the irrigation and municipal/industrial uses (Oklahoma Water Resources Board, 2014c). Total use attributed to groundwater increased from 2005, at which time it supplied 37 percent of all uses, including 18 percent of public drinking water, 100 percent of domestic water with 3.3 percent of the population using domestic wells for their water supply, 73 percent of irrigation, 34 percent of livestock, and 7 percent of commercial/industrial/power/mining (Tortorelli, 2009).

Table 8-1. Aquifers shared by Oklahoma and Texas and naming conventions.

Oklahoma	Texas	U.S. Geological Survey aquifer names
Blaine Aquifer	Blaine Aquifer	Blaine Aquifer
Antlers Aquifer	Part of the Trinity Aquifer	Trinity Aquifer, part of the Edwards-Trinity Aquifer System
Ogallala Aquifer	Ogallala Aquifer	High Plains Aquifer
North Fork of the Red River Alluvium and Terrace Aquifer	Not recognized	North Fork Red and Red Rivers Alluvial Aquifer
Canadian River Alluvium and Terrace Aquifer	Not recognized	Canadian River Alluvial Aquifer
Washita River Alluvium and Terrace Aquifer	Not recognized	Washita River Alluvial Aquifer
Red River Alluvium and Terrace Aquifer	Not recognized	North Fork Red and Red Rivers Alluvial Aquifer
Not recognized	Seymour Aquifer	Not recognized in Oklahoma
Not recognized	Rita Blanca Aquifer	Not recognized in Oklahoma
Not recognized	Woodbine Aquifer	Not recognized in Oklahoma
Not recognized	Blossom Aquifer	Not recognized in Oklahoma
Not recognized	Nacatoch Aquifer	Not recognized in Oklahoma
Tillman Terrace Aquifer	Not recognized	Not recognized

Source: Ryder (1996); Oklahoma Water Resources Board (2014); Wilkins (1997); and TWDB (2007).

8.1.2 Groundwater monitoring

Several state and federal agencies monitor groundwater conditions in Oklahoma. The Oklahoma Water Resources Board monitors water chemistry and water levels in aquifers throughout the state (Todd and others, 2009). In 1999, the agency completed an evaluation using the DRASTIC index method and generated a statewide map of the relative vulnerability of groundwater basins to pollution. The evaluation included 30 hydrogeologic basins and 12 major aquifers that are exposed at the land surface, which increases the risk for pollutants entering the groundwater. Results indicated that the alluvial aquifers were most vulnerable and the bedrock aquifers least vulnerable (OWRB, 1999).

As of September 2016, the U.S. Geological Survey monitors 281 wells in 26 Oklahoma counties and 3 springs in order to monitor changes in water levels as part of its active water level network (U.S. Geological Survey, 2016e). The Oklahoma Department of Environmental Quality monitors water quality and regulates public water suppliers. In addition, the U.S. Environmental Protection Agency provides assistance in the state's Baseline Monitoring Program for major freshwater aquifers statewide. The Oklahoma Water Quality Monitoring Council does not monitor groundwater resources directly but is responsible for developing a statewide water quality monitoring plan.

8.2 Groundwater law, management, planning, and availability

Oklahoma manages and permits uses of both groundwater and surface water, based on reasonable use, correlative rights, and allocation. Surface water permits are based on landowner's riparian rights limited by reasonableness and use of the water for beneficial purposes. Groundwater law changed from the rule of capture used in the 1800s to reasonable use through a 1936 legal case. In 2012, the state updated the 1995 statewide water plan using 82 geographic watershed boundaries rather than political boundaries. Oklahoma plans for groundwater basins based on the surface area associated with the basin and the saturated thickness for a minimum aquifer yield of at least 20 years, with statute requiring 20-year updates on groundwater basin studies. The state envisions managing all groundwater resources using maximum annual yield. This section discusses groundwater law, management, planning, and availability.

8.2.1 Groundwater law

Agricultural water needs have been key in affecting Oklahoma's development of groundwater law (Roberts and Gros, 1987). Water law in Oklahoma, originally based on rule of capture and later reasonable use, correlative rights, and allocation, was changed intermediately to a "prior appropriation" doctrine beginning in 1949 (Roberts and Gros, 1987; Chapman and others, 2005). This system recognized existing groundwater rights but was never implemented, possibly due to the restrictiveness of requiring withdrawals to be limited to the amount of natural recharge, particularly in the intensively irrigated western part of the state (Roberts and Gros, 1987).

Although Oklahoma law recognizes groundwater ownership as a legal property right associated directly with the surface landowner, groundwater use is regulated by the state under the Oklahoma Groundwater Law (Oklahoma Water Resources Board, 2013b) through a permitting system based on the limitations of available groundwater (Vaughan, 1988). Oklahoma statute Title 82, Chapter 11, Section 1020.1 defines groundwater as being fresh underground water standing or moving in a geologic structure located outside the cut bank of a defined stream (Savage, 2002a). This section defines freshwater as containing less than 5,000 milligrams per liter of total dissolved solids (Oklahoma Legislature, 2013). Water with salinity greater than 5,000 milligrams per liter is considered saltwater in Oklahoma (Oklahoma Legislature, 2013).

Oklahoma courts have addressed conveyance of water rights, federal intervention in groundwater regulation, decisions about real property, and the use of groundwater in oil and gas exploration. In 1936, a pivotal Oklahoma case pertaining to groundwater , when the courts opined that groundwater use should not cause harm intentionally to neighboring properties (Meazell, 2008) and prohibited transfer of water off the land where it was withdrawn (Roberts and Gros, 1987). This case, *Canada v. City of Shawnee* (1936), changed groundwater use practices when the Oklahoma the Oklahoma Supreme Court discarded the common-law doctrine rule of capture specifically relating to percolating water that the territorial legislature adopted in 1890 and had used dating back to 1843 (Roberts and Gros, 1987; Savage, 2002b; Savage, 2002a). The court then declared reasonable use, or the "American Rule," the basis for groundwater rights and allocation in Oklahoma (Savage, 2002a).

Oklahoma established the 1949 Groundwater Law, supporting the conservation of groundwater through limiting withdrawals to safe annual yield through court adjudication, which was tied to the annual aquifer recharge rate based on hydrologic surveys (Savage, 2002a). Despite the failure of an authorized court adjudication system to be developed, the Oklahoma Planning and Resources Board's Division of Water Resources issued permits for two acre-feet per year, which was the amount allocated under the 1949 law (Roberts and Gros, 1987). In 1957, the Oklahoma Legislature authorized the Oklahoma Water Resources Board to manage groundwater withdrawals with an emphasis on developing efficient water supplies to meet every need rather than reducing allocations (Roberts and Gros, 1987). In 1972, new legislation introduced and enforced the policy of utilization of groundwater resources (Savage, 2002a). Under the 1972 Groundwater Act, effective in 1973, a water use permit allocates to the applicant a proportionate share of the maximum annual yield of the basin for beneficial use (Savage, 2002a). In addition to not recognizing critical groundwater areas, the 1972 Groundwater Act neither recognizes nor mentions preferences or conflicting beneficial uses (Meazell, 2008).

In 1976, the Oklahoma Supreme Court held in *Lowrey v. Hodges* a case addressing the use of the Ogallala Aquifer by one landowner as affecting the water levels in the well of a neighboring landowner that a temporary permit (discussed below) is not equivalent to a regular permit (Vaughan, 1988). A key argument made in the case was that the proposed use of the Ogallala Aquifer was wasteful (Vaughan, 1988). The Oklahoma Water Resources Board's practice of automatic permit revalidation was held to be inconsistent with the Court's earlier position and contrary to the statutory mandate to the Oklahoma Water Resources Board to provide reasonable regulations for the allocation of fresh groundwater resources for reasonable use (711 P.2d 47).

In 1977 the Oklahoma Supreme Court considered the issue of use of fresh groundwater for secondary and tertiary oil recovery. In *Texas County Irrigation v. Cities Ser. Oil Co.*, 570 P.2d 49 (Okl. 1977), the Court looked at the statutory authority of the Oklahoma Groundwater Law and legislative intent to evaluate the practice of using freshwater for secondary oil recovery as wasteful (Vaughan, 1988). Court findings indicated that fresh groundwater use in a water flood secondary oil recovery program may constitute waste under some circumstances (Vaughan, 1988).

In *Ricks Exploration Company v. Oklahoma Water Resources Board* (1984), the Oklahoma Supreme Court found that "a mineral owner's claim to groundwater use is a 'vested right' created by common law" (Webber II, 1985). The court recognized that depriving the mineral rights owner of the ability to extract the mineral by disallowing water pumping constitutes a taking of the right; without the ability to use a reasonable amount of water needed to extract the mineral, the mineral ownership in and of itself would be useless (Webber II, 1985). In addition, the law establishing groundwater management practices indicates the Oklahoma Water Resources Board should not issue permits to an applicant who does not own the land on which the well is to be located or hold a valid lease from the owner of such land permitting withdrawal of water from the relevant basin or subbasin (Webber II, 1985). Although the mineral rights may be severed from the land, the mineral rights owner may not pump water unless he also owns the surface land or has the express permission of the owner to pump water (Webber II, 1985). This case confirmed that the 1972 Oklahoma Groundwater Law does not prohibit groundwater from being transported off the producing premises, so long as the applicant is in compliance with all other codified regulations of reasonable use (Webber II, 1985).

Regarding the broader scope of constitutionality of the Oklahoma groundwater law allocation system, in a 1998 case *Kline v. State (Oklahoma Water Resources Board)* the Oklahoma Supreme Court upheld that the state may regulate and restrict a landowner’s groundwater use (Meazell, 2008). This outcome was to protect against groundwater waste and to prevent infringing on the rights of others (Meazell, 2008). This legislation is considered a resource utilization law, allowing for resource depletion meant for creating economic benefit (Oklahoma Water Resources Board, 2008).

8.2.2 Groundwater management

The 1973 Oklahoma Groundwater Law requires water use permits, issued by the Oklahoma Water Resources Board, for every use of groundwater except for domestic or household use (Oklahoma Water Resources Board, 2011b). Domestic uses are exempted from regulation include a natural person (a human being rather than a legal entity), family, or household using groundwater for domestic, livestock, and irrigation use not exceeding three acres with no specific extraction volume, or non-household use of five acre-feet per year or less (Oklahoma Water Resources Board, 2011c). Statewide well spacing requirements are 1,320 feet between wells in a bedrock aquifer with established yields and 660 feet in alluvial or terrace aquifers with established yields, with exceptions allowed in certain instances (Oklahoma Water Resources Board, 2013a).

Permitted use is limited to a specific volume per year per acre of property owned, based on the estimated maximum available yield of the groundwater basin in which the property lies. Maximum available yield is an amount determined by hydrogeologic studies conducted by the Oklahoma Water Resources Board (Oklahoma Water Resources Board, 2013a). In basins for which the maximum available yield has not yet been estimated, only temporary permits can be issued (Oklahoma Water Resources Board, 2013a). Temporary permits allow a correlative right of two acre-feet per year per acre of land (Oklahoma Water Resources Board, 2013a). The state allows transfer or re-assignment of groundwater permits, and there is a provision for temporarily exceeding allowed permitted amounts for up to six months (Oklahoma Water Resources Board, 2013b).

8.2.3 Groundwater planning

The Oklahoma Legislature first mandated the development of a state water management guide through the passage of Senate Bill 510 in 1974 (Oklahoma Water Resources Board, 1975). The state’s first 50-year Oklahoma Comprehensive Water Plan was published by the Oklahoma Water Resources Board on September 1, 1975 (Oklahoma Water Resources Board, 1975) and updated in 1980 (Oklahoma Water Resources Board, 2014d). In 1992, House Bill 2036 required the plan to be updated every 10 years (Oklahoma Water Resources Board, 1997), leading to the development and release of the 1995 plan and issuance of annual status reports from 2007 through 2010 (Oklahoma Water Resources Board, 2007, 2010). The goal of the Oklahoma Comprehensive Water Plan is to identify reliable water supplies for a 50-year planning window (Oklahoma Water Resources Board, 1975). The plan describes water resources, other natural resources, and socioeconomic characteristics of the state; presents statewide water use projections; evaluates water supplies by region; identifies significant problems; and recommends legislation and governmental activities to improve state water management (Oklahoma Water Resources Board, 1997). In 2006, the Oklahoma Legislature appropriated funds to complete a five-year study, using a consensus-based regional water planning approach similar to the ones used in Texas and New Mexico, and release a third update. In 2012, the Oklahoma Water Resources Board released the updated water plan, citing unprecedented public participation and expertly developed data supporting four future success factors: (1) new or improved infrastructure development, (2) revitalization of data collections efforts, (3) a more conservation-oriented management approach, and (4) use of formalized regional water planning as the standard (Oklahoma Water Resources Board, 2012).

Two federal legal issues relevant to state water issues and planning, and recognized by the Oklahoma State Water Plan, are “federal reserved rights” and the Winters Doctrine (Oklahoma Water Resources Board, 1997) Both are described in more detail in Section 3.2.

8.2.4 Groundwater availability

As discussed above, groundwater rights in Oklahoma are based on estimates within groundwater basins what is called maximum annual yield. Maximum annual yield, defined in 1973, is “the total amount of fresh groundwater that can be withdrawn while allowing a minimum 20-year life of the basin,” and groundwater basins are defined as “distinct underground bodies of water under continuous land having substantially the same geological and hydrological characteristics and yield capabilities.” To calculate the maximum annual yield, the Oklahoma Water Resources Board or another agency conducts a hydrologic study of a basin to estimate the area of land overlying the basin, amount of groundwater in storage, proportionate share, rate of natural recharge and total discharge, transmissivity, and potential for pollution from natural sources (Oklahoma Water Resources Board, 2012). Most hydrologic studies have included the development and use of a groundwater flow model (Oklahoma Water Resources Board, 2014b). A critical study component for conjunctive use management efforts is validation of groundwater-surface water interaction, this interaction help’s quantify maximum annual yield (Oklahoma Water Resources Board, 2012).

In 2012, Oklahoma (Oklahoma Water Resources Board, 2012) updated aquifer conditions and withdrawals included:

- Recharge rates and aquifer storage volumes for 11 major alluvial aquifers and six permitted aquifer withdrawal values ranging from 0.5 to 1.5 acre-feet per acre (5 have temporary withdrawals of 2 acre-feet per acre of surface land).
- Aquifer conditions in 13 minor alluvial aquifers and 4 permitted aquifer withdrawal values (9 have temporary withdrawal limits of 2 acre-feet per acre of surface land).

- Aquifer conditions in 10 major bedrock aquifers and 3 permitted aquifer withdrawal values ranging from 1.0 to 2.1 acre-feet per acre (6 have temporary withdrawals of 2 acre-feet per acre of surface land).
- Aquifer conditions in 17 minor bedrock aquifers and 2 permitted fixed withdrawal values at 1.6 and 2.0 acre-feet per acre (9 have temporary withdrawal limits of 2 acre-feet per acre of surface land).

The Oklahoma Water Resources Board based the statutory definition of the 20-year life of a groundwater basin on 1) the surface area associated with a basin, 2) the saturated thickness, and 3) the statute requiring 20-year updates on groundwater basin studies. Ultimately, the state aims toward managing all the groundwater resources sustainably using maximum annual yield (Oklahoma Water Resources Board, 2012).

8.3 Institutions

A variety of agencies and organizations actively monitor, study, plan for, or manage groundwater resources in the state. Most are governmental agencies or exist in response to governmental legislation.

8.3.1 National and regional institutions

U.S. Geological Survey — Groundwater projects currently or recently being conducted by the Oklahoma Water Science Center of the U.S. Geological Survey include studies of shallow groundwater contamination at a landfill site overlying the Canadian River Alluvium and Terrace Aquifer, geochemistry in the Arbuckle-Simpson Aquifer, and groundwater availability in the Garber-Wellington Aquifer. The U.S. Geological Survey monitors water levels in wells and spring discharge, primarily in the central and south-central parts of the state.

U.S. Environmental Protection Agency — Oklahoma is within Region 6 of the U.S. Environmental Protection Agency. The EPA authorized the Oklahoma Department of Environmental Quality, the Oklahoma Corporation Commission, and the Oklahoma Conservation Commission and other state agencies to implement many of its regulatory functions.

U.S. Fish and Wildlife Service — The U.S. Fish and Wildlife Service is the principal agency that oversees the Endangered Species Act. If an endangered species is recognized as being dependent on groundwater, the maintenance of the groundwater supply can become federally protected.

Natural Resources Conservation Service, U.S. Department of Agriculture — The Natural Resources Conservation Service provides technical and financial assistance to help reduce soil erosion, protect water supplies, and promote sustainable agriculture, and monitors and inventories soil and water resources. In 2009, the Natural Resources Conservation Service approved funding for irrigation efficiency improvement projects in two areas that overlie the Ogallala, Blaine, and the North Fork of the Red River Alluvium and Terrace aquifers.

Communities Unlimited — As a non-profit rural development organization, based in Fayetteville, Arkansas, Communities Unlimited provides resources for education and guidance programs in seven states, including Arkansas, Louisiana, Oklahoma, and Texas. The group provides technical and financial assistance, training, and publications to help provide small communities with safe water supplies and wastewater facilities.

Southeastern Regional Small Public Water Systems Technical Assistance Center — The Southeastern Regional Small Public Water Systems Technical Assistance Center, administered by Mississippi State University and funded by the U.S. Environmental Protection Agency, funds training programs, technical assistance, and pilot projects to help small public water systems meet the goals of the Safe Drinking Water Act. It serves an 11-state region, that includes Arkansas, Louisiana, Oklahoma, and Texas, and fosters public and private partnerships to share resources to protect public health. Most projects address small groundwater systems issues.

8.3.2 Statewide institutions

Oklahoma Water Resources Board — The Oklahoma Water Resources Board is the primary agency responsible for water management and policy. The agency provides financial assistance for water infrastructure projects, develops the state comprehensive water plan, and is responsible for a variety of technical and regulatory duties. The agency monitors water levels in aquifers and water quality in surface waters and groundwater, conducts hydrologic investigations and water availability studies, provides water resources data to the public, and maintains an online water well record database. In addition, the agency is responsible for developing water quality standards, issuing groundwater permits for non-exempt groundwater withdrawals, and supervising the state licensing program for water well drillers and water well pump installers.

Oklahoma Department of Environmental Quality — The Oklahoma Department of Environmental Quality is the state's primary environmental regulatory agency and administers many programs required by state and federal environmental laws. Functions of the Water Quality Division include regulating public water suppliers and wastewater facilities, monitoring surface water and groundwater quality, responding to complaints about environmental pollution, issuing wastewater permits, and implementing the state's Wellhead Protection and Source Water Protection programs.

Oklahoma Water Quality Monitoring Council — The Oklahoma Water Quality Monitoring Council leads a collaborative effort to develop monitoring standards and collect and interpret water quality data for all water resources in the state. The council is responsible for developing the Oklahoma Water Quality Monitoring Plan, which addresses data management processes, data interpretation, and quality assurance.

Oklahoma Geographic Information Council — The Oklahoma Geographic Information Council is charged with helping the Oklahoma Conservation Commission coordinate the development of a statewide geographic information system.

Oklahoma Corporation Commission — The Oklahoma Corporation Commission is a state agency that regulates the oil and gas, fuel, public utilities, and transportation industries. The agency also helps to implement the state's Underground Injection Control Program.

Oklahoma Conservation Commission — The Oklahoma Conservation Commission works to conserve and restore natural resources in the state. It is the state agency responsible for assisting and coordinating conservation districts in the state. The agency's Water Quality Division leads the technical aspects of nonpoint source pollution management programs and implements the state Comprehensive Wetlands Conservation Plan. In addition, the agency leads state programs for erosion control, abandoned mine land reclamation, soil conservation, and flood control, and is charged with developing a geographic information system for the state with the help of the Oklahoma Geographic Information Council.

Oklahoma Geological Survey — The Oklahoma Geological Survey investigates the state's land, energy, water, and mineral resources and communicates the results to industries and the public. Working with the U.S. Geological Survey, the Oklahoma Geological Survey performs geological and hydrogeological studies of Oklahoma's geological and water resources, and produces a series of hydrologic investigation atlases that address water availability and water quality based on their findings. The survey is affiliated with the University of Oklahoma College of Earth and Energy.

Oklahoma State University, Water Research and Extension Center — Part of the Division of Agricultural Sciences and Natural Resources, the Water Research and Extension Center works to sustain water supplies for agricultural use in the state. Research and extension activities address agricultural water conservation, the development of water management practices, studies of drought tolerance in plants, water law and economics in the state, and the relationship between land use and water quality.

Oklahoma Water Resources Research Institute — The Oklahoma Water Resources Research Institute, based at Oklahoma State University, conducts research, education, outreach, and pilot programs. The institute is helping the Oklahoma Water Resources Board to gather public input for state water planning. It has a Water Research Advisory Board, which prioritizes funding for water research and provides feedback on state water planning and related technical studies by the Oklahoma Water Resources Board. The institute is a member of the National Institutes for Water Resources.

Oklahoma Rural Water Association — The Oklahoma Rural Water Association is a non-profit organization that provides free training programs and technical assistance for rural water and wastewater systems, non-profit rural water corporations, and communities of less than 10,000. The association provides on-site technical assistance and field and classroom training.

Oklahoma Water for 2060 Advisory Council — Oklahoma Water for 2060 Advisory Council, a 14-member group chaired by the Oklahoma Water Resources Board Executive Director, is appointed by the Governor, Speaker of the House, and President Pro Tempore. Council members review and recommend appropriate water conservation practices, evaluate incentives, and develop program goals developed to moderate statewide water usage while preserving Oklahoma's population growth and economic development goals.

8.3.3 Local institutions

Conservation districts — Oklahoma has 87 conservation districts, which are local units of government that promote natural resource management on private and public lands. The districts work with the Natural Resources Conservation Service to provide educational outreach and technical assistance to farmers and ranchers as well as other citizens, community planners, developers, and public health officials.

8.4 Interactions with Texas

Oklahoma shares its entire southern border with Texas, based on both political subdivision and river boundaries. States have a variety of ways to interact regarding shared water resources. This section includes details about two specific kinds of interactions which may or may not address groundwater.

8.4.1 Interstate compacts

Currently there are no interstate compacts between Oklahoma and Texas that directly address groundwater; however, Oklahoma participates in two interstate stream compacts with Texas that address the development and storage of water supplies on interstate streams, including quantities to be delivered to downstream states and water quality and pollution (Oklahoma Water Resources Board, 1997). These compacts are the 1878 Red River Compact between Oklahoma, Arkansas, Louisiana, and Texas and the 1950 Canadian River Compact between Oklahoma, Texas, and New Mexico (Oklahoma Statutes Title 82, §821431, 1978; Oklahoma Statutes Title 82, §82526.1) (Oklahoma Water Resources Board, 1997).

Although these compacts focus on the use and availability of surface water, they also affect and are affected by groundwater supplies. Where aquifers are hydrologically connected to streams, water level declines can lead to reduced streamflow. The Oklahoma Water Resources Board, along with the U.S. Geological Survey, is conducting a study that would determine possible effects of groundwater withdrawals within the Beaver-North Canadian River Basin (Ryter, 2014). An extensive project studying the relationship between the Arbuckle-Simpson Aquifer in Oklahoma and the Canadian River is also underway (Oklahoma Water Resources Board, 2011a). In 2003, Oklahoma Senate Bill 288 imposed a moratorium on issuing temporary groundwater permits in out-of-basin-use areas for a sole-source basin until the relationship between the aquifer and the river are better understood and withdrawals are known not to reduce stream or springflow (Oklahoma Water Resources Board, 2014a). Special requirements are necessary for groundwater permits within the Canadian River Basin (Oklahoma Legislature, 2003). The 2012 Oklahoma State Water Plan suggests that interstate water issues may be addressed through creating standing planning committees based on existing interstate stream compacts or through other federal and state forums designed to work on shared water resource management issues (Oklahoma Water Resources Board, 2012).

8.4.2 Interstate commissions

The Red River Compact Commission facilitates negotiations between member states in order to avoid litigation over the waters of the Red River and its tributaries. The commission addresses problems concerning the distribution of streamflow, equitable development, and water (Oklahoma Water Resources Board, 2014e). The Canadian River Compact Commission is a similar commission that administers the Canadian River Compacts (New Mexico Office of the State Engineer, 2014a).

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9. Mexico

Water in Mexico is a public asset, however, Constitutional Article 27 allows for groundwater rights to be appropriated to private parties via a deed and then it may become a private property right (Comisión Nacional del Agua, 2012b). Federal groundwater management in Mexico occurs primarily at the local or regional level with several federal agencies, primarily Comisión Nacional del Agua and Secretaría del Medio Ambiente y Recursos Naturales, collecting and analyzing groundwater-related information. Groundwater is the only reliable source of water in the Texas-Mexico border area outside of the Rio Grande-Rio Bravo Basin, supplying most rural citizens for domestic and other uses. Locally elected or appointed boards develop and maintain groundwater monitoring programs that vary according to local citizen engagement and resources.

9.1 Groundwater resources

Mexico borders the entire southern border of Texas. Groundwater provides close to half of all water resources in the four neighboring Mexican states for a variety of uses. This section includes details about Mexico's aquifers and monitoring.

9.1.1 Aquifers

For management purposes, Mexico has been divided into 653 aquifers (Comisión Nacional del Agua, 2011b). The aquifers shared with Texas are shown in Table 9-1. In 2009, an estimated 4.4 million acre-feet of groundwater was used in the four Mexican states bordering Texas, accounting for approximately 42 percent of total water use in the area (Comisión Nacional del Agua, 2011b). Groundwater is the only reliable source of water in the Texas-Mexico border area outside of the Rio Grande-Rio Bravo Basin. Aquifers are the main source of water for many rural communities as well as many industrial developments. As much as 62 percent of the border residents use groundwater (Table 9-2), and groundwater is also used to irrigate approximately 4.9 million acres of land (Comisión Nacional del Agua, 2008e).

Over the past few decades, aquifer overdrafting or mining defined as the extraction/recharge ratio, has increased (Secretaría de Medio Ambiente y Recursos Naturales, 2009). In 1975, 32 out of the 653 aquifers were considered overdrafted (Secretaría de Medio Ambiente y Recursos Naturales, 2009). In 1985, that number increased to 60, and in 2015 it rose to 106, with 31 of those having saline soils and brackish water, and 15 have saltwater intrusion (Comisión Nacional del Agua and Secretaría de Medio Ambiente y Recursos Naturales, 2015). The Comisión Nacional del Agua (Comisión Nacional del Agua, 2008c) documented problems associated with overdrafting, including damage to ecological resources, groundwater pollution, and saltwater intrusion, all of which limit the amount of water available.

Table 9-1. Aquifers shared by Mexico and Texas and naming conventions.

Mexico Aquifers	Texas Aquifers	U.S. Geological Survey aquifer names
Allende-Piedras Negras, Bajo Rio Bravo, Hidalgo, and Lampazos-Anáhuac Acuíferos	Carrizo-Wilcox Aquifer	Lower Claiborne-Upper Wilcox and Middle Wilcox aquifers, part of the Texas Coastal Uplands Aquifer System in Texas
Cerro Colorado-la Partida, Palestina, Presa la Amistad, Santa Fe del Pino, and Serranía del Burro Acuíferos	Edwards-Trinity (Plateau) Aquifer	Edwards-Trinity Aquifer, part of the Edwards-Trinity Aquifer System
Bajo Rio Bravo Acuífero	Gulf Coast and Yegua-Jackson aquifers	Coastal Lowlands Aquifer System
Valle de Juárez and Valle de Peso Acuíferos	Hueco-Mesilla Bolsons Aquifer	Hueco and Mesilla basins, part of the Rio Grande Aquifer System)
Álamo Chapo and Valle de Peso Acuíferos	Igneous Aquifer	Igneous Aquifer
Álamo Chapo, Bajo Rio Conchos, Valle de Peso Acuíferos	West Texas Bolsons Aquifer (Presidio-Redford, Green River Valley, Red Light Draw)	Red Light and Presidio basins, and additional unnamed parts of the Rio Grande Aquifer System

***Note:* U.S. Geological Survey aquifer definitions do not extend into Mexico.**
Source: Ryder (1996); TWDB (2007); and Comisión Nacional del Agua (2008).

Table 9-2. Groundwater use in 2009 in the Mexican states bordering Texas.

State	Cubic hectometers/year	Acre-feet/year	Percent of total water use
Coahuila de Zaragoza	1,060	859,356	54
Chihuahua	3,191	2,586,986	62
Nuevo León	886	718,292	43
Tamaulipas	392	317,800	10
Total	5,529	4,482,434	Average 42

Source: Comisión Nacional del Agua (2011b).

9.1.2 Groundwater monitoring

By 2006, the Comisión Nacional del Agua established piezometric networks in 211 aquifers, with at least 8,100 measurement points (Comisión Nacional del Agua, 2007a). The Comisión

Nacional del Agua also operates a national water quality monitoring network, which includes 702 sites that monitor groundwater conditions (Comisión Nacional del Agua, 2011b).

9.2 Groundwater law, management, planning, and availability

Water resources in Mexico are the property of the federal government and are managed under federal policies; therefore, the four Mexican states that border Texas—Chihuahua, Coahuila de Zaragoza, Nuevo León, and Tamaulipas—are discussed together under a summary of Mexico's federal groundwater management policies.

9.2.1 Groundwater law

Groundwater regulation in Mexico dates back to 1917, when Article 27 of the United Mexican States Constitution took effect (National Research Council, 1995). This article provided a legal means of requiring a water right concession for using or extracting water in Mexico; however, this was not always enforced. The Ley de Aguas Nacionales (National Water Law), adopted in 1992, created a reform of federal water policy. The Ley de Aguas Nacionales provides four methods for administering water policy: regulatory, economic, order and control, and participatory. Regulatory methods include concession entitlements for water use, registration in the Registro Público de Derechos de Agua (Public Water Rights Registry), and well-drilling prohibitions. Economic methods include user fees and tradable water rights. Order and control methods include inspections, measurement, and sanctions. Participatory methods include river basin councils and groundwater technical committees (Asad and Garduño, 2005). Comisión Nacional del Agua administers Ley de Aguas Nacionales.

Official standards in Mexico are called Normas Oficiales Mexicanas or Normas. Normas related to water management include, but are not limited to:

- NOM-127-SSA1-1994: provides limits on chemical and biological characteristics in water for human consumption; also, provides the methods of treatment depending on which contaminant is present.

- NOM-003-CNA-1996: sets requirements for water well construction to prevent contamination of aquifers.

- NOM-004-CNA-1996: requires aquifer protection during well maintenance and closure of wells.

- NOM-179-SSA1-1998: regulates the monitoring and evaluation of water quality for water distributed by public supply systems for human consumption.

- NOM-011-CNA-2000: sets the specifications and methods for compiling the nation's water availability (Comisión Nacional del Agua, 2008a).

9.2.2 Groundwater management

The basic unit for water management in Mexico is the watershed (Comisión Nacional del Agua, 2007a). The country is divided into 731 watersheds which are grouped into 37 hydrological regions, and those regions are grouped into 13 hydrologic-administrative regions (Figure 9-1). These regions are delineated by surface water features and municipalities rather than state or hydrogeologic boundaries (Comisión Nacional del Agua and Secretaría de Medio Ambiente y Recursos Naturales, 2015). This delineation serves to reflect the primary water resources management approach and factors in a seasonal distribution of rainfall, location, and scale of analysis, when quantifying the majority of water resources (Comisión Nacional del Agua, 2008f). Nationally, groundwater provides about 37 percent of total volume allocated for use (Comisión Nacional del Agua, 2008f). The states bordering Texas lie mostly within Region VI–Rio Bravo, but are also covered in part by Region VII–Cuencas Centrales del Norte and Region IX–Golfo Norte. Aquifer divisions in Mexico (Figures A1-1, A6-4, A9-1, and A11-1), which are based on watersheds, do not compare directly to the aquifer divisions in Texas, although the geologic units are comparable (Figure 2-2). Each region is administered by a basin organization, a regional Comisión Nacional del Agua office, which is responsible for managing and preserving water resources within the basin.

Groundwater withdrawal, impoundment, or diversion in Mexico requires a water right concession deed (Comisión Nacional del Agua, 2009b). Until Ley de Aguas Nacionales took effect in 1992, only 2,000 concessions had been issued (Asad and Garduño, 2005). As of 2009, there had been 244,667 concessions issued for groundwater (Comisión Nacional del Agua, 2011b). Concessions are issued for time periods of between five and 30 years and are recorded in the Registro Público de Derechos de Agua (Comisión Nacional del Agua, 2009b). The Ley de Aguas Nacionales stipulates the requirements for concession applications, responsibilities of concession holders, and activities that must be followed in order to avoid possible suspension or termination of the permits (Comisión Nacional del Agua, 2009b).

Ley de Aguas Nacionales prohibits concession holders from extracting more than their specified volume, and users are required by law to install meters to measure the volume of water used within 45 days of receiving their concession. Concession holders are also required to pay user fees, which contribute to water resources development. Water concessions are defined volumetrically, and the Comisión Nacional del Agua has the authority to reduce the volume of water stipulated during drought conditions (Comisión Nacional del Agua, 2009b). Reis (Reis, 2014) indicated that there are both formal and informal water markets that may be supported due to prohibition on sale of water rights, leading to informal privatization of water which does not stem overdrafting.

Figure 9-1. Regiones Hidrológicas Administrativas in Mexico (Comisión Nacional del Agua, 2007a).

When considering a concession application, the Comisión Nacional del Agua is required by the Ley de Aguas Nacionales to take into account annual water availability, current rights, and well drilling bans. Domestic and urban public uses are considered preferred uses over other uses (Comisión Nacional del Agua, 2009b). A water use concession is only granted when availability exists (Arreguín-Cortés and López-Pérez, 2007); however, many aquifers have already been over-permitted. Over-concession is a more serious problem with groundwater than surface water, since groundwater availability was previously undetermined. In 2003, the Comisión Nacional del Agua published the first estimates of groundwater availability for 202 aquifers nationwide, (Arreguín-Cortés and López-Pérez, 2007) and in 2008 it published estimates for an additional 282 aquifers (Comisión Nacional del Agua, 2008f).

In an effort to reduce water overdrafting, since 1929 the Comisión Nacional del Agua has issued zonas de veda decrees, which are areas that may have prohibitions on additional groundwater or surface water withdrawals (Comisión Nacional del Agua, 2012a). Three types of concerns identified through these decrees include impaired water quality or quantity, harm to hydrological sustainability, or damage to surface water or groundwater (Comisión Nacional del Agua, 2012a). As of September 2015, there were 160 areas closed to new groundwater withdrawal nationwide, covering about 55 percent of the nation, with 25 areas identified in the four states bordering Texas (Comisión Nacional del Agua, 2011b). Only two areas appear to be near the Rio Grande, one area near Juarez-El Paso has the least stringent withdrawal limitations and one area west and south of Matamoros-Brownsville allows only for additional domestic withdrawals (Reis, 2014).

Mexico has also developed water banks as an instrument to facilitate the water rights market. The water banks were developed to ensure water rights transactions comply with the law and to prevent hoarding of water resources. As of 2010, 15 water banks had been established (Comisión Nacional del Agua, 2011b).

9.2.3 Groundwater planning

As required by the Ley de Aguas Nacionale and the Ley de Planeación (Planning Act), the Comisión Nacional del Agua develops a national water plan. The Programa Nacional Hídrico 2014–2018 (National Water Program) sets forth goals and strategies to help Mexico achieve integrated water resources management, sustainable water use, and environmental conservation (Comisión Nacional del Agua, 2014). Goals related to groundwater resources in the Programa Nacional Hídrico include developing management plans addressing overdrafted aquifers that will be implemented through local authorities and users, monitoring aquifer water levels, measuring withdrawals and discharges, and assessing groundwater availability (Comisión Nacional del Agua, 2008d). The Programa Nacional Hídrico also encourages water enhancement projects such as artificial recharge, brackish groundwater desalination, and evapotranspiration management (Comisión Nacional del Agua, 2008e).

The Programa Nacional Hídrico discusses an overall lack of awareness within the country of the importance of water conservation, efficient use, and payment of fees (Comisión Nacional del Agua, 2008d). The plan recommends increasing user participation in planning and encouraging compliance with the Ley de Aguas Nacionales in order to achieve the objectives of Mexico's water policy (Comisión Nacional del Agua, 2008e). As part of the 1992 reform to the country's water laws, Mexico also formed river basin councils and technical groundwater committees to create a bottom-up planning process and provide an opportunity for public participation.

The National Water Program encourages technical groundwater committees to promote the efficient use of water in agriculture to conserve groundwater availability. Users are asked to utilize needed water more efficiently so that aquifers can reach equilibrium and maintain good water quality (Comisión Nacional del Agua, 2008e).

The U.S.-Mexico Border 2020 program has two multi-state workgroups, assisted by the U.S. Environmental Protection Agency and Mexico's Secretaría del Medio Ambiente y Recursos Naturales, dedicated to identifying and understanding shared water issues. One workgroup, the Texas/New Mexico/Chihuahua Water Task Force, provides a forum for international communication and is a source of information for stakeholders in the Paso del Norte Region (West Texas, Southern New Mexico & Northern Chihuahua). This group helps stakeholders address the Border 2020 goals and objectives and functions as a technical advisory group to Rural Task Forces on water-related issues. Similarly, the Texas/Tamaulipas/Nuevo León/Coahuila Water Task Force addresses issues along the southcentral Texas-Mexico border.

9.2.4 Groundwater availability

Groundwater availability is calculated based on what the Norma Oficial Mexicana NOM-011-CNA-2000 defined as the average annual volume of groundwater that can be extracted from a hydrogeologic unit for various purposes (Comisión Nacional del Agua, 2007b). This amount must take into account extraction, water right concessions, and committed natural discharge without jeopardizing the balance of all ecosystems (Comisión Nacional del Agua, 2007b). Natural discharge is calculated to include a portion allocated for surface water supplies as storage, to prevent negative environmental impacts, and/or as storage to prevent migration of poor quality water into the aquifer (Comisión Nacional del Agua, 2002). Groundwater availability, or the average annual groundwater availability for a hydrogeological unit, is calculated as the total average annual recharge, minus the annual committed natural discharge, minus the annual volume of groundwater authorized and registered in the Public Water Rights Registry (Comisión Nacional del Agua, 2002, 2009a).

Groundwater provides about 33 percent of all water resources nationwide, with the agricultural sector demanding about 62 percent of all water resources (Comisión Nacional del Agua, 2014). Groundwater and surface water demand combined exceed sustainable supply by almost 15 percent, with over half of the exceedance originating from overdrafted aquifers (Comisión Nacional del Agua, 2014). Groundwater availability reports for all aquifers in Mexico are posted on the Comisión Nacional del Agua's website and are published in the Diario Oficial de la Federación (Official Journal of the Federation). The Estadísticas del Agua en México report also publishes the amount of groundwater used annually by hydrological-administrative region and by state (Comisión Nacional del Agua, 2011b).

9.3 Institutions

A variety of agencies and organizations actively monitor, study, plan for, or manage groundwater resources in Mexico. Most are governmental agencies or exist in response to governmental legislation.

9.3.1 International and national institutions

World Bank —The World Bank has provided and continues to provide assistance to Mexico in a variety of sectors, including water resources management. The World Bank's Water Resources Management (PROMMA) project, active from 1996 to 2005, provided Mexico with loans, technical assistance, and training to improve water resources management. These resources were used to help develop the Public Water Rights Registry, monitoring networks, groundwater models, and preliminary aquifer management plans. Training in water resources management and institution building was provided to Comisión Nacional del Agua personnel as well as to members of river basin councils and technical groundwater committees.

Border Environment Cooperation Commission (Comisión de Cooperación Ecológica Fronteriza) — The binational Border Environment Cooperation Commission, together with the North American Development Bank, works to plan, finance, and implement environmental and public health infrastructure projects in the United States-Mexico border area. These institutions focus on projects that provide potable water treatment and distribution, wastewater collection and treatment, water conservation, and municipal solid waste management. The Border Environment Cooperation Commission provides technical assistance during project development, certifies projects as technically feasible, identifies the impacts of projects on the environment and public health, and ensures that communities are involved in project development.

North American Development Bank — The North American Development Bank is a binational institution that administers the financing for environmental and public health infrastructure projects certified by the Border Environment Cooperation Commission. The institutions focus on projects that provide potable water treatment and distribution, wastewater collection and treatment, water conservation, and municipal solid waste management. In addition to funding project implementation through loans and grants, the North American Development Bank provides financial guidance and technical assistance.

Southwest Consortium for Environmental Research and Policy (Consorcio de Investigación y Politica Ambiental del Suroeste) — The Southwest Consortium for Environmental Research and Policy is a consortium of universities in the United States and Mexico that implements projects assessing possible solutions to water, air, and hazardous waste problems in the United States-Mexico border area. Projects consist of research, policy development, outreach, education, and community capacity building. Past projects have addressed hydrology, access to drinking water, and transborder water management in the region. Participating universities in Mexico are el Colegio de la Frontera Norte, Instituto Tecnológico de Ciudad Juárez, Instituto Tecnológico y de Estudios Superiores de Monterrey, Universidad Autónoma de Baja California, and Universidad Autónoma de Ciudad Juárez.

Paso del Norte Water Task Force — The Paso del Norte Water Task Force is a regional partnership between Las Cruces, New Mexico; El Paso, Texas; and Ciudad Juárez, Chihuahua that is involved in binational water issues in the Paso del Norte area, which includes parts of the Rio Grande and Hueco-Mesilla Bolson aquifers. The task force consists of water managers, water experts, water users, and citizens. Goals of the task force are to determine priority water issues in the area, promote information sharing, and make policy recommendations to relevant authorities in Mexico and the U.S.

The Mexico Section of the International Boundary and Water Commission (Comisión Internacional de Límites y Aguas) — The Mexico Section of the Comisión Internacional de Límites y Aguas, part of the Secretaría de Relaciones Exteriores (Ministry of Foreign Relations), is charged with applying treaties between the United States and Mexico that address boundaries and water and with settling disputes related to these treaties. The Commission helped develop and publish a binational aquifer study and data report on the Tularosa, Hueco Bolson, and Rio Grande aquifers shared by Mexico, New Mexico, and Texas.

Comisión Nacional del Agua (National Water Commission) — The Comisión Nacional del Agua (CONAGUA) is the federal agency responsible for the planning, management, and development of water resources in Mexico. The agency implements the Ley de Aguas Nacionales, develops national water policy, and enforces compliance with these policies. As part of these duties, the agency provides financing for water infrastructure and sanitation projects; develops and implements the national water program; grants permits for water use and wastewater discharge; administers the national public registry of water rights; collects monitoring data on water resources; and maintains a national information system on the use, quantity, quality, and conservation of water. The agency has decentralized many of its functions to its 13 regional offices, called organismos de cuenca (river basin organizations), which are based on watershed boundaries and cover the same territory as the nation's 13 hydrologic-administrative regions. Region 6 (Río Bravo) includes the areas near the U.S. border in the four Mexican states in the study area.

Secretaría de Medio Ambiente y Recursos Naturales (Ministry of Environment and Natural Resources) — Secretaría de Medio Ambiente y Recursos Naturales (SEMARNAT) is Mexico's environmental agency. The agency is responsible for developing national policies and official standards for natural resources and is also involved in monitoring compliance with laws, proposing and managing natural protected areas, and conducting environmental studies. The agency represents Mexico in many international treaties and agreements and is a national coordinator of the Border 2020 program in the U.S.-Mexico border area.

Instituto Nacional de Estadística y Geografía (National Institute of Statistics and Geography) — Instituto Nacional de Estadística y Geografía is responsible for conducting the national census and for developing national systems of geographic and statistical information about Mexico's population demographics, economy, geography, and environment. The agency manages and distributes reports and geographic data for the country. Geographic datasets available describe topography, hydrology, water infrastructure, geology, transportation and navigation, land use and vegetation, and other variables relevant to water management.

Instituto Mexicano de Tecnología del Agua (Mexican Institute of Water Technology) — The Instituto Mexicano de Tecnología del Agua is charged with developing technology and training experts to support integrated water resource management. The organization conducts research and development of technology; offers specialized training, consulting, laboratory services, and technical assistance; provides student scholarships and grants academic degrees; helps to develop national standards; and proposes policies related to water use and management.

Consejo Consultivo del Agua (Water Advisory Council) — The Consejo Consultivo del Agua is a non-profit organization in Mexico whose main goal is to promote strategic changes needed for the sustainable management of water resources by providing support to the public and private sectors. The advisors within the council are comprised of both individuals and organizations.

9.3.2 State institutions

Chihuahua: El Honorable Congreso del Estado de Chihuahua (State Congress) — Chihuahua has a state environmental law, the Ley de Equilibrio Ecológico y Protección al Ambiente para el Estado de Chihuahua (Law of Ecological Balance and Environmental Protection for the State of Chihuahua) that aims to protect natural resources, prevent air, water and land contamination, and promote sustainable development.

Coahuila de Zaragoza: Secretaría de Medio Ambiente (Ministry of the Environment) — The Subsecretaría de Recursos Naturales, a branch of the State of Coahuila Secretaría de Medio Ambiente (Ministry of the Environment), aims to protect, conserve, restore, and manage biodiversity in the state. The agency promotes the sustainable use of natural resources and environmental education. It also helps monitor compliance with federal regulations and regulates the state Ley del Equilibrio Ecológico y la Protección al Ambiente del Estado de Coahuila (Law of Ecological Equilibrium and Environmental Protection of the State of Coahuila), which promotes sustainable development while preserving an ecological balance and preventing the pollution of air, water, and land.

Nuevo León: Agencia de Protección al Medio Ambiente y Recursos Naturales (Natural Resource and Environmental Protection Agency) — The Nuevo León Agencia de Protección al Medio Ambiente y Recursos Naturales seeks to maintain an ecological balance between environmental protection and sustainable development. The agency uses regulatory instruments, plans, and projects to promote sustainable use of the state's resources and prevent the contamination of air, water, and land. It also implements the Ley Ambiental del Estado de Nuevo León (Environmental Law of the State of Nuevo León). The agency also promotes environmental education.

Tamaulipas: Secretaría de Desarrollo Urbano y Medio Ambiente (Ministry of Urban Development and Environment) — The Tamaulipas Secretaría de Desarrollo Urbano y Medio

Ambiente promotes sustainable use of natural resources, conservation of protected areas, and efficient use of water resources. The state law in Tamaulipas governing the water is the Ley de Aguas del Estado de Tamaulipas (Water Law of the State of Tamaulipas).

9.3.3 Local institutions

Consejos de cuenca (river basin councils) — Consejos de cuenca are entities that consist of government representatives from the federal, state, and municipal levels, as well as non-governmental representatives of various water user and stakeholder groups. The councils act as facilitators between the government and water users to coordinate water policies and programs within the respective hydrologic region. The Ley de Aguas Nacionales specifies a number of council functions, including encouraging participation from governments and users, publicizing guidelines of the national and regional water policies, developing and implementing programs to improve water management, developing water infrastructure, and aiding the conservation and restoration of watersheds.

Comités técnicos de aguas subterráneas (technical groundwater committees) — Comités técnicos de aguas subterráneas are auxiliary groups under the consejos de cuenca. Comprised of water users, these civil society organizations are a means for stakeholders to communicate with the government by acting as a liaison between users and government authorities. The primary objective of the committees is to assist in the design and implementation of programs to stabilize, recover, and conserve the country's overdrafted aquifers and to prevent other aquifers from becoming unsustainable. Functions of the committees include collaborating with other entities to implement the national water law, assisting in the development of regulations to improve groundwater management, promoting studies of availability, developing educational programs, and assisting in water user conflicts.

Consejos ciudadanos del agua estatales (state citizen's water councils) — The consejos cuidadanos del agua estatales are independent organizations that provide water information and promote sustainable water use on local levels.

Junta Municipal de Agua y Saneamiento de Juárez, Chihuahua (City of Juárez Utilities) — The Junta Municipal de Agua y Saneamiento de Juárez provides municipal water and wastewater for Ciudad Juárez. The "Plan maestro para el mejoramiento de los servicios de agua potable alcantarillado y saneamiento" (Master Plan for Improvement of Drinking Water Supply and Sanitation Services), developed in 2001, explored water supply alternatives because data indicated that the city was relying solely on the Hueco Bolson Aquifer for municipal water while water levels were dropping significantly.

9.4 Interactions with Texas

In addition to the treaties and other agreements between Mexico and the United States described earlier, several agreements exist between governmental entities in Texas and Mexico. Nuevo León and Texas share a Strategic Environmental Plan, originally developed in 1997 and updated in 2005. The plan establishes a framework for cooperation between the environmental agencies of Texas (the Texas Commission on Environmental Quality) and Nuevo León (the Natural Resource and Environmental Protection Agency) and outlines an action plan to address environmental issues. Goals within the plan include guiding effective interagency cooperation and making the best use of existing resources in addressing priorities for environmental protection of air, water, and land. Objectives include enhancing regulatory and institutional frameworks, innovative planning, and increasing public awareness and participation. Examples of specific projects in the 2005–2007 action plan include Project #4: "Appropriate environmental infrastructure, including water and wastewater treatment and groundwater protection, in the development of the Community of Colombia in Nuevo Leon," and Project # 6: "Texas-Mexico GIS," where the Texas Commission on Environmental Quality, Texas Natural Resources Information System, and Nuevo León Natural Resource and Environmental Protection Agency will work together to identify needs and develop spatial databases in the Texas-Northeast Mexico region (Texas Commission on Environmental Quality, 2005). Similar strategic plans also exist between Texas and Chihuahua, Coahuila de Zaragoza, and Tamaulipas.

In Chihuahua, Junta Municipal de Agua y Saneamiento de Juárez, Chihuahua (City of Juárez Utilities) and the El Paso Utilities Public Service Board of the City of El Paso, Texas, signed a Memorandum of Understanding in 1999. The memorandum "seeks to identify the mechanisms between the parties in order to increase communication, cooperation and implementation of transboundary projects of common interests". Objectives of the agreement include sharing groundwater, population, and economic data; technical support; and developing a plan to extend the water supply from the Hueco Bolson Aquifer (El Paso Water Utilities Public Service Board and Junta Municipal de Agua y Saneamiento de Juarez, 1999).

In 2004, the governors of Chihuahua, Coahuila de Zaragoza, Nuevo León, Tamaulipas, and Texas signed an Agreement for Regional Progress. This agreement serves to strengthen the competitiveness and development of the states through cooperative programs. The environment is identified as a top priority in furthering development and improving quality of life (Texas Commission on Environmental Quality, 2005). United States-Mexico Border 2020 is the U.S. Environmental Protection Agency's and Secretaría del Medio Ambiente y Recursos Naturales' ongoing effort to address a number of shared environmental concerns involving water quality, drinking water, and wastewater (U.S. Environmental Protection Agency, 2014c).

In 2006, a federal U.S. law authorized federal and multiple state agencies to collaborate on developing information through the International Boundary and Water Commission (IBWC), with help from stakeholders and Mexican officials. This program, Transboundary Aquifer Assessment Program, managed though the U.S. Geological Survey, serves to assess transborder aquifers and develop new scientific aquifer data. Reports developed conjunctively will help to establish a science-based framework for addressing water information needs of border communities and resolve water-resource challenges along the U.S. – Mexico border. The U.S. Geological Survey released the first five-year interim report in 2013 and addressed aquifers shared by Arizona and Sonora, Mexico, and New Mexico and Texas with Chihuahua, Mexico (U.S. Geological Survey, 2013b).

In the past, some have argued that the number of agreements and institutions that address water issues in the United States-Mexico border region have made it more difficult to address these problems. Gunning (1996) points out that the authorities of institutions often overlap and that agreements do not provide specific actions or mechanisms for meeting goals. As a result, critics said that there had been little leadership in addressing water management issues, even as states continued to grow (Gunning, 1996).

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10. Discussion and conclusion

States that share common groundwater resources without shared management processes will experience unknown and unquantifiable consequences to those future groundwater resources. Each state independently managing these shared resources could alter groundwater withdrawals in other states that rely on specific volumes being available in the future. However, moving forward agencies and entities responsible for planning for future groundwater withdrawals in Arkansas, Louisiana, Oklahoma, New Mexico, Texas, and Mexico, will have better information available for more informed planning.

Strategies for moving forward can employ existing, historical, or develop new approaches to water management with agencies and laws in place, even without federal agreements, interstate compacts, or international treaties on groundwater in place. For example, the memorandum of understanding between the cities of El Paso and Juarez serves as a template and working example of successful collaboration at a local level, the level where planning for groundwater resources might be most successful between states and countries. This agreement addressed the advantages of economies of scale for project implementation, joint outreach programs, sharing technical information, funding opportunities, and groundwater data.

Additionally, the United States-Mexico Border 2020 is an ongoing federal program to address natural resource issues that include water. This program offers a framework to both preserve and develop natural resources responsibly. Another collaborative example of a network developed to integrate water management is the Global Water Partnership, a United Nations Development Program and World Bank initiative. Connecting stakeholders with groundwater managers together at the local level by supporting the implementation of integrated water resources management through this program incrementally builds global water security. This initiative seeks to break out of isolating sector-based planning to collaborate and coordinate natural resources development by addressing people, food, nature, and industry. The binational Transboundary Aquifer Assessment Program also serves to provide detailed scientific information about shared aquifers.

Each state follows its own path-dependent approach to managing its groundwater resources. In each state, future resource management and utilization paths are subject to past groundwater withdrawals, uses, public preferences and priorities. However, there may be opportunities to share information and planning efforts for this shared common pool resource that transcends political boundaries, thereby supporting the future management of aquifers shared between Texas and its neighboring states. Examples of shared opportunities are:

- education, data sharing, and public outreach with neighboring states focusing on the expanding TWDB groundwater website information while including links to other state's activities,
- greater outreach extended through intrastate and international participation in the Texas regional water planning and groundwater management area efforts;
- encouraging and facilitating collaboration between local groups that use, manage, or plan for groundwater in shared aquifers,

- developing and supporting instruments like memorandums of understanding, with existing state or national agencies facilitating this collaboration

- establishing and supporting joint groundwater studies in aquifers spanning state boundaries, starting with TWDB staff outreach to other federal, state and local agency resources; and

- partnering in integrative international collaborations due to the central position Texas plays as an international, aquifer-sharing participant in planning for future groundwater supplies.

This document is the first in a series of new TWDB reports designed to address advances and new understandings in aquifer science, distribute data on groundwater availability and quality, and provide technical support for decision-makers responsible for groundwater resource management and planning. The work documented in these reports will support the agency's mission to provide leadership, information, education, and support for planning, financial assistance, and outreach for the conservation and responsible development of water for Texas.

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Appendix A: Transborder aquifer summaries

Texas' border has 23 aquifers or aquifer systems in common with surrounding states and Mexico. This appendix provides 24 brief summaries of combinations of these systems—including the geological context and the major features of groundwater occurrence, flow, quality, and usage. The emphasis of these summaries is on the portions of the aquifers and groundwater resources in the states bordering Texas and Mexico, with minimal description of the aquifers in Texas. For a more detailed treatment of the aquifers in Texas, refer to TWDB Report 380 "*Aquifers of Texas*."

While these summaries are not to be exhaustive or comprehensive in scope, they provide relevant context and include references that will allow interested stakeholders to further evaluate the features of the aquifers that need to be understood as a basis of appropriate management.

The aquifer summaries are presented here in alphabetical order by aquifer name and listed below. In some areas, there may be differing amounts of information available reflected in the disparate descriptions. As more information becomes available, the summaries may be improved and updated.

A1 - Acuífero Allende-Piedras Negras and Acuífero Hidalgo

A2 - Blaine Aquifer

A3 - Blossom Aquifer

A4 - Bone Spring-Victorio Peak Aquifer

A5 - Capitan Reef Complex Aquifer

A6 - Carrizo-Wilcox Aquifer

A7 - Cretaceous and Jurassic Aquifers

A8 - Dockum Aquifer

A9 - Edwards-Trinity (Plateau) Aquifer

A10 - Gulf Coast Aquifer (Texas/Louisiana)

A11 - Gulf Coast Aquifer (Texas/Mexico)

A12 - Hueco-Mesilla Bolsons Aquifer

A13 - Igneous Aquifer and West Texas Bolsons Aquifer

A14 - Nacatoch Aquifer

A15 - Ogallala Aquifer (Texas/New Mexico)

A16 - Ogallala Aquifer (Texas/Oklahoma)

A17 - Pecos Valley Aquifer

A18 - Queen City Aquifer

A19 - Rustler Aquifer

A20 - Seymour Aquifer

A21 - Sparta Aquifer

A22 - Trinity Aquifer

A23 - Woodbine Aquifer

A24 - Yegua-Jackson Aquifer

A1 - Acuífero Allende-Piedras Negras and Acuífero Hidalgo (Mexico/Texas)

The Acuífero Allende-Piedras Negras and Acuífero Hidalgo are located across the border from Maverick County and northwest Webb County, Texas (Figure A1-1). Together, these aquifers cover an area of 5,644 square miles of varied topography, mountainous in the west toward the Sierra Del Burro and flatter in the east. These administrative aquifers are generally equivalent to a combination of individual aquifer systems in Texas, ranging from the Edwards-Trinity (Plateau) Aquifer to the Carrizo-Wilcox Aquifer system. Within this area, the flat alluvial plains comprise the major aquifer for the regions south of the Rio Grande. This information is not meant to correlate all the units for these two aquifers, but to cover these areas as related to aquifers in Texas. The Carrizo-Wilcox Aquifer is covered in a later section in the report.

Geologic Conditions

Most of the Cretaceous geological formations mapped in Texas have been identified south of the border in Coahuila. The oldest unit is the Glen Rose Formation, composed of fossiliferous limestone and dolomite that reach up to about 1,300 feet thick. Above the Glen Rose is the Telephone Canyon Formation, consisting of alternating yellowish and laminated clays, and fine-grained carbonates. Next, from oldest to youngest, the other formations in the area include the Del Burro Reef Complex, also known in Texas as the Devils River Formation, a massive, rudist limestone; the West Nueces Formation, medium-grained limestone, is overlain by the McKnight Formation, which consists of a sequence of thin-layered limestone, evaporite, and collapse breccia; Salmon Peak Formation consists of alternating carbonate and clay with substantial marcasite mineralization; and above this is the Del Rio Clay composed of dark-colored, fossiliferous shale.

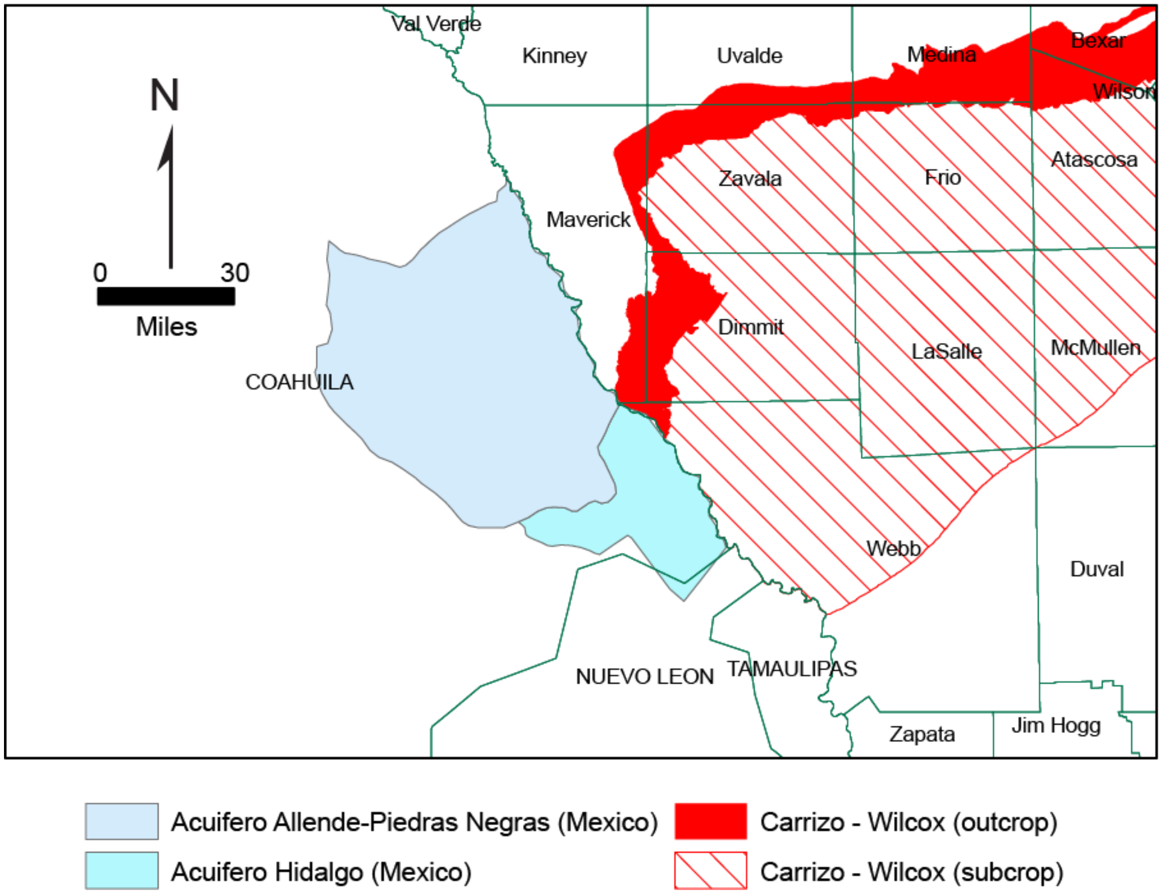

Figure A1-1. Acuífero Allende-Piedras Negras and Acuífero Hidalgo in relation to the location of the Carrizo-Wilcox Aquifer in Texas (modified from Comisión Nacional del Agua).

Younger carbonate rich-units in the area include the Buda Formation, consisting of gray, medium-grained carbonate; the Eagle Ford Formation, consisting of thin, fine-grained sediments alternating with clayey carbonates; the light gray carbonate rocks of the Austin Formation; and the Upson Formation, composed of limestone with alternating fine-grain sediments. The upper formations include sand rich units, including the San Miguel Formation, a fine to medium fossiliferous sandstone, the Olmos Formation, a fine to medium calcareous sandstone, and the Escondido Formation, made up of an abundantly fossiliferous, fine-to medium-grained calcareous sandstone. The Paleogene-age Sabinas-Reynosa Conglomerate, an unconfined aquifer, is poorly cemented and is the product of erosion, transport, and sedimentation of material from the highlands on the Allende-Piedras Negras alluvial plain. The conglomerate sits unconformably on the Upper Cretaceous rocks. The conglomerates consist of carbonate fragments that are approximately 0.1 to 3 feet in size. The thickness of the Sabinas-Reynosa Conglomerate can be over 130 feet. Quaternary alluvium, consisting of conglomerates, gravels, and sands, covers the low-lying areas near the Río Grande, and is approximately 7 to 20 feet thick. The regional geologic structure is primarily the result of Upper Cretaceous to Paleogene-age mountain building that formed northwest to southeast trending fold belts. These structures are occasionally interrupted by normal and lateral faults. The El Cedral fault affects the western side of the El Burro anticline. This normal fault has over 4,100 feet of vertical displacement and is an important hydrogeologic barrier and represents the southern limit of the Acuífero Allende-Piedras Negras.

Groundwater conditions

Acuífero Allende-Piedras Negras and Acuífero Hidalgo are recharged in the highlands of Sierra del Burro. Groundwater flows towards the southeast under confined and semiconfined conditions towards the Rio Grande, which is the main discharge feature for Acuífero Allende-Piedras Negras and Acuífero Hidalgo. Groundwater discharges through springs associated with fractured conditions in the rock. The springs occur in the locations of the towns of Zaragoza, Morelos, and Allende.

Transmissivity values for the Acuífero Allende-Piedras Negras range from about 0.22 square feet per second to 0.43 square feet per second for wells completed in limestone rocks. In the Allende-Piedras Negras plain, the Sabinas-Reynosa Conglomerate is very permeable and the reported transmissivity exceeds 0.43 square feet per second due, in part, to the presence of caliche beds with large cavities. Other parts of the conglomerate have lower values from 0.001 square feet per second to 0.054 square feet per second. Reported storage coefficients range from 0.001 to 0.01 in the Morelos area and were reported at 0.005 to 0.03 and 0.0001 in other areas of the Allende-Piedras Negras plain. No information on hydraulic properties was available for the Acuífero Hidalgo.

In the Acuífero Allende-Piedras Negras, most of the water levels measured in 2008 were less than 100 feet in depth. To the northwest of the northeast-southwest trending Mexico Highway 57 between Allende and Piedras Negras on the Mexican-Texas border, depths to groundwater in wells ranged from 23 to 66 feet. Similar depths to groundwater were recorded in the Minera Carbonifera Río Escondido, Sociedad Anónima de Capital Variable (MICARE) coal surface mining area, where dewatering activities for mining occurs. Just to the northeast of the coal mining area, groundwater levels were shallower, between 15 to 23 feet. The groundwater pumped out for coalmine dewatering returns to the aquifer as artificial recharge, which causes water levels in the aquifer to rise. To the southeast of Nava, depths to water ranged from 10 to 15 feet because of the lower elevation of the alluvial plain and irrigation return flows in cultivated areas. To the southwest of Morelos, depths to groundwater were greater, between 33 feet to 100 feet, which is the effect of higher land surface elevation towards the west. No water level information was available for Acuífero Hidalgo.

Groundwater flow directions based on measurements in 2008 were from Sierra del Burro (Zaragoza, Morelos, Allende, and Villa Unión) towards the Río Bravo and between Piedras Negras and Guerrero (Figure A1-2). The highest groundwater elevation was 1,444 feet above mean sea level and declined gradually towards east-northeast (Figure A1-2). Near the town of Morelos, the groundwater elevation was 1,181 feet above mean sea level. In the MICARE coal mining area, northeast of Nava, the closed 919-foot contour (280 meters on Figure A1-2) suggests the presence of a cone of depression possibly caused by mining-related dewatering operations. The flow of groundwater continued toward the Río Bravo, with the lowest water-level elevation being 722 feet above mean sea level.

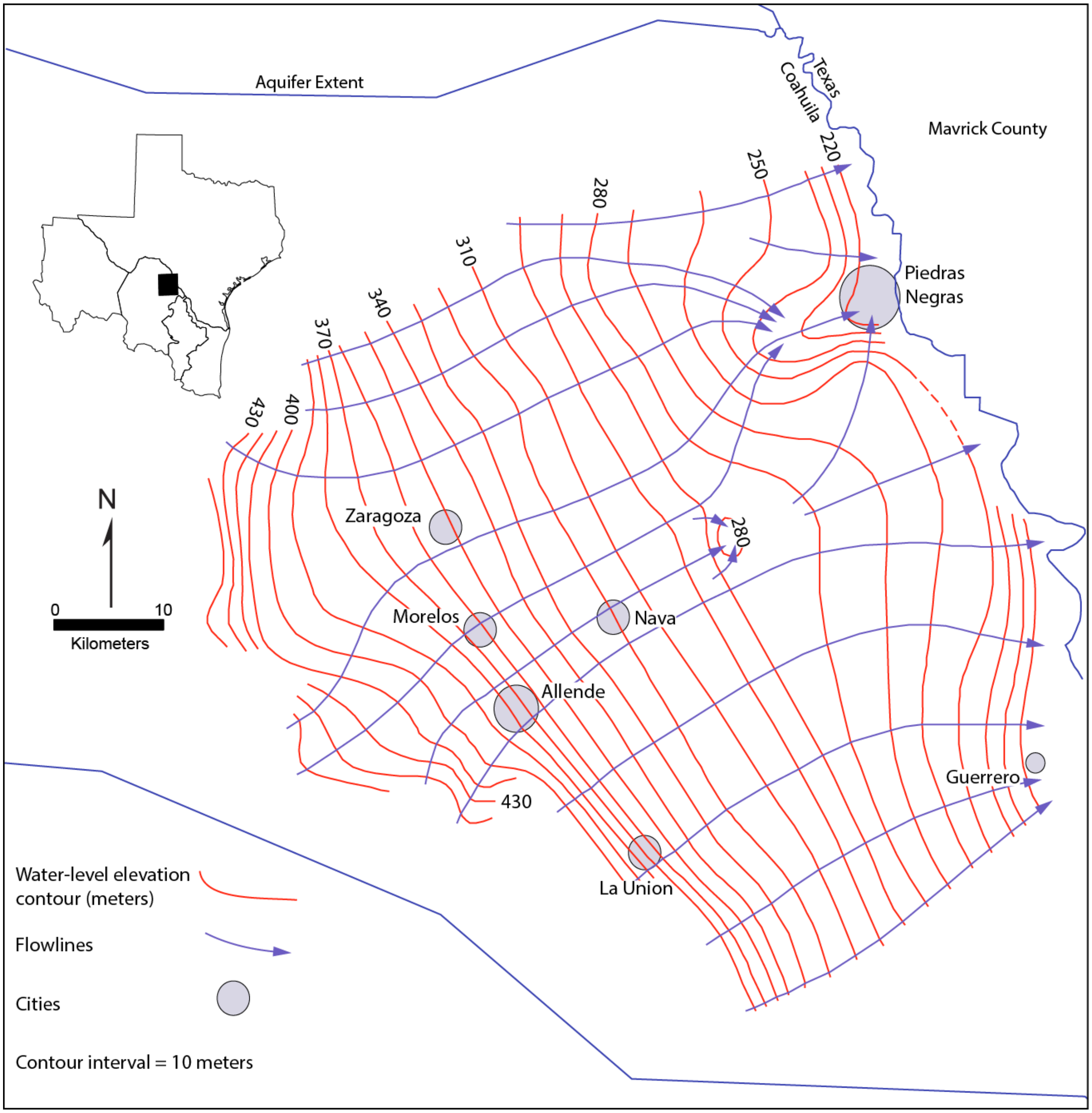

Figure A1-2. Potentiometric surface of Acuífero Allende-Piedras Negras near Allende and Piedras Negras, Coahuila from (Comisión Nacional del Agua, 2011b).

Based on use data and fieldwork in 2008, the estimated total volume of groundwater extracted from the aquifer was about 345,283 acre-feet per year with most used for irrigation at 269,400 acre-feet per year. Industries used 48,643 acre-feet per year; public municipal supplies withdrew 14,998 acre-feet per year; and domestic uses accounted for 12,323 acre-feet per year.

Groundwater quality is variable in the Acuífero Allende-Piedras Negras. In the west, total dissolved concentrations are below 400 parts per million, and sulfate concentrations are also low, typically below 42 parts per million. Groundwater in the west is of a calcium-bicarbonate facies, typical of carbonate aquifers. In contrast, the groundwater in the central and eastern part of Acuífero Allende-Piedras Negras exceeds 1,000 parts per million total dissolved solids, has high sulfate concentrations, and belongs to a calcium-sulfate facies. These high sulfate and total dissolved solids concentrations are localized near Zaragoza and Morelos and are caused by dissolution of the gypsum and anhydrite of the McKnight Formation.

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A2 - Blaine Aquifer (Texas/Oklahoma)

Geologic conditions

The Blaine Aquifer in Oklahoma lies within the Hollis basin, a large structural basin located in southwestern Oklahoma and adjacent parts of Texas. The basin formed early in the Pennsylvanian Period and contains about 3,000 to 12,000 feet of late Cambrian to Permian age sediments. Rocks in the basin were folded and faulted during the Ouachita-Marathon Orogeny. Younger Permian strata drape across the deep-seated structures, and outcropping rocks are flat-lying, dipping less than one degree. The Blaine Formation, which constitutes the Blaine Aquifer, is part of these younger strata (Figure A2-1).

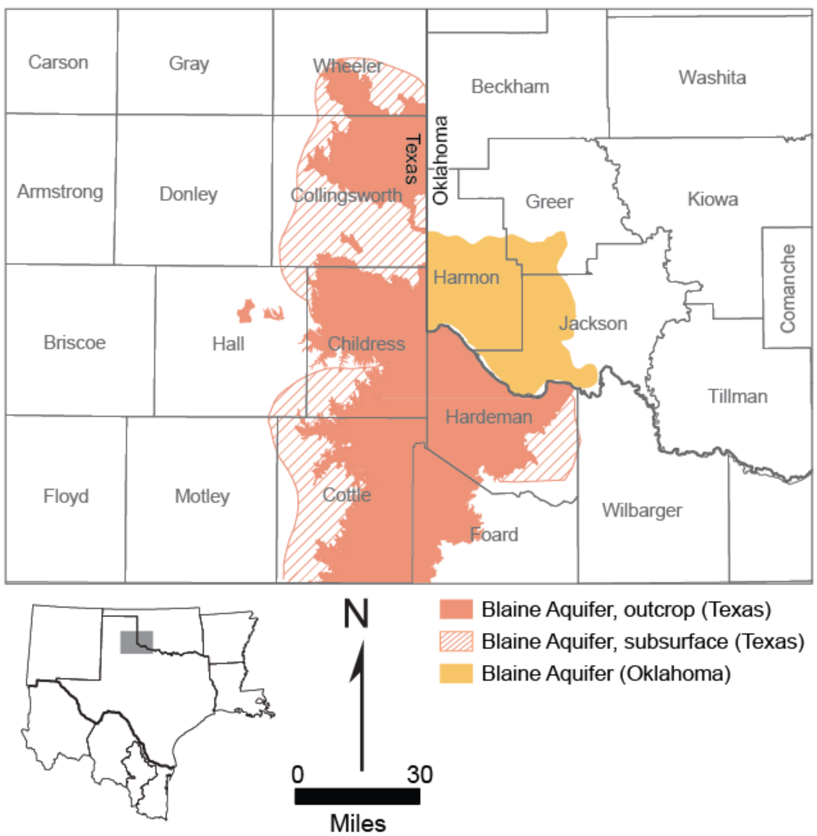

Figure A2-1. Blaine Aquifer extent in Oklahoma and Texas.

In general, the younger Permian strata consist of red beds and evaporites deposited in the Hollis Basin when a broad, shallow sea covered much of the southwestern United States. The evaporite beds originated from marine deposition, and the sandstones and shale were derived from fluvial input into the sea. Individual beds of gypsum and dolomite are generally laterally continuous in the basin. Specifically, the Blaine Formation is part of the El Rio Group (equivalent to the Pease

River Group in Texas) and consists of multiple cycles of interbedded gypsum, anhydrite, shale, and dolomite (Figure A2-2). Each cycle consists of a thin layer of dolomite (0.5 to 5 feet thick), overlain by a layer of gypsum or anhydrite (5 to 30 feet thick), and topped with a layer of shale (1 to 50 feet thick). The formation ranges from 180 to 220 feet thick and averages 200 feet thick. The Blaine Formation is overlain by the Dog Creek Shale. The Dog Creek Shale consists of up to 180 feet of red-brown shale with several gypsum-dolomite beds in the lower 50 feet of the formation. The Blaine Formation is underlain by the Flowerpot Shale, which is made up of about 150 to 300 feet of red-brown shale interbedded with thin layers of gypsum, dolomite, siltstone, and green-gray shale.

In parts of the basin, the Permian strata are overlain by Quaternary alluvial and terrace sediments deposited by modern rivers and streams. In Texas, these deposits constitute the Seymour Aquifer (refer to discussion in A20). In Oklahoma, these deposits range from 10 to 130 feet thick and consist of unconsolidated sand, gravel, silt, and clay. The alluvial and terrace deposits along Sandy Creek in Oklahoma are in hydraulic connection with the Blaine aquifer.

<table>
<tr><th>System</th><th>Series</th><th>Group</th><th>Formation</th></tr>
<tr><td rowspan="11">Permian</td><td>Ochoa</td><td></td><td>Quartermaster</td></tr>
<tr><td rowspan="5">Guadalupe</td><td>Whitehorse</td><td></td></tr>
<tr><td rowspan="4">Pease River (Texas)
El Rio (Oklahoma)</td><td>Dog Creek Shale</td></tr>
<tr><td>Blaine Formation</td></tr>
<tr><td>Flowerpot Shale</td></tr>
<tr><td>San Angelo</td></tr>
<tr><td rowspan="5">Leonard</td><td rowspan="3">Clear Fork</td><td>Choza</td></tr>
<tr><td>Vale</td></tr>
<tr><td>Arroyo</td></tr>
<tr><td rowspan="2">Wichita
(upper portion only)</td><td>Lueders</td></tr>
<tr><td>Clyde</td></tr>
</table>

Figure A2-2. Blaine Formation stratigraphy in Oklahoma and Texas.

Groundwater conditions

The Blaine Aquifer is a karst aquifer, created by the hydration of anhydrite to gypsum and the dissolution of gypsum along fractures and bedding planes. The dissolution has resulted in the development of solution channels and caverns, some as large as five feet in diameter. This causes variable hydraulic conductivity over short distances. In Oklahoma, where the overlying Dog Creek Shale is thin (less than 60 feet thick) or absent, the hydraulic conductivity of the aquifer ranges between approximately 17 to 71 feet per day. This is because of the enhanced ability of dissolving water to reach the underlying Blaine Formation. In areas where the thickness of the Dog Creek Shale is 60 feet or more, a value of 4.2 feet per day is assumed (Runkle and McLean, 1995). The presence of the solution channels and caverns also results in variable water transmissivity within the aquifer, with areas of high water yield located near areas of low water yield. Average transmissivities ranging from 16,000 to about 61,000 feet squared per day have been estimated for the Blaine Formation in Oklahoma.

Groundwater in the aquifer generally moves southeast, with local movement towards streams, where water discharges (Figure A2-3). Recharge occurs by direct infiltration of precipitation and flow into the aquifer from sinking streams losing water to near-surface fractures and solution openings. Recharge also occurs through sinkholes and recharge wells. Recharge is greatest where the overlying Dog Creek Shale is thin or absent and least where the shale is greater than 60 feet thick. Recharge is estimated to be about 7 percent of the average annual precipitation of 24 inches, or about 56,000 acre feet per year (Steele and Barclay, 1965). Water is discharged from the aquifer by pumping wells or naturally by seepage to streams in hydraulic connection with the aquifer. Water also is discharged by evaporation and transpiration from riparian vegetation, although at lesser amounts. Wells completed in the Blaine Aquifer commonly yield from 100 to 500 gallons per minute, but in some cases yields are as high as 2,500 gallons per minute. Major springs are common in rocks of the Pease River Group, including the Blaine Formation. In addition, large discharging springs tend to be close to rivers, especially the Red River.

Pumpage from the Blaine Aquifer is almost exclusively for irrigation and livestock watering purposes. The aquifer is the primary source of irrigation water in parts of southwestern Oklahoma. Irrigation wells are typically 50 to 300 feet deep and yield 300 to 2,000 gallons per minute. The highest yielding wells are drilled within three miles of Sandy Creek, where aquifer permeability and cavern development are greatest. Annual pumpage from the Blaine Aquifer in southwestern Oklahoma since 1967 has averaged 17,130 acre-feet per year. The lowest reported water use was 6,004 acre-feet in 1992, and the highest was 23,925 acre-feet in 1980.

The Blaine Aquifer is a potential source of drinking water, as defined by the U.S. Environmental Protection Agency, but is too highly mineralized to be widely used as a drinking water supply. Water from the aquifer is a calcium-magnesium sulfate type and is generally not suitable for many industrial uses because of its mineral content. Concentrations of dissolved solids are generally between 2,000 and 6,000 milligrams per liter, and the sulfate concentration ranges from about 1,000 to 2,000 milligrams per liter. The chloride content can also be large, with concentrations above 1,000 milligrams per liter being reported.

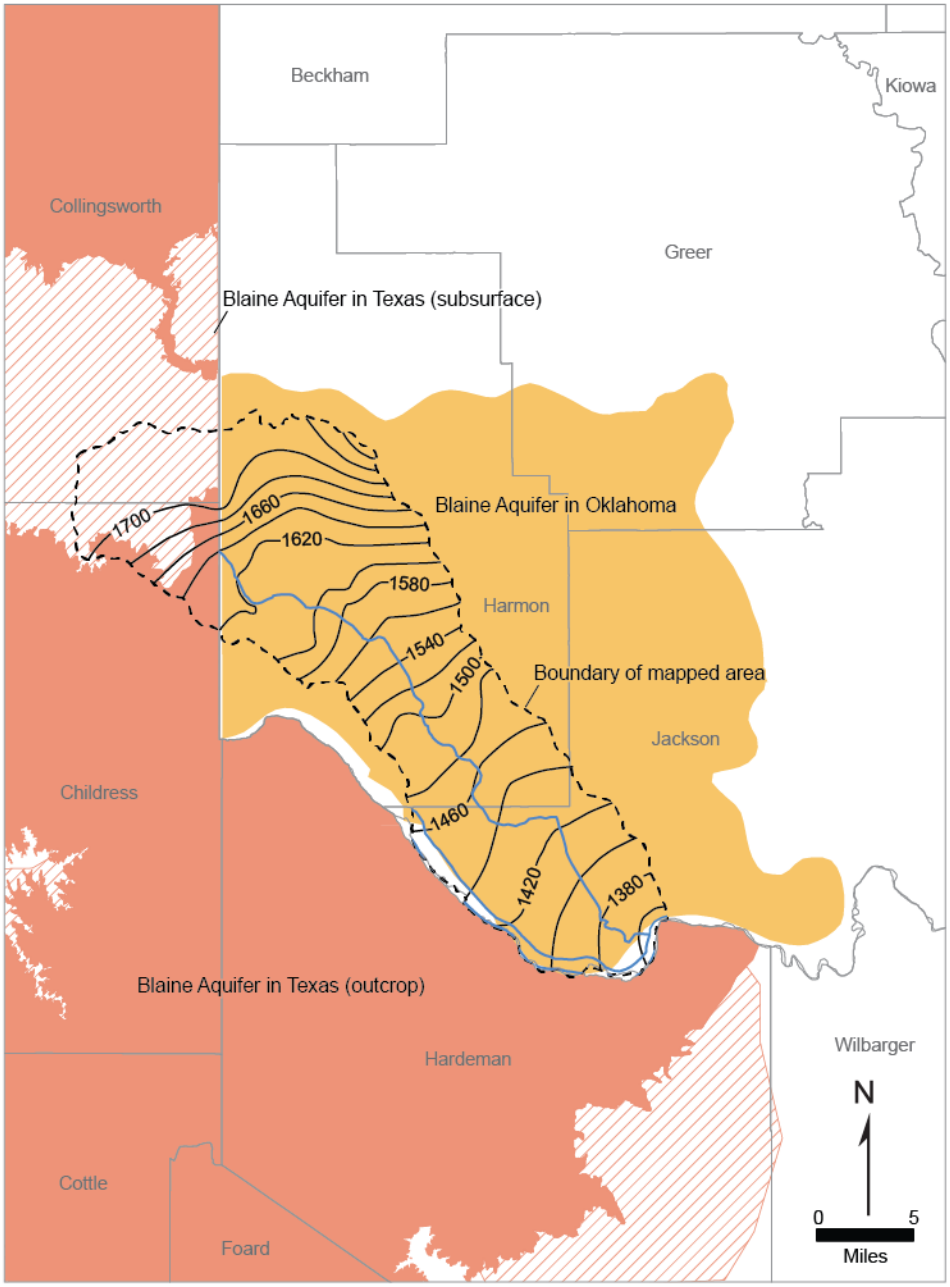

Figure A2-3 Potentiometric surface of part of the Blaine Aquifer from wells measured in February 1994 (modified from Osborn and Others, 1997). Hydraulic heads elevations are shown in feet above mean sea level

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A3 - Blossom Aquifer (Texas/Oklahoma/Arkansas)

The Blossom Aquifer extends from northeast Texas through southeast Oklahoma and into southwest Arkansas (Figure A3-1). The aquifer is defined as a minor aquifer in Texas, but not as a unified bedrock or alluvial hydrogeologic unit in Oklahoma. In Arkansas, it is recognized as the Tokio Aquifer. This aquifer summary focuses mainly on the Tokio Aquifer of Arkansas.

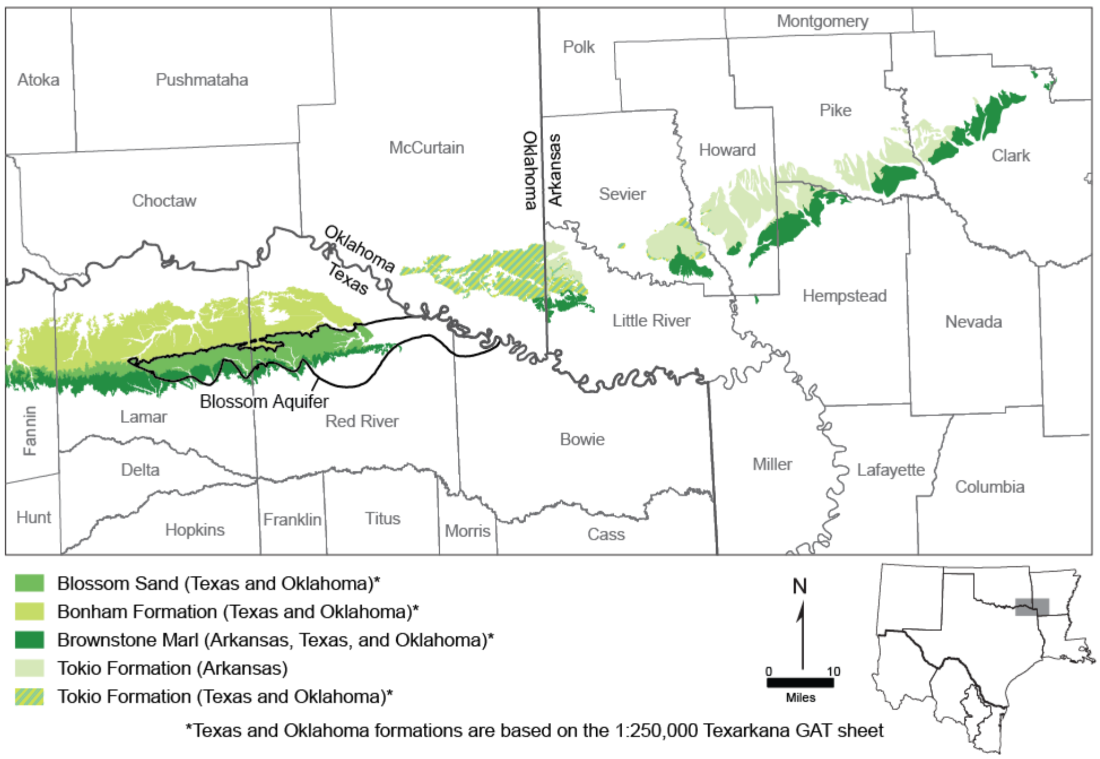

Figure A3-1. Location of the Blossom (Tokio) Aquifer and associated formations.

Geologic Conditions

The Blossom Aquifer of northeast Texas and southeast Oklahoma consists of the Blossom Sand. It consists of alternating sequences of sand and clay. The aquifer is as much as 400 feet thick in places, although no more than about one-third of this thickness consists of sand. The part of the aquifer that is saturated with freshwater averages about 25 feet.

The Tokio Formation of the Austin Group in Arkansas ranges in thickness from about 50 feet to more than 300 feet and dips towards the southeast. The Tokio Formation is composed of discontinuous, interbedded gray clay and poorly sorted, cross-bedded quartz sands, lignite, and prevalent basal gravel. The gravel is variable in thickness, ranging from 1 to 25 feet, and it consists of chert and quartzite that may be cemented by iron oxide in places to form a conglomerate. The sands tend to be brown to gray, medium- to coarse-grained, and are generally cross-bedded. The sand contains considerable lignite.

The lower contact of the Tokio Formation is unconformable, resting on successively older units eastward, ranging in age from Mississippi to Late Cretaceous. The formation underlies the Brownstone Marl, which is composed of Late Cretaceous clay, thin, sometimes sandy marl, sandy limestone, marl, and some fine-grained sand (Figure A3-2).

<table>
<tr><th>System</th><th>Series</th><th>Group</th><th>Northeast Texas Formations</th><th>Arkansas Formations</th></tr>
<tr><td rowspan="10">Cretaceous</td><td rowspan="10">Gulf</td><td rowspan="4">Taylor</td><td>Pecan Gap</td><td rowspan="2">Marlbrook</td></tr>
<tr><td>Wolfe City</td></tr>
<tr><td rowspan="2">Ozan</td><td>Annona</td></tr>
<tr><td>Ozan</td></tr>
<tr><td rowspan="4">Austin</td><td>Gober Chalk</td><td rowspan="2">Brownstown</td></tr>
<tr><td>Brownstown</td></tr>
<tr><td>Blossom Sand</td><td rowspan="2">Tokio</td></tr>
<tr><td>Bonham</td></tr>
<tr><td>Eagle Ford</td><td>Eagle Ford</td><td>(absent)</td></tr>
<tr><td>Woodbine</td><td>undifferentiated</td><td>Woodbine</td></tr>
</table>

Figure A3-2. Blossom Aquifer stratigraphy in Texas (McLaurin, 1988) and the Tokio Aquifer in Arkansas (McFarland, 2004).

Groundwater conditions

The direction of groundwater flow in the Tokio Aquifer is generally towards the south or southeast. Artesian conditions exist in southeastern Pike, northeastern Hempstead, and northwestern Nevada counties, as evidenced by eight flowing wells. Figure A3-3 shows water-level measurements from 2002, which are very similar to maps prepared in 1996 and 1999.

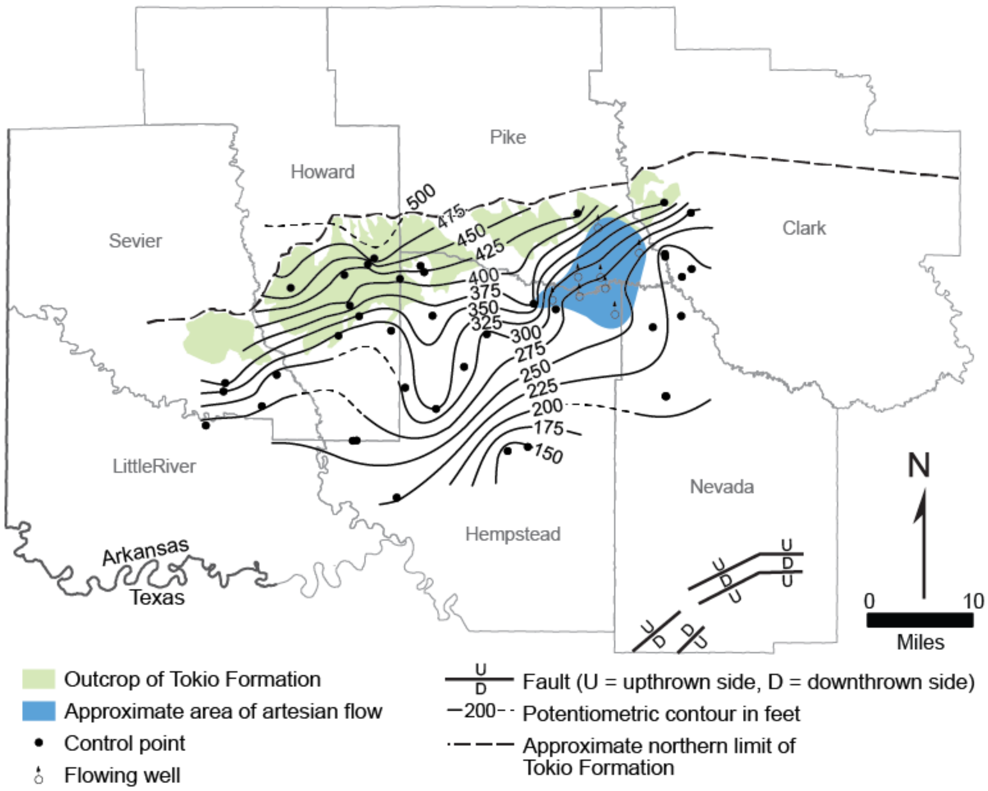

Figure A3-3. **Potentiometric surface of the Tokio Aquifer in Arkansas defined by 25 foot contour lines (modified from Schrader and Scheiderer, 2002).**

The Tokio Aquifer is recharged directly from precipitation where it outcrops or from shallow groundwater where the aquifer is in contact with overlying permeable alluvial and terrace deposits. Wells penetrating the aquifer range in depth from a few feet in the outcrop area to about 1,200 feet in Hempstead and Nevada counties. The Tokio Aquifer is under artesian conditions south of its outcrop area. The range of values for the annual average rise or decline in water level for Tokio Aquifer wells during a period in 2002 was -1.9 to 2.9 feet per year, with a median value of 0.1 feet per year. Wells in central Hempstead County produce up to 300 gallons per minute, and wells in the bottom-land areas adjacent to streams produce up to 90 gallons per minute.

The Tokio Aquifer is a source of water for industrial, public supply, domestic, and agricultural uses. In terms of total amount of groundwater withdrawal, it is a small source relative to other aquifers in Arkansas. It accounts for only 0.03 percent of total withdrawals, as compared to 3.34 percent for the Sparta/Memphis Aquifers and 95.17 percent from the Alluvial Aquifer. Estimated water withdrawal from the Tokio Aquifer in 1965 was 2.0 million gallons per day and 6.02 million gallons per day in 1980 (Figure A3-4). Water withdrawn from the Tokio aquifer was estimated to be 1.17 million gallons per day in 2000, a decrease of about 80 percent from 1980.

The Tokio Aquifer yields potable water to wells in eastern Little River County, southeastern Sevier County, southern Howard and Pike counties, western Clark County, northern and central

Hempstead County, and northwestern Nevada County. Concentrations of total dissolved solids increase downdip to the south-southeast.

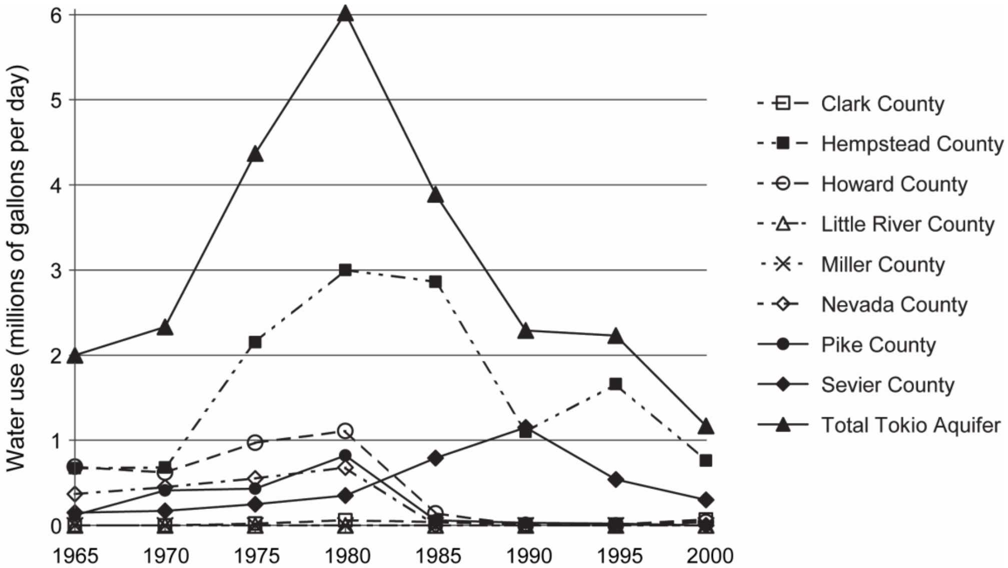

Figure A3-4. Historical water use in the Tokio Aquifer in Arkansas (from Schrader and Scheiderer, 2004).

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A4 - Bone Spring-Victorio Peak Aquifer (Texas/New Mexico)

The equivalent aquifer to the Bone Spring-Victorio Peak Aquifer in Texas is referred to as the "carbonate" or "limestone" aquifer in New Mexico. The aquifer includes the Bone Spring Formation and the Victorio Peak and San Andres limestone. Its boundaries are not formally defined but it is located within the Salt Basin (a declared Underground Water Basin). In New Mexico, the Salt Basin includes a gently eastward-dipping elevated plateau known as Otero Mesa, a central valley known as Crow Flats, a prominent zone of fracturing known as the Otero Break, and a steep westward-facing escarpment that borders the Guadalupe and Brokeoff Mountains (Figure A4-1).

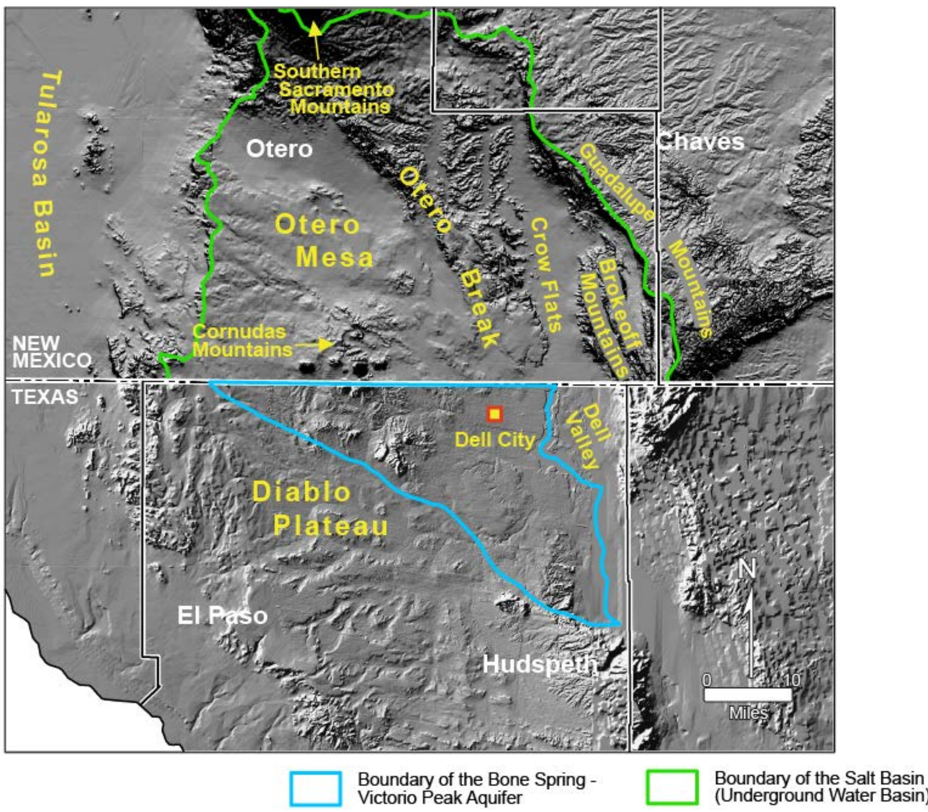

Figure A4-1. Major physiographic features in far west Texas and southern New Mexico outlined in green and north of the Bone Spring-Victorio Peak Aquifer in Texas outlined in blue (modified from Hutchison, 2006; Livingston and Associates and Shomaker and Associates, 2002; Ashworth, 1995; George, Mace, and Mullican, 2005; Mayer, 1995; and Mayer and Sharp, 1998).

Geologic conditions

The Otero Mesa lies between an area of Paleogene, Neogene, and Quaternary-aged faulting in the Rio Grande rift to the west (Tularosa Basin) and similar extensional faulting in the Salt Basin graben (Crow Flats and Dell Valley) to the east. The area mostly includes surface outcrops of the San Andres, Hueco, and Yeso formations (Figure A4-2). The San Andres Formation is equivalent to the Victorio Peak Formation and undivided Leonardian rocks in Texas. The combined Yeso and Hueco formation rocks in New Mexico are correlative to the Hueco in Texas, as the Yeso is not recognized in Texas. The San Andres Formation (Figure A4-2) is composed of dolomite, dolomitic limestone, limestone, and minor sandstone units at its base. The Yeso Formation (Figure A4-2) includes gypsum, shale, and limestone, and the Hueco Formation is a dark gray, cherty limestone. Note that some units are consolidated to "undivided" for simplification.

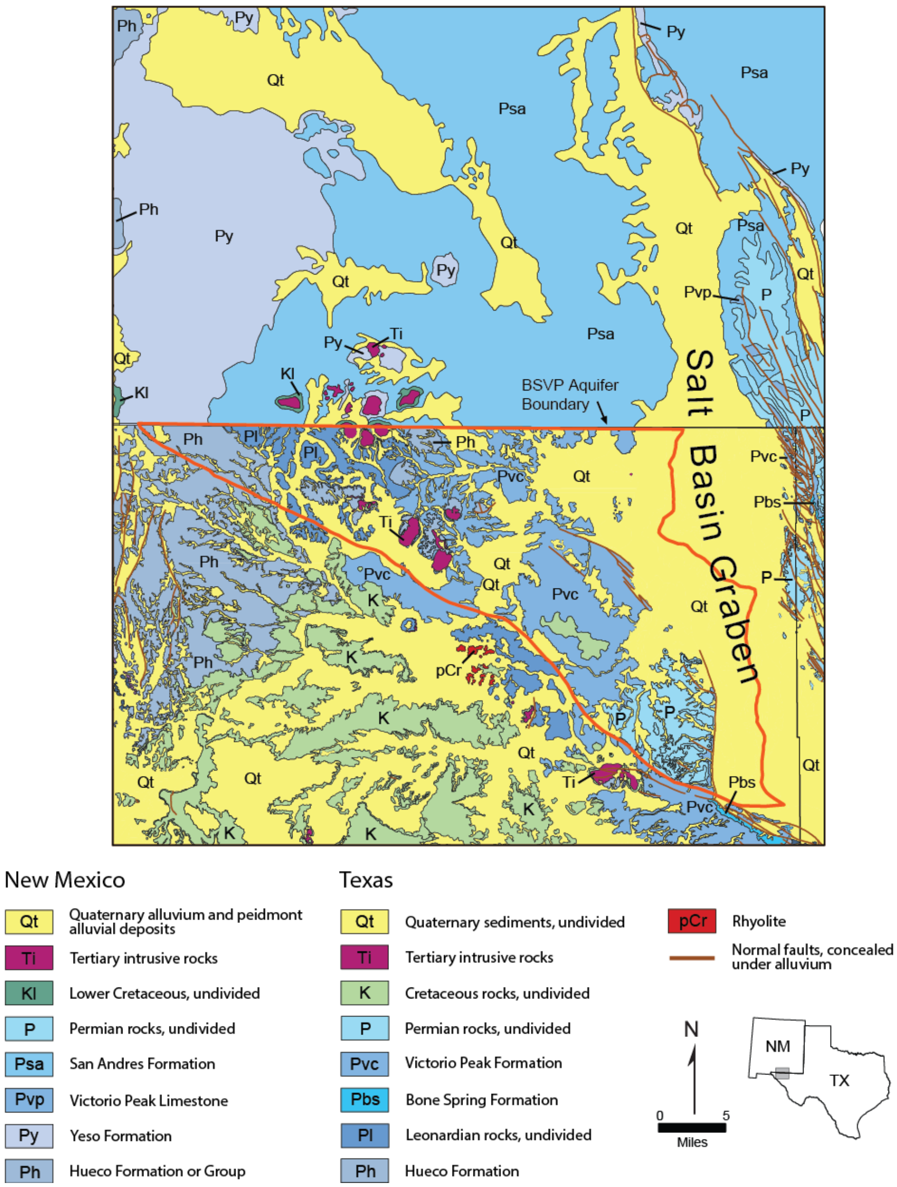

Figure A4-2. **Bone Spring-Victorio Peak Aquifer geologic units (based on the 1:500,000 geologic map of New Mexico (Livingston and Associates and Shomaker and Associates, 2002, and and U.S. Geological Survey, 2003) and the 1:250,000 Digital Geological Atlas of Texas (U.S. Geological Survey and TWDB, 2006)).**

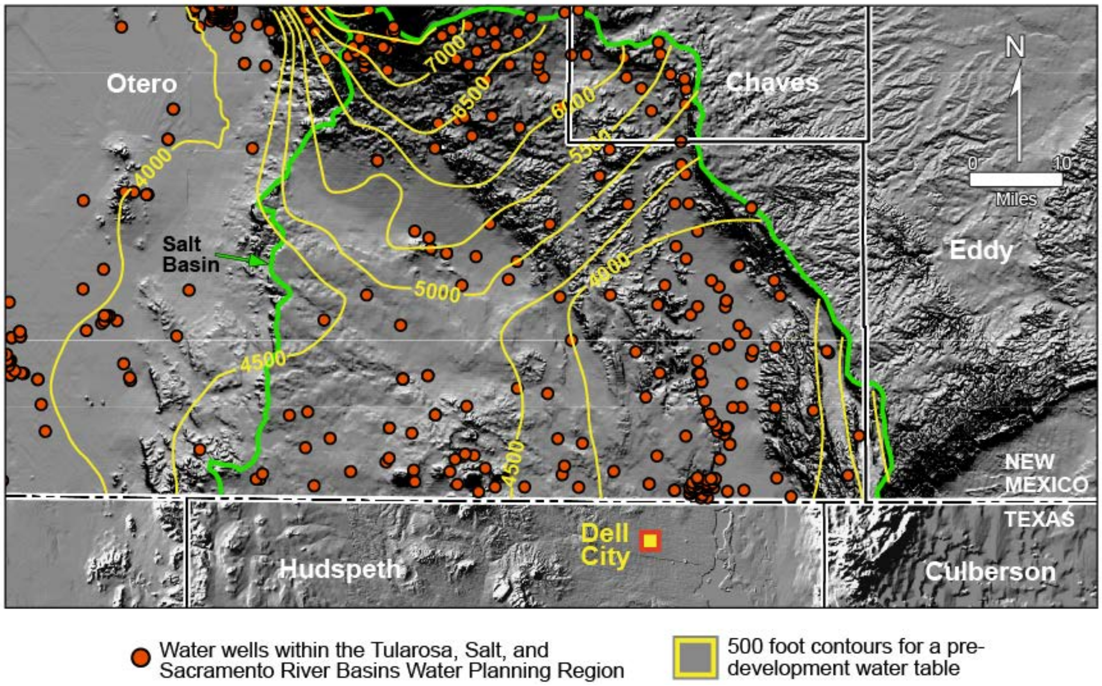

Figure A4-3. **Pre-development groundwater flow in the Salt Basin is to the south and southeast (modified from New Mexico Office of the State Engineer and New Mexico Interstate Stream Commission, 2002).**

The area of Crow Flats and its equivalent to the south, Dell Valley, lie within the Salt Basin graben. The Salt Basin graben is an extensional feature formed in Paleogene-Neogene and Quaternary times. As such, it is filled with similar age sediments eroded from adjacent highlands such as the Brokeoff and Guadalupe mountains. It is the northernmost of four elongate, structurally integrated grabens that form a north-trending, narrow rifted zone that connects to the Rio Grande rift about 200 miles to the south (Figure A4-4). Just west of the Brokeoff Mountains, the basin has about 1,650 to 2,300 feet of basin fill consisting of alluvial, fluvial, eolian, and lacustrine sediments.

The Otero Break is a broad fracture zone extending some 50 miles from the southern Sacramento Mountains towards Dell City in Texas (Figure A4-1). Fractures along the zone are mostly subparallel to major normal faults in the area, and karst features such as solution channels and sinkholes are related to fracturing. The fracture zone serves as a conduit for large volumes of groundwater from the mountains in the north to the irrigated acreage to the south.

Groundwater conditions

Permeability and well yields in the Bone Spring-Victorio Peak Aquifer can vary several orders of magnitude over a short distance due to karst features such as fracturing and joints. Well yield likely decreases with depth as the fracturing decreases. In addition, it is likely that well yield increases towards major faults. Well depths range from 100 feet to greater than 1,000 feet, and reported well yield is as high as 6,000 gallons per minute with most of the irrigation wells producing over 1,000 gallons per minute (Livingston Associates and John Shomaker and Associates, 2002). Transmissivity is estimated to be 80,000 square feet per day in the Otero Break fracture zone, but just 800 square feet per day within the Otero Mesa (Mayer, 1995). Depth to water in the center of the Salt Basin is typically 200 feet (Livingston Associates and John Shomaker and Associates, 2002) but can be up to 400 feet in the adjacent uplands (Bjorklund, 1959). Groundwater flows generally to the south and southeast across the Salt Basin (Figure A4-3). Along the Otero Break near the Texas border, however, the potentiometric surface forms a prominent trough coincident with an area of intense fracturing and a plume of relatively fresh groundwater.

Groundwater recharge in the Salt Basin is primarily from infiltration of precipitation during flash flooding along ephemeral channels (Bjorklund, 1959). Most of the recharge starts in the higher elevations of the Sacramento River and Piñon Creek watersheds. Virtually all surface water discharge derived from these watersheds is likely transmitted downward as groundwater recharge through fractures and solution channels. Total maximum annual average recharge for the Salt Basin is estimated to be about 35,000 acre-feet per year (Livingston Associates and John Shomaker and Associates, 2002). Groundwater in the carbonate aquifer generally is very hard and has dissolved-solids concentrations ranging from 500 to 6,500 milligrams per liter (Huff and Chace, 2006). However, most of the groundwater across the state line in Texas is less than 500 milligrams per liter total dissolved solids. It is estimated that there is approximately 29 million acre-feet of recoverable groundwater in the New Mexico portion of the Salt Basin (Livingston Associates and John Shomaker and Associates, 2002). Of this, about 15 million acre-feet of fresh water (less than 1,000 milligrams per liter total dissolved solids) is recoverable.

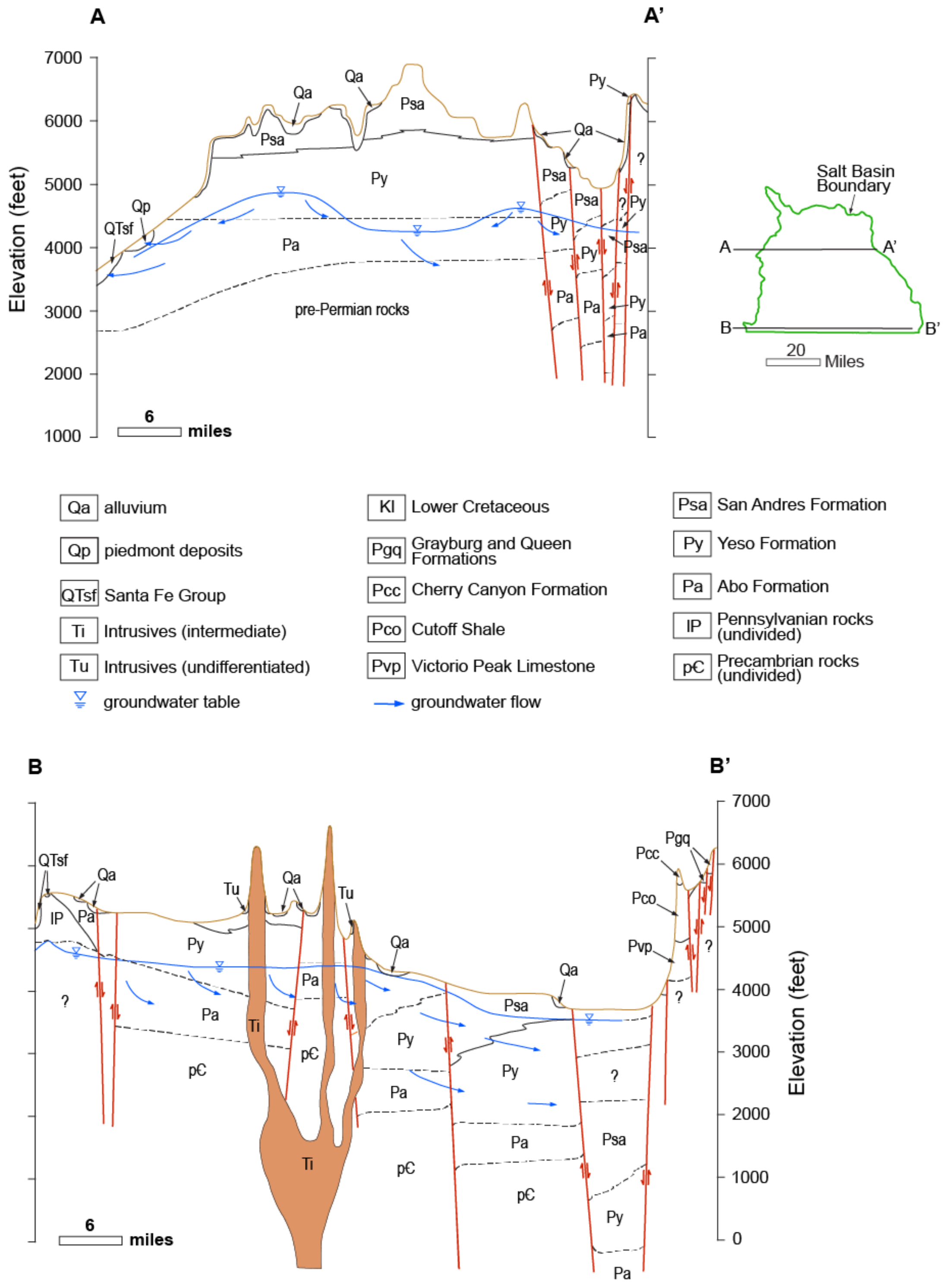

Figure A4-4. **Hydrogeologic Cross-sections across the Salt Basin (modified from Livingston Associates and John Shomaker and Associates, 2002).**

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A5 - Capitan Reef Complex Aquifer (Texas/New Mexico)

The Capitan Reef Complex Aquifer is considered a minor aquifer in Texas but a major aquifer in New Mexico (Figure A5-1). The aquifer is nearly circular in extent, a result of having formed along the edge of the Permian Delaware Basin. Aquifer rocks are spectacularly exposed in the Guadalupe Mountains of New Mexico and Texas and in the Apache and Glass mountains of Texas.

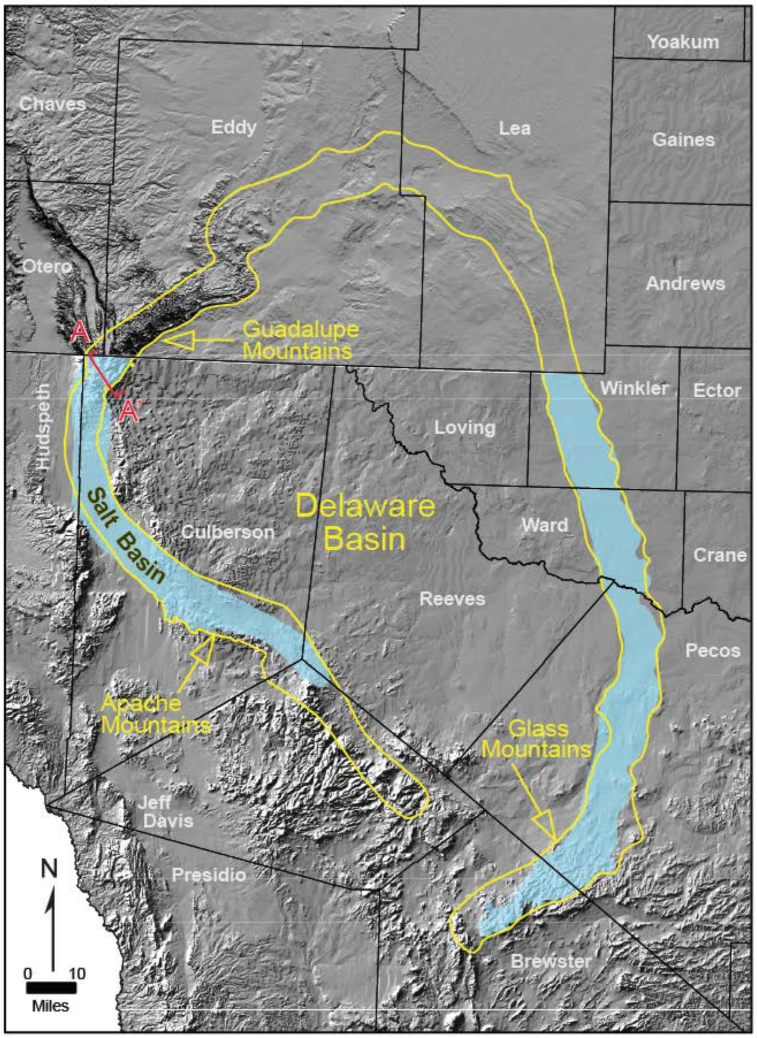

Figure A5-1. **Capitan Reef Complex Aquifer architecture and proposed new boundaries.Note: The yellow outline is a proposed boundary based on additional subsurface data (Hiss, 1975; Standen and others, 2009). Cross section A–A' is shown in Figure A5-2; current aquifer extent shown in blue.**

Geologic conditions

Due to their exposure and the extensive oil and gas exploration of the Delaware Basin, the Capitan Reef Complex rocks have been the subject of nearly 80 years of research. In general, the aquifer consists of massive, cavernous dolomite and limestone formed in reef, back-reef, and fore-reef depositional settings. In the Guadalupe Mountains, reef and fore-reef rocks are represented by the Goat Seep Limestone and Capitan Limestone. Back-reef rocks include those of the Artesia Group, including the Tansill, Yates, Queen, Seven Rivers, and Grayburg formations.

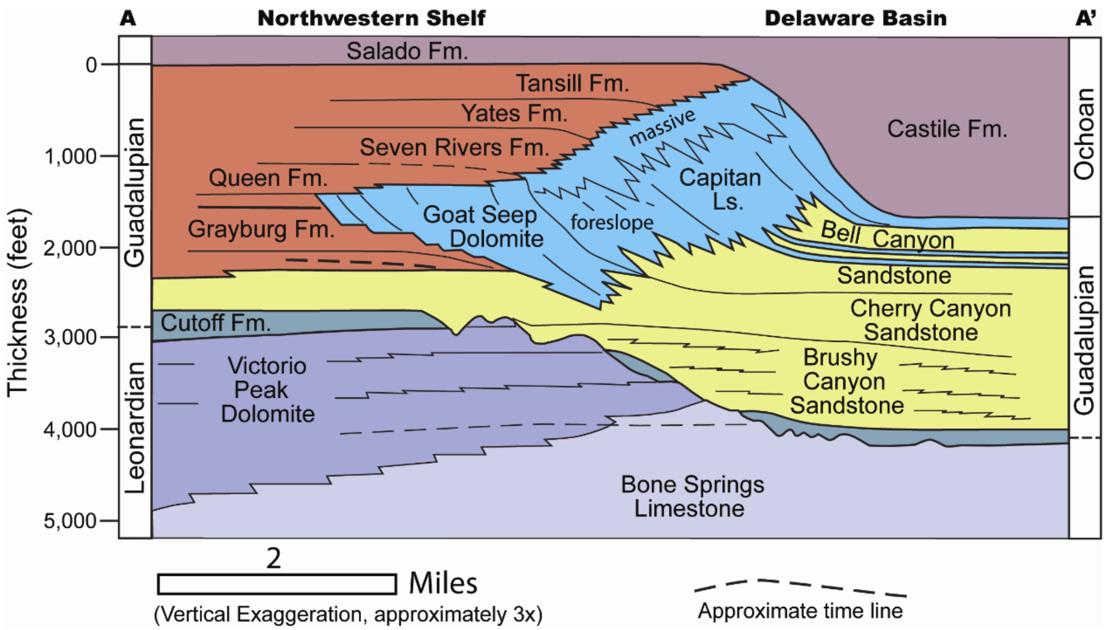

Figure A5-2. Stratigraphic cross section of Permian strata in the Guadalupe Mountains in Texas along line A–A' (modified from King [1948], Hayes [1964], Tyrrell [1969], and Pray [1988]).

Reef and fore-reef rocks consist of massive white to gray fossiliferous limestone. The limestone grades into back-reef rocks characterized by cyclic deposits of sandstone, sandy dolomite, and dolomite. The aquifer thickness generally increases from about 200 feet to 2000 feet towards the Delaware Basin from back-reef areas (Figure A5-3).

Structural and stratigraphic features greatly affect groundwater flow through the aquifer. Numerous Paleogene and Neogene-aged faults along the west side of the Salt Basin serve as a divide between groundwater flow to the northeast and southeast (northwest corner of Culberson County, shown in Figure A5-4). Uplift associated with faulting likely created a topographic gradient for regional groundwater flow. Karstification by acidic groundwater, during faulting and uplift, produced cave systems and smaller voids that allow for flow. Age dating of minerals from the Carlsbad Caverns area indicates that cave formation occurred from about 11 million years ago to present.

Groundwater Conditions

The permeability and distribution of the various rock types affect groundwater flow. In particular, clastic channels formed during the middle to late Guadalupian period and filled with clay and silt deposits may hinder groundwater flow. These channels cut across backreef settings, pass through the reef, continue down into the Delaware Basin, and are typically oriented perpendicular to groundwater flow directions.

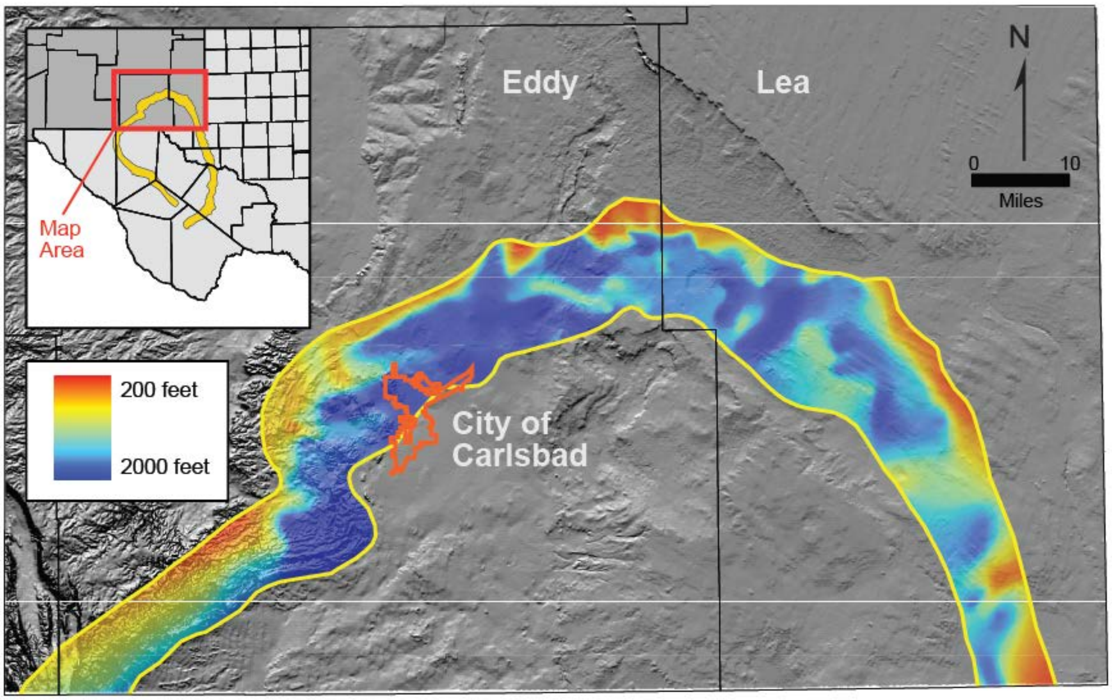

Figure A5-3. Thickness of the northern extent of the Capitan Reef Complex Aquifer (modified from Standen and others, 2009).

Downcutting by the Pecos River across the aquifer and pumping in the Delaware Basin have both affected regional groundwater flow through the aquifer. Prior to the incision by the Pecos River, the regional flow in the aquifer was to the north and east, and the main discharge was hypothesized to be a point near Hobbs, New Mexico. Water exiting the aquifer there moved into the San Andres Limestone, where it flowed further eastward. After downcutting of the Pecos River, possibly in Pleistocene time, and with the advent of recent groundwater pumping, the regional flow in New Mexico is now primarily toward the south into Winkler County, Texas.

The Capitan Reef Complex Aquifer is the main source of freshwater for the City of Carlsbad and several other communities in Eddy County, New Mexico. It is the source of irrigation water for southeastern New Mexico and as water supply for drilling operations for oil and gas. The distribution of fresh and saline water in the aquifer is related to periods of uplift and subaerial exposure in late Permian and Pliocene–Pleistocene times. During uplift, large amounts of possibly saline connate water were flushed from elevated areas west of the Pecos River, which explains why this area generally has more freshwater (Gail, 1974; Hiss, 1975). Extensive flushing of the aquifer has likely not occurred in areas east of the Pecos River, so groundwater there has high concentrations of total dissolved solids (Hiss, 1975; Huff, 2004). Groundwater located at depths of 2,923 to 4,695 feet from Lea County has total dissolved solids concentrations ranging from 12,800 to 173,448 milligrams per liter.

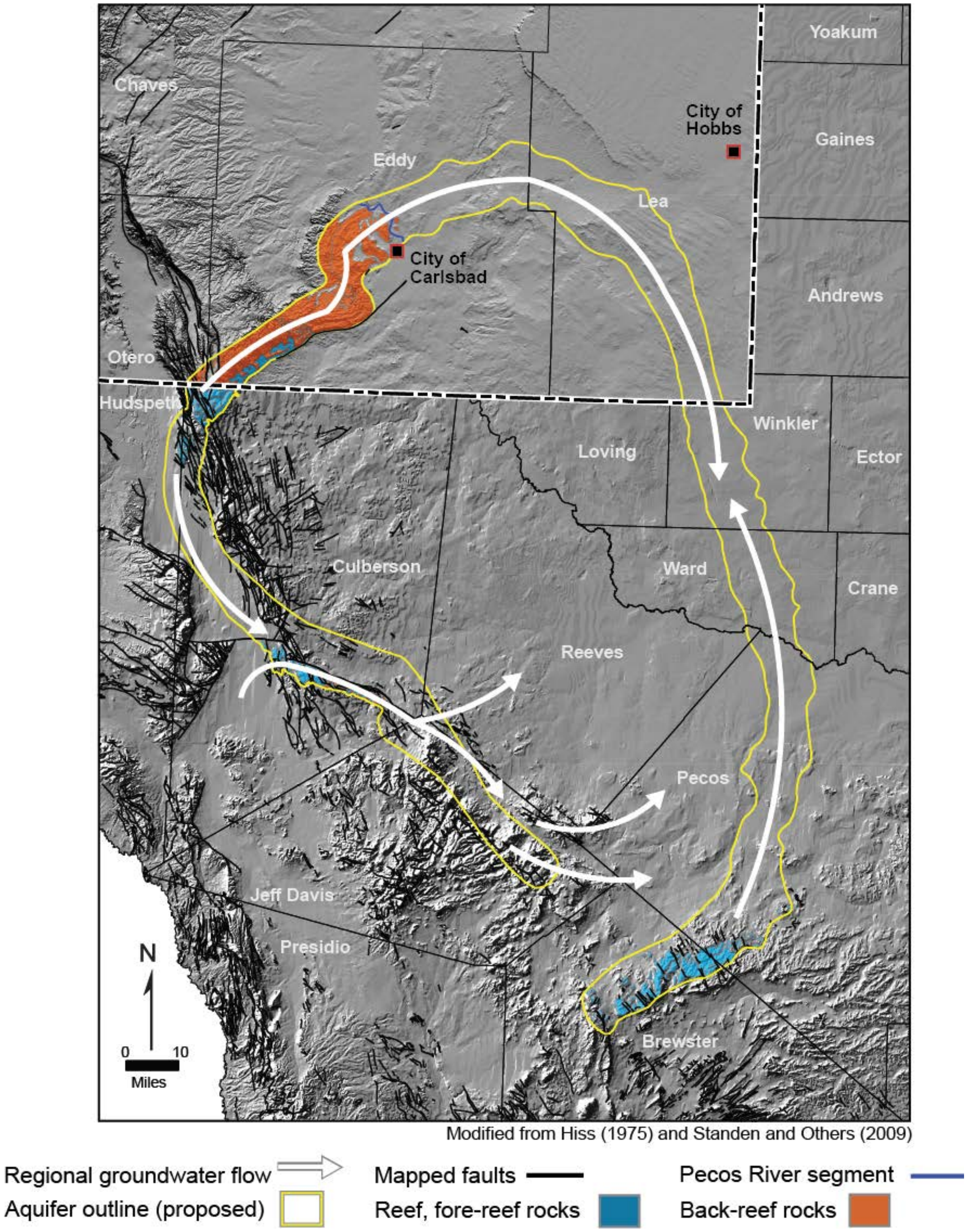

Figure A5-4. Regional groundwater flow in the Capitan Reef Complex Aquifer. Both structural (faults, fissures, and fractures) and stratigraphic features (lithologic changes, erosional unconformities) likely affect flow direction.

Hydraulic conductivity of the aquifer in New Mexico ranges from 1 to 25 feet per day west of the Pecos River and averages about 5 feet per day to the east. Transmissivity may be as great as

10,000 feet squared per day in thicker parts of the aquifer that have well-developed porosity. Flows of 3,500 gallons per minute have been recorded at Carlsbad Springs issuing from the Carlsbad and Capitan limestone. The area of the aquifer containing saline water may yield up to 500 gallons per minute to wells.

In Eddy County, based on aquifer extent and an assumed specific yield of 0.05, there is an estimated 2.2 million acre-feet of stored groundwater in the top 100 feet below the water table (New Mexico Interstate Stream Commission, 2001). In Lea County, this number is much lower, at 467 acre-feet, estimated using a specific yield of 0.000001 (New Mexico Interstate Stream Commission, 1999; Hiss, 1975).

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A6 - Carrizo-Wilcox Aquifer (Texas/Arkansas/Louisiana, Texas/Mexico)

The Carrizo-Wilcox aquifer system is a vast groundwater resource extending from northern Mexico, across Texas, and into Arkansas and Louisiana. Because the geologic framework and groundwater conditions are very different in these areas, these aquifers are discussed separately in the following paragraphs.

Arkansas/Louisiana

The Carrizo-Wilcox Aquifer of East Texas extends into northwestern Louisiana and southwestern Arkansas. The map (Figure A6-1) defining the aquifer in Louisiana and Arkansas is based on a map by the Louisiana Geological Survey. However, work by the U.S. Geological Survey on the Mississippi Embayment Regional Aquifer system defines a Lower Claiborne Aquifer (Figure A6-2) as being equivalent to the Carrizo Aquifer (Figure A6-3). A Middle Wilcox Aquifer is defined in Arkansas and Louisiana.

Geologic Conditions

In Louisiana and Arkansas, the Carrizo-Wilcox Aquifer includes the Carrizo Sand of the Eocene Claiborne Group and the Wilcox Group of Eocene and Paleocene age (Figure A6-2). Wilcox Group rocks in southern Arkansas consist of interbedded layers of clay, sandy clay, sand, and lignite. The sand beds are generally thin and discontinuous. The Carrizo Sand consists of fine to coarse micaceous massive-bedded quartz sand with minor amounts of interbedded clays and silts and occasional lenses of lignite. Carrizo-Wilcox strata are underlain by shale of the Midway Group and overlain by terrace deposits and alluvium of Quaternary age where the Cane River Formation and younger units are not present.

In southwestern Arkansas, the Carrizo Sand (Lower Claiborne Aquifer) dips to the southeast and the unit is generally up to 100 feet thick, but in some areas can reach around 100 to 200 feet. In northwestern Louisiana, regional dip shifts to the northeast due to the influence of the Sabine Uplift. In Louisiana, the Lower Claiborne Aquifer is up to 100 feet thick, increasing in some areas to around 100 to 200 feet. Regional dip of the Wilcox Group in southwestern Arkansas and northwestern Louisiana, defined by the upper surface of the Middle Wilcox Aquifer, is also trending to the southeast and northeast, respectively. The thickness of the Middle Wilcox Aquifer ranges from up to 400 feet in southwestern Arkansas up to about 2,400 feet in northern Louisiana.

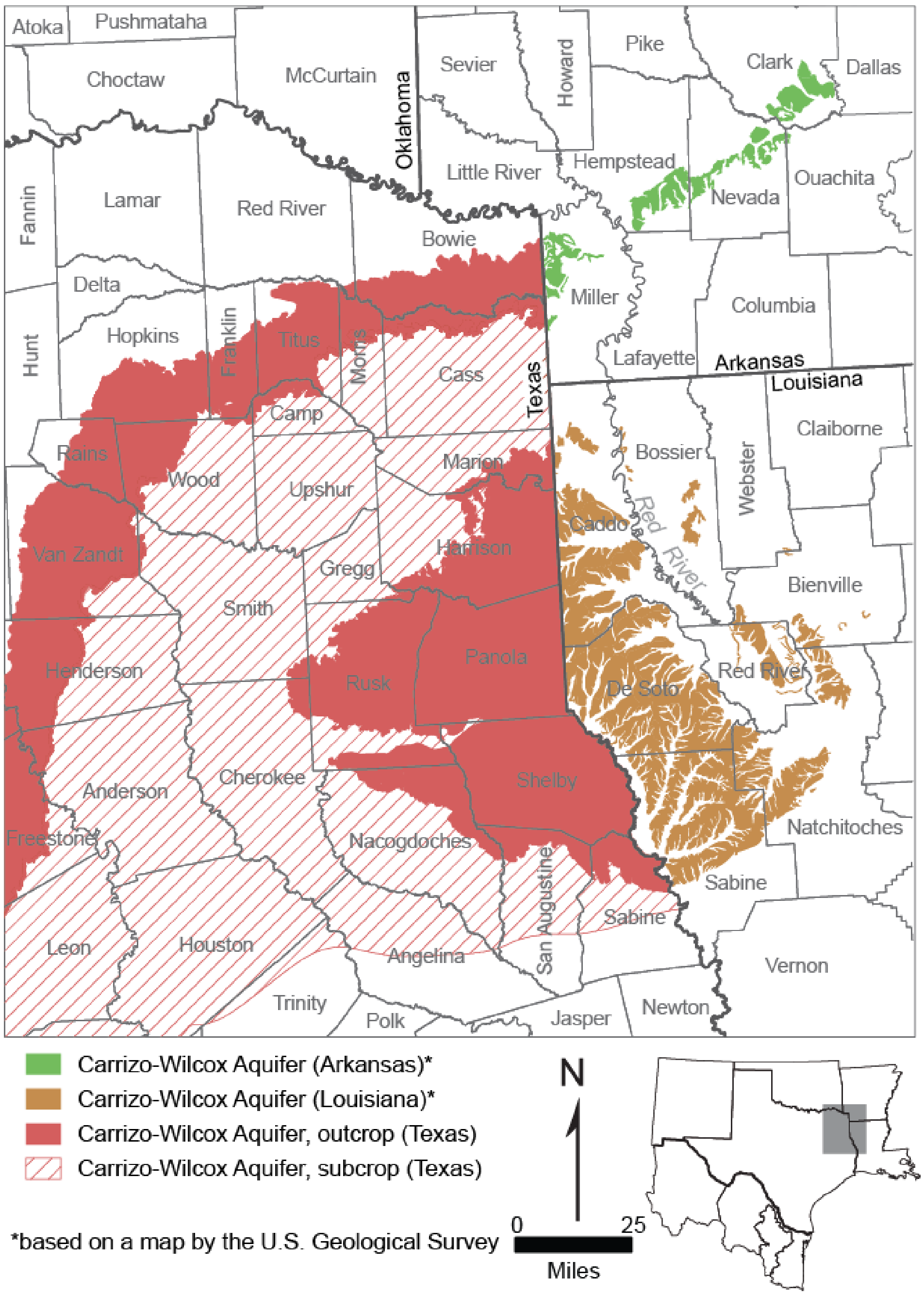

Figure A6-1. Carrizo-Wilcox Aquifer extent in Texas, Louisiana, and Arkansas.

System	Series	Stratigraphic unit		Hydrogeologic unit, Northern Louisiana
Tertiary	Eocene	Jackson Group, undifferentiated		Jackson confining unit
		Claiborne Group	Cockfield Formation	Cockfield Aquifer or surficial confining unit
			Cook Mountain Formation	Cook Mountain Aquifer or confining unit
			Sparta Sand	Sparta Aquifer or surficial confining unit
			Cane River Formation	Cane River Aquifer or confining unit
			Carrizo Sand	Carrizo-Wilcox Aquifer or surficial confining unit
		?		
	Paleocene	Wilcox Group, undifferentiated		Wilcox Aquifer
		Midway Group, undifferentiated		Midway confining unit

Figure A6-2. **Stratigraphy of the Wilcox and Claiborne group aquifers in Louisiana (modified from Johnston and others, 2000).**

Groundwater Conditions

Based on 2009 water levels, the direction of flow in southern Arkansas is generally toward the east, except for two cones of depression in Nevada and Clark counties and two areas of elevated water levels in Hot Spring and Hempstead counties (Figure A6-3). The lowest water-level elevation measured in this part of the aquifer was 147 feet, within a cone of depression located in Clark County. Hempstead County is an area of elevated water levels in the Carrizo outcrop where the highest water-level altitude measured was 400 feet (Pugh, 2010).

In northwestern Louisiana, a potentiometric surface map of the Carrizo-Wilcox Aquifer, based upon water-level data measured from October through December 1991, shows that regional groundwater flow is generally towards the Red River Valley (Seanor and Smoot, 1995). Groundwater pumping in southeastern Caddo and southwestern Webster parishes has created large cones of depression that locally alter this regional pattern.

The Carrizo-Wilcox Aquifer in Louisiana has a fresh groundwater zone that ranges between 50- to 850-foot thick, with wells typically ranging from 100- to 600-feet. Well yields are typically between 30 and 300 gallons per minute, hydraulic conductivities of range from 2 to 40 feet per day, and specific capacities range between 0.5 to 4 gallons per minute per foot of drawdown.

In Arkansas, the Wilcox Group has a maximum estimated thickness of 1,100 feet with the following estimated aquifer characteristics: (1) a mean transmissivity of 10,700 square feet per day, (2) a mean specific capacity of 142 gallons per minute per foot, (3) a hydraulic conductivity of 9.73 feet per day, and (4) a mean storage coefficient of 0.0232. Figure 6-4 show the geologic map of the Carrizo and Wilcox formations, subsurface structural elements, and related geologic units in eastern Texas, northeastern Louisiana, and southwestern Arkansas.

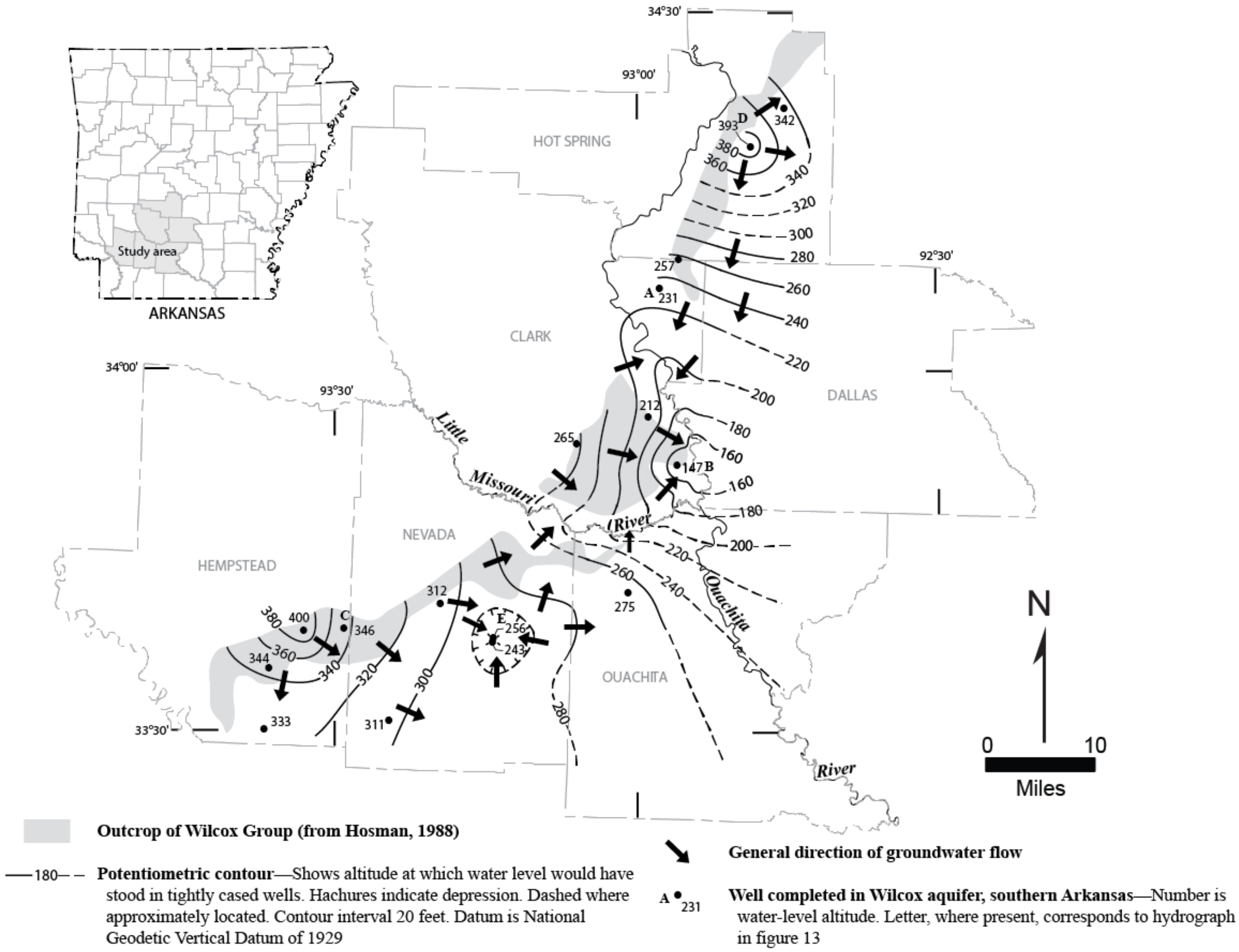

Figure A6-3. Potentiometric surface of the Wilcox Aquifer in Arkansas in 2009 (from Pugh, 2010).

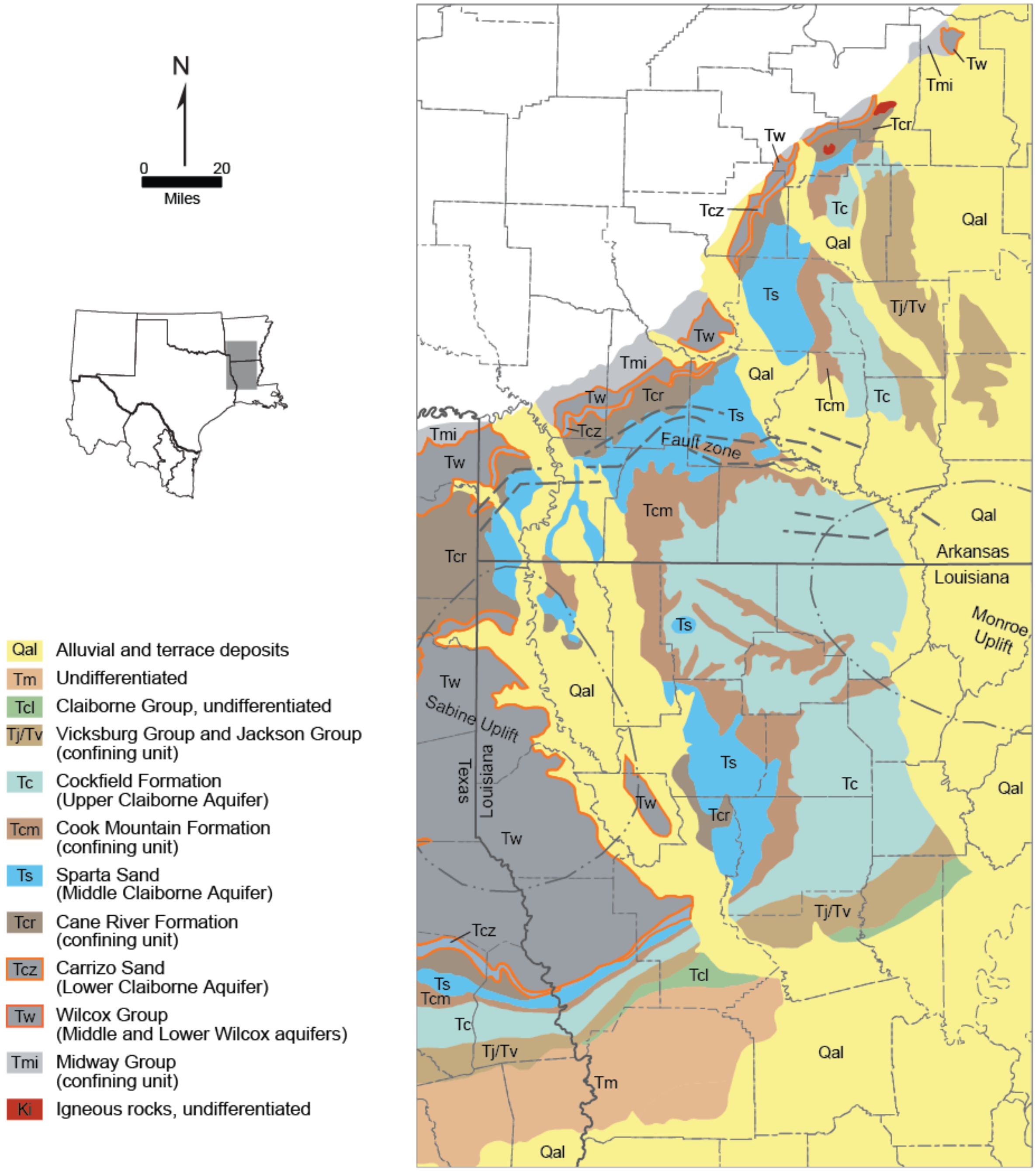

Figure A6-4. **Claiborne and Wilcox aquifers geologic units and related units in Arkansas and Louisiana (from Hosman, 1988; McKee and Clark, 2003; and Hart and others, 2008).**

The quality of Carrizo-Wilcox groundwater in Louisiana is considered generally good. Total dissolved solids range in concentration from about 208 to 719 parts per million, with an average of about 480 parts per million. Chloride concentrations range from less than 1.25 parts per million to 170 parts per million.

Iron ranges from less than 0.02 parts per million to 17.8 parts per million, with an average value of 1.90 parts per million (the current secondary Maximum Contaminant Levels for iron is 0.3 milligrams per liter). Nitrate values are from less than 0.05 to 0.59 parts per million. In southwestern Arkansas, the groundwater type is generally sodium bicarbonate, although sodium chloride and calcium bicarbonate type waters also occur. Total dissolved solids concentrations increase downdip to the southeast from the 0 to 500 milligrams per liter range in outcrop areas to the 3,000 to 10,000 milligrams per liter range in south-central Arkansas.

Mexico

The Carrizo Formation and Wilcox Group extend over approximately a 1,275-square mile area within the Mexican states of Coahuila, Nuevo Leon, and Tamaulipas. A map (Figure A6-5) of the outcrop and subcrop of the Carrizo-Wilcox Aquifer in Texas shows the differences in how these aquifers are defined on each side of the border, with the adjacent three aquifers in Mexico: Acuíferos Bajo Rio Bravo, Hidalgo, and Lampazos-Anahuac. The Carrizo Formation and Wilcox Group are not specifically identified as aquifers within Mexico by the Comisión Nacional del Agua, yet they correlate as geologic formations (Figure A6-6). The equivalent aquifers in Mexico are described in Appendix section A1.

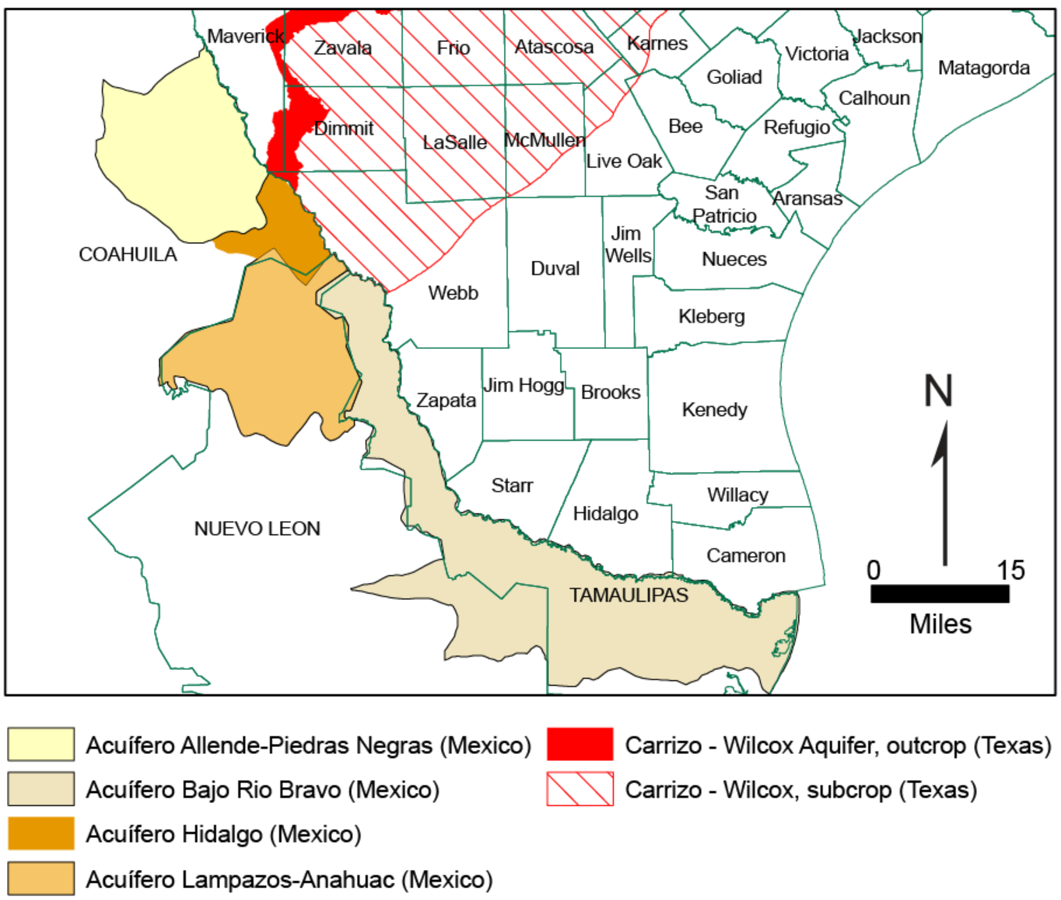

Figure A6-5. Carrizo-Wilcox Aquifer and adjacent aquifers in Mexico.

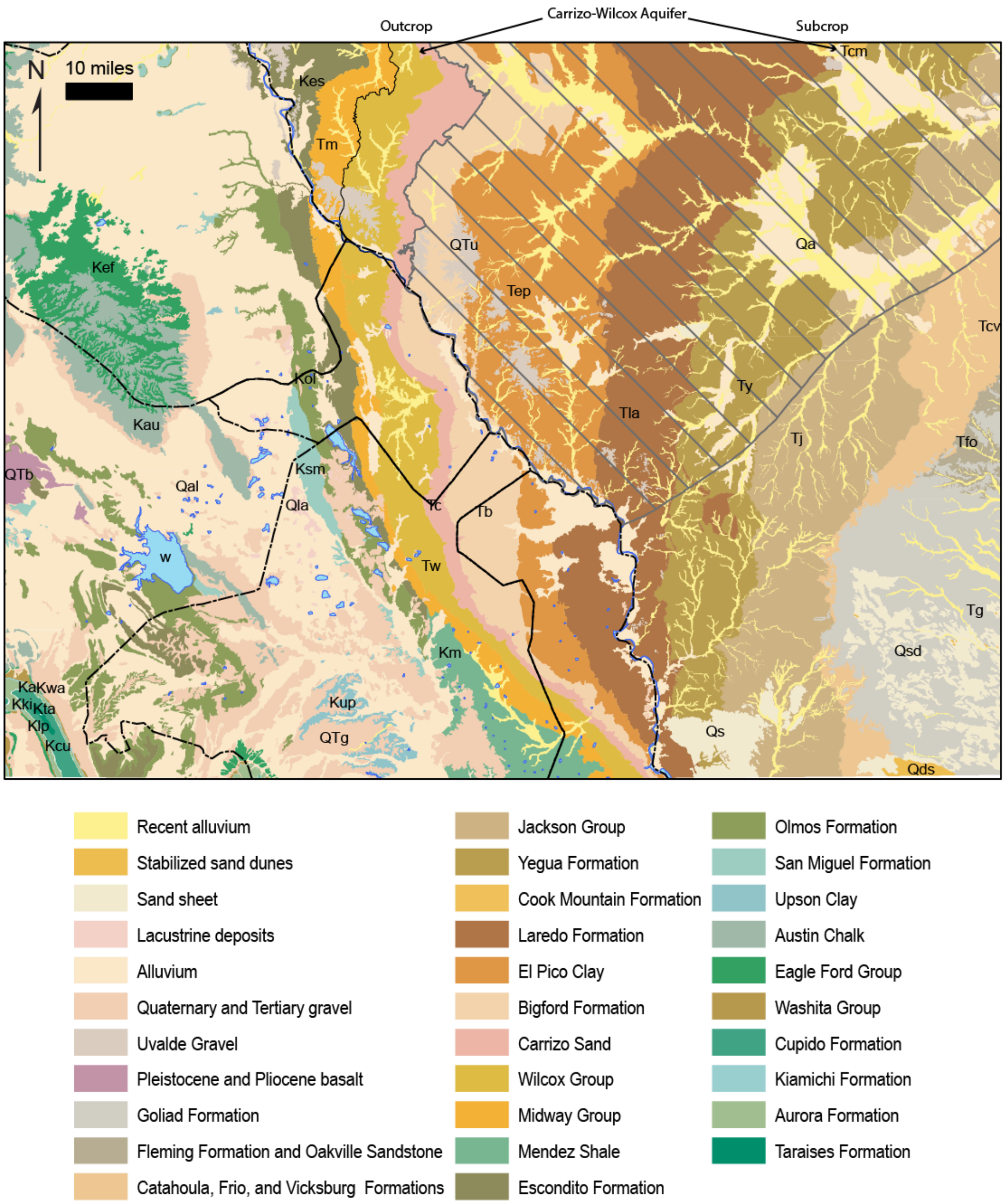

Figure A6-6. Carrizo-Wilcox Aquifer geology and adjacent formations in Mexico (from Berry and others, 2005).

Groundwater conditions

Wells within the Wilcox Group commonly yield less than 15 gallons per minute and produce fresh to saline groundwater. The quality of water in the Wilcox Group deteriorates with depth. The Carrizo Formation gradually thins to the southeast and shows an increase in clay content. Wells in the Carrizo in Mexico have low yields (less than 4 gallons per minute) and produce poor quality water.

Based on 1981 water-level measurements, the groundwater flowed to the east and northeast with gradients of up to 0.006 in the outcrop northwest of La Jarita; the gradient flattens (0.001) as flow continues into the subsurface into Texas (Figure A6-7).

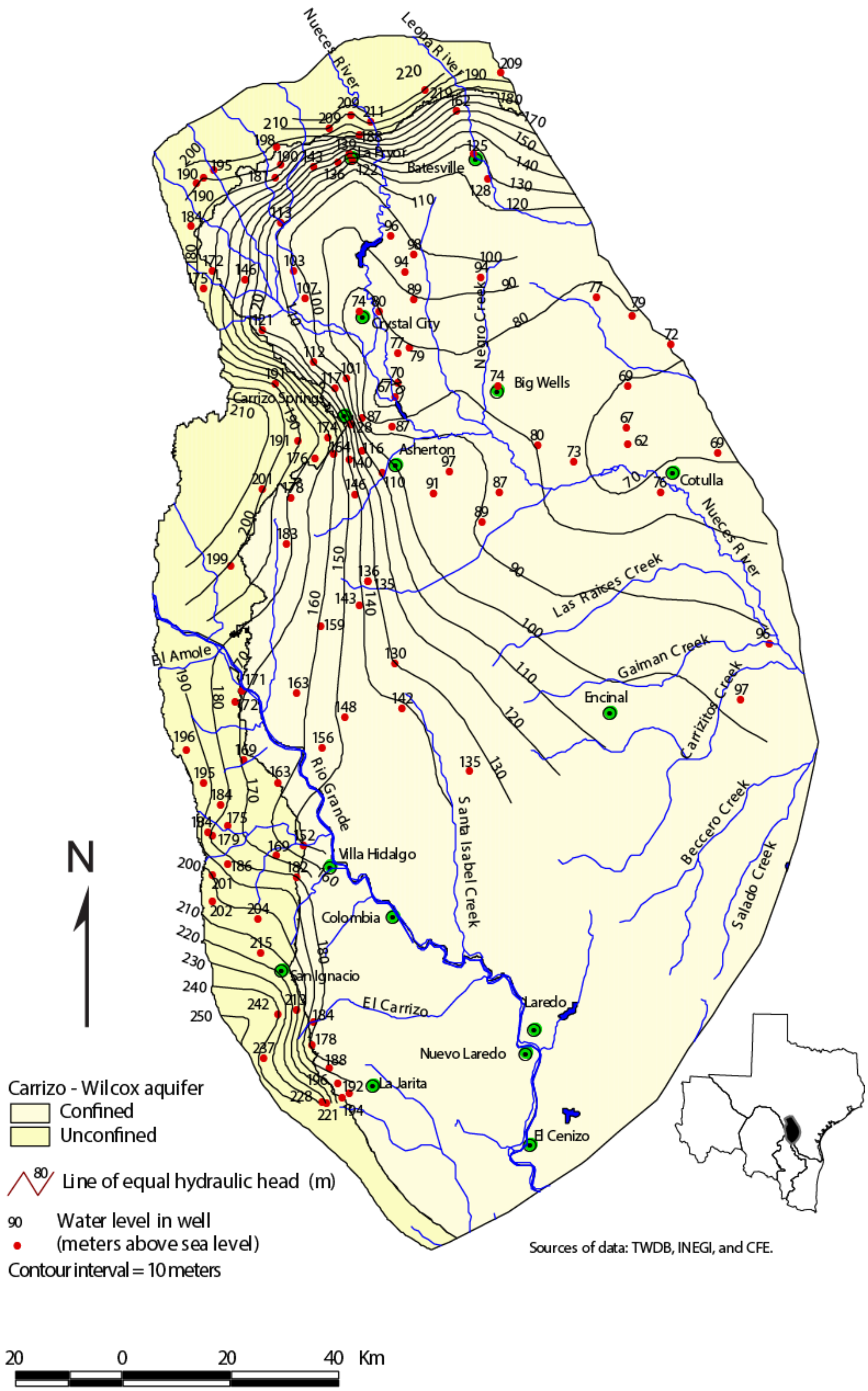

Figure A6-7. **Carrizo-Wilcox Aquifer potentiometric surface based on 1981 data (from Boghici, 2002).**

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A7 - Cretaceous and Jurassic Aquifers (Texas/New Mexico)

Several informal aquifers, referred to as the Cretaceous and Jurassic aquifers, have been delineated in the Northeast New Mexico Regional Water Plan (Figure A7-1).

Geologic Conditions

The aquifers include the Jurassic Entrada and Morrison formations, as well as those of the Cretaceous Lytle Formation and the Dakota Group (Figure A7-2). These Jurassic strata to the west of the Rita Blanca Aquifer are almost entirely non-marine in origin. A large part of the section consists of massive eolian sands that are conducive to groundwater production. The Cretaceous strata are also mainly non-marine rocks, although some marine shale and sand occur higher up in the section.

The stratigraphic nomenclature for the Texas Panhandle and northeastern New Mexico is very similar, although there are some key differences (Figure A7-2). The Summerville Formation of New Mexico is not recognized in Texas, possibly due to a lack of good exposures. In Dallam County, Texas, only the Exeter Sandstone is described and in New Mexico it is named as an upper member of the Entrada Sandstone. The nomenclature of the Cretaceous rocks changes toward the south and Jurassic rocks are missing (Figures A7-2 to A7-4).

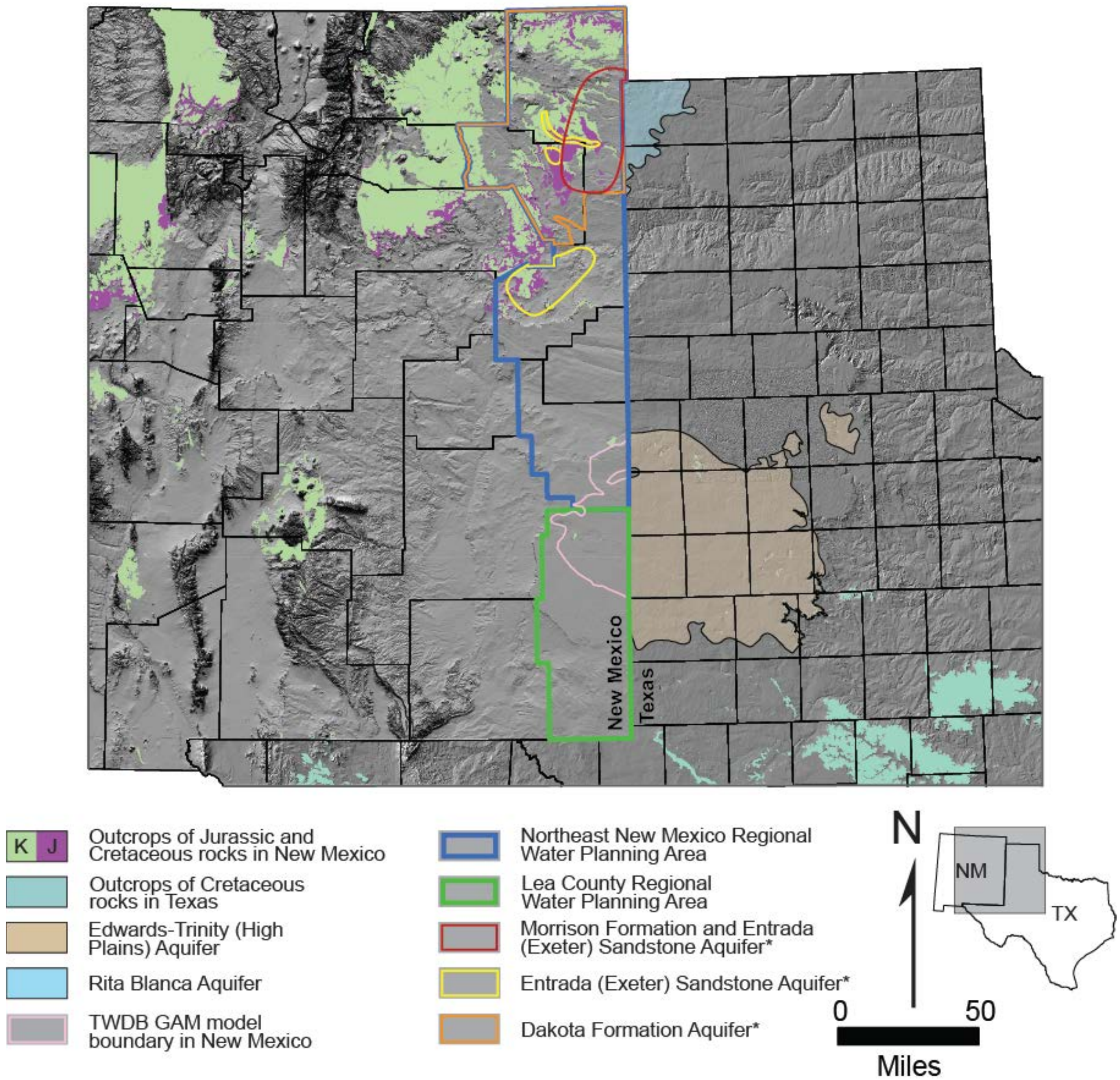

Figure A7-1. **New Mexico and Texas administrative and aquifer boundaries.Some surface geology is also shown, taken from the 1:500,000 Geological Map of New Mexico (New Mexico Bureau of Geology and Minernal Resources and U.S. Geological Survey, 2003) and the 1:250,000 Digital Geological Atlas of Texas (U.S. Geological Survey and TWDB, 2006). TWDB GAM is a Texas Water Development Board Groundwater Availability Model.**

System	Dry Cimarron Valley, NM	Dallam County, TX	Geology	Hydrology
Cretaceous	Graneros Shale	Graneros Shale	Dark gray shale with limestone beds	Aquiclude
Cretaceous	Dakota Group	Dakota Group	In ascending order; (1) Mesa Rica Sandstone is a massive sandstone and fluvial in origin, (2) the Pajarito Formation consists of interbedded siltstone, sandstone, and shale, continental in origin, (3) the Romeroville Sandstone is a marine sandstone.	Small to moderate volumes of fresh water from Mesa Rica Sandstone, Pajarito Formation interval is aquiclude, and small volumes of fresh water for the Romeroville Sandstone
Cretaceous	Glencairne Formation	Glencairne Formation	Dark gray marine shales with some interbedded sands, a tidal-esturine deposit.	Aquiclude
Cretaceous	Lytle Sandstone	Lytle Sandstone	Light colored sandstone with cross bedding, locally conglomeratic	Moderate to large volumes of fresh water
Jurassic	Morrison Formation	Morrison Formation	Upper part is greenish gray, green, and reddish brown sandy clay with locally interbedded sandstone, siltstone, and limestone. Lower part with thin bedded, light brown siltsone and sandstone with some mudstone.	Yields small volumes of fresh to slightly saline water from sandstones.
Jurassic	Summerville Formation; Exeter Member; Entrada Sandstone	? Exeter Sandstone (aquifer)	The Exeter Sandstone is a light colored, fine-grained eolianite. The Summerville Formation, recognized in New Mexico, consists of thinly and repetitively bedded, fine-grained sandstone, gypsum, siltstone, and sandy mudstone. The Entrada Sandstone is a trough-crossbedded, yellowish-gray to pale reddish-brown eolian deposit.	Yields small volumes of fresh to slightly saline water

Figure A7-2. Cretaceous and Jurassic stratigraphic units along the northwest Texas-northeastern New Mexico border in the vicinity of the Rita Blanca Aquifer. Compiled from Christian (1989) and Lucas and Anderson (1998).

System	Group	Formation	Geology	Hydrology
Cretaceous	Washita	Duck Creek	Yellow, sandy shale and thin gray to yellowish brown argillaceous limestone beds.	Aquitards; yielding small amounts of water locally to wells, not part of the Edwards-Trinity (High Plains) Aquifer.
Cretaceous	Fredericksburg	Kiamichi	Gray to yellowish brown shale with thin interbeds of gray argillaceous limestone and yellow sandstone.	
Cretaceous	Fredericksburg	Edwards	Light gray to yellowish gray, thick to massive bedded, fine to coarse-grained limestone.	Generally yields small amounts of water, but may yield large amounts of water locally due to fractures and solution cavities.
Cretaceous	Fredericksburg	Comanche Peak	Light gray to yellowish brown, irregularly bedded argillaceous limestone with thin interbeds of light gray shale.	
Cretaceous	Fredericksburg	Walnut (aquifer)	Light gray to yellowish brown argillaceous sandstone; thin beddedgray shale; light gray to grayish yellow argillaceous limestone.	Not known to yield water to wells.
Cretaceous	Trinity	Antlers	White, gray, yellowish brown to purple, argillaceous, loosely cemented sand, sandstone, and conglomerate with interbeds of siltstone and clay.	Yields small to moderate amounts of water to wells.
Unconformable contact with red beds of the Triassic Dockum Group				

Figure A7-3. Cretaceous stratigraphic units along the Texas-New Mexico border near the Edwards-Trinity High Plains Aquifer. Compiled from Walker (1979), Knowles and others (1984), Nativ and Gutierrez (1988), Fallin (1989), and Blandford and others (2008).

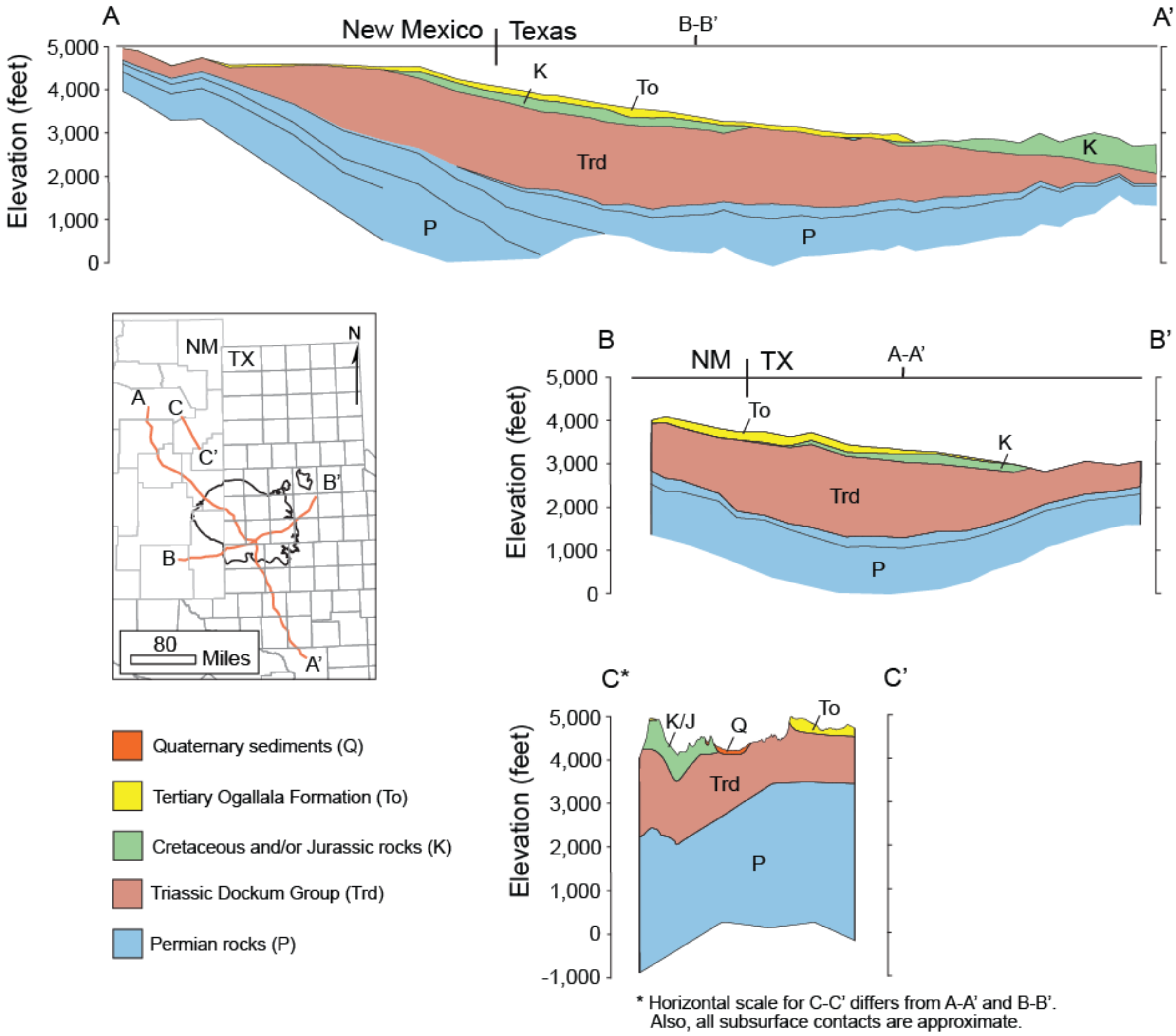

Figure A7-4. **Cross-sections A–A' and B–B' modified from Blandford and others (2008) and C–C' from Daniel B. Stephens & Associates, Inc. (2007).**

Groundwater conditions

Hydraulic parameters for the main Cretaceous and Jurassic aquifers in the Northeast Regional Planning area of northeastern New Mexico are summarized in Table A7-1. Transmissivity values for the Antlers Formation in the Texas Panhandle range from 19 to 6,260 square feet per day. Values reported for the Kiamichi Formation in Texas are an average value of 230 square feet per day.

Table A7-1. Hydrogeologic parameters of Cretaceous and Jurassic aquifers in northeastern New Mexico.

Unit	Thickness (feet)	Yield (gpm)	Transmissivity (ft^2/day)	Specific Capacity (gpm/ft)	Specific Conductance (µS/cm)	Storage Coefficient
Dakota Group, Glencairn Formation, and Lytle Sandstone	0 - 300	0-400	490 – 8,800	0.5 - 5	40- 5,640	0.00007
Morrison Formation	0-600	1 -2	low to moderate	<1	813 - 2,520	unknown
Entrada Sandstone	0-300	0-600	55 - 450	0.5-5	540-3,190	0.0002-0.144

Note: gpm is gallons per minute; ft2/day is feet squared per day; µs/cm is microsiemens per centimeter.

Recharge to the Northeast Regional Water Planning area is estimated at 247,000 acre-feet per year or 2.5 percent of average annual precipitation. However, this value is not specific to the Jurassic and Cretaceous aquifers and includes the Ogallala Aquifer. It occurs through direct rainfall and localized recharge of precipitation from playa lakes. Much of the precipitation occurs from May through October when rates of evapotranspiration are high, resulting in little effective recharge.

In northeast New Mexico near the Texas border, the regional groundwater flow is to the east-southeast, except near the Canadian River where pre-development water-level contours indicate flow towards the river. Farther south this trend of east-southeast regional flow continues. The amount of subsurface flow from New Mexico to Texas in the Jurassic, Cretaceous, Paleogene and Neogene aquifers of the Northeast Regional Water Planning Area has been estimated at 54,000 acre-feet per year. Flow between the Jurassic and Cretaceous aquifers is believed to be small. Cross-formational flow between Jurassic and Cretaceous rocks and the Ogallala Aquifer does occur, as it does with the Dockum Group, near the Edwards-Trinity (High Plains) Aquifer.

Water quality for Cretaceous rocks in New Mexico, equivalent to those of the Edwards-Trinity (High Plains) Aquifer, is generally fresh with total dissolved solids concentrations of about 400 to 1,100 milligrams per liter. Total dissolved solids concentrations increase to the southeast into Texas. Water quality information from aquifers west of the Rita Blanca Aquifer in New Mexico has not been reported for specific aquifers and may well include groundwater from the Ogallala Aquifer, along with the deeper Jurassic and Cretaceous aquifers. Values of total dissolved solids concentrations in groundwater from this area are mostly less than 500 milligrams per liter but may locally be greater than 2,000 milligrams per liter.

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A8 - Dockum Aquifer (Texas/New Mexico)

The Dockum Aquifer occurs in eastern New Mexico and western Texas (Figure A8-1). The delineation of the Dockum Aquifer in Texas is based on a limit of 5,000 milligrams per liter total dissolved solids; therefore, not all of the Dockum Group's extent is delineated as a minor aquifer in Texas. This detail is reflected in the aquifer extent boundary, showing the aquifer being absent in the center of the Dockum Group depositional basin. In New Mexico, the upper boundary of the aquifer is generally placed along topographic highs or rivers since these features behave as lateral no-flow boundaries.

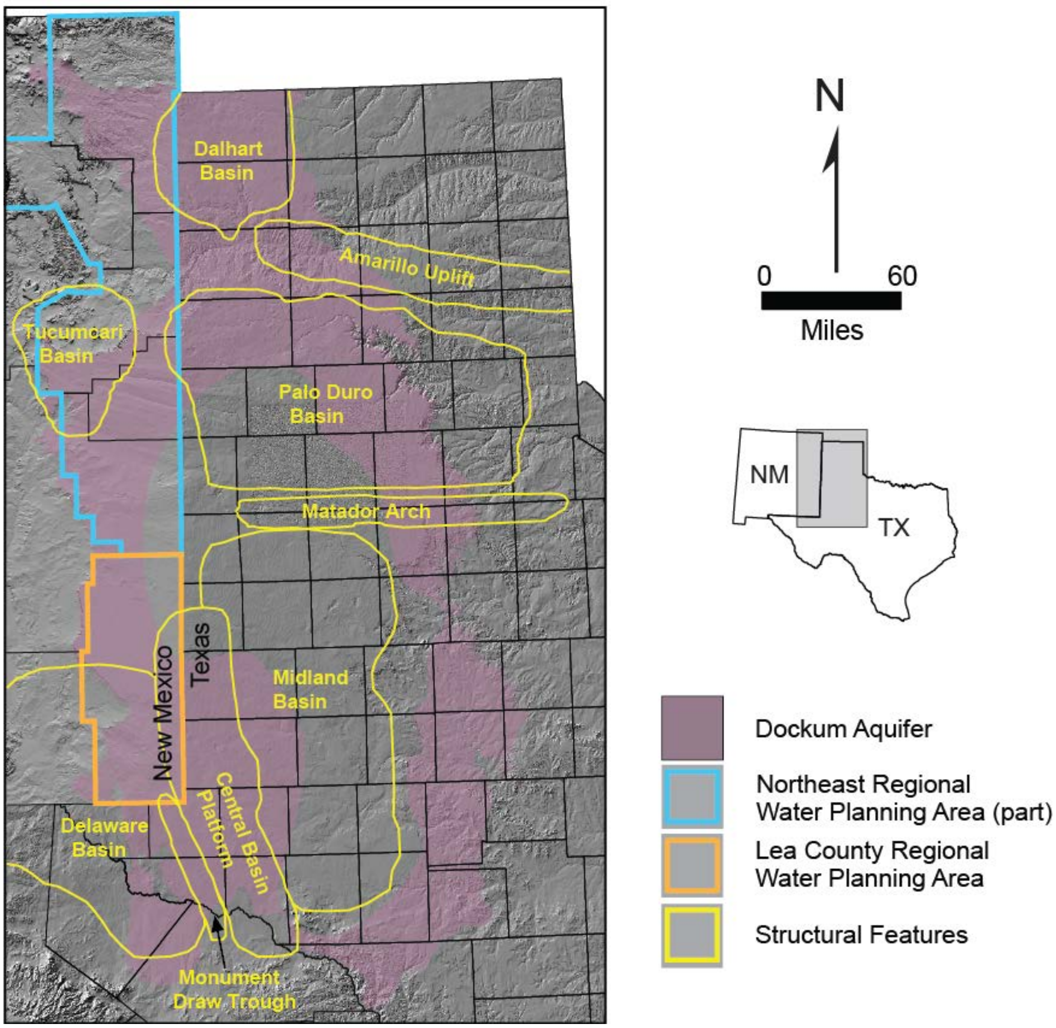

Figure A8-1. Locations for administrative and Dockum Aquifer boundaries. The boundary of the Dockum Aquifer and the approximate boundaries of major structural features are modified from Ewing and others (2008).

Geologic Conditions

Dockum Group rocks are Triassic in age and accumulated in pre-existing late-Paleozoic mid-continent structural basins that include the Dalhart, Tucumcari, Palo Duro, Midland, and

Delaware basins. Areas of positive structural relief separating these basins include the Amarillo Uplift, Matador Arch, and the Central Basin Platform. In Lea County, in southeasternmost New Mexico, the Monument Draw Trough contains Dockum Group sediments located in an area of dissolution of underlying Permian-age salts.

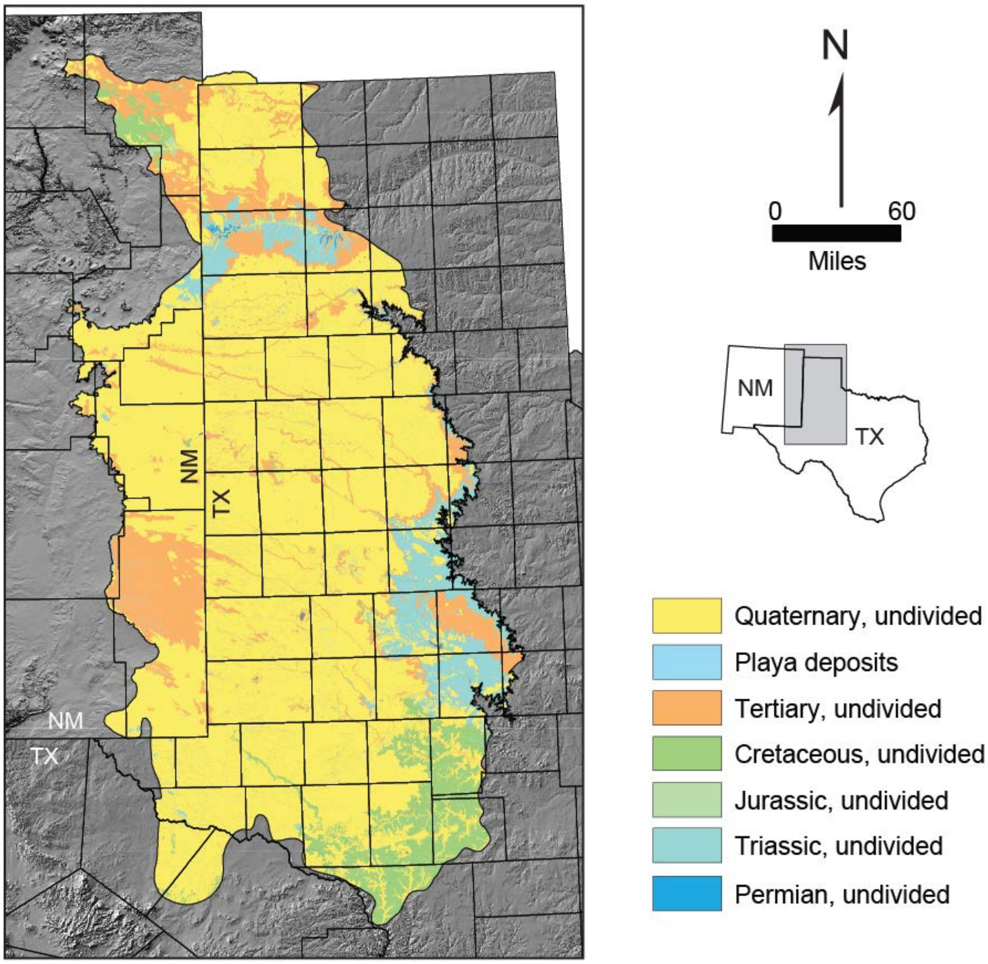

Figure A8-2. Surface geology within the boundaries of the Dockum AquiferUnits have been grouped by age. Taken from the 1:250,000 Digital Geological Atlas of Texas (U.S. Geological Survey and TWDB, 2006), and the 1:500,000 Geological Map of New Mexico (New Mexico Bureau of Geology and Mineral Resources and U.S. Geological Survey, 2003).

The Dockum Group consists of terrigenous fluvial and lacustrine sediments ranging from mudstone to conglomerate. The coarser-grained sediments were deposited in stream channels, and siltstones and mudstones were deposited on floodplains, on interfluves, and in small ponds. The formations of the Dockum Group are, from oldest to youngest, the Santa Rosa Sandstone, the Tecovas Formation, the Trujillo Sandstone, the Cooper Canyon Formation, and the Redonda Formation (based on Lehman, 1994a, 1994b; see Figure A8-2 and map and stratigraphic column of Figure A8-3). The lowermost Santa Rosa Sandstone consists of extensive sandstone and conglomerate beds and the overlying Tecovas Formation consists of variegated mudstone and siltstone. Together these formations have been informally grouped together as the sand-rich Lower Dockum Unit.

The Trujillo Sandstone consists of massive cross-bedded sandstones and conglomerates and the uppermost Cooper Canyon Formation consists of mudstone with some siltstone, sandstone, and conglomerate. The Redonda Formation is made up of laterally continuous, repetitively-bedded fine sandstone, siltstone, and mudstone. These units are combined to form the mud-rich Upper Dockum Unit.

Dockum Group rocks are underlain by Permian-age rocks and overlain by Jurassic-, Cretaceous-, Paleogene-, Neogene-, and Quaternary-age formations (Figure A8-2). Paleogene, Neogene, and Quaternary units include the Ogallala and Blackwater Draw formations. Permian-age rocks generally consist of siltstone, mudstone, and evaporate beds. Dissolution of thick sections of Permian evaporites has resulted in collapse features affecting the Dockum Aquifer in local areas.

<table>
<tr><th>McGowen and others (1975; 1977; 1979)</th><th>Granata (1981)</th><th colspan="2">Lehman (1994a; 1994b)</th><th colspan="2">Lucas, Heckert, and Hunt (2001)</th></tr>
<tr><td>Southern High Plains Texas & New Mexico</td><td>Northeastern New Mexico</td><td colspan="2">Southern High Plains Texas & New Mexico</td><td colspan="2">East-central New Mexico</td></tr>
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<tr><td rowspan="2">Chinle Formation</td><td>Cooper Canyon Formation</td><td>Bull Canyon Formation</td></tr>
<tr><td>Trujillo Sandstone</td><td>Trujillo Formation</td></tr>
<tr><td rowspan="2">Lower (2) Dockum</td><td rowspan="2">Santa Rosa (3) Sandstone</td><td>Tecovas Formation</td><td>Garita Creek Formation</td></tr>
<tr><td>Santa Rosa (3) Sandstone</td><td>Santa Rosa (3) Formation</td></tr>
</table>

Figure A8-3. Stratigraphic nomenclature of the Triassic Dockum Group (modified from Bradley and Kalaswad, 2003; Ewing and others, 2008). (1) in New Mexico only, (2) informal stratigraphic name, (3) referred to as “Best Sandstone” by Bradley and Kalaswad (2003).

Groundwater conditions

The Upper and Lower Dockum units are considered two distinct hydrostratigraphic units and have been modeled as two separate layers in the TWDB Dockum Aquifer Groundwater Availability Model (Ewing and others, 2008). Sandstones in the lower part of the Dockum Group, especially the Santa Rosa Sandstone, are generally more continuous and produce more water than those in the upper part of the Dockum Group. The overall percentage of sandstone is also higher in the lower part of the Dockum Group than in the upper part.

Some groundwater flow to and from the Dockum Aquifer occurs vertically across formations (Figure A8-4). The water-level elevations in the upper part of the Dockum Aquifer are higher than in the lower part of the aquifer. The magnitude of the difference is greatest in New Mexico and decreases towards the southeast. On a local scale, flow in outcrop areas is controlled by topography, with groundwater flowing towards streams and rivers.

Predevelopment water levels indicate that regional groundwater flow in the Dockum Aquifer generally was to the east and southeast (Figure A8-5). Based on analysis of water levels of Dockum Group wells and overlying units, as well as geochemical evidence, the Dockum Aquifer appears to be hydraulically connected, at least in places, to overlying formations. This connection occurs where sands in the Dockum Group are in direct contact with alluvial sediments of the Pecos Valley and Ogallala aquifers. In addition, groundwater can flow into or out of the Dockum Aquifer into these interconnected aquifers, depending on head differences. Based on similarities in chemical and isotopic compositions of well water, there also seems to be cross-formational flow between overlying Cretaceous-age rocks and those of the Dockum Group. In other areas where the mud-rich Upper Dockum Unit separates the lower sand-rich unit from younger sediments (which is most of the area covered by the TWDB Groundwater Availability Model) there is little evidence of cross-formational flow.

The Dockum Group in Oklahoma is not designated a major or minor aquifer at this time—however, the recommendations for the maximum annual yield and equal proportionate share for both the Dockum-Dakota and Canadian River Alluvium and Terrace Aquifer groundwater basins are pending submission to the Oklahoma Water Resources Board. The Dockum Group, where it is present in the Oklahoma panhandle, provides some groundwater for irrigation to southwestern Cimarron County and west-central Texas County. The Dockum Group consists of sandstone and interbedded shales that grade upward into a shale-sandstone or siltstone sequence.

Well yields in Oklahoma are 10 to 50 gallons per minute of water for stock and domestic use. However, well yields in a few places can yield as much as 500 gallons per minute. The groundwater of the Dockum Formation is more mineralized than water in the overlying aquifers and not as mineralized as the older Permian aquifers. The quality typically degrades with depth.

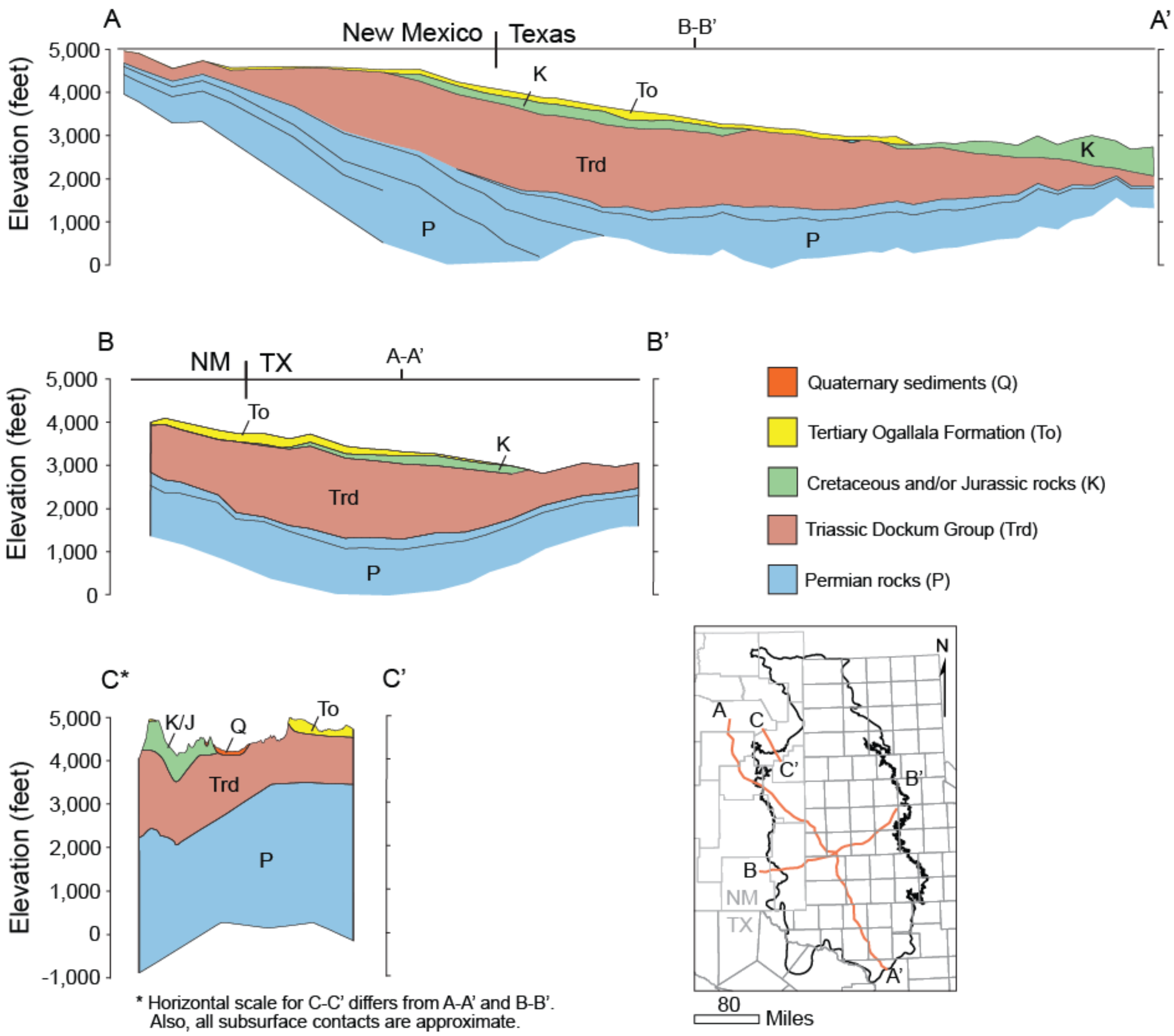

Figure A8-4. **Cross-sections A–A' and B–B' modified from Blandford and others (2008) and C–C' from Daniel B. Stephens & Associates, Inc. (2007).**

Groundwater flow through the Dockum Aquifer, as with all clastic aquifers, is dependent on the type of sediment present and its lateral continuity. More porous and permeable sediments that are coarser grained are more conducive to flow than permeable, discontinuous, fine-grained sediments. The Dockum Aquifer varies significantly in terms of lithology; therefore, so does its ability to transmit water. This variation occurs over small distances due to the aquifer's heterogeneity. Hydraulic properties such as conductivity, transmissivity, specific capacity, and storativity can be used to describe the variability. Hydraulic conductivity for the Lower Dockum unit in New Mexico ranges from 0 to 5 feet per day to 10 to 15 feet per day based on data from the TWDB groundwater model (Ewing and others, 2008) and between 0 and 10 feet per day for the Upper Dockum (noting that these estimates are based on Texas data extrapolated into New Mexico). Estimates of storativity of the Dockum Aquifer in Texas range from 5×10^{-5} to 2×10^{-3} with a geometric mean equal to 1.6×10^{-4}. Similar hydraulic data from New Mexico are sparse.

In Lea County, specific capacities range from 0.14 to 0.2 gallons per minute per foot of drawdown. Well yields there range widely, from 6 to 100 gallons per minute.

In the Northeast Regional Planning Area (Figure A8-1), specific capacities range from 0.03 to 1.0 gallons per minute per foot for the Redonda and Chinle formations and less than 1.0 gallons per minute per foot for the Santa Rosa Sandstone. Transmissivities there are considered very low to low. Well yields are about 0 to 20 gallons per minute for the Redonda and Chinle formations and less than 10 gallons per minute, on average, with a maximum of 150 gallons per minute, for the Santa Rosa Sandstone. Thicknesses of the Redonda and Chinle formations in the Northeast region are from zero to 1,200 feet and are 1 to 375 feet for the Santa Rosa Sandstone, generally, with a maximum of 450 feet.

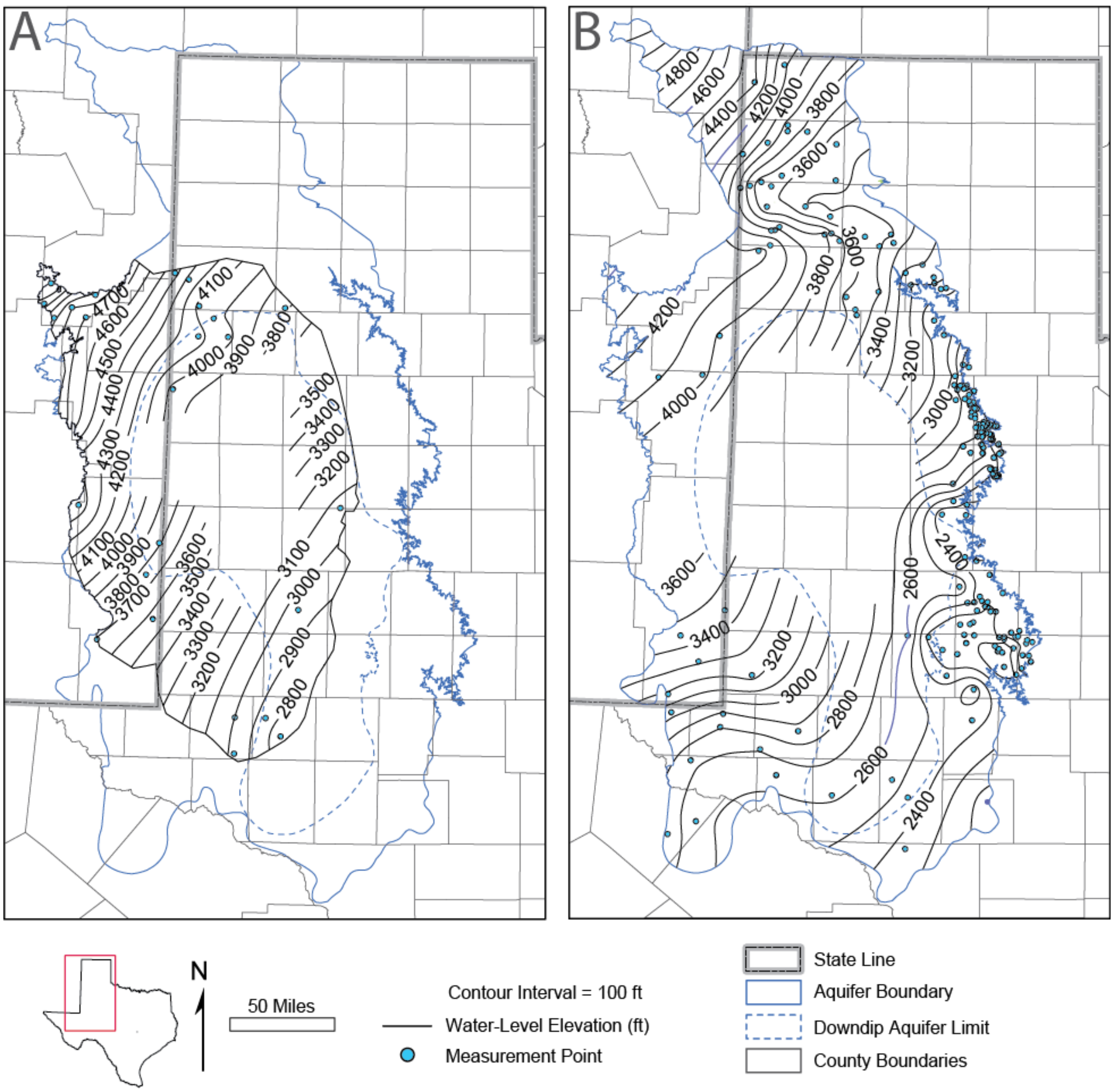

Figure A8-5. Estimated predevelopment water-levels map of the Dockum Aquifer (upper in A-left and lower in B-right). Modified from Ewing and others (2008).

Potential sources for surface recharge to the Dockum Aquifer include precipitation, irrigation return flow, and stream or reservoir leakage. Recharge to the aquifer is considered to be shallow recharge with none expected to reach the confined portions of the aquifer, based on the location and extent of Triassic-age outcrops. It has been proposed that the source of groundwater in the lower part of the Dockum Group was precipitation on higher elevation outcrops in New Mexico during the Pleistocene. These sandy outcrops were subsequently eroded from the Pecos Plains and Pecos River Valley, which cut off recharge to the aquifer. Estimates of recharge rates vary widely for the Dockum Aquifer, ranging from 0.007 inches per year to 4.3 inches per year. Recharge rates of 0.03 to 0.3 inch per year were used in the TWDB Groundwater Availability Model (Ewing and others, 2008) for the outcrop belt along the Canadian River, which extends somewhat into New Mexico.

Discharge from an aquifer can occur through either natural or man-made processes. Natural processes include cross-formational flow or discharge to rivers, streams, and springs. Pumping is the sole artificial abstraction from the aquifer. The withdrawal of groundwater by pumping far exceeds any estimates of natural discharge (Figure A8-6). As with the Panhandle region of Texas, the majority of the withdrawn groundwater is used for irrigated agriculture.

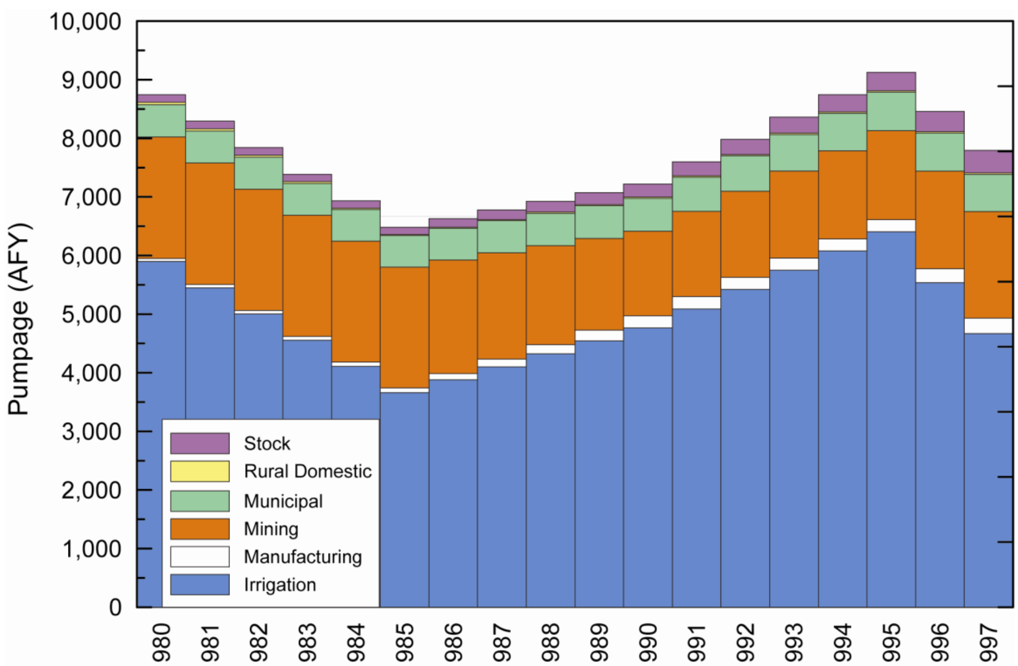

Figure A8-6. Total groundwater withdrawals from the Dockum Aquifer in New Mexico (from Ewing and others, 2008). Reported in acre-feet per year (AFY).

The quality of water that is withdrawn from the Dockum Aquifer is considered marginal to poor over a large part of its area. The best water occurs in shallow outcrop areas around the fringes of the aquifer's extent. In some areas, the aquifer is sufficiently fresh (less than 1,000 milligrams per liter total dissolved solids) to meet safe-drinking water standards. Toward the center of the Dockum Group depositional basin, the total dissolved solids range from 5,000 up to near 70,000 milligrams per liter (Figure A8-7). The source of the high concentrations of total dissolved solids is due in large part to prevalence of evaporite deposits.

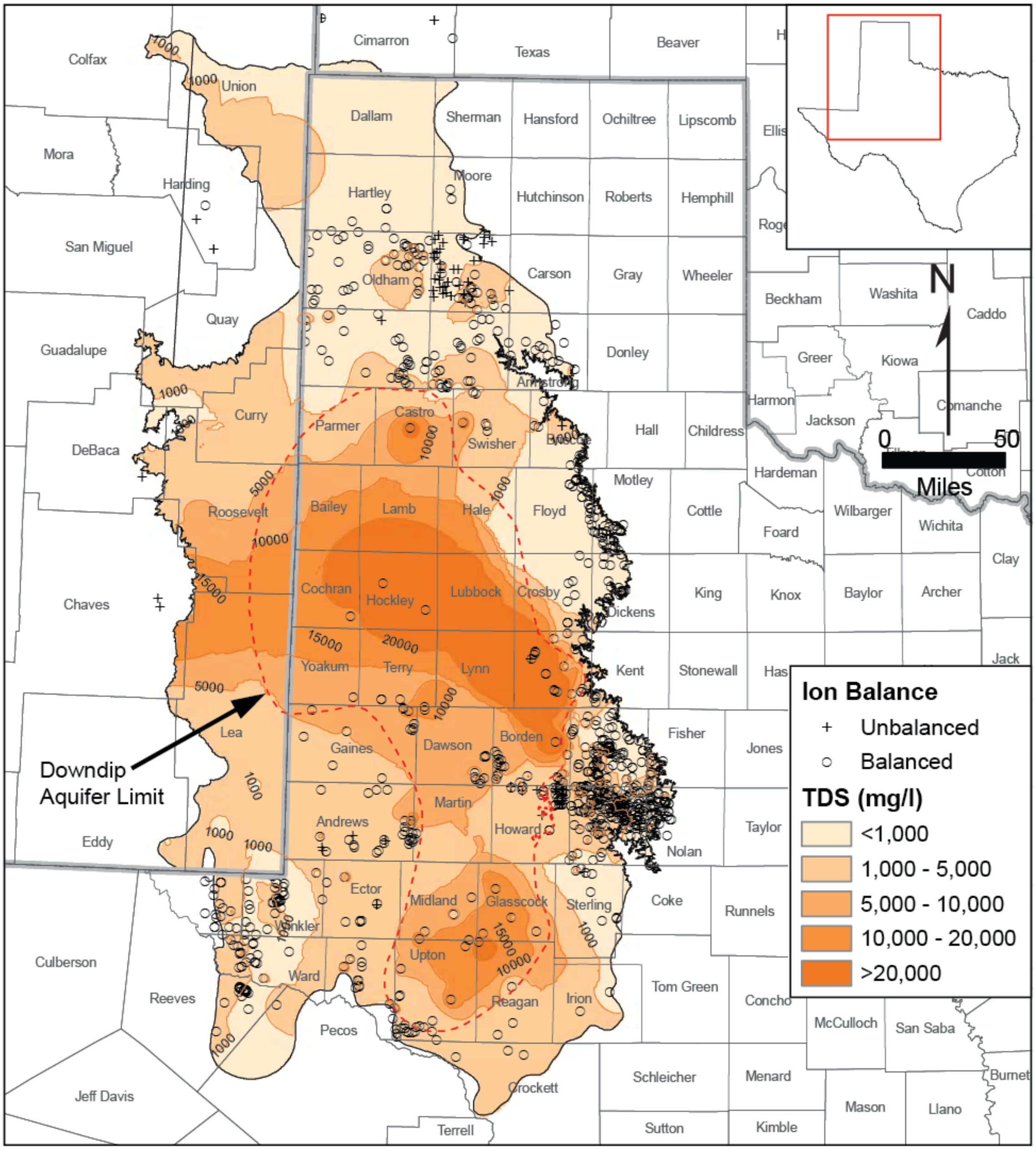

Figure A8-7. Total dissolved solids concentrations in milligrams per liter in groundwater from the Dockum Aquifer (from Ewing and others, 2008).

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A9 - Edwards-Trinity (Plateau) Aquifer (Texas/Mexico)

The Edwards-Trinity (Plateau) Aquifer is adjacent to five administrative aquifer regions in Mexico. Across the Rio Grande River from Terrell to Maverick counties in Texas lie the Acuífero Cerro Colorado-La Partida, Acuífero Presa La Amistad, and Acuífero Palestina (Figure A9-1); together, the aquifers cover approximately 4,519 square miles in the State of Coahuila. Across from Brewster to Terrell counties are Acuífero Santa Fe del Pino and Acuífero Serranía del Burro; together, these two areas cover an area of 5,548 square miles.

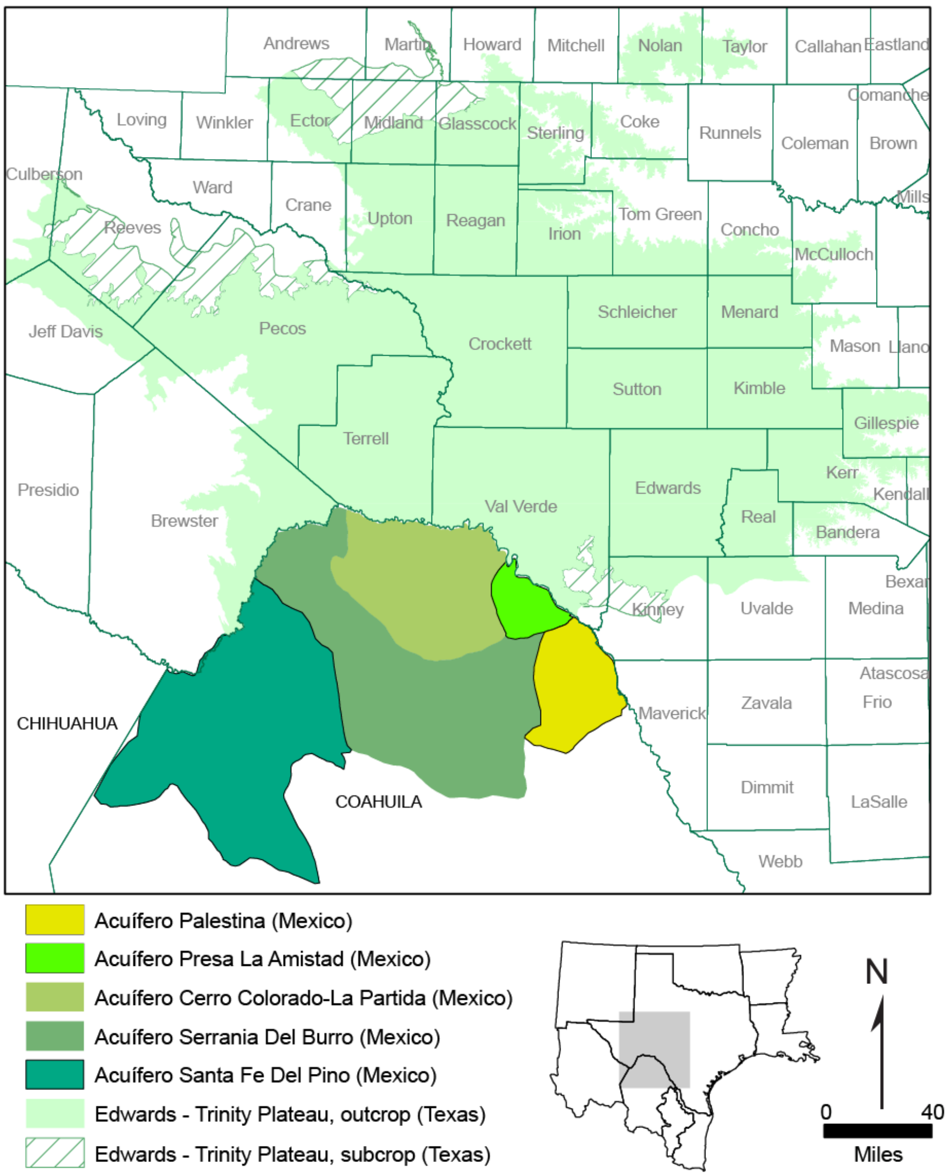

Figure A9-1. **Edwards-Trinity (Plateau) Aquifer extent and adjacent aquifers in Mexico.**

Geologic Conditions

The Acuífero Cerro Colorado-La Partida, Acuífero Presa La Amistad, and Acuífero Palestina consist of marine and continental rock units ranging from Lower Cretaceous to Recent. These units consist of limestone, sandstone, shale, and conglomerate. Paleogene and Neogene igneous rocks also exist within the area. Farther away from the Rio Grande toward the southwest lie the highlands that comprise the Sierra del Burro. This area consists of generally massive carbonate rocks of Lower to mid-Cretaceous age. The middle and northern sections of the aquifers consist of gently-sloping hills where Cretaceous limestone and clay sequences are mapped. Recent deposits of poorly consolidated alluvial materials are adjacent to the low-lying areas along the Rio Grande.

The Acuífero Santa Fe del Pino and Acuífero Serranía del Burro consist of marine and continental rock units of Lower Cretaceous to Recent age. These units consist of limestone, sandstone, shale, and conglomerate. Intrusive and extrusive Paleogene and Neogene igneous rocks also occur within the aquifer areas.

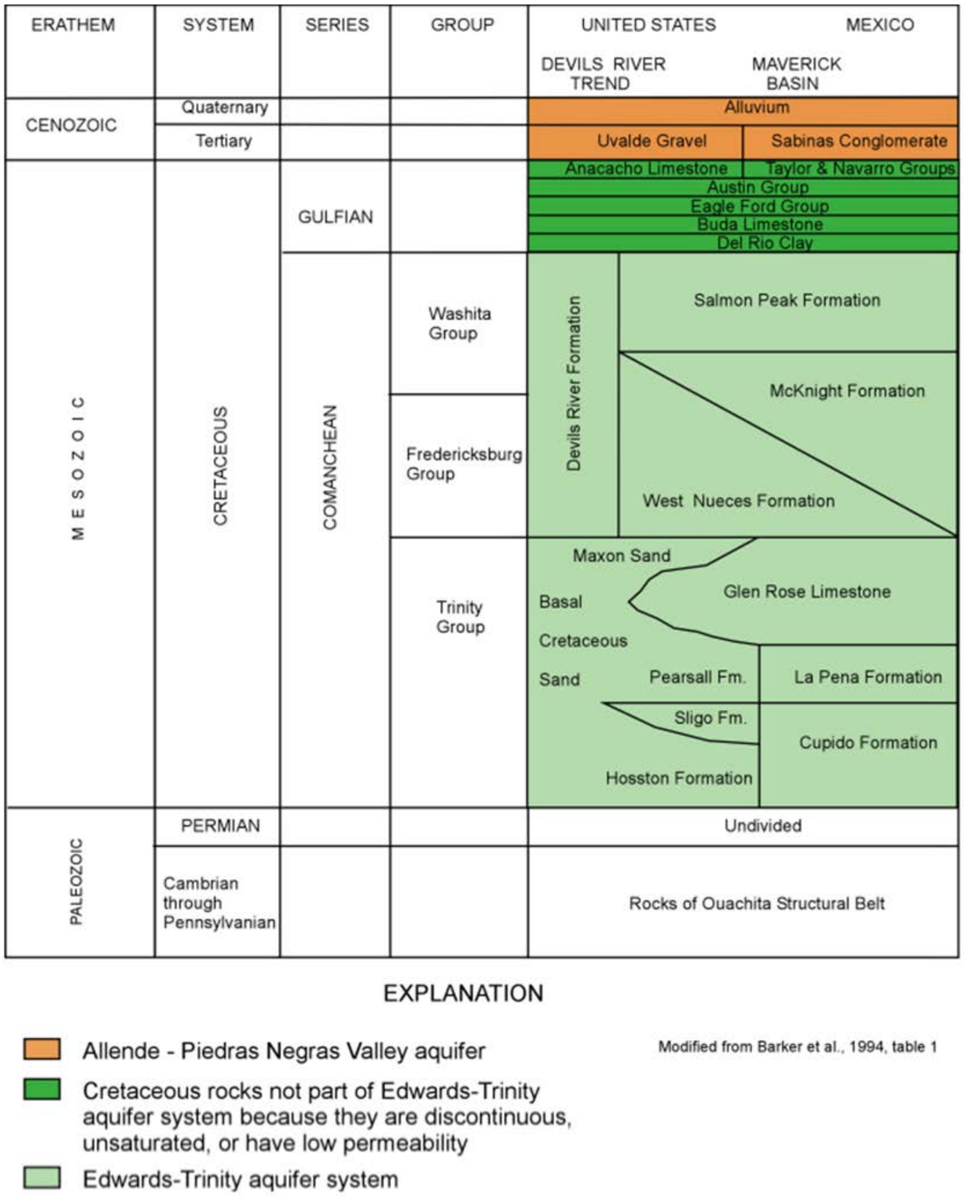

Figure A9-2. Stratigraphic column showing Edwards–Trinity Aquifer System geologic and hydrogeologic units in Texas and Coahuila, Mexico (from Barker and others, 1994).

Most of the Cretaceous geological formations mapped in Texas have also been identified in Coahuila, Mexico. Listed from youngest to oldest are the Cupido Formation (limestone and dolomite), La Peña Formation (fine-grained carbonate), Aurora Formation (medium to massive gray carbonate with pyrite and iron nodules), Santa Elena Formation (fine-grained carbonate, outcropping in massive 500 feet thick strata), Loma de Plata Formation (fine-grained carbonate equivalent to the Georgetown Formation in Texas), Boquillas Formation (thin, alternating dark-colored carbonate and clay), Del Rio Clay (dark-colored, fossiliferous clay thickening to almost 700 feet towards the south), Buda Formation (grey, medium-grained carbonate), Eagle Ford Formation (thin, fine-grained sediments alternating with clayey), Austin Formation (light gray carbonate), and Upson Formation (limestone alternating with fine-grained sediment).

The Neogene Sabinas Conglomerate is poorly cemented and is the product of erosion, transport, and sedimentation of material from the highlands in Acuífero Santa Fe del Pino. The conglomerates consist of carbonate fragments 2 to 40 inches in size. The Sabinas Conglomerate is up to 100 feet in thickness.

Igneous rocks are common throughout the Acuífero Santa Fe del Pino and Acuífero Serranía del Burro. Igneous intrusive rocks such as diorite, granite, and syenite pierce the Cretaceous sequences in Serranía del Burro. Paleogene and Neogene extrusive rock such as rhyolite and tuff are also present in the Sierra El Carmen Mountains. In addition, Quaternary alluvium, consisting of conglomerate and sand, covers the low-lying areas near the Rio Grande River.

Groundwater conditions

Potentiometric and geochemical data, as well as hydraulic properties, for the Acuífero Cerro Colorado-La Partida, Acuífero Presa La Amistad, and Acuífero Palestina, were not available from published sources at the time of this writing. The combined estimated recharge for these three aquifers is approximately 31,942 acre-feet per year. The combined estimated discharge from the aquifers, including springflow, baseflow to surface streams, and pumping, is 12,160 acre-feet per year.

The upper part of Acuífero Santa Fe del Pino and Acuífero Serranía del Burro is the main groundwater-producing interval, which is under unconfined conditions and exhibits heterogeneous and anisotropic characteristics. It consists of poorly consolidated alluvial sediments of varying particle sizes, which yields water primarily to springs. Springs provide sufficient water to local communities for their domestic use, which keeps aquifer usage low. The underlying carbonate rocks are potential groundwater sources that have yet to be explored.

Aquifer tests in the Acuífero Santa Fe del Pino indicate transmissivities from 9.3 up to 21,000 feet squared per day. The estimated range of transmissivity for the Acuífero Serranía del Burro, based on aquifer tests in the neighboring Acuífero Allende-Piedras Negras, is approximately 280 to 1,900 feet squared per day.

Water quality for the Acuífero Santa Fe del Pino and Acuífero Serranía del Burro show total dissolved solids concentrations for these aquifers ranging from 220 to 4,830 parts per million, with the brackish water occurring only in the Acuífero Santa Fe del Pino. The higher salinity waters are dominated by sulfate, calcium, and sodium, whereas the fresher groundwater is mainly bicarbonate mixed with other cations.

The combined estimated recharge for these two aquifers is 24,456 acre-feet per year. The combined estimated discharge from the aquifers, including springflow, baseflow to surface streams, and pumping, total 1,702 acre-feet per year.

Based on previous studies (Boghici, 2002; Figure A9-3), the hydraulic flow toward the Rio Grande and the groundwater flow is generally from the highlands in Coahuila toward Amistad Reservoir and the Rio Grande. The uplands of Serranía del Burro show a hydraulic gradient of 0.016. Just south of Amistad Reservoir, the hydraulic gradient flattens to approximately 1×10^{-4}. The gradient becomes steeper (0.003) near Del Rio-Ciudad Acuña.

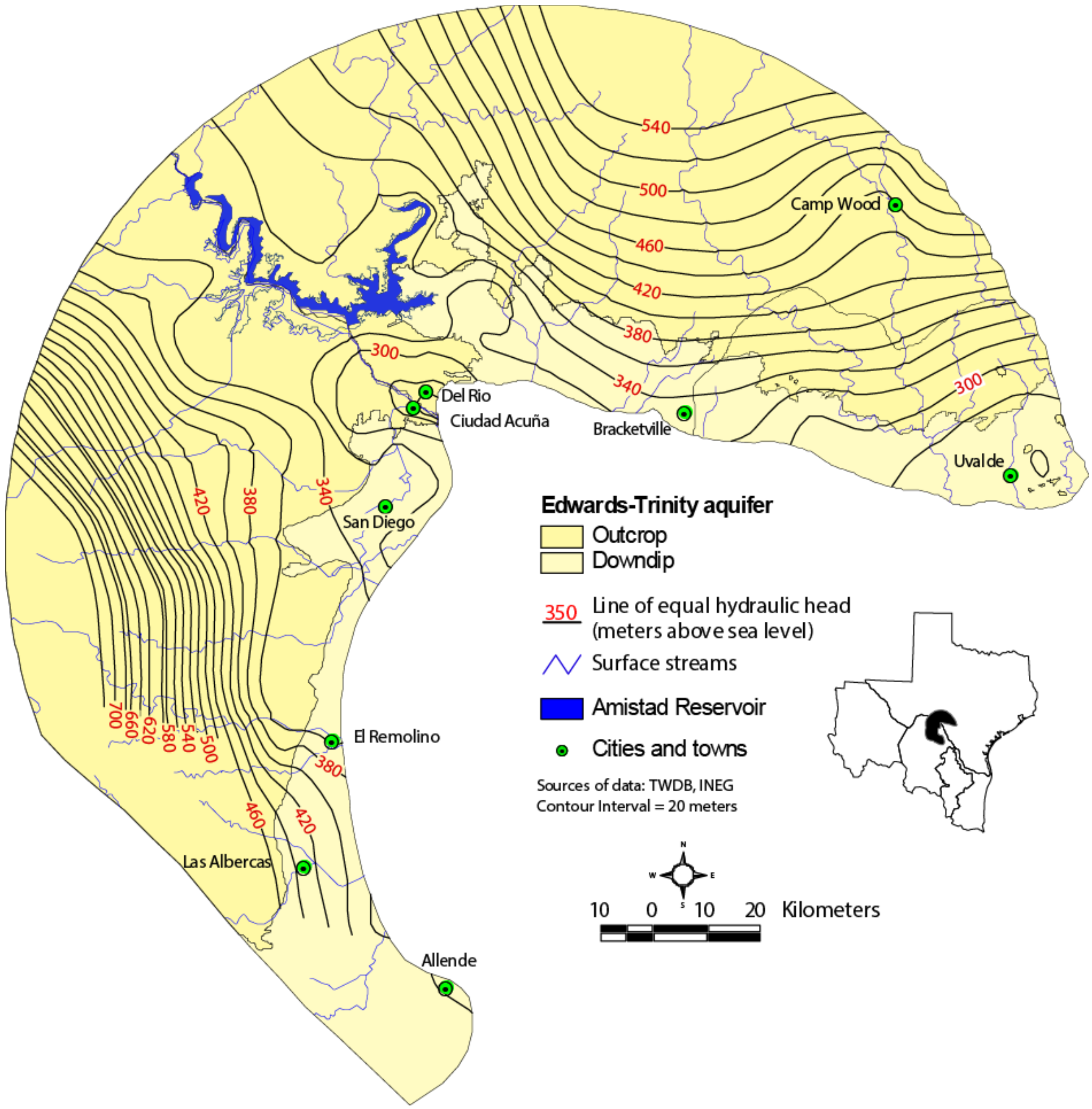

Figure A9-3. Edwards–Trinity Aquifer potentiometric surface map from data for 1980–1981 (modified from Boghici, 2002).

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A10 - Gulf Coast Aquifer (Texas/Louisiana)

In Louisiana, the Miocene, Evangeline, and Chicot/Terraces aquifer systems are equivalent to the Gulf Coast Aquifer in Texas (Figure A10-1).

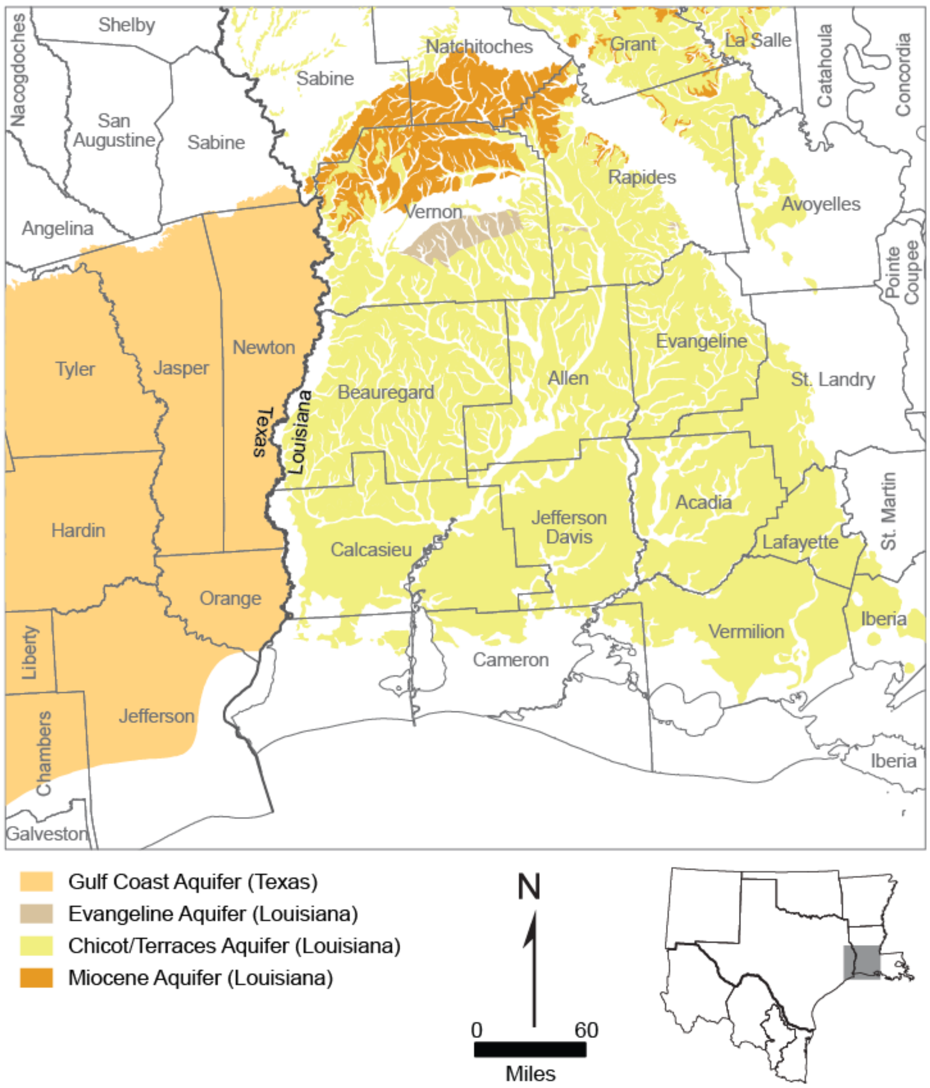

Figure A10-1. Gulf Coast Aquifer extent in Louisiana (from Louisiana Department of Environmental Quality, 2006; Lovelace and others, 2002 and 2004; and Martin and Whiteman, 1984 and 1985).

Geologic Conditions

The Miocene Aquifer System includes several geologic units. The Catahoula Aquifer, which is defined by the Catahoula Formation (Figure A10-2), occurs at the base of the Miocene Aquifer System. The Oligocene- and Miocene-age Catahoula Formation consists of alternating and interfingering layers of sand, silt, and clay deposited under mainly non-marine conditions. As in

Texas, many Catahoula beds are tuffaceous. Downdip Catahoula sediments were deposited in marine deltaic, littoral, and near-shore environments. Sands of the Catahoula Formation are discontinuous, lenticular, and interbedded with silt and clay. The formation overlies marine clay and silt of the Vicksburg and Jackson groups. The formation is overlain by calcareous clays of the Lena Member of the Fleming Formation downdip from the outcrop area. Regional dip is to the south and southeast at about 50 to 100 feet per mile, increasing with depth.

In addition to the Catahoula Aquifer, the Miocene Aquifer System includes the Williamson Creek, Dough Hills, Carnahan Bayou, and Lena members of the Fleming Formation (Figure A10-2). Collectively, the first three members are called the Jasper Aquifer. Aquifer sands are primarily within the Williamson Creek and Carnahan Bayou members. The Williamson Creek consists of sands, silts, silty clays, and some gravel. The Carnahan Bayou consists of sands, silts, and clays with some gravel.

The Evangeline Aquifer of Louisiana is equivalent to the Blounts Creek Member of the Fleming Formation and is mainly Pliocene in age (Figures A10-2 and A10-3). The Blounts Creek Member consists of gray to green silty clay, siltstone, and silt with abundant sand beds, and some lignite and lenses of black chert gravel. The sands of the aquifer are moderately well to well sorted and fine to medium grained with interbedded coarse sand, silt, and clay. Downdip from the exposures of the Blounts Creek Member, the aquifer thickens and includes Pliocene sand beds that do not outcrop. The confining clay of the Castor Creek member impedes the movement of water between the Evangeline and the underlying Miocene aquifer systems. The Evangeline is separated in most areas from the overlying Chicot Aquifer by clay beds. In some areas, the clays are missing and the upper sands of the Evangeline are in direct contact with the lower sands and gravels of the Chicot. In Texas alluvial systems consisting of terrace gravels, sand deposits and point bar sediments that are correlated to the Chicot/Terraces Aquifer in Louisiana are local in nature and are lumped in with the Gulf Coast Aquifer definition (Chowdhury and Turco, 2006).

System	Series	Stratigraphic unit		Hydrogeologic unit Central Louisiana		Southwestern Louisiana Lake Charles area	Southwestern Louisiana rice growing area
Quaternary	Pleistocene	Red River alluvial deposits Mississippi River alluvial deposits Northern Louisiana terrace deposits Unnamed Pleistocene deposits		Alluvial aquifer, undifferentiated or surficial confining unit Prairie Aquifer Montgomery Aquifer Williana-Bentley Aquifer	Chicot Aquifer system or surficial confining unit	"200-foot" sand	Upper sand unit
						"500-foot" sand “700-foot” sand	Lower sand unit
Tertiary	Pliocene ?	Fleming Formation	Blounts Creek Member	Evangeline Aquifer or surficial confining unit			
	Miocene	Fleming Formation	Castor Creek Member	Castor Creek confining unit			
		Fleming Formation	Williamson Creek Member Dough Hills Member Carnahan Bayou Member	Jasper Aquifer system or surficial confining unit	Williamson Creek Aquifer Dough Hills confining unit Carnahan Bayou Aquifer		
		Fleming Formation	Lena Member	Lena confining unit			
	? Oligocene	Catahoula Formation		Catahoula Aquifer			

Figure A10-2. Gulf Coast Aquifer stratigraphy in Louisiana (modified from Johnston and others, 2000).

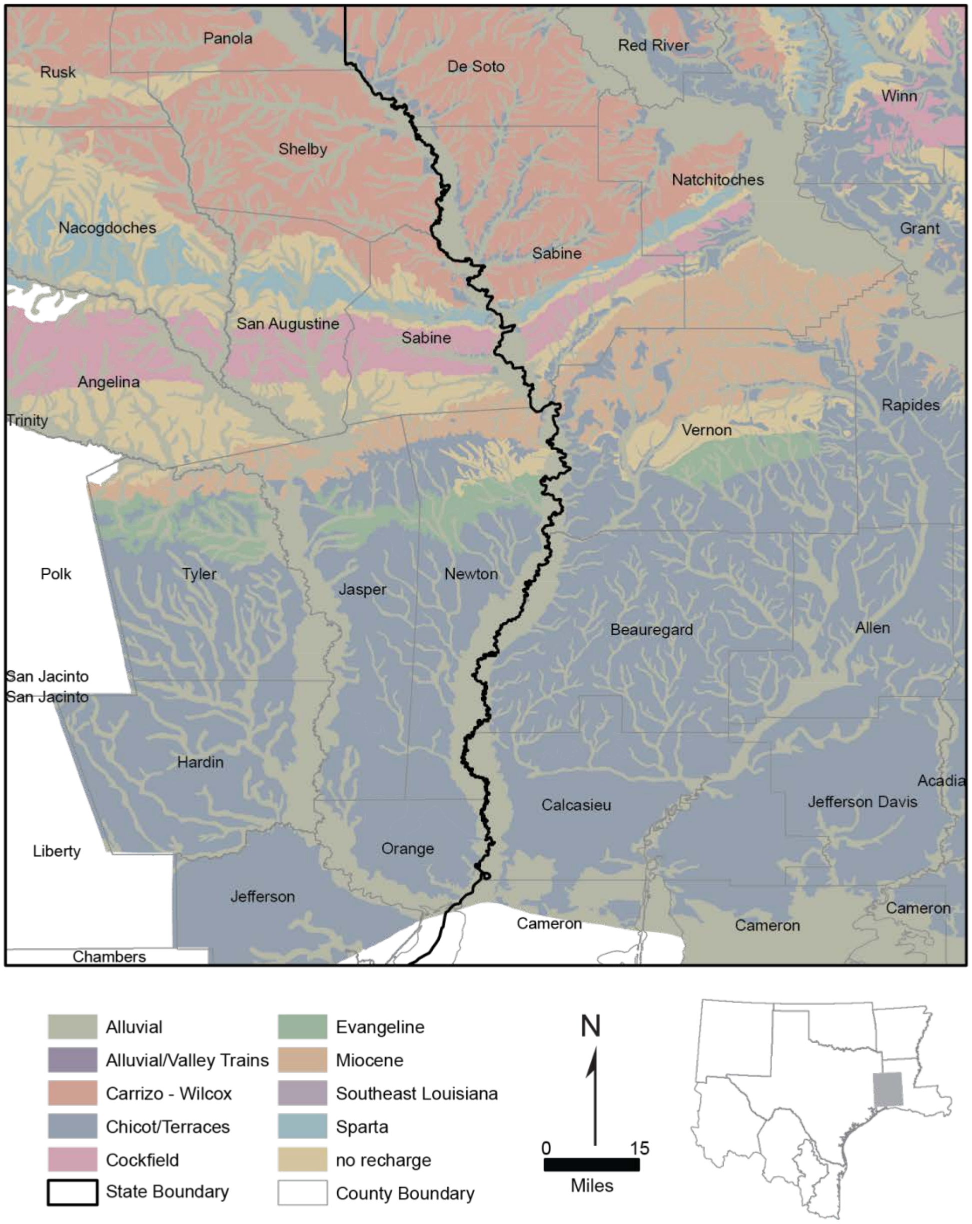

Figure A10-3. Geologic unit equivalents in western Louisiana and eastern Texas.

Groundwater Conditions

The Catahoula Aquifer is recharged by the direct infiltration of rainfall in interstream, upland outcrop areas; movement of water through overlying terrace deposits; and leakage from other aquifers. The hydraulic conductivity of the Catahoula varies between 20 and 260 feet per day (Louisiana Department of Environmental Quality, 2006a). Flow in the Catahoula is generally toward the south and southeast, with localized flow towards draining streams that flow to the

Gulf of Mexico Basin. Discharge occurs along streams; springs and seeps are common where Catahoula sands are cut by streams draining upland areas. Groundwater that flows southward between stream valleys is discharged by leakage upwards through the Lena Member to younger overlying sediments.

The maximum depths of occurrence of freshwater in the Catahoula range from 250 feet above sea level to 2,200 feet below sea level. The range of thickness of the fresh water interval in the Catahoula is 50 to 450 feet. Water from the Catahoula Aquifer is used for municipal, industrial, and domestic purposes. In 1980, over 1.1 million gallons per day were pumped from the aquifer.

Recharge to the Evangeline Aquifer occurs by infiltration of rainfall in interstream, upland outcrop areas; the flow of water through overlying terrace deposits; and leakage from other aquifers. The hydraulic conductivity of the Evangeline varies between 20 and 100 feet per day. The maximum depths of occurrence of freshwater in the Evangeline range from 150 feet above sea level to 2,250 feet below sea level. The range of thickness of the fresh water interval in the Evangeline is 50 to 1,900 feet. Regional flow of groundwater in the Evangeline Aquifer is primarily to the south at gradients 6 to 8 feet per mile. Discharge occurs to flowing streams or to younger overlying sediments located at lower elevations, such as in the Louisiana coastal plain or the Mississippi River Valley.

The Evangeline Aquifer is heavily pumped in certain areas of Louisiana, such as near Baton Rouge, causing definable cones of depression. Heavy pumping in the overlying Chicot Aquifer also affects the Evangeline Aquifer, suggesting that the two are relatively well connected hydraulically. The Chicot Aquifer extends across 9,000 square miles in southwestern Louisiana where it is the main source of groundwater in the region. In 2000 about 800 million gallons of water per day were withdrawn from the aquifer, and some 540 million gallons per day of that were used for rice irrigation. Rice irrigation has resulted in an elongated cone of depression in the potentiometric surface over much of the region.

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A11 - Gulf Coast Aquifer (Texas/Mexico)

The aquifer in Mexico across the border from the Gulf Coast Aquifer is designated the Acuífero Bajo Rio Bravo. This aquifer is in northeast Mexico and comprises the northern part of the state of Tamaulipas and a small part of the state of Nuevo León, covering an area of approximately 6,750 square miles (Figure A11-1).

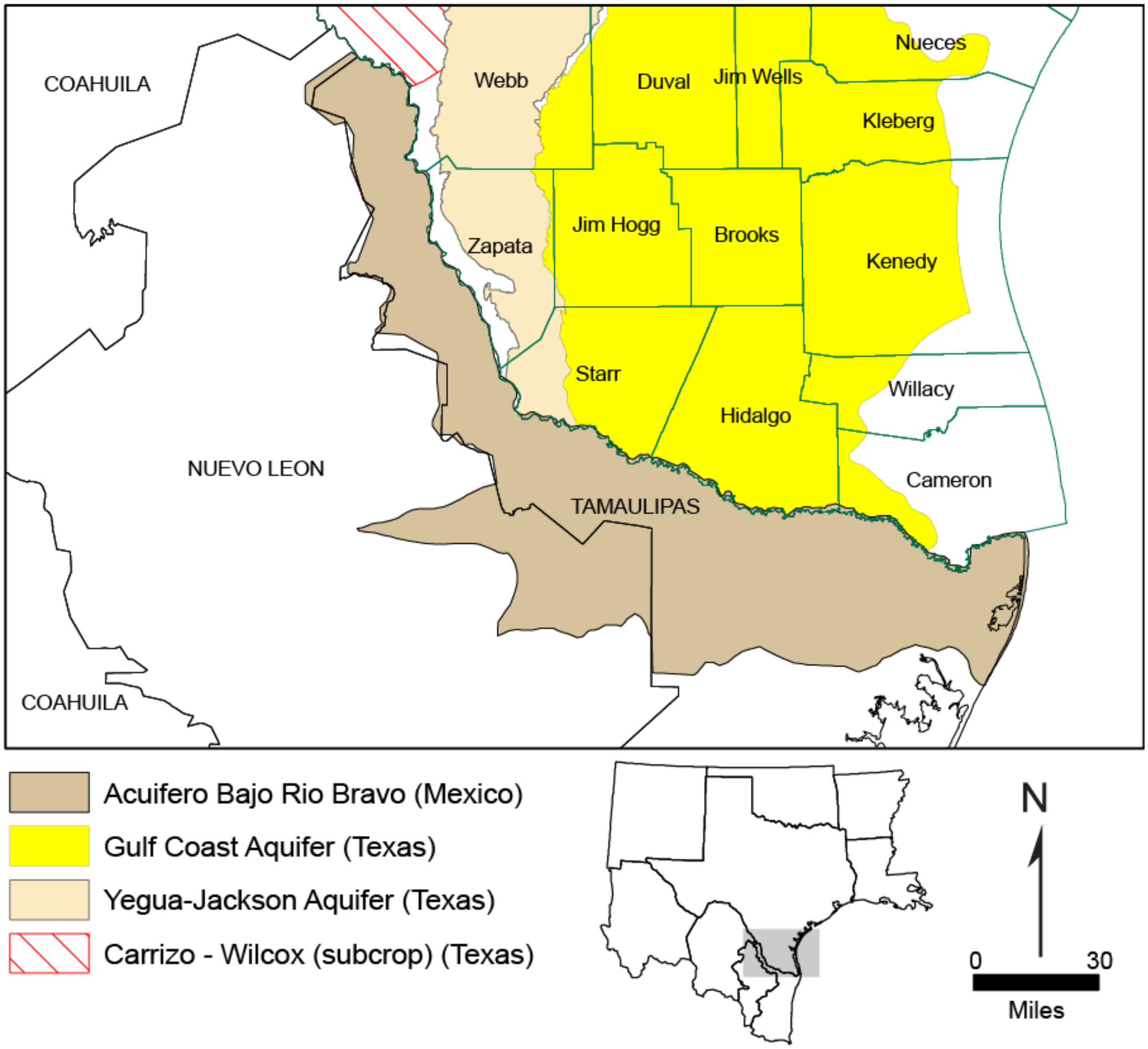

Figure A11-1. Acuífero Bajo Rio Bravo and adjacent aquifers in Texas.

Equivalent units in the Texas Gulf Coast Aquifer System consist of the upper Oligocene to Holocene Anahuac, Catahoula, Oakville, Lagarto, Goliad (Reynosa), Lissie, Willis, and Beaumont formations (Figures A11-2 and A11-3). These geologic units consist of complex stratified layers and lenses of clay, silt, sand, and gravel in floodplain and deltaic depositional systems. The lithologic units are both laterally and vertically discontinuous over short distances. Primary groundwater resources occur in alluvial and fluvial deposits of the Rio Grande and in old abandoned channels of the river. Other sources of groundwater are in sandy portions of the Paleogene and Neogene formations. These geologic units have been traditionally considered as a single aquifer that includes Paleogene and Neogene-age deposits as well as all materials associated with the Rio Grande, although there are some recognized productivity and water quality differences within the aquifer system attributable to local conditions.

System	Series		Bajo Rio Bravo stratigraphic units	CONAGUA hydrogeological units (2006)	Texas stratigraphic units		Hydrogeologic units common in Texas	
Quaternary	Holocene		alluvium	Units IV-VII	alluvium		Chicot aquifer	
	Pleistocene		Beaumont Formation	Unit III	Beaumont Formation			
			Lissie Formation	Unit II	Montgomery Formation			
					Bentley Formation			
					Willis Sand			
Tertiary	Neogene	Pliocene	Reynosa Conglomerate (Goliad Sand)		Goliad Sand		Evangeline aquifer	
		Miocene	Lagarto Formation	Unit I	Fleming Formation		Burkeville confining unit	
			Oakville Formation		Oakville Sandstone			Jasper aquifer
					Catahoula Sandstone or Tuff	Anahuac Formation	Catahoula confining unit (restricted)	
	Paleogene	Oligocene	Catahoula Formation			Frio Formation		
			Anahuac Formation					
			Norma Conglomerate					
			Frio Formation		Frio Clay	Vicksburg Formation	Vicksburg-Jackson confining unit	
			Vicksburg Formation					
		Eocene	Jackson Group		Jackson Group			

Figure A11-2. **Texas Tertiary and Quaternary sediments and Acuífero Bajo Rio Bravo in Mexico (Baker, 1979; Hosman and Weiss, 1991; and Comisión Nacional del Agua, 2009).**

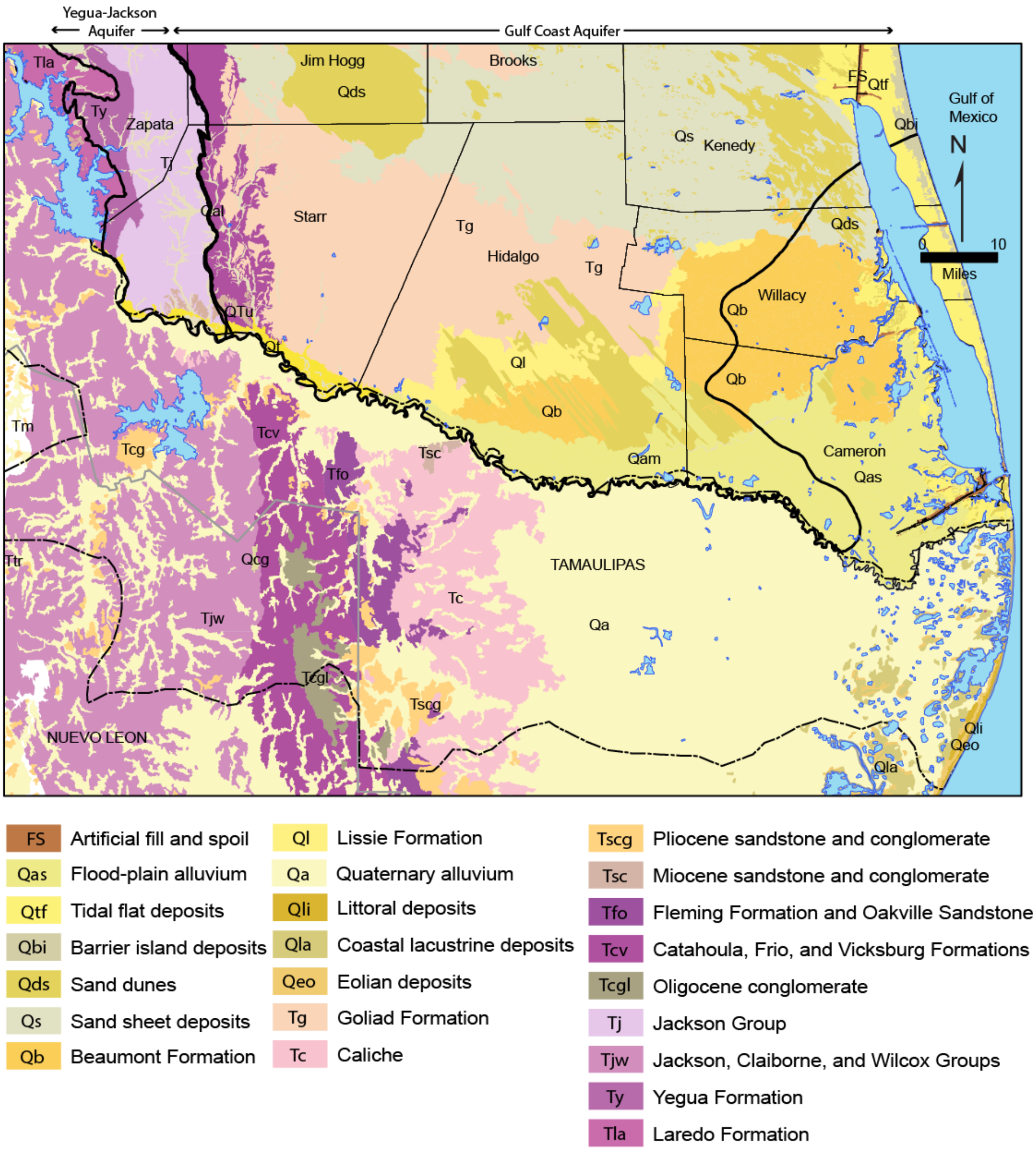

Figure A11-3. Texas Gulf Coast and Tamaulipas, Mexico geologic units(modified from Page and others, 2005).

Groundwater conditions

The Comisión Nacional del Agua (2008) delineated seven hydrogeological units (Units I to VII) based on aquifer properties and on chemical characteristics of the groundwater.

Unit 1 consists of Miocene and older units, including the Lagarto, Oakville, Catahoula, Anahuac, Conglomerado Norma, Frio, and Vicksburg formations (Figure A11-2). South of the Rio Grande, Unit I has poor to very poor aquifer production and poor quality groundwater.

Unit II consists of the Pliocene Goliad and Pleistocene Lissie formations in northern Mexico. This unit is a moderately good aquifer with good to fair water quality. The Goliad and Lissie formations are also associated with the Reynosa Conglomerate found in northern Mexico. The Goliad Formation consists of gravels, sands, and clays with some occurrences of gypsum. The Lissie Formation is comprised of sands and clays deposited in a deltaic environment. These formations are in the east-central Acuífero Bajo Rio Bravo, dip to the east, and are approximately 900 feet below land surface in the southeast Acuífero Bajo Rio Bravo.

Unit III is equivalent to the Beaumont Formation and is composed of layers of clay interspersed with lenticular sands. The Beaumont Formation in this area can be either a confining unit or low-potential-aquifer with poor quality groundwater. It is in the eastern portion of the Acuífero Baja Río Bravo.

Unit IV is formed by sediments that accumulated in old channels of the Rio Grande (Rio Bravo) along the eastern portion of the area. It is a thin, medium- to low-potential aquifer containing poor quality groundwater.

Unit V consists of the Rio Grande Holocene alluvium, which exhibits a medium production potential with good quality groundwater. This unit is exposed mainly in the area between Reynosa and Matamoros, where its thickness varies from approximately 49 feet to 656 feet.

Unit VI consists of thin alluvial sediments located in the south-central and southeastern parts of the area. This unit shows very low to low production potential with water quality ranging from poor to normal.

Unit VII is a confining unit with groundwater of poor to very poor chemical quality occurring in the coastal sediments in the far eastern Acuífero Baja Río Bravo.

The most important hydrogeologic units with respect to potential groundwater development are Units II and V, based on the quantity and quality of the groundwater. These units contain the two principal aquifer systems in the Acuífero Baja Río Bravo. The first is called Aquífero Sur de Reynosa and the second Acuífero Reynosa-Matamoros. Hydrogeologic Unit III (Beaumont Formation) is an aquitard that separates these two aquifer systems. Only the sandiest sections of the Beaumont Formation can form low-producing aquifers yielding high-salinity groundwater.

The permeable zones in Acuífero Reynosa-Matamoros are connected hydraulically at depth with the adjacent permeable units from west to east: the Goliad Sand, the Lissie Formation, and the Beaumont Formation. The alluvial sediment along Río Bravo has a variable thickness, estimated to be 49 feet near the city of Camargo, 82 feet to 98 feet at Reynosa, and 246 feet to 295 feet between Matamoros and Río Bravo. The Aquífero Sur de Reynosa, comprised of the Goliad Sand and Lissie Formation, is overlain by the Beaumont Formation and overlies the Lagarto

Formation. The aquifer is recharged by precipitation falling on the aquifer outcrop west of Reynosa.

The groundwater-producing zones alternate with clay rich, less permeable units that behave as a semi-confined aquifer. There is little to no lateral hydraulic connection between these aquifers as shown by the differences in salinity between adjacent units. Likewise, it has been observed that groundwater salinity tends to increase away from the outcrop. South of Reynosa, the total dissolved solids concentrations usually exceed 1,000 milligrams per liter; however, in areas close to the outcrop, salinity is lower, ranging from 800 to 1,000 milligrams per liter. Localized areas away from the outcrop, or sites with deep groundwater production, have salinities ranging from 3,000 to 5,000 milligrams per liter (Comisión Nacional del Agua, 2009a).

Based on tests done in 2006, the transmissivity values range from 3.23×10^{-2} to 1.84×10^{-1} feet squared per second and the hydraulic conductivity values range from 0.56 to 39 feet per day. Storage coefficient values range from 1.3×10^{-5} to 1.0×10^{-3}.

In Acuífero Reynosa-Matamoros, groundwater is shallow with the maximum (26 feet) static levels recorded near the Río Bravo channel (Figure A11-4). The shallower levels (up to 13 feet) were recorded southeast of Nuevo Progreso, while depths to groundwater of 16 feet to 20 feet were observed inside Bajo Río Bravo Irrigation District. In Acuífero Sur de Reynosa, groundwater levels varied between 49 feet and 164 feet below land surface. Static levels were deeper on the western side, and on the south side depths to groundwater ranged from 72 feet to 82 feet.

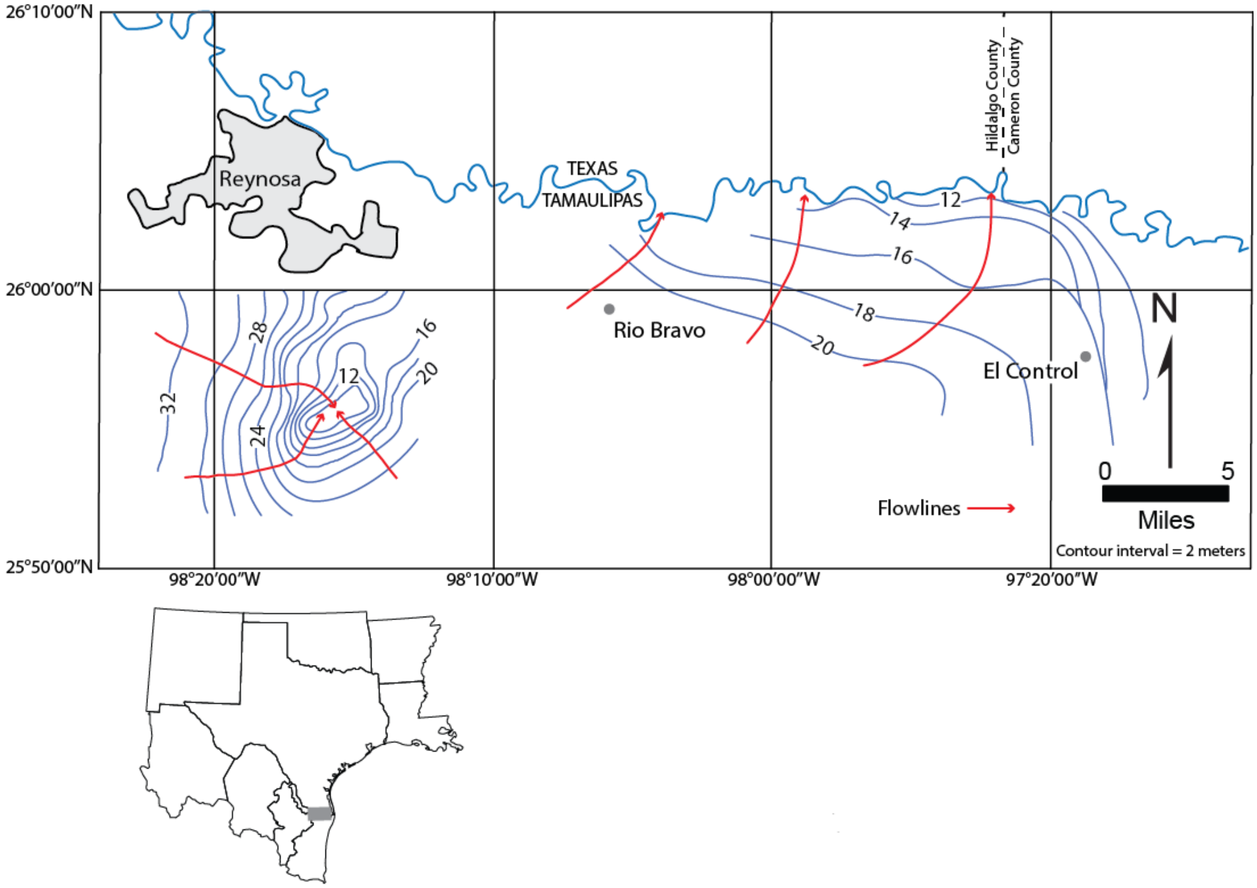

Figure A11-4. **Potentiometric surface and flowlines near Reynosa, Tamaulipas in 2006 (modified from Comisión Nacional del Agua, 2006).**

Groundwater flow in the Acuífero Reynosa-Matamoros is from the south-southwest toward the northeast, following the local topography. In Acuífero Sur de Reynosa, the groundwater flow is from west to east. Static water level elevations range from 197 feet above mean sea level in the Los Realitos region to less than 66 feet above mean sea level in the irrigated areas. There are two areas of water-level declines (one east of the town of Río Bravo, and the other south of where the Cameron/Hidalgo county lines intersect the Rio Grande) where water levels have dropped by about 16 feet between 1982 and 2006. During the same period, static levels in the Acuífero Sur de Reynosa have declined predominantly in the northeast, where groundwater is being drawn from aquifer storage. Significant groundwater withdrawals also have occurred in the central-southeastern portion of the aquifer. Some water level recovery was observed in the southwest and southeast portions of the Acuífero Sur de Reynosa.

Recharge for the aquifer is estimated to be approximately 160,000 acre-feet per year and discharge from springflow, baseflow, and pumpage is approximately 47,000 acre-feet per year.

Groundwater quality in Acuífero Bajo Río Bravo ranges from 600 milligrams per liter to more than 11,000 milligrams per liter, with a good part of the aquifer having high salinity. The ions contributing to the high total dissolved solids concentrations are mainly sodium and chloride. The best quality groundwater is found along the Rio Grande, with a gradual deterioration of groundwater quality away from the river. Saline groundwater is generally found at or below about 500 feet deep; however, some shallower groundwater has increased salinity due to irrigation return flows.

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A12 - Hueco-Mesilla Bolsons Aquifer (Texas/New Mexico/Mexico)

In Texas, the Hueco and Mesilla bolsons have similar geology, but available data suggest that these aquifers are not hydrologically connected. At the El Paso Narrows along the Rio Grande, bedrock impedes much of the groundwater from exiting the Mesilla valley and connecting to the Hueco Bolson. The Mesilla Basin Aquifer System extends into Doña Ana County, New Mexico and south into Chihuahua, Mexico, where it is within part of the Conejos-Medanos Aquifer. The Hueco Bolson extends north of the state line where it blends into the adjacent and hydrologically connected Tularosa Basin. Because the two basins are hydraulically connected, they can be referred to as the Hueco-Tularosa Aquifer (Figure A12-1).

Geologic Conditions

The Hueco and Mesilla bolsons are composed of basin-fill deposits of silt, sand, gravel, and clay that were deposited within the basins. The Hueco Bolson has a maximum thickness of 9,000 feet, and the Mesilla Bolson has a maximum thickness of over 2,000 feet (Figure A12-2). The entire Hueco Bolson extends over 1,700 square miles and the entire Mesilla Basin covers approximately 1,100 square miles.

Groundwater occurs within the Mesilla Basin in Late Pleistocene to Holocene Rio Grande alluvium deposits and the upper Neogene and Quaternary Santa Fe Group. The Santa Fe Group is the major source of fresh water and consists of alternating layers of fine- to coarse-grained sand, silty clay, and gravel. Due to its heterogeneity, the hydrological characteristics of the Santa Fe Group vary throughout its extent. The Santa Fe Group can be divided into upper, middle, and lower hydrostratigraphic units. The upper unit consists of gravel and lenticular clay deposits and is, in general, saturated only in the northern third of the basin. The middle hydrostratigraphic unit is also composed of gravel and lenticular clay deposits but is less permeable than the upper unit due to more cementation.

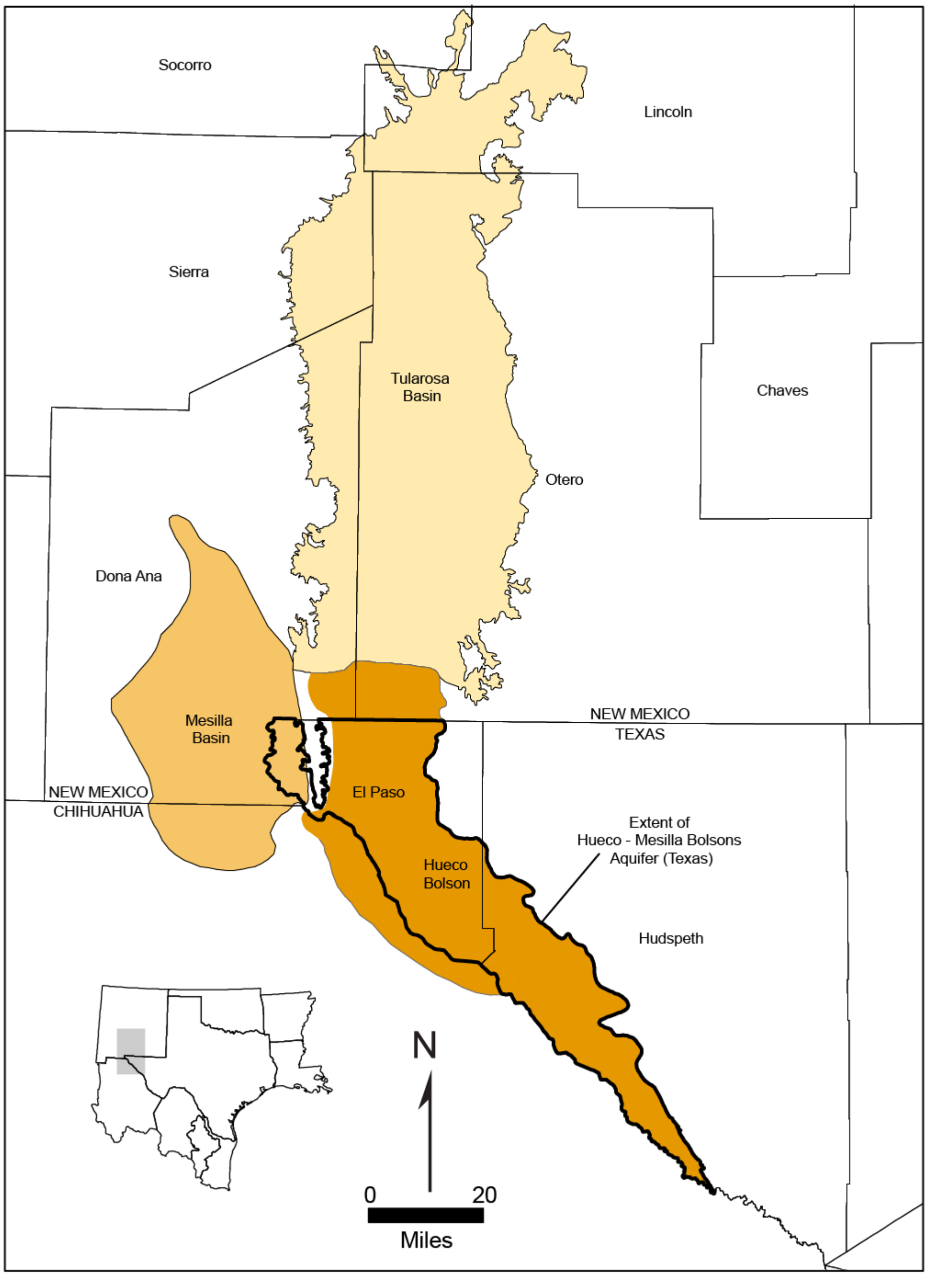

Figure A12-1. **Extents of the Hueco Bolson, Mesilla Basin, and Tularosa Basin in Texas, New Mexico, and Mexico (New Mexico Water Resources Research Institute, 2007a, 2007b, 2007c).**

Note: The Hueco-Mesilla Bolsons Aquifer as delineated in Texas consists of the Hueco Bolson and the Mesilla Bolson, which are located to the east and west of the Franklin Mountains, respectively. These two bolsons extend into New Mexico and Mexico as continuous but separate aquifer systems.

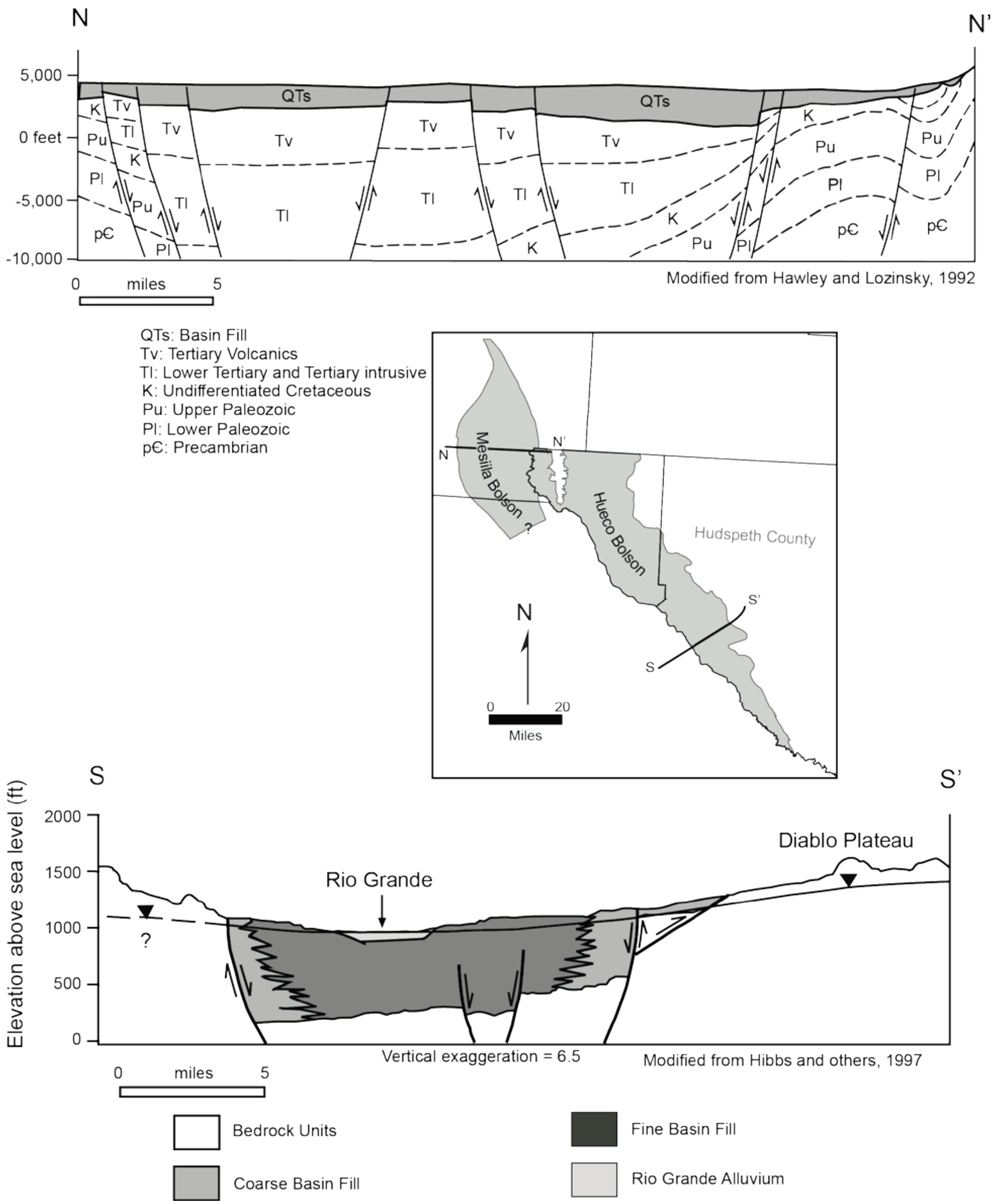

Figure A12-2. Mesilla Bolson (N–N') and Hueco Bolson (S–S') cross-sections (modified from Hibbs and others, 1997, and Hawley and Lozinski, 1992).

The lower unit is a layer of uniformly fine sand averaging about 600 feet in thickness. As a whole, the basin fill deposits are thickest along Mesilla Valley and generally thin toward the edges of the basin. This lower unit rests on largely impervious limestone and conglomerate bedrock units.

The Hueco Bolson Aquifer is composed of Paleogene, Neogene, and Quaternary age gravel and fine- to medium-grained sand that is interbedded with lenses of clay, silt, gravel, and caliche. The bottom of the aquifer is primarily silt and clay. Precambrian igneous rocks and Paleozoic and Mesozoic age sedimentary units underlie and surround the Hueco Bolson. Most of the groundwater in the bolson is withdrawn from the Camp Rice Formation consisting of moderately sorted stream channel and floodplain deposits. The formation is thickest along the Franklin and Organ mountains, thinning and fining toward the east. Figure A12-3 shows the thickness of alluvial deposits in the Hueco Bolson in meters, modified from Heywood and Yager (2003). The percentage of clay throughout the basin generally increases with depth.

The Hueco Bolson in Texas is adjacent to two administrative aquifer areas in Mexico, the Acuífero Valle De Juarez and the northern tip of the Acuífero Valle Del Peso (Figure A12-4). The bolson deposits supply the urban centers of Ciudad Juárez, Chihuahua, and El Paso, Texas.

Geologically, the Acuífero Valle De Juarez consists of a sequence of semi-consolidated and unconsolidated deposits from the upper Neogene to Quaternary period, comprised of conglomerate, silt, and sand, with lacustrine and eolian deposits. The upper unit consists of alluvial fan and floodplain deposits.

A bedrock section consists of fractured units with karstified sedimentary and igneous rocks that function as conduits, allowing infiltration through faults and fractures to lower units. A variable thickness clay layer in the southern part of the Acuífero Valle De Juarez along the Rio Grande flood plain creates confined conditions in the lower units.

Groundwater Conditions

The most productive unit of the Santa Fe Group is the fluvial facies consisting of well sorted sand and gravel deposits. This part of the aquifer varies in depth from 280 feet in the northern part of the bolson to over 2,000 feet near the center of the bolson.

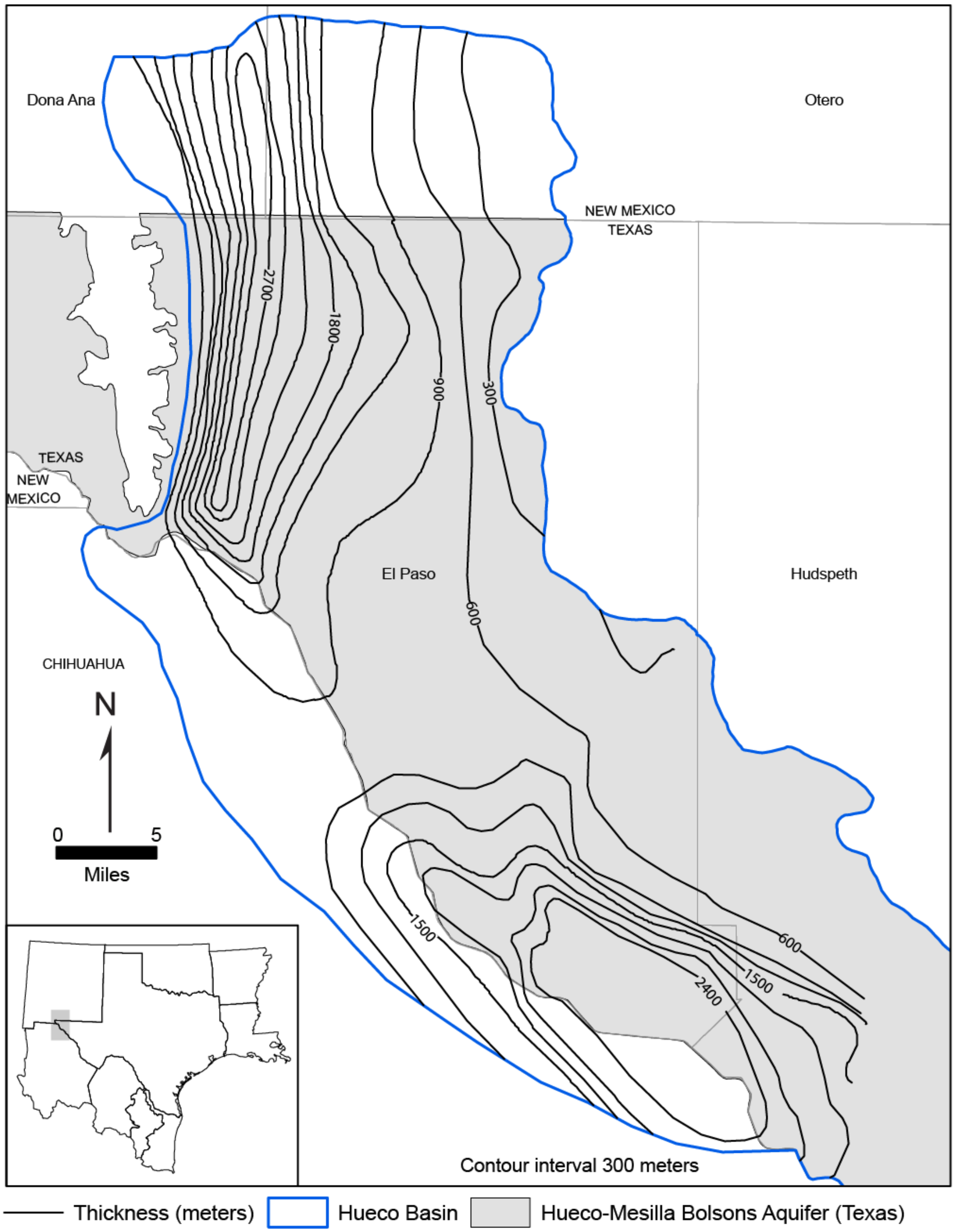

Figure A12-3. Thickness of alluvial deposits in the Hueco Bolson (modified from Heywood and Yager, 2003).

The hydrologic extent of the Mesilla Bolson is bounded by faults surrounding the bolson, which restrict groundwater flow. The Santa Fe Group has thick sequences of clay and silt facies that interfinger with fluvial deposits creating confining and leaky aquifer conditions within the basin fill. The transmissivity of the Mesilla Bolson ranges from 700 to 40,000 square feet per day, and hydraulic conductivity ranges from 1 to 100 feet per day. Because there are semi-confined to confined conditions within the aquifer, the storage coefficient ranges from 0.00002 to 0.001 (Hibbs and others, 1997).

Most of the recharge to the Santa Fe Group occurs through mountain front recharge and vertical flow of groundwater from the floodplain alluvium in the Mesilla Valley region. Cones of depression have formed in the aquifer, which also influence recharge movement.

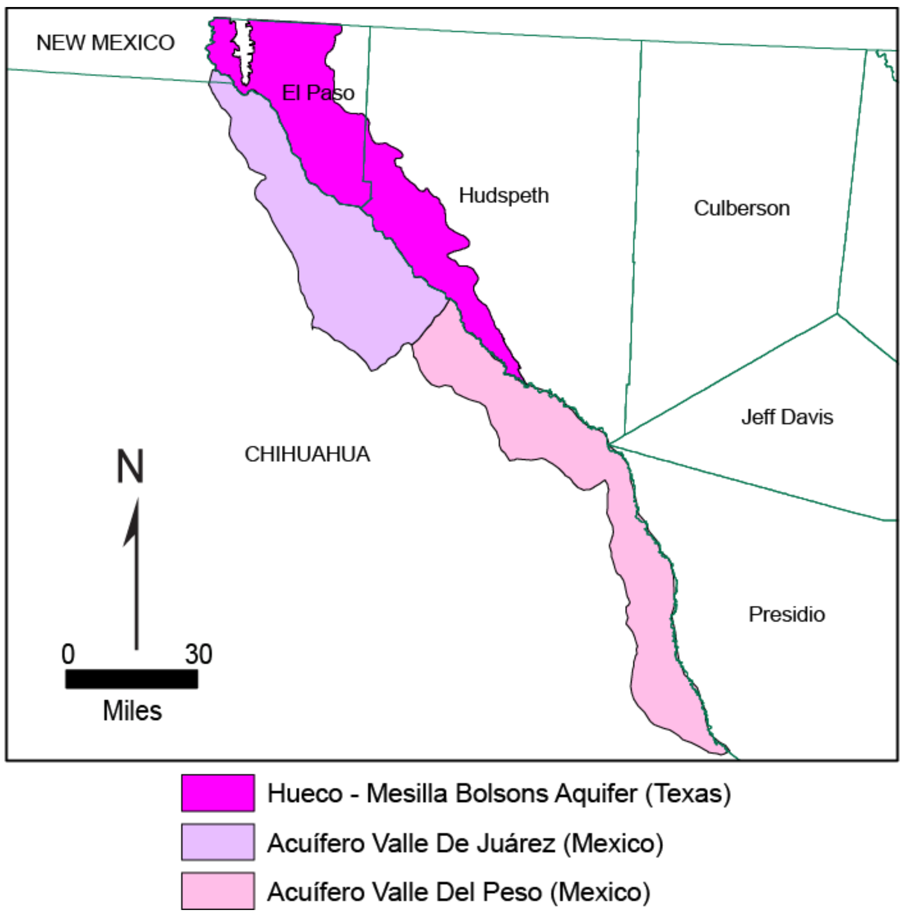

Figure A12-4. Hueco-Mesilla Bolsons, Acuíferos Valle De Juárez and Valle Del Peso in Mexico.

Transmissivity values in the Acuífero Valle de Juarez range from 775 to 15,580 feet squared per day. Transmissivities are higher in the northwest and gradually decrease towards the southeast. Storage coefficients range between 0.00044 and 0.00063 and the specific yield value varies from 0.12 to 0.26 with an average of 0.15 (Comisión Nacional del Agua, 2009c).

Water levels reported in 2008 range from just a few feet down to 475 feet below land surface. The shallower water levels are found in the southeast near the Rio Grande and the deepest water levels are in terraces west of the Ciudad Juarez metropolitan area.

In Juarez, the water level depths range approximately between 130 and 300 feet. Water level changes between 1990 and 2008 in urban and irrigation areas show declines ranging from about 16 to 147 feet, which represents a decline of about 1 to 8 feet per year (Figure A12-5). Groundwater withdrawals over several decades in the Ciudad Juarez area have caused a large cone of depression, which has intercepted the natural flow toward the Rio Grande and reversed the gradient in those areas toward pumping centers.

Generally, Acuífero Valle de Juarez has fresh water with total dissolved solids concentrations of 400 to 800 parts per million, but brackish areas do occur. These brackish areas are due to excess irrigation return flows, wastewater, and naturally occurring saline water within the bolson. This brackish water ranges from 1,200 to 3,000 parts per million.

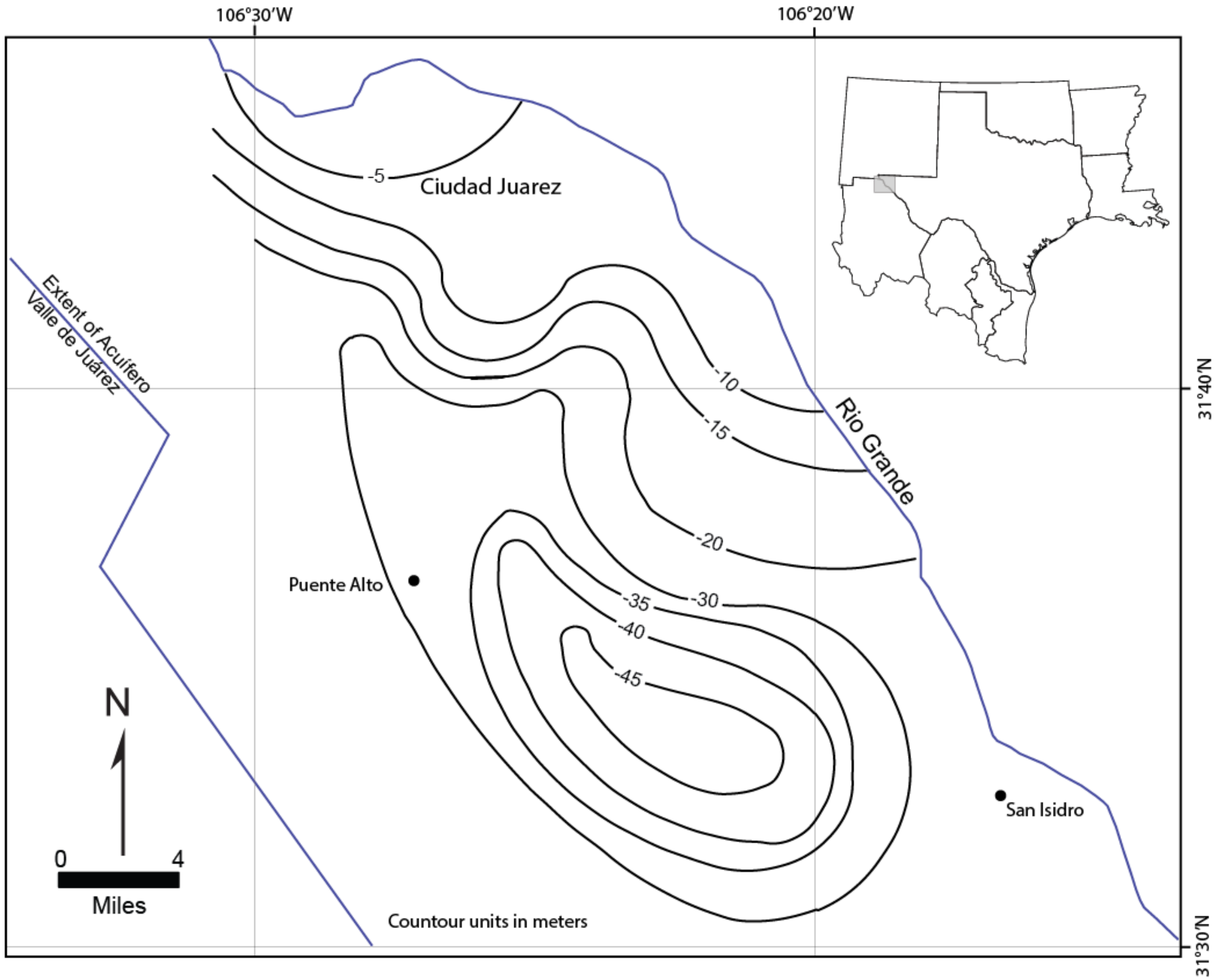

Figure A12-5. **Water-level declines near Juarez, Mexico (1990-2008) (modified from Comisión Nacional del Agua, 2009d).**

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A13 - Igneous Aquifer and West Texas Bolsons Aquifer (Texas/Mexico)

The Igneous Aquifer and West Texas Bolsons Aquifer of Texas are generally equivalent in origin and characteristics to three administrative aquifers in Mexico. These aquifers include Acuífero Valle del Peso, Acuífero Álamo Chapo, and Acuífero Bajo Rio Conchos (Figure A13-1). The upper groundwater units within these aquifers consist of alluvial sediments that include portions of the Red Light Draw Bolson equivalent in Mexico and the Presidio and Redford Bolsons.

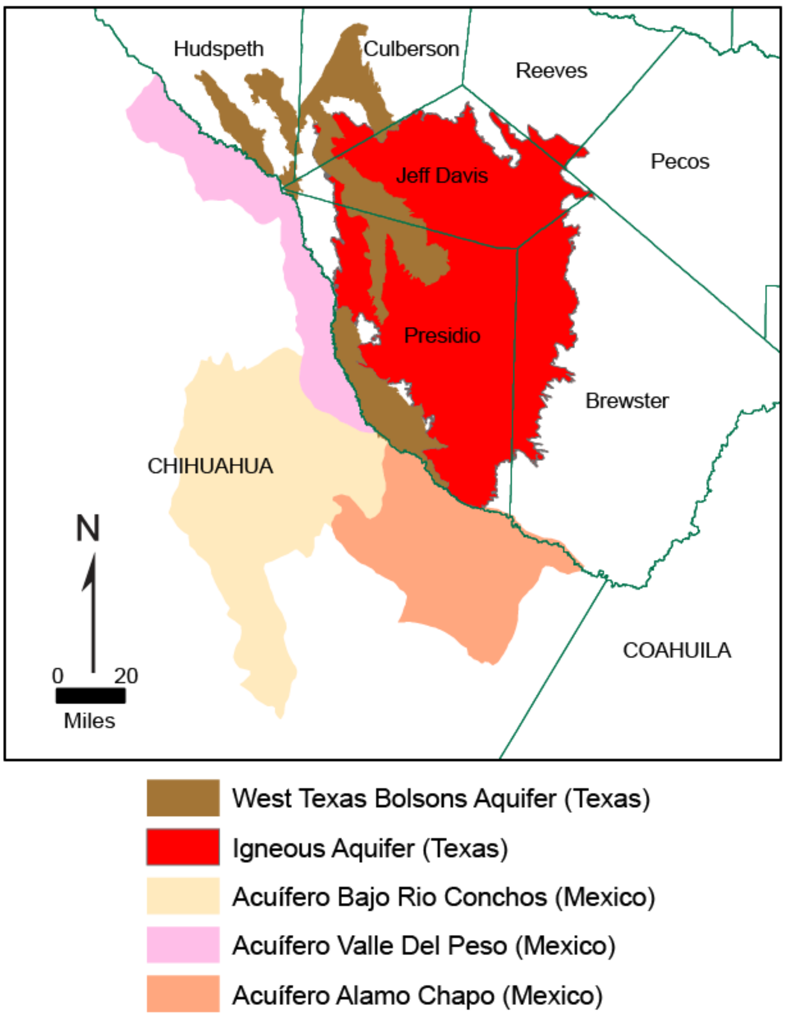

Figure A13-1. Igneous and West Texas Bolsons aquifers and Mexico aquifers.

Geologic Conditions

The first groundwater unit within the Acuífero Valle De Peso is in alluvial and colluvial sediments, including some conglomerates. These units have low to medium permeability. The lower groundwater units within the area consist of highly fractured extrusive igneous rocks, including basalts, tuffs, and rhyolites. Because of the fracturing, these units have high permeability. The boundary of the igneous groundwater system is where fractures become less widespread. Deeper formations, including the Ojinaga, Buda, and Del Rio formations, form deep aquifers that have not been explored. These deeper formations include some alternating shale and siltstone layers, which may lead to confined conditions within these units.

Adjacent to the southernmost part of Presidio County, Texas, are the following administrative aquifer areas: the Acuífero Bajo Río Conchos and Acuífero Alamo Chapo. These two aquifers are adjacent to the Presidio and Redford bolsons and the Igneous Aquifer in Texas. The aquifers cover an area of 5,295 square miles. The Acuífero Bajo Río Conchos and Acuífero Alamo Chapo consist of intrusive and extrusive igneous rocks (granite, diorite, rhyolite, acid tuff, and others) in the north and west, as well as sedimentary rocks (limestone, conglomerate, and alluvial deposits) in the central and eastern parts of the area.

The Presidio and Redford bolsons are the result of faulting and the subsequent accumulation of sedimentary deposits in the basins derived from erosion of the adjacent mountain blocks. The Rio Grande and related streams added complexity to the aquifer architecture, and erosion resulted in a rugged landscape in the area. The thickness of the bolson deposits at the center of the basin is up to 5,000 feet (Figure A13-2).

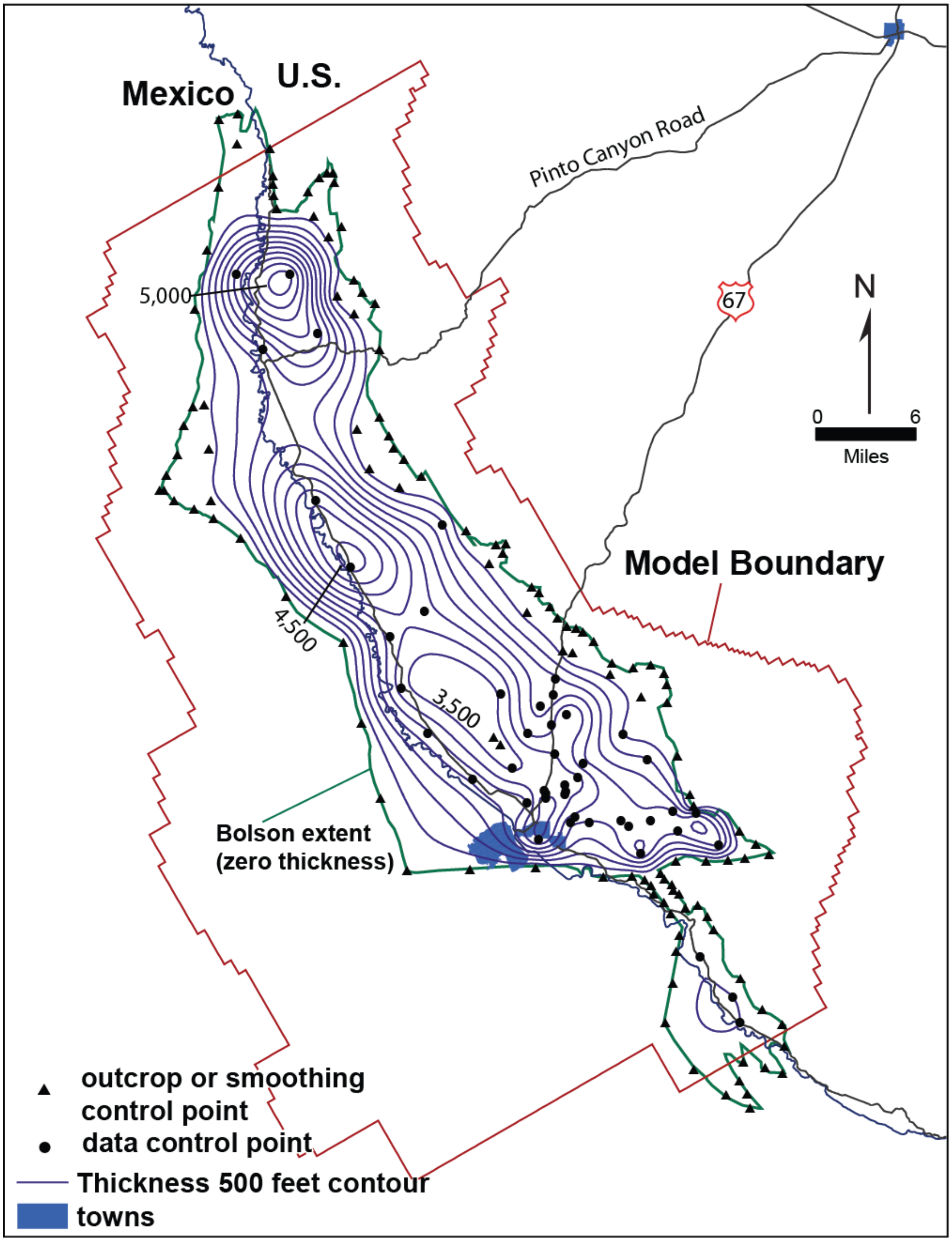

Figure A13-2. Thickness map of the Presidio and Redford bolsons (Wade and others, 2011).

Groundwater Conditions

The groundwater system of the Presidio and Redford bolsons consists of the Rio Grande alluvium deposits, bolson deposits, volcanic rocks, and older Cretaceous units. The hydraulic connection between bolson deposits and the younger alluvial deposits varies throughout the area. The Presidio and Redford bolsons are the main source of water used for drinking, livestock, and irrigation for the area surrounding Presidio, Texas, and Ojinaga, Mexico.

The estimated average horizontal hydraulic conductivity for the Presidio Bolson is approximately 8 feet per day. Recharge occurs through high flow flash-flood events along the mountains that surround the bolson and through permeable river and alluvial sediments associated with the bolson. The groundwater within the bolsons flows from higher elevation along the western and eastern boundaries toward the Rio Grande (Figure A13-3).

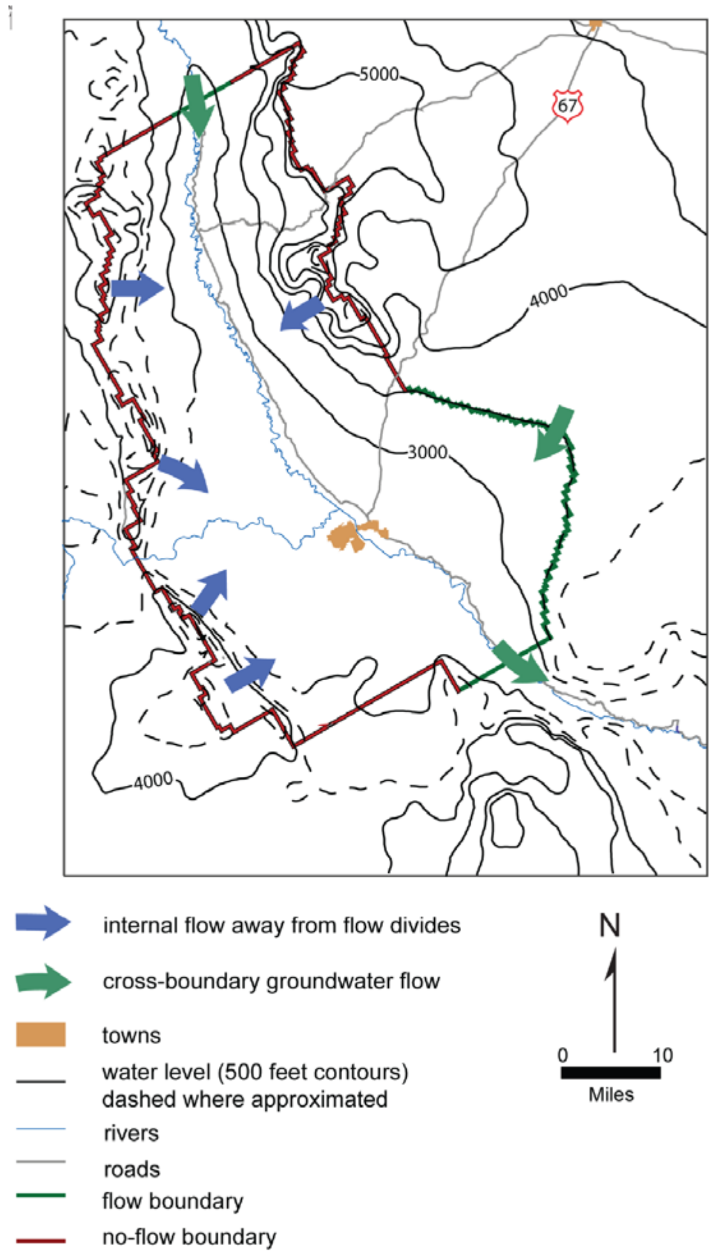

Figure A13-3. Estimated water-level elevation and flow direction for Presidio Bolson (Wade and others, 2011).

The total recharge has been estimated to be approximately 3,600 to 7,000 acre-feet per year. However, the river flood plain is a thick brush-covered region with vegetation that may consume most of the regional groundwater discharge.

Further from the river, groundwater discharge from these aquifers occurs because of discharge from springs and groundwater wells. Groundwater use in Mexico from the Presidio and Redford bolsons is primarily municipal, with some domestic, livestock, and irrigation use. In 2007, Comisión Nacional del Agua permitted 9,000 acre-feet per year.

In Mexico, recharge to the administrative aquifers occurs through infiltration of rainwater from the bordering mountains from within surface streams, and to a lesser extent by direct infiltration within the valley (Figure A13-4 and A13-5). Recharge for the Acuífero Valle de Peso is from infiltration of rainwater from the nearby mountains. Discharge from the aquifer occurs as evapotranspiration and by wells. Use from the aquifer is limited and pumping from wells is estimated to be less than 33 acre-feet per year. Comisión Nacional del Agua reports a limited number of water level measurements for the Acuífero Valle de Peso and reports an average of 4,930 parts per million total dissolved solids concentrations for the area (Comisión Nacional del Agua, 2011a). Part of the Acuífero Valle de Peso is transected by the Red Light Draw Bolson equivalent in Mexico, where it is estimated to be over 2,500 feet in thickness (Figure A13-6).

The combined estimated recharge for the Acuífero Bajo Río Conchos and Acuífero Alamo Chapo is about 149,982 acre-feet per year. The combined estimated discharge from the aquifers including springflow, baseflow, and pumping is approximately 15,997 acre-feet per year.

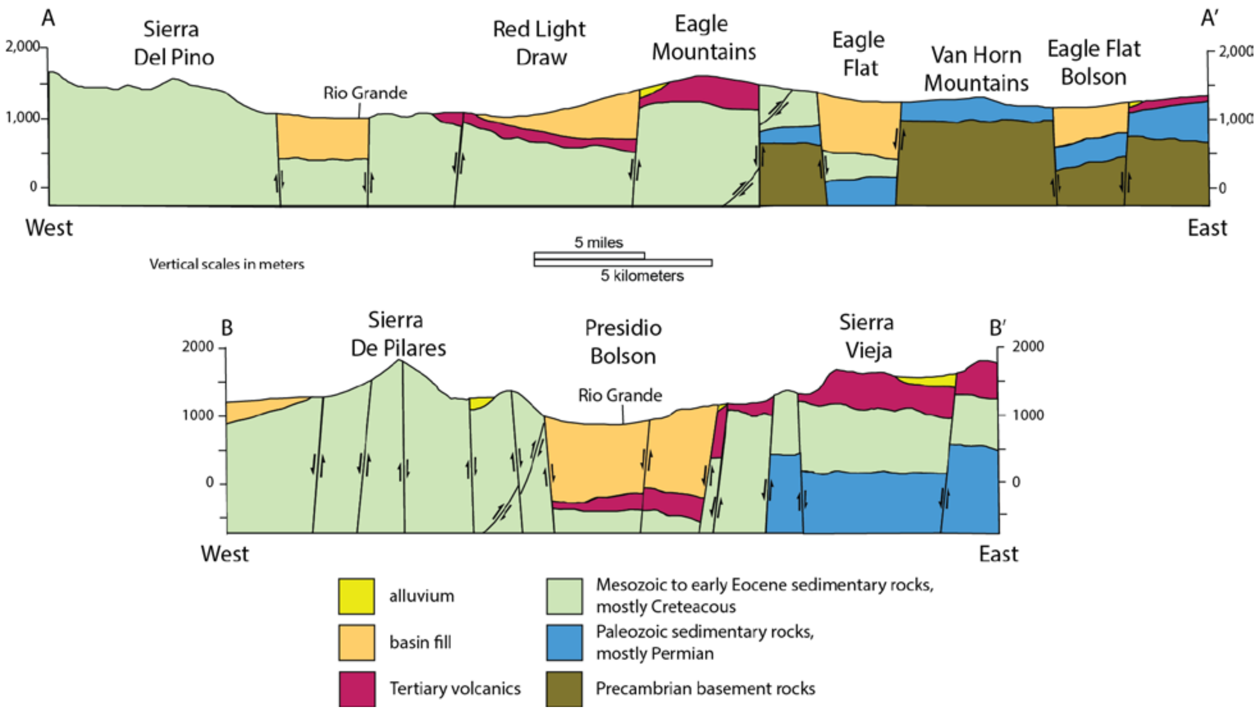

Figure A13-4. Cross-sections across the Red Light Draw and Presidio Bolson. Location of the sections is shown in Figure A13-5 (modified from Henry, 1979).

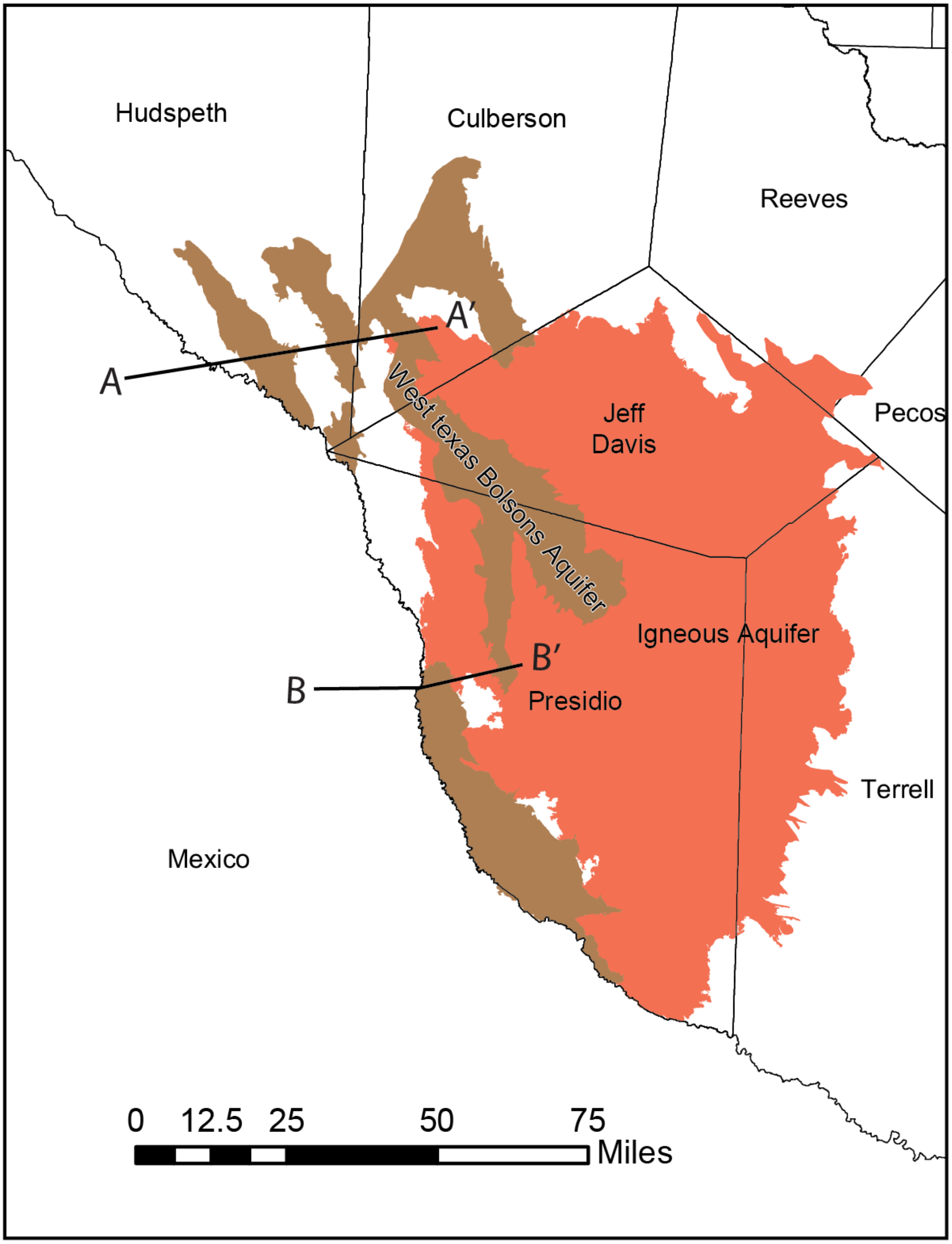

Figure A13-5. Red Light Draw and Presidio Bolson cross section locations (modified from Henry, 1979).

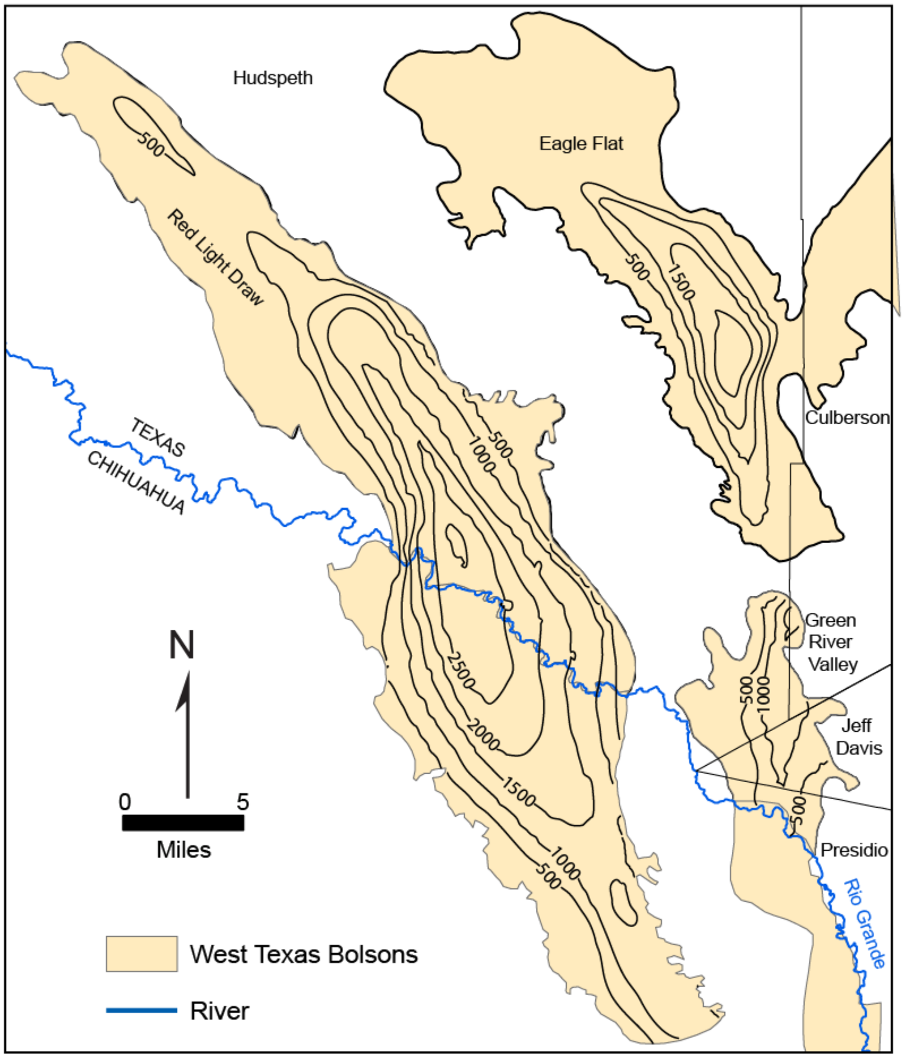

Figure A13-6. Thickness map of the Red Light Draw Bolson **(modified from Beach and others, 2004).**

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A14 - Nacatoch Aquifer (Texas/Arkansas)

In Texas, the Nacatoch Aquifer consists of the Nacatoch Sand, which is part of the Navarro Group (Figures A14-1 and A14-2). The Nacatoch Sand extends into Arkansas, where it is exposed along a narrow, northeast-trending three to eight-mile-wide belt. In Louisiana, the unit occurs entirely in the subsurface and is not considered part of any formally recognized aquifer. The U.S. Geological Survey groups the Nacatoch Aquifer of southwestern Arkansas with the McNairy Sand of northern Mississippi and includes it in the larger Mississippi Embayment Aquifer System.

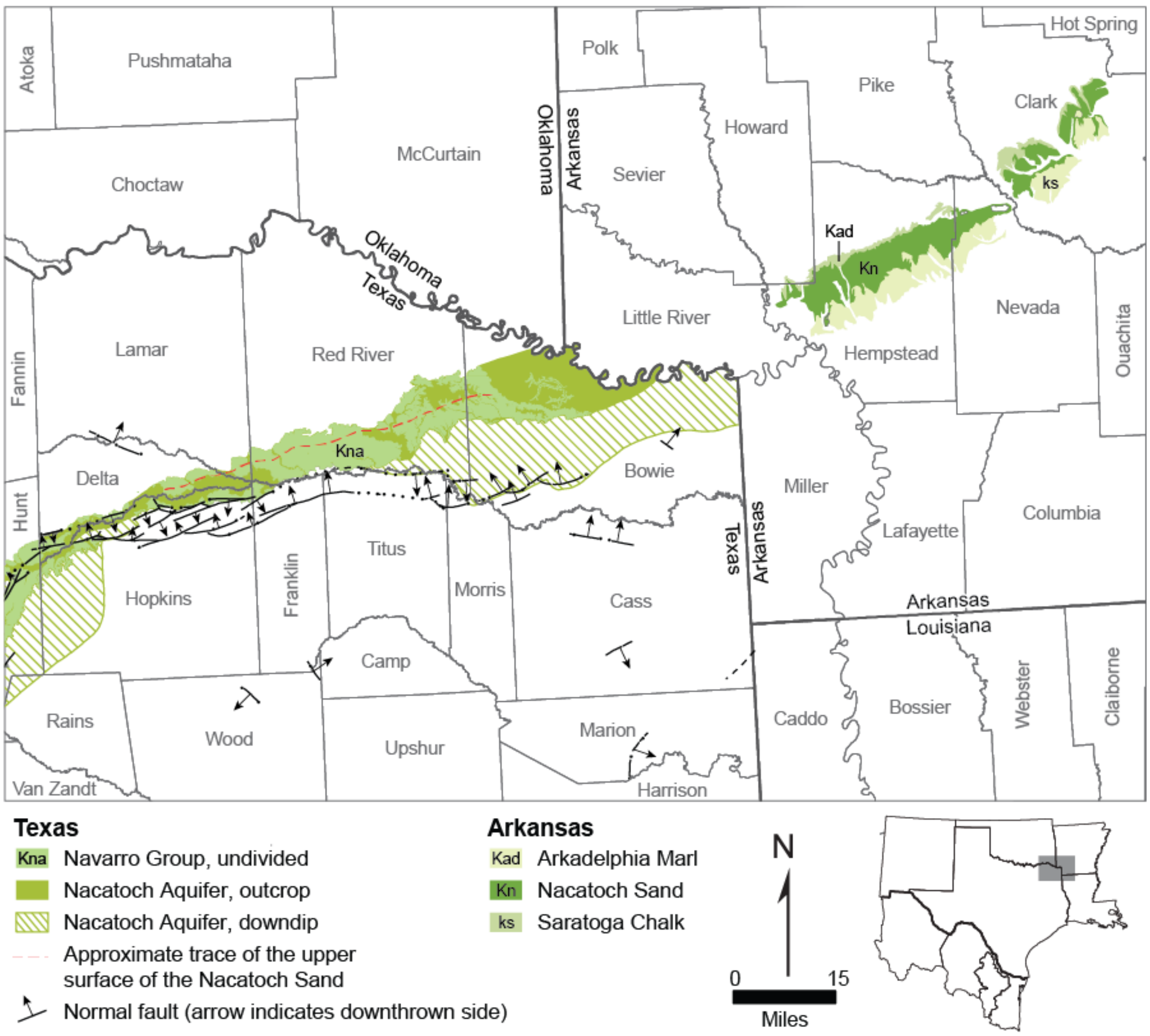

Figure A14-1. Nacatoch Aquifer extent in Arkansas and Texas.

Geologic conditions

In Texas, the Nacatoch Sand dips south and southeast in the subsurface toward the central axis of the East Texas Basin (Figure A18-1, Figure A6-2, and A6-4, for map locations of major structural elements). In southwestern Arkansas, Nacatoch strata dip east to southeast toward the axis of the Mississippi Embayment (Peterson and Broom, 1985). There, the top of the Nacatoch Sand has an elevation of about 300 feet at its outcrop, descending to about 800 feet below sea level towards the embayment. The Nacatoch Sand is about 100 feet thick near the outcrop and has a maximum thickness of about 300 feet.

The Nacatoch Sand is overlain by the Arkadelphia Marl and underlain by the Saratoga Chalk. In southwestern Arkansas, the Nacatoch consists of three distinct units. The upper unit, which is the main water-bearing layer, consists of unconsolidated, gray, fine-grained quartz sand. The sands are commonly crossbedded, and locally massive. The middle unit consists of fossiliferous dark-green sand, while the lower unit includes interbedded gray clay, sandy clay and marl, dark clay-rich fine-grained sand, and hard irregular concretionary beds. Together these units are part of the larger McNairy-Nacatoch Aquifer of Arkansas and Mississippi that was deposited in a deltaic to prodeltaic setting.

System	Series	Group	Stratigraphic unit Texas	Stratigraphic unit Arkansas
Tertiary	Paleocene	Midway	Midway, undifferentiated	Midway
Cretaceous	Gulf	Navarro	Kemp Clay	Arkadelphia Marl
			Nacatoch Sand	
			Neylandville Formation	Saratoga Chalk
		Taylor	Marlbrook Marl	

Figure A14-2. Stratigraphy of the Nacatoch Aquifer, Texas and Arkansas (modified from Beach and others, 2009).

Groundwater conditions

The Nacatoch Aquifer recharges by precipitation in its outcrop areas in Clark, Nevada, and Hempstead counties, Arkansas, as well as by downward flow through the overlying alluvial and terrace deposits in Little River County and in northeastern Texas. Average recharge is about 0.8 to 1.0 inches per year and is similar to northeastern Texas.

The Nacatoch Sand in Arkansas has a mean transmissivity of 161 square feet per day and an estimated hydraulic conductivity of 0.64 feet per day (Pugh, 2008). Well yields range from 50 to 500 gallons per minute. In southwestern Arkansas, groundwater flow in the Nacatoch Aquifer is generally towards the south-southeast in Little River, Miller, and Hempstead counties and to the east-southeast in Nevada and Clark counties (Figure A14-3). Cones of depression have developed in southeastern Hempstead County and in southwestern Clark County.

The quality of groundwater in the Nacatoch Aquifer is marginally acceptable for rural-domestic and public supply. The concentration of total dissolved solids in groundwater increases to the southeast downdip from the outcrop. On a regional scale, the McNairy-Nacatoch Aquifer generally contains more than 3,000 milligrams per liter total dissolved solids concentration in its deepest parts. The aquifer has a sodium bicarbonate water type where the groundwater is less than 2,000 milligrams per liter total dissolved solids and is a sodium chloride type groundwater where it contains water with more than 2,000 milligrams per liter total dissolved solids (Renken, 1998).

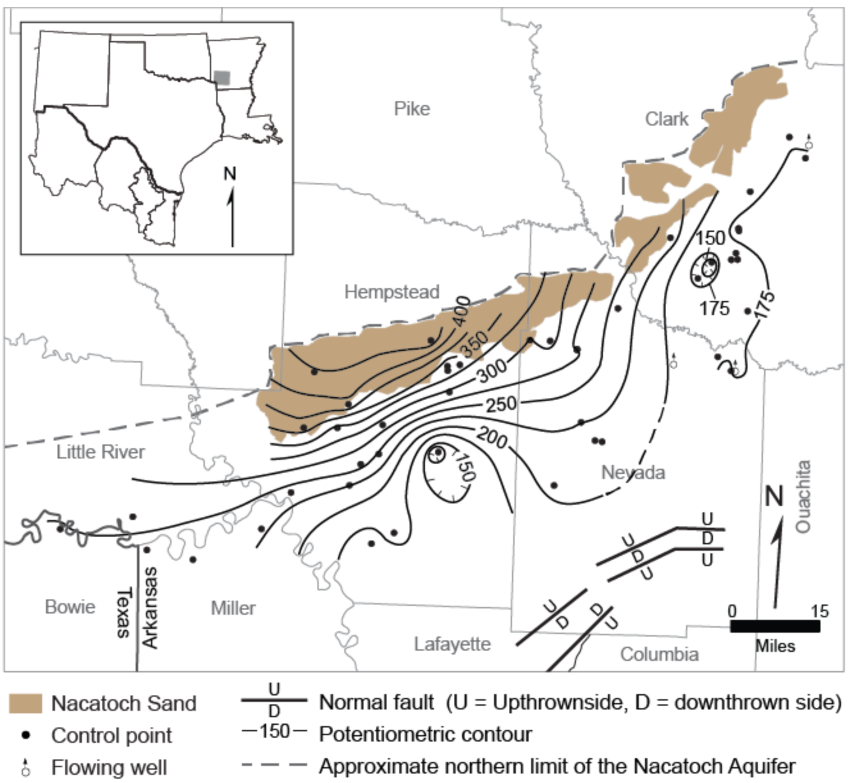

Figure A14-3. Potentiometric surface contours (25 foot) from January–February 2002, in the Nacatoch Aquifer in Arkansas (from Schrader and Scheiderer, 2004).

Water withdrawn from the Nacatoch Aquifer in southwestern Arkansas was estimated to be 2.11 million gallons per day in 1965 and increased by 125 percent to 4.75 million gallons per day in 1980 (Figure A14-4.). Water withdrawn from the aquifer decreased by 93 percent to 0.32 million gallons per day in 2000. The decrease is explained by counties relying more on surface water during the 1980s and 1990s.

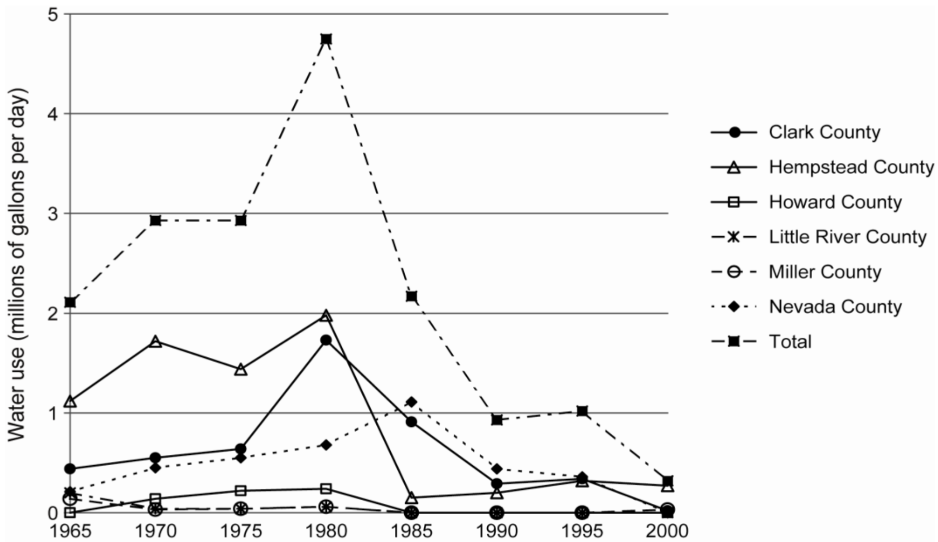

Figure A14-4. Estimated water use by county from Nacatoch Aquiferin southwest Arkansas (from Schrader and Scheiderer, 2004).

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A15 - Ogallala Aquifer (Texas/New Mexico)

The Central and Southern High Plains aquifers of eastern New Mexico and northwest Texas are part of the larger High Plains Aquifer (Figure A15-1) that extends from South Dakota to Texas. The High Plains Aquifer, as defined by the U.S. Geological Survey, includes the Neogene Ogallala Formation as well as overlying Quaternary age sediments. The Ogallala Aquifer of Texas is equivalent for the most part to the High Plains Aquifer but differs in not including the Quaternary age deposits.

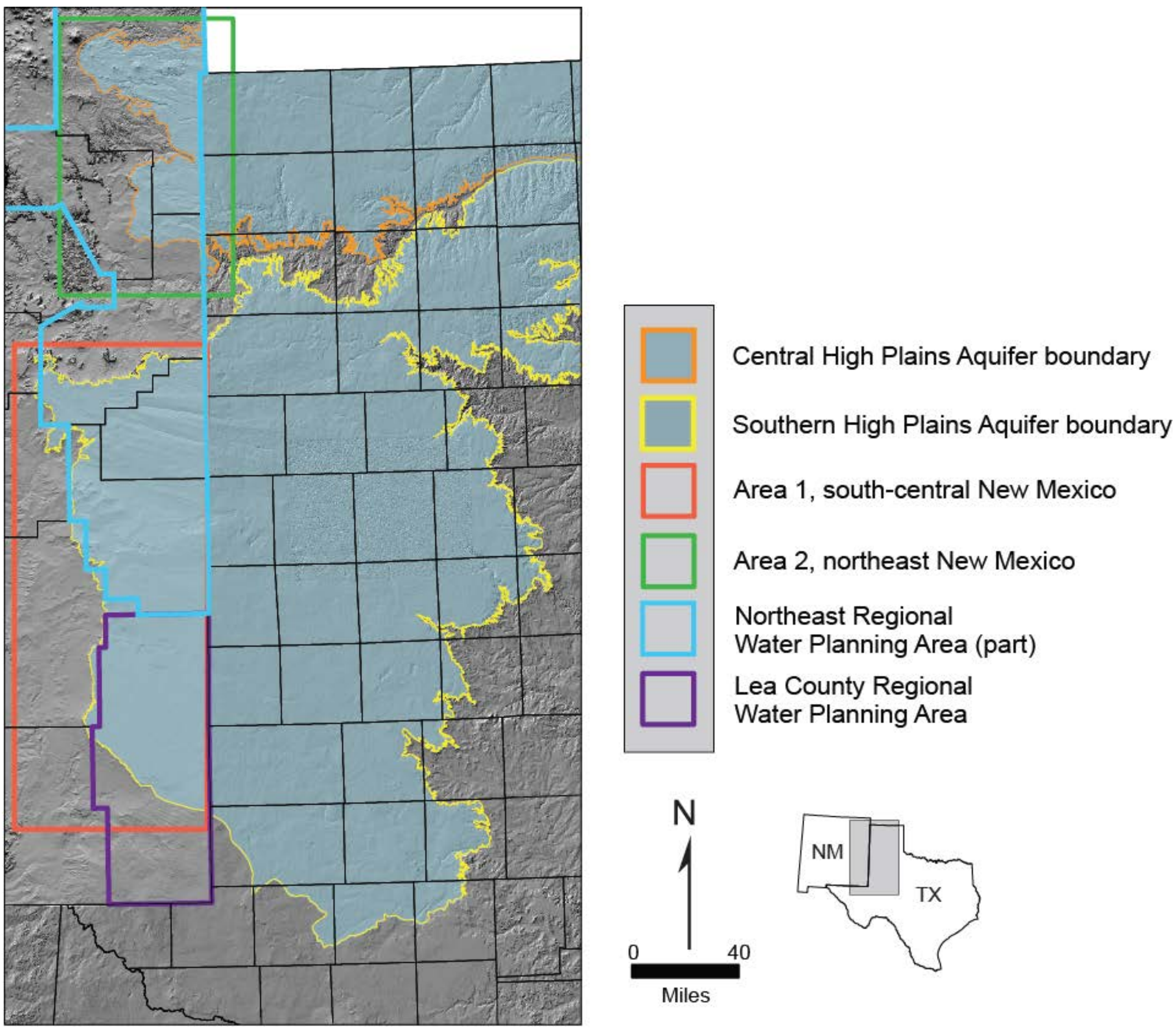

Figure A15-1. Location of administrative and Ogallala Aquifer boundaries. The boundary of the High Plain Aquifer is from Qi (2010).

Geologic conditions

The Ogallala Formation consists of clay, silt, fine to coarse-grained sand, gravel, and caliche deposited on an irregular Paleogene and Neogene-aged erosional surface. The topography of this surface controlled, in part, the lithology of the Ogallala Formation where coarse-grained deposits tended to accumulate in paleovalleys cut into the underlying Permian, Triassic, Jurassic, and Cretaceous rock. Coarse-grained sand and gravel were deposited along the paleochannels, generally oriented in a northwest to southeast direction. Between channels, sand and clay were deposited as overbank deposits along with some eolian sand and loess. The upper surface of the Ogallala Formation is defined by the "Caprock" calcrete, which represents a period of landscape stability and little eolian deposition, probably during an extended interval of increased humidity. The "Caprock" calcrete separates the Ogallala Formation from younger Quaternary sediments deposited as unconsolidated alluvium, eolian sand, and silt and clay in ephemeral ponds (playas).

Groundwater conditions

The water tables in both the Central and Southern High Plains aquifers have a general east-southeast slope towards the Texas state line, and groundwater generally flows in this direction. Depth to groundwater across the southern part of Area 1 generally increases east to west from about 50 feet to 300 feet (Figure A15-2). In the northern part of the area, depth to water is about 100 feet except for a northwest to southeast trending band of deeper water (200–450 feet) that likely corresponds to a paleochannel at the base of the Ogallala Formation. In Area 2, depth to groundwater also increases to the west from about 75 feet to 200 feet, although there are places where it is in the 225 to 500-foot range (Figure A15-3).

Saturated thicknesses for the Southern High Plains Aquifer in New Mexico, based on data from 2004 through 2007, are shown in two maps (Figures A15-4 and A15-5). The maps show large areas where the High Plains Aquifer is not saturated or where the amount of saturation is highly variable. Elsewhere, saturation is often greatest in associated areas of high water-level declines. Underlying paleotopography along the erosional unconformity at the base of the Ogallala Formation also seems to control saturated thickness.

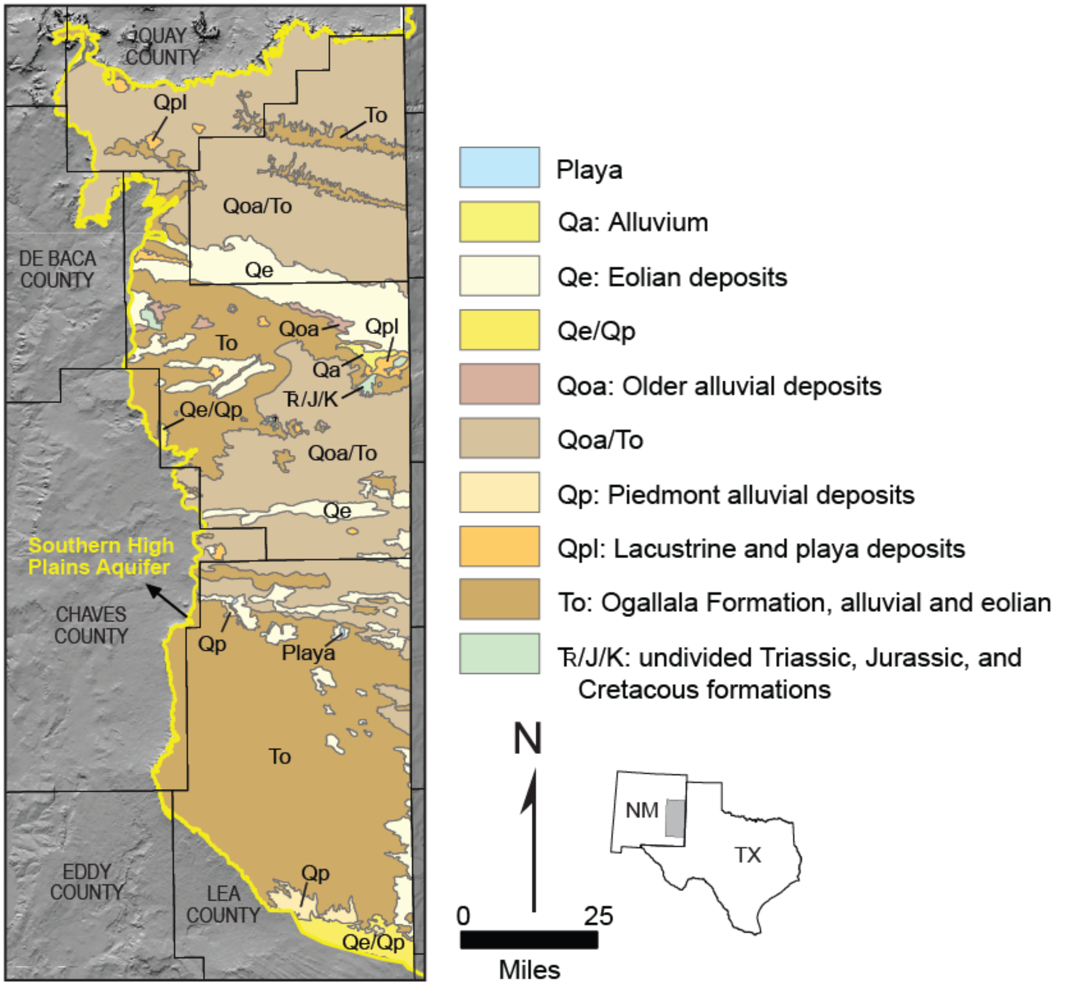

Figure A15-2. **New Mexico Area 1 surface geology from the 1:500,000 Geological Map of New Mexico within the Southern High Plains Aquifer boundary (New Mexico Bureau of Geology and Mineral Resources and U.S. Geological Survey, 2003).**

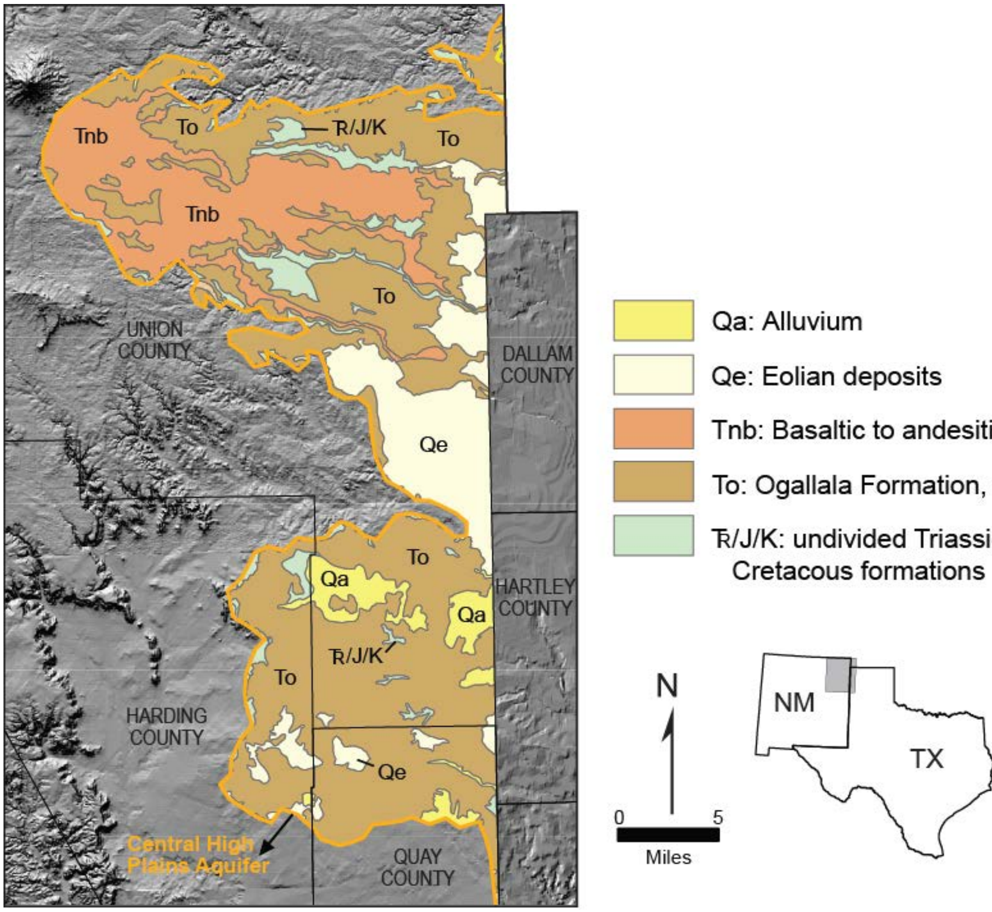

Figure A15-3. New Mexico Area 2 surface geology from the 1:500,000 Geological Map of New Mexico within the Central High Plains Aquifer boundary (New Mexico Bureau of Geology and Mineral Resources and U.S. Geological Survey, 2003).

Values for hydraulic conductivity and specific yield from the Ogallala Formation in eastern New Mexico vary geographically and with lithologic changes. Hydraulic conductivity ranges from about 25 to 300 feet per day and averages 60 feet per day. Specific yield ranges from about 10 to 30 percent and averages 15 percent (Gutentag and others, 1984). When hydraulic conductivity is mapped on a regional scale, a pattern emerges that is the product of deposition along northwest-southeast trending fluvial systems (Blandford and others, 2003). Well yields for the aquifer are, in large part, a function of lithology and can reach 1,600 gallons per minute (Kilmer, 1987).

Groundwater from the Ogallala Formation, although very hard, is generally of high quality and suitable for stock, domestic, and irrigation use. Total dissolved solids concentrations from municipal wells in the Northeast Regional Water Planning Area generally range from 185 milligrams per liter to 590 milligrams per liter, which is considered fresh (less than 1,000 milligrams per liter). To the south in the Lea County Regional Water Planning Area, total dissolved solids concentrations range from 300 to 415 milligrams per liter, although they may exceed 700 milligrams per liter in some instances.

The High Plains Aquifer, consisting mainly of the Ogallala Formation, is the principal aquifer and primary source of water in eastern New Mexico. The aquifer has and is experiencing water-level declines due to pumping. Water levels from predevelopment conditions to 2007 have declined as much as 175 feet near the Texas state line in the northern part of Area 1. From there to the west values progressively decrease to less than 25 feet. In the southern part of Area 1, in Lea County, water-level declines along the Texas border generally range from 50 to 100 feet, decreasing to less than 10 feet in the western part of the county.

The water-level declines have resulted from an imbalance between recharge and discharge to and from the aquifer. Discharge has occurred primarily from groundwater withdrawals for irrigation, but also by evapotranspiration and seepage to streams, springs, and other surface-water bodies. Recharge occurs mainly from precipitation, although seepage from streams, canals, and reservoirs, and irrigation return flows are also involved. Estimates of recharge as a percentage of rainfall for the southern High Plains region varied from 0.007 to 0.67 inch per year, with values from playa areas of 0.48 to 4.72 inches per year. Since the early 1950s groundwater withdrawals have exceeded recharge. By 2005, due to this discrepancy, the estimated decrease in water storage in the New Mexico part of the High Plains Aquifer since predevelopment was 9.7 million acre-feet.

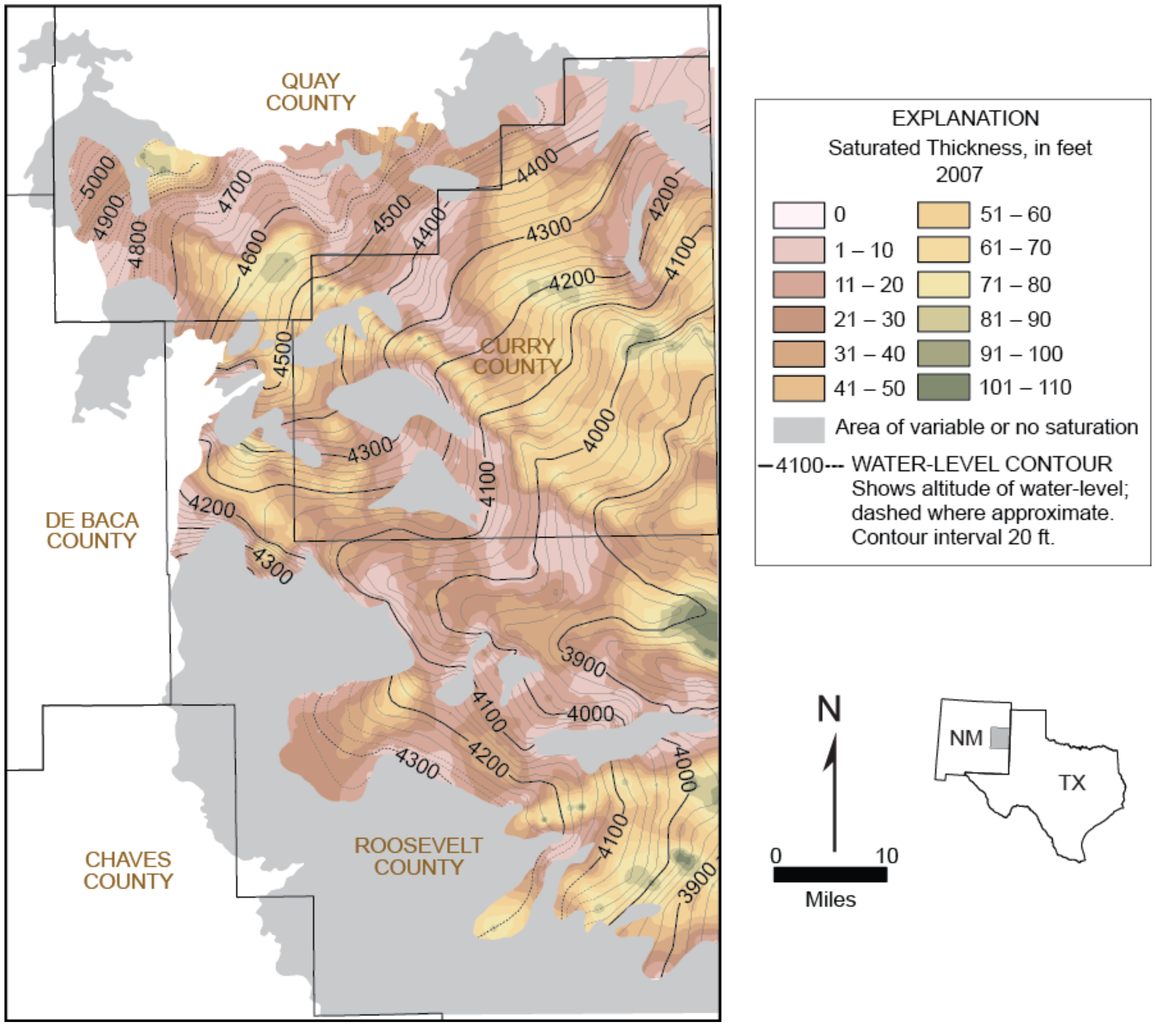

Figure A15-4. **Northern part of New Mexico Area 1, 2007 High Plains Aquifer levels and saturated thickness (modified from Tillery, 2008).**

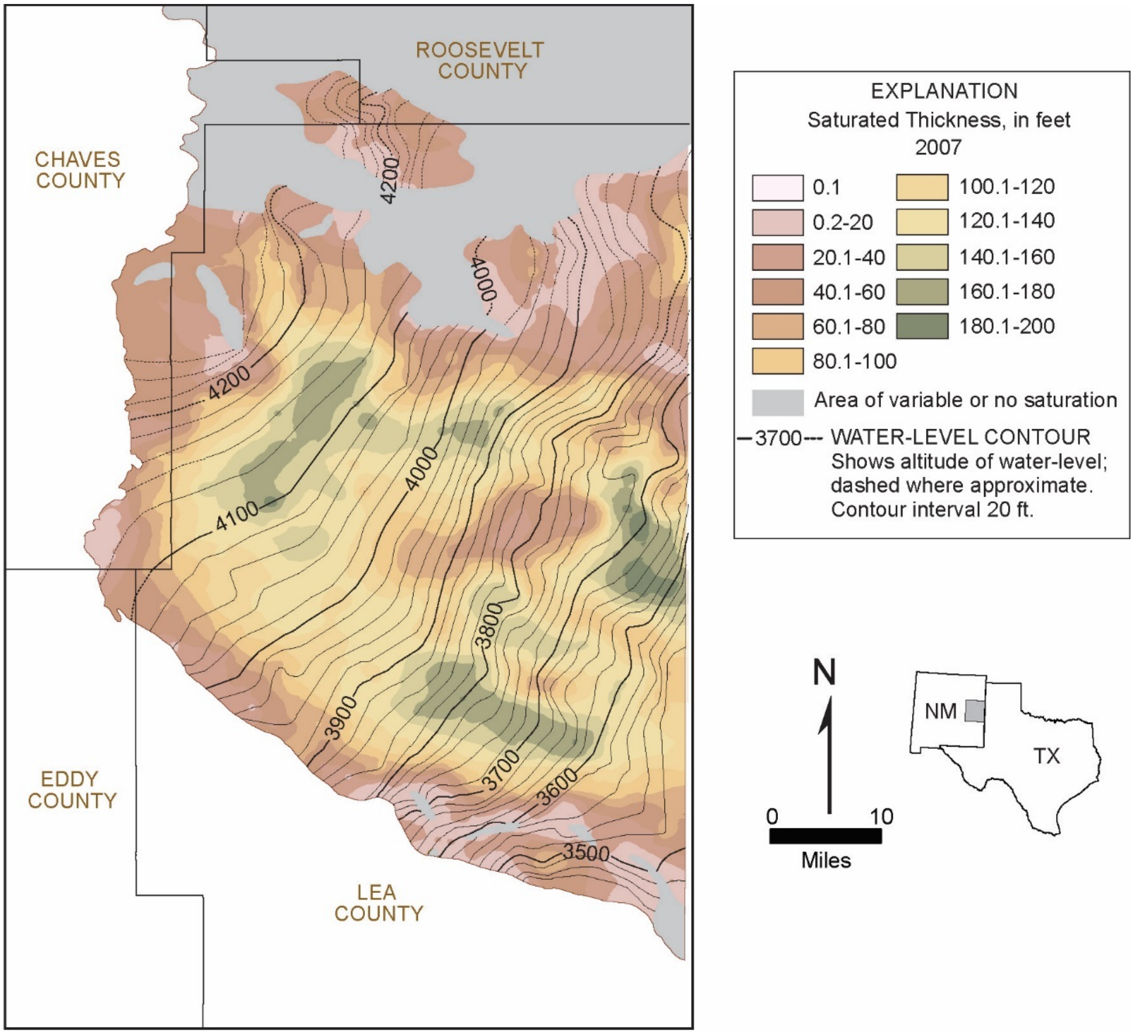

Figure A15-5. **Southern part of New Mexico Area 1, 2007 High Plains Aquifer levels and saturated thickness in southeast New Mexico (modified from Tillery, 2008).**

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A16 - Ogallala Aquifer (Texas/Oklahoma)

The central High Plains Aquifer in Oklahoma, or called the Ogallala Aquifer in Texas, covers about 7,100 square miles (Figure A16-1). Aquifer properties vary significantly from north to south and from west to east.

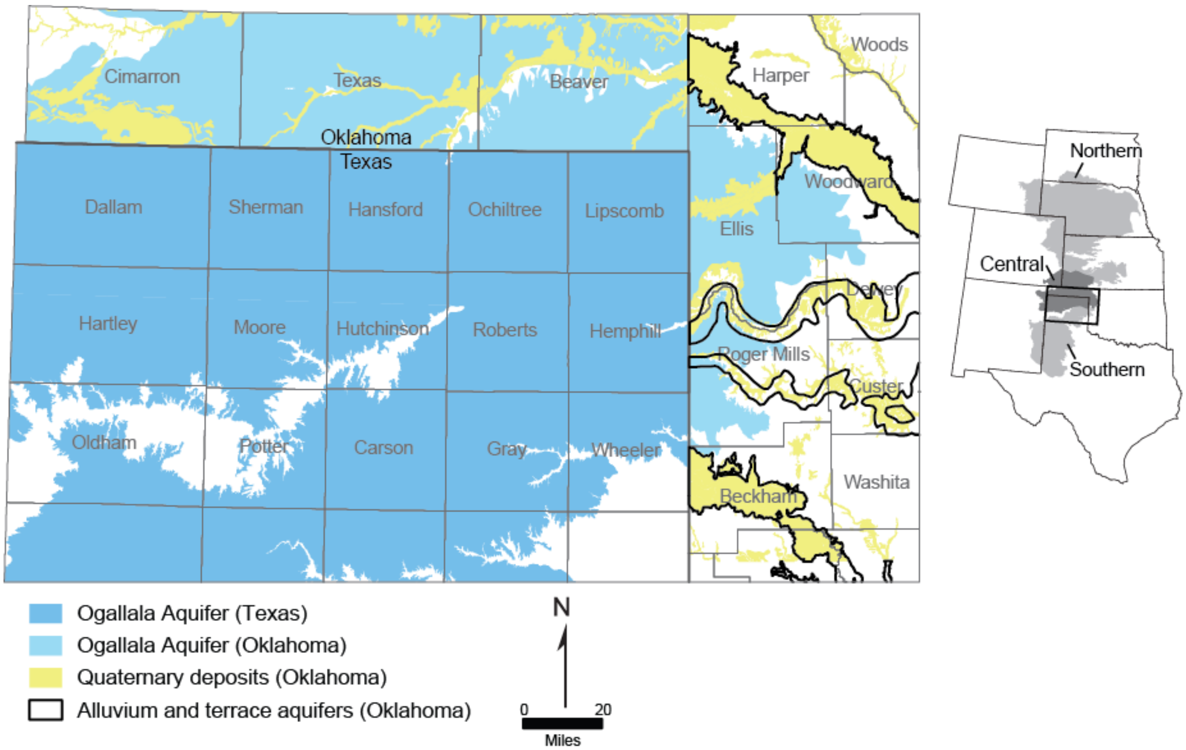

Figure A16-1. Central High Plains Aquifer extent in northern Texas and Oklahoma.

Geologic conditions

The High Plains Aquifer in Oklahoma consists mainly of the saturated part of the Neogene Ogallala Formation but also includes some saturated Quaternary sediments. The Ogallala Formation is a remnant of a large eastward-sloping alluvial plain formed from sediments eroded from the ancestral Rocky Mountains and deposited eastward by aggrading streams filling valleys on a pre-Ogallala surface. The topography of the underlying surface (Figure A16-2), as well as salt dissolution in Permian-age rocks, largely determined the thickness of the formation. In the Oklahoma Panhandle, the Ogallala Formation can be as thick as 650 feet. In Roger Mills and Ellis counties, the formation thins eastward from a maximum thickness of about 320 feet (Hart and others, 1976).

The Ogallala Formation consists of interbedded sand, gravel, silt, and clay deposited by fluvial (braided stream) and eolian processes. The sediments are poorly sorted and generally unconsolidated but cemented, in part, by calcium carbonate and some silica. Overlying Quaternary-age sediments include alluvial gravel, dune sand, and loess deposits. Because most of these sediments were deposited by meandering streams, they were continuously reworked.

This produced extremely heterogeneous layers in terms of grain size, which largely determines porosity and permeability.

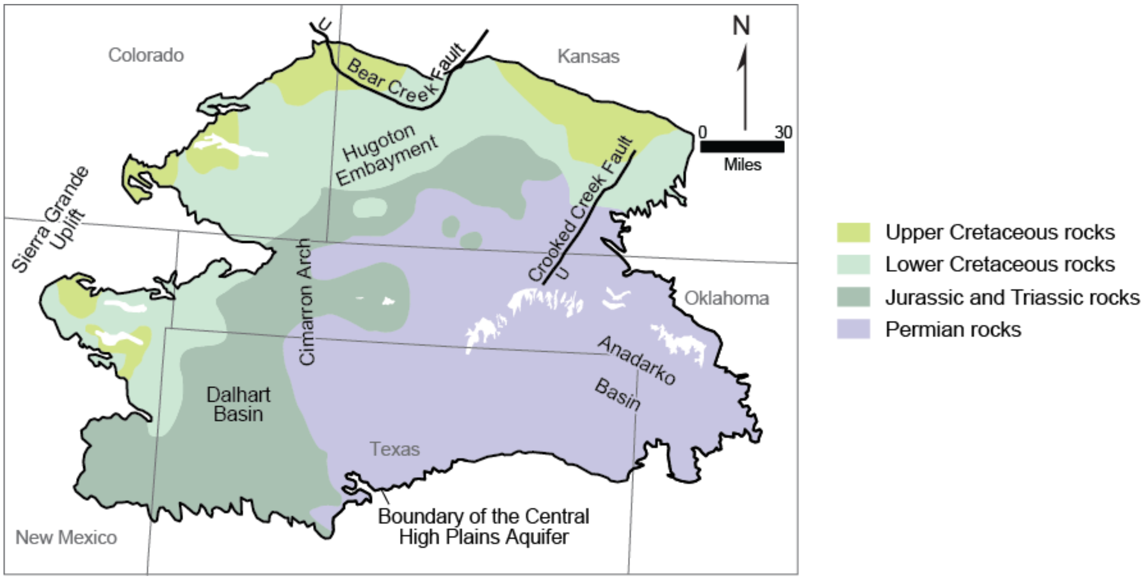

Figure A16-2. Major structural features and units underlying High Plains Aquifer (modified from Hart and others, 1976; Gutentag and others, 1984; and Luckey and Becker, 1999).

Groundwater conditions

Sand and gravel deposits in the central High Plains Aquifer are the primary source of water to wells, and their distribution correlates to the locations of the paleovalleys on the pre-Ogallala depositional surface. It is in these areas that the saturated thickness of the aquifer is greatest, as are well yields. A study based on 1998 data (Luckey and Becker, 1999) indicated a mean saturated thickness of 125 feet for the aquifer in Oklahoma with a range of essentially zero to almost 430 feet. Groundwater occurs primarily under unconfined conditions, although confined conditions likely exist locally. Groundwater flows generally from west to east along the Ogallala Aquifer in Oklahoma (Figure A16-3).

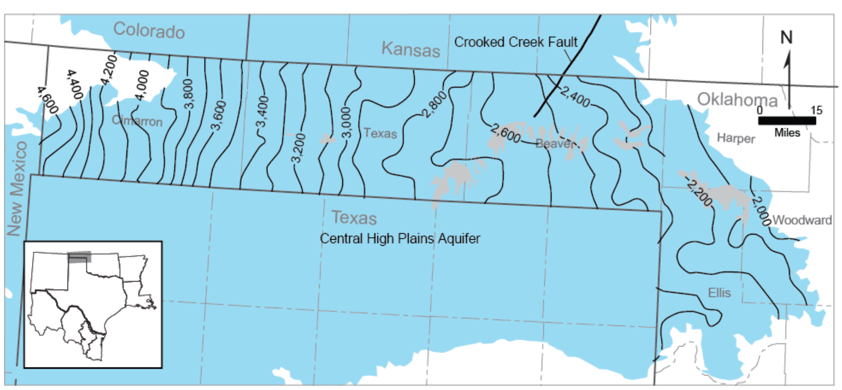

Figure A16-3. Potentiometric contours (100-foot) in 1998 in High Plains Aquifer in Oklahoma (modified from Luckey and Becker, 1999); gray indicates areas where the aquifer is absent.

Natural recharge to the aquifer occurs primarily through precipitation, but also from seepage in stream channels, subsurface inflow from the aquifer in Texas, and irrigation return flows. The recharge is highly variable in both time and space, and likely affected by soil type, depth to water, playa lakes, and the presence of caliche or clay layers. Estimates of natural recharge from precipitation range from 0.22 to 2.2 inches per year (Hart and others, 1976; Havens and Christenson, 1984; and Morton, 1980). Natural discharge from the aquifer occurs as flow to streams, evapotranspiration in areas of a shallow groundwater table, flow to underlying aquifers, and diffuse groundwater flow across the eastern boundary of the aquifer.

Water in the aquifer is generally a calcium-bicarbonate type with concentrations of dissolved solids in the 300 to 650 milligrams per liter range. However, near the base of the aquifer concentrations of dissolved solids are in the 850 to 4,000 milligrams per liter range and the water is predominately calcium-sulfate and sodium-chloride type. The change in water quality is likely due to the dissolution of gypsum or anhydrite and halite in underlying Permian rocks. There are also effects to water quality from the use of fertilizers and agricultural chemicals on cropland. The majority of groundwater from the central High Plains Aquifer has elevated levels of nitrate, as well as the presence of the pesticide atrazine and its metabolite, deethylatrazine. Areas with longer irrigation histories, counties with larger application rates of atrazine and nitrogen, and areas with smaller depths to groundwater are more affected by agricultural activities.

Aquifer tests indicate transmissivity values range from 500 to 11,800 square feet per day, storage coefficient values range from 0.002 to 0.11, and hydraulic conductivity values from range from about two feet per day to more than 100 feet per day. The aquifer commonly produces 500 to 1,000 gallons of water per minute (Hart and others, 1976). Specific yield estimates range from 0.04 and 0.30, with an average of about 0.15 (Belden and Osborn, 2002).

The central High Plains Aquifer in Oklahoma is the largest aquifer in the state and contains an estimated 86.6 million acre-feet of groundwater supply. Use of this water is primarily for the irrigation of crops such as corn, hay, sorghum, and wheat. Total estimated groundwater withdrawal, based on 2005 data, was about 252 million gallons per day. Changes in water levels from predevelopment times to 2007 generally are less than in adjoining states and are in the +10 foot to -150-foot range (Figure A16-4).

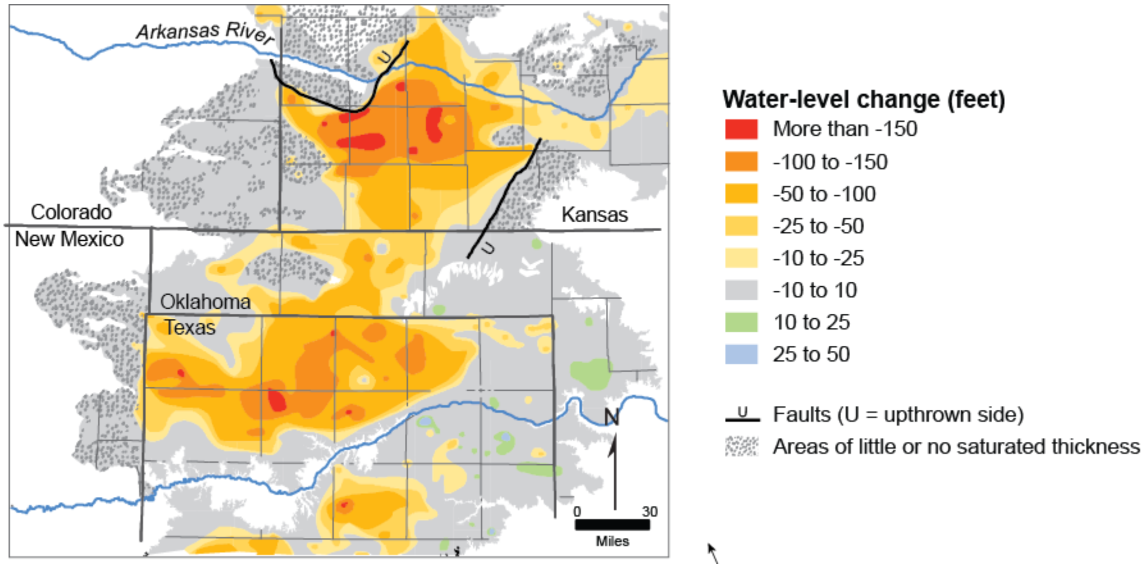

Figure A16-4. Water-level change in High Plains Aquifer in Kansas, Oklahoma, and Texas predevelopment to 2007 (modified from Lowry and others, 1967; Gutentag and others, 1984; Luckey and others, 1981; Burbach, 2007; and McGuire, 2009).

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A17 – Pecos Valley Aquifer (Texas/New Mexico)

The Pecos Valley Aquifer equivalent in New Mexico occurs in Lea and Eddy counties in southeastern New Mexico (Figure A17-1). In New Mexico, it is called the Pecos River Basin Alluvial Aquifer, or simply the Alluvial Aquifer.

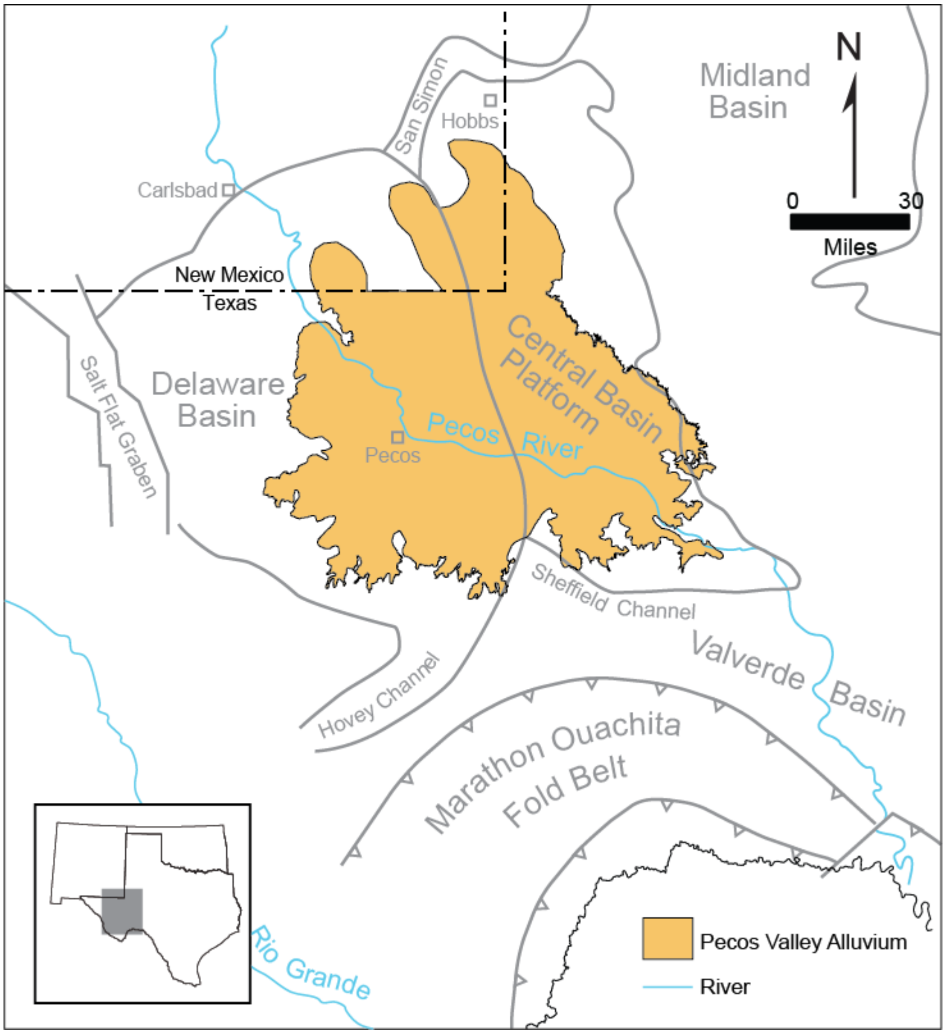

Figure A17-1. Location for the Pecos Valley Aquifer in Texas and New Mexico (modified from Hills (1984), TWDB (2007), and Anaya and Jones (2009)).

Geologic conditions

The aquifer generally consists of Neogene and Quaternary age alluvium but also includes lacustrine, eolian, and valley fill sediments. These deposits are unconsolidated or poorly cemented clay, sand, gravel, and caliche overlain in places by windblown sand (Figure A17-2). The Late Pleistocene Tahoka Formation and the Pliocene to Middle Pleistocene Gatuna Formation are part of the aquifer and are exposed in southeastern New Mexico. The Tahoka Formation is mostly clay and mud and includes molluscan and vertebrate fossils deposited in a lacustrine setting. The Gatuna Formation consists mostly of sand but also mudstone, siltstone, conglomerate, limestone, shale, and gypsum deposited in valley fill settings.

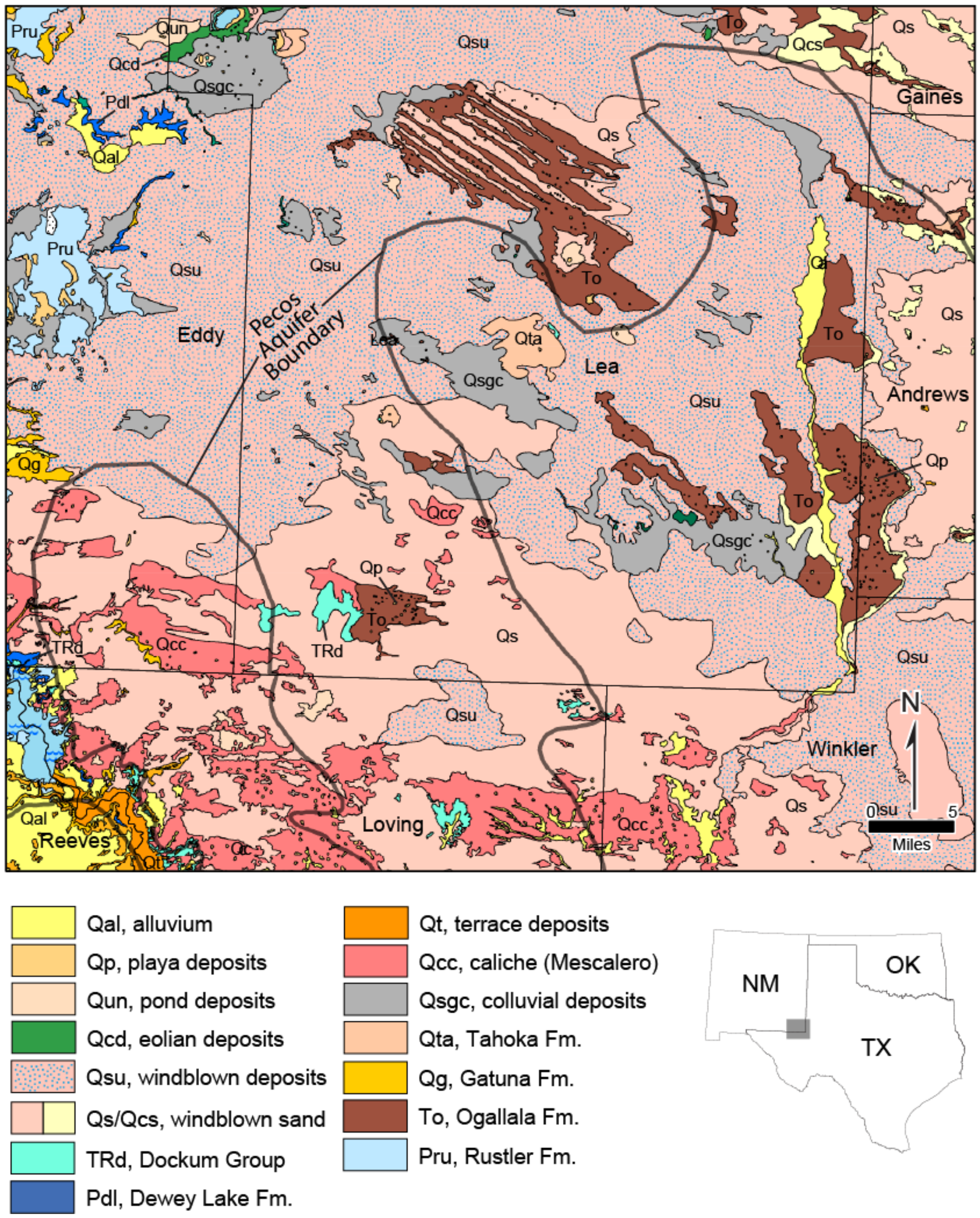

Figure A17-2. Geologic map of the southeastern New Mexico and parts of Texas based on the 1:250,000 Digital Geological Atlas of Texas (from U.S. Geological Survey and TWDB, 2006).

During the early Pleistocene, accelerated erosion of the Rocky Mountains, along with solution collapse of underlying Permian evaporates, provided the material and depositional setting for the accumulation of valley fill sediments. Specifically, aquifer sediments began to fill two large north-south trending basins, the Monument Draw and Pecos troughs. The northern ends of the two troughs extend into southeastern New Mexico, defining the aquifer's northern boundary

(Figure A15-2). In Middle Pleistocene time, the area's Mescalero Caliche developed during an interglacial stage. In Late Pleistocene time, the Mescalero Caliche subsided locally and collapsed into sinks. Lacustrine deposits represented by the Tahoka Formation accumulated in the area in the Late Pleistocene, as did alluvial and valley fill deposits in the two structural troughs. During Holocene time, eolian deposition has predominated.

Groundwater conditions

The general flow of groundwater in Lea County is to the southeast, based on pre-development water elevation data. In Lea County, the Pecos Valley Aquifer equivalent covers approximately 9,600 acres and has an average saturated thickness of about 300 feet. Its thickness is greatest near the City of Jal, but thins at most other locations. Transmissivity values for the aquifer range from 2,140 to 3,075 square feet per day, with depth to water ranging from 50 to 100 feet. In a water well field in the City of Jal, the saturated thickness of the aquifer is reported to exceed 500 feet, with a transmissivity of 2,400 square feet per day and an average effective porosity of 16 percent. A pump test from a City of Jal municipal well produced flow of 450 gallons per minute for 36 hours.

In Eddy County in the Carlsbad Groundwater Basin, the alluvium ranges up to 500 feet thick. Well yields vary significantly from 2 to 3,500 gallons per minute. Groundwater flow is more directed centrally towards the Pecos River Valley.

Discharge from the aquifer is mainly through groundwater pumping, although evapotranspiration along the Pecos River Valley and discharge into the Pecos River are also factors. Evapotranspiration losses are mainly due to uptake by phreatophytes such as mesquite and salt cedar, which can be substantial. Recharge is from infiltration of surface water in uplands and along channels of ephemeral streams. Flow from the Rustler Formation may also be occurring and contributing to increased salinity in the overlying sands alluvium (New Mexico Interstate Stream Commission, 1999).

Salinity values for the alluvial aquifer in Lea County vary widely from 130 to 9,750 milligrams per liter. Fluoride concentrations tend to be high, ranging from 0.3 to 10 milligrams per liter and chlorides can be very high, ranging from 5 to 7,500 milligrams per liter. Sodium concentrations approach 70 milligrams per liter and sulfate concentrations are low, ranging from 30 to 120 milligrams per liter (New Mexico Interstate Stream Commission, 1999).

Groundwater storage for the aquifer has not been determined, although in the 15-square mile area of the Jal Underground Water Basin, there is an estimated 476,160 acre-feet of water in the alluvial aquifer (New Mexico Interstate Stream Commission, 1999). Overall groundwater use for Lea and Eddy counties includes water for municipalities, agriculture, livestock, oil and gas development, and potash mining. This groundwater use is not differentiated, and it includes the Capitan Limestone and the Cenozoic alluvium groundwater.

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A18 - Queen City Aquifer (Texas/Arkansas/Louisiana)

The Cane River Formation of southern Arkansas and northern Louisiana is equivalent to the Reklaw Formation, the Queen City Sand, and the Weches Formation of Texas (Figure A18-1).

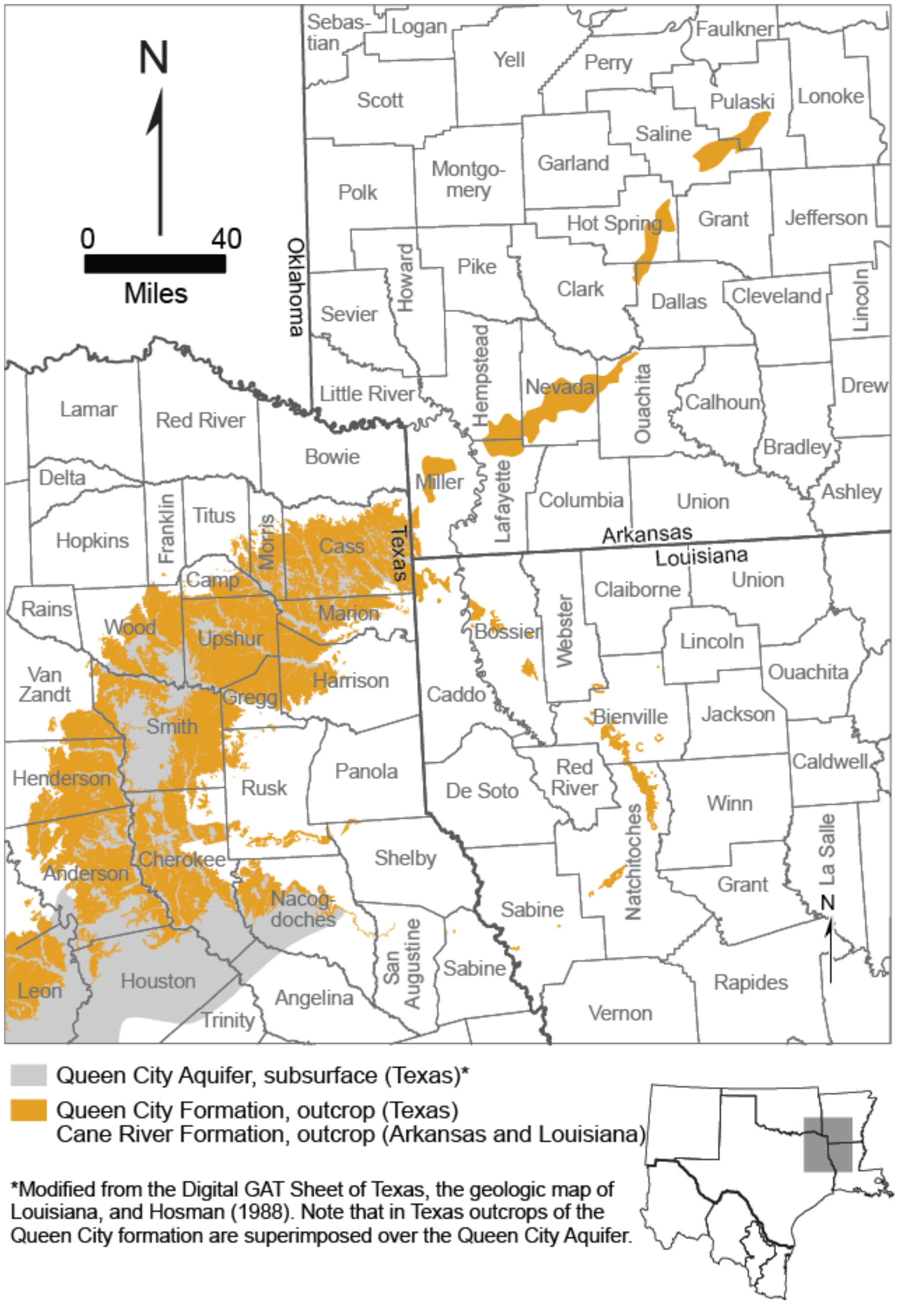

Figure A18-1. Queen City Aquifer and equivalents in Texas, Arkansas, and Louisiana.

Geologic conditions

The Reklaw and Weches formations are mainly marine shales, and much of the Cane River Formation was deposited under marine conditions. However, there are areas where the Cane River Formation is sandy and acts as an aquifer. Aside from the areas with sand deposits, the Cane River Formation consists mainly of shale and clay with some interbedded sand, silt, marl, and lignite. The sands are fine-grained, micaceous, locally glauconitic and fossiliferous, and thin-bedded.

In south-central and southwestern Arkansas and in north-central and northwestern Louisiana, the regional dip of the Cane River Formation is to the east and southeast at 25 to 50 feet per mile into the Mississippi Embayment and Desha Basin. The formation thins over the Sabine Uplift in northwestern Louisiana, as the Queen City Formation does in East Texas (Figure A18-2). The formation also thins to about 70 feet in La Salle Parish, Louisiana. Along the central parts of the Mississippi Embayment and Desha Basin, the formation is about 400 to about 600 feet thick, reaching 650 to 750 feet in Desha County in southeastern Arkansas. Maximum sand-unit thickness of the formation in northwestern Louisiana is about 25 to 50 feet, increasing to 50 to 125 feet in southeastern Arkansas.

Groundwater Conditions

The Cane River Formation is an aquifer in northwestern Louisiana and parts of Arkansas (Figure A18-3). Because the sand bodies are poorly connected, the aquifer may only supply water for short periods of time until water levels recover. In other parts of Louisiana and Arkansas, the formation is considered an aquitard due to high clay content. The Cane River Formation is mainly recharged by precipitation over outcrop areas in Arkansas, Louisiana, and Mississippi (Figure A18-4). Some recharge may occur through upward flow from Wilcox Group rocks. Discharge, other than withdrawal from wells, occurs by upward leakage through confining beds and losses to streamflows (Payne, 1972).

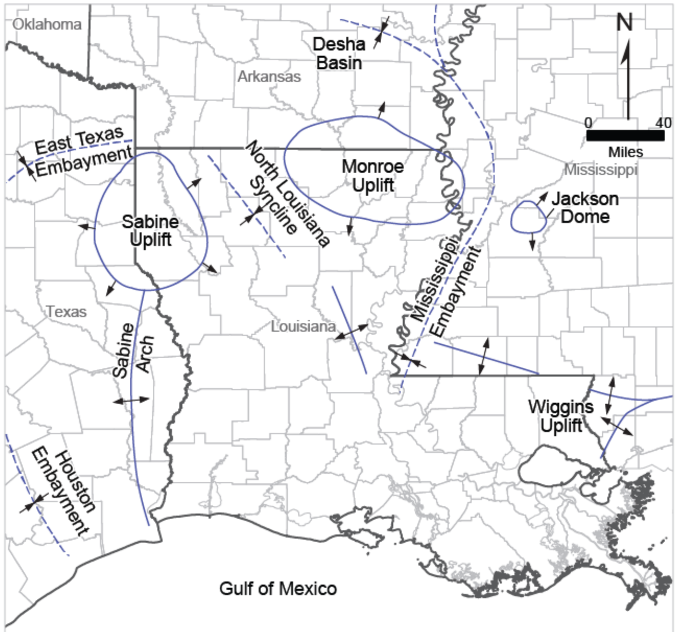

Figure A18-2. Major structural features in and surrounding Louisiana (modified from Hosman, 1988).

Regional groundwater flow in southern Arkansas and northwestern Louisiana is down dip (regional) to the south and southeast. Regional flow is accompanied by increasing salinity. Near the outcrop areas total dissolved solid values increase from 1,000 to 3,000 milligrams per liter. Water from sands near the outcrop areas generally show a higher proportion of calcium and magnesium, while farther downdip sodium becomes the dominant cation. Chloride makes up a significant proportion of the total anion concentration. Because sand bodies in this part of the Gulf Coast are oriented normal to flow, flushing of these layers is limited. Farther to the east, where sand bodies are more oriented parallel to flow, flushing lowers salinity values. In Ouachita County, Arkansas, high salinity values may be attributed to faults impeding flushing of Cane River sands (Payne, 1972).

System	Series	Stratigraphic units of southern Arkansas and northern Louisiana		Stratigraphic units of northeastern Arkansas
Tertiary	Eocene	Jackson Group, undifferentiated		Jackson Group, undifferentiated
		Claiborne Group	Cockfield Formation	Memphis Sand
			Cook Mountain Formation	
			Sparta Sand	
			Cane River Formation	
			Carrizo Sand	
	Paleocene	Wilcox Group, undifferentiated		Wilcox Group, undifferentiated

Figure A18-3. Stratigraphy of the Cane River Aquifer and related units (modified from Johnston and others, 2000).

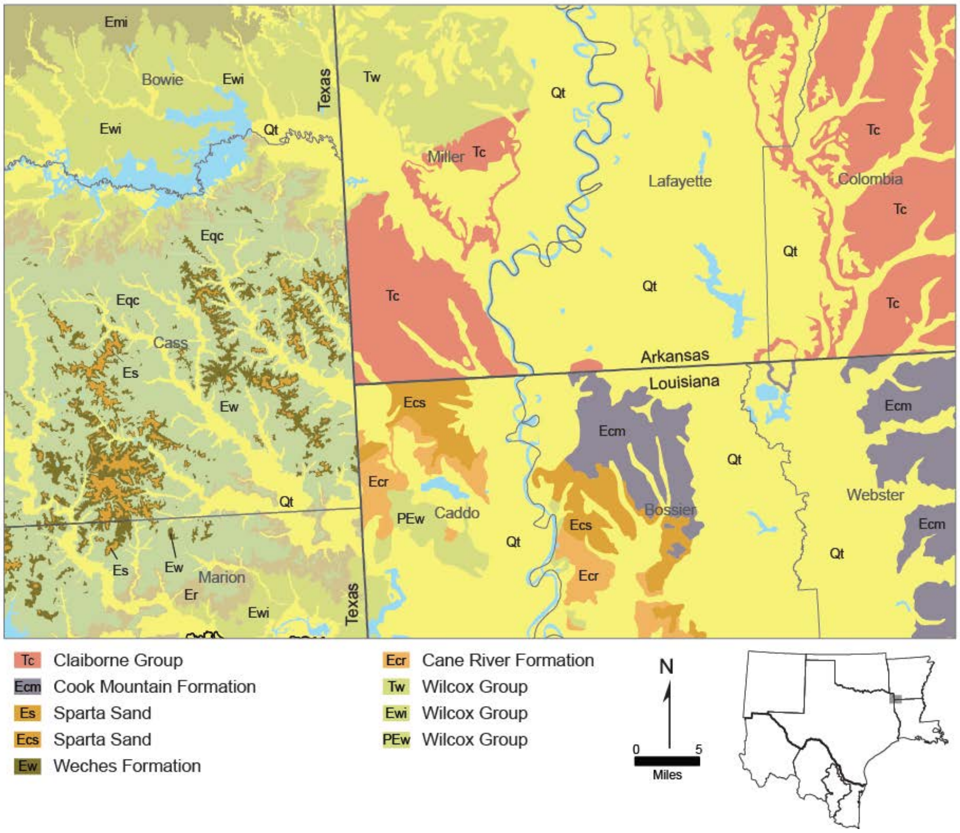

Figure A18-4. **Cane River Aquifer and related units in Arkansas, Louisiana, and Texas (modified from the 1:250,000 scale Geologic Atlas of Texas Sheets and the 1:500,000 scale geologic maps of Arkansas and Louisiana).**

Information on water use from the Cane River Formation is limited. One study described withdrawals of 5 million gallons per day from the aquifer in 1980 in Arkansas. Data from 2004 indicate only 0.55 million gallons per day of groundwater withdrawals in the state. In Louisiana, the Cane River Aquifer is not formally recognized so groundwater use data are not available.

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A19 - Rustler Aquifer (Texas/New Mexico)

The Rustler Aquifer consists of the Rustler Formation, which includes a variety of rock types including interbedded sulfate, carbonate, clastic, and halite (Figure A19-1).

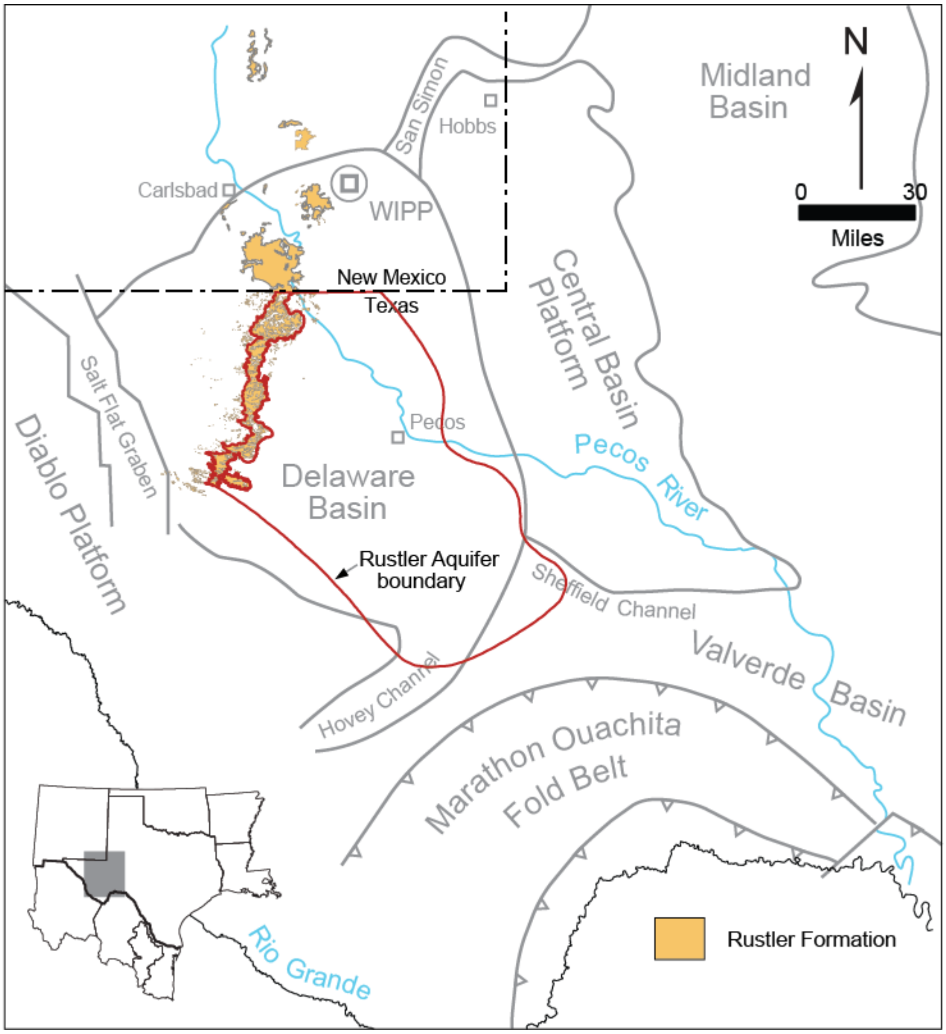

Figure A19-1. Rustler Aquifer in Texas and New Mexico and related geologic features (modified from Hills (1984) and Powers and Holt (1999)).

Geologic conditions

The Rustler Formation is subdivided into five members (Figure A19-2); the oldest is the Los Medaños Member, consisting of interbedded siltstone, sandstone, halite, and anhydrite. Two confining beds and two water producing units have been recognized within this unit. The Culebra Dolomite Member lies above Los Medaños Member and is the most transmissive hydrologic unit within the Rustler Formation. Near the Waste Isolation Pilot Plant (WIPP) site in New Mexico (Figure A19-1), the Culebra Dolomite member is a finely crystalline, locally argillaceous and arenaceous, vuggy dolomite that is about 25 feet thick. Above the Culebra

Dolomite member is the Tamarisk Member, composed of a mudstone sandwiched between two anhydrites, and above the Tamarisk Member is the Magenta Dolomite Member. The Magenta Dolomite Member is a fine-grained, gypsiferous, arenaceous dolomite. Finally, there is the Forty-niner Member, which is composed of two anhydrite and/or gypsum units separated by siltstone, mudstone, and claystone. The anhydrite/gypsum units act as confining beds, while the claystone is a water-producing unit.

The Rustler Formation lies above the Salado Formation and below the Dewey Lake Formation (Figure A19-2). The former was deposited within a subsiding Delaware Basin as evaporites accumulating in a shallow lagoon. The Salado Formation mostly consists of halite but also has thin beds of anhydrite, polyhalite, shale, and potash-bearing salts. Its contact with the Rustler Formation is conformable in the central part of the Delaware Basin, but unconformable and characterized by dissolution features along the basin's northern and western margins. The dissolution of Salado evaporites is evidenced by thickness changes in the overlying Rustler Formation as sediments filled in collapse structures. In some places, such as near the Capitan Reef escarpment, the Salado Formation is entirely missing and the Rustler Formation lies directly on the Castile Formation. Resting unconformably above the Rustler formation is the 100 to 500-foot-thick siliciclastic red-bed sequence of the Dewey Lake Formation. Dewey Lake rock types consist mainly of reddish-brown, fine-grained sandstone, siltstone, and silty claystone.

System/ Series		Formation/ Members		Formation/ Members	
		Eddy County, NM		Culberson and Reeves Counties, TX	
TRIASSIC		Santa Rosa		Dockum	
PERMIAN	Ochoan	Dewey Lake		Dewey Lake	
		Rustler	Forty-niner	Rustler	Forty-niner
			Magenta Dolomite		Magenta Dolomite
			Tamarisk		Tamarisk
			Culebra Dolomite		Culebra Dolomite
			Los Medaños		Lower Gypsum & Mud
					Siltstone
		Salado		Salado	
		Castile		Castile	

Figure A19-2. Rustler Formation stratigraphy and other units in New Mexico (Powers and Holt, 1999) and Texas (Hentz and others, 1989).

The Rustler Formation dips to the east due to late Mesozoic and Cenozoic uplift of the western part of the Permian Basin. It varies in thickness from tens of feet, where exposed in the west, to over 500 feet in the northeastern part of the Delaware Basin. Where the unit crops out or is in the shallow subsurface it has been extensively affected by karst processes. In Lea and Eddy counties the formation also dips to the east-southeast (Figure A19-3).

Groundwater conditions

There is little evidence of significant recharge to the Rustler Formation, although there is the possibility of some recharge from precipitation and by seepage from surface water features such as the Pecos River. The aquifer appears not to be at steady-state but instead is draining, following a Late Pleistocene recharge event. Groundwater flow near the Eddy-Lea county line and the Waste Isolation Pilot Plant site is to the south and southwest, and much of the water discharges into the Pecos River through a series of springs. Generally, the direction of groundwater flow throughout much of the formation in the Delaware Basin is influenced locally by variations in the potentiometric surface caused by pumping or flowing wells, as well as by local characteristics of the formation affected by evaporite dissolution and collapse.

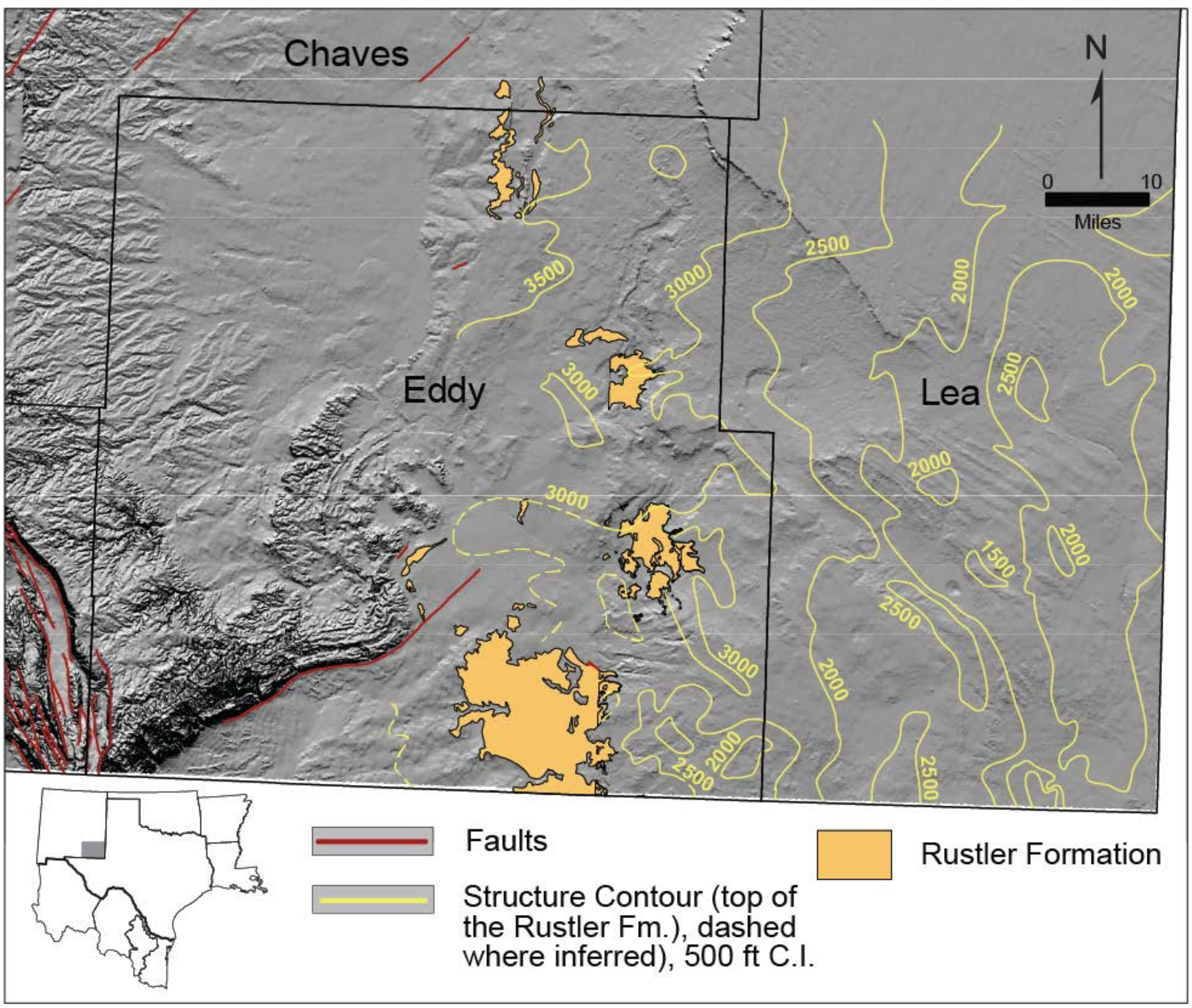

Figure A19-3. Structure contour map for Rustler Formation top in New Mexico (modified from Hiss (1976)).

The hydraulic characteristics of the Rustler Formation reflect the lithologic variability between members, as well as the distribution of dissolution features within the formation. Testing of mudstones and siltstones of the Los Medaños Member near the Waste Isolation Pilot Plant site indicates hydraulic conductivity ranges of 2.86×10^{-9} to 2.86×10^{-4} feet per day. The Culebra Dolomite Member, however, is a much more transmissive hydrologic unit. Internally it also is highly variable, as much as six orders of magnitude in transmissivity across the Waste Isolation Pilot Plant site, from less than 0.004 to 1.25×10^{3} feet squared per day. Most of the permeability in the Culebra Dolomite is along fractures, and transmissivity appears to be related to degrees of fracturing. The overlying Tamarisk Member appears to have extremely low hydraulic conductivity, while that of the Magenta Dolomite is much higher. Hydraulic tests of the dolomite at numerous locations indicate transmissivity values less than or equal to 0.1 feet squared per day. Transmissivities reported for the claystone range from 0.0025 to 0.071 feet squared per day.

The Rustler Formation produces brackish to saline groundwater and is highly variable in terms of water quality. The total dissolved solids concentrations of groundwater produced from the basal portion of the Rustler Formation, near the contact with the underlying Salado Formation, ranges from 311,000 to 325,800 milligrams per liter total dissolved solids. Groundwater produced from the Culebra Dolomite and the Magenta Dolomite Members ranges from 23,721 to 118,292 milligrams per liter and 10,347 to 29,683 milligrams per liter, respectively. The high total dissolved solids concentrations are generally attributed to the presence of gypsum beds within the formation.

Groundwater produced from the Rustler Formation is primarily used for stock watering and secondary recovery of oil. It is also an important source of water for potash mines and small-scale irrigation near Carlsbad, New Mexico. Wells generally yield from 10 to 300 gallons per minute. Estimates for groundwater in storage in Lea County range from about 630 to 760 acre-feet. There are no such similar estimates for the formation in Eddy County.

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A20 - Seymour Aquifer (Texas/Oklahoma)

The Seymour Aquifer includes many of the alluvial aquifers that occur along rivers in Oklahoma (Figure A20-1). Those rivers that extend into Texas include the Canadian, the Washita, the North Fork of the Red, and the Red.

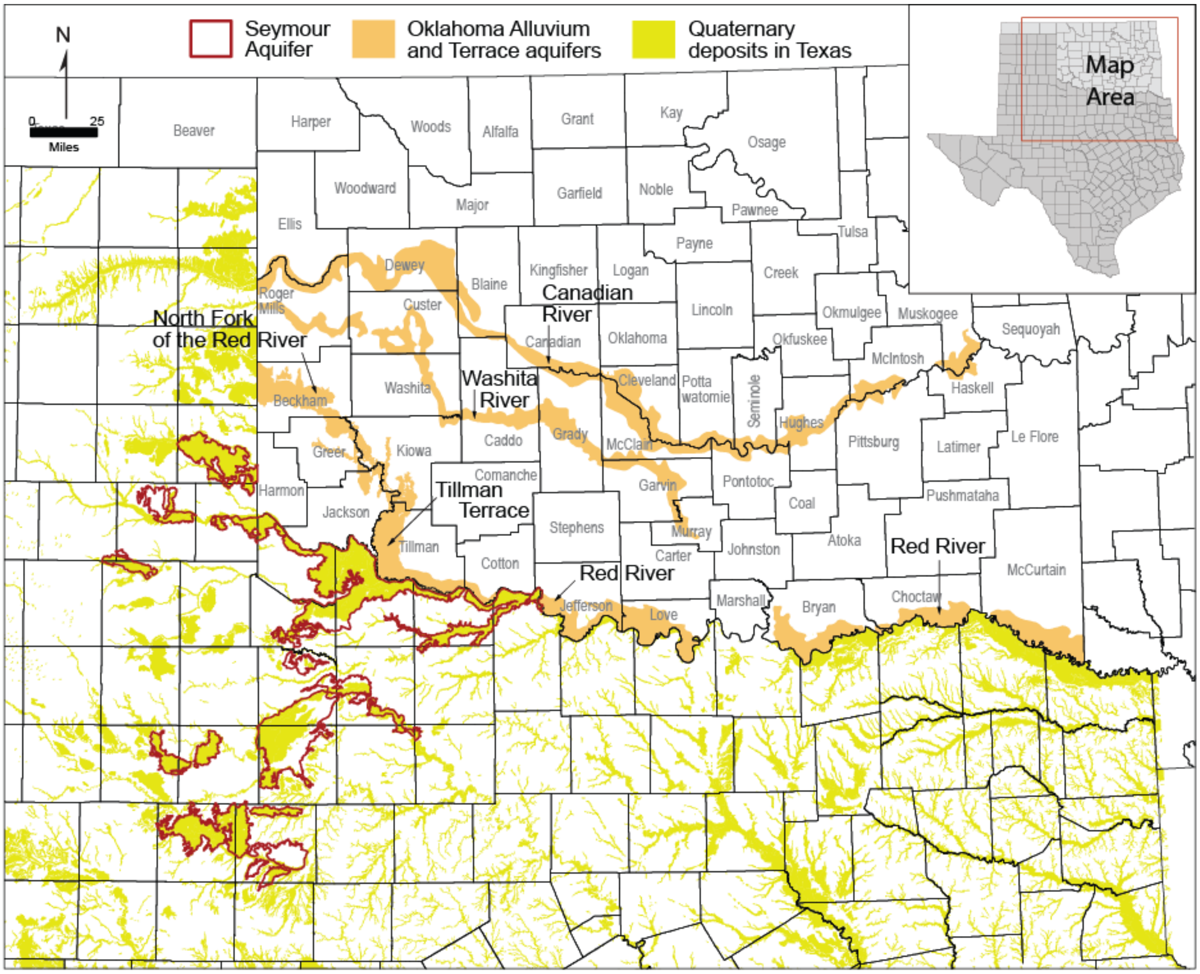

Figure A20-1. Oklahoma Alluvium and Terrace aquifers and Seymour Aquifer in Texas.

Geologic conditions

In Oklahoma during Paleogene, Neogene, and Quaternary time, downcutting and deposition by rivers produced stacked alluvial terraces, along with recent deposits of alluvium confined to present flood plains. The alluvium and alluvial terraces commonly form a single aquifer, while some outlying alluvial terraces are hydraulically separate. Highly permeable windblown sand overlies many of these deposits, which allows for enhanced recharge from precipitation (Ryder, 1996).

The alluvium and terrace deposits extend from 1 to 15 miles from the river banks and their thickness ranges from a few feet to about 200 feet (OWRB, 2007). These deposits consist of sand

and gravel with some clay and silt. The coarser grained sand and gravel form lenses that provide significant amounts of water in parts of Oklahoma throughout the year.

Groundwater conditions

Natural recharge to the aquifers occurs from precipitation that falls directly on the alluvial deposits, by infiltration of runoff from adjacent slopes, and by infiltration from the streams that cross the deposits, especially during higher flows. Additional recharge may occur from stream infiltration when groundwater pumpage lowers the water table below the stream levels. Discharge during dry periods is from the alluvium into the streams, thus contributing to base flow. Discharge also occurs as transpiration from phreatophytes.

Under natural conditions, groundwater flows from recharge areas where precipitation infiltrates the alluvial terraces downgradient to where it discharges as baseflow. The relatively short distance from the recharge area to the discharge points accounts for the fresh quality of the groundwater. Most of the groundwater from the alluvium and terrace deposits has less than 1,000 milligrams per liter total dissolved solids concentrations. Water from the aquifers is typically very hard. Groundwater is generally withdrawn primarily for irrigation and domestic supply. In some areas, public supply is limited due to high nitrate, chloride, and sulfate levels.

Wells yields from the alluvial aquifers are generally greater than yields of wells drawing from underlying bedrock. Alluvium and terrace deposits in Oklahoma are estimated to have an approximate average yield of 100 to 300 gallons per minute in the western parts of the state, 100 to 500 gallons per minute in the central parts of the state, and 20 to 1,000 gallons per minute in the east. Locally, some wells produce several thousand gallons per minute.

The Oklahoma Water Resources Board (2007) indicates that average levels in the state’s major aquifers have declined in virtually all areas from 2001 through 2006. Mean water level changes for alluvium and terrace aquifers include -4.68 feet for the North Fork Red River, -5.64 feet for the Washita River, -2.49 feet for the Red River, and -2.79 feet for the Canadian River (Oklahoma Water Resources Board, 2007).

Groundwater conditions in each of the state’s primary terrace deposit aquifers are described separately in the following paragraphs.

Canadian River—The alluvial terraces along the Canadian River are about 50 feet above the flood plain. The terraces, along with the alluvium, consist of clay, silt, sand, and basal gravel and are as much as 80 feet thick. Dune sands cover much of these deposits, which facilitate recharge from precipitation.

The alluvial deposits of the Canadian River contain a large amount of fresh water. Well yields are as much as 500 gallons per minute. However, the chemical quality of the water is highly mineralized in places, which limits its use for wide-scale development.

Groundwater recharge in the Norman area is about 8 inches per year, or about one-fourth of normal annual precipitation. The specific yield of the saturated deposits is estimated to be 15 percent, and the average hydraulic conductivity of the aquifer is 134 feet per day.

Washita River—Alluvium and alluvial terrace deposits along the Washita River are on the order of 2 to 3 miles wide and 50 to 120 feet in thick. Depth to water in the alluvium is generally less than 20 feet and wells are commonly between 50 and 100 feet in depth. Well yields completed in alluvium are about 100 to 300 gallons per minute and 20 to 100 gallons per minute from wells completed in the alluvial terraces.

Recharge to older terrace deposits is mainly from local precipitation and runoff from adjacent uplands. During high river stages, river water also recharges the aquifer. Natural discharge from the alluvium enters the Washita River as base flow.

Groundwater from this aquifer is used for municipal, industrial, and irrigation supplies. The water is usually a calcium-magnesium bicarbonate type with total dissolved solids concentrations of less than 1,000 milligrams per liter.

North Fork Red River and Red River—Quaternary alluvium and alluvial terraces are an important water source along the North Fork Red River. Wells completed in terrace deposits supply water for municipal, industrial, rural domestic, and agricultural uses. In central Beckham County, the alluvial terraces consist of varying proportions of clay, silt, sand, and gravel. The terraces are underlain by poorly permeable Permian rocks and overlain by highly permeable dune sands. The maximum width of the saturated part of the deposits is about 7 miles. The terraces range from 18 to 195 feet in thickness and average about 70 feet. The saturated part averages about 33 feet in thickness. The water table in the alluvial terraces of central Beckham County slopes toward the North Fork Red River, and water discharges from the aquifer to the river.

Yields from wells in the alluvial terrace deposits are from 200 to 500 gallons per minute. The groundwater is slightly saline, and concentration of total dissolved solids range from 1,000 to 2,000 milligrams per liter.

Tillman Terrace—The Tillman Terrace Groundwater Basin encompasses about 290 square miles in western Tillman County (Figure A20-2). Unconsolidated alluvium and terrace deposits of Quaternary age rest unconformably on the eroded surface of Permian redbeds. The terrace deposits resting on the Permian bedrock are composed of small gravel, sand, silt, and clay. Terrace deposits above these lower sediments are composed of light red and reddish-brown sand and gravel. The gravel is composed predominantly of quartz pebbles with some shale. Layers of caliche as much as a foot thick occur throughout the deposits. Recent alluvium deposits consist of dark-gray to red sand and silt, clay, and gravel eroded from bedrock and alluvial terrace sediment. The gravel and very coarse sand make up most of the saturated portion of the alluvium. Thickness of the alluvium ranges from 27 to 47 feet, and averages 34 feet. Dune sands occur along the western side of the terrace deposits, ranging in thickness from 15 to 69 feet and averaging 46 feet.

Recharge to the Tillman Terrace aquifer occurs through infiltration of precipitation. The sandy soil in the area facilitates high infiltration rates, while discontinuous layers of clay and caliche slow the rate down. The average recharge rate for the area is estimated at 2.87 inches per year, or about 12 percent of the mean annual precipitation. Recharge to the aquifer also occurs from infiltration of surface water along streams when the water table is lower than the river stage. Some water is also recharged by subsurface inflow from alluvium and terrace deposits that extend north of the area.

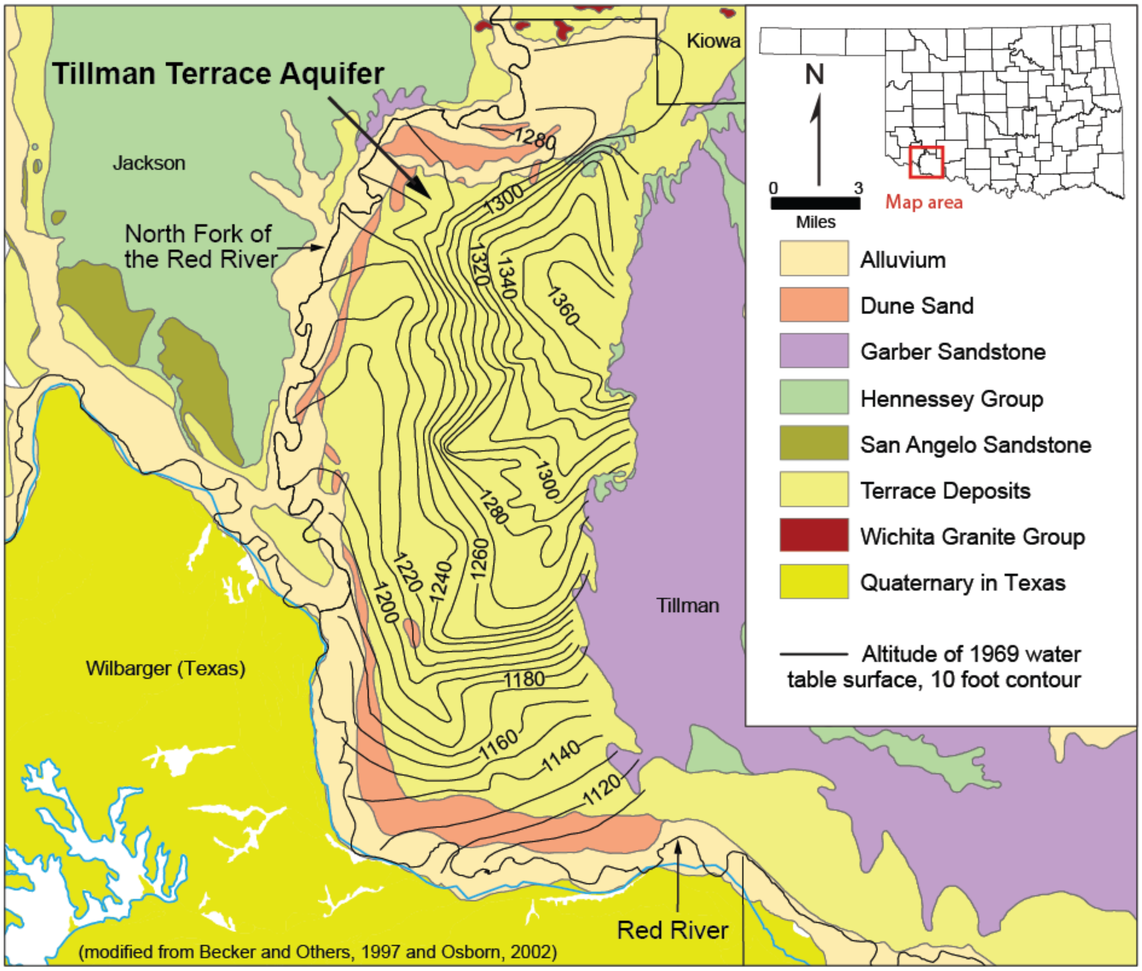

Figure A20-2. Extent of the Tillman Terrace Aquifer.

Natural discharge from the aquifer is to rivers and streams where the water table is higher than the river stage. Groundwater discharges to springs and seeps along the terrace-redbed (Garber Sandstone) contact in the eastern part of the area. Some groundwater discharges as evapotranspiration, as evidenced by the occurrence of saline seeps and cottonwood and willow trees along stream valleys. Discharge also occurs by subsurface outflow to the southeast into the alluvium and terrace deposits of the Red River.

Depth to water in the Tillman Terrace Aquifer ranges from about 5 to 45 feet. Groundwater flow is toward streams to the north, west, and southeast at an average hydraulic gradient of about 0.003 (Figure A20-2). Estimates of average transmissivity for the aquifer range from 1,750 to

2,680 square feet per day. Estimates of hydraulic conductivity range from 20 to 300 feet per day, and those for specific yield are between 0.10 and 0.32. Basin storage in 2000 has been estimated to be about 1,283,000 acre-feet assuming an area of 186,000 acres, an average saturated thickness of 23 feet, and an average specific yield of 0.30. Wells in the area are drilled to an average depth of about 50 feet. On average, irrigation wells yield 400 gallons per minute, but can produce up to 1,000 gallons per minute given favorable permeability and saturated thicknesses.

Concentrations of total dissolved solids for the aquifer range from about 400 milligrams per liter to 4,000 milligrams per liter, with a median total dissolved concentration of about 790 milligrams per liter. The major cations are sodium, calcium, and magnesium, while the major anions are chloride and sulfate. In general, the groundwater changes from a mixed-bicarbonate type in the east to a sodium-chloride type in the west. Sodium chloride and sulfate waters from terrace deposits are likely from recharge from river water or from upward leakage from underlying Permian geologic units.

Groundwater from the aquifer is used primarily for irrigation, but also for public water supply, mining, stock, and domestic purposes. From 1980 to 1999 reported groundwater use declined, though use increased from about 7,000 acre-feet in 1998 to about 10,000 acre-feet in 1999.

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A21 - Sparta Aquifer (Texas/Arkansas/Louisiana)

The Sparta-Memphis Aquifer is an aquifer of regional importance within the Mississippi Embayment Aquifer System, as defined by the U.S. Geological Survey. It extends from south Texas, north into Louisiana, Arkansas, and Tennessee, and eastward into Mississippi and Alabama (Figure A21-1). In Texas, the aquifer is referred to singularly as the Sparta Aquifer because the Memphis Sand is a stratigraphic term for a formation in northeast Arkansas and areas east. In southeastern Arkansas and north-central Louisiana, the aquifer covers more than 32,500 square miles and is a major source of water for municipal, industrial, and agricultural uses.

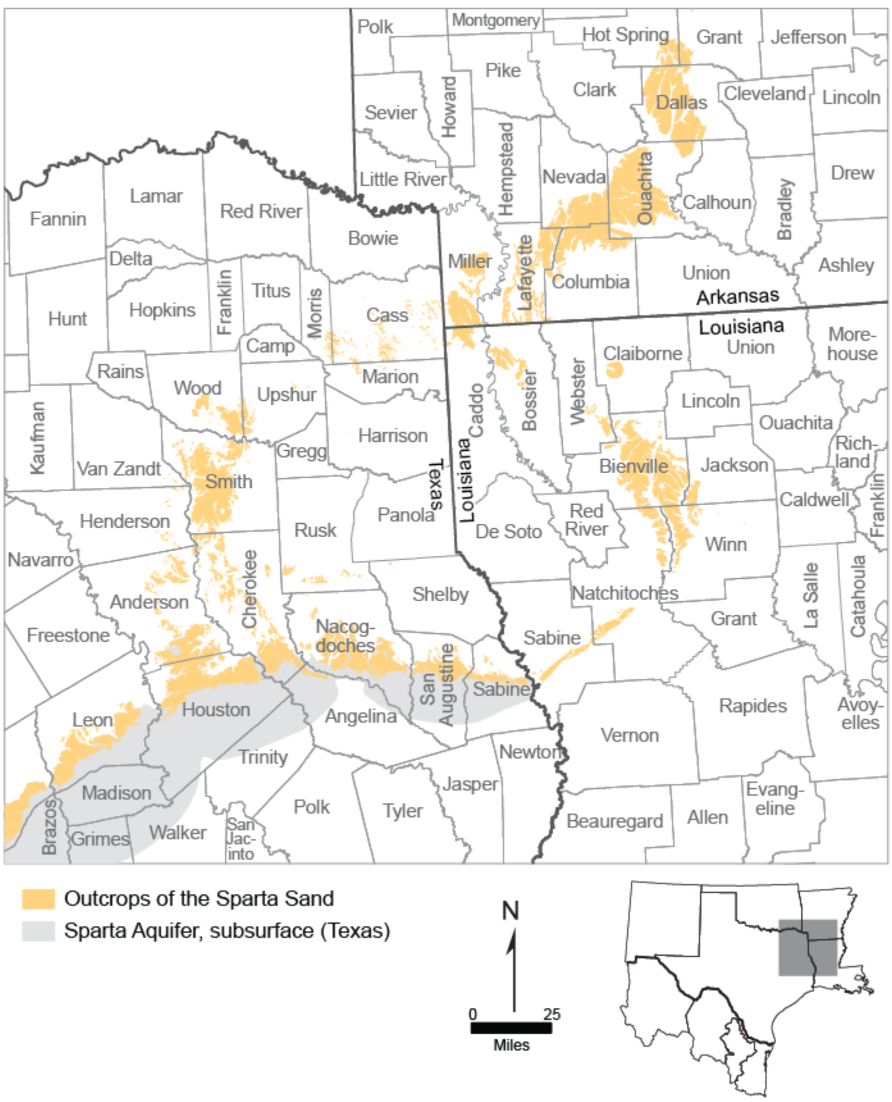

Figure A21-1. Sparta Aquifer and Sparta Sand in Texas, Arkansas, and Louisiana.

Geologic Conditions

In southern Arkansas and northern Louisiana, the aquifer consists of unconsolidated sediments of the Sparta Sand (Figure A21-2), part of the Eocene-age Claiborne Group. The Sparta Sand is composed mainly of fine to medium sand, with some silt, clay, and lignite in upper parts of the formation. The sand was deposited by meandering streams on a fluvial-deltaic flood plain is also characterized by finer grained sediments deposited in lakes and swamps. The sand units are mostly interconnected, but separately identifiable sands can be traced for short distances. The Cook Mountain Formation of Claiborne Group overlies the Sparta Sand and serves as an upper confining unit, and it is underlain by the Cane River Formation. The Cane River Formation acts as both confining unit and aquifer depending upon geographic location and lithology.

In Arkansas and Louisiana, the Sparta Sand is 50 to 200 feet thick within the outcrop (along its western limit) and thickens to the southeast to nearly 1,200 feet. Total sand thickness within the aquifer generally ranges from 200 to 600 feet. The Sparta Sand is unconfined in the outcrop area and confined as it dips at about 25 to 50 feet per mile eastward towards the Mississippi embayment and southward towards the Gulf of Mexico Basin. The Sparta Sand also thickens and thins over structures such as the Sabine Arch, Jackson Dome, and Mississippi embayment, all of which were structurally active during deposition.

System	Series	Stratigraphic units of southern Arkansas and northern Louisiana		Stratigraphic units of northeastern Arkansas
Tertiary	Eocene	Jackson Group, undifferentiated		Jackson Group, undifferentiated
		Claiborne Group	Cockfield Formation	Memphis Sand
			Cook Mountain Formation	
			Sparta Sand	
			Cane River Formation	
			Carrizo Sand	
	Paleocene	Wilcox Group, undifferentiated		Wilcox Group, undifferentiated

Figure A21-2. Sparta-Memphis Aquifer stratigraphy, Arkansas and Louisiana (modified from Johnston and others, 2000).

Groundwater conditions

Recharge to the Sparta-Memphis Aquifer occurs by infiltration of precipitation over outcrops, leakage from streams flowing across exposures, leakage from alluvium where the Sparta subcrops, and leakage from adjacent aquifers through confining layers where the vertical hydraulic gradient is towards the Sparta Aquifer. Aside from pumping, natural discharge is to streams in the outcrop and to adjacent formations with lower potentiometric surfaces.

Hydraulic conductivity ranges from 10 to 200 feet per day with an average of about 70 feet per day over the extent of the Mississippi embayment. Individual wells completed in the aquifer yield 100 to 500 gallons per minute.

A 2007 potentiometric map of the Sparta-Memphis Aquifer indicates that the natural direction of regional groundwater flow is towards the axis of the Mississippi Embayment (Figure A21-3). The natural direction of flow has been altered in many areas by large groundwater withdrawals (Schrader and Jones, 2007). These withdrawals have produced some twenty cones of depression (Schrader and Jones, 2007). Five cones of depression with greater than 40 feet of water-level decline are centered at cities with large withdrawals for public supply and industrial uses (Schrader and Jones, 2007). The remainder represents withdrawal from areas near small and intermediate sized cities (Schrader and Jones, 2007).

The groundwater of the Sparta-Memphis Aquifer has been grouped into three chemical provinces: a bicarbonate water province, a chloride water province, and a sulfate water province. Groundwater from southwestern Arkansas and central and northern Louisiana lie within the bicarbonate province. There the bicarbonate distribution is a function of the rate of water movement and time. A greater degree of flushing, in areas of higher sand content, produces a greater proportion of bicarbonate.

Specific conductance data, which is related to total dissolved solids concentration in groundwater, indicate regionally diverse zones of mineralized water within the Sparta-Memphis Aquifer. Along the western border of the Sparta-Memphis Aquifer near the outcrop in Arkansas, groundwater has low specific conductance. From there specific conductance increases to the east and south, gradually increasing towards the Louisiana state line. In addition, there are some high specific conductance values near cones of depression located in Union and Columbia counties in southern Arkansas (Figure A21-3). The higher values may be caused by leakage of water with greater conductance from an underlying aquifer, such as the Nacatoch. Total dissolved solids concentrations data from northern Louisiana increase from about 100 parts per million to 1,100 parts per million from west to east across the state.

The Sparta-Memphis Aquifer supplies water for municipalities, industries such as paper production, and to a lesser amount irrigation of agricultural crops. Water use of the aquifer in Arkansas generally increased from 1980 to 2000. In 1980, water use was about 185 million gallons per day. In 2000, water use was about 287 million gallons per day, an increase of 55 percent. Water use from the Sparta-Memphis Aquifer in Louisiana was approximately 68 million gallons per day in 2000. Of that amount, approximately 38 million gallons per day (56 percent) was used for public supply, approximately 27 million gallons per day (40 percent) was used for industrial purposes, and the remaining 3 million gallons per day (4 percent) was used for rural domestic, livestock, irrigation, and aquaculture.

In both Louisiana and Arkansas, long-term pumping stresses to the Sparta Aquifer have reduced amounts of water in storage, decreased well yields, produced regionally extensive water-level declines, and formed regional-scale cones of depression. This has caused concern about sustainability. To address this concern, the U.S. Geological Survey constructed a groundwater flow model to predict the effects of three hypothetical withdrawal scenarios on water levels over a 30-year period from 1998 to 2027. The results of the modeling scenario produce water level declines of 10 to 17 feet in southern Arkansas. Cones of depression continue to deepen and expand, and areas where water levels have dropped below the top of the Sparta Sand grow to 1,787 miles squared in size in Arkansas and 2,821 miles squared in Louisiana by 2027.

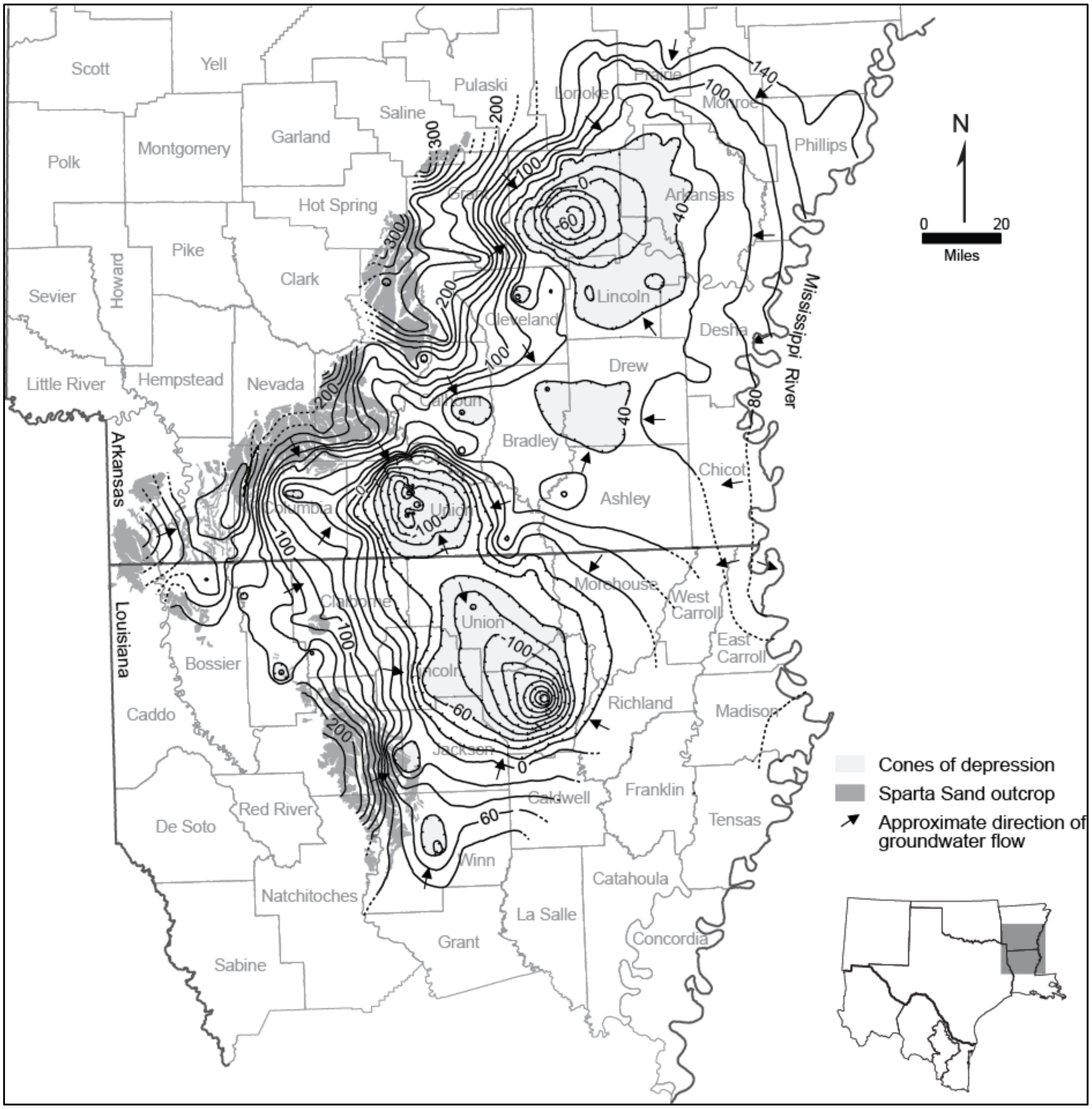

Figure A21-3. **Potentiometric surface contours (20 foot) in Sparta-Memphis Aquifer in Arkansas and Louisiana from 2007 (modified from Schrader, 2008).**

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A22 - Trinity Aquifer (Texas/Arkansas/Oklahoma)

The Trinity Aquifer extends from north-central Texas into Oklahoma, where it is known as the Antlers Aquifer (also known as the Antlers hydrogeologic basin), and is primarily defined by the extent of the Antlers Sandstone (Figure A22-1). It also includes the DeQueen Limestone and Holly Creek Formation in its easternmost part. The Antlers Sandstone is equivalent to that part of the Trinity Aquifer in north Texas that includes the Antlers Formation (Figure A22-2). To the south, in Texas, the Antlers Formation is equivalent to the Paluxy, Glen Rose, and Travis Peak/Twin Mountains formations. The area underlain by the Antlers Aquifer in southeastern Oklahoma covers about 4,400 square miles compared to about 5,400 square miles in Texas.

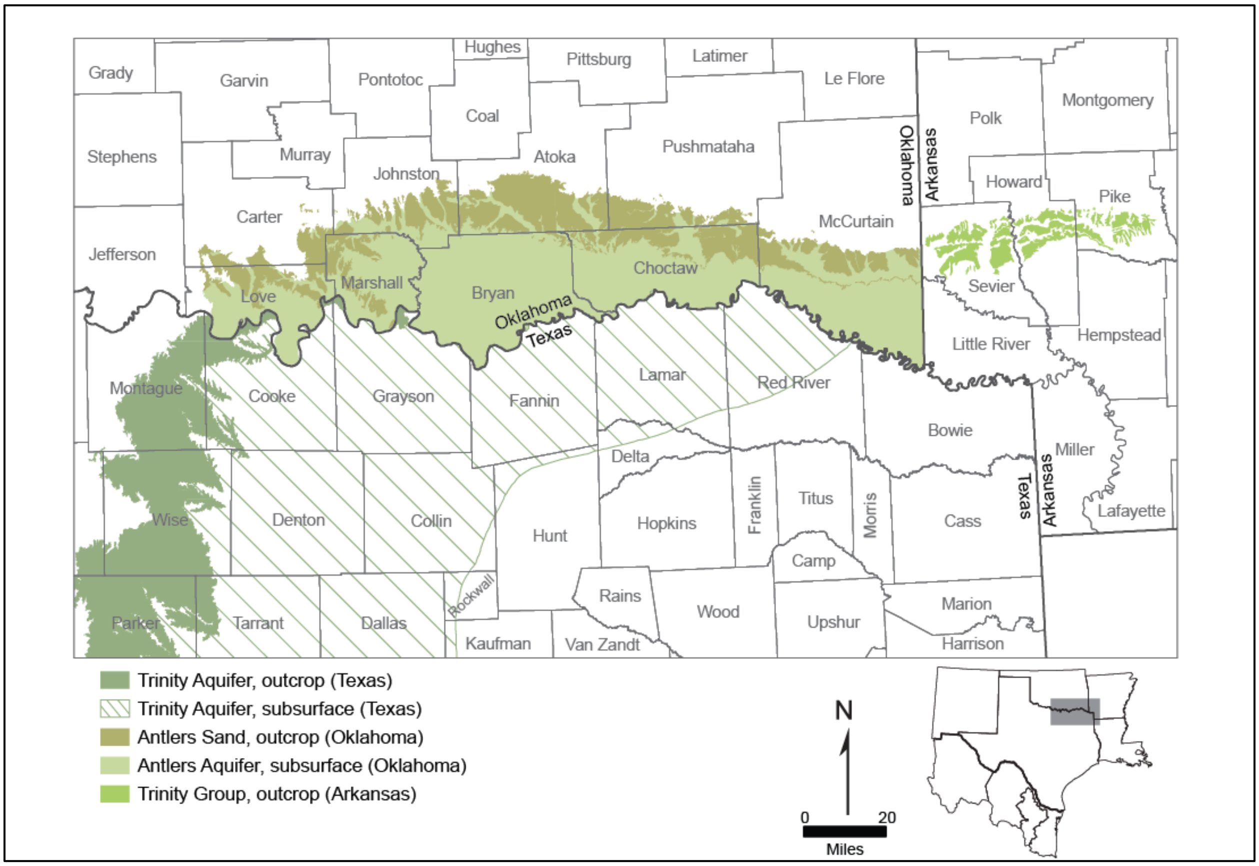

Figure A22-1. Antlers Aquifer in Oklahoma and equivalents in Texas and Arkansas (modified from Haley and others, 1993; Oklahoma Water Resources Board, 1997; and Harden and Associates, 2004).

Geologic conditions

The Antlers Aquifer is composed of the Early Cretaceous (late Aptian through early Albian) Antlers Sandstone, which outcrops along a west to east belt parallel to the Red River. Groundwater is unconfined within the outcrop and becomes confined in the subsurface to the south and further south into Texas. In outcrop, the Antlers Sandstone generally dips to the south and southeast at 30 to 80 feet per mile. In the subsurface, the maximum dip is about 200 feet per mile. Younger Cretaceous rocks overlie the Antlers Sandstone in the subsurface.

The Antlers Sandstone is a transgressive sheet of sand deposited along the shoreline of a slowly advancing sea. This sheet of sand unconformably overlies an erosional surface cutting older Paleozoic rocks. The basal unit of the Antlers Sandstone consists of conglomerate or calcareous-cemented sandstone. The conglomerate occurs locally in lens-like bodies throughout the lower part of the formation. The upper part of the Antlers Sandstone consists of beds of sand, weakly cemented sandstone, sandy shale, silt, and clay.

System	Series	Group	Formation: North-central Texas		Formation: Love County, Oklahoma
Cretaceous	Comanchean	Fredericksburg	Goodland		Goodland
			Walnut Clay		Walnut Clay
		Trinity	Paluxy	Antlers Sand	Antlers Formation
			Glen Rose		
			Travis Peak/ Twin Mountains		

Figure A22-2. Stratigraphy of the Trinity and Antlers aquifers, Texas and Oklahoma (Frederickson and Redman, 1965; Klempt and others, 1975; Nordstrom, 1987; and Harden and Associates, 2004).

The greatest percentage of sand compared to total thickness of the aquifer is in the outcrop area and just to the south (Figure A22-3). The sand makes up as much as 80 percent of the formation's total thickness, with the remaining 20 percent being clay. South and southeast of the outcrop, the percentage of the sand to total thickness decreases to less than 40 percent. The Antlers Sandstone also thickens southward so that even though the overall percentage of sand decreases southward, the composite thickness of sand increases. Saturated thickness in the Antlers ranges from several inches at the updip limit to probably more than 2,000 feet, 25 to 30 miles south of the Red River (Morton, 1992).

Groundwater conditions

Recharge to the Antlers Aquifer occurs through precipitation and seepage from bodies of surface water in the outcrop and from vertical and lateral movement of water from adjacent aquifers. Recharge has been estimated from winter stream discharge at an average of 1.7 inches per year. Discharge from the aquifer occurs by groundwater flow into streams, leakage to overlying porous rock, underflow out of Oklahoma to the south and southeast, and pumping. Increased streamflow in creeks draining the Antlers Aquifer area indicates that the Antlers Sandstone is actively discharging and supplying much of stream base flow. Measurements from six streams indicate total base flow at 30 cubic feet per second, or 21,720 acre-feet per year.

The potentiometric surface in the Antlers Aquifer slopes to the south-southeast except along streams, where the gradient is approximately perpendicular to them **(**Figure A22-4)**.** In confined parts of the aquifer, potentiometric contours still show groundwater flow toward northwest- to southeast-trending streams. This is an indication that the aquifer is leaking into overlying confining beds and that vertical hydraulic conductivity of these confining units is sufficient to allow groundwater to move into overlying or underlying units.

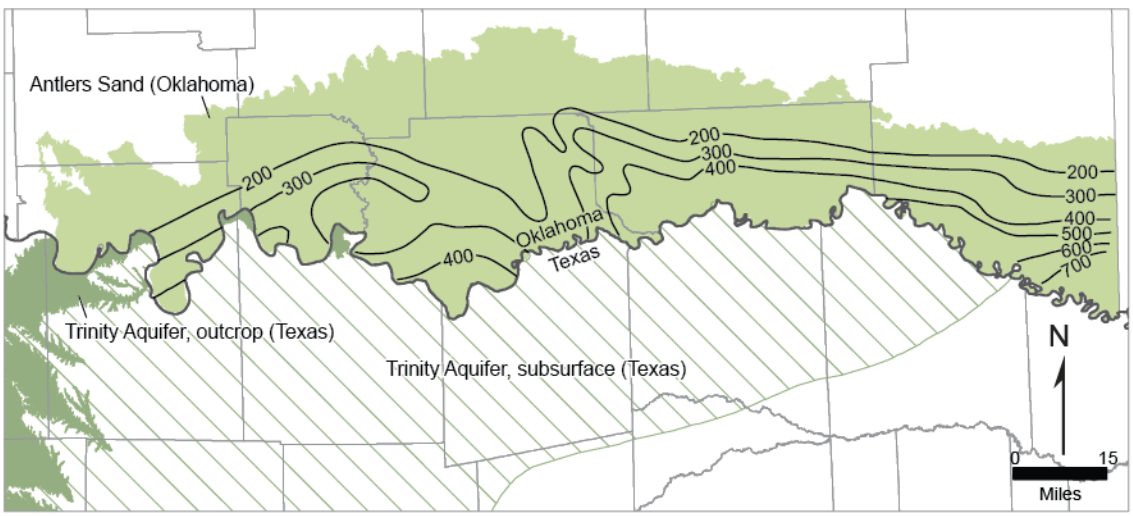

Figure A22-3. Map showing composite sand thickness of the Antlers Sandstone (modified from Hart, 1981).

Aquifer hydraulic conductivity values calculated from transmissivity values range from 0.87 to 3.75 feet per day. An average storage coefficient of 0.0005, based on aquifer tests, was determined for the confined part of the aquifer. A specific yield of 0.17 has been applied to the unconfined part of the aquifer.

Groundwater well yields range from 5 gallons per minute to 50 gallons per minute in the unconfined part of the aquifer and from 50 to 650 gallons per minute in the confined area to the south. An average yield for wells completed in the aquifer is 100 to 150 gallons per minute. Large capacity wells drawing from the aquifer commonly yield 100 to 500 gallons per minute, with reported production as high as 1,700 gallons per minute.

A total of 45 million acre-feet is estimated to be in storage in the aquifer, with 44.6 million acre-feet in the unconfined aquifer and 0.5 million acre-feet in the confined aquifer (Hart and Davis, 1981).

Water quality is good in the outcrop areas of the Antlers Sandstone and is suitable for industrial, municipal, and irrigation use. In these areas, from the upper part of the aquifer, the groundwater is fresh with total dissolved solids concentrations of less than 1,000 milligrams per liter. It has been estimated that about 32 million acre-feet of groundwater is fresh. However, downdip the quality of the water deteriorates somewhat and wells have total dissolved solids values that exceed 1,000 milligrams per liter.

Groundwater from the Antlers Aquifer is variable in terms of chemical composition. In areas where the Antlers Sandstone is exposed groundwater is sodium bicarbonate in type, as well as just downdip. As water moves downdip it changes into a sodium chloride type. Concentrations of most trace elements in groundwater from the Antlers Sandstone are lower than maximum limits set by the U.S. Environmental Protection Agency. Some wells exhibit high iron and magnesium levels above accepted levels.

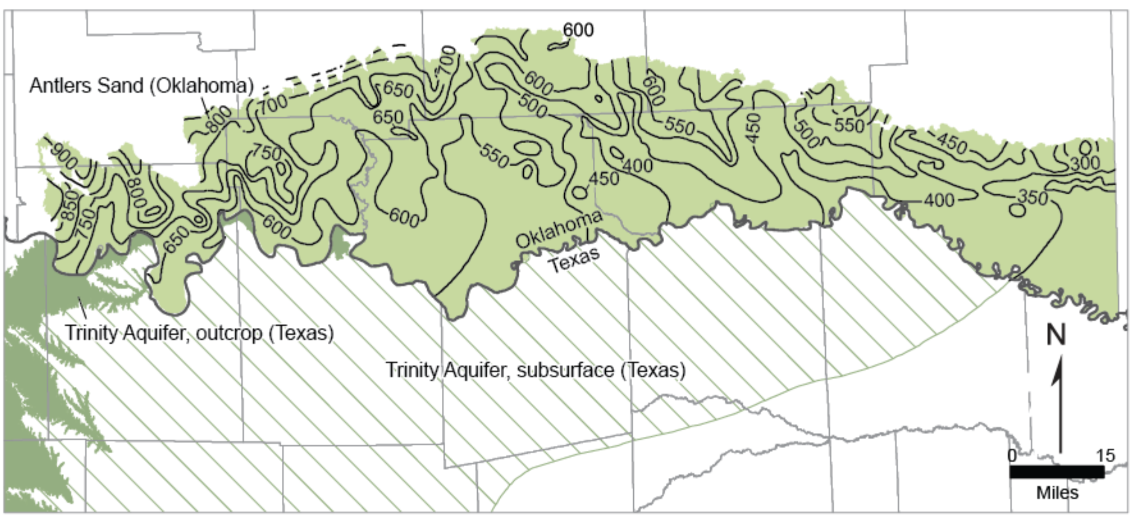

Figure A22-4. Water-level contours (50 foot) in 1970 of Antlers Sand in Oklahoma (modified from Morton, 1992; Abbott and others, 1997).

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A23 - Woodbine Aquifer (Texas/Arkansas/Oklahoma)

The rocks of the Woodbine Formation that make up the Woodbine Aquifer occur mainly in north-central Texas, but also in southern Oklahoma and southwestern Arkansas (see Figure A23-1). Unlike in Texas, the aquifer is not formally recognized in Oklahoma and Arkansas. The U.S. Geological Survey does include a combined Tokio-Woodbine Aquifer in their Groundwater Atlas of the United States, calling it a minor aquifer of southwestern Arkansas.

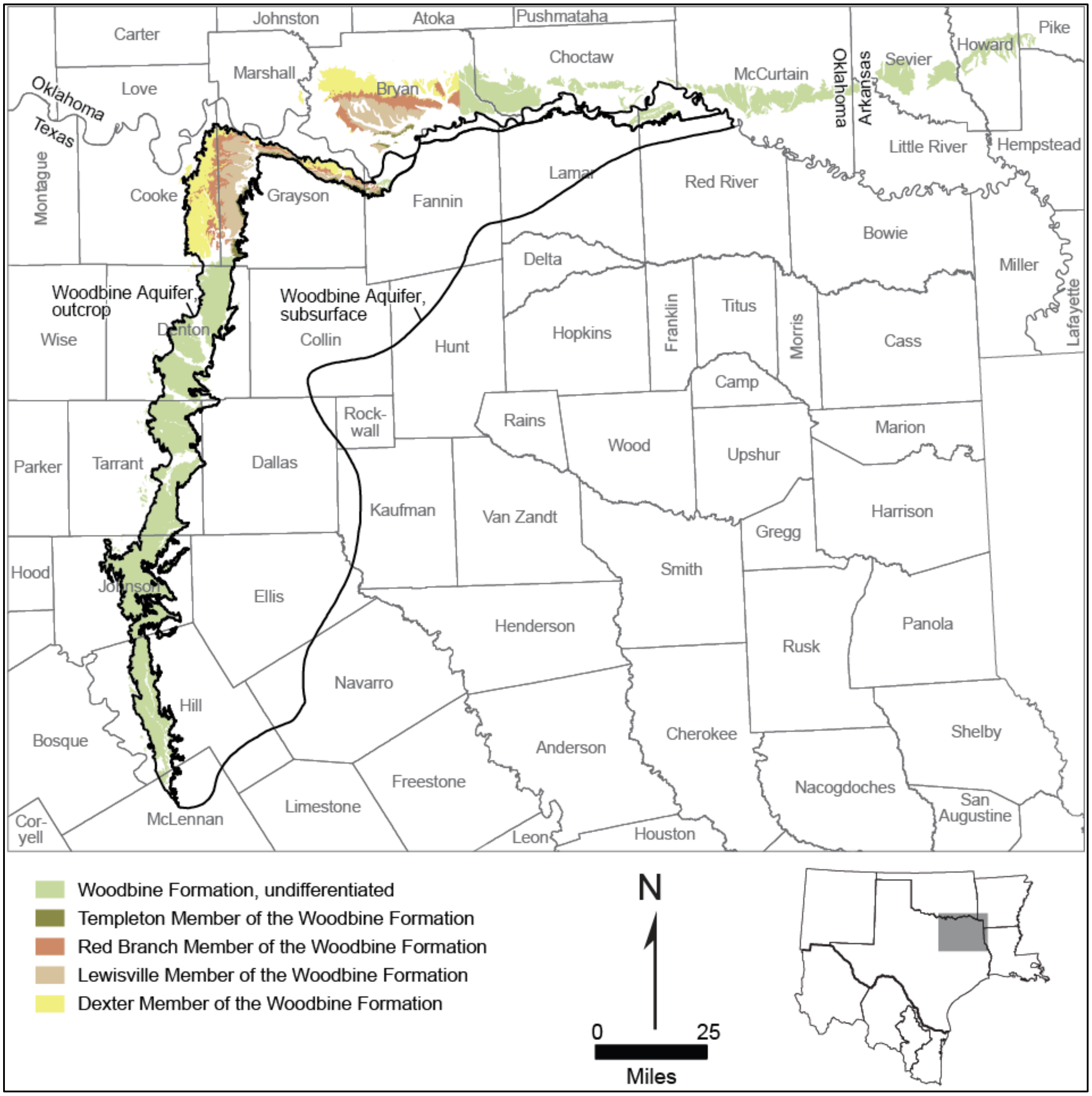

Figure A23-1. Woodbine Aquifer in north-central Texas, Oklahoma, and Arkansas.

Geologic conditions

In Texas, the Woodbine Formation is Late Cretaceous in age and is part of the Gulfian Series. It is composed of sand, silt, clay, and some gravel deposited in fluvial, high-destructive deltaic, and shelf-strand plain depositional systems. The Ouachita Mountains in southern Oklahoma and Arkansas were the source area of Woodbine sediments, which were subsequently deposited into the actively subsiding East Texas Basin. The Woodbine Formation is unconformably overlain by shale and limestone of the Eagle Ford Group throughout most of the region, which acts as a confining unit. In Cooke, Grayson, and Fannin counties near the Oklahoma border, the formation is subdivided into four members. The members in ascending order are: Dexter, Lewisville, Red Branch, and Templeton. The four members represent a change from an onshore to a more nearshore marine environment of deposition.

In Marshall County, Oklahoma, only 17 feet of the basal Dexter Member of the Woodbine Formation is exposed. It overlies the eroded surface of the marine Grayson Marlstone. The Dexter Member is composed of reddish-brown, ferruginous pebble conglomerate overlain by light-brown, fine-grained sandstone with medium-scale cross-bedding. To the east in Bryan County, all four members of the Woodbine Formation are exposed over an area of about 350 square miles. There, the Dexter Member includes 85 to 90 feet of yellow-brown, ferruginous, fine- to medium-grained, cross-bedded sandstone at its base and about 40 feet of varicolored shale above. The shale is overlain by about 60 to 70 feet of the Red Branch Member consisting of tuffaceous sandstones, ferruginous sandstones, carbonaceous sand, and lignitic coal. Above the Red Branch Member are 100 to 120 feet of the Lewisville Member that consists of red to yellow, ferruginous, glauconitic sandstones and tan to brown clay. The Templeton Member is primarily shale, blue-gray to black in color, with thin beds of yellow sandstone.

In Arkansas, the Woodbine Formation is composed of gravel, sand, clay, and water-laid volcanic tuff and ash. The basal part of the formation is composed of gravel-bearing beds of variable thickness. The overlying water-laid volcanic tuffs are sandy and cross-bedded. Rare leaf fossils are noted from some clay layers in the Woodbine Formation. The formation was deposited upon an unconformable surface separating the Early and Late Cretaceous and ranges from 0 to 350 feet in thickness.

Groundwater conditions

The Tokio-Woodbine Aquifer in Arkansas serves only as a local source of water for domestic use. The aquifer overlies and in places is hydraulically interconnected with the Trinity Aquifer. Fresh water in the Tokio-Woodbine Aquifer is very limited in Arkansas and is restricted to a narrow band that extends southward from the outcrop area. Factors that appear to control the occurrence of freshwater in the aquifer include the degree of incision by rivers in outcrop areas and a rapid downdip decrease in permeability as the aquifer extends southeast into the subsurface.

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A24 - Yegua-Jackson Aquifer (Texas/Louisiana/Mexico)

The Eocene Cockfield Formation in Louisiana and Mississippi is equivalent to the Yegua Formation in Texas, which makes up the lower part of the Yegua-Jackson Aquifer (Figure A24-1).

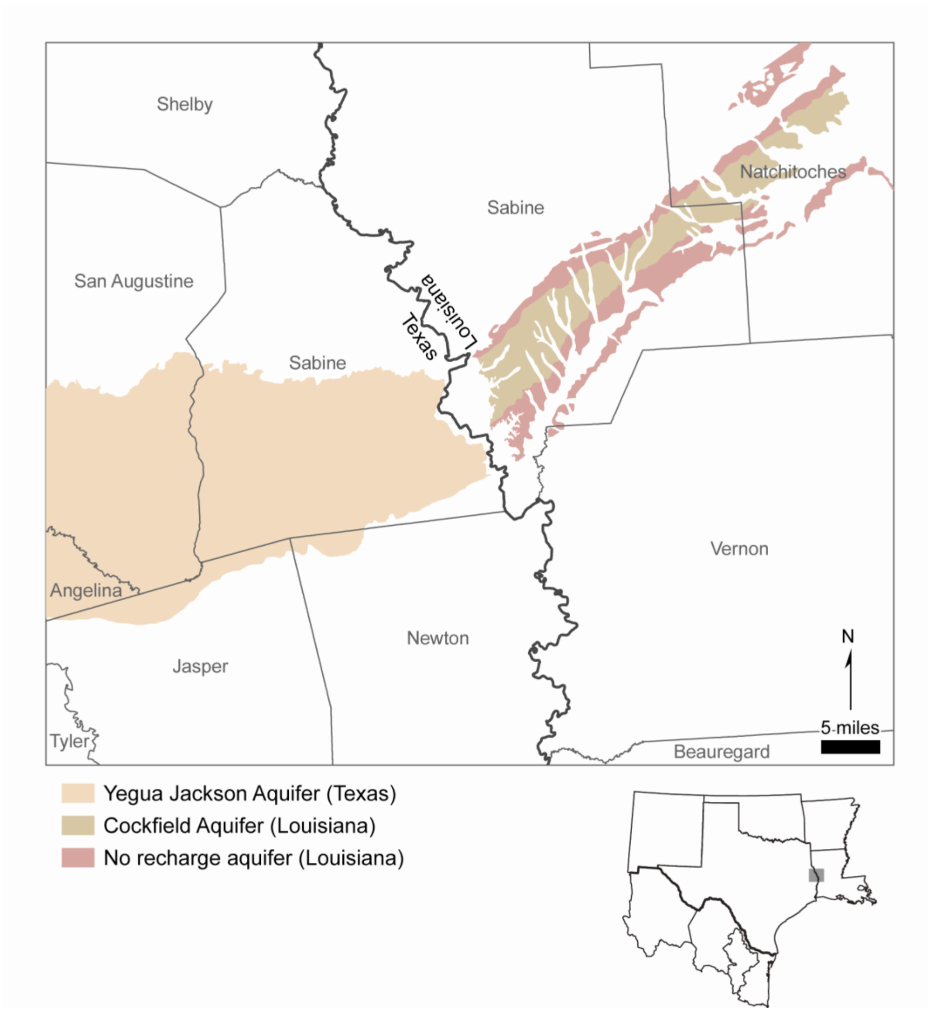

Figure A24-1. Extent of the Yegua-Jackson Aquifer along the Texas-Louisiana border.

Geologic conditions

The Cockfield Formation consists of sands, silts, clays, and minor amounts of lignite. In northeastern Louisiana, the regional dip of the Cockfield Formation is 15 to 50 feet per mile to the east-southeast and southeast into the Mississippi Embayment. In central and southern Louisiana, the regional dip is 50 to 100 feet per mile to the south. The Cockfield Formation thins from about 900 feet to 500 feet to the northeast across Louisiana as distance increases away from a major Yegua Formation depocenter in Montgomery, Liberty, and Hardin counties in Texas (Figure A24-2).

Locally, the formation thins or thickens over both major and minor structures along the Gulf Coast, including salt domes in eastern Louisiana. The Cockfield Formation was deposited in a deltaic-fluvial plain environment characterized by north to northeast trending channel sands and intervening swamp and marsh silts and clays.

Groundwater conditions

Groundwater in the Cockfield Aquifer or confining unit (depending on location) may be a locally important source of groundwater. It occurs just above the Cook Mountain Aquifer and below the Jackson Group (Figure A24-3). Hydraulic conductivity values vary greatly from one area to another, ranging from 30 to 55 feet per day. Recharge of the Cockfield Formation occurs by precipitation in the outcrop area, by transfer of water from other adjoining aquifers (especially the Sparta Sand), and by a minor amount of infiltration from streams. Discharge from the Cockfield Formation occurs by withdrawal from wells and by natural discharge. Natural discharge takes place primarily by leakage of water from the Cockfield Formation through the overlying confining beds of Jackson Group rocks and, to a lesser extent, by movement of water into streams incised into the formation.

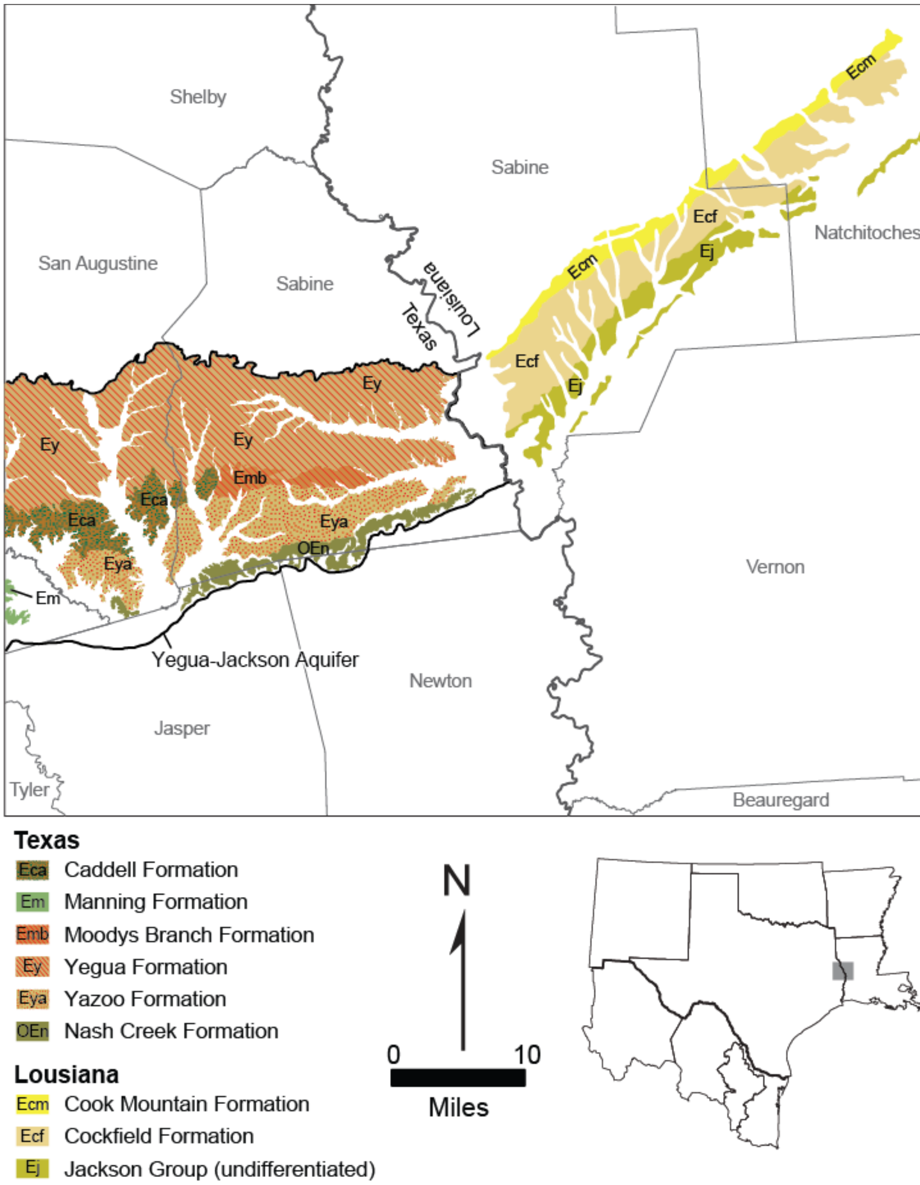

Figure A24-2. **Cockfield Formation and correlated units in Texas and Louisiana.**

The direction of flow of groundwater in the Cockfield Formation is towards the Gulf of Mexico Basin in eastern Louisiana and towards the Mississippi River alluvial valley in the western and central parts of the state. The flow of groundwater is constrained by clays in the underlying Cook Mountain Formation and overlying, undifferentiated Jackson Group sediments. On a local scale in Sabine Parish, near the Texas border, the potentiometric surface of the aquifer indicates flow to the south, southeast, and east from elevations of 260 feet above mean sea level to 120 feet above mean sea level (Brantly and Seanor, 1996).

System	Series	Stratigraphic unit		Hydrogeologic unit, Northern Louisiana
Tertiary	Eocene	Jackson Group, undifferentiated		Jackson confining unit
		Claiborne Group	Cockfield Formation	Cockfield Aquifer or surficial confining unit
			Cook Mountain Formation	Cook Mountain Aquifer or confining unit
			Sparta Sand	Sparta Aquifer or surficial confining unit
			Cane River Formation	Cane River Aquifer or confining unit
			Carrizo Sand	Carrizo-Wilcox Aquifer or surficial confining unit Wilcox Aquifer
	Paleocene	Wilcox Group, undifferentiated		
		Midway Group, undifferentiated		Midway confining unit

Figure A24-3. Stratigraphy of the Cockfield Formation, northern Louisiana (modified from Johnston and others, 2000).

Groundwater in the Cockfield Formation contains appreciable amounts of calcium and magnesium near outcrop areas and where the formation is directly overlain by Mississippi River alluvium. In these areas, the water is moderately to very hard. Based on anion ratios groundwater from the Cockfield Formation can be grouped into bicarbonate, chloride, and sulfate-water provinces. The Cockfield Formation contains freshwater in north-central and northeast Louisiana in a narrowing diagonal band extending toward Sabine Parish. Total dissolved solids concentrations range from about 500 to 800 milligrams per liter. The range of thickness of the freshwater interval in the Cockfield Aquifer is 50 to 600 feet. In Natchitoches, Sabine, and Vernon parishes, freshwater is present at a greater depth in the Cockfield Aquifer than in any other aquifer in western Louisiana. Freshwater is produced at depths of almost 2,000 feet in southwestern Natchitoches Parish and northwestern Vernon Parish.

The Cockfield Aquifer is an important groundwater source for northern Louisiana. Withdrawals from the aquifer for public supply increased from 1.2 million gallons per day in 1965 to 5.7 million gallons per day in 1985. In 1990 public supply withdrawals decreased to 4.2 million gallons per day, while total withdrawals in Louisiana were 5.8 million gallons per day in the same year. The aquifer is present in Arkansas, Mississippi, Tennessee, Kentucky, and Alabama as part of the Mississippi Embayment Aquifer System.

The Yegua Formation and Jackson Groups in Mexico are not considered good aquifers for groundwater production based on limited production and poor quality.

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Appendix B: Institutional entity websites

Table B-1. Water-related institutions and associated websites for more information.

Websites are current as of April 2017 and are listed in alphabetical order.	
Institution	**Website**
Arkansas Association of Conservation Districts	http://aracd.org/
Arkansas Department of Environmental Quality	https://www.adeq.state.ar.us/
Arkansas Department of Health	http://www.healthy.arkansas.gov/Pages/default.aspx
Arkansas Geographic Information Office	http://gis.arkansas.gov/
Arkansas Geological Survey	http://www.geology.ar.gov
Arkansas Natural Resources Commission	http://www.anrc.arkansas.gov
Arkansas Oil and Gas Commission	http://www.aogc.state.ar.us
Arkansas Pollution Control and Ecology Commission	http://www.adeq.state.ar.us/commission
Arkansas Rural Water Association	http://www.arkansasruralwater.org
Arkansas Water Resources Center	http://www.uark.edu/depts/awrc/
Arkansas Water Well Construction Commission	http://www.arkansas.gov/awwcc
Arkansas Watershed Advisory Group and Watershed Outreach and Education Program	http://www.adeq.state.ar.us/poa/watershed_outreach_education/default.htm
Border Environment Cooperation Commission (Comisión de Cooperación Ecológica Fronteriza)	http://www.becc.org/ http://www.cocef.org
Capital Area Ground Water Conservation Commission	http://www.cagwcc.com
Coahuila de Zaragoza Secretaría de Medio Ambiente (Ministry of the Environment)	http://www.sema.gob.mx
Comisión Nacional del Agua	http://www.conagua.gob.mx

Websites are current as of April 2017 and are listed in alphabetical order.	
Comités técnicos de aguas subterráneas (technical groundwater committees)	http://cotas.org/
Commission for Environmental Cooperation of North America	http://www.cec.org/
Communities Unlimited	https://www.communitiesu.org/
Consejos ciudadanos del agua estatales (State citizen's water councils)	http://transparencia.tamaulipas.gob.mx/wp-content/uploads/2013/10/PLAN-ESTATAL-DE-DESARROLLO-2011_2016.pdf http://www.nl.gob.mx/servicios/consejos-practicos-para-el-cuidado-del-agua http://coahuila.gob.mx/
Consejos de cuenca (River basin councils)	http://www.gob.mx/conagua/documentos/consejos-de-cuenca
Consejo Consultivo del Agua (Water Advisory Council)	http://www.aguas.org.mx/sitio/
Good Neighbor Environmental Board	https://www.epa.gov/faca/gneb
Ground Water Management Advisory Task Force (Louisiana)	http://www.legis.la.gov/legis/BoardMembers.aspx?boardId=739
Instituto Mexicano de Tecnología del Agua (Mexican Institute of Water Technology)	http://www.imta.gob.mx
Instituto Nacional de Estadística y Geografía (National Institute of Statistics and Geography)	http://www.inegi.org.mx
International Boundary and Water Commission	http://www.ibwc.gov
Junta Municipal de Agua y Saneamiento de Juárez, Chihuahua (City of Juárez Utilities)	https://www.jmasjuarez.gob.mx/
Louisiana Conservation Districts	http://www.ldaf.state.la.us/conservation/soil-water-conservation-districts/
Louisiana Department of Environmental Quality	http://www.deq.louisiana.gov
Louisiana Department of Health	http://www.dhh.louisiana.gov

Websites are current as of April 2017 and are listed in alphabetical order.	
Louisiana Department of Natural Resources, Louisiana Office of Conservation	http://dnr.louisiana.gov/index.cfm?md=pagebuilder&tmp=home&pid=46&ngid=4/
Louisiana Department of Transportation and Development	http://www.dotd.state.la.us
Louisiana Geographic Information Center	http://lagic.lsu.edu/
Louisiana Geological Survey	http://www.lgs.lsu.edu
Louisiana Levee Districts	http://albl.org/
Louisiana Rural Water Association	http://lrwa.org
Louisiana Sparta Ground Water Commission	http://www.spartaaquifer.com
Louisiana State Soil and Water Conservation Commission	http://www.ldaf.state.la.us/conservation/state-soil-and-water-conservation-commission/
Louisiana State University, AgCenter Research and Extension	http://www.lsuagcenter.com
Louisiana Water Resources Research Institute	http://www.lwrri.lsu.edu
Louisiana Ground Water Resources Commission	http://dnr.louisiana.gov/index.cfm?md=newsroom&tmp=detail&aid=925
Natural Resources Conservation Service, U.S. Department of Agriculture	http://www.nrcs.usda.gov
New Mexico Acequia Commission	http://www.nmacequiacommission.state.nm.us
New Mexico Acequias	http://www.lasacequias.org/
New Mexico Artesian Conservancy District	http://pvacd.com/
New Mexico Drought Task Force	http://www.nmdrought.state.nm.us/index.html
New Mexico Energy, Minerals and Natural Resources Department, Oil Conservation Division	http://www.emnrd.state.nm.us
New Mexico Environment Department, Ground Water Quality Bureau	http://www.nmenv.state.nm.us/gwb/

Websites are current as of April 2017 and are listed in alphabetical order.	
New Mexico Environment Department, Water Quality Control Commission	http://www.nmenv.state.nm.us/wqcc
New Mexico Institute of Mining and Technology, New Mexico Bureau of Geology and Mineral Resources	http://geoinfo.nmt.edu/
New Mexico Office of the State Engineer and the Interstate Stream Commission	http://www.ose.state.nm.us
New Mexico Regional Water Planning Areas	http://www.ose.state.nm.us/Planning/regional_planning.php
New Mexico Resource Geographic Information System Program	http://rgis.unm.edu
New Mexico Rural Water Association	http://www.nmrwa.org
New Mexico Soil and Water Conservation Districts	http://www.nmacd.org/swcds
New Mexico State University, College of Agricultural, Consumer and Environmental Sciences	http://www.extension.nmsu.edu
New Mexico Water Resources Research Institute	https://nmwrri.nmsu.edu/
New Mexico Water Trust Board	http://www.nmfa.net/financing/water-programs/water-trust-board/
New Mexico Water User Associations (Lee Acres example)	http://www.leeacreswater.com/
North American Development Bank	http://www.nadb.org
Nuevo León Agencia de Protección al Medio Ambiente y Recursos Naturales (Natural Resource and Environmental Protection Agency)	http://www.nl.gob.mx/dependencias/desarrollosustentable/subsecretaria-de-proteccion-al-medio-ambiente-y-recursos 2016-2021 Plan: http://www.nl.gob.mx/series/documento-completo-y-en-capitulos-del-plan-estatal-de-desarrollo-2016-2021
Oklahoma Water for 2060 Advisory Council	http://www.owrb.ok.gov/2060/

Websites are current as of April 2017 and are listed in alphabetical order.	
Oklahoma Conservation Commission	http://www.ok.gov/conservation
Oklahoma Conservation Districts	http://www.ok.gov/conservation/documents/CD-numbered-map-list.pdf
Oklahoma Corporation Commission	http://www.occeweb.com
Oklahoma Department of Environmental Quality	http://www.deq.state.ok.us
Oklahoma Geographic Information Council	http://www.okmaps.onenet.net
Oklahoma Geological Survey	http://www.ogs.ou.edu
Oklahoma Rural Water Association	http://www.okruralwater.org
Oklahoma Water Quality Monitoring Council	http://acwi.gov/monitoring/regional_councils_files/stcouncil_contacts.html
Oklahoma Water Resources Board	http://www.owrb.ok.gov/
Oklahoma Water Resources Center	http://water.okstate.edu/programs/owrri
Paso del Norte Water Task Force	http://www.meadowscenter.txstate.edu/rg/database_profile.php?iid=31
Secretaría de Medio Ambiente y Recursos Naturales (Ministry of Environment and Natural Resources)	http://www.semarnat.gob.mx
Southwest Consortium for Environmental Research and Policy (Consorcio de Investigación y Politica Ambiental del Suroeste)	http://irsc.sdsu.edu/scerp.htm
Tamaulipas Secretaría de Desarrollo Urbano y Medio Ambiente (Ministry of Urban Development and Environment)	http://transparencia.tamaulipas.gob.mx/informacion-publica/dependencias/secretaria-de-desarrollo-urbano-y-medio-ambiente/
Texas A&M University, Texas AgriLife Extension Service	http://agrilifeextension.tamu.edu/
Texas Alliance of Groundwater Districts	http://www.texasgroundwater.org
Texas Commission on Environmental Quality	http://www.tceq.texas.gov/

Websites are current as of April 2017 and are listed in alphabetical order.	
Texas Department of Licensing and Regulation	http://www.tdlr.texas.gov/
Texas Ground Water Association	http://www.tgwa.org/
Texas Groundwater Conservation Districts	http://www.twdb.texas.gov/groundwater/conservation_districts
Texas Groundwater Protection Committee	http://www.tgpc.state.tx.us
Texas Natural Resources Information System	http://www.tnris.org
Texas-New Mexico-Chihuahua Regional Workgroup	https://www.epa.gov/border2020/tx-nm-chih-workgroup-overview
Railroad Commission of Texas	http://www.rrc.state.tx.us
Texas Parks and Wildlife	http://www.tpwd.texas.gov/
Texas Regional Water Planning Groups	http://www.twdb.texas.gov/waterplanning/rwp/regions/
Texas Rural Water Association	http://www.trwa.org
Texas Soil and Water Conservation Districts	http://www.tsswcb.texas.gov/en/swcds/
Texas State Auditor's Office	http://www.sao.state.tx.us
Texas State Drought Preparedness Council	https://www.txdps.state.tx.us/dem/CouncilsCommittees/droughtCouncil/stateDroughtPrepCouncil.htm
Texas State Soil and Water Conservation Board	http://www.tsswcb.texas.gov/
Texas Tech University, College of Agricultural Sciences and Natural Resources Water Resources Center	http://www.depts.ttu.edu/casnr/water
Texas Water Conservation Association	http://www.twca.org
Texas Water Development Board	http://www.twdb.texas.gov
Texas Water Resources Institute	http://twri.tamu.edu/
The University of Texas, Bureau of Economic Geology; Center for Sustainable Water Resources	http://www.beg.utexas.edu/

Websites are current as of April 2017 and are listed in alphabetical order.	
The University of Texas, Center for Research in Water Resources	http://www.crwr.utexas.edu/
The Water Institute of the Gulf	http://thewaterinstitute.org
U.S. Bureau of Indian Affairs	http://www.bia.gov/
U.S. Bureau of Reclamation	http://www.usbr.gov/
U.S. Fish and Wildlife Service	http://www.fws.gov
U.S. Geological Survey	http://www.usgs.gov
United States-Mexico Border Field Coordinating Committee	http://www.cerc.usgs.gov/fcc/
University of Arkansas, Division of Agriculture	http://division.uaex.edu
World Bank	http://www.worldbank.org

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Appendix C: Texas groundwater policy statements and volumes

Table C-1. Texas' desired future conditions potentially affecting shared aquifers.

States	Shared aquifer	Texas' desired future conditions 2010 through 2060	Date adopted	Groundwater management area
Arkansas and Louisiana	Carrizo-Wilcox (major aquifer)	Average drawdown of 17 feet in 50 years.	4/13/2010	11
	Blossom (minor aquifer)	From estimated year 2009 conditions, Bowie County: average drawdown of the unconfined zone should not exceed approximately 5.4 feet after 50 years	4/27/2011	8
	Nacatoch (minor aquifer)	Drawdown by county: Bowie County: 10 feet in the Red River Basin, 17 feet in the Sulphur River Basin	6/23/2011	8
	Queen City (minor aquifer)	Average drawdown of 17 feet in 50 years.	4/13/2010	11
	Sparta (minor aquifer)	Average drawdown of 17 feet in 50 years.	4/13/2010	11
	Woodbine (minor aquifer)	None specified.	Not applicable.	8
Louisiana	Gulf Coast (major aquifer)	Chicot Aquifer in Jefferson County: Average drawdown not to exceed 25 feet after 52 years. Chicot Aquifer in Newton County: Average drawdown not to exceed 9 feet after 52 years. Chicot Aquifer in Orange County: Average drawdown not to exceed 14 feet after 52 years. Evangeline Aquifer in Jefferson County: Average drawdown not to exceed 26 feet in 52 years. Evangeline Aquifer in Newton County: Average drawdown not to exceed 20 feet in 52 years. Evangeline Aquifer in Orange County: Average drawdown not to exceed 19 feet in 52 years. Burkeville confining unit in Newton County: Average drawdown not to exceed 22 feet in 52 years. Jasper Aquifer in Newton County: Average drawdown not to exceed 18 feet in 52 years.	8/25/2010	14
	Queen City (minor aquifer)	Average drawdown of 17 feet in 50 years.	4/13/2010	11

States	Shared aquifer	Texas' desired future conditions 2010 through 2060	Date adopted	Groundwater management area
Louisiana (continued)	Sparta Aquifer (minor aquifer)	Average drawdown of 17 feet in 50 years.	4/13/2010	11
	Yegua-Jackson (minor aquifer)	Declared not relevant.	8/25/2010	14
New Mexico and Oklahoma	Blaine Aquifer (minor aquifer)	Childress and Hardeman counties in Gateway Groundwater Conservation District: No more than 2-foot decline in 50 years; Childress and Collingsworth counties in Mesquite Groundwater Conservation District: 50 percent of the volume in storage remaining in 50 years.	7/22/2010	6
		Wheeler County: 50 percent of volume remaining in 50 years.	6/03/2010	1
	Blossom Aquifer (minor aquifer)	Bowie, Lamar, and Red River counties: Maintain 100 percent of saturated thickness in 50 years.	4/27/2014	8
	Capitan Reef Aquifer	Loving and Reeves Counties: not relevant.	8/09/2014	3
	Dockum Aquifer (minor aquifer)	Deaf Smith, Gaines, and Parmer counties: Average drawdown of 40 feet in 50 years; in Andrews County: not relevant.	8/05/2010	2
		Dallam, Hartley, and Oldham counties: Average drawdown of 30 feet in 50 years.	6/03/2010	1
		Reeves and Winkler counties: Average drawdown of less than 200 feet in 50 years.	8/09/2010	3
	Ogallala Aquifer/Rita Blanca Aquifer (major aquifer)	Dallam and Hartley counties: 40 percent volume remaining in 50 years.	7/07/2009	1
		Hansford, Lipscomb, Ochiltree, Oldham, Sherman and Wheeler counties: 50 percent volume remaining in 50 years.		

States	Shared aquifer	Texas' desired future conditions 2010 through 2060	Date adopted	Groundwater management area
		Hemphill County: 80 percent volume remaining in 50 years.		
New Mexico and Oklahoma (continued)	Ogallala Aquifer (major aquifer)	In Bailey, Cochran, Deaf Smith and Parmer counties: 50 percent volume remaining in 50 years.	8/05/2010	2
	Pecos Valley Aquifer (major aquifer)	Andrews County: not addressed.	-	2
	Pecos Valley Aquifer (major aquifer)	Loving and Winkler counties: No more than 28 feet drawdown in 50 years.	8/09/2010	3
	Rustler Aquifer (minor aquifer)	Loving County: No more than 300 feet of drawdown in 50 years; in Reeves County: in the confined portion, no more than 300 feet drawdown in 50 years, in the unconfined portion, no more than 15 feet of drawdown in 50 years; Winkler County: not relevant.	8/09/2010	3
Oklahoma	Blaine Aquifer (minor aquifer)	Pod 1 - Childress County (Gateway Groundwater Conservation District): No more than 2 feet drawdown in 50 years. Childress and Collingsworth (Mesquite Groundwater Conservation District) counties: 50 percent of volume remaining in 50 years. Wilbarger County: Not relevant	7/22/2010	6
	Seymour Aquifer (major aquifer)	Childress, Collingsworth, and Hardeman (Gateway Groundwater Conservation District) counties: No more than 1 foot drawdown in 50 years. Childress and Collingsworth (Mesquite Groundwater Conservation District) counties: 50 percent of volume remaining in 50 years. Wichita and Wilbarger counties: No more than 1 foot drawdown in 50 years.	7/22/2010	6

States	Shared aquifer	Texas' desired future conditions 2010 through 2060	Date adopted	Groundwater management area
	Trinity Aquifer (major aquifer)	Clay, Wichita, and Wilbarger counties: No more than 2 feet drawdown in 50 years.	4/27/2011	8
	(continued) Trinity Aquifer (major aquifer)	In Cooke County: no more than 26 feet drawdown in the Paluxy; no more than 42 feet drawdown in the Glen Rose; no more than 60 feet drawdown in the Hensell; no more than 78 feet drawdown in the Hosston in 50 years. Fannin County: no more than 212 feet drawdown in the Paluxy; no more than 196 feet drawdown in the Glen Rose; no more than 182 feet drawdown in the Hensell; no more than 181 feet drawdown in the Hosston in 50 years. Grayson County: no more than 175 feet drawdown in the Paluxy; no more than 160 feet drawdown in the Glen Rose; no more than 161 feet drawdown in the Hensell; no more than 165 feet drawdown in the Hosston in 50 years. Lamar County: no more than 132 feet drawdown in the Paluxy; no more than 130 feet drawdown in the Glen Rose; no more than 136 feet drawdown in the Hensell; no more than 134 feet drawdown in the Hosston in 50 years. Montague County: no more than 0 feet drawdown in the Paluxy; no more than 1 foot drawdown in the Glen Rose; no more than 3 feet drawdown in the Hensell; no more than 12 feet drawdown in the Hosston in 50 years. Red River County: no more than 82 feet drawdown in the Paluxy; no more than 77 feet drawdown in the Glen Rose; no more than 78 feet drawdown in the Hensell; no more than 78 feet drawdown in the Hosston in 50 years.	4/27/2011	8
Mexico	Edwards-Trinity (Plateau) Aquifer (major aquifer)	Brewster County: No more than 3 feet drawdown in 50 years.	5/19/2011	4
		Terrell and Val Verde counties: No more than 7 feet drawdown in 50 years.	7/29/2010	7

States	Shared aquifer	Texas' desired future conditions 2010 through 2060	Date adopted	Groundwater management area
Mexico (continued)	Gulf Coast Aquifer (major aquifer)	Cameron, Hidalgo, and Starr counties: no more than 94 feet drawdown in 50 years.	8/30/2010	16
	Hueco-Mesilla Bolsons Aquifer (major aquifer)	El Paso and Hudspeth counties: none established.	-	5
	Igneous Aquifer (minor aquifer)	Presidio County: No more than 14 feet drawdown in 50 years.	8/13/2010	4
	West Texas Bolsons (minor aquifer)	Hudspeth County: not relevant; in Presidio County: no more than 72 feet drawdown in 50 years.	8/13/2010	4
	Yegua-Jackson Aquifer (minor aquifer)	Starr County: not relevant.	8/30/2010	16

Table C-2. Groundwater availability in Groundwater Management Area 1 near New Mexico and Oklahoma.

Aquifer	County	Modeled available groundwater (acre-feet/year)		
		2020	2030	2040
Dockum	Dallam	4,034	4,034	4,034
Dockum	Hartley	3,567	3,567	3,567
Dockum	Oldham	2,972	2,972	2,972
Dockum	Sherman	591	591	591
Ogallala	Hansford	284,588	262,271	240,502
Ogallala	Hemphill	45,170	41,759	42,398
Ogallala	Lipscomb	290,510	283,794	273,836
Ogallala	Ochiltree	269,463	246,475	224,578
Ogallala	Oldham	24,505	22,482	21,607
Ogallala	Sherman	322,683	300,908	263,747
Ogallala	Wheeler	125,708	119,556	114,817
Ogallala-Rita Blanca	Dallam	404,607	352,474	309,076
Ogallala-Rita Blanca	Hartley	452,459	389,548	337,001

Table C-3. Groundwater availability in Groundwater Management Area 2 bordering New Mexico.

Aquifer	County	Modeled available groundwater (acre-feet/year)		
		2020	2030	2040
Dockum	Bailey	1	1	1
Dockum	Cochran	0	0	0
Dockum	Deaf Smith	4,712	4,712	4,712

Aquifer	County	Modeled available groundwater (acre-feet/year)		
		2020	2030	2040
Dockum	Gaines	0	0	0
Dockum	Parmer	2	2	2
Edwards-Trinity (High Plains)	Bailey	279	279	279
Edwards-Trinity (High Plains)	Cochran	264	264	264
Edwards-Trinity (High Plains)	Gaines	85,058	46,202	30,316
Edwards-Trinity (High Plains)	Yoakum	2,532	1,893	1,757
Ogallala	Bailey	62,538	41,283	34,907
Ogallala	Cochran	48,345	36,208	42,697
Ogallala	Deaf Smith	129,167	118,166	106,868
Ogallala	Gaines	350,369	240,110	175,175
Ogallala	Parmer	68,694	63,065	56,584
Ogallala	Yoakum	82,297	59,745	43,575

Table C-4. Groundwater availability in Groundwater Management Area 3 bordering New Mexico.

Aquifer	County	Modeled available groundwater (acre-feet/year)		
		2020	2030	2040
Capitan Reef Complex	Reeves	1,007	1,007	1,007
Capitan Reef Complex	Winkler	1,061	1,061	1,061
Dockum	Loving	1,000	1,000	1,000
Dockum	Reeves	5,000	5,000	5,000
Dockum	Winkler	10,000	10,000	10,000
Edwards-Trinity (Plateau)	Reeves	3,389	3,389	3,389

Aquifer	County	Modeled available groundwater (acre-feet/year)		
		2020	2030	2040
Pecos Valley/Edwards-Trinity (Plateau)	Loving	2,984	2,984	2,984
Pecos Valley/Edwards-Trinity (Plateau)	Reeves	186,722	186,722	186,722
Pecos Valley/Edwards-Trinity (Plateau)	Winkler	39,984	39,984	39,984
Rustler	Loving	1,183	1,183	1,183
Rustler	Reeves	1,976	1,976	1,976

Table C-5. Groundwater availability in Groundwater Management Area 4 near New Mexico, and Chihuahua and Coahuila, Mexico.

Aquifer	County	Modeled available groundwater (acre-feet/year)		
		2020	2030	2040
Bone Spring-Victorio Peak	Hudspeth	101, 429	101,429	101,429
Capitan Reef Complex	Brewster	2,100	2,100	2,100
Capitan Reef Complex	Culberson	7,580	7,580	7,580
Edwards-Trinity (Plateau)	Brewster	1,394	1,394	1,394
Edwards-Trinity (Plateau)	Culberson	2,154	2,154	2,154
Igneous	Brewster	2,586	2,586	2,586
Igneous	Culberson	99	99	99
Igneous	Jeff Davis	4,584	4,584	4,584
Igneous	Presidio	4,064	4,064	4,064
Marathon	Brewster	7,580	7,580	7,580
Rustler	Brewster	0	0	0
West Texas Bolsons	Culberson	35,826	35,749	35,678
West Texas Bolsons	Jeff Davis	6,074	6,074	6,074

Aquifer	County	Modeled available groundwater (acre-feet/year)		
		2020	2030	2040
West Texas Bolsons	Presidio	9,126	9,112	8,982
West Texas Bolsons – Presidio-Redford	Presidio	6,282	6,282	6,282
West Texas Bolsons – Upper Salt Basin	Culberson	16,851	16,851	16,851

Table C-6. Groundwater availability in Groundwater Management Area 6 bordering Oklahoma.

Aquifer	County	Modeled available groundwater (acre-feet/year)		
		2020	2030	2040
Blaine	Childress	15,206	15,206	15,206
Blaine	Collingsworth	185,376	185,376	185,376
Blaine	Hardeman	5,198	5,198	5,198
Seymour	Childress	716	732	717
Seymour	Clay	787	787	787
Seymour	Collingsworth	17,542	16,010	14,250
Seymour	Hardeman	430	430	430
Seymour	Wichita	2,240	2,295	2,295
Seymour	Wilbarger	29,263	29,421	29,421

Table C-7. Groundwater Availability in Groundwater Management Area 7 bordering Coahuila, Mexico.

Aquifer	County	Modeled available groundwater (acre-feet/year)		
		2020	2030	2040
Edwards-Trinity (Plateau)	Kinney	70,338	70,338	70,338
Edwards-Trinity (Plateau)	Terrell	1,421	1,421	1,421
Edwards-Trinity (Plateau)	Val Verde	24,988	24,988	24,988

Table C-8. **Groundwater availability in Groundwater Management Area 8 bordering Oklahoma and Arkansas.**

Aquifer	County	Modeled available groundwater (acre-feet/year)		
		2020	2030	2040
Blossom	Bowie	201	201	201
Blossom	Red River	1,678	1,678	1,678
Nacatoch	Bowie	5,013	5,013	5,013
Nacatoch	Red River	1,105	1,105	1,105
Trinity	Cooke	6,850	6,850	6,850
Trinity	Fannin	700	700	700
Trinity	Grayson	9,400	9,400	9,400
Trinity	Lamar	1,322	1,322	1,322
Trinity	Montague	2,674	2,674	2,674
Trinity	Red River	530	530	530
Woodbine	Cooke	154	154	154
Woodbine	Fannin	3,297	3,297	3,297
Woodbine	Grayson	12,087	12,087	12,087
Woodbine	Lamar	3,644	3,644	3,644
Woodbine	Red River	166	166	166

Table C-9. **Groundwater availability in Groundwater Management Area 11 bordering Arkansas and Louisiana.**

Aquifer	County	Modeled available groundwater (acre-feet/year)		
		2020	2030	2040
Carrizo-Wilcox	Bowie	11,126	8,216	7,976
Carrizo-Wilcox	Cass	3,533	3,533	3,533
Carrizo-Wilcox	Harrison	8,911	8,911	8,911

Aquifer	County	Modeled available groundwater (acre-feet/year)		
		2020	2030	2040
Carrizo-Wilcox	Marion	2,077	2,077	2,077
Carrizo-Wilcox	Panola	9,097	9,097	9,097
Carrizo-Wilcox	Sabine	6,866	6,866	6,866
Queen City	Cass	43,193	43,193	43,193
Queen City	Harrison	10,373	10,373	10,373
Queen City	Marion	15,549	15,549	15,549
Queen City	Panola	0	0	0
Queen City	Sabine	0	0	0
Queen City	Shelby	0	0	0
Sparta	Sabine	296	296	296
Yegua-Jackson	Sabine	4,299	4,299	4,299

Table C-10. Groundwater availability in Groundwater Management Area 13 near Coahuila, Nuevo Leon, and Tamaulipas, Mexico.

Aquifer	County	Modeled available groundwater (acre-feet/year)		
		2020	2030	2040
Carrizo-Wilcox	Maverick	2,043	2,043	2,043
Carrizo-Wilcox	Webb	916	916	916
Queen City	Webb	0	0	0
Sparta	Webb	0	0	0
Yegua-Jackson	Webb	19,999	19,999	19,999
Yegua-Jackson	Zapata	7,999	7,999	7,999

Table C-11. Groundwater availability in Groundwater Management Area 14 bordering Louisiana.

Aquifer	County	Modeled available groundwater (acre-feet/year)		
		2020	2030	2040
Gulf Coast	Jefferson	2,445	2,445	2,445
Gulf Coast	Newton	34,177	34,177	34,177
Gulf Coast	Orange	20,013	20,013	20,013

Table C-12. Groundwater availability in Groundwater Management Area 16 bordering Tamaulipas, Mexico.

Aquifer	County	Modeled available groundwater (acre-feet/year)		
		2020	2030	2040
Gulf Coast	Cameron	50,560	50,560	50,560
Gulf Coast	Hidalgo	41,926	41,926	41,926
Gulf Coast	Starr	7,526	7,526	7,526