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Conceptual Model Report for the Cross Timbers Aquifer

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Executive Summary

The Cross Timbers Aquifer includes all or portions of 31 counties in north-central Texas and covers an area of approximately 17,800 square miles. The aquifer was designated as a minor aquifer by the Texas Water Development Board in 2017. A minor aquifer is one that produces minor amounts of water over large areas or major amounts of water over small areas; the Cross Timbers Aquifer falls into the first category. The Cross Timbers Aquifer extent is encompassed by five Regional Water Planning Groups, three Groundwater Management Areas, and six groundwater conservation districts. All of the groundwater conservation districts are on the edge of the Cross Timbers Aquifer extent.

The purpose of this report is to collect and analyze available data in order to develop a conceptual model for groundwater flow in the Cross Timbers Aquifer. Information and data from the conceptual model will be used to assist with and guide the construction of a groundwater availability model at a later time.

The Cross Timbers Aquifer is composed of rocks of Paleozoic age that include the Clear Fork, Wichita-Albany, Cisco, Canyon, Strawn, and Atoka Groups. Which rocks serve as a source of groundwater is dependent on location within the aquifer. The younger geologic units outcrop in the western portion of the aquifer and older formations progressively outcrop moving east. Groundwater is obtained for limited uses from whatever formations yield water near surface at a given location; overall aquifer permeability and well yield are generally small. Even though wells completed in the Cross Timbers Aquifer often have limited yield, they are generally sufficient for domestic or stock supply, and in many places there is no other reliable option for water. Groundwater occurrence can be erratic, with dry wells drilled in close proximity to producing wells. In some regions, the Seymour or Trinity Aquifers overlay the Cross Timbers Aquifer. Where this occurs, these other aquifers are typically used for groundwater supply due to superior well yield and water quality.

The Cross Timbers Aquifer consists of a shallow groundwater flow system, bounded below by a high salinity/brine water interface that occurs at relatively shallow depth (often several hundred feet), and in some locations very shallow depths (100 feet or less). The transition from fresh or slightly saline water to highly saline water or brine appears to be abrupt, meaning that it occurs over a short vertical distance.

Review of well hydrographs indicate that Cross Timbers Aquifer water levels are relatively stable, and even where trends in water levels are apparent, changes over time were typically several tens of feet or less. Many of the hydrographs show water level fluctuations in response to pumping and probably groundwater recharge. In addition, particularly in the north-central and northern portions of the study area, some wells have a pronounced increase in water levels, possibly due to increased recharge due to changing land use.

Groundwater flow is driven primarily by groundwater recharge and topography. Groundwater recharge occurs on the outcrop of the various aquifer units, and discharges primarily to stream channels. The high-permeability saturated alluvial sediments adjacent to stream channels act as conduits to transmit water from the Cross Timbers Aquifer to the streams or along the stream channels in the subsurface.

Based on watershed modeling, the mean annual recharge ranges from about 0.19 to 0.45 inch per year across the study area, or about 0.73 to 1.62 percent of average annual precipitation. However, the majority of water that infiltrates into alluvium along the stream channels likely discharges farther downstream and never enters the underlying Cross Timbers Aquifer rocks. Assuming that recharge to the alluvium does not enter the Paleozoic rocks beneath the alluvium, mean annual recharge ranges from 0.16 to 0.32 inch per year, or about 0.62 to 1.18 percent of average annual precipitation. The amounts of recharge fluctuate from year to year based on climatic conditions

The interaction of the Cross Timbers Aquifer with other aquifers is also governed primarily by topography. Trinity Aquifer outcrops typically form areas of high topography. Consequently, groundwater in the Trinity Aquifer that is not pumped or does discharge to streams or springs will eventually seep downward to recharge the Cross Timbers Aquifer. The same is true for the Seymour Aquifer where it occurs in topographically high areas, but where saturated Seymour Formation sediments occur along stream channels, Cross Timbers Aquifer water discharges into the Seymour Aquifer.

Overall groundwater pumping from the Cross Timbers Aquifer is small; it is estimated to be about 14,000 to 18,000 acre-feet per year (excluding mining use, which is often very low depending on economic conditions) over an aquifer area of 17,790 square miles.

Surface water is commonly used in the Cross Timbers Aquifer area due to limited well yield and in some cases marginal water quality. Portions of four major river basins (the Red, Trinity, Brazos, and Colorado Rivers) occur within the aquifer extent. There are 34 significant reservoirs that occur within the aquifer extent, with dates of impoundment ranging from 1901 to 1991. The reservoirs are an important source of public water supply for populations inside, and in some cases outside, the study area.

1. Introduction

The Cross Timbers Aquifer includes all or portions of 31 counties in north-central Texas and covers an area of approximately 17,800 square miles (Figure 1-1). Larger cities and towns in the region include Wichita Falls, Abilene, Mineral Wells, Breckenridge, Brownwood, and Graham (Ballew and French, 2019).

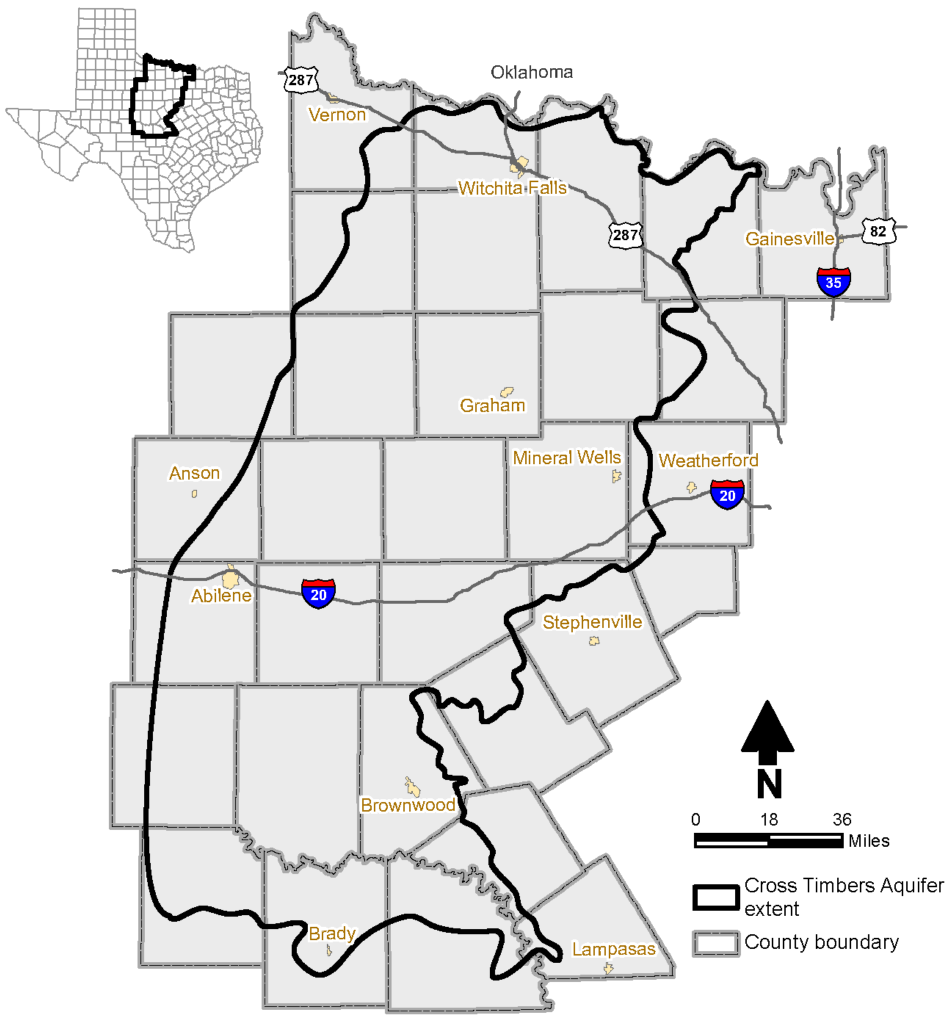


Figure 1-1. Study area.

The Cross Timbers Aquifer was designated as a minor aquifer by the Texas Water Development Board (TWDB) in 2017. A minor aquifer is one that produces minor amounts of water over large areas or major amounts of water over small areas; the Cross Timbers Aquifer falls into the first category. The aquifer is composed of rocks of Paleozoic age, which include the Clear Fork, Wichita-Albany, Cisco, Canyon, Strawn, and Atoka (also known as Bend) Groups. Which rocks serve as a source of groundwater is dependent on location within the aquifer; the younger geologic units outcrop in the western portion of the aquifer and older formations progressively outcrop moving east. In some regions, the Seymour or Trinity Aquifers overlay the Cross Timbers Aquifer. Where this occurs, these other aquifers are typically used as groundwater supply due to superior well yield and water quality.

Surface water has been used preferentially in the cross timbers Aquifer area due to limited well yield and in some cases marginal water quality. However, groundwater use has increased in recent years, particularly during drought conditions. In addition, the oil and gas industry is important within the study area, and mining water use has increased substantially, and subsequently declined, in the recent past. Even though wells completed in the Cross Timbers Aquifer often have limited yield, they are generally sufficient for domestic or stock supply, and in many places there is no other reliable option for water.

The remainder of this report presents an overview of the conceptual model for the Cross Timbers Aquifer. Information and data from the conceptual model will be used to assist with and guide the construction of a groundwater availability model at a later time. The following sections present information and analysis on the physiography, geology, hydrostratigraphy, aquifer properties, groundwater recharge, and water quality of the Cross Timbers Aquifer. The resulting conceptual model developed based on this information is summarized in Section 12.

2. Study Area and Physiography

There are 16 Regional Water Planning Groups in Texas that generally align with the major river systems. The Cross Timbers Aquifer extent is encompassed by five regions (Figure 2-1) designated as Regions B (primarily Red River Basin), C (upper portion of the Trinity River Basin), G (Brazos River), F (upper portion of the Colorado River Basin), and K (Lower Colorado River Basin).

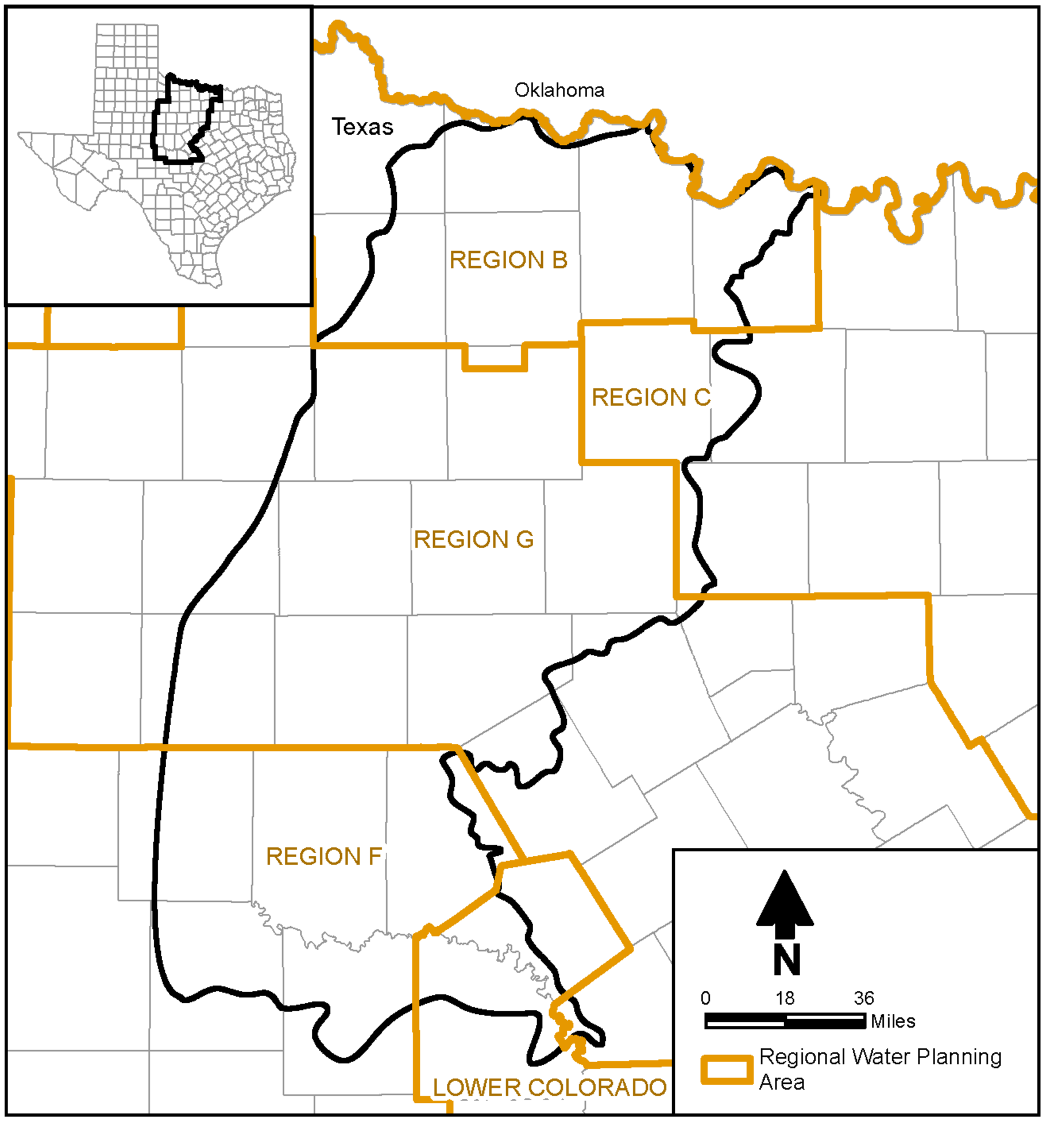


Figure 2-1. Regional Water Planning Groups that encompass portions of the Cross Timbers Aquifer.

Portions of the Cross Timbers Aquifer are covered by six groundwater conservation districts, most of which are multiple county districts. These are the Northern Trinity

Groundwater Conservation District, the Middle Trinity Groundwater Conservation District, the Saratoga Underground Water Conservation District, the Hickory Underground Water Conservation District No. 1, the Lipan-Kickapoo Water Conservation District, and the Rolling Plains Groundwater Conservation District (Figure 2-2). All of these districts are on the edge of the Cross Timbers Aquifer, but the Upper Trinity, Lipan Kickapoo and Rolling Plains districts cover the largest areas within the aquifer extent.

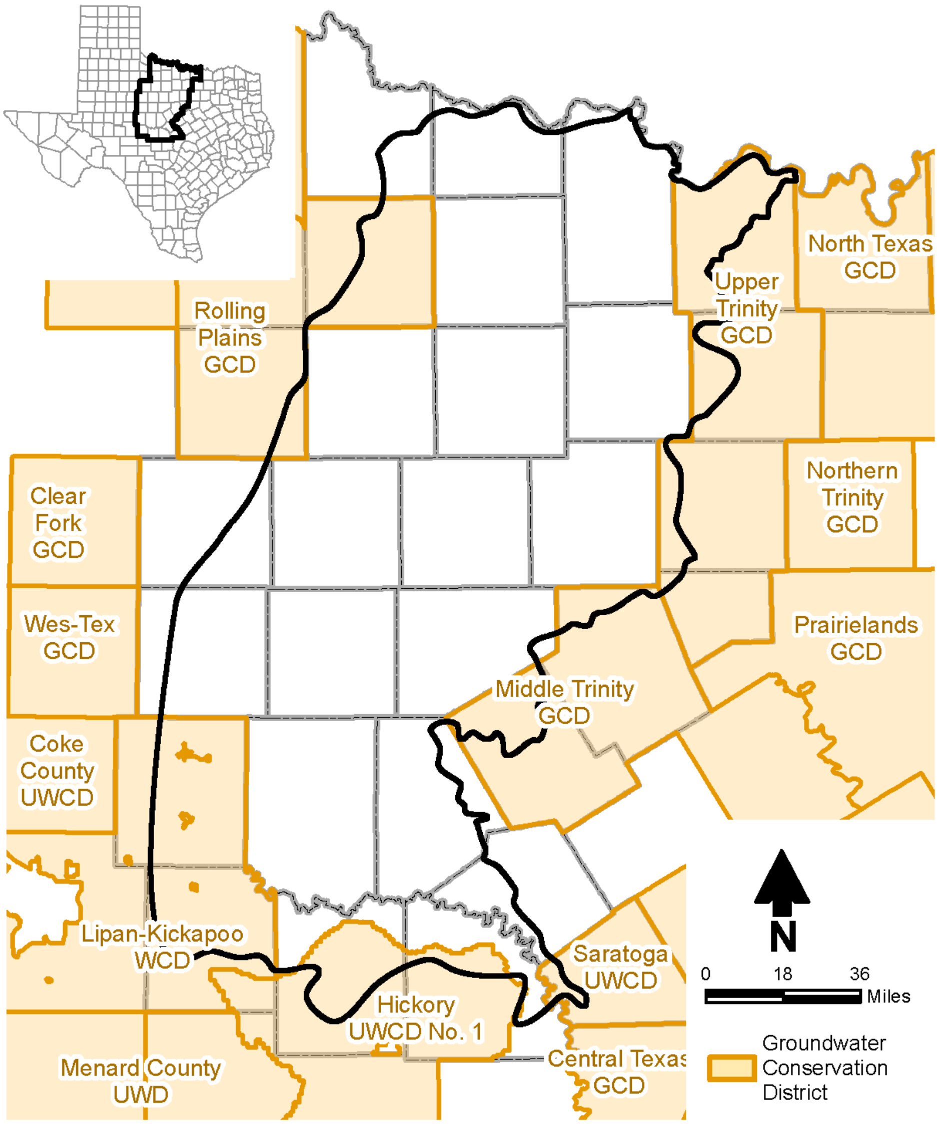


Figure 2-2. Groundwater conservation districts that encompass portions of the Cross Timbers Aquifer.

There are 16 Groundwater Management Areas in Texas, the extents of which approximately coincide with designated aquifers. The Cross Timbers Aquifer is covered by portions of Groundwater Management Areas 7, 8, and 9 (Figure 2-3). The Groundwater

Management areas were formed prior to the designation of the Cross Timbers Aquifer as an official minor aquifer. Groundwater Management Area 8 covers the eastern edge and south-central portions of the aquifer, approximately coincident with the Trinity Aquifer outcrop areas. Groundwater Management Area 7 covers the Lipan and Llano uplift minor aquifers and the Edwards-Trinity Plateau major aquifer to the south. Groundwater Management Area 6 covers the Seymour and Blaine Aquifers and now the largest portion of the Cross Timbers Aquifer.

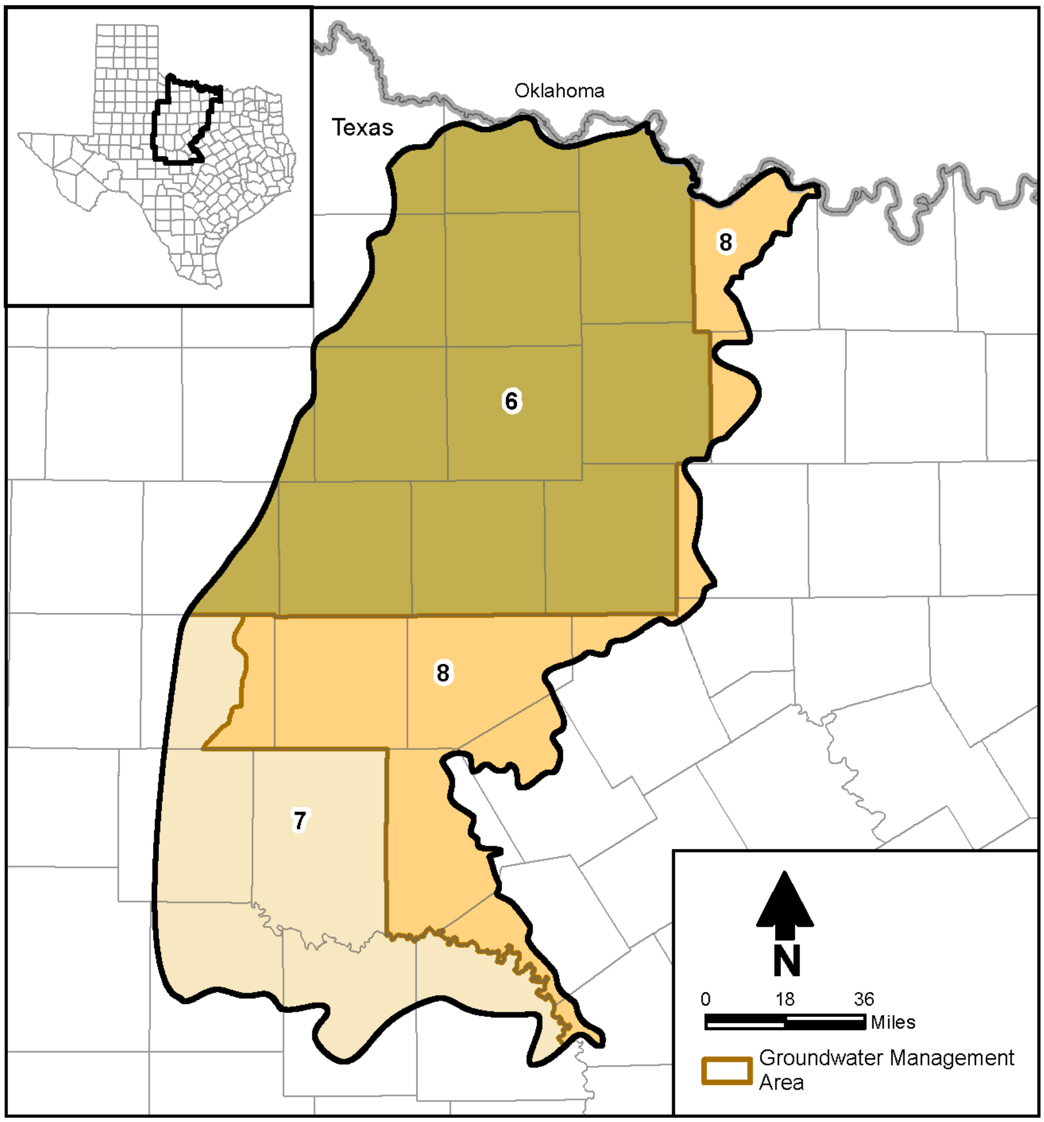


Figure 2-3. Groundwater Management Areas that encompass portions of the Cross Timbers Aquifer.

The major surface water features within the extent of the Cross Timbers Aquifer are illustrated in Figure 2-4. As shown in the figure, portions of four major river basins (the Red, Trinity, Brazos, and Colorado) occur with the aquifer extent. The Trinity River headwaters are within the Cross Timbers Aquifer extent; all of the other river basins extend to the west beyond the western extent of the Cross Timbers Aquifer.

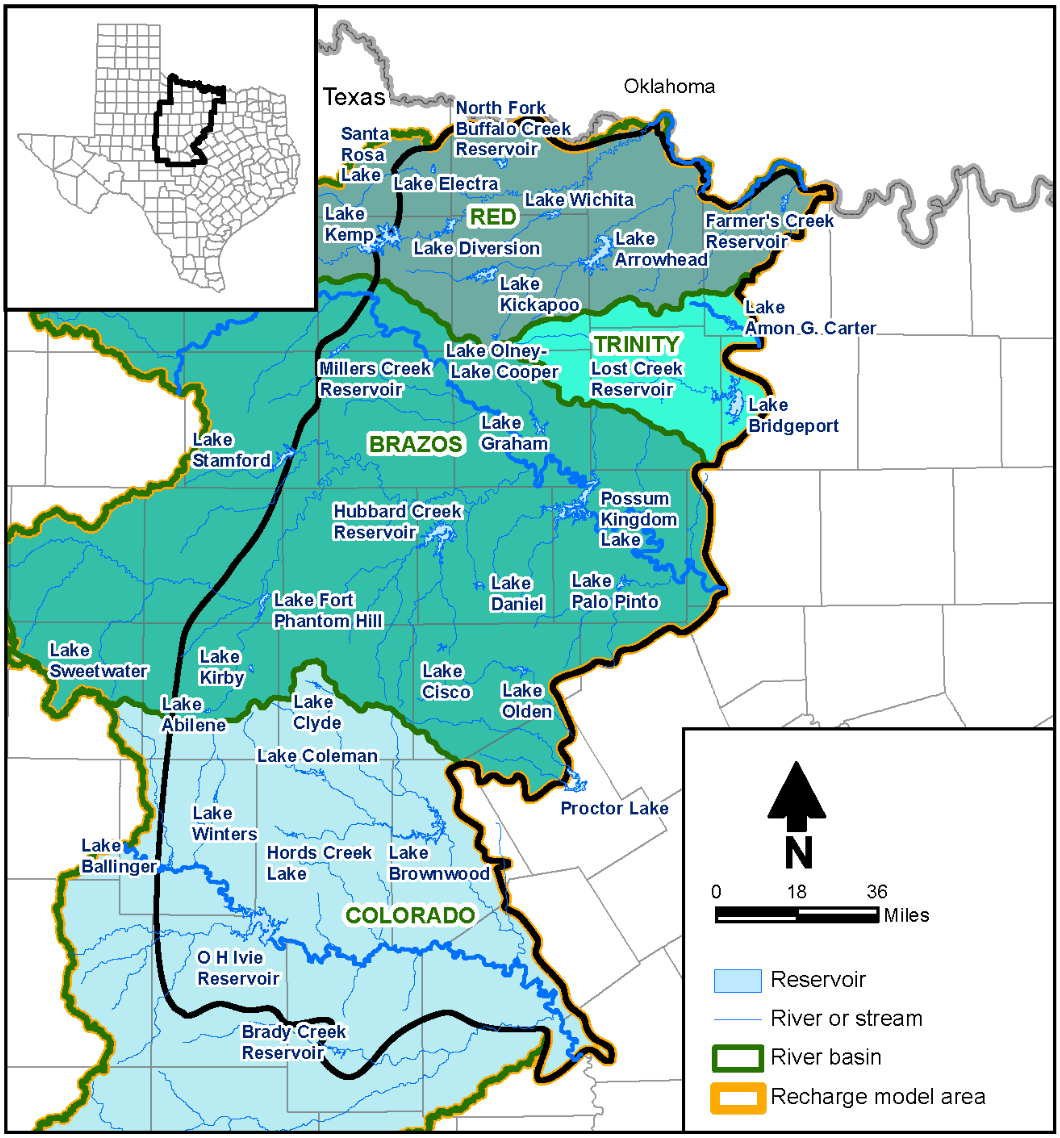


Figure 2-4. Major river basins and surface water features.

There are 34 significant reservoirs that occur within the aquifer extent, so surface water flows on the major streams is highly regulated. Surface water accounts for approximately two-thirds of the water supply within the aquifer area, although the percentage of supply by groundwater has noticeably increased in recent years, particularly during the period of 2011 to 2014, which included some severe drought years (Ballew and French, 2019).

Land surface topography ranges from a maximum of about 2,466 feet above mean sea level in Taylor County to a low of about 709 feet above mean sea level in Montague County at the Red River (Figure 2-5). The major river basin boundaries are evident in the land surface topography, with a particularly prominent high region extending east to west across Eastland, Callahan, and Taylor Counties, and extending south into northern Coleman County. This topographic high that forms the boundary between the Brazos River Basin to the north and the Colorado River Basin to the south is called the Callahan Divide, and it is formed by erosional remnants of Cretaceous rocks that form the Trinity Aquifer.

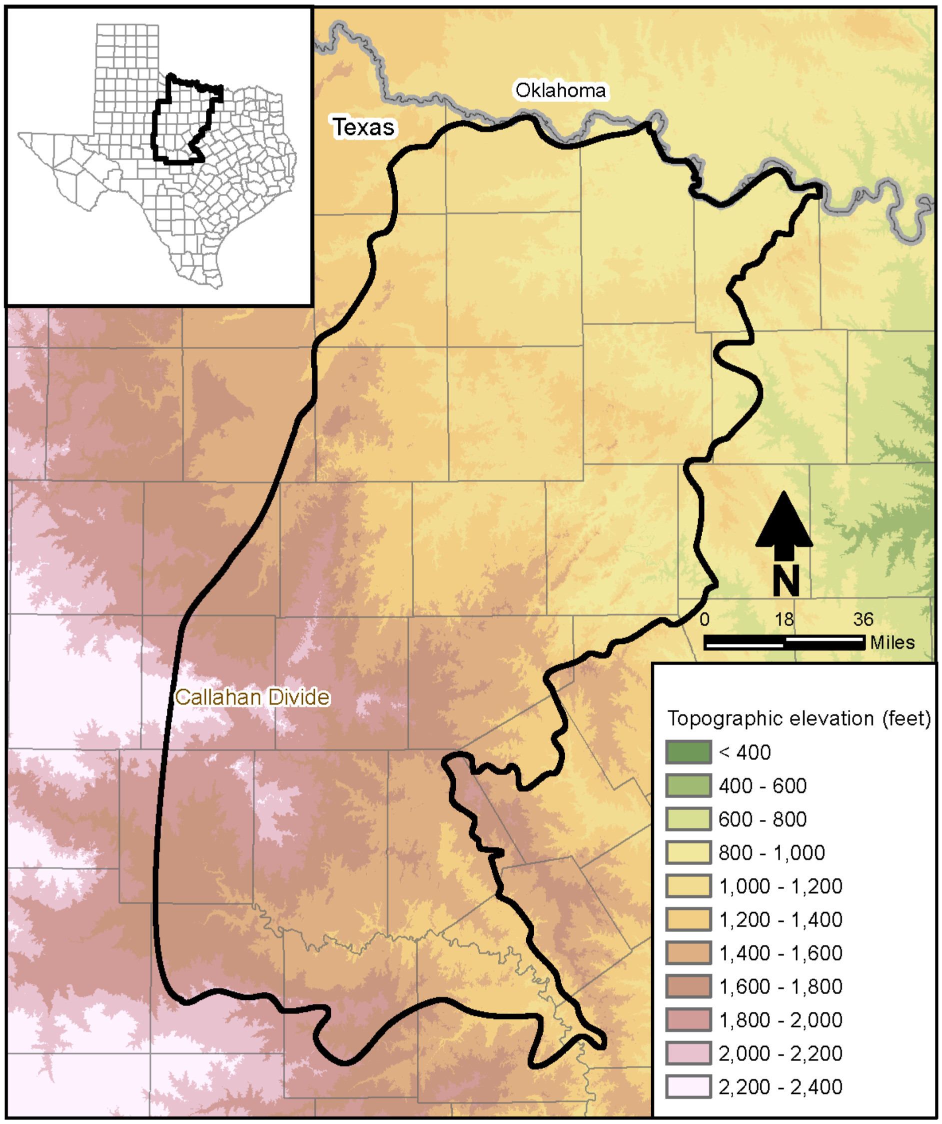


Figure 2-5. Land surface topography.

The Cross Timbers Aquifer occurs almost exclusively within the North-Central Plains Physiographic Province (Figure 2-6) as defined by the Texas Bureau of Economic Geology (http://www.beg.utexas.edu/UTopia/images/pagesizemaps/physiography.pdf), and the aquifer occurs in the Texas Climate Divisions 2 (Low Rolling Plains), 3 (North Central), and 6 (Edwards Plateau) as defined by the National Oceanic and atmospheric Administration (https://www.ncdc.noaa.gov/monitoring-references/maps/us-climate-divisions.php) (Figure 2-7). Both websites were accessed on May 14, 2021.

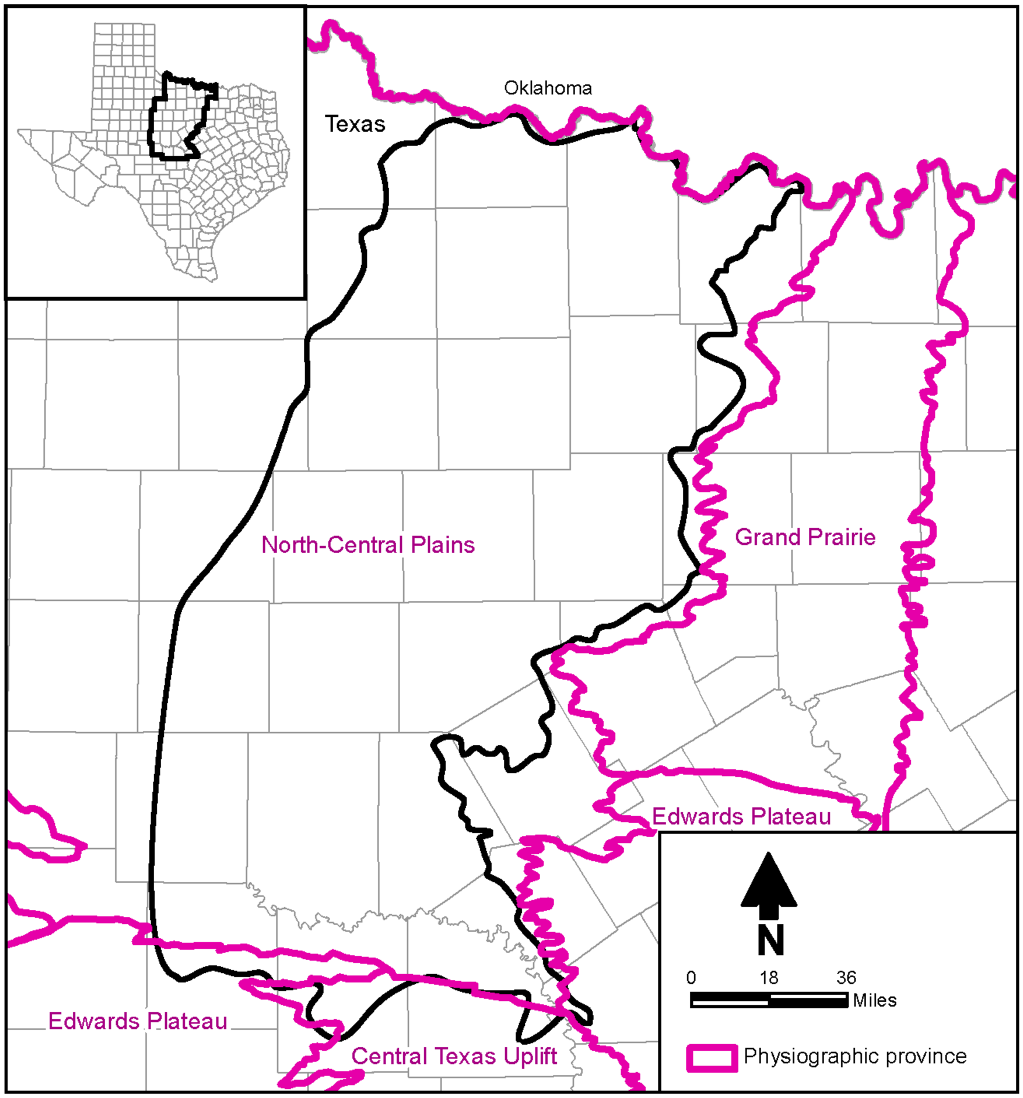


Figure 2-6. Physiographic provinces.

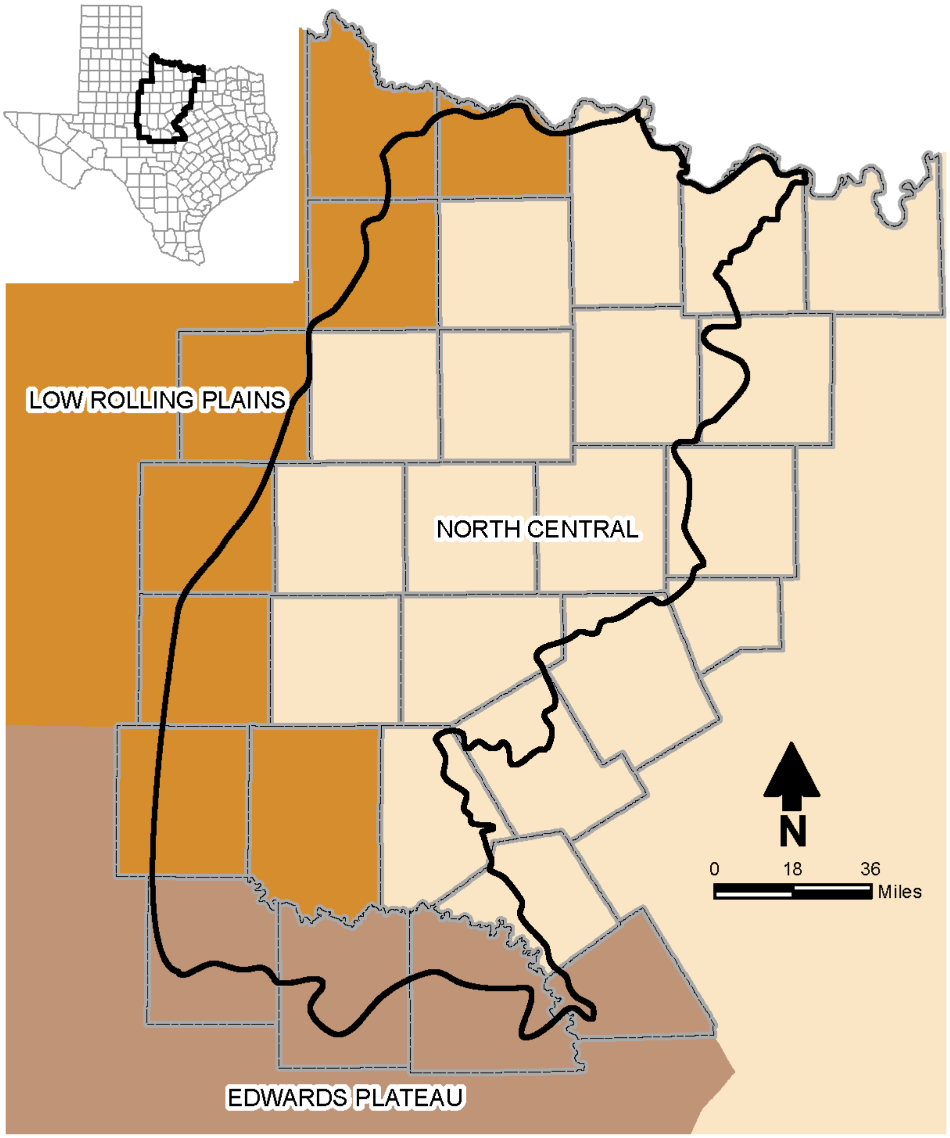


Figure 2-7. Climate divisions as delineated by the National Climatic Data Center.

Average annual precipitation decreases moving west across the Cross Timbers Aquifer, with the highest precipitation of almost 37 inches per year in the northeast corner of the aquifer extent in Montague County and the lowest average annual precipitation of slightly over 24 inches per year occurring in western Runnels County (Figure 2-8). In the larger watershed area extending to the west, average annual precipitation rates continue to decline to a low approaching 21 inches per year (Figure 2-8).

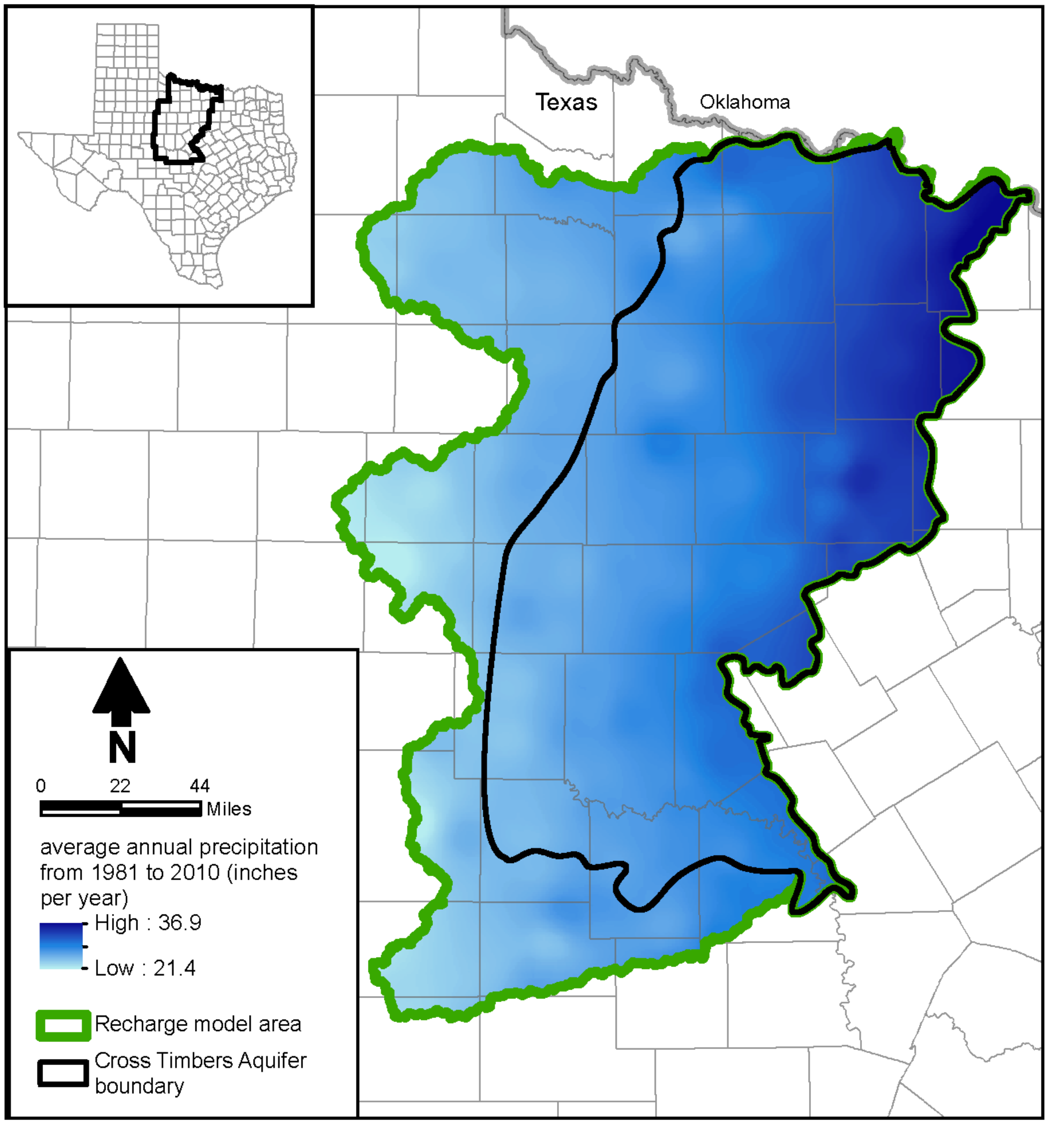


Figure 2-8. Average annual precipitation, 1981 to 2010, based on PRISM.

The average annual temperature is influenced by elevation, and is highest in the Colorado River Valley and lowest along the Callahan Divide and in north-central Clay County (Figure 2-9). The high average annual temperature is 77.4 degrees Fahrenheit in Lampasas County, and the low average temperature is 71.1 degrees Fahrenheit in the high elevation region of Coleman County. In the larger watershed area extending to the west, average annual temperatures generally decline (Figure 2-9).

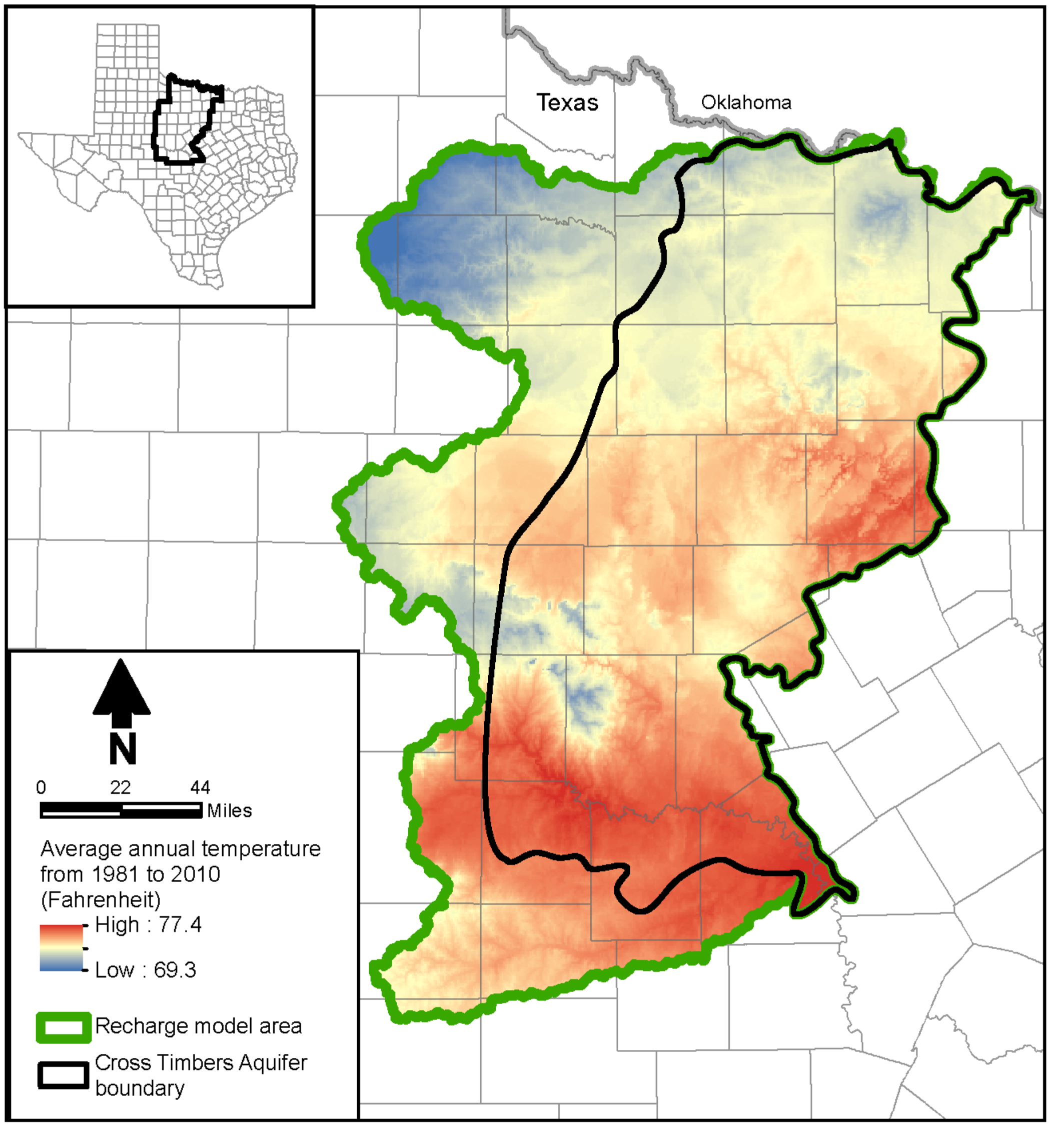


Figure 2-9. Average annual temperature, 1981 to 2010, based on PRISM.

Figure 2-10 shows monthly average precipitation and minimum and maximum temperature for three weather stations within the aquifer extent distributed from north to south. As indicated in the figure, highest temperatures occur during the months of July and August, and lowest temperatures occur during December and January. All of the stations indicate a similar pattern of precipitation despite their geographic separation. Maximum monthly precipitation occurs in May and June, but falls off significantly by July. From July, precipitation steadily increases until a secondary maximum period occurs in October, followed by the lowest precipitation period of November through January.

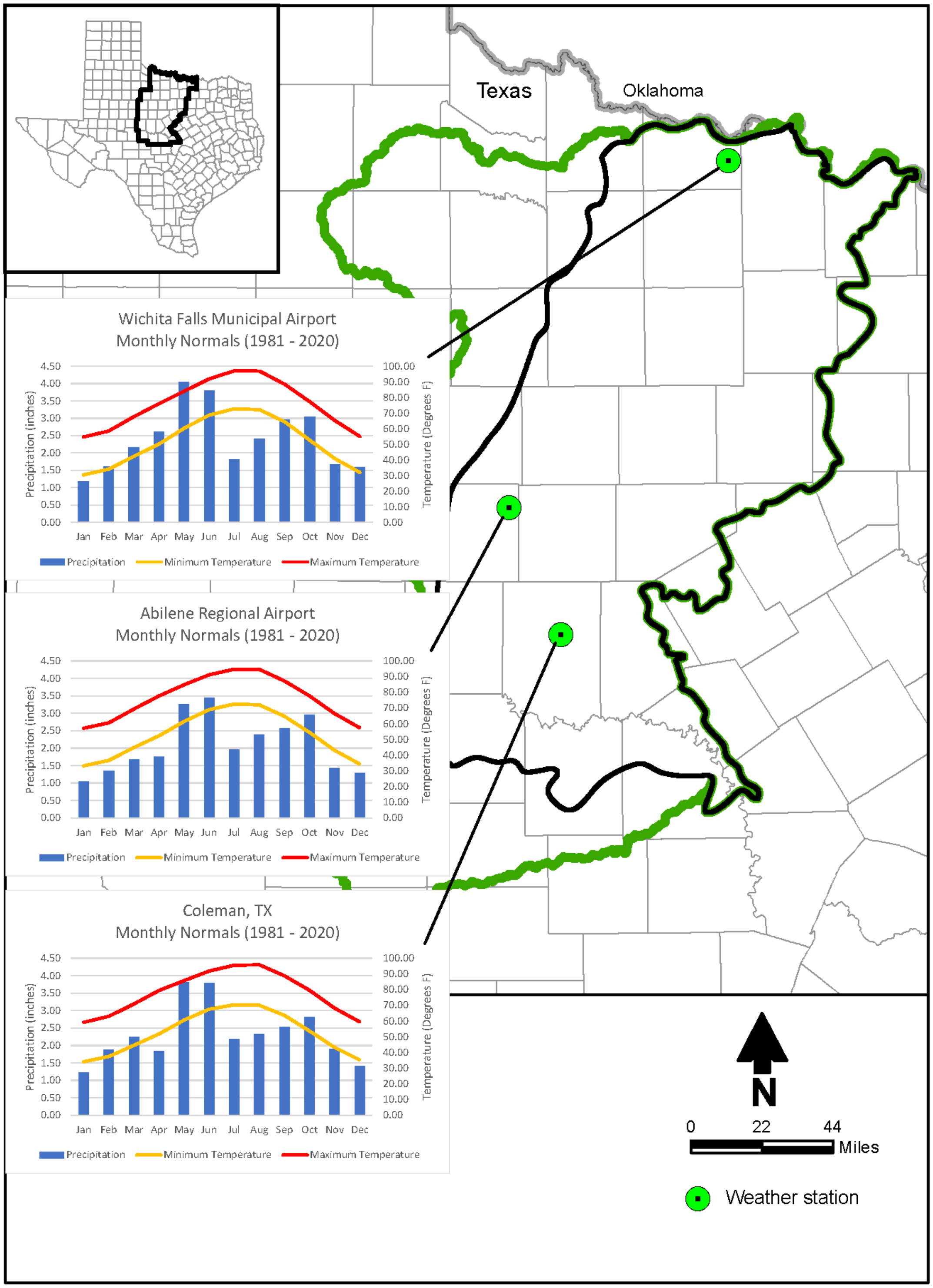


Figure 2-10. Mean monthly precipitation and temperature for selected weather stations.

Net annual lake evaporation is provided in Figure 2-11 developed from data at the Water for Texas website accessed May 18, 2021 (https://waterdatafortexas.org/lake-evaporation-rainfall). Net lake evaporation ranges from over 40 inches per year in the southwestern portion of the Cross Timbers Aquifer study area to just over 20 inches per year or the northeastern portion of the aquifer extent.

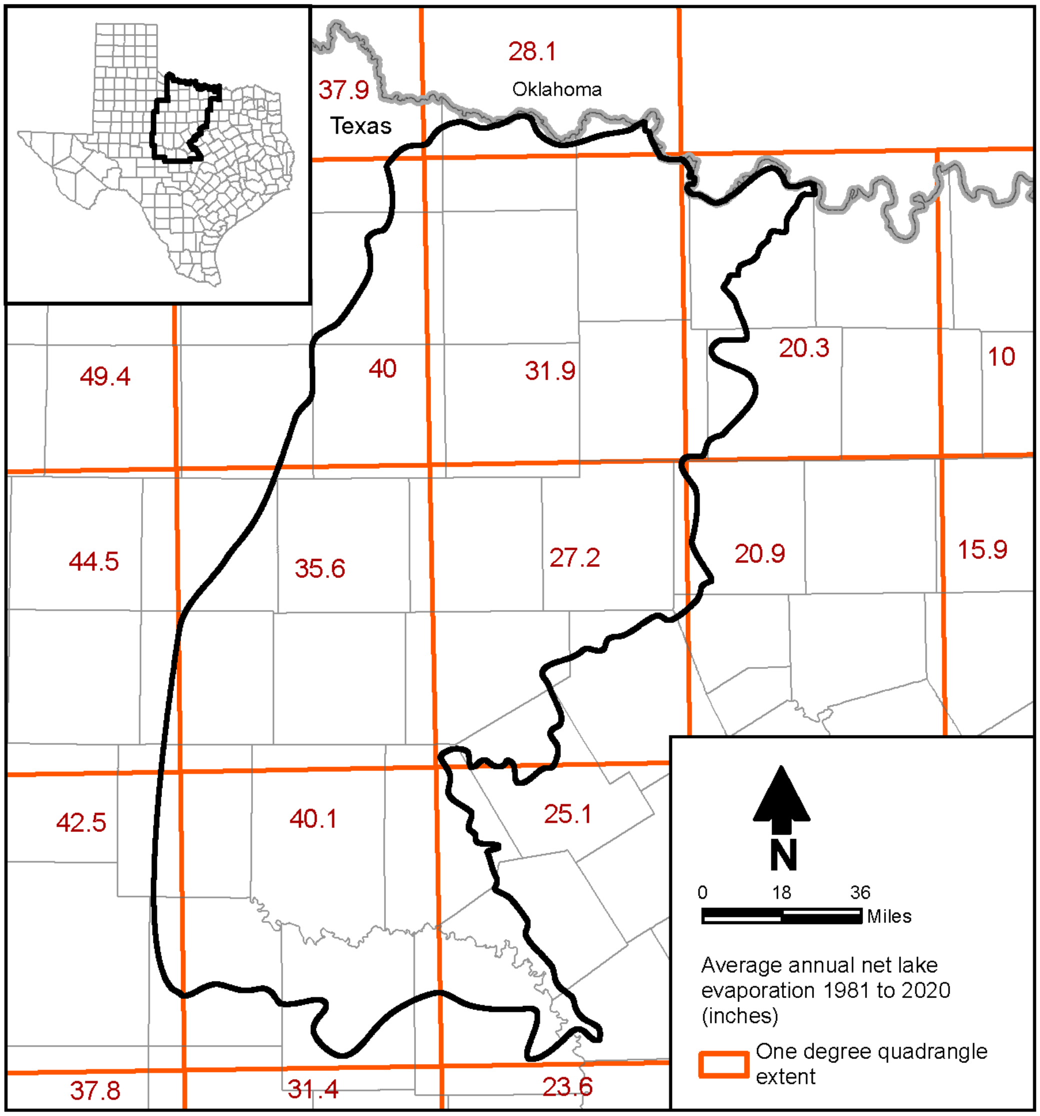


Figure 2-11. Net lake evaporation.

A map of vegetation distribution is provided in Figure 2-12. The data for this map was obtained from the 2016 National Land Cover Database, downloaded on January 13, 202. The predominate vegetation types within the Cross Timbers Aquifer extent are shrub/scrub and herbaceous. Significant regions of cultivated crops also occur, but most of these are west of the aquifer boundary overlying the Seymour or Lipan Aquifers.

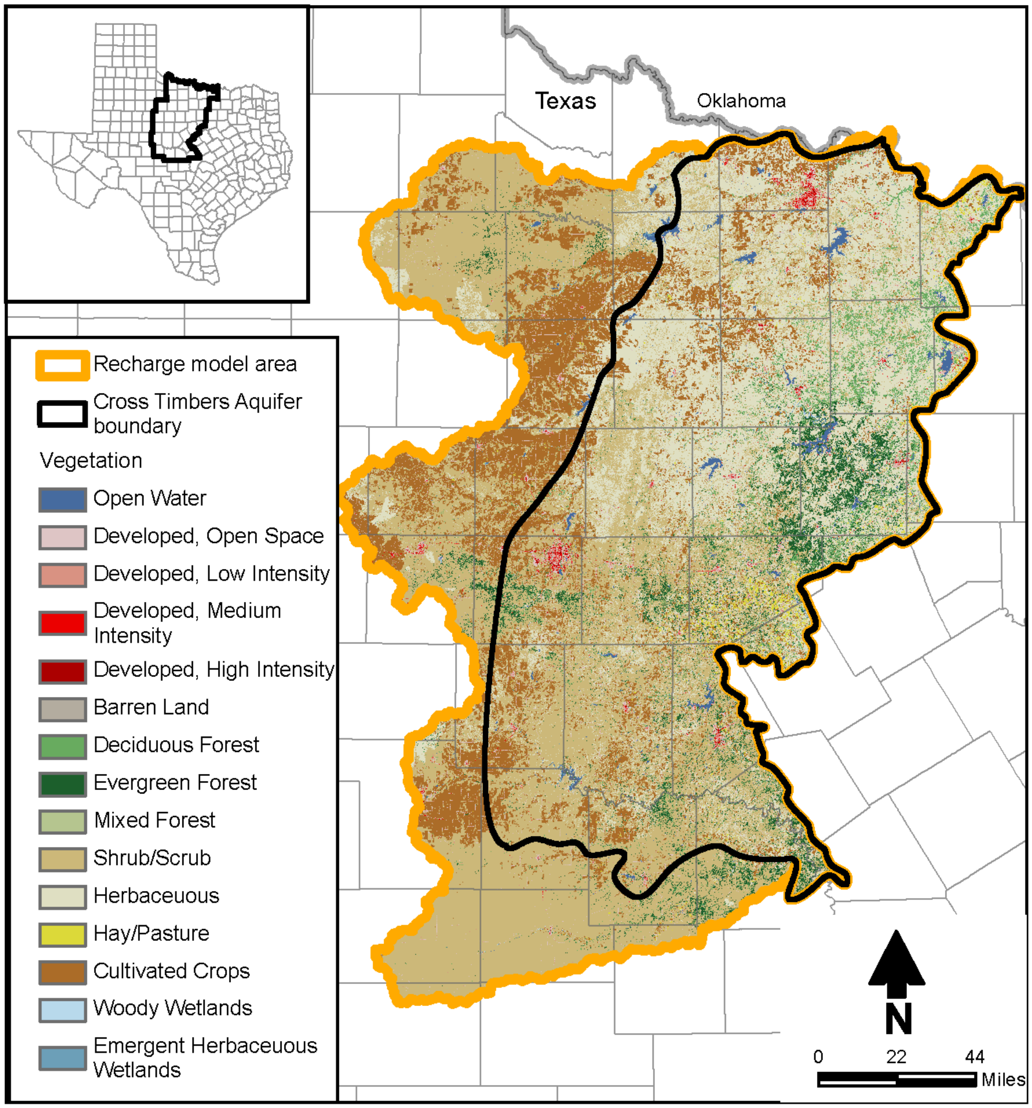


Figure 2-12. Distribution of vegetation across the study area.

Soils data were obtained directly or estimated based on soils data published by the U.S. Department of Agriculture SSURGO database accessed December 14, 2020 (https://sdmdataaccess.nrcs.usda.gov/Citation.htm). A map of soil texture derived from SSURGO database is provided in Figure 2-13. Additional information on how this map was developed is provided in Section 7, along with a map of soil hydraulic conductivity used in the recharge modeling and tables of soil properties.

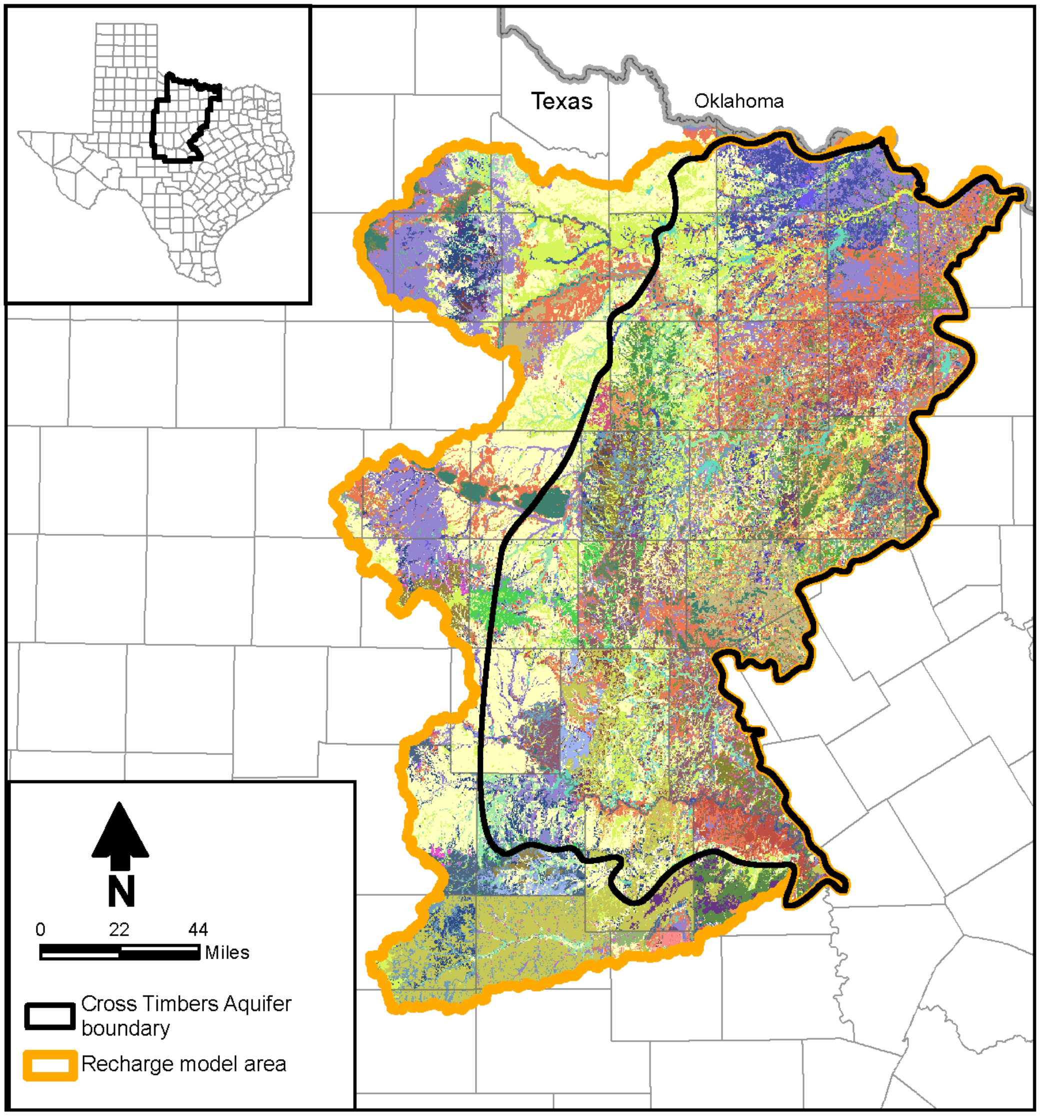


Figure 2-13a. Distribution of soil texture across the study area.

Figure 2-13b. Legend for distribution of soil texture map (Figure 2-13a).

3. Overview of Previous Investigations

The Permian and Pennsylvanian formations within the Cross Timbers Aquifer study area were the focus of numerous Bureau of Economic Geology and the University of Texas, Austin graduate degree studies. These studies focused on the complex stratigraphy and the potential for hydrocarbon resources of the Eastern Shelf of the Midland Basin. Hydrogeologic studies of the region have been relatively limited. Ballew and French (2019) provide an overview of the Cross Timbers Aquifer system.

3.1. University of Texas, Austin Thesis and Dissertations

From the 1970s through the early 2000s, several graduate students from the University of Texas, Austin completed a geological thesis or dissertation on areas within or in the vicinity of the Cross Timbers Aquifer. These studies include Galloway (1971), Solis (1972), Cleaves (1975), Erxleben (1975), Peterson (1977), Thompson (1982), Wan (1995), and Kier (2004).

3.2. TWDB Groundwater Availability Models

There are three TWDB groundwater availability models with model surfaces that have been integrated into the hydrostratigraphic framework of the Cross Timbers Aquifer conceptual model. The Seymour Aquifer (Ewing and others, 2004) forms a few shallow alluvial basins on the western edge of the Cross Timbers Aquifer in Jones County, Baylor and Throckmorton Counties and along the northern boundary of the Cross Timbers Aquifer in Wichita and Wilbarger Counties (Figure 3-1).

The Northern Trinity Aquifer groundwater availability model (Kelly and others, 2014) includes localized Comanche and Edwards Limestones, Glen Rose, Antlers, Travis Peak, or Twin Mountains Formation outcrops along the total eastern and southern edges of the Cross Timbers Aquifer area. Also, large surficial areas of Cretaceous Trinity Formation outcrops occur in Taylor, Callahan, Coleman, Eastland, and Comanche Counties (Figure 3-1).

The southern edge of the Cross Timbers Aquifer study area overlies the Llano Uplift groundwater availability model (Shi and others, 2016a). In this region, the Marble Falls Formation dips to the north off of the Llano Uplift and forms a localized base for the Cross Timbers Aquifer stratigraphic model (Figure 3-1).

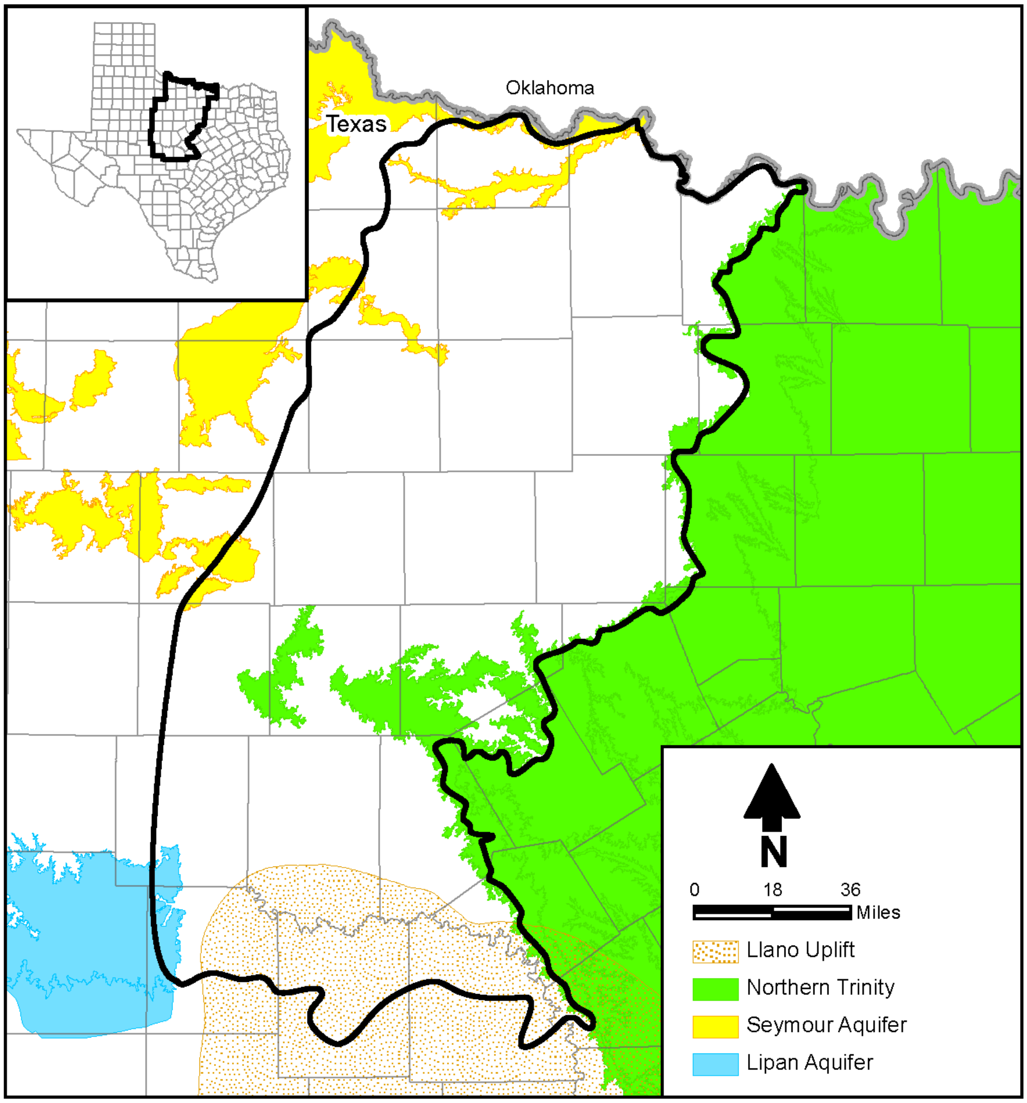


Figure 3-1. TWDB groundwater availability models within and adjacent to the study area.

3.3. TWDB County Reports

During the 1950s through the 1990s, over half of the counties within the Cross Timbers Aquifer study area had been the focus of TWDB or Texas Board of Water Engineers bulletin groundwater reports. These reports include descriptions of the local stratigraphy, lithology, well yield, water levels, and water quality. The erratic or spotty occurrence of groundwater availability and quality were noted in some of these reports. Table 3-1 summarizes these reports by county. Other TWDB reports reviewed include Core Laboratories Inc. (1972), Duffin and Beynon (1992), Preston and others (1996), and Ballew and French (2019). Each of these reports was reviewed for this study.

Table 3-1. Summary of TWDB and Texas Board of Water Engineers county reports within Cross Timbers Aquifer study area.

County	TWDB Report Number	TBWE Bulletin Number	Reference
Archer	52	—	Morris (1967)
Baylor	218	—	Preston (1978)
Brown	46	—	Thompson (1967)
Callahan	278	—	Price and others (1983)
Clay	—	—	No report
Coleman	57	—	Walker (1967)
Concho	—	—	No report
Comanche	—	—	No report
Eastland	—	—	No report
Erath	331	—	Beynon (1991)
Haskell	—	6209	Ogilbee (1962)
Hood	—	—	No report
Jack	308	—	Nordstrom (1988)
Jones	215	—	Price (1978)
Lampasas	—	—	No report
McCulloch (only addresses the Hickory Aquifer)	—	6017	Mason (1961)
Mills	—	—	No report
Montague	58	—	Bayha (1967)
Palo Pinto	—	—	No report
Parker	—	5103	Stramel (1951)
Runnels	—	—	No report
San Saba	—	—	No report
Shackelford	100	—	Preston (1969)
Stephens	—	6412	Bayha (1964)
Taylor	224	—	Taylor (1978)
Throckmorton	113	—	Preston (1970)
Young	—	6415	Morris (1964)
Wichita	—	—	No report
Wilbarger	240	—	Price (1979)
Wise	—	—	No report

3.4. Bureau of Economic Geology Studies

During the late 1950s through the early 1990s, Bureau of Economic Geology researchers were active in the Cross Timbers Aquifer study area. Between 1959 and the early 1990s, Dr. Brown authored or co-authored more than a dozen Bureau of Economic Geology publications for the Cross Timbers region of Texas. Brown and others (1990) is the stratigraphic "Rosetta stone" for this report. Brown and others (1973 and 1987), Cleaves (1975), and Erxleben (1975) were also extensively relied upon.

Other Bureau of Economic Geology researchers that published reports in this study area include Cheny (1929), Wermund and others (1962), Wermund and Jenkins (1969), McGowen (1964), McGowen and others (1972 and 1991), Galloway and Brown (1972), Cleaves (1975), Erxleben (1975), Nicot and others (2011), Hentz (1988), and Hentz and Brown (1987). In recent work, Hentz and others (2017) expanded the correlation of the lower Permian (Wolfcamp) and Pennsylvanian limestone stratigraphic correlations of the Brown, Cleaves, and Erxleben study areas to the southwest, to include Runnels County.

Nicot and others (2011) cover the northeast quadrant of the Cross Timbers Aquifer study area, which includes Clay, Montague, Jack Wise, Palo Pinto, Parker, Erath, and Hood Counties (Figure 1). The Pennsylvanian formations of the Cisco, Canyon and Strawn Groups provide frack water for Barnett Shale well completions. Nicot and others (2011) constructed a conceptual groundwater model that considers groundwater chemistry, estimated groundwater recharge, groundwater/surface water interaction, aquifer hydraulic properties, and groundwater flow direction.

Ewing (2016) provides detailed descriptions on the genesis, interactions, and timing between geological features within the study area, and Ruppel (2019) provides a detailed geologic description of the evolution of the Midland Basin's Eastern Shelf.

3.5. Geological Atlas of Texas

All or portions of five 1 to 250,000 scale, digital Geologic Atlas of Texas sheets were used to compile the surface geology for the Cross Timbers Aquifer study area. The Geologic Atlas of Texas sheets used were the Abilene (Brown and others, 1972), Brownwood (Kier and others, 1976), Dallas (McGowen and others, 1972), Sherman (McGowen and others, 1991), and Wichita Falls-Lawton (Hentz and Brown, 1987) sheets.

3.6. Other Publications

Other useful references reviewed include field trip guides, studies and cross sections by the Abilene Geological Society (1949 and 1954), a North Texas Geological Society 1940 Field Guide (North Texas Geological Society, 1940), and U.S. Geological Survey publications by Kier and others (1979) and Eargle (1960).

4. Geology and Hydrostratigraphy

4.1. Stratigraphic Framework

This section provides an overview of the stratigraphic framework and selected hydrostratigraphic units delineated, as well as the approach for development of the framework.

4.1.1. Conceptual Model Surfaces and Layering

4.1.1.1. Initial Proposed Framework

A stratigraphic column was constructed by integrating stratigraphic columns from Brown and others (1990), Cleaves (1975), and Erxleben (1975) to create a sequence from the Quaternary through the Pennsylvanian Marble Falls Formation. The TWDB water well database was used to identify the Paleozoic formations known to produce groundwater and the number of water wells (based on the TWDB assigned aquifer code) in the TWDB database completed within each Paleozoic group, formation, or member. Based on this analysis and the corresponding formation descriptions of the Geologic Atlas of Texas rock units, it was determined that Paleozoic sandstones were the dominant groundwater-producing units of the Cross Timbers Aquifer, although there are a few Paleozoic limestones (e.g., Leuders and Palo Pinto) and shales (e.g., Colony Creek and Placid) that can locally produce limited amounts of groundwater.

Brown and others (1990), Cleaves (1975), and Erxleben (1975) published Paleozoic limestone and sandstone formation cross sections that were reviewed to determine the geographic extent of individual limestones within the Cross Timbers Aquifer. These studies correlated regionally persistent limestone units or their stratigraphic equivalent to develop regional lithostratigraphic frameworks. Stratigraphic equivalents are the result of a local facies change because of channel erosion or a pinch out, and define an equivalent concordant surface.

Based on preliminary analyses of these cross sections and considering the Paleozoic formations with water wells from the TWDB database, a preliminary stratigraphic model framework “Layer” (assuming mappable limestones and/or stratigraphic-equivalent formations that covered the model extent) was initially conceptualized.

4.1.1.2. Updated Framework

Figure 4-1 presents an updated approach to conceptual model layering based on detailed hydrostratigraphic analysis completed during this study and several project meetings held with the TWDB. The stratigraphic column in Figure 4-1 includes all Paleozoic groups, formations, and selected members (Layers, 2, 3, 4, 5, 6, 7, 8, and 9) from the five Geologic Atlas of Texas sheets, grouped Cretaceous Edwards-Trinity formations and members (Layer 1B), and the Seymour Aquifer (Layer 1A). Figure 4-1 also includes additional key limestone formations correlated by Brown and others (1990), Cleaves (1975), Erxleben (1975), and Hentz and others (2017).

Million Years Ago (Ewing, 2016)	Era	System	Series or Stage	Group	Formation	Reef	Member or Limesone	Model Layer
2	Cenozoic	Quaternary - Pleistocene			Alluvium			1A
					Leona			
					Seymour			
	Mesozoic	Cretaceous		Albian	Edwards			1B
				Comanchean	Trinity		Antlers	
							Twin Mtn	
				Coahuilan			Travis Peak	
130							Hosston	
275	Paleozoic	Permian	Leonard	Clear Fork	Choza		Lytle	2
					Vale		Bullwagon	
					Arroyo		Standpipe	
280				Wichita - Albany	Leuders			3
					Clyde, Waggoner Ranch (GAT)		Talpa	
							Grape Creek	
			Wolfcamp		Belle Plains, Petrolia (GAT)		Bead Mountain	
							Jagger Bend, Valera	
							Elm Creek	
					Putnam, Nocona, (GAT)		Admiral	
292							Coleman Junction	
				Cisco	Santa Anna Branch			4
					Sedwick			
					Moran		Dothan, Camp Colorado	
					Pueblo		Stockwether, Saddle Creek	
		Pennsylvanian	Virgilian		Harpersville		Crystal Falls	
							Breckenridge	5
300					Thrifty	Carbonate Banks	Blach Ranch	
							Ivan	
					Graham		Gunsight, Bunger	
303			Missourian	Canyon	Caddo Creek		Home Creek	6
							Colony Creek	
					Brad		Ranger	
							Clear Creek, Cedarton	
					Placid			
					Winchell			
					Wolf Mountain			
					Palo Pinto		Wiles, Wynn	7
307				Strawn	Mineral Wells		Dog Bend	8
			Desmoinesian		Brazos River			
					Mingus		Capps, Dobbs Valley	
					Grindstone Creek		Buck Creek	
					Lazy Bend			
			Atokian	Atoka	Smithwick			
320			Morrowan	Morrow	Marble Falls		Marble Falls	9

Figure 4-1. Hydrostratigraphic column for the Cross Timbers Aquifer.

Brown and others (1990), Cleaves (1975), and Erxleben (1975) mapped many limestone units that are geologic group members not mapped as discrete units on the Geologic Atlas of Texas sheets; rather, they are encompassed within a geologic formation or group that is mapped on the Geologic Atlas of Texas sheets. Figure 4-1 illustrates the revised Cross Timbers stratigraphic column that considers all the Paleozoic GAT rock units and key limestone members from Brown and others (1990), Cleaves (1975), and Erxleben (1975). The blue color in Figure 4-1 represents groups, formations, or members identified as groundwater production zones.

Reference limestone and/or stratigraphic-equivalent surfaces for the Cross Timbers Aquifer study area were correlated to build a framework to confine and provide a depth reference (from land surface) for the packages of sandstone isopaches created by Brown and others (1990), Cleaves (1975), and Erxleben (1975) used to form the Cross Timber model layers. When the TWDB Cross Timbers proposal was submitted, the full lateral extent and continuity of individual Paleozoic Geologic Atlas of Texas limestones and/or time-equivalent formations was only partially understood. A complete understanding was developed when more than 1,400 geophysical logs from Brown and others (1990), Cleaves (1975), and Erxleben (1975) and over 900 additional Brackish Resources Aquifer Characterization System and Bureau of Economic Geology geophysical logs and scout tickets in the southern third of the study area were selected, screened, scanned, compiled and correlated to determine the areal extents of individual limestones.

Two Permian (top of Leuders Formation, base of Coleman Junction member) and five Pennsylvanian (top of Breckenridge member, top of Home Creek member, top of Palo Pinto Formation, top of the Dog Bend member of the Mineral Wells Formation, and top of Marble Falls Formation) limestones and/or time-equivalent surfaces were identified that cover their respective portion of the Cross Timbers Aquifer (Figure 4-1). The geographic extent of each Cross Timbers Aquifer conceptual model layer is illustrated through the surface geology provided in Figure 4-2.

The Mississippian Barnett Shale and Ordovician Ellenburger Formation occur along the far southern edge of the study area in San Saba and McCulloch Counties. Due to normal faulting resulting in horsts and grabens, isolated blocks of the Pennsylvanian Marble Falls Formation occur adjacent to, or surrounded by, Barnet Shale or Ellenburger Formation faulted blocks. Revision of the southern boundary of the Cross Timbers Aquifer by excluding the Mississippian Barnet Shale or the Ordovician Ellenburger Formation would impact the included extent of the Marble Falls Formation, and is not recommended.

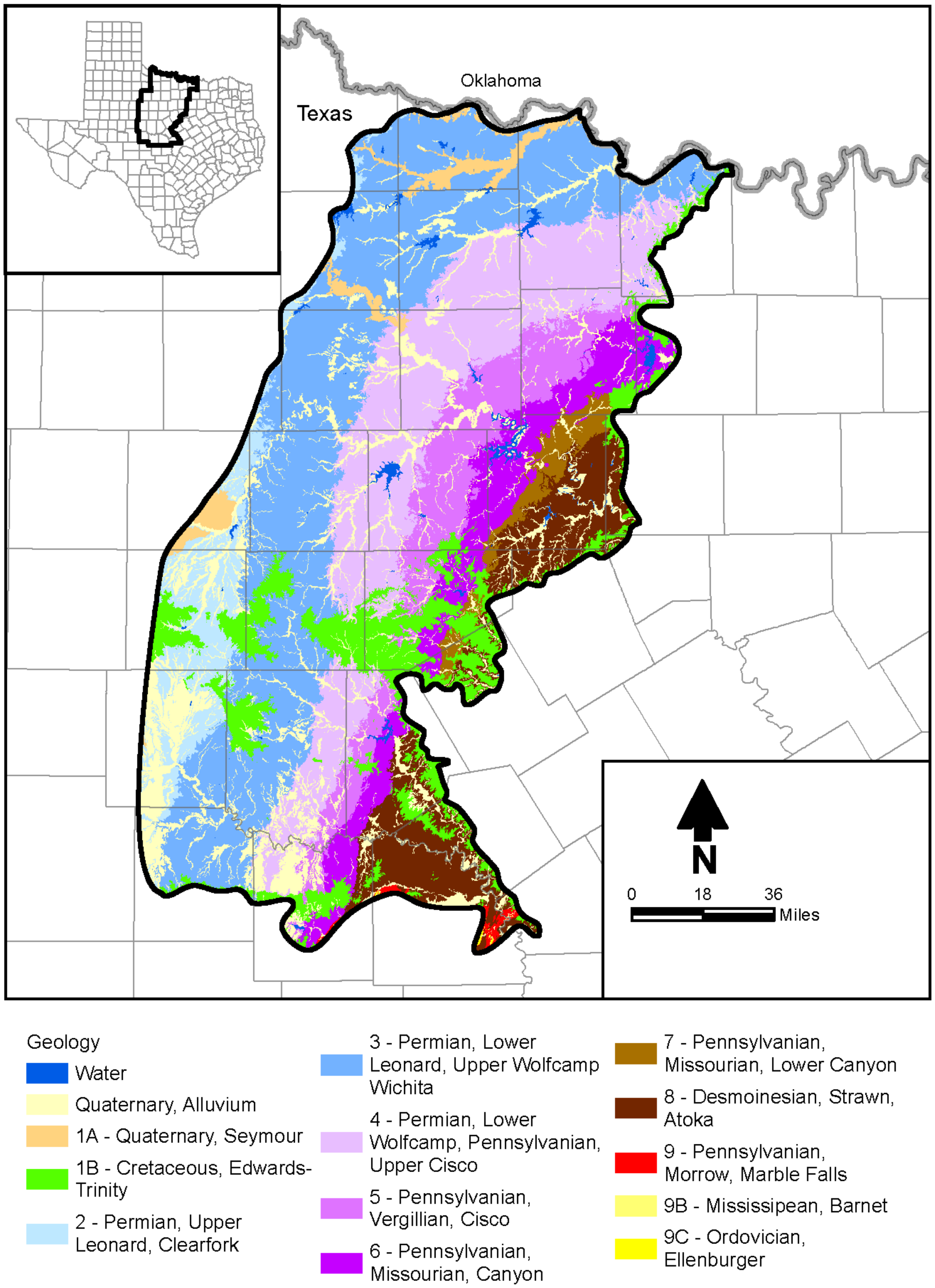


Figure 4-2. Surface geology.

4.1.2. Description of Hydrostratigraphic Units

This section describes the nine conceptual model hydrostratigraphic units (referred to as layers) selected for analysis and mapping as presented in Section 3.1.2. The description is ordered by the geologic units encompassed within each conceptual model layer. The shallow Cenozoic and Mesozoic units host shallow aquifer systems addressed in existing groundwater availability models, and are not the primary focus of this study. The majority of the work completed for this project focused on the Paleozoic Era geologic units (specifically the Permian and Pennsylvanian systems), and it is these units that are discussed in detail in the following subsections. Layer thicknesses referenced in the following subsections are for subcrop areas only; obviously, the layer thicknesses transition from the values identified below to zero at the outcrop extents.

4.1.2.1. Cenozoic and Mesozoic Units

Model Layer 1A consists of the Cenozoic alluvium and Leona and Seymour Formations. All surficial alluvial sediment types have been grouped together as one geographic information system shapefile as "Quaternary Alluvium" (Figures 4-1 and 4-2) as Layer 1 in the Mod_Lay attribute column of the Model Layer GIS shapefile. Polygon outlines from the most recent version of Seymour Aquifer were used to edit the Wichita Falls-Lawton and Abilene Geologic Atlas of Texas sheet polygons to represent the present TWDB Seymour Aquifer outline. The Seymour Aquifer (Figures 4-1 and 4-2) is identified as Layer 1A in the Mod_Lay attribute column of the Model Layer GIS shapefile.

Model Layer 1B consists of the Cretaceous Edwards and Trinity Formations. All Cretaceous formations within the study area are grouped together (Figures 4-1 and 4-2) as Layer 1B in the Mod_Lay attribute column of the Model Layer shapefile.

4.1.3. Paleozoic Units

Brown and others (1973), Cleaves (1975), and Erxleben (1975) determined that regional shelf limestones are the most accurate regional marker beds that can be recognized on geophysical logs. These limestones were deposited during periods of sea level rise and shoreline transgressions, and exhibit remarkable continuity from the Bend Arch throughout the Eastern Shelf and into the adjacent Midland Basin. Locally, a limestone may be absent because of channel erosion or, less commonly, because of local pinch-out onto abandoned fluvial/deltaic platforms. Facies variations may also locally affect geophysical log responses, especially in thin beds. Depositional sequences were correlated westward from the outcrop, across the Eastern Shelf, over shelf edges and downslope to pinch out on the floor of the Midland Basin (Brown and others, 1990).

A network of correlated limestones based on over 4,000 geophysical logs and a total of 5,100 control points was completed by Brown and others (1990), Cleaves (1975), and Erxleben (1975). Cores and samples were used to locally calibrate the lithic interpretation of geophysical logs. During these studies, no attempts were made to correlate sandstone facies from well to well because of the lenticular nature of fluvial-deltaic sandstone bodies. Subsequent Bureau of Economic Geology studies to the south and west of the Cross Timbers Aquifer study area have been completed by Hentz (1988) and Hentz and others (2017).

Permian Formations

During the Permian time period, extensive carbonate shelf and shelf-edge facies gradually restricted circulation on the landward parts of the Eastern Shelf. The facies on the Eastern Shelf graded from terrestrial red beds on the northeast near the sediment source to shallow marine on the southwest approaching the Midland Basin. Conceptual model Layers 2 and 3 are composed of Permian formations as described below.

Conceptual model Layer 2 is composed of the Clear Fork Group (Figure 4-1). The Clear Fork Group of north-central Texas is of continental origin in the north, and includes interbeds of increasing thickness of marine limestones and dolomites moving southward. The strata dip to the west in the southern half of the study area, and change dip direction to the northwest north of the study area (Wermund and Jenkins, 1969; Hentz, 1988). Strata are highly heterogeneous open marine, marginal marine, and continental facies of interstratified mudstones, carbonates, and sandstones with regionally discontinuous mappable sandstone bodies (Hentz, 1988). The thickness of the Clear Fork Group ranges from 700 to 900 feet (Brown and others, 1972).

Conceptual model Layer 3 is composed of the Wichita-Albany Group, which begins with the Lueders Formation and ends with the base of the Coleman Junction member (Figure 4-1). During the Wolfcamp time period, the rate of sediment supply continued to diminish, and subsidence of the Midland Basin decelerated, resulting in the slope wedges gradually decreasing in thickness. By the end of the Wolfcamp, the Eastern structural shelf of north-central Texas had become primarily a carbonate-evaporite-tidal flat province with terrigenous sediments supplied only by minor delta systems. The Wichita-Albany stratigraphic sequence consists of alternating mudstones, limestones, shales, and minor siltstones (Brown and others, 1973). Sandstone deposition was very limited during this time period. The thickness of Layer 3 ranges from 695 to over 1,250 feet, and has a mean value of 1,095 feet.

The Leuders Limestone is 50 to 70 feet thick and consists of alternating carbonate rich mudstones and limestones (Hentz and Brown, 1987; Brown and others, 1972). The Coleman Junction member is 50 to 95 feet thick and consists of very fine-grained limestone and mudstone with thin sandstone beds (Brown and others, 1973).

Conceptual model Layer 4 includes the mid- to upper Cisco Group, beginning from the base of the Coleman Junction member and ending with the top of the Breckenridge Limestone member. This conceptual model layer is composed primarily of Permian formations, but the bottommost Harpersville Formation is of Pennsylvanian age (Figure 4-1).

Uplift of the Ouachita Mountains increased during the Upper Pennsylvanian, leading to active deposition of the sandstone rich Cisco Group, dominated by fluvial-deltaic sediments with beds of limestone, shale, mudstone, and conglomerate (Hentz, 1988; Brown and others, 1990). In upslope areas, Cisco fluvial fades are tabular to sheet-like complexes of anastomosing sandstones; braided or coarse-grained meander belts are common upslope near source areas. Downslope, narrower, fine-grained meander belt sand bodies become more common, and they grade distally into relatively straight distributary channel deposits (Brown and others, 1990).

The Harpersville Formation of Pennsylvanian age is composed of alternating sandstone, mudstone, and limestone facies that extend westward into the subsurface 50 to 60 miles, where they grade into equivalent shelf margin carbonate and slope terrigenous facies. The base of the Harpersville Formation is the Breckenridge Limestone, which is thin (generally less than 10 feet) but widespread, and a very useful stratigraphic reference surface. The top of the Breckenridge Limestone is the base of Layer 4. The thickness of Layer 4 ranges from 575 to over 1,400 feet, and has a mean value of 940 feet.

Pennsylvanian Formations

Pennsylvanian strata are composed of fluvial, deltaic, interdeltaic, and shelf deposits derived from nearby mountainous areas uplifted during the Ouachita Orogeny (Brown and others, 1990). Shelf-edge reefs and slope and basinal terrigenous clastics exist west of the study area. Pennsylvanian sediments mark a change from earlier platform related depositional environments and consist of, from older to younger, the Atoka (also known as Bend), Strawn, Canyon, and Cisco Groups. During the Cisco and Strawn time periods, there was more extensive deposition of sandstone-rich siliciclastics. During the Canyon time period, less sandstone was deposited because the source area uplift decreased, and as erosion progressed, sediment input declined and a generally carbonate- and mud-rich environment persisted. Locally however, during the Canyon time period, sandstones were deposited within valley fill, distributary channel fill, and delta-front deposits within the Perrin and Henrietta delta systems (Figure 4-3) in Wichita, Clay, Archer, Jack and Wise Counties (Erxleben, 1975; Cleaves and Erxleben, 1982). Conceptual model Layers 5 through 9 are composed of Pennsylvanian formations as described below.

Conceptual model Layer 5 includes the lower portion of the Cisco Group (Thrifty and Graham Formations) not included in conceptual model Layer 4. During upper Canyon deposition, rejuvenation of the Ouachita fold belt and eastern Fort Worth Basin slightly increased paleogradient sand and significantly increased sediment supply. With this increased supply of terrigenous elastics, extensive lower Cisco delta-fluvial systems began building westward across the Eastern Shelf. Thin Cisco delta systems prograded 10 to 15 times across the relatively stable Eastern Shelf of the Midland Basin (Figures 4-1, 4-2, and 4-3). Accelerated subsidence of the Midland Basin provided up to 1,500 feet of relief between Cisco shelf edges and the bottom of the Midland Basin (Brown and others, 1973). The Thrifty and Graham Formations include alternating sandstones, mudstones, and limestones. The thickness of Layer 5 ranges from 260 to over 1,280 feet, and has a mean value of 727 feet.

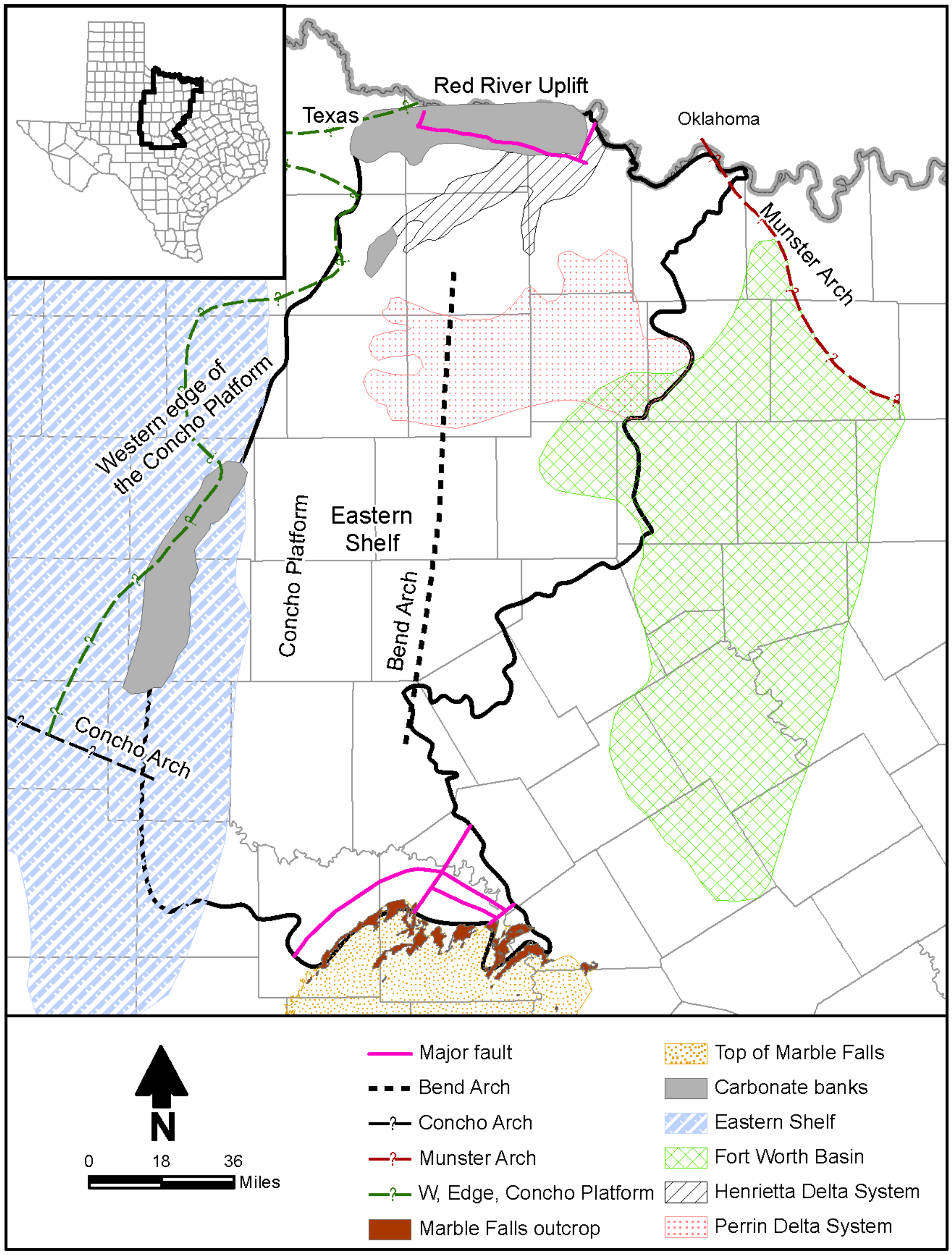


Figure 4-3. Geologic structure features within and adjacent to the study area.

Conceptual model Layer 6 includes the Canyon Group formations, except for the basal Palo Pinto Formation (Figure 4-1). The top of the Canyon Group is the Home Creek Limestone, which is 10 to 50 feet thick. The Canyon Group is a westward-dipping carbonate and clastic facies deposited upon a stable Concho Platform (Figure 4-3). As source area uplift clastic sediment decreased and erosion progressed, a generally carbonate-mud rich environment persisted throughout deposition of the group (Erxleben, 1975). Alternating shelf-margin delta systems and regressive limestone shelf-edge systems built westward from the Eastern Shelf into the relatively deep Midland Basin. Individual deltaic lobes and fan deltas reached far out onto the stable shelf between carbonate banks. With deltaic abandonment, shelf carbonates spread out from the old carbonate banks and from outer shelf areas and on lapped compacting deltaic sands and muds. This process of deltaic outbuilding, abandonment, compaction, and carbonate onlap created the cyclical sequence of deltaic-clastic and shelf carbonate rocks of the Canyon Group (Erxleben, 1975). The thickness of Layer 6 ranges from 160 to over 1,655 feet, and has a mean value of 698 feet.

Some sandstone facies occur locally in the Canyon Group from valley fill, channel fill, and delta-front deposition, mostly related to the Perrin delta system in Jack and Wise Counties (Erxleben, 1975; Cleaves and Erxleben, 1982). The Henrietta fan-delta system occurs only in the subsurface in Montague, Clay, Wichita, Archer, and Baylor Counties (Figure 4-3).

Conceptual model Layer 7 is composed of the Palo Pinto Formation (limestone), which is at the base of the Canyon Group. This layer extends to the top of the Dog Creek member of the underlying Mineral Wells Formation (Figure 4-1); at many locations, this is coincident with the base of the Palo Pinto Formation, but locally there may be other members (e.g., Turkey Creek) at the top of the Mineral Wells Formation. The Palo Pinto Formation represents a change from siliclastic to carbonate-dominated deposition, and has proven to be a consistent and reliable marker bed for the study area (Figures 4-1 and 4-2). The Palo Pinto Formation has several members, including the Wiles Limestone, Willow Point Limestone, Oran Sandstone, and Wynn Limestone. The Palo Pinto Formation is primarily a shaley to cherty dense limestone (Cleaves, 1975; Erxleben, 1975). Some limestone members have intervals containing distinctive fusulinaceans and algae. The thickness of Layer 7 ranges from 110 to over 1,010 feet, and has a mean value of 698 feet.

Conceptual model Layer 8 is composed of the Strawn Group (beginning at the top of the Dog Bend member) and the Smithwick Formation. The Strawn Group consists of alternating sandstone, limestone, and shale layers deposited in deltaic and some fluvial environments with alternating transgressive, marine limestones. The Strawn Group includes the Mineral Wells, Brazos River, Mingus, Grindstone Creek, and Lazy Bend Formations (Figures 4-1 and 4-2). These formations have numerous members. The clastic deposition of the Strawn Group occurred during a period of relatively high sedimentary input from multiple delta complexes sourced from the Ouachita and Arbuckle Mountains to the east and north. During deposition of the Mingus and Grindstone Creek Formations, fluvial and deltaic sandstones channels prograded across the basin as far westward as the Concho Platform (Cleaves, 1975; Brown and others, 1973). The thickness of Layer 8 ranges from 55 to over 3,560 feet, and has a mean value of 1,163 feet.

The Smithwick Formation occurs below the base of the Strawn Group and forms the base of conceptual model Layer 8. The Smithwick Formation is a black, fissile, siliceous, phosphatic shale containing calcareous planktonic foraminifera and rare ammonoid and gastropod fauna. The upper section of the Smithwick Formation, however, is coarser-grained silt to sand, containing abundant bed forms in the Llano area. The Smithwick (Formation) is approximately 300 feet thick (Wright, 2006).

Conceptual model Layer 9 is composed of the Marble Falls Formation. The Marble Falls Formation of north-central Texas was deposited in a broad carbonate ramp system during the initial stages of Ouachita orogenesis (Figures 4-1 and 4-2). The formation gradually thickens eastward from its subcrop along the Bend Arch to more than 600 feet along the axis of the Fort Worth Basin (Berend, 2015). The Marble Falls Formation is dominantly limestone with some shale. The limestone is light to dark gray, and is commonly oolitic and/or contains abundant other fossils. The limestone is locally siliceous and is fractured. The average thickness of the Marble Falls Formation is 300 feet (Brown and others, 1972).

4.2. Structure

The Cross Timbers Aquifer study area has a complex structural, erosional, and depositional evolution starting before the Pre-Paleozoic and continuing through the Cenozoic Era. The study area includes large and smaller scale basins, uplifts and arches, carbonate platforms and banks and fault zones (Figure 4-3). The following discussion of the time and evolution of the geological features illustrated in Figure 4-3 begins with features in the north and ends in the south.

4.2.1. Red River Uplift/Fault Zone and Muenster Arch

The Cross Timbers Aquifer study area is bounded on the north by the Red River Uplift/ Fault Zone and on the northeast by the Muenster Arch. During the early Pennsylvanian time period (Atoka), the Red River Uplift faulting and the Muenster Arch were formed by the Ouachita orogeny/thrusting (Ewing, 2016). The western edge of the Ouachita thrust faulting is east of the study area and is not illustrated in Figure 4-3.

Extensive platform limestones or carbonate banks were deposited on the Red River Uplift fault blocks during the Pennsylvanian Strawn and Canyon time periods (Cleaves, 1975; Erxleben, 1975). Fluvial and fan-delta systems were initially confined north the Red River Uplift and eventually overflowed onto and buried the carbonate platforms during the Cisco time period (Brown and others, 1987). Thick fan-delta systems (Henrietta Delta System) were deposited on the south flank of the Red River Uplift in northern Clay County (Erxleben, 1975). Red River Uplift faults have vertical throws ranging from less than 100 to 500 feet (mapped faults in Figure 4-3). One graben (downthrown) fault block consisting of four faults was delineated using geophysical logs in the Red River Uplift area.

During the early Pennsylvanian, faulting occurred along the western margin of the Muenster Arch, which elevated rocks in Montague and eastern Clay Counties during the Cisco time period, creating an angular unconformity (Erxleben, 1975).

4.2.2. Henrietta Fan-Delta System

The Henrietta fan-delta system consists of coarse wedges of the Pennsylvanian Wolf Mountain Formation (Figure 4-1) in northern Montague, Clay, eastern Wichita, northern Archer, and eastern Baylor Counties (Figure 4-3). Henrietta fan-deltas are generally thick, massive and coarse-grained, often with sharp erosional bases and tops. The fans generally consist of granite wash that is poorly sorted (Erxleben, 1975).

The largest lobe of the Henrietta System prograded southwest through northern Clay County and into Wichita and Archer Counties. A thick lobe in eastern Clay County has a well-defined, narrow feeder trend that extends southwestward from the northwest corner of Montague County. The Henrietta system was deposited in a relatively shallow, yet subsiding, trough (Erxleben, 1975).

4.2.3. Perrin Fan-Delta System

The Perrin fan-delta system is composed of terrigenous sediments including the Wolf Mountain, Placid, and Colony Creek Formations (Figure 4-1) deposited during the middle Canyon time period (Figure 4-3). The Perrin fan-delta system prograded northwestward through eastern Jack and western Wise Counties (Erxleben, 1975).

Deltaic depositional events ceased periodically in these fan-delta systems due to (1) decreased tectonism in the Ouachita folded belt, (2) changing climatic conditions, (3) basinal sea level changes, (4) shifts to deltaic deposition in other areas, or (5) combinations of these factors. During these periods of halted deltaic deposition or destruction, marine transgressions deposited shelf carbonates (Erxleben, 1975).

The Placid and Colony Creek Formations (Figure 4-1), primarily shales according to Brown and others (1972), contain lenses of coarse-grained channel-fill fluvial sandstones and chert-pebble conglomerates. These coarse-grained channel-fill fluvial sandstones occur in medium- to large-scale trough cross-beds that are up to 10 to 20 feet thick. The maximum sandstone thickness within the Perrin system occurs south of the town of Jacksboro, 5 to 10 miles downdip from the sandstone outcrops (Erxleben, 1975).

4.2.4. Fort Worth Basin

Prior to and continuing during the early Pennsylvanian (Atoka), the Ouachita Orogeny structural activity created the Fort Worth Basin (Figure 4-3). Platform and shelf-edge carbonate environments, like the Pennsylvanian Marble Falls Formation (Figures 4-1 and 4-2) were deposited on the southwestern edge of the subsiding Fort Worth Basin (Brown and others, 1973).

The Fort Worth Basin shallows to the west toward the Bend Arch (Ewing, 2016). The southwestern edge of the Fort Worth Basin forms the southeastern edge of the Cross Timbers Aquifer study area (Brown and others, 1973). Strawn Group formations overlie and outcrop over the underlying Marble Falls Formation in Palo Pinto and Parker Counties (Figure 4-3).

4.2.5. *Bend Arch*

The development of the Bend Arch as a long, northward plunging flexural hinge likely occurred due to Ouachita Orogeny tectonic stresses and regional upwarping that affected the Llano Block in early Pennsylvanian time. The Bend Arch represents the flexure axis and outer shelf margin for the rising Fort Worth Basin to the east and the subsidence of Midland Basin to the west (Figure 4-3) (Brown and others, 1987).

East of the Bend Arch, the Pennsylvanian Canyon (northeastern edge of Cross Timbers Aquifer study area) and Strawn (southeastern edge of Cross Timbers Aquifer study area) formations outcrop. Cisco formations outcrop along most of the Bend Arch axis (Figure 4-2). The regional dip ranges from 5 to 20 feet to the west per mile in the north to 50 feet per mile dipping west of the southern end of the Bend Arch.

West of the Bend Arch axis, younger Pennsylvanian Cisco and then Permian Wichita and Clear Fork formations outcrop. The top of the Clear Fork, the Leuders Formation, outcrops along the western edge of the Cross Timbers Aquifer study area (Figure 4-2). The regional dips range from approximately 20 feet per mile dipping west up north to around 50 feet per mile to the west on the southern end of the Bend Arch.

4.2.6. *Eastern Shelf*

The Eastern Shelf (Figure 4-3) represents the eastern portion of the Midland Basin, which has undergone much less subsidence than the central portion of the Midland Basin formed during the Ouachita Orogeny. The relatively stable Eastern Shelf has Pennsylvanian Canyon and Strawn formations that generally thicken to the west and are capped with relatively thin Cisco delta systems that had advanced and retreated numerous times as sea levels fluctuated through time (Brown and others, 1973). Eastern Shelf Permian and Pennsylvanian formations thin to the south toward the Llano Uplift (Ruppel, 2019). Figure 4-4 is a west to east cross section from the three-dimensional model that illustrates the Eastern Shelf (left to central) and Bend Arch axis (right).

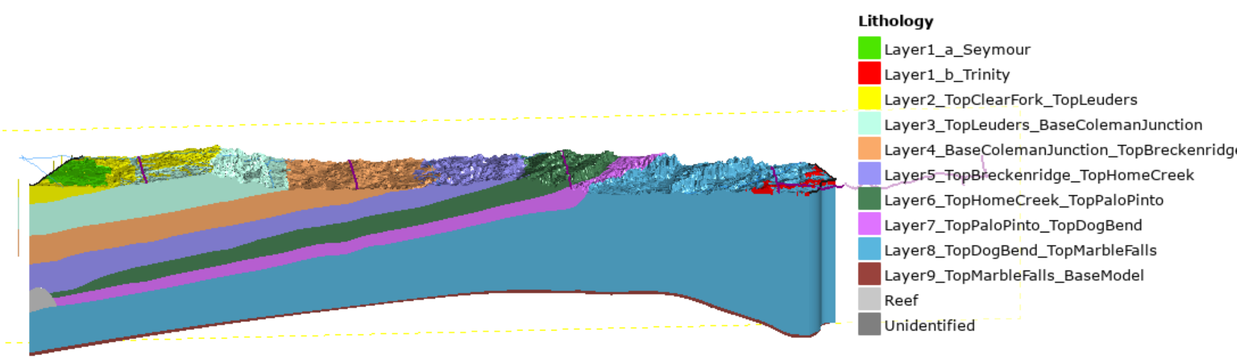


Figure 4-4. West (Jones County) to east (Parker County) cross section.

4.2.7. Concho Platform

The Concho Platform is located west of the Bend Arch, and covers most of the Eastern Shelf extending westward to the western border of the Cross Timbers Aquifer model (Figure 4-3). Alternate sea level fluctuations created by continental glaciation resulted in alternating transgressive and regressive movement of the shorelines while the Concho platform was slowly subsiding, resulting in interbedded carbonate clastic deposit sequences (Erxleben, 1975).

Numerous sequences of alternating aggrading and prograding fluvial deltaic and carbonate shelf systems were deposited constructing the Eastern Shelf while the Midland Basin was subsiding during late Pennsylvanian and early Permian time. Alternating shelf-margin delta systems and regressive shelf-edge limestone systems were deposited on the Eastern Shelf westward into the deeper central Midland Basin (Brown and others, 1973).

During late Strawn deposition, delta-fluvial sedimentation continued as the Concho Platform underwent a gradual westward tilting and increased subsidence. This structurally positive element still provided support for the development of numerous Upper Strawn and Canyon Group reef and limestone banks (Cleaves, 1975). Limestone carbonate formations generally become thicker and more continuous to the south and west within the Concho Platform.

4.2.8. Western Edge of the Concho Platform

The western edge or extent of the Concho Carbonate Platform (Figure 4-3) is located adjacent to or west of the western boundary of the Cross Timbers Aquifer study area (Erxleben, 1975; Cleaves, 1975). High water levels caused bedded carbonate deposition, which dominated the Concho Platform with localized biohermal reefs or carbonate banks created. During low water levels, fluvial or deltaic shale and sandstones dominated (Harrison, 1973).

Along the western edge of the Concho Platform are a few Strawn-Canyon carbonate bank sequences that tend to be elongate and essentially oriented northeast-southwest. These carbonate banks consist of non-framework organisms like bryozoa, crinoids, and marine plants that mixed with mud and skeletal debris building depositionally high areas (Erxleben, 1975).

4.2.9. Carbonate Banks

There are three isolated and elongated carbonate sequences along the western edge of the Concho Shelf that are within the Cross Timbers Aquifer study area (Figure 4-3). These carbonate banks began around the time of deposition of the Pennsylvanian Palo Pinto Formation and continued as late as the middle Cisco. The "Reef" column in Figure 4-1 illustrates the time period of carbonate bank creation.

One large carbonate bank extends northeastward on the Concho Shelf's western edge from north Runnels County through Taylor and Jones Counties. A second large carbonate bank is associated with the Red River Uplift; it starts in Wilbarger County and extends eastward through Wichita and into Clay County. This carbonate structure forms the northern boundary of the Cross Timbers Aquifer study area. The third carbonate bank is small and is located in central Baylor County (Figure 4-3).

4.2.10. Concho Arch

The Concho Arch is a major structural feature trending northwest from the Llano Uplift in the southwestern corner of the Cross Timbers Aquifer study area (Figure 4-3). The creation of this positive feature occurred before the Pennsylvanian time period. The Concho Arch became largely obscured by regional westward tilting incident to subsidence of the Permian Basin during the Ouachita Orogeny, and forms the southwestern boundary for the deposition within the Concho Platform (Brown and others, 1973; Kier and others, 1979; Cheny, 1929; Ovalle-Rauch, 2012).

4.2.11. Llano Uplift

The Llano outcrop area (predominantly intrusive and metamorphosed rocks) has a geologically long (over 1.3 billion years) and complex structural history provided in detail in Ewing (2016). During the Mississippian time period, the Llano outcrop area was impacted by the Ouachita Orogeny's compressional and tensional tectonic stresses on pre-existing, earlier Paleozoic normal faults, resulting in a net upward movement.

This area is now known as the Llano Uplift, which has had Paleozoic Cambrian through Mississippian formations locally draped on an irregular, sloped, domal surface prior to the deposition of Pennsylvanian formations. The Llano Uplift is the southern boundary of the Cross Timbers Aquifer study area (Figure 4-3). The basal Pennsylvanian (Morrowan age) Marble Falls Formation (Figures 4-1 and 4-2) was deposited over the earlier, pre-existing Paleozoic formations during the Ouachita deformation. Moving northwest from the Marble Fall's outcrop, in McCulloch County, a sequence of northwesterly dipping Pennsylvanian formations from Atokian through the Cisco (Figure 4-1) were conformably deposited (Ewing, 2016).

Five faults were delineated using geophysical logs and considering previous fault locations from the Geologic Atlas of Texas Brownwood sheet and the Llano Uplift groundwater availability model. The faults appear to be radial and concentric from the Llano Uplift and were probably created or reactivated during the Ouachita Orogeny. Fault throws range from less than 200 feet to over 400 feet.

5. Hydrostratigraphic Framework

This section provides an overview of the technical approach used to conduct stratigraphic analysis based on geophysical logs, and explains how net sand thickness was determined for the appropriate conceptual model layers.

5.1. Hydrostratigraphic Framework Datasets

Geophysical log analysis provided the foundation of our hydrostratigraphic framework. If geophysical logs were not available for an area, the dataset was supplemented with scout ticket and well record data. Table 5-1 summarizes the datasets used to develop the hydrostratigraphic framework and the number of records associated with each. For each geophysical log or record outside the Brackish Resources Aquifer Characterization System geophysical well log collection, a scanned image file is included in the geodatabase.

Table 5-1. Summary of datasets used for hydrostratigraphic analysis.

Source	Collection	Count
TWDB	Brackish Resources Aquifer Characterization System geophysical well logs	682
TWDB	Brackish Resources Aquifer Characterization System unprocessed	1
Bureau of Economic Geology	Dr. Frank Brown collection – geophysical well logs	1,530
Bureau of Economic Geology	Well records and scout tickets	81
Bureau of Economic Geology	IGOR - geophysical well logs	79
	Total	**2,373**

5.2. Stratigraphic Analysis

The stratigraphic analysis focused on developing aquifer-wide surfaces for geologic formations that met the following criteria:

1. Stratigraphic unit is hydrogeologically significant to the Cross Timbers Aquifer system
2. There is aquifer-wide coverage of a mappable unit or identifiable equivalent
3. Unit can be correlated to the Geologic Atlas of Texas surface geology

This process resulted in identification of the following stratigraphic surfaces that form the tops and bottoms of the conceptual model layers presented in Section 2:

- Top of Leuders Formation: Forms base of the Clear Fork Group, which is hydrogeologically independent of the Upper Wichita Group, which is predominantly an aquitard.

- Base of Coleman Junction Limestone or equivalent: Separates the upper section of Wichita Group from the lower Wichita Group and the upper Cisco Group sands and sandstones.
- Top of Home Creek Limestone or equivalent: Separates the Cisco and Canyon Groups, which are likely hydrogeologically independent due to the combined low permeability of the Home Creek Limestone and the underlying Colony Creek Shale.
- Top of Palo Pinto Formation or equivalent: Creates a mappable unit that forms the top of water-bearing layers within the Palo Pinto (limestone) and the upper Mineral Wells (sandstone) Formations.
- Top of Dog Bend member or equivalent: Forms the base of the aquifer system in areas outside Marble Falls Formation coverage.
- Top of Marble Falls Formation: Forms the base of model along southern and eastern edges where the Lower Strawn Group and the upper Atoka (or Bend) are the predominant aquifer units.

5.3. Geophysical Log Analysis

Geophysical log interpretations were the primary data source used to develop the stratigraphic surfaces. Geophysical log availability was limited in the southern counties and along the southeastern edge of the study area; in these regions, well record and scout ticket data that include driller tops and bottoms for various formations were incorporated into the dataset. Type log data were sourced from Dr. Frank Brown's geophysical log collection located at the Bureau of Economic Geology. In addition, stratigraphic sections within Brown and others (1987), Cleaves (1975), Erxleben (1975), Hentz and others (2017), Preston (1969 and 1970), Price (1978), Price and others (1983), and Walker (1967) were referenced.

Emphasis was placed on correlating and collecting Dr. Brown's collection of geophysical logs because many of these logs included peer-reviewed stratigraphic picks for the hydrostratigraphic model layers. Where stratigraphic picks were not marked on Dr. Brown's logs and for logs outside of the collection, standard stratigraphic correlation techniques were applied where marker beds were identified using Blueview software in conjunction with development of on-the-fly working cross sections. The geophysical log, scout ticket, or well record data points used to delineate the top surface of conceptual model Layers 3 through 9 in subcrop are provided in Figures 5-1 through 5-7, respectively. In most cases, a geologic pick was also made for the base of the layer (top surface of the next layer) at the same data point unless log quality or some other factor precluded it. In the outcrop area (Figure 4-2), the land surface serves as the control for the top of a given layer, and these points are not shown on Figures 5-1 through 5-7.

An integrated quality assurance approach was implemented for all control points. The approach included a statistical outlier analysis of each surface where high/low and low/high data points were identified and reviewed for accuracy using the ArcGIS Getis-Ord General G spatial statistics tool and a visual inspection and review of control points within the three-dimensional workspace that appeared anomalous to the surrounding wells or stratigraphic controls. In addition, randomized sampling and on-the-fly cross sections were frequently used to ensure continuity of the stratigraphic surfaces.

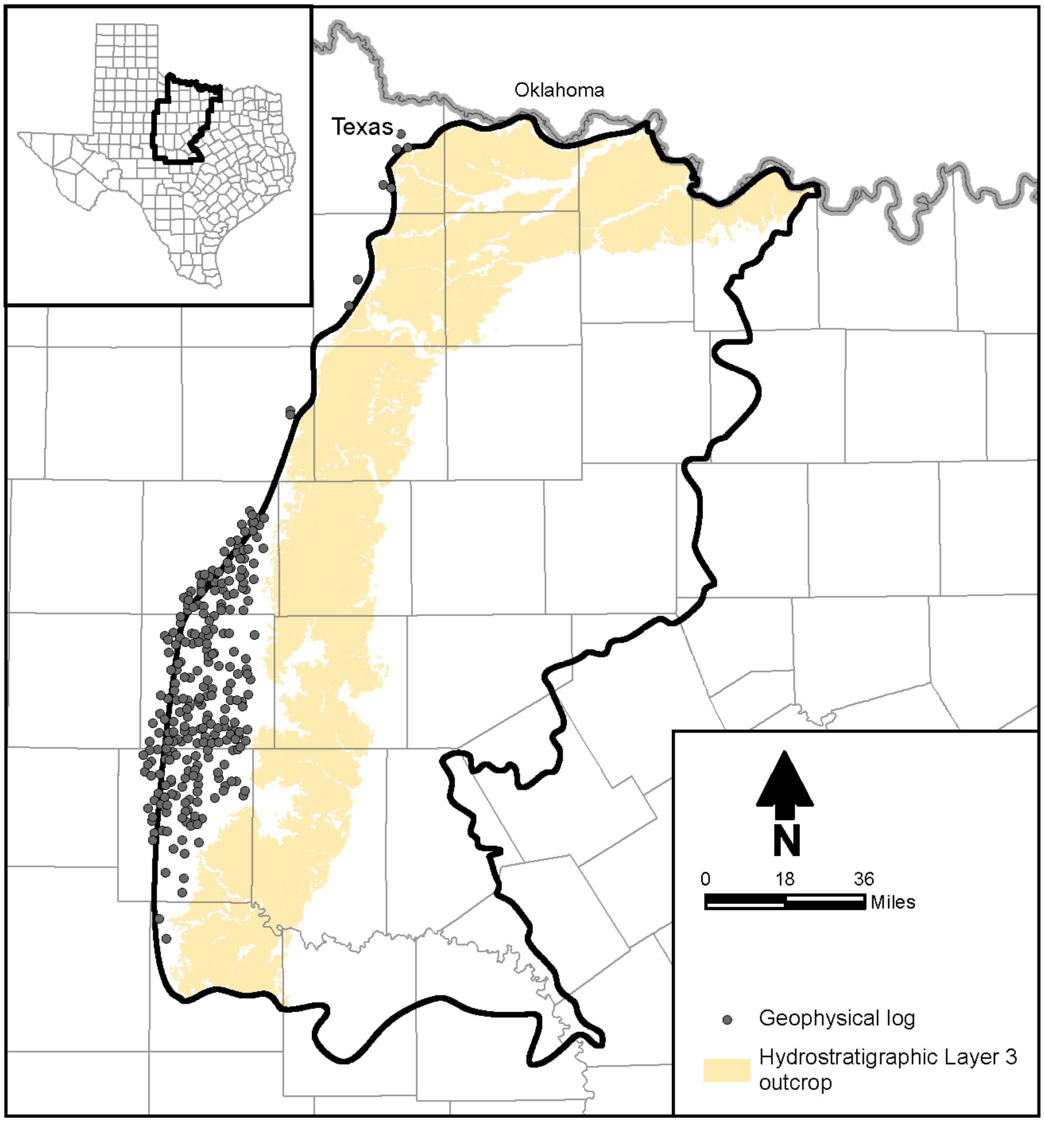


Figure 5-1. Layer 3 (Wichita-Albany Group) top surface control points.

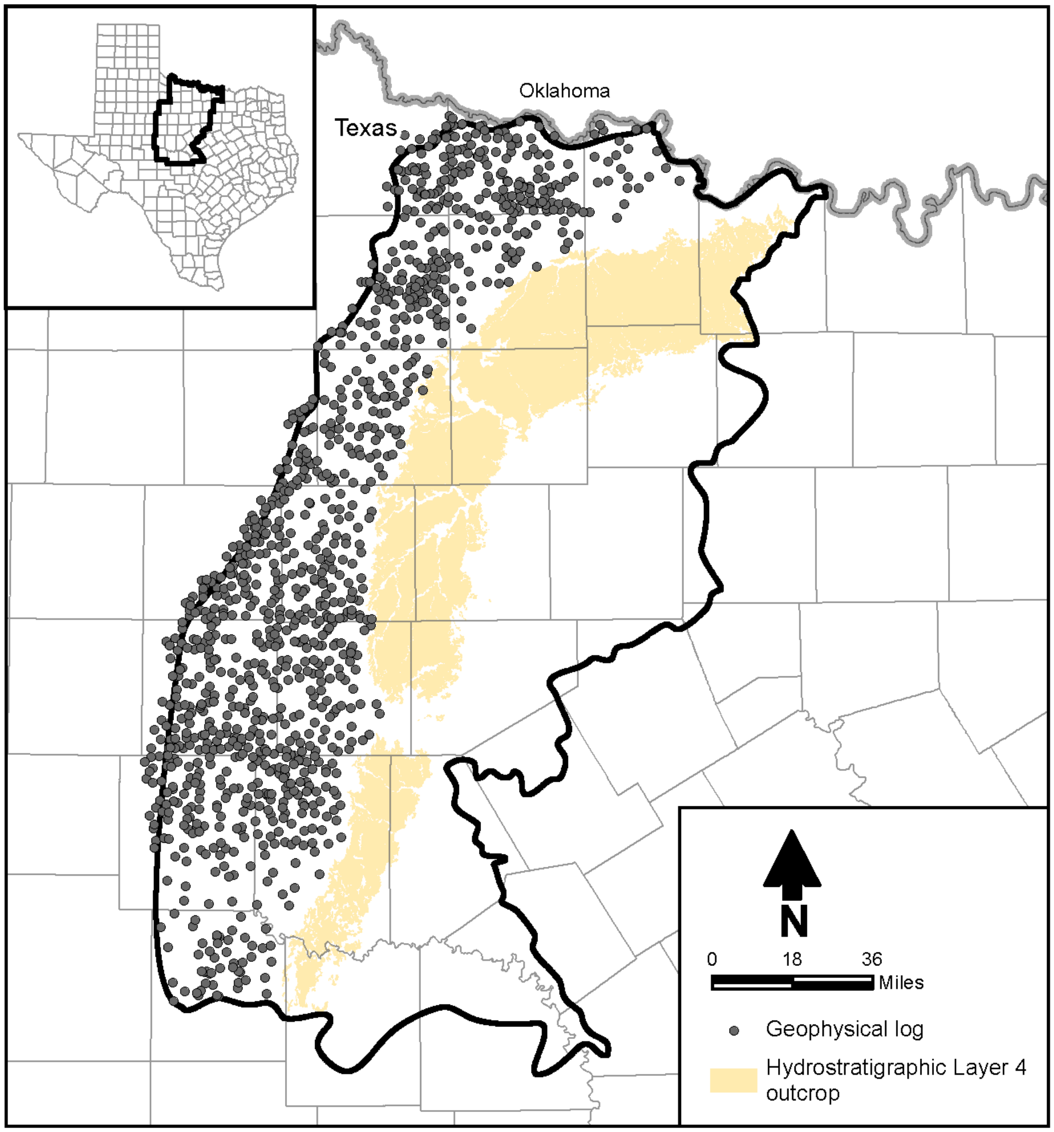


Figure 5-2. Layer 4 (Upper Cisco Group) top surface control points.

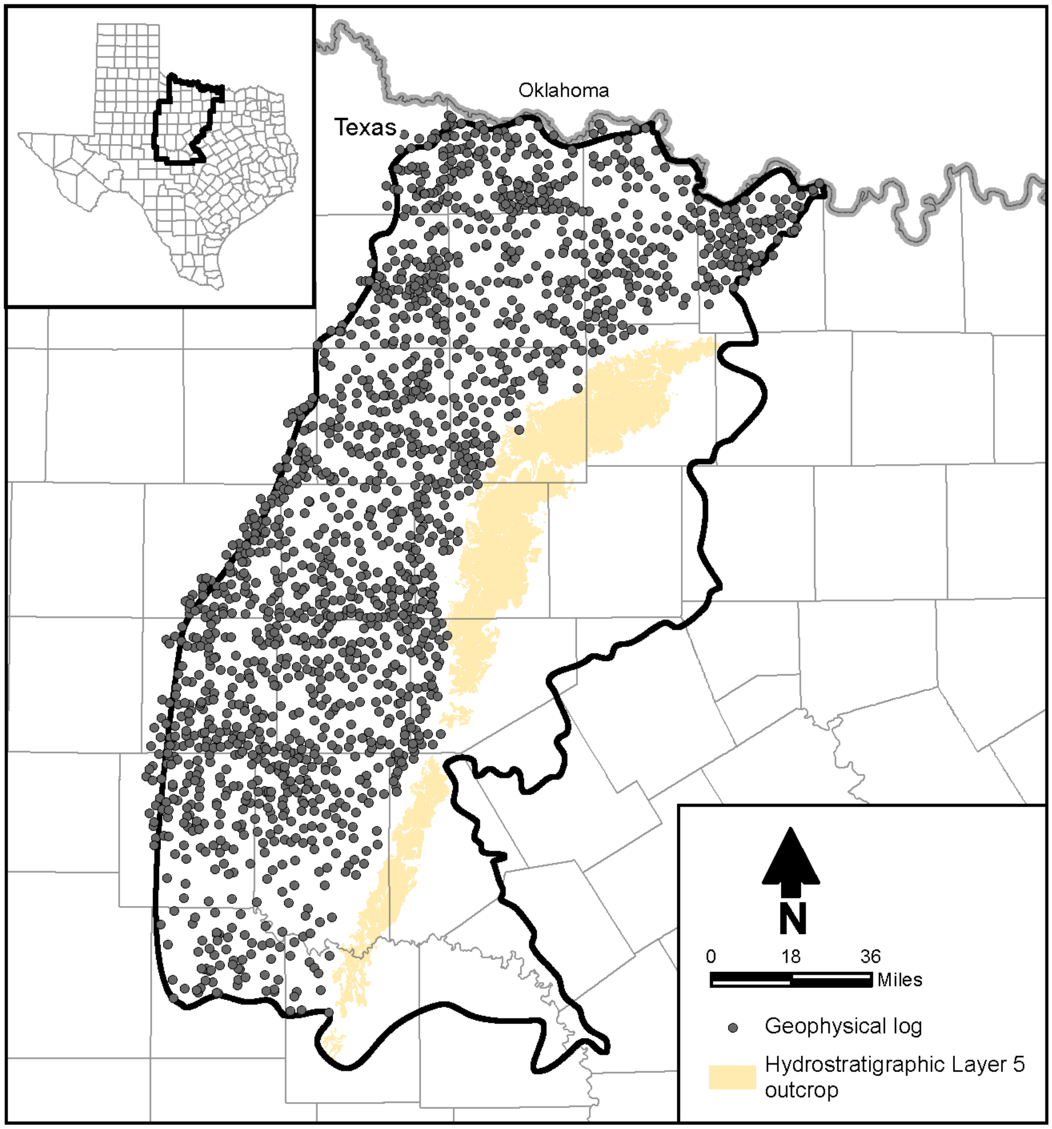


Figure 5-3. Layer 5 (Lower Cisco Group) top surface control points.

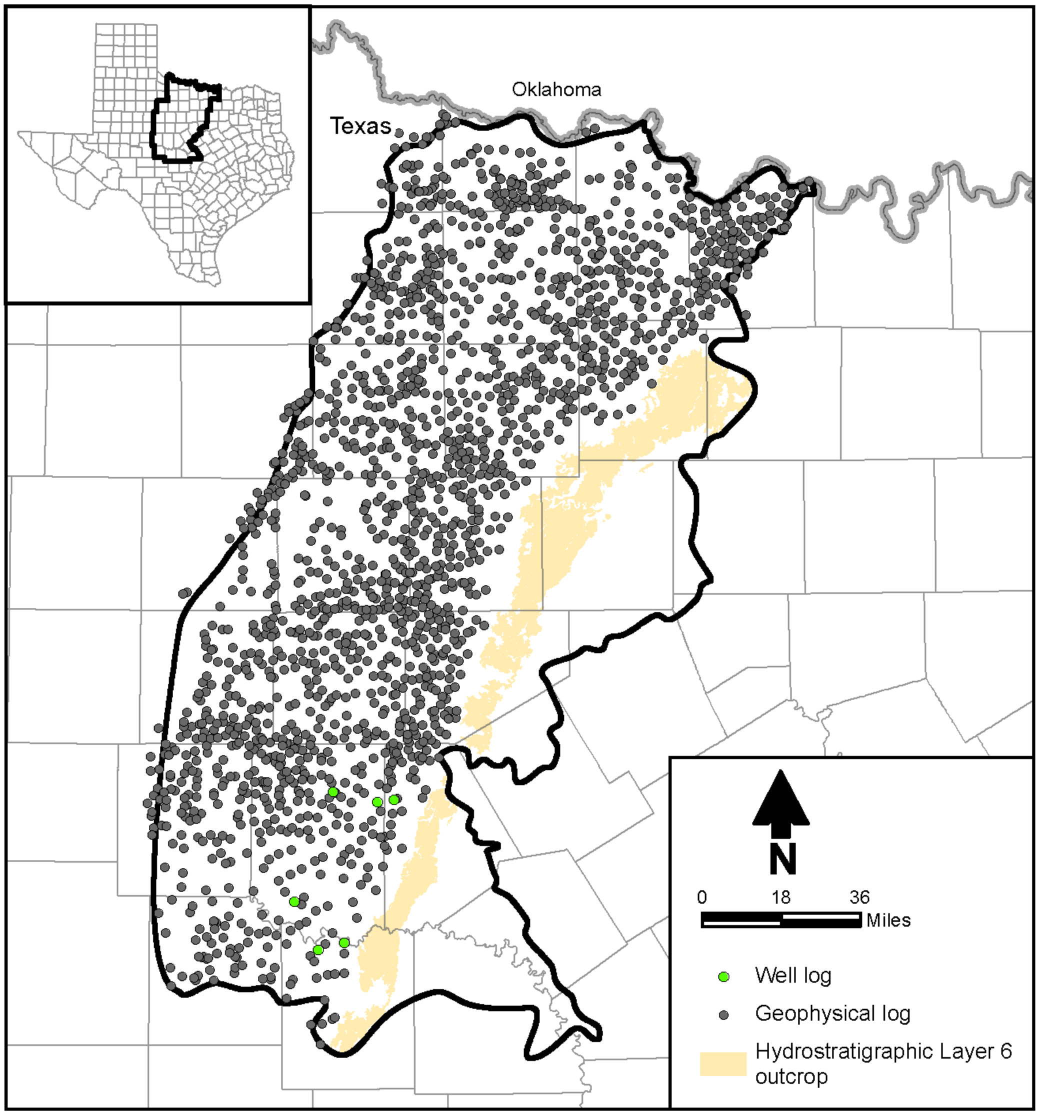


Figure 5-4. Layer 6 (Upper Canyon Group) top surface control points.

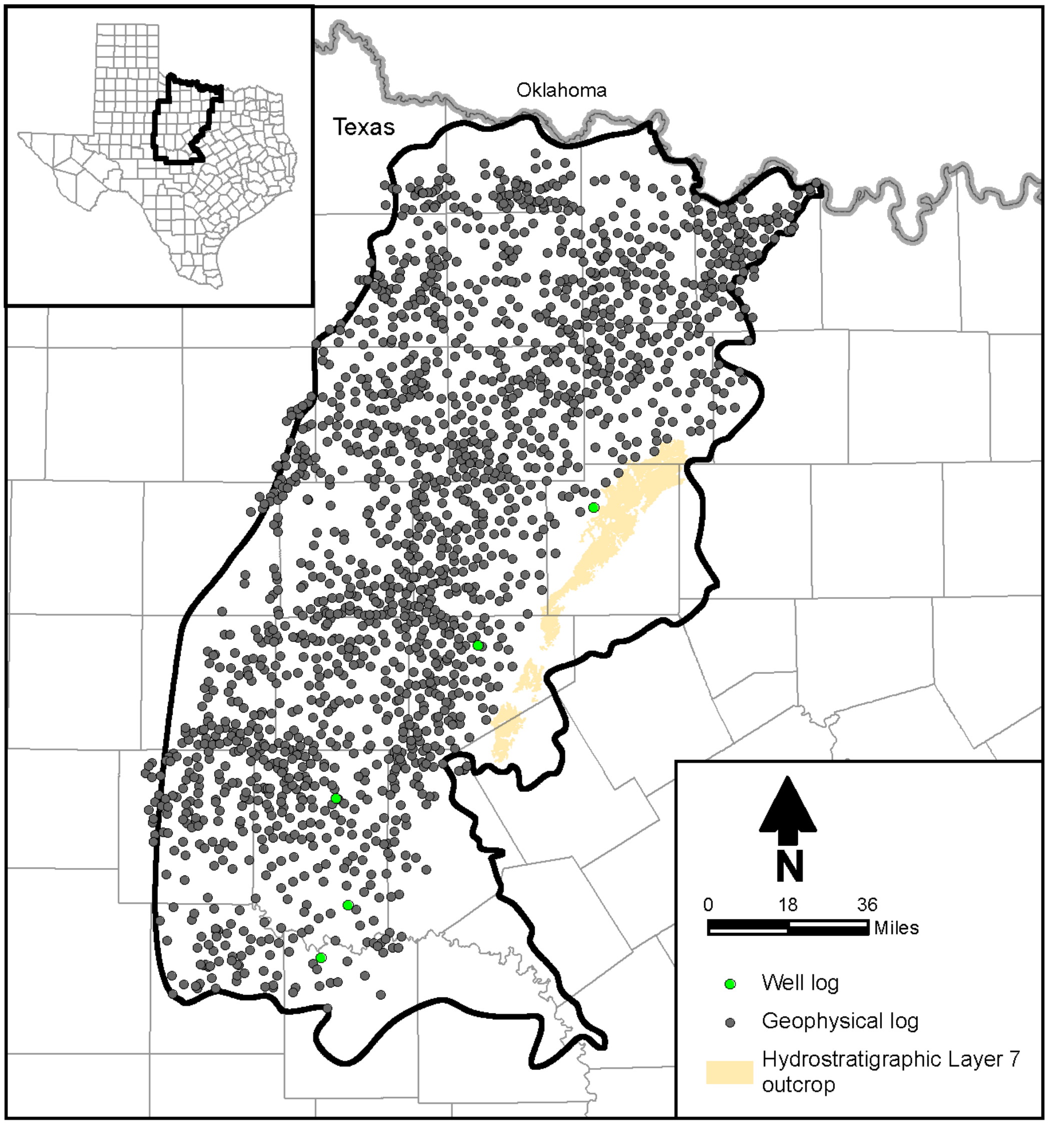


Figure 5-5. Layer 7 (Lower Canyon Group) top surface control points.

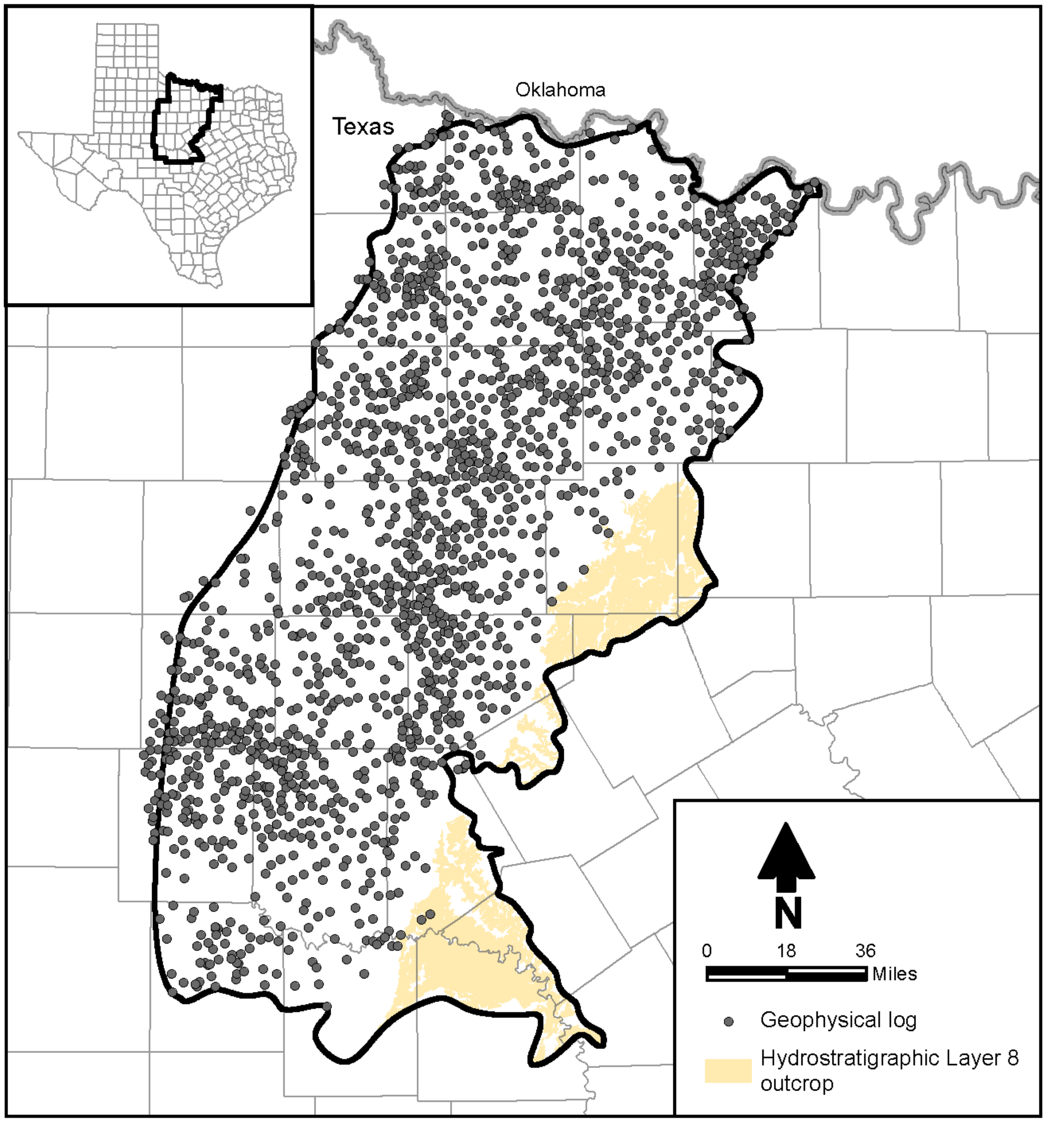


Figure 5-6. Layer 8 (Strawn and Atoka Groups) top surface control points.

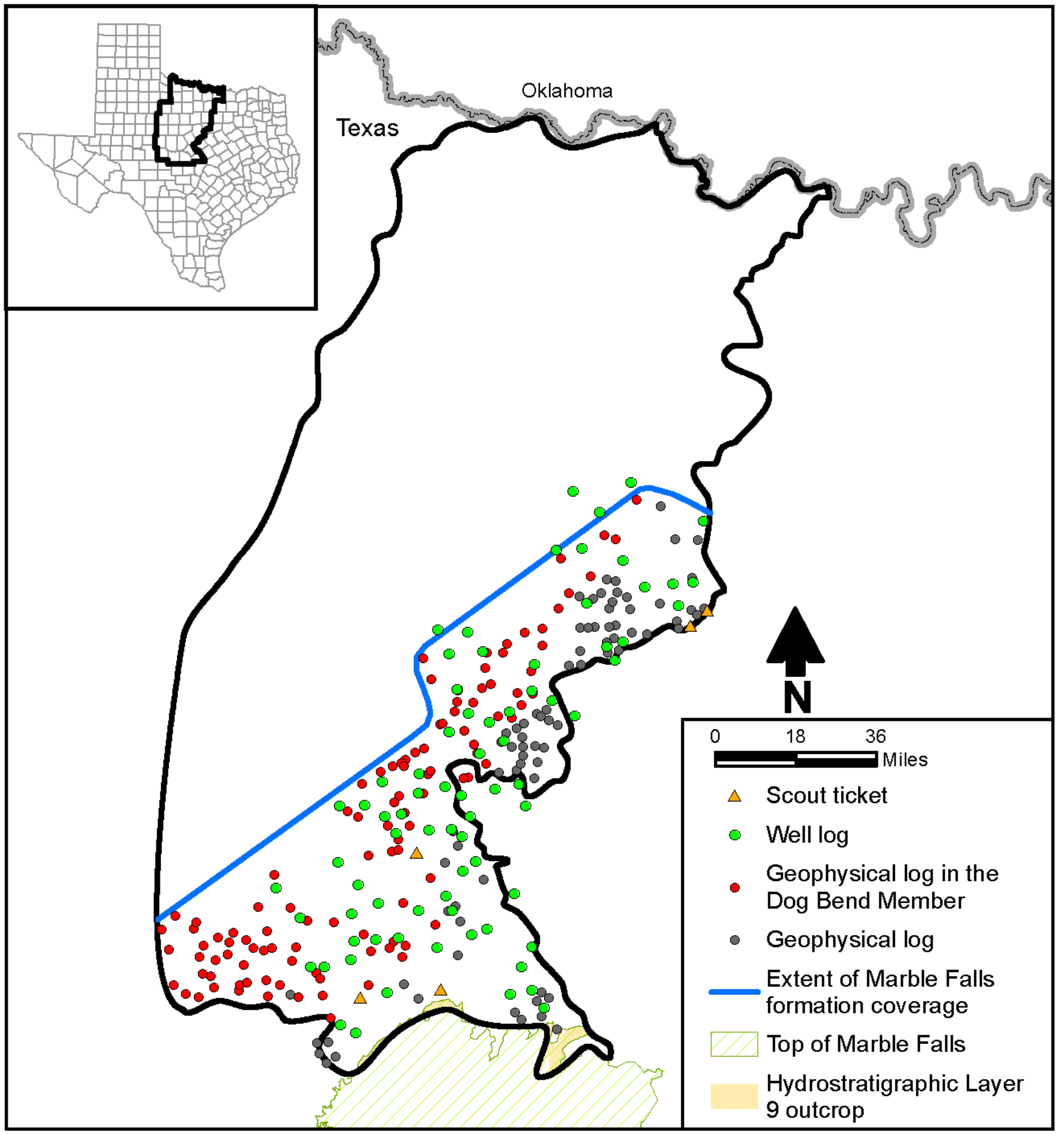


Figure 5-7. Layer 9 (Morrow Group) top surface control points.

5.4. Net Sand Analysis

Net sand analysis includes the digitization of published maps and geophysical log interpretations. This dual approach allowed for the integration of highly detailed peer-reviewed data that were not previously in a digital format with sound geophysical log analysis. The geophysical log analysis allowed us to successfully infill the southern model area where these peer-reviewed datasets were not available.

5.4.1. Net Sandstone Isolith Map Digitization

Net sandstone maps were digitized from Brown and others (1990), Erxleben (1975), and Cleaves (1975), and are listed in Table 5-2. These publications were found to be the most comprehensive and provided a widespread analysis of our study area. Many other publications were reviewed and considered; however, they either overlapped one of these more comprehensive studies (e.g., Galloway and Brown, 1972) or did not provide sufficient detail (e.g., Wilson, 1952, Pennsylvanian Strawn) in our areas of interest. Brown and others (1990) created useful type logs and cross sections that were referenced during development of the hydrostratigraphic framework.

Table 5-2. Data sources for net sandstone map digitization.

Source	Plate	Conceptual Model Layer
Brown and others (1990)	Plate II – Regional Sandstone Isolith Home Creek to Salem School Interval	4
	Plate V – Regional Sandstone Isolith Salem School to Bunger Interval	
	Plate VI – Regional Sandstone Isolith Bunger to Gunsight Interval	
	Plate VII – Regional Sandstone Isolith Gunsight to Ivan Interval	
	Plate VIII – Regional Sandstone Isolith Ivan to Black Ranch Interval	
	Plate IX – Regional Sandstone Isolith Black Ranch to Breckenridge Interval	
	Plate X – Regional Sandstone Isolith Breckenridge to Crystal Falls Interval	5
	Plate XI – Regional Sandstone Isolith Crystal Falls to Flippen Interval	
	Plate XII – Regional Sandstone Isolith Flippen to Saddle Creek Interval	
	Plate XIII – Regional Sandstone Isolith Saddle Creek Interval to Lower Stockwether Interval	
	Plate XIV – Regional Sandstone Isolith Lower Stockwether to Stockwether Interval	
	Plate XV – Regional Sandstone Isolith Stockwether to Camp Colorado Interval	
	Plate XVI – Regional Sandstone Isolith Camp Colorado to Dothan Interval	
	Plate XVII - Regional Sandstone Isolith Dothan to Sedwick Interval	
	Plate XVIII – Regional Sandstone Isolith Sedwick to Coleman Junction Interval	
Erxleben (1975)	Plate IV – Net Sandstone Thickness Wolf Mountain Shale Interval	6
	Plate VI – Net Sandstone Thickness Placid Shale Interval	
	Plate VIII – Net Sandstone Thickness Colony Creek Shale Interval	
Cleaves (1975)	Plate XII – Net Sandstone Isolith Map Devil's Hollow Fluvial-Deltaic Facies	7
	Plate XIV – Net Sandstone Isolith Map Turkey Creek Fluvial-Deltaic Facies	

Net sandstone isolith map digitization was conducted using the following steps:

1. Net sandstone maps were georeferenced in ArcGIS using the ‘adjust’ transformation method, with a focus on the Cross Timbers Aquifer study area. This approach allowed areas outside the aquifer boundary to become distorted, but created well-fitted results within the study area. These georeferenced plates are included in the geodatabase.
2. Using the ArcScan extension in ArcGIS, each plate was prepared for digitization using the raster cleanup function. This step included, for example, the removal of map labels, well locations, county lines, and location names, as well as cleanup of contour lines.
3. Using the ArcScan extension in ArcGIS, contour line isolith shapefiles were generated from each prepared contour plate.
4. Contour line isolith shapefile artifacts from the digitation process, such as overhangs and undershoots, were corrected.
5. Contour intervals were assigned to contour line isolith shapefiles.
6. Isopach rasters were generated for each sandstone isolith shapefile using the ArcGIS Topo to Raster tool.

Figures 5-8 and 5-9 are included in this summary report to illustrate how we successfully digitized each isolith plate. Figure 5-8 is Plate V from Brown and others (1990), and illustrates the regional sandstone isolith for the Salem School to Bunger interval within the Lower Cisco Group. Figure 5-9 includes the isopach raster derived from this plate for the Cross Timbers Aquifer study area. To ensure the validity of the digitized isolith plates, a randomized sampling of geophysical logs was conducted, and the sands for each log interval were matched to the corresponding plates. This allowed confirmation of the accuracy of the georeferenced plates and the underlying net sandstone data. For every plate listed in Table 5-2, the georeferenced plate, corresponding sandstone isolith shapefile, and raster isopach file are included in the geodatabase.

5.4.2. Geophysical Log Net Sand Analysis

A total of 352 geophysical logs were correlated to extend the net sand/sandstone isopaches developed as described above through the southern and western edges of the model area. Geophysical logs used for stratigraphic interpretations were included in this analysis. Hydrogeologically significant sandstones, selected as 5 feet or greater in thickness, were aggregated between the interpreted model layer surfaces. This approach discounts minor (i.e., less than 5 feet) interbedded sand lenses and provides a more realistic representation of potential water-bearing units.

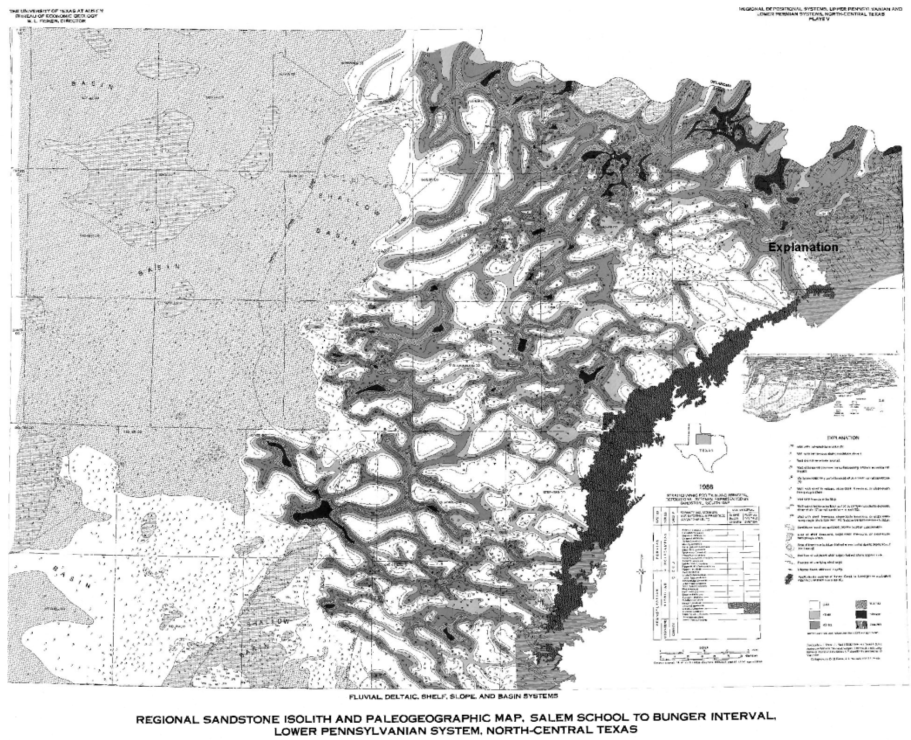


Figure 5-8. Plate V from Brown and others (1990) illustrating the regional sandstone isolith for the Salem School to Bunger interval within the Lower Cisco Group.

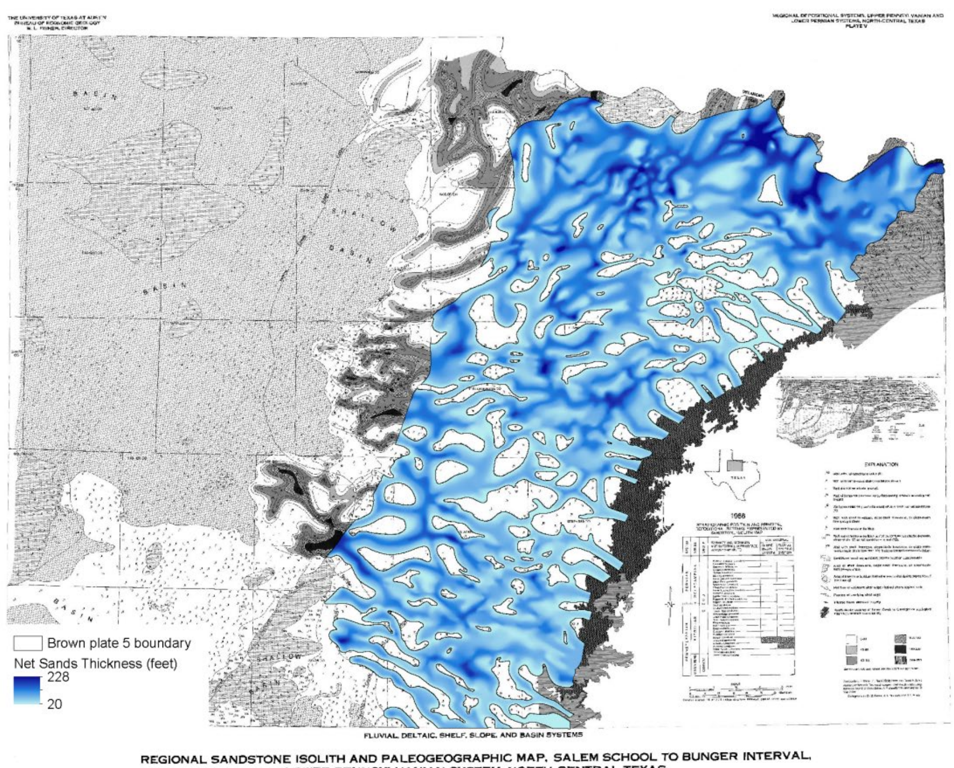


Figure 5-9. Plate V from Brown and others (1990) with the isopach raster derived from this plate for the Cross Timbers Aquifer study area.

5.4.3. Model Layer Net Sandstone Composite Isopaches

Through analysis of the aquifer system and the conceptual model layer structure, it was determined that composite sandstone production interval isopaches were important for conceptual model Layers 4, 5, 6, and 7. Layers 2 and 3 include interbedded limestones, shales, and evaporites with no mappable production intervals, and Layers 8 and 9 serve as aquifer model base layers.

Net sandstone composite isopaches were developed for each model layer by combining the isopach rasters generated from the digitization of net sandstone isoliths in Table 5-2 into composite isopach rasters and through the rasterization of our geophysical log net sand analysis.

Raster isopaches for plates within each layer were aggregated in ArcGIS using the Mosaic to New Raster tool, where the output cell value includes the sum of the overlapping raster cells. Raster isopach values less than 20 feet in model Layers 4, 5, and 7 were excluded from this analysis before the sum of overlapping cells was calculated. Model Layer 6, (Erxleben, 1975, Plates IV and VI) was originally created with 50-foot contours; therefore, no contours less than 50 feet were available.

To ensure that overlapping cells were properly aggregated, a snap-referenced grid was used to create each isopach raster and was enforced when processing the composite isopaches. Net sand/sandstone composite isopaches were created for each model layer using the ArcGIS Topo to Raster tool. Figures 5-10 through 5-13 provide the results of this approach and illustrate the composite net sand isopaches for model Layers 4 through 7, respectively, for the corresponding coverage areas.

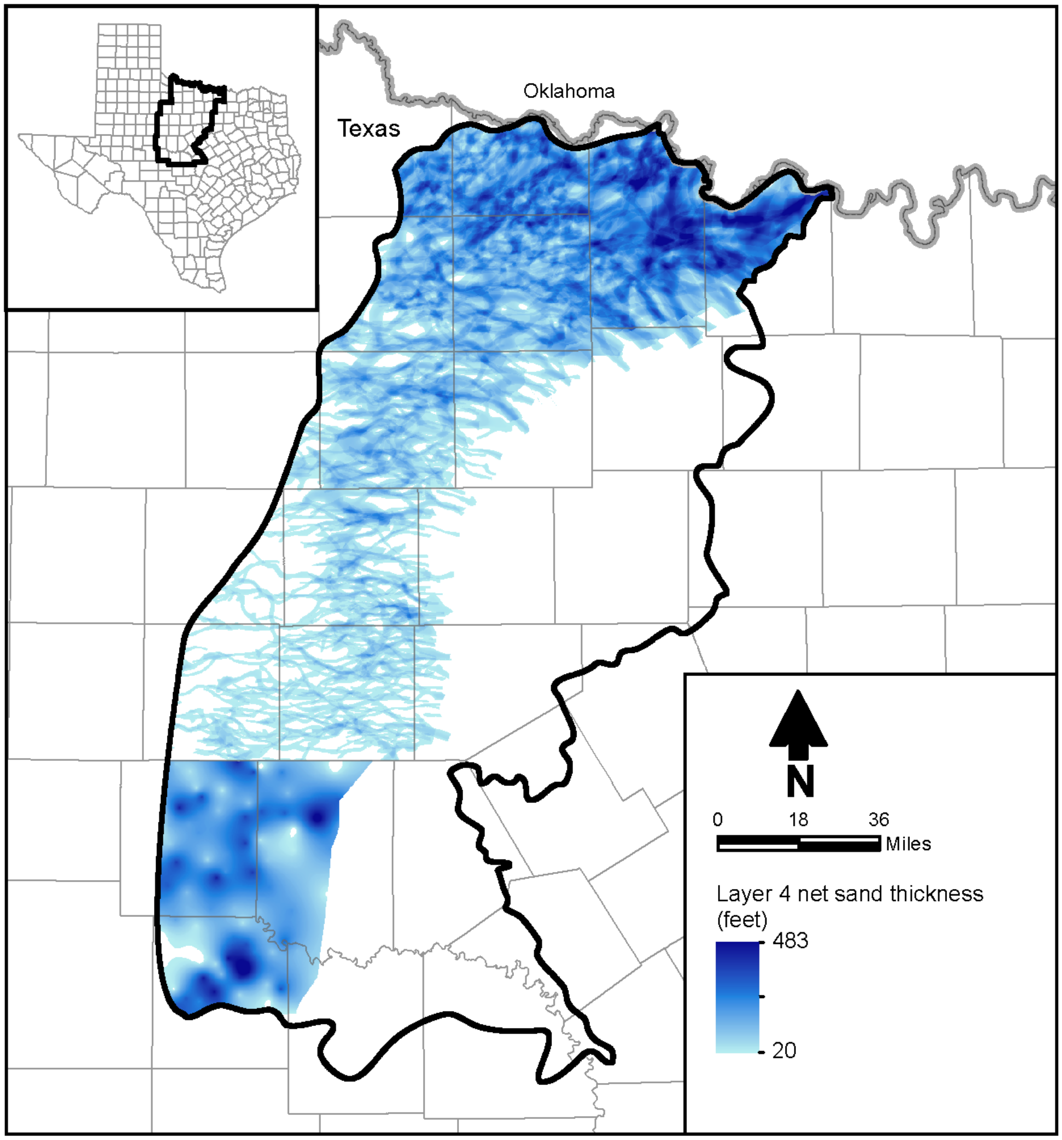


Figure 5-10. Layer 4 (Upper Cisco Group) net sand isopach.

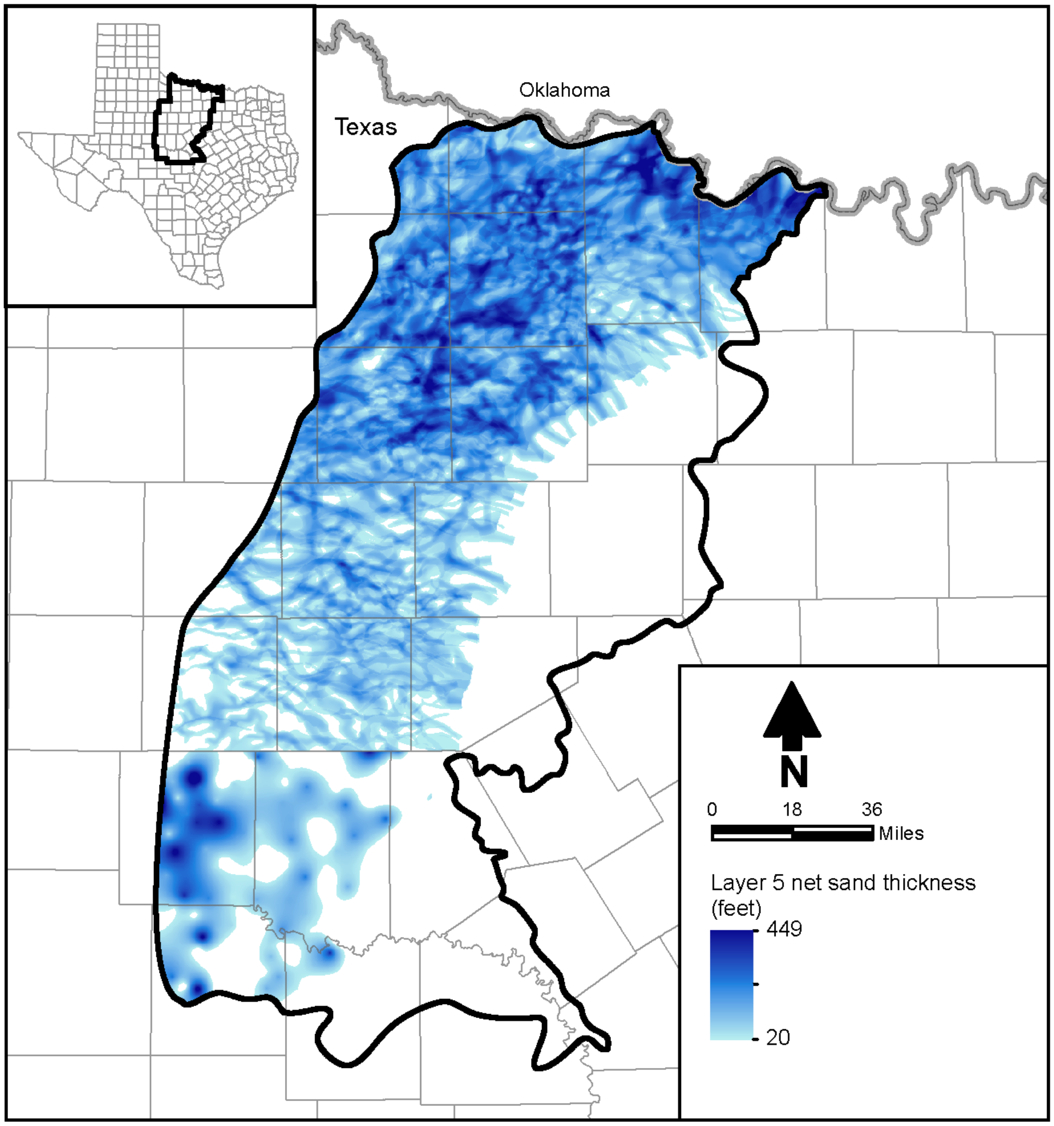


Figure 5-11. Layer 5 (Lower Cisco Group) net sand isopach.

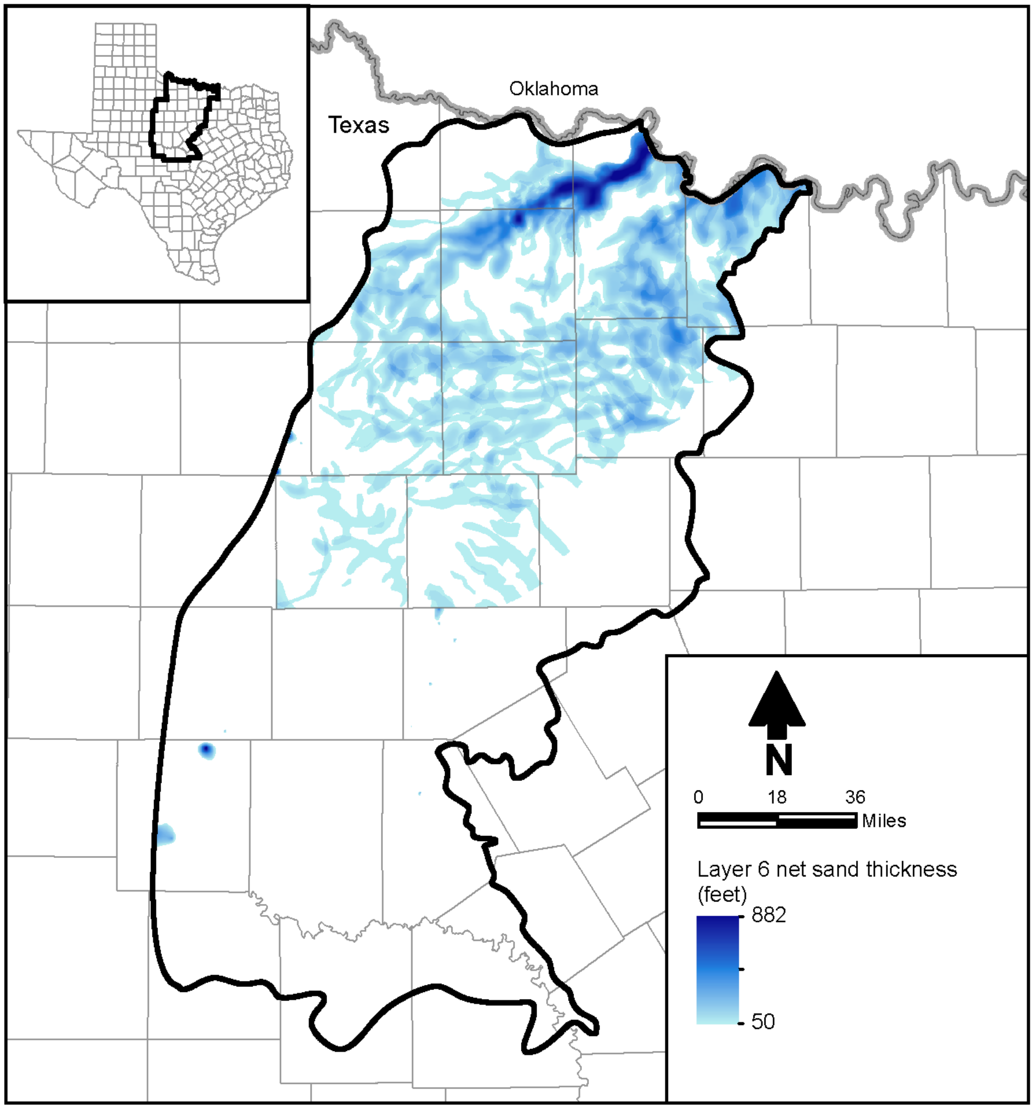


Figure 5-12. Layer 6 (Upper Canyon Group) net sand isopach.

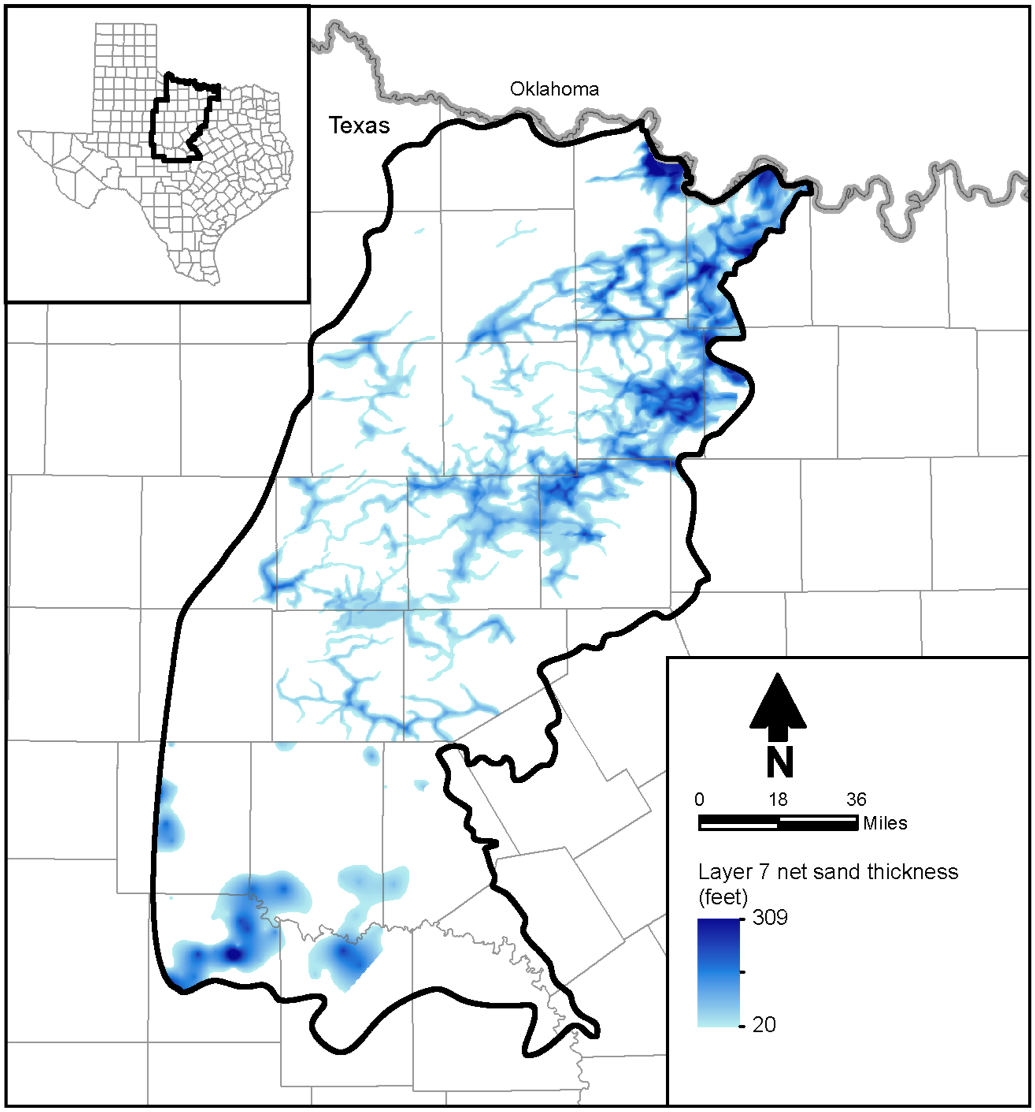


Figure 5-13. Layer 7 (Lower Canyon Group) net sand isopach.

5.5. Water Well Datasets

A total of 2,963 water wells were selected to provide groundwater production intervals, water quality, estimated yield, and pump test information for the study area (Figure 5-14). The TWDB and Texas Department of Licensing and Regulation water well datasets were compiled and screened for (between geophysical logs, well logs, or scout tickets) depth (deepest available), availability of screen intervals, estimated well yield, and/or pump tests and water quality information.

The 2019 TWDB well dataset within the Cross Timbers Aquifer included over 8,100 wells (TWDB, 2019). Selective screening reduced the initial dataset to 1,106 water wells, of which 877 have the top and base of screened interval. The 2019 Texas Department of Licensing and Regulation well dataset within the Cross Timbers Aquifer included over 13,700 wells. Selective screening reduced the initial dataset to 1,857 water wells, of which 1,826 have the top and base of the well screen interval. Additional analysis using these datasets will be conducted during remaining project tasks, and the water well datasets (selected well locations and screened intervals) will be integrated into the three-dimensional model with final project delivery.

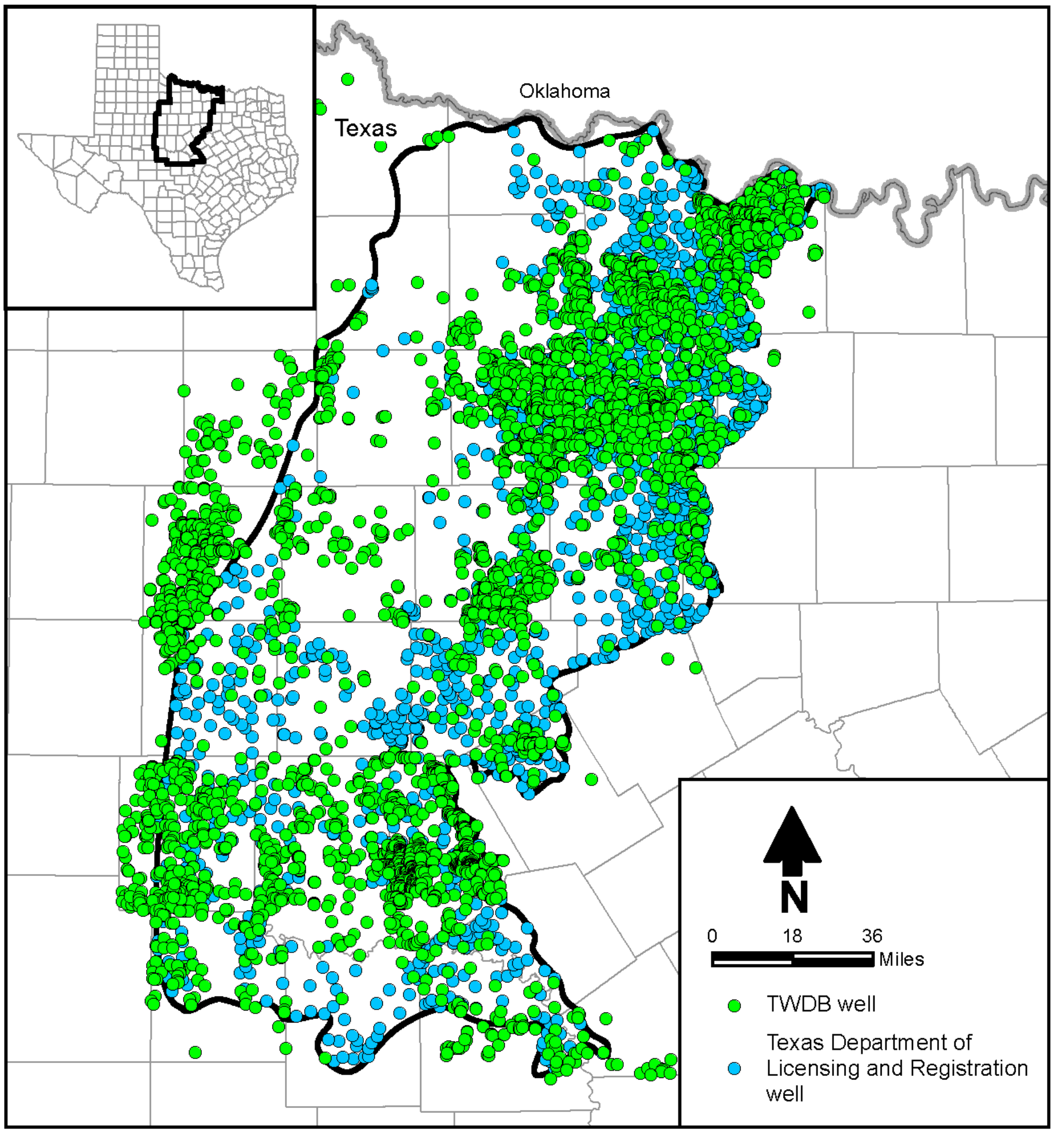


Figure 5-14. Selected TWDB and TDLR water wells.

5.6. Leapfrog Model

A Leapfrog geologic model using Leapfrog Works was developed. The model covers the Cross Timbers Aquifer extent from the ground surface to at least 100 feet below the picks of the Marble Falls Formation, or to an elevation 3,850 feet below mean sea level, whichever is greater. In the southern portion of the study area, the Marble Falls Formation either outcrops or is near ground surface, resulting in a model thickness of only several hundred feet. In the northern portion of the model, the Marble Falls Formation occurs below the 3,850 feet below mean sea level elevation. In the northern portion of the study area, the three-dimensional model thickness is greater than 5,000 feet in places.

Picks from 2,373 points (Figures 5-1 through 5-7), in addition to the surface geology taken from the Geologic Atlas of Texas coverages (Figure 4-2), were used to control the surfaces for conceptual model Layers 2 through 9. For Layer 1, the bottom elevation of active Layer 1 from the Seymour groundwater availability model (Ewing and others, 2004) and the bottom elevation of groundwater availability model Layer 8 from the Northern Trinity and Woodbine Aquifers (Kelly and others, 2014) were imported into Leapfrog.

Major faults in the north (Red River) and southern (Llano uplift) regions were included in the Leapfrog model, which resulted in dividing the Cross Timbers Aquifer area into seven "fault blocks" (Figure 5-15). Figures 5-16 through 5-22 show the thickness of conceptual model Layers 2 through 8 as interpreted using Leapfrog.

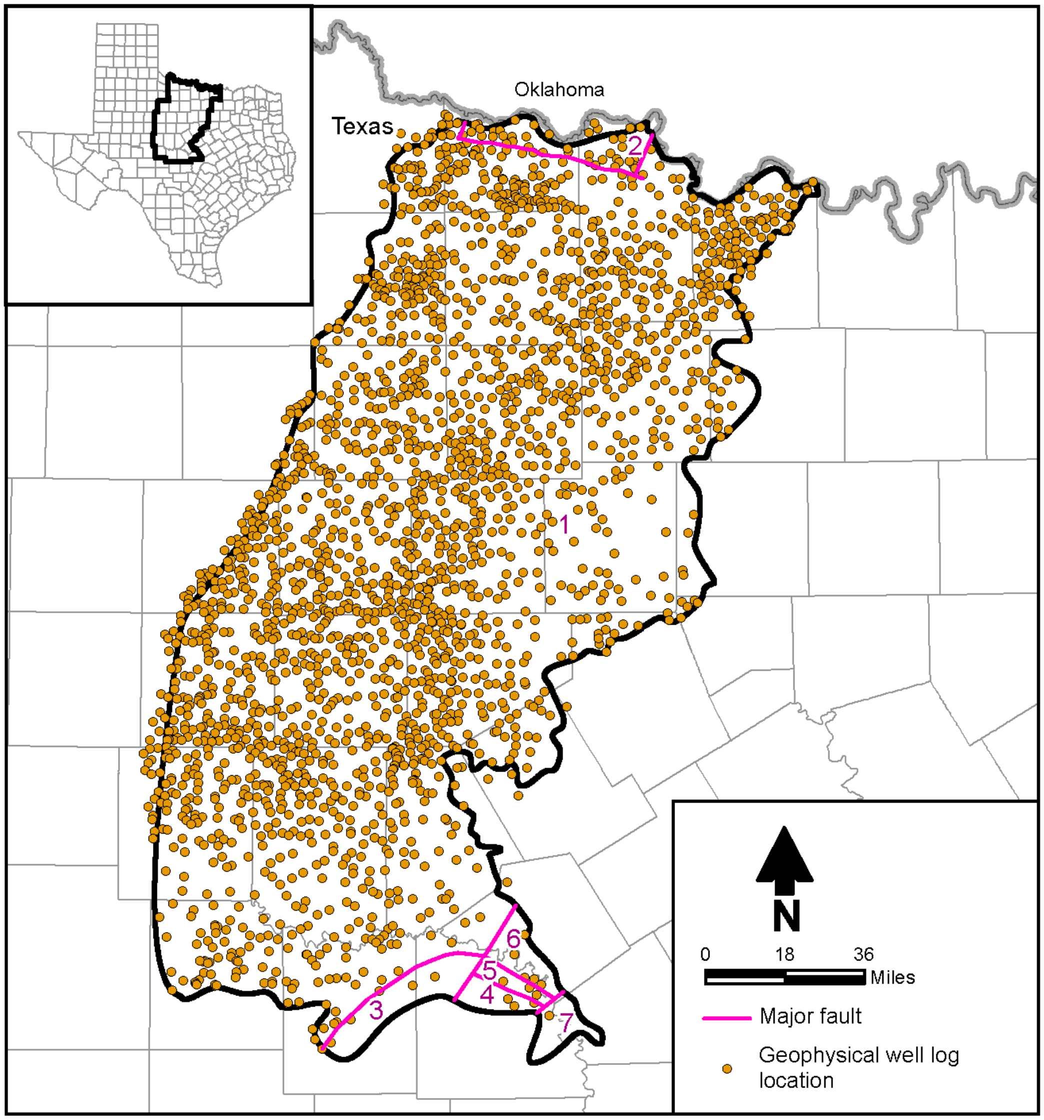


Figure 5-15. Data points and fault locations used in Leapfrog.

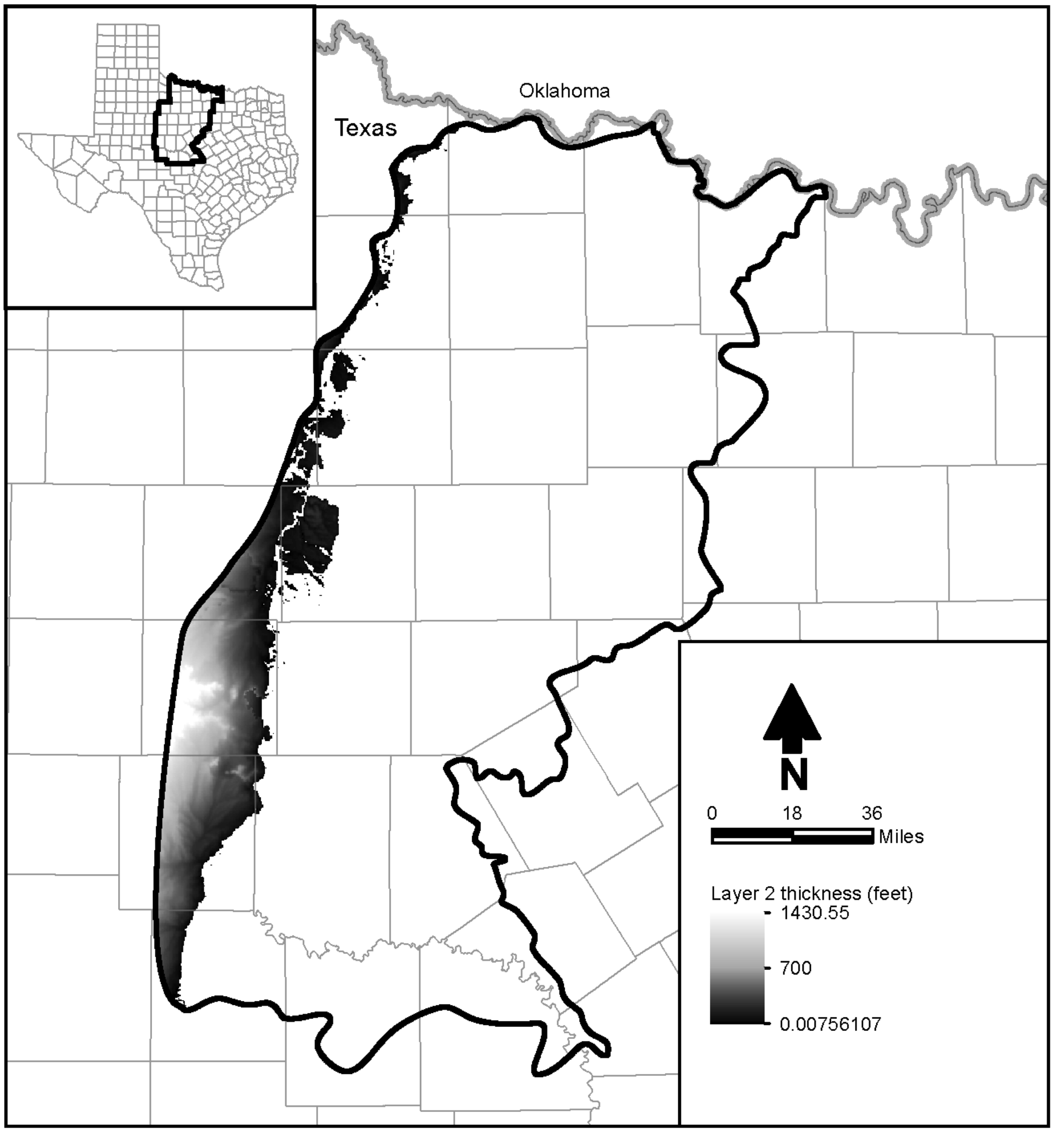


Figure 5-16. Thickness of Layer 2 (Clear Fork Group) from Leapfrog.

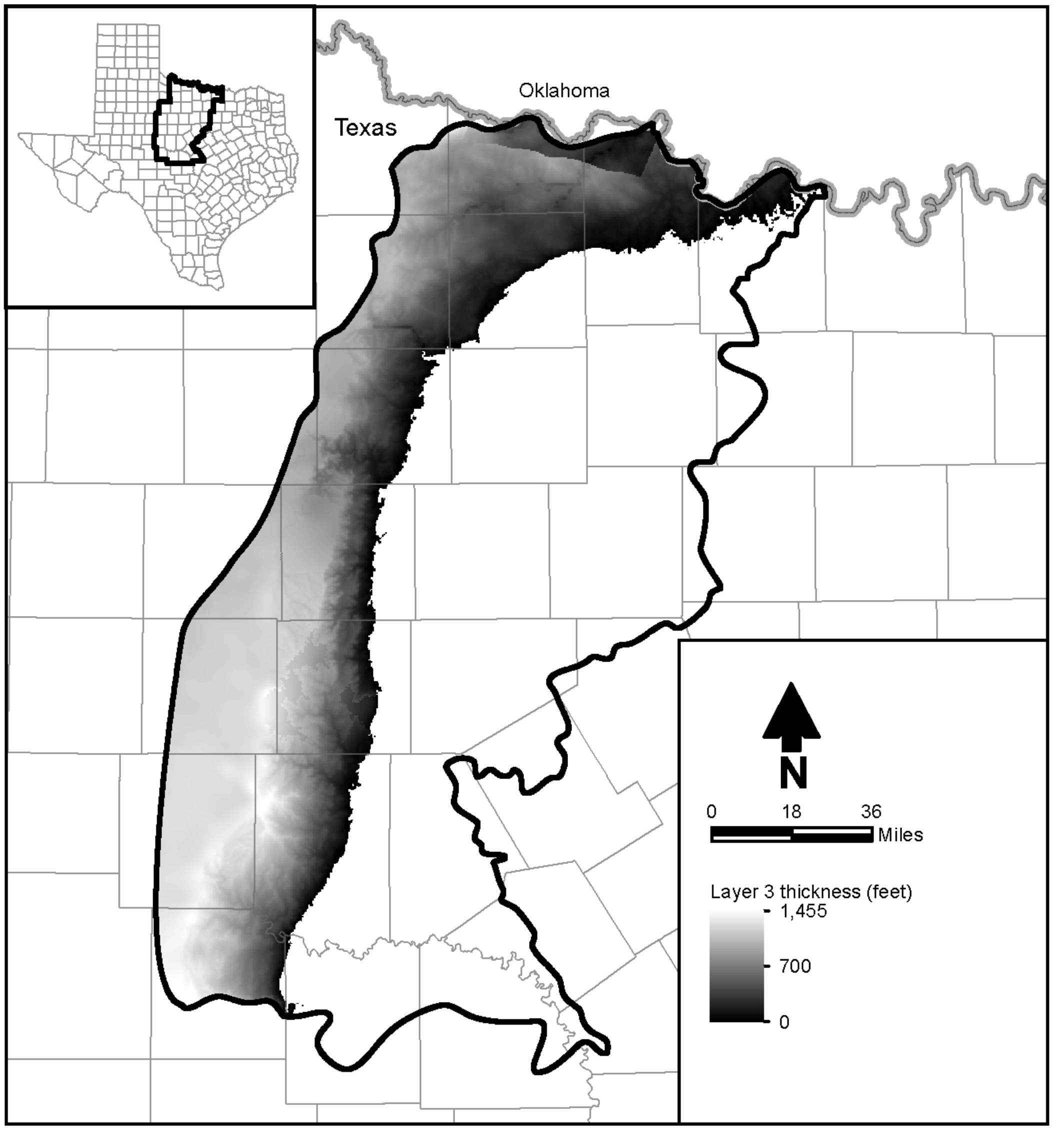


Figure 5-17. Thickness of Layer 3 (Wichita-Albany Group) from Leapfrog.

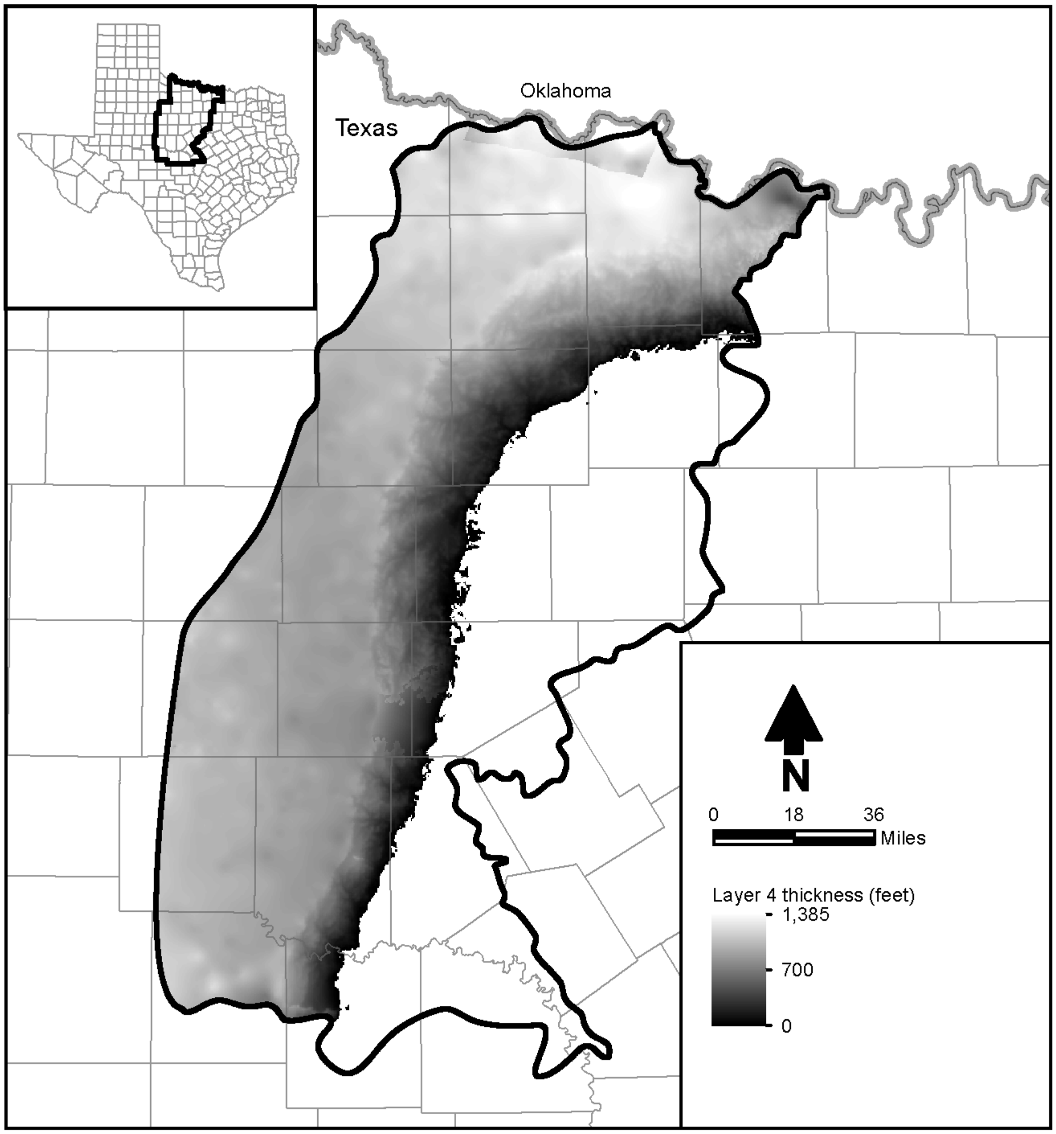


Figure 5-18. Thickness of Layer 4 (Upper Cisco Group) from Leapfrog.

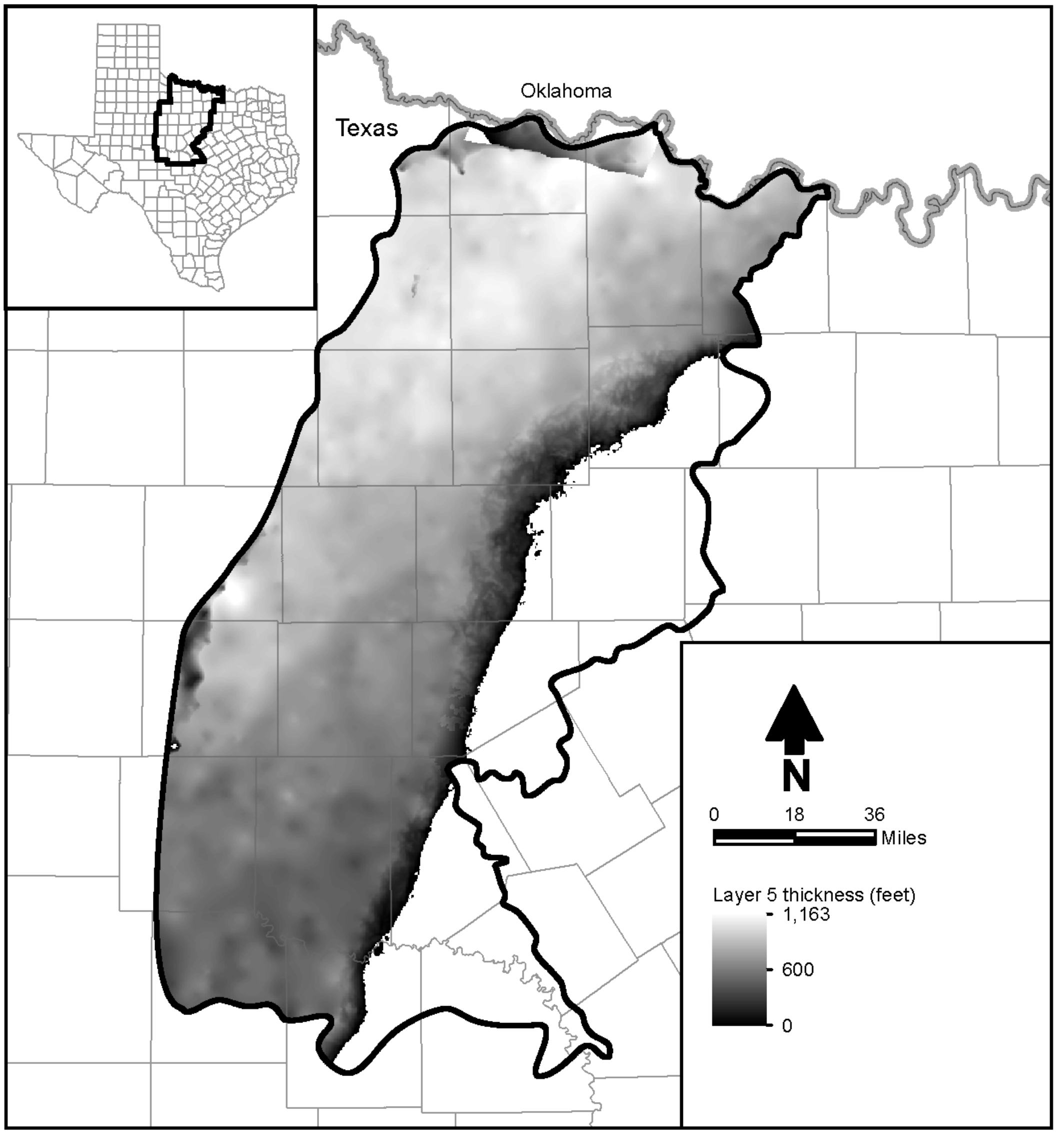


Figure 5-19. Thickness of Layer 5 (Lower Cisco Group) from Leapfrog.

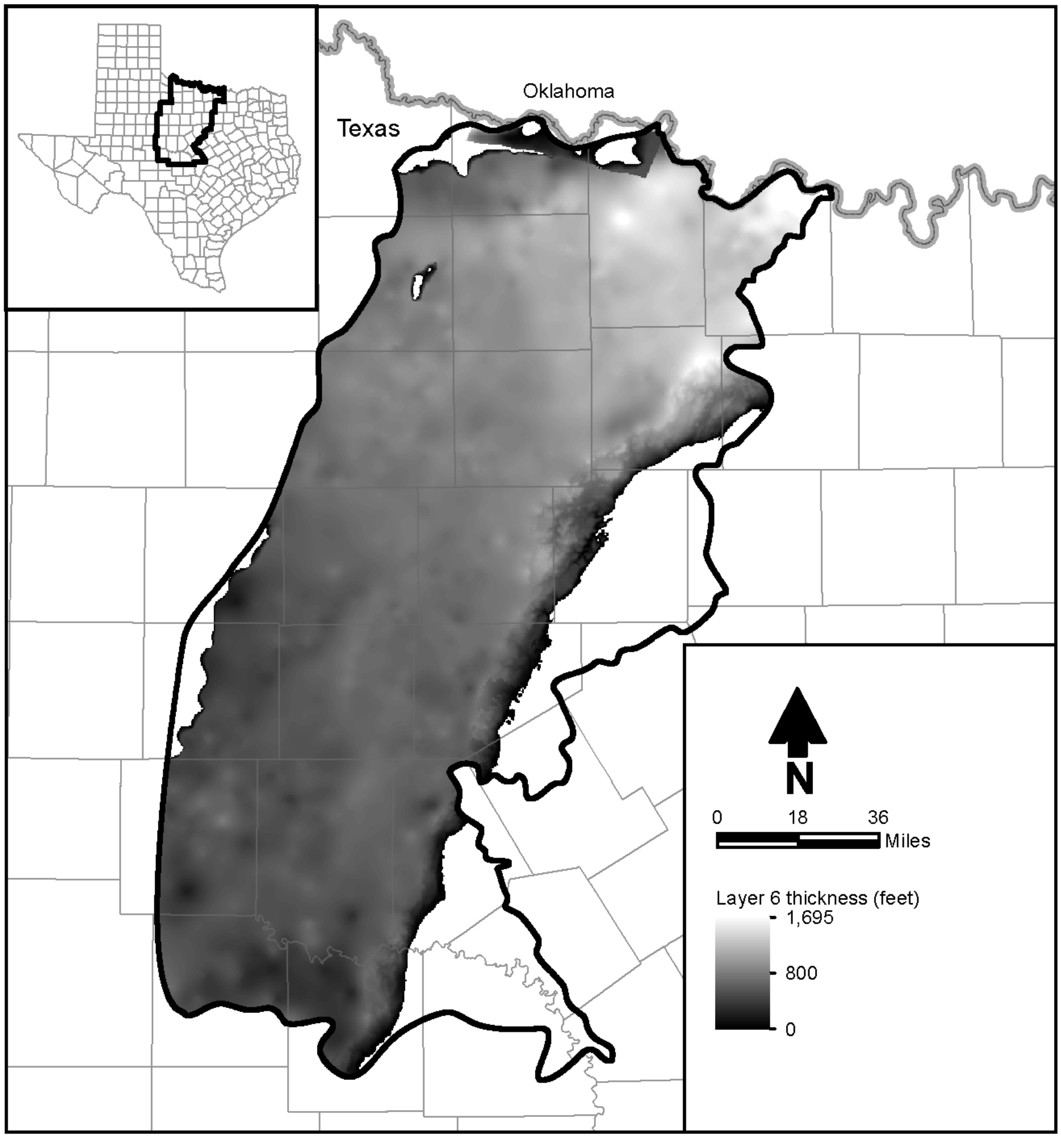


Figure 5-20.   Thickness of Layer 6 (Upper Canyon Group) from Leapfrog.

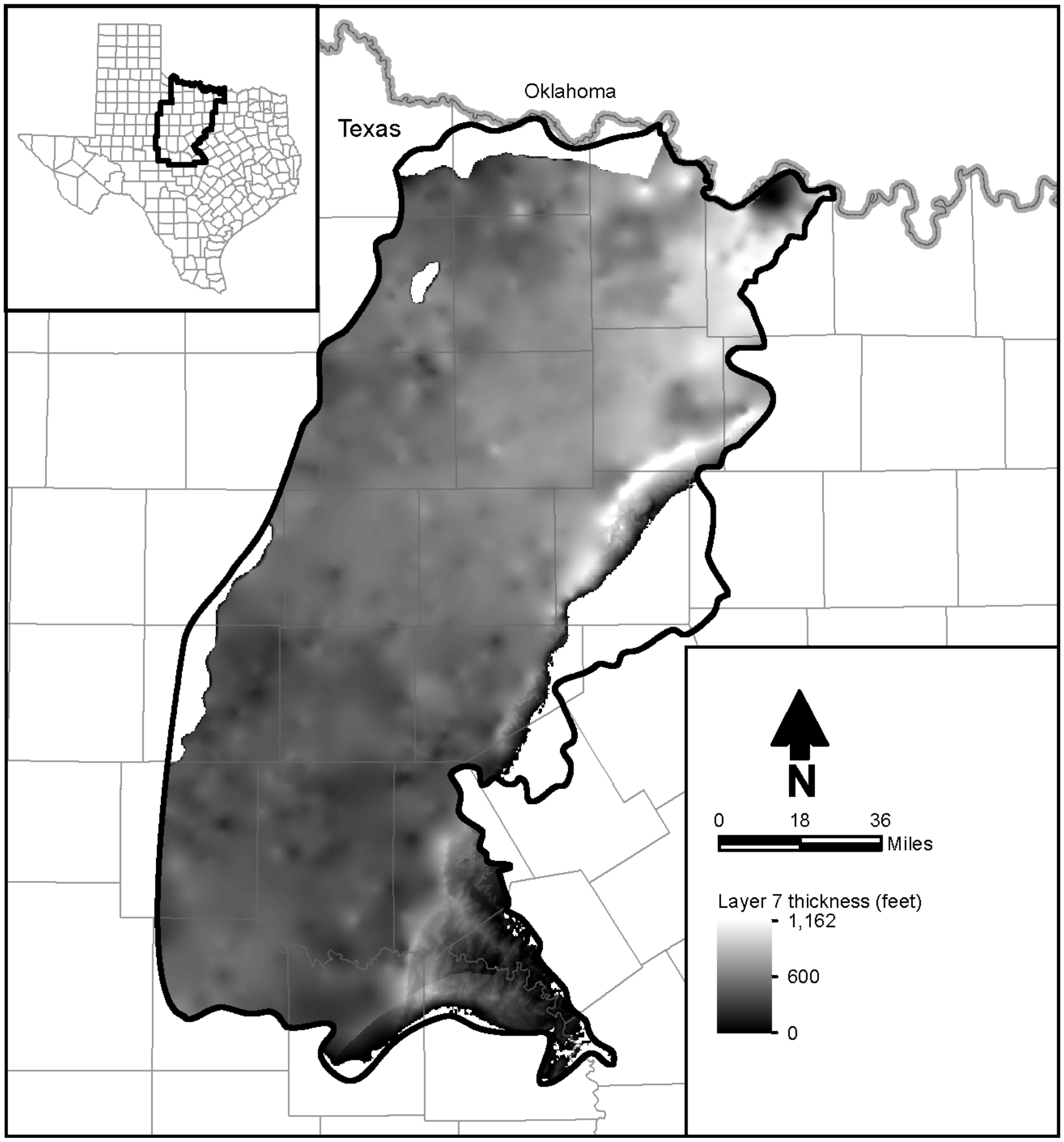


Figure 5-21 Thickness of Layer 7 (Lower Canyon Group) from Leapfrog.

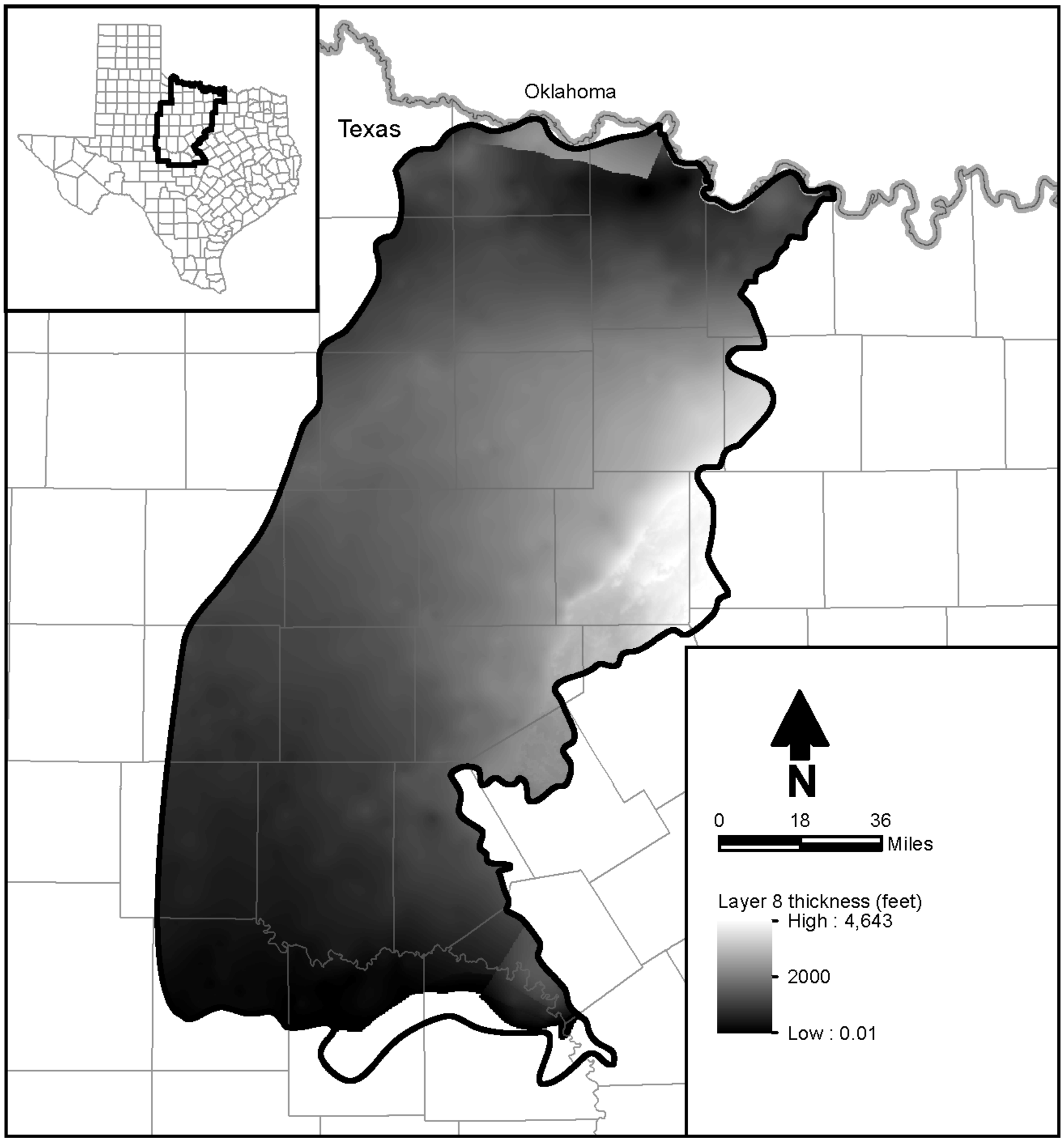


Figure 5-22. Thickness of Layer 8 (Strawn and Atoka Groups) from Leapfrog.

6. Water Levels and Regional Groundwater Flow

To our knowledge, there are no existing maps of water levels for the full extent of the Cross Timbers Aquifer. Nicot and others (2013) provide a water level contour map for their eight-county study area within and adjacent to the northeast portion of the Cross Timbers Aquifer study area; the four counties that predominantly overlie the Cross Timbers Aquifer in their study are Clay, Montague, Jack, and Palo Pinto Counties. Nicot and others (2013) note that higher groundwater levels occur in interfluvial areas and lower water levels occur in valleys.

Multiple authors have noted the apparent topographic control on Cross Timber Aquifer water levels, although they did not develop water level contour maps due to the erratic and discontinuous occurrence of groundwater. For example, Avakian and Wermund (1994, p. 57) investigated the groundwater beneath Fort Wolters in Palo Pinto and Parker Counties and note that ". . . topography becomes the principal control for the piezometric surface. . ." This conceptual model of topographically driven flow is also hypothesized in a later study of the same region by Fisher and others (1996). Richter and Kreitler (1985, p. 6) investigated groundwater conditions in Concho and Runnels Counties, and state that "ground-water flow in the shallow aquifer units is governed by topography." Nordstrom (1988, pp. 54 and 67) states that groundwater in the Canyon and Cisco Groups of Jack County moves "away from ground-water highs and toward the surface drainage system."

Older studies often do not describe topographic controls explicitly, but include statements along the lines that groundwater recharged in the outcrop area probably flows "a relatively short geographic extent" (Morris, 1967, p. 76), implying regions of discharge relatively close to aquifer outcrops. It appears, and in some reports is explicitly stated, that water level maps were not constructed due to the localized and "erratic" nature of groundwater occurrence.

6.1. Hydrographs

Prior to constructing water level maps, the hydrographs (plots of water levels through time at a given location) for wells with more than five measurements through time were reviewed. The hydrograph data were obtained from the TWDB groundwater database. Selected hydrographs are provided in Figures 6-1 through 6-4.

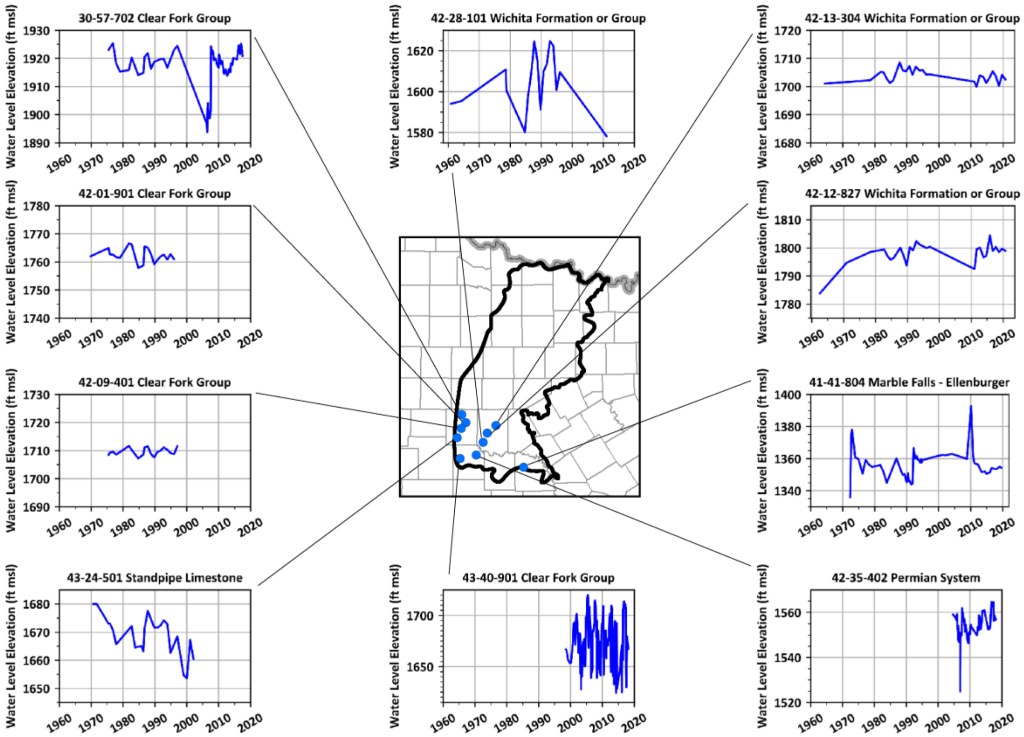


Figure 6-1. **Hydrographs for selected wells in the southern portion of the Cross Timbers Aquifer.**

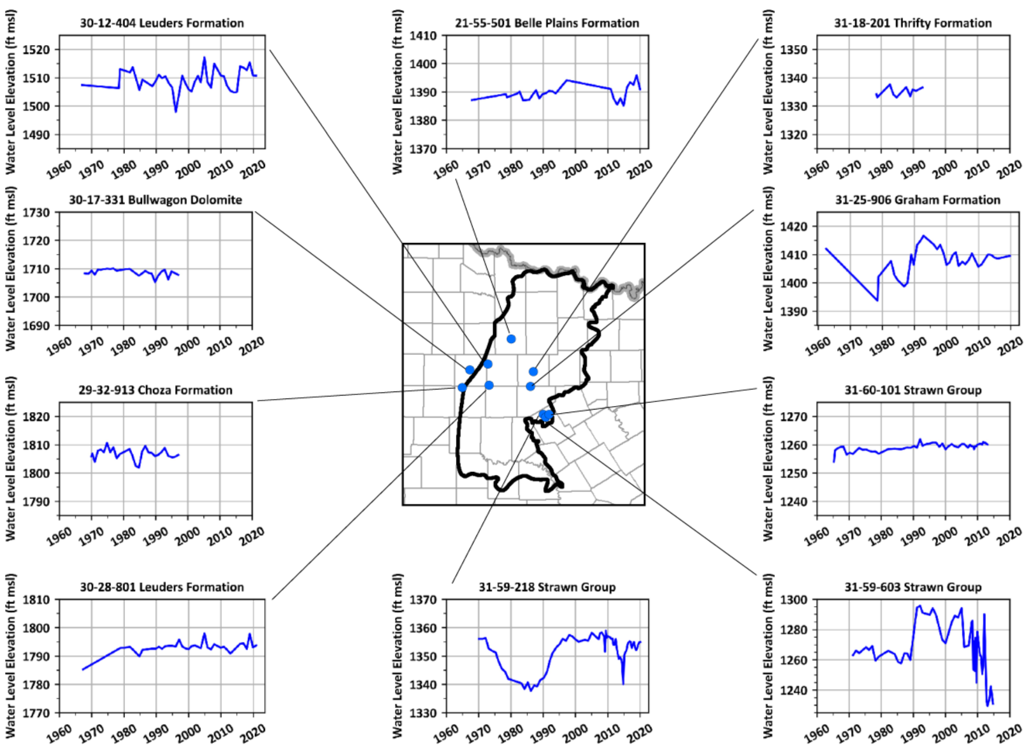


Figure 6-2. **Hydrographs for selected wells in the central portion of the Cross Timbers Aquifer.**

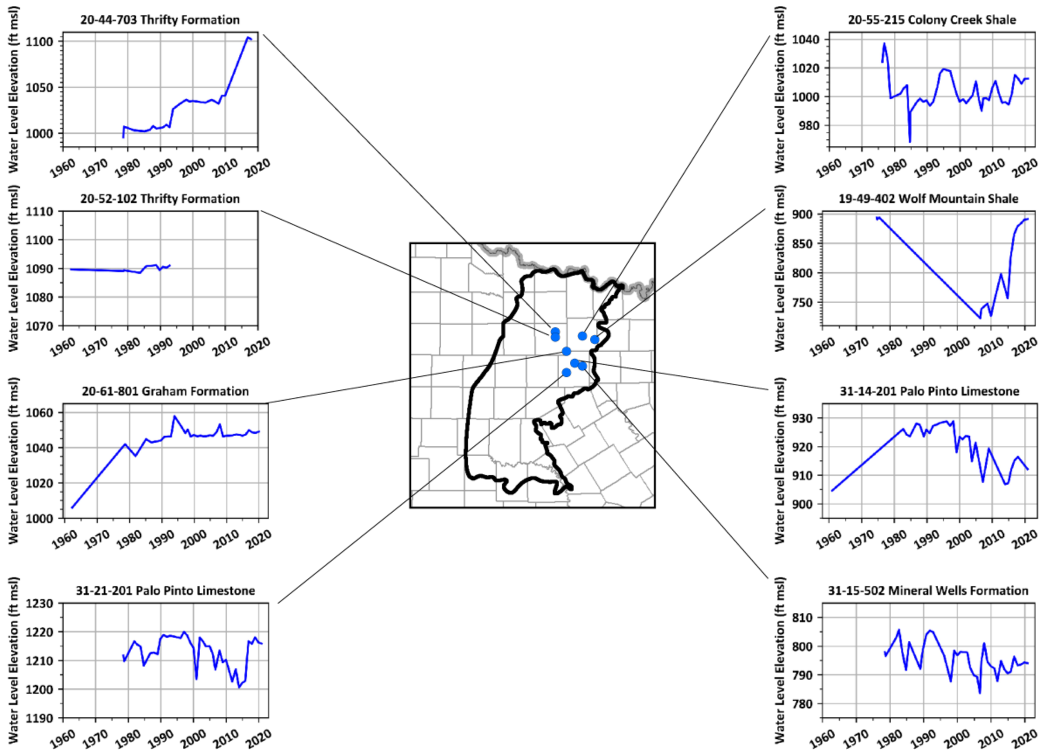


Figure 6-3. Hydrographs for selected wells in the east-central portion of the Cross Timbers Aquifer.

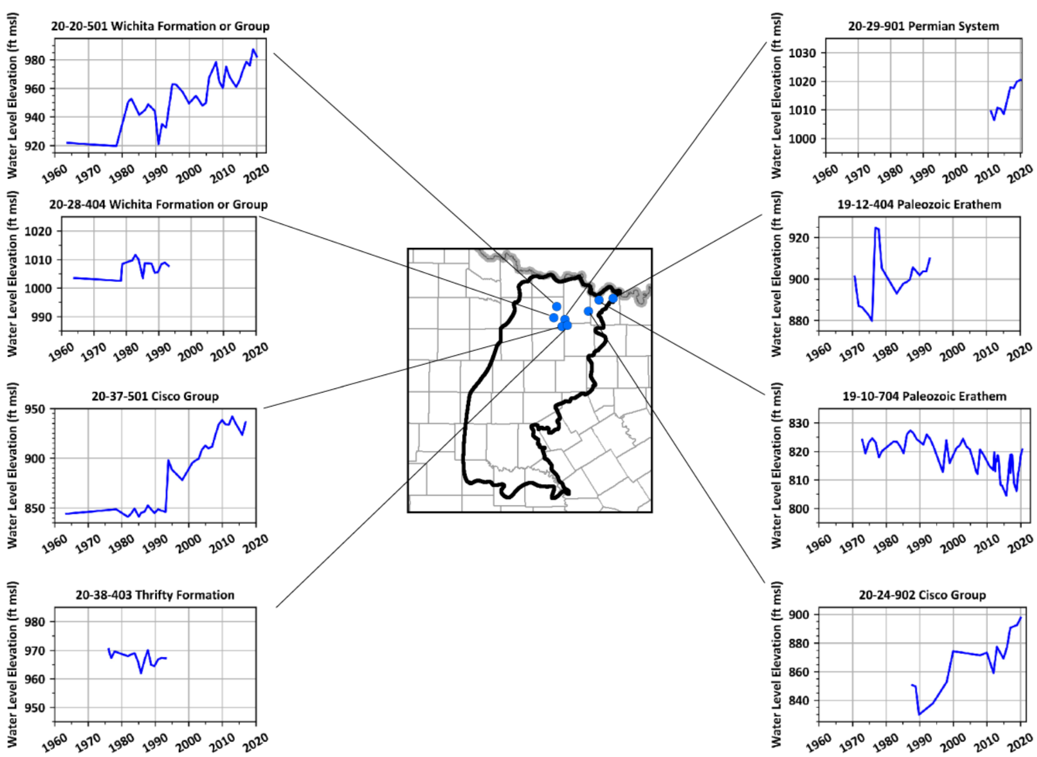


Figure 6-4. Hydrographs for selected wells in the northern portion of the Cross Timbers Aquifer.

Review of the hydrographs indicates that Cross Timbers Aquifer water levels are relatively stable overall, and even where trends in water levels are apparent, changes over time are typically several tens of feet or less. These observations are consistent with those of Ballew and French (2019). Some of the hydrographs exhibit a confined aquifer fluctuation, where changes in water levels are large over short periods of time (e.g., Clear Fork Group well 43-40-901 on Figure 6-1). Many of the hydrographs show water level fluctuations in response to pumping and likely groundwater recharge (e.g., Choza Formation well 29-32-913 and Leuders Formation well 30-12-404 on Figure 6-2). In addition, particularly in the north-central and northern portions of the study area, some wells have a pronounced increase in water levels (e.g., Thrifty Formation well 20-44-703 on Figure 6-3 and Wichita Formation well 20-20-501 and Ciso Group well 20-37-501 on Figure 6-4). The reason for these water level rises is unknown without a more detailed analysis of the conditions at and adjacent to these well locations. Nicot and others (2013) also note rising water levels in some wells, and hypothesize that the cause may be increased recharge through time due to changing land use; this is a good working hypothesis, as such behavior has been observed elsewhere in Texas and other states.

6.2. Water Level Maps

In order to develop spatial water-level contour maps, wells with observed water level information from the TWDB database were plotted by decade so that the spatial distribution of data points could be reviewed. Based on this information, it was decided to contour observed water levels for the period 2010 through 2018 using a 100-foot contour interval. The year 2018 was selected for the end year because Texas Department of Licensing and Registration data were downloaded in January 2019 for use during the project. The combination of TWDB and Texas Department of Licensing and Registration data led to the best spatial coverage of data points.

The water level contouring was conducted as follows:

1. Water levels for all hydrostratigraphic unit-specific wells (not cross-screened wells) available for the period 2010 through 2018 from the TWDB and Texas Department of Licensing and Registration databases were plotted on a base map. Texas Department of Licensing and Registration wells had one water level; for wells in the TWDB database that had multiple water levels during this period, the mean water level was used.
2. Water levels for wells determined to be cross screened across multiple hydrogeologic units were not used for contouring water levels.
3. Stream and reservoir elevations from the digital elevation model were also plotted on the base maps at approximately 3-mile intervals.
4. Groundwater level contours were developed by hand on an outcrop by outcrop basis in an attempt to recognize if discontinuities in contours were apparent between hydrostratigraphic units.
5. Stream channels were examined for different dates in Google Earth© to determine if base flow was apparent; where base flow was observed or in some cases suspected

(e.g., based on vegetation), the stream channel elevations were also considered in the contouring. Reservoir elevations from the digital elevation model were considered in the contouring.

6. Water levels beneath Cretaceous (Trinity Aquifer) rock outcrops were checked to confirm that they were lower than the water levels in the overlying Trinity Aquifer.
7. For locations where a well hydrograph was available from the TWDB data for a period that ended prior to 2010, the water-level contours were cross checked to confirm consistency with the hydrograph, assuming that water levels were unlikely to fluctuate a significantly greater amount at the well location than they had in the past.

Figures 6-5 through 6-11 are provided to illustrate the process followed in constructing the Cross Timbers Aquifer water levels for each hydrostratigraphic unit. On each of the figures, the outcrop of the hydrostratigraphic unit is provided, along with the water level data points used in the contouring. Not shown due to scale are numerous elevations from the digital elevation model for major stream channels and reservoirs. All contours were hand drawn.

Figure 6-12 is the final Cross Timbers Aquifer water level map for recent (i.e., 2010 through 2018) conditions. Streams, reservoirs, and major river drainages are also marked on the figure. The fact that water levels and the direction of groundwater flow are largely controlled by topography is evident on the map; the highest water levels generally occur along the drainage basin divides between major streams and tributaries, and the lowest water levels occur at streams where groundwater discharge occurs.

A predevelopment water level map was not constructed for the Cross Timbers Aquifer due to a lack of data. The first local (county scale) groundwater studies that collected significant water level data and other information were generally conducted during the 1960s and later (Table 3-1). Predevelopment aquifer conditions would be variable from region to region and could date back to the early 1900s; observed water levels for the 1950s and earlier are nonexistent across much of the study area. The major factors that would drive changes in water levels through time are changes in land use, the construction and filling of reservoirs, and the development of petroleum resources. At the scale of maps presented in this section, and considering the general lack of long-term fluctuations in water levels (with some regions of rising water levels excluded), a predevelopment water level map would likely bare close resemblance to the water level contours in Figure 6-12.

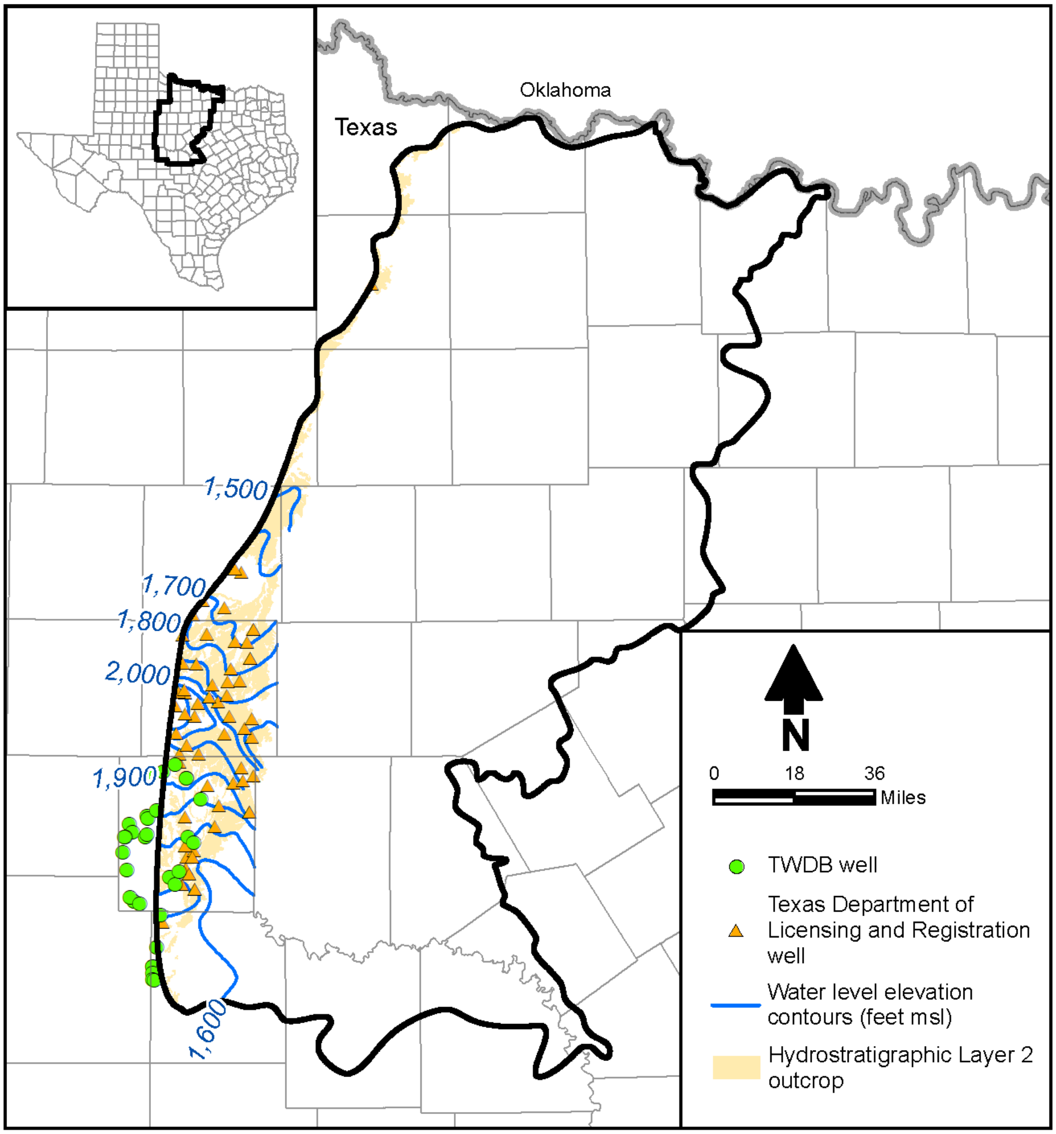


Figure 6-5. Water level contours and observed data points for 2010 through 2018 for hydrostratigraphic Layer 2 (Clear Fork Group).

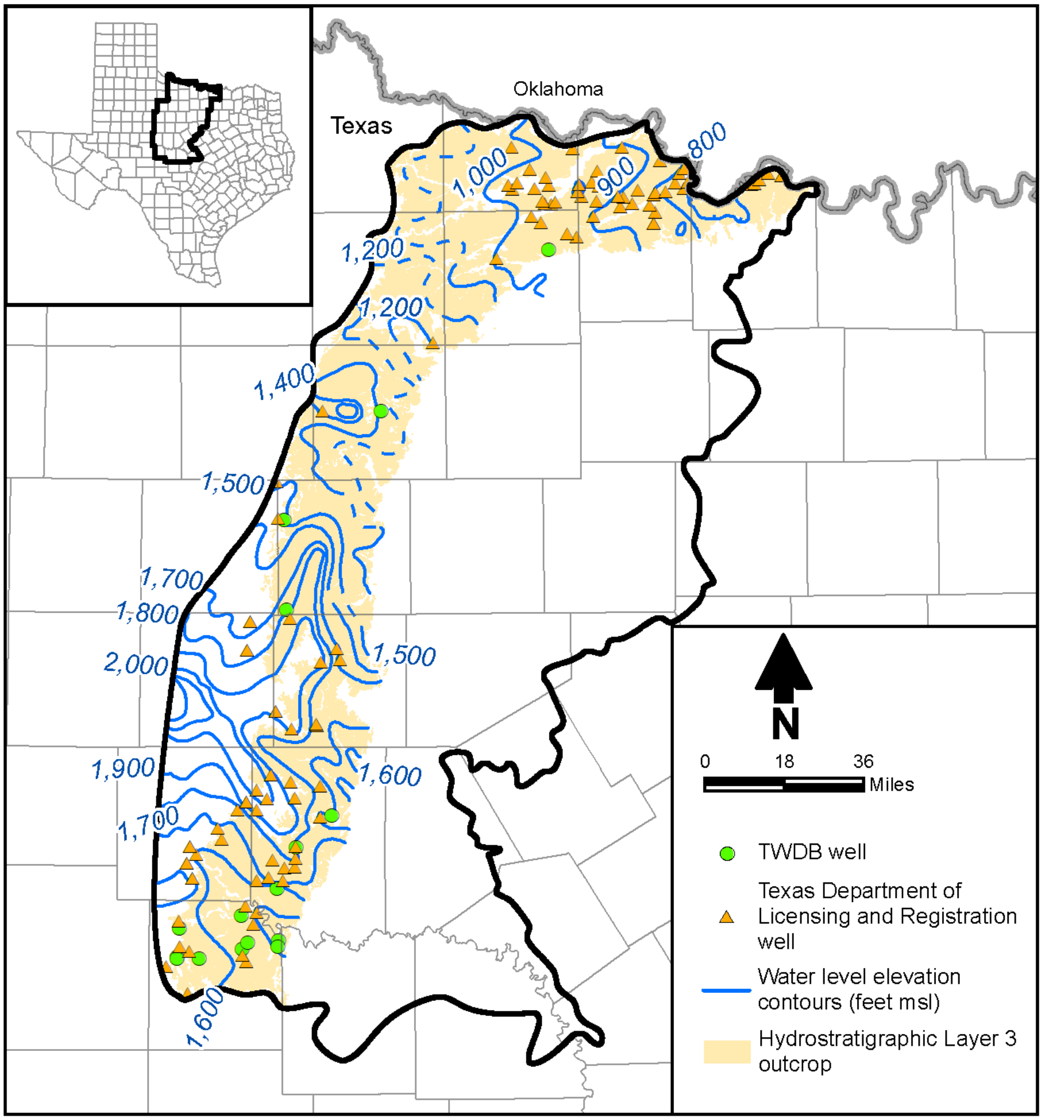


Figure 6-6. Water level contours and observed data points for 2010 through 2018 for hydrostratigraphic Layer 3 (Wichita-Albany Group).

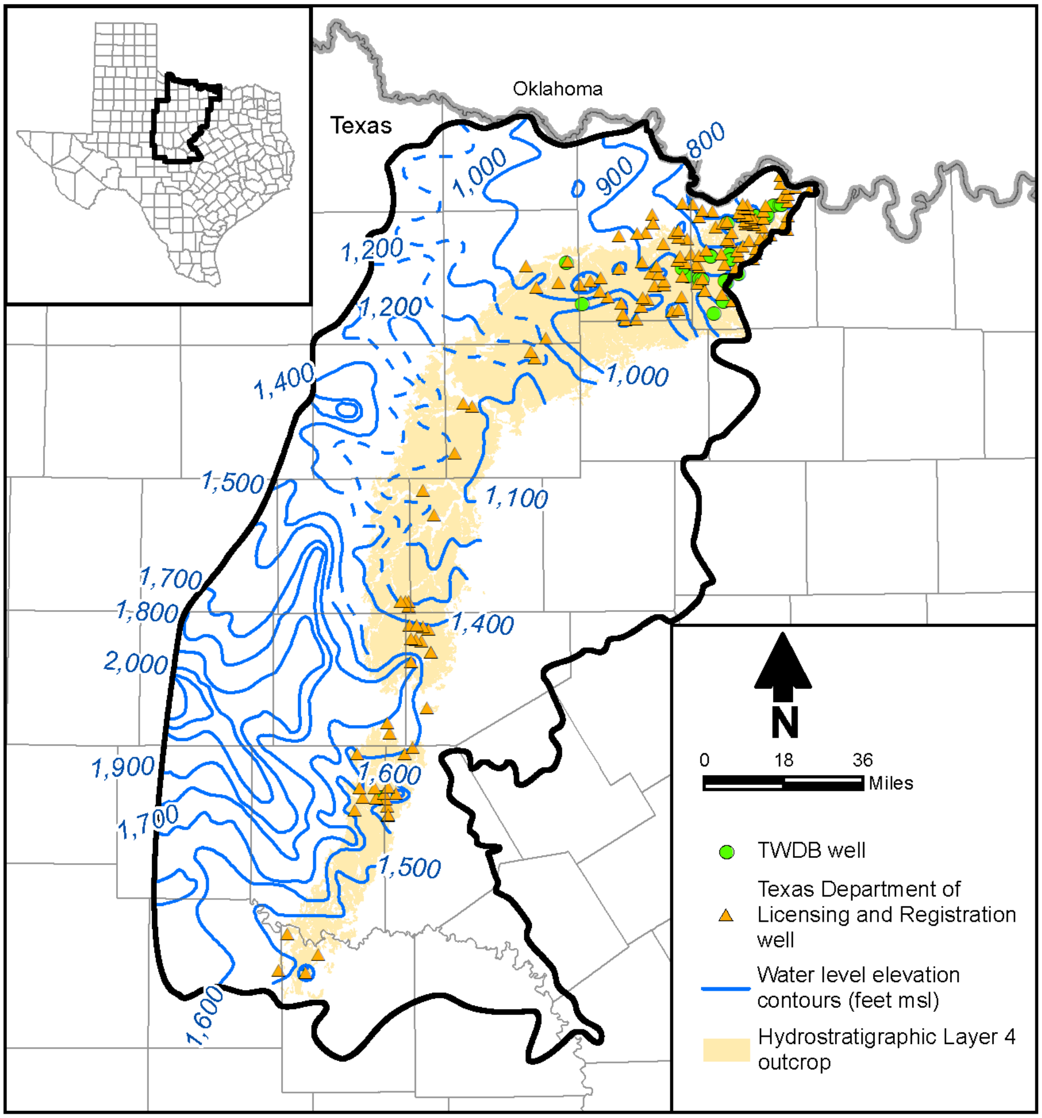


Figure 6-7. Water level contours and observed data points for 2010 through 2018 for hydrostratigraphic Layer 4 (Upper Cisco Group).

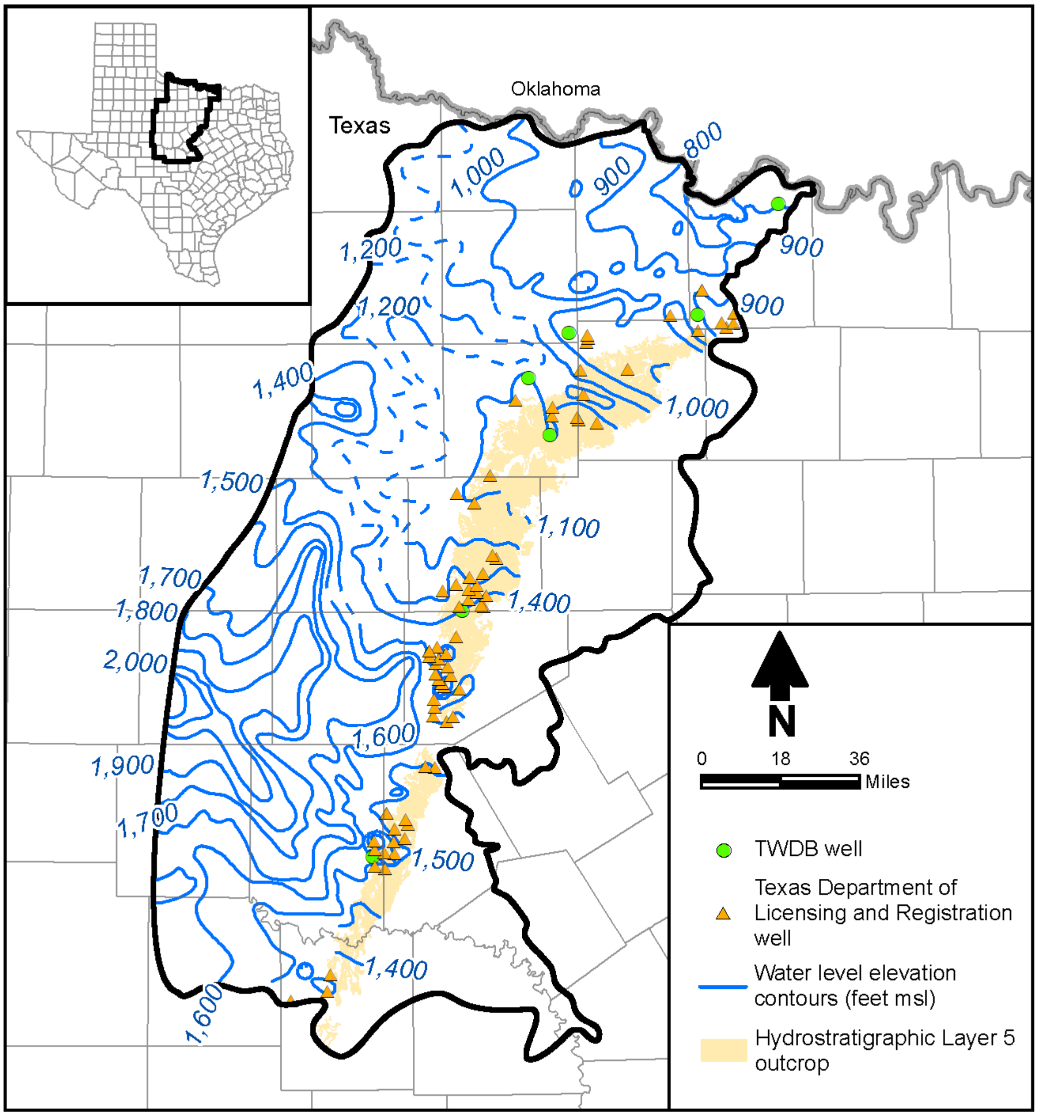


Figure 6-8. Water level contours and observed data points for 2010 through 2018 for hydrostratigraphic Layer 5 (Lower Cisco Group).

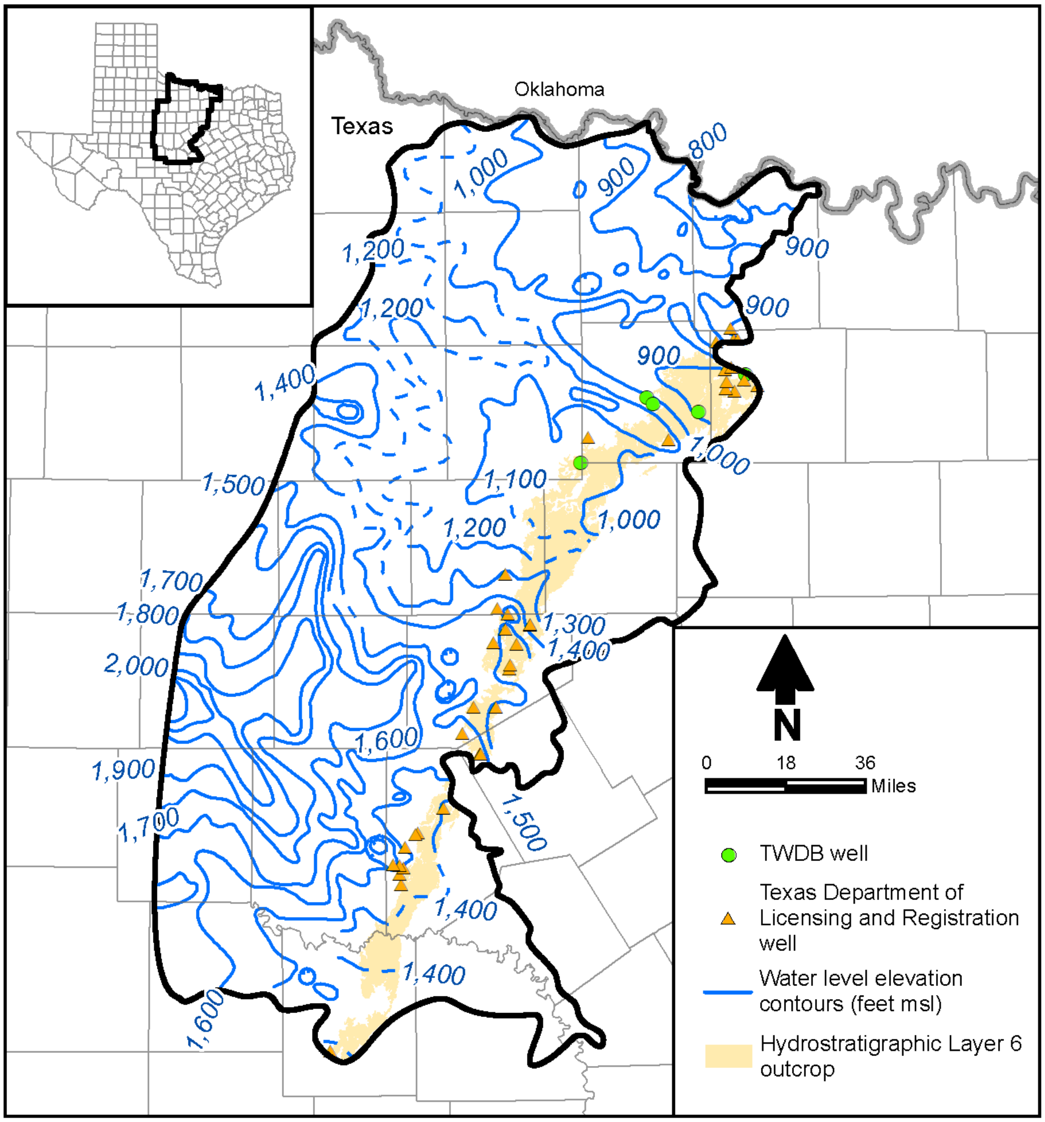


Figure 6-9. Water level contours and observed data points for 2010 through 2018 for hydrostratigraphic Layer 6 (Upper Canyon Group).

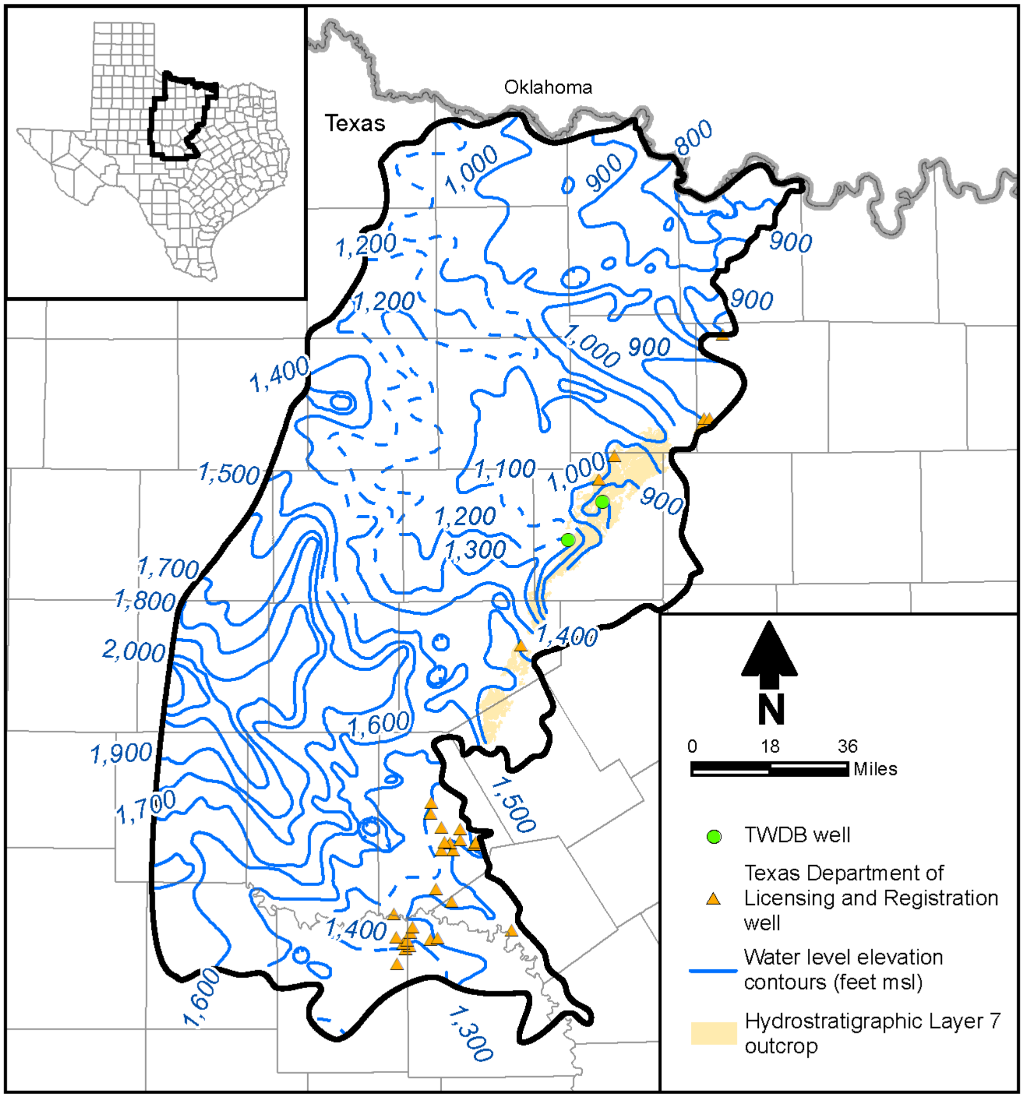


Figure 6-10. Water level contours and observed data points for 2010 through 2018 for hydrostratigraphic Layer 7 (Lower Canyon Group).

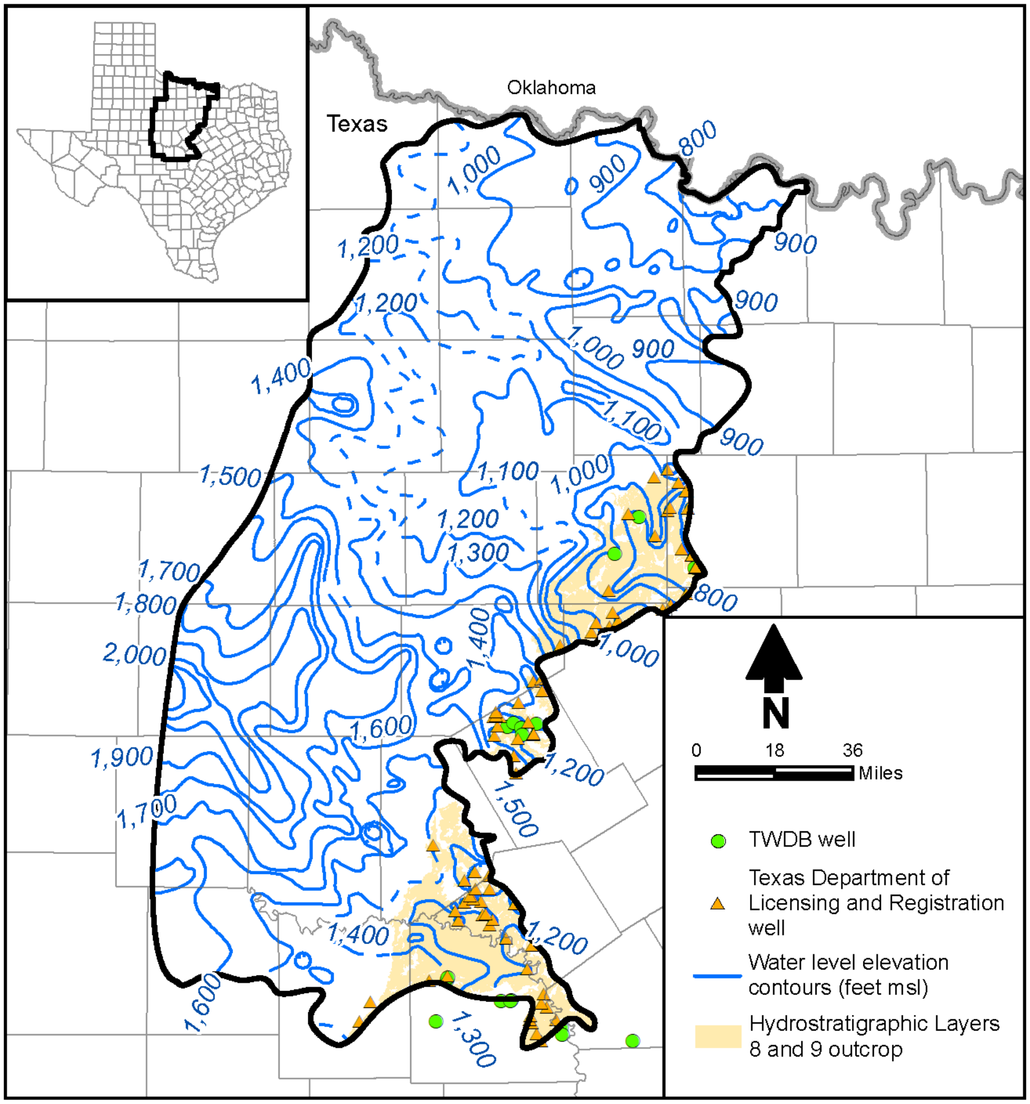


Figure 6-11. Water level contours and observed data points for 2010 through 2018 for hydrostratigraphic Layers 8 and 9 (Strawn, Atoka, and Morrow Groups).

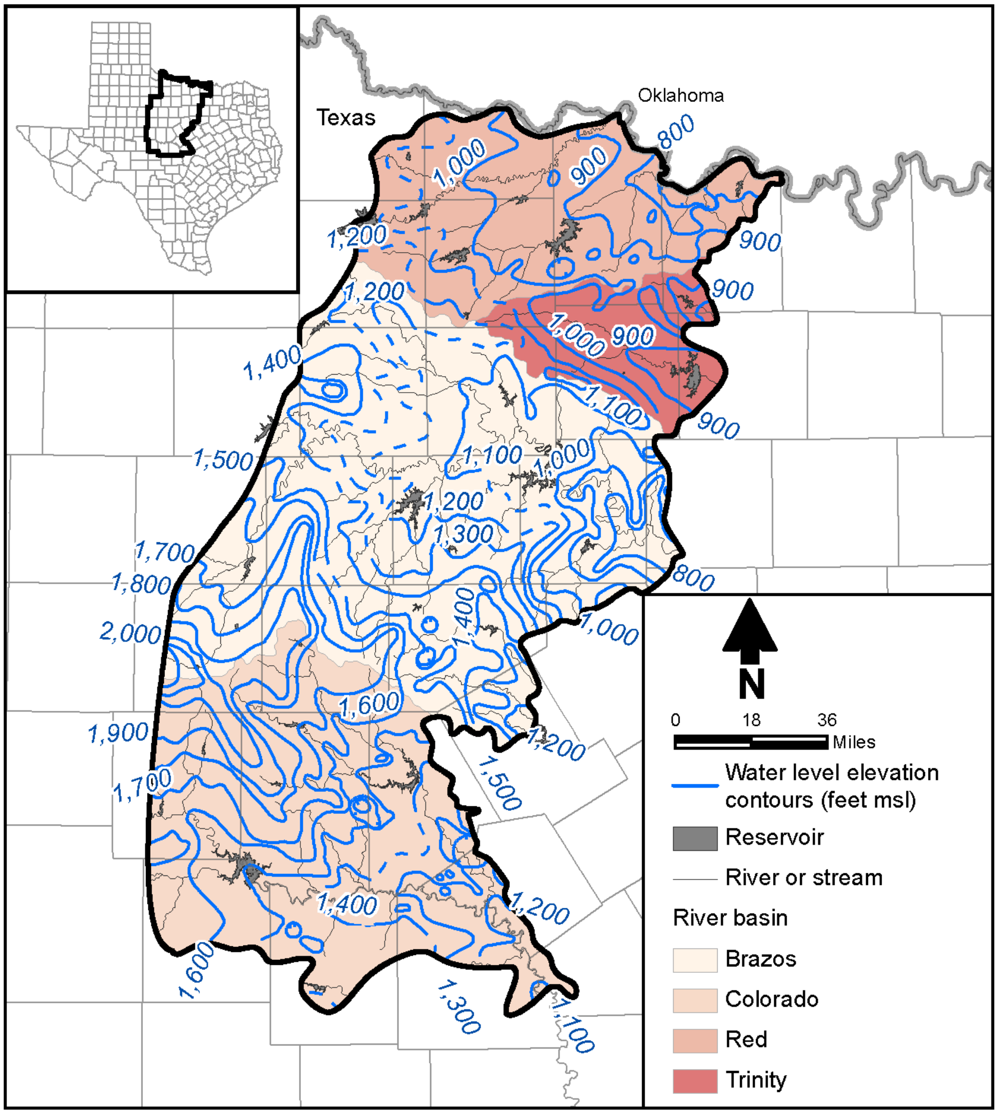


Figure 6-12. Water level contours and observed data points for 2010 through 2018 for all layers in the Cross Timbers Aquifer and major drainages.

6.3. Aquifer Thickness

The base of fresh water in the Cross Timbers Aquifer is generally shallow. Nicot and others (2013, p. 54) state that ". . . a common characteristic of Paleozoic Formations is a relatively abrupt transition from fresh to brackish and saline waters." Similar to the water level maps, some past investigators have viewed a base of fresh water map as impractical due to data limitations. For example, Nordstrom (1988, p. 3) states in his study of Jack County that "[d]ue to the discontinuous nature of the sandstone units and the wide range laterally and vertically in water quality, maps delineating water levels and base of useable-quality water were deemed to be both impractical and misleading."

Although a map of the base of fresh water does not exist for the Cross Timbers Aquifer, and development of such a map was outside the scope of this study, information was collected from prior studies and several sources to provide information on this issue.

6.3.1. TWDB Reports

Many of the county-specific studies conducted by the TWDB in the 1960s were a continuation of studies undertaken in 1962 by the predecessor agency the Texas Water Commission to meet the growing need for groundwater information in the Cross Timbers Aquifer area. One of the goals of these studies was to gain a better understanding of "useable" quality water so that the resource could be adequately protected from oil and gas drilling and production operations (e.g., Morris, 1967). Several of these reports provide estimates of the base of useable quality water on maps or cross sections, many provide a summary of recent surface casing requirements for oil and gas well drilling (which is a surrogate for fresh water thickness), and all discuss the need to protect the groundwater through appropriate surface casing installation. The term useable quality groundwater is not defined in the reports, but it appears to be used interchangeably with the term fresh water, at least in some cases. Information on surface casing requirements in TWDB reports is summarized in Table 6-1.

The base of useable quality water in Montague County is provided as maps and marked on several cross sections by Bayha (1967). The depth the base of useable quality water for the Cross Timbers Aquifer portion of Montague County is about 700 to 800 feet below land surface. Morris (1964) provides three cross sections for Young County with the approximate base of fresh water delineated; the depths to base of fresh water on these cross sections range from near land surface to about 600 feet in the northern portion of the County. Littleton (1956, p. 8) states that "[g]round water enters sandstone beds of the Cisco group at their outcrops and percolates downdip and forms an interface or mingles with brine. The depth of ground-water occurrence is controlled by stratigraphic and hydrostatic conditions and, in southeast Young County, is not known to exceed 100 feet."

6.3.2. Railroad Commission Surface Casing Estimator

More recent surface casing requirements from the Railroad Commission of Texas have been compiled under a surface casing estimator website at https://coastal.beg.utexas.edu/surfacecasing/#!/. This website was queried on April 21, 2021 to obtain compiled surface casing depths in Coleman County and the portions of Brown and Comanche Counties covered by the Cross Timbers Aquifer. This analysis confirmed that required surface casing in these counties ranged from about 200 to 500 feet below land surface in these counties to protect water that is 10,000 milligrams per liter or less in total dissolved solids concentration, which means that the base of fresh water (1,000 milligrams per liter or less) is even shallower.

Table 6-1. Summary of the depth of useable quality water from past reports.

County	Surface Casing Recommendations by the Surface Casing Section of the Texas Water Commission			Reference
	Year	No. of Recommendations Prepared	Depth (feet)	
Archer	1965	325	60–750	Morris (1967)
Brown	1963	38	60–450	Thompson (1967)
Coleman	1966	67	100–200	Walker (1967)
Concho	Maps obtained in 1985	28	100–300; most values less than 300	Richter and Kreitler (1985)
Montague	1966	113	175–1,400 (includes Trinity outcrop)	Bayha (1967)
Shackelford	1967	250	60–100	Preston (1969)
Stephens	1963	87	100–550	Bayha (1964)
Taylor	1978 and prior	—	Water of useable quality found from near land surface to depths of nearly 300 feet; in southern part of county useable-quality groundwater may occur at depths of 500 feet or more	Taylor (1978)
Throckmorton	1968	143	60–100	Preston (1970)
Runnels	Maps obtained in 1985	32	100–225; most values less than 200	Richter and Kreitler (1985)
Young	1963	212	100–800	Morris (1964)

6.3.3. Permitted Injection Well Intervals

The Railroad Commission of Texas online database was queried for injection wells within the study area. Figure 6-13 shows injection wells where the depth of the top of the shallowest permitted injection zone is 500 feet or less, and Figure 6-14 shows injection wells where the depth of the top of the shallowest permitted injection zone is between 500 and 1,000 feet. By regulation, there should not be injection of produced water (the purpose of the vast majority of these wells) in formation waters that have a total dissolved solids content of 10,000 milligrams per liter or less. Groundwater that can be used without treatment should therefore be found shallower than the shallowest injection depths at the locations shown in the figures.

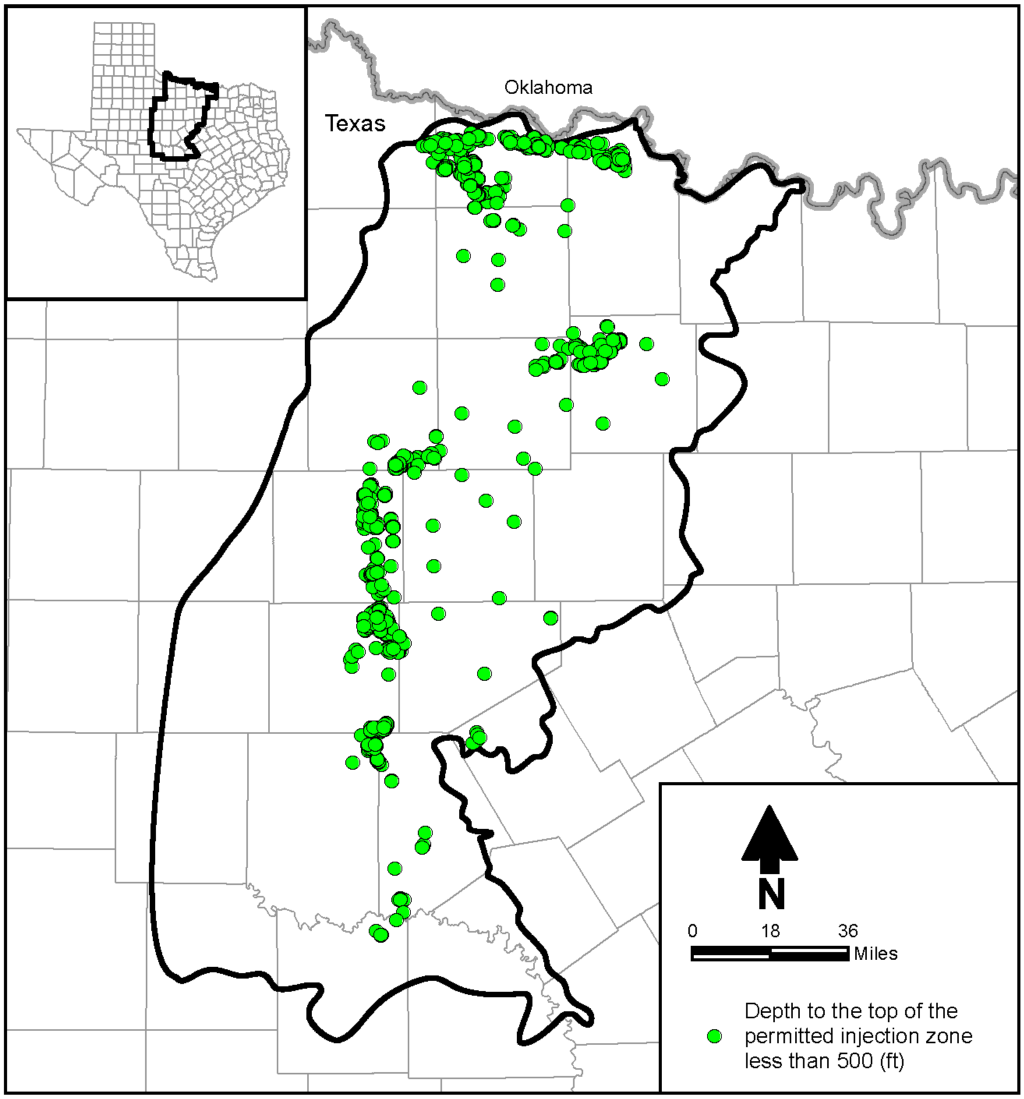


Figure 6-13. Petroleum industry injection wells with the shallowest injection zone less than 500 feet below land surface.

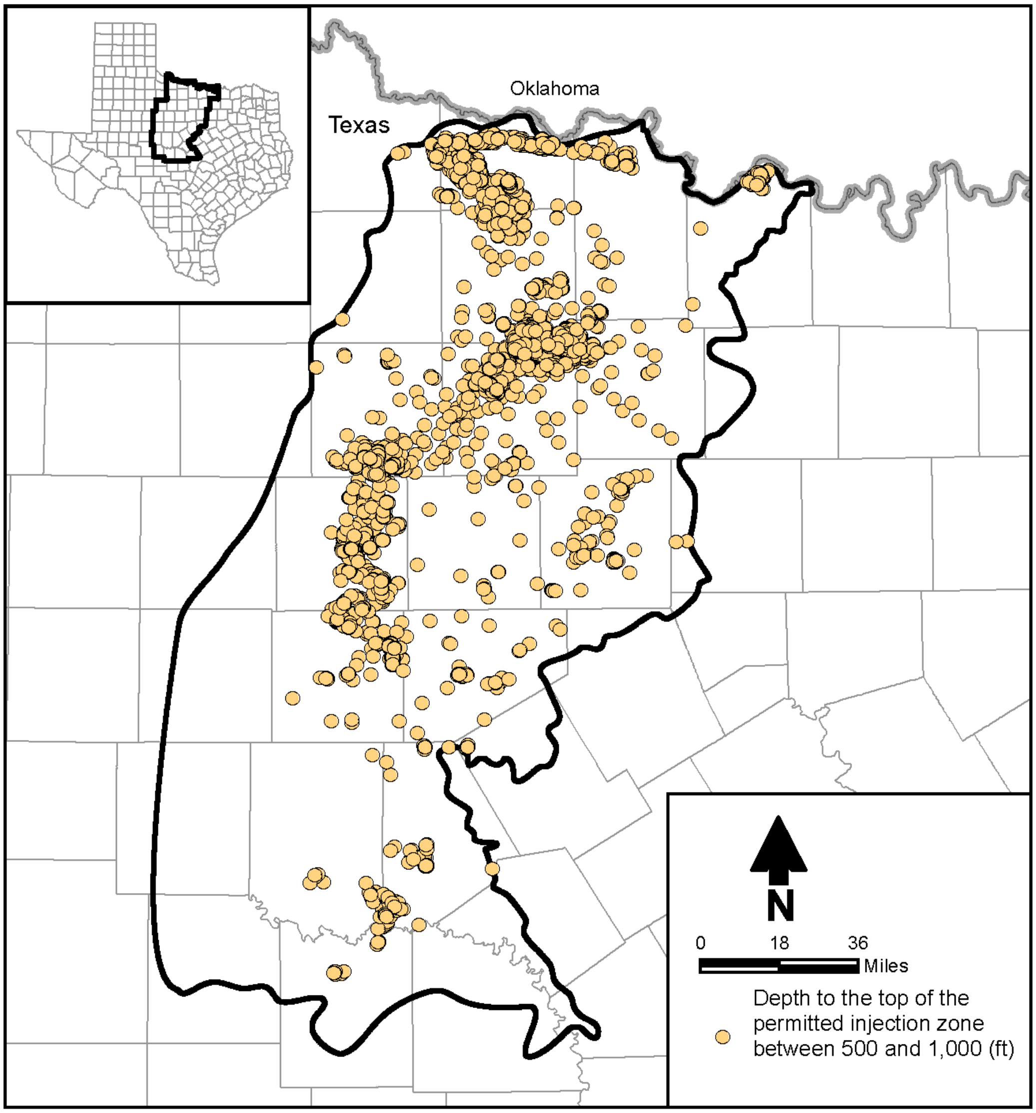


Figure 6-14. Petroleum industry injection wells with the shallowest injection zone between 500 and 1,000 feet below land surface.

6.3.4. Aquifer Thickness Summary

Consideration of the above information indicates that the regional water level maps are representative of a variable thickness of aquifer depending on location, predominantly ranging from less than 100 feet up to several hundred feet. The majority of the Cross Timbers Aquifer appears to have a saturated thickness of fresh or slightly saline water of 500 feet or less, and the entirety of the aquifer has a depth of fresh or slightly saline water of less than 1,000 feet. Nicot and others (2013, pp. 64-65) note that groundwater in the shallow fresh water zone water is not stratified in terms of water quality, and they draw the conclusion that "[b]ecause salinity sharply increases downdip, we expect a stable salinity stratification and limited mixing restricting deep recharge. . . ."

6.4. Aquifer Unit Continuity

Many of the aquifer units that comprise the Cross Timbers Aquifer as a whole consist of layered sediments that have wide-ranging permeability. Nicot and others (2013, p. 55) observed that "[d]iscontinuity is a characteristic of the hydrogeology of Paleozoic formations, and the extent of regional connectivity remains an open question."

Based on the water level contour maps (Figures 6-5 through 6-12), groundwater flow in the Cross Timbers Aquifer appears to be continuous across geologic units. This implies that sufficient primary or secondary (i.e., fracture) permeability exists within near-surface geologic units such that groundwater can pass through the rock, although there is undoubtedly a wide range of hydraulic conductivity. Given the regional nature of the existing water level dataset, however, this issue is one to keep in mind, and may not yet be settled. However, considering all data together, such as observed water levels, well distributions, and base flows, regional hydraulic connectivity appears to exist.

To further investigate the issue of regional hydraulic connectivity of the Cross Timbers Aquifer units, two counties—Coleman and Jones Counties—were selected for additional water level analysis for a period of time during the 1960s for which a greater density of water level measurements is available. The results of this analysis are provided in Figures 6-15 and 6-16 for Coleman and Jones Counties, respectively.

In Coleman County, observed water levels were available for the late 1960s for wells in the Clear Fork, Wichita, and Cisco Groups, which outcrop along a northeast to southwest trend (Figure 6-15). As indicated in the figure, the observed water levels appear to indicate the presence of a regionally hydraulically connected water level surface. Stated another way, groundwater appears to move cross dip, from the upgradient Clear Fork Group through to the Cisco Group rocks. In addition, the shape and orientation of the water levels are similar to those in Figure 6-12, representative of more recent conditions.

In Jones County, observed water levels were available for the late 1960s for wells predominantly in the Choza Formation, the Vale Formation (including the Bullwagon Dolomite), and the Leuders Formation that outcrop from west to east across the county (Figure 6-15). The formally designated extent of the Cross Timbers Aquifer covers about 40 percent of the eastern and southeastern portion of the county. As is the case in Coleman County, the observed water levels in Jones County indicate the presence of a hydraulically connected water level surface.

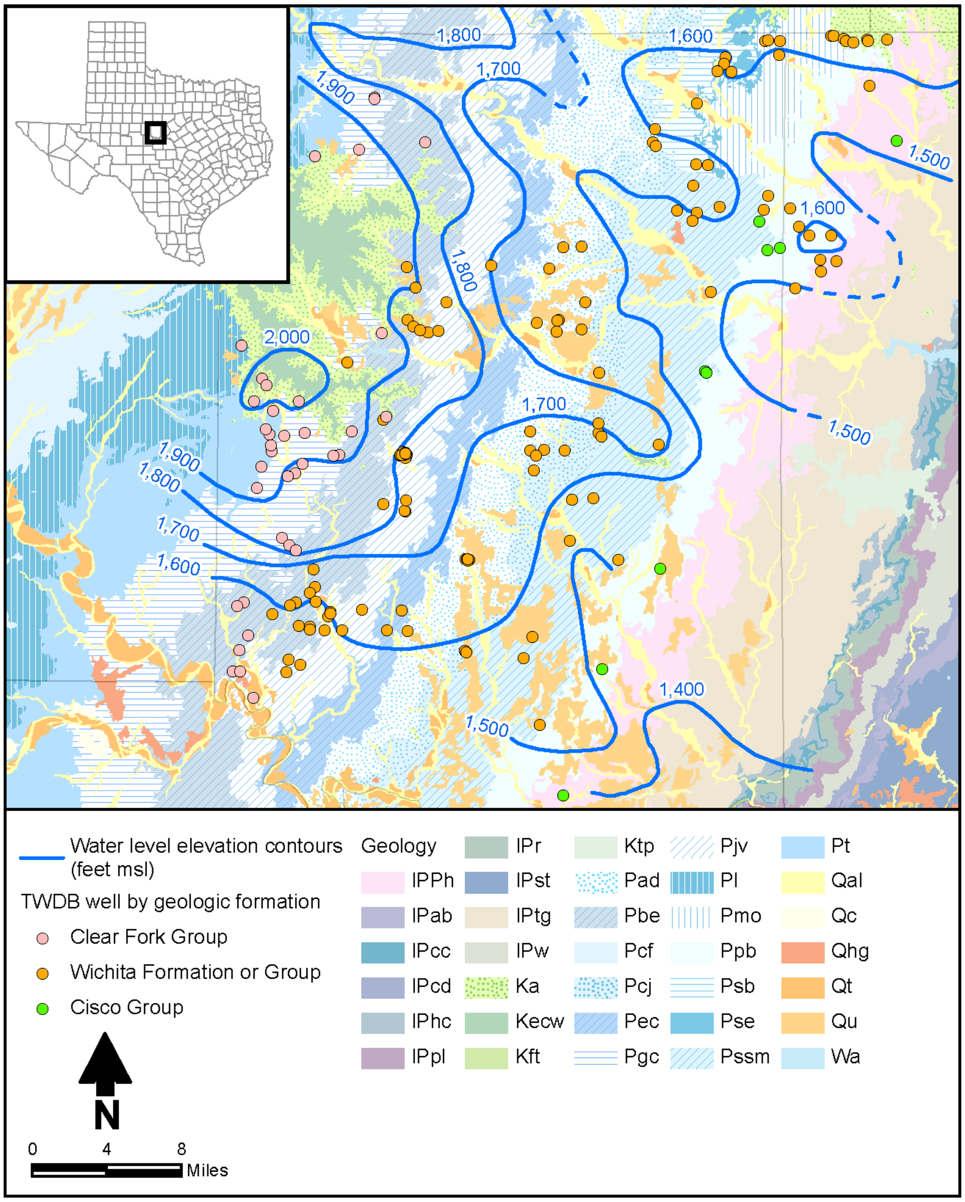


Figure 6-15. **Cross Timbers Aquifer water level map for Coleman County based on 1960s water level data.**

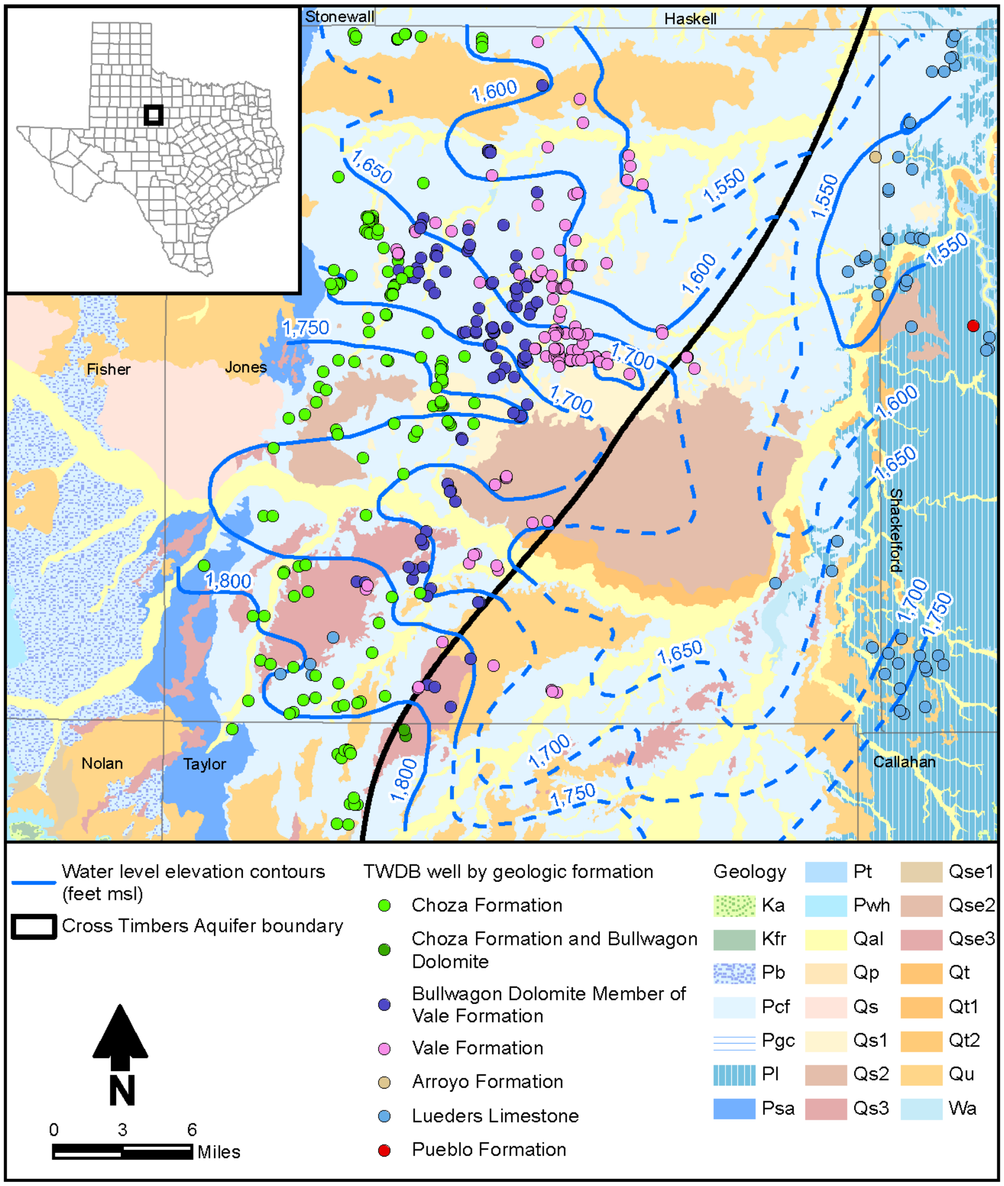


Figure 6-16. Cross Timbers Aquifer water level map for Jones County based on 1960s water level data.

6.5. Cross-Formational Flow

This section discusses the flow of groundwater between the Cross Timbers Aquifer and other recognized aquifer units.

6.5.1. Quaternary Alluvium

Relatively narrow deposits of Quaternary alluvium of limited thickness occur along most significant stream courses and tributaries within the Cross Timbers Aquifer area. Where saturated, these deposits may serve as significant sources of groundwater for stock or domestic use despite their limited saturated thickness. At some locations, such as along Jim Ned Creek in Taylor County, saturated alluvium is a major source water supply (Taylor, 1978). At other locations, such as Archer County, the alluvium is not identified as a source of water (Morris, 1967).

Groundwater in these units may seep downward to recharge the Cross Timbers Aquifer, or groundwater in the Cross Timbers Aquifer may seep upward into the alluvium. Because Cross Timbers Aquifer water discharges primarily to streams, and because the hydraulic conductivity of the alluvium is significantly higher than that of the Cross Timbers Aquifer, it is believed that groundwater flow in the alluvium is primarily horizontal and upward where it discharges to streams.

6.5.2. Seymour Aquifer

Seymour Aquifer sediments occur primarily in the southeastern corner of Jones County, along the Brazos River in southeastern Baylor County and northeastern Throckmorton County, and along the Wichita River in southern Wichita County and northern Clay County (Figure 4-2). These portions of the Seymour Formation are not included in more recent TWDB reports by Jones and others (2012) and Jigmond and others (2014), but are included in the first groundwater availability modeling report by Ewing and others (2004).

Jones and others (2012) investigated the cross-formational flow of water between the Seymour Aquifer and the underlying Clear Fork Group in Haskell and Baylor Counties immediately west of the Cross Timbers Aquifer boundary. They state that it was difficult to determine a direction of vertical groundwater flow based on water levels due to uncertainties in the land surface elevations of the available wells, but that if flow does occur, it is probably small due to the low permeability of the Clear Fork Group rocks—a conclusion they say is also supported by differences in the chemical quality of the water in each aquifer unit. In their groundwater model of the Seymour aquifer in Haskell, Knox, and Baylor Counties, Jigmond and others (2014) considered the Clear Fork Group rocks underlying the Seymour Aquifer to be an aquitard, and they simulated the bottom of the Seymour Aquifer as a no-flow boundary.

In order to further investigate the cross-formational flow of water between the Seymour and Cross Timbers Aquifers in Jones County, the water level contour map developed using 1960s Cross Timbers Aquifer water levels (Figure 6-16) was compared to the water levels plotted on two hydrogeologic cross sections provided in Price (1978). Although Price (1978) includes water level contour maps of the Seymour Aquifer, he does not provide a water level contour map for Cross Timbers Aquifer wells, probably because the Seymour Aquifer is the primary aquifer used in Jones County in terms of water production. The hydrogeologic cross sections in Price (1978) show that groundwater flow is topographically driven, with the highest water levels occurring beneath topographically high areas between stream valleys, and the lowest water levels occurring in the stream valleys where there is groundwater discharge.

The two hydrogeologic cross section locations in Price (1978) are marked on Figure 6-17, as are the Seymour Aquifer water levels at the identified locations along the sections estimated from Figures 39 and 40 in Price (1978). Comparison of the Seymour Aquifer water levels along the cross sections to the contoured Cross Timbers Aquifer water levels confirms the vertical hydraulic head difference that would be expected. The direction of vertical groundwater flow is downward from the Seymour Aquifer into the Cross Timbers Aquifer beneath the topographically high areas (i.e., away from the stream channels delineated in the figure by quaternary alluvium [Qal]). In the vicinity of the stream channels, which are points E and D' on the respective cross sections in Figure 6-17, groundwater flow is upward from the Cross Timbers Aquifer into the alluvium, and in some cases into the immediately adjacent Seymour Formation.

Even though the hydraulic gradient between the Cross Timbers Aquifer and overlying Seymour Aquifer may be up or down, the amount of water that flows between aquifer units is dependent on the vertical hydraulic conductivity, which is generally low for the Cross Timbers Aquifer. Because both the horizontal and vertical hydraulic conductivities of the Seymour Formation sediments are much larger than those of the Cross Timbers Aquifer, the majority of groundwater in the Seymour Aquifer will flow laterally from areas of recharge to areas of discharge, rather than flow downward into the Cross Timbers Aquifer.

Other than the Seymour Aquifer in Jones County, Seymour Formation outcrops are limited to several major drainages in Baylor, Throckmorton, Wichita, and Clay Counties. Because the stream channels in these regions are zones of groundwater discharge, it is believed that groundwater flow is upward from the Cross Timbers Aquifer to the Seymour Aquifer in these regions. If limited areas or periods of downward flow occur, water is unlikely to migrate far in the Cross Timbers Aquifer before it would reemerge in the downgradient stream channels and shallow Seymour Formation and alluvial sediments.

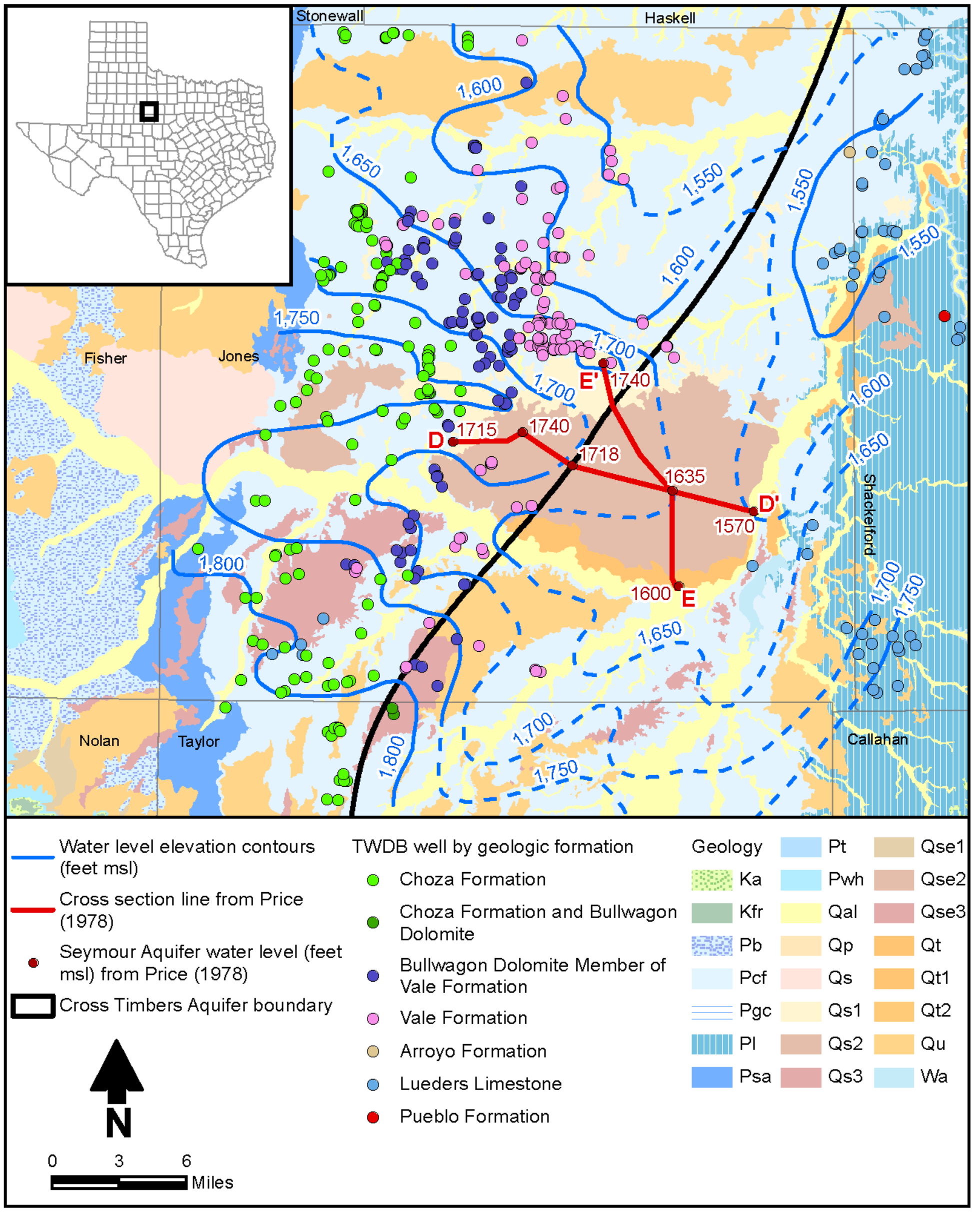


Figure 6-17. Cross Timbers Aquifer water level map for Jones County based on 1960s water level data with cross sections Seymour Aquifer water levels from Price (1978).

6.5.3. Northern Trinity and Edwards-Trinity (Plateau) Aquifers

Significant outcrops of Cretaceous rocks occur in multiple counties in the southern third of the Cross Timbers Aquifer area (Figure 4-2). These outcrops are erosional remnants of multiple Cretaceous units, and form topographic highs. Review of water levels in wells completed in these units indicates that water levels tend to be distinctly higher than those in the underlying Cross Timbers Aquifer, and in fact, the number of Cross Timbers wells beneath these outcrops is limited because the Cretaceous rocks are preferentially used for water supply due to their yield, water quality, and shallower depth. For example, Walker

(1967) reports that 45 percent of the useable quality groundwater in Coleman County is supplied by the Fredericksburg and Trinity Group outcrop north and east of Talpa, even though the outcrop area covers far less than 45 percent of the county.

Detailed water level maps for the Cretaceous aquifer units are available for Taylor and Callahan Counties in Taylor (1978) and Price and others (1983). These maps are not reproduced in this report, but they were considered when constructing the water level maps presented in Section 6.2. The aquifers contained in the Cretaceous outcrops appear as islands of water, with the highest water levels at the center of the outcrop areas and concentric rings of declining water level elevations emanating from the center and progressing toward the edges.

Kelly and others (2014) identify the possibility of the exchange of water between the Northern Trinity Aquifer and the underlying Paleozoic sediments in their conceptual model of groundwater flow, but in their numerical model, the exchange of water between these aquifer units is not explicitly simulated. Because the potential exchange of water between aquifers is not simulated, it can be intuited that Kelly and others (2014) assumed that the volume of water would be small and inconsequential relative to groundwater flow in the Northern Trinity Aquifer.

Groundwater within the Cretaceous outcrops not withdrawn by wells must either discharge to springs and streams or seep downward into the Cross Timbers Aquifer.

6.5.4. Llano Uplift Aquifer

Shi and others (2016b) simulated the exchange of water between the Cretaceous rocks and underlying Permian and Pennsylvanian formations in central and southern Concho and McCulloch Counties and the portion of Mills County covered in their model. Vertical hydraulic conductivity of the Cretaceous rocks ranges from about 5.3×10^{-3} to 0.05 feet per day in Concho and McCulloch Counties, and from about 0.03 to 0.3 feet per day in Mills County. The vertical hydraulic conductivity of the Cisco, Canyon, and Strawn Groups (considered as one hydrogeologic unit in the model) that underlie the Cretaceous rocks ranges from about 3×10^{-5} to about 3×10^{-4} feet per day in Coleman, Concho, and McCulloch Counties, and is about 2.5×10^{-3} feet per day in Mills County.

The volume or rate of vertical groundwater flow between their model layers 1 and 2 is not reported by Shi and others (2016b), but based on the conceptual model, groundwater flow in the Cretaceous aquifer units that overlay the Cross Timbers Aquifer units is downward, unless the water is removed by pumping or discharges naturally as spring or stream flow at the edge of the Cretaceous aquifer rocks.

7. Groundwater Recharge

7.1. Background

There has been little detailed study on the occurrence of recharge in the Cross Timbers Aquifer. Early reports on the occurrence of groundwater within the study area did not address recharge at all (e.g., Bayha, 1967; Morris, 1964), or only defined what recharge meant and how it occurred (e.g., Preston, 1970). Taylor (1978) estimated a recharge rate to the alluvium in Taylor County along Jim Ned Creek of 1.44 inches per year, and documented changes in water levels due to changes in precipitation in alluvial, Choza Formation, and Choza Formation/Bullwagon Dolomite wells.

Later studies on groundwater in the region acknowledged that determination of the amount of recharge was difficult due to data limitations (e.g., Walker, 1979), and provided only generalized estimates of recharge over large regions (e.g., Baker and others, 1990; Duffin and Beynon, 1992). Preston and others (1996) discuss recharge in general and detail stream gain and loss studies in their study area, which overlies the southern quarter of the Cross Timbers area, but do not offer details on recharge estimates. More recently, Nicot and others (2013) used the chloride mass balance method to estimate recharge for their study area, which includes Clay, Montague, Jack, Wise, Palo Pinto, Parker, Erath, and Hood Counties. Nicot and others (2013) estimated groundwater recharge to be 0.1 inch per year on average, or about 0.3 percent of average annual precipitation. Avakian and Wermund (1994) investigated groundwater beneath Fort Wolters in Palo Pinto and Parker Counties and observed that, although records were incomplete, it appeared that historical water level changes in Strawn Group wells seemed to reflect variation in annual rainfall.

Scanlon and others (2000) analyzed and assessed the reliability of past estimates of recharge, and developed conceptual models for recharge for all of the major aquifers in Texas. Although most of the Cross Timbers area is not located within the footprint of the major Texas aquifers, portions of three major aquifers overlie parts of the study area. The south-central part of the Cross Timbers study area, primarily in Callahan and Eastland Counties, lies within the outcrop of the Trinity Aquifer, and much of the remainder of the Trinity Aquifer outcrop lies immediately east of the Cross Timbers study area. Likewise, small portions of the Seymour Aquifer are present in Baylor, Jones, and Wichita Counties, and the remainder of the Seymour Aquifer lies immediately west of the Cross Timbers Aquifer study area. The Edwards-Trinity (Plateau) Aquifer is located to the south and southwest of the Cross Timbers Aquifer study area, and small parts of that aquifer are also present within the Cross Timbers Aquifer footprint southwest of Abilene.

Scanlon and others (2000) note that a wide variety of techniques have been used to estimate recharge, including water budget, Darcy's Law, modeling, base flow discharge, and stream flow loss study approaches. They determined that historical recharge estimates for both the Trinity and Edwards-Trinity (Plateau) Aquifers generally ranged from 0.1 to 2 inches per year, and recharge estimates to the Seymour Aquifer ranged from 1 to 2.5 inches per year.

With the initiation of the TWDB groundwater availability modeling program, more rigorous estimates of recharge began to be made as part of the modeling studies. As noted above, because much of the study area is outside the footprints of major and minor aquifers, recharge estimates from the development of other groundwater availability models is limited to relatively small portions of the study area and areas immediately adjacent to the study area. A summary of recharge estimates available from the groundwater availability models that adjoin and in some cases overlay the Cross Timbers Aquifer are provided in the following subsections.

7.1.1. Seymour Aquifer

One of the first groundwater availability models that was developed was of the Seymour Aquifer (Intera, 2003; Ewing and others, 2004), which has small portions present in the western portion of the Cross Timbers Aquifer study area and the remainder of the aquifer west of the Cross Timbers Aquifer study area.

Although Ewing and others (2004) note that recharge estimates were initially lower in their modeling efforts, ultimately the calibrated rates of recharge for this aquifer had to be increased to an average of 1.9 inches per year, ranging from 0.8 to 2.5 inches per year, within the Seymour Aquifer "pods." In the updated Seymour groundwater availability model conceptual model report (Jones and others, 2012; Jigmond and others, 2014), which focused on the Seymour pod in Haskell, Knox, and Baylor Counties, final calibrated average recharge rates averaged around 3.2 inches per year.

Jigmond and others (2014) estimated Seymour Aquifer recharge of about 0.1 inch per year to nearly as high as 5 inches per year in Baylor and Haskell Counties. The higher recharge values, however, include irrigation return flow.

7.1.2. Northern Trinity Aquifer

The Northern Trinity Aquifer lies at the eastern edge of the Cross Timbers Aquifer. This aquifer was first modeled by Bené and others (2004), and an updated model was completed by Kelly and others (2014). Bené and others (2004) noted that recharge in the Trinity outcrop area, which is immediately adjacent to the current study area, averaged around 1.4 inches per year, with recharge in a majority of the area less than 1 inch per year. Kelly and others (2014) considered multiple recharge estimation methods, including stream hydrograph separation, water balance, and chloride mass balance to estimate recharge. They noted that there was a wide range in estimated recharge rates, from less than 0.25 to over 3 inches per year. They also noted that chloride mass balance recharge estimates were generally lower along the western edge of the Northern Trinity Aquifer outcrop area, which would be immediately adjacent to the Cross Timbers Aquifer eastern boundary, and that recharge was generally less than 0.5 inch per year for the portion of the Northern Trinity Aquifer present as outcrop within the footprint of the Cross Timbers Aquifer study area in Taylor, Callahan, and Eastland Counties (Figure 4-2).

Kelly and others (2014) ultimately decided on the stream hydrograph separation method as the most appropriate estimate. They estimated average annual recharge to the Cretaceous units over a 30-year period to be 0 to 0.5 inch per year for the outcrop in Callahan, Eastland, Brown, Comanche, Erath, and Hood Counties. The Cretaceous outcrop in Parker, Jack, and Wise Counties had an estimated average recharge of 0.5 to 1 inch per year. The outcrop in Montague County has estimated recharge of 1 to 2 inches per year. Estimated recharge increases to the north due to higher precipitation. The average annual recharge was scaled temporally based on annual precipitation records.

7.1.3. Edwards-Trinity (Plateau) Aquifer

A portion of the Edwards-Trinity (Plateau) Aquifer occurs as an isolated outcrop of Cretaceous rocks southwest of Abilene (Figure 3-1). Beginning with Anaya and Jones (2004), recharge to the aquifer has been estimated based on a percentage of annual precipitation, divided into zones within the model area. A subsequent recalibration of the first groundwater availability model (Anaya and Jones, 2004), retained this basic approach (Young and others, 2010), and a third update spatially distributed annual recharge based on average annual recharge (Hutchison and others, 2011). The average annual recharge for 1930 (the base year) presented in Hutchison and others (2011) is 0 to 1.5 inches per year for the Edwards-Trinity outcrop area that occurs southwest of Abilene. The TWDB is currently working on an updated model of the Edwards-Trinity (Plateau) Aquifer that will include updated estimates of groundwater recharge.

7.1.4. Llano Uplift Aquifer

A regional groundwater model of the Llano Uplift aquifers was developed in 2016 (Shi and others, 2016a and 2016b). Using stream base flow, Shi and others (2016b) estimated groundwater recharge of less than 0.2 inch per year in southeastern Runnels County, the southern portion of Coleman County, and the northern portions of Concho and McCulloch Counties. To the east in Brown, Mills, and San Saba Counties, they estimated average annual recharge rates of 0.2 to 0.5 inch per year. The groundwater model used initial recharge rates estimated from PRISM precipitation raster data, and ultimately had a final average recharge of 0.62 inch per year in the Cretaceous units and 0.27 inch per year for the Permian and Pennsylvanian units above the Marble Falls Formation, which correspond to the Cross Timbers Aquifer hydrostratigraphic layer 8.

7.1.5. Lipan Aquifer

Beach and others (2004) estimated the groundwater recharge in southwestern Runnels and western Concho Counties to range from 0.65 to 0.61 inch per year, with recharge rates increasing moving to the east. Beach and others (2004) used percent of precipitation to estimate recharge, and adjusted their final values during groundwater model calibration.

7.2. Estimation of Recharge Using the Distributed Parameter Watershed Model

7.2.1. Overview of the Distributed Parameter Watershed Model

Daniel B. Stephens & Associates, Inc. developed the Distributed Parameter Watershed Model based on the Mass Accounting System for Soil Infiltration and Flow model developed by Sandia National Laboratories (2007) for the Yucca Mountain Project. The Distributed Parameter Watershed Model is similar in concept to water balance models used by the U.S. Geological Survey (e.g., PRMS [Leavesley and others, 1983], INFIL [Hevesi and others, 2003], BCM [Flint and Flint, 2007]). The Distributed Parameter Watershed Model uses a daily time step over regular grid cell sizes that are user-defined. The model generally relies on the widely accepted FAO-56 procedure for computing actual evapotranspiration from the reference evapotranspiration estimated using the Penman-Monteith method (Allen and others, 1998). Water budget components accounted for in the model include precipitation, bare soil evaporation, transpiration, runoff, run-on, snow accumulation, snowmelt, snow sublimation (direct evaporation of snow into the atmosphere), soil water storage, and net infiltration. A bedrock boundary is placed at the bottom of Distributed Parameter Watershed Model cells with shallow soil depths; this boundary may restrict infiltration when the saturated hydraulic conductivity of the bedrock is less than that of the soil.

Surface water runoff is estimated by the model when either the rate of precipitation exceeds the saturated hydraulic conductivity of the soil (infiltration excess or Hortonian runoff) or the soil-water content of the soil exceeds the water-holding capacity of the soil (saturation excess or Dunnian runoff). Surface water runoff is routed between model cells based on topography obtained from a digital elevation model. The Distributed Parameter Watershed Model accounts for focused runoff by modeling washes and streams as a separate water balance calculation within each model cell. Where washes and streams are present, runoff is routed from overland flow to the washes and streams within a model cell, and then runoff is routed to the wash and stream in the next downstream cell. The model does not simulate interflow in the subsurface between the model cells; the only hydrologic connection between cells occurs as the surface water component.

The model is constructed and executed using metric units to efficiently capitalize on existing data sources. A schematic representation of model operation is provided in Figure 7-1.

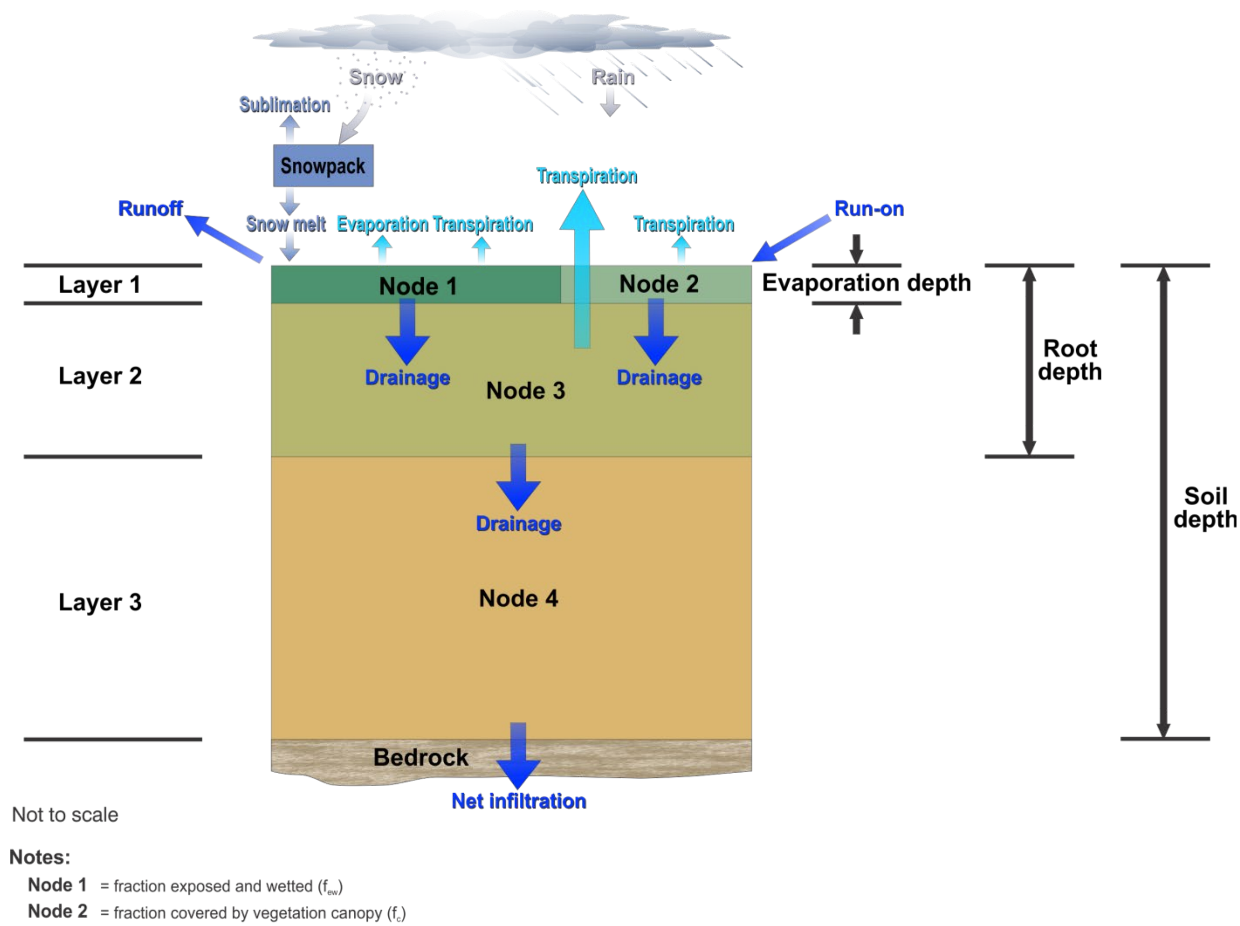


Figure 7-1. Schematic representation of Distributed Parameter Watershed Model operation.

7.2.2. Simulation Approach

A recharge model grid size of 161,874 square meters (¼ mile by ¼ mile) was deemed to be adequate for the goals of this study. However, given that the Distributed Parameter Watershed Model can be run efficiently for grid sizes up to about 100,000 cells, in order meet this goal, the recharge model was divided into six separate models based on sub-watersheds. In addition, because surface water flow from outside the aquifer boundary can contribute to recharge within the aquifer boundary, the active Distributed Parameter Watershed Model grids were extended west of the Cross Timbers Aquifer area. This approach led to six recharge models referred to as Little Wichita, Middle Brazos-Millers, Middle Brazos-Palo Pinto, Upper Clear Fork Brazos, Middle Colorado, and San Saba (Figure 7-2). Once the grid was constructed for each of these areas, other required inputs were obtained as described in the following subsections.

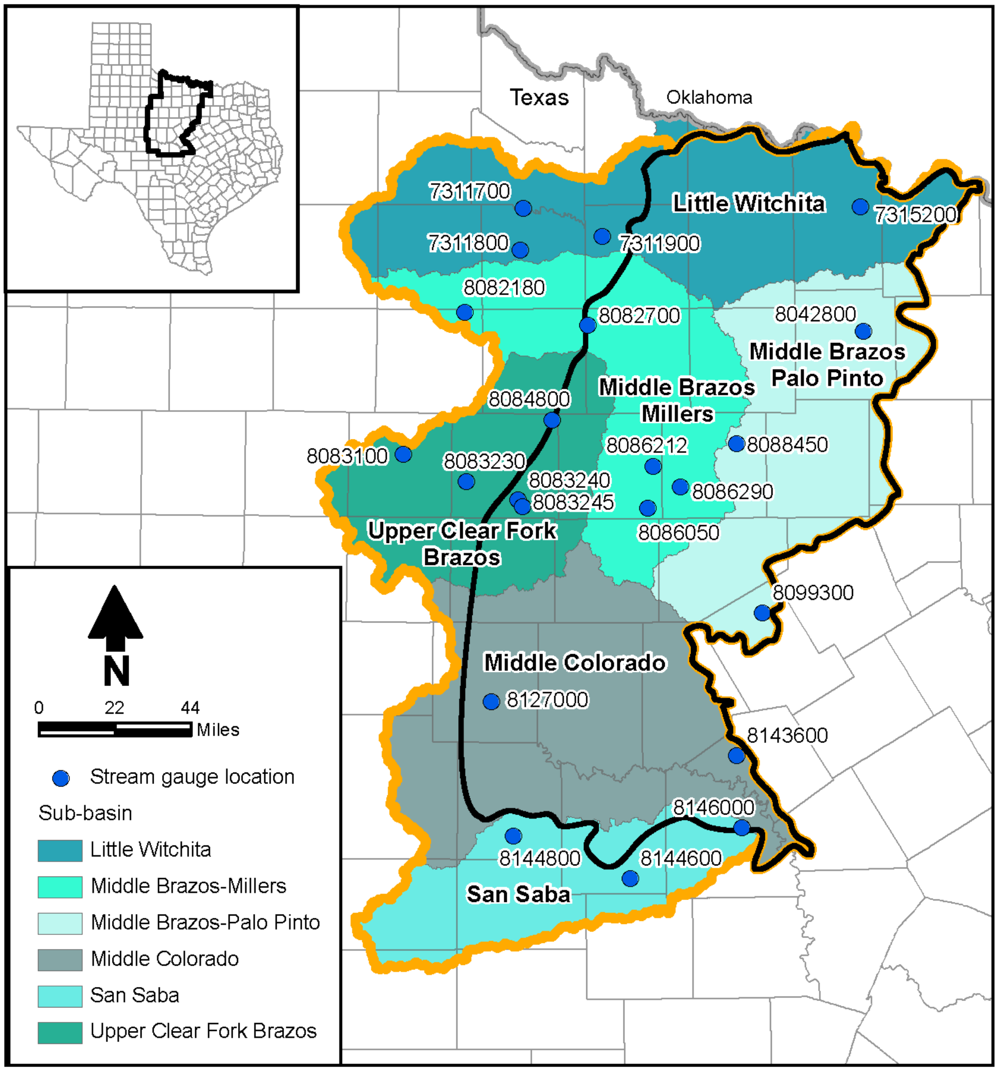


Figure 7-2. Distributed Parameter Watershed Model sub-basin simulation domains and gauges used for base flow estimation.

The time period of simulation is water years 1981 through 2020 (October 1980 through September 2020) to correspond with readily available climatic data required as model input.

7.2.3. Recharge Model Inputs

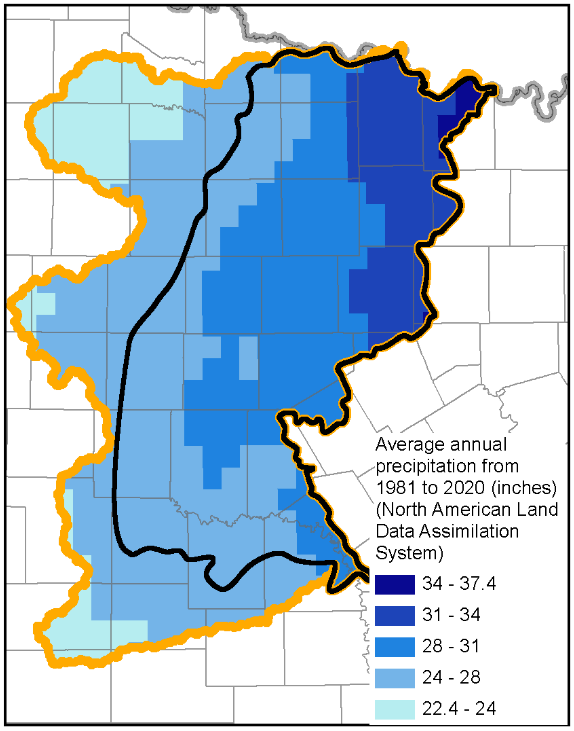
To estimate the spatial and temporal distribution of groundwater recharge, the Distributed Parameter Watershed Model assimilates published data from multiple sources. The primary model inputs and data sources are outlined in the following subsections. Tables summarizing primary model inputs are provided in Appendix A due to the large number of model inputs that had to be documented.

7.2.3.1. Climate

For each grid cell in the modeling domain, the Distributed Parameter Watershed Model requires daily minimum and maximum temperatures, precipitation amount and duration, and wind speed. Reliable estimation of climate data in both space and time from sparse weather stations is complex. Standard practice is to rely on climate models published by specialists. Two widely used climate models are PRISM (2004) and the North American Land Data Assimilation System (Xia and others, 2009 and 2012), commonly referred to as NLDAS. The North American Land Data Assimilation System was selected for recharge modeling because it is the only climate model that provides hourly estimates of all parameters required by the Distributed Parameter Watershed Model. Sub-daily precipitation is important for estimating precipitation duration, which can have a significant effect on simulated runoff. One potential disadvantage of the North American Land Data Assimilation System is that it is more coarsely gridded than PRISM. However, the model area is large enough that there is no significant advantage to the higher spatial resolution of PRISM. The two data sources were compared, and the North American Land Data Assimilation System and PRISM indicate similar amounts of precipitation across the Cross Timbers Aquifer recharge modeling area (Figure 7-3).

North American Land Data Assimilation System data used in the Distributed Parameter Watershed Model are temperature, precipitation, and wind speed. Hourly North American Land Data Assimilation System estimates were converted to daily inputs for the Distributed Parameter Watershed Model. Minimum and maximum daily temperatures were inferred from the minimum and maximum estimated hourly temperatures. Daily wind speed was assumed to be the average (mean) of the hourly wind speeds. Precipitation amount is the sum of hourly precipitation. Precipitation duration was assumed to be the number of hours on a given day that received more than 0.1 inch of precipitation, with a minimum duration of 1 hour for days with greater than zero precipitation.

North American Land Data Assimilation System monthly normals of precipitation, minimum temperature, and maximum temperature were validated against three National Oceanic and Atmospheric Administration weather stations (Menne, 2012) within the study area. These stations are the Abilene Regional Airport, the Wichita Falls Municipal Airport, and Coleman, Texas (Figure 7-4).



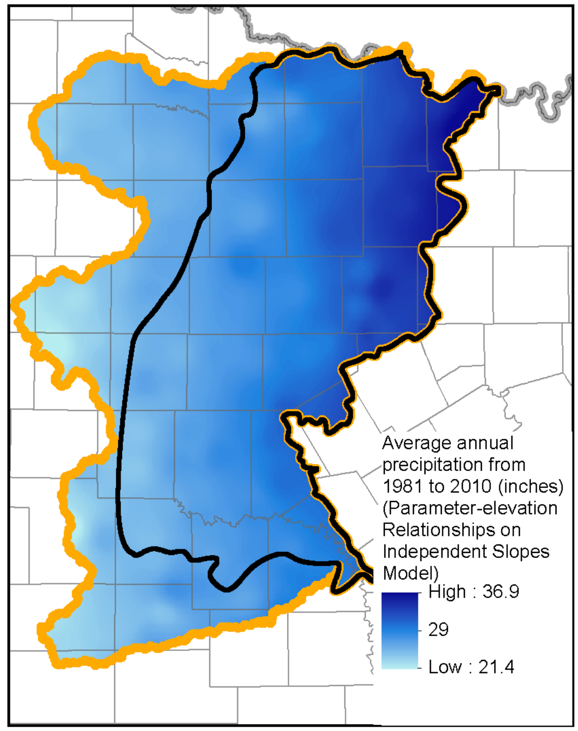


Figure 7-3. Comparison of PRISM and North American Land Data Assimilation System precipitation across the watershed model area.

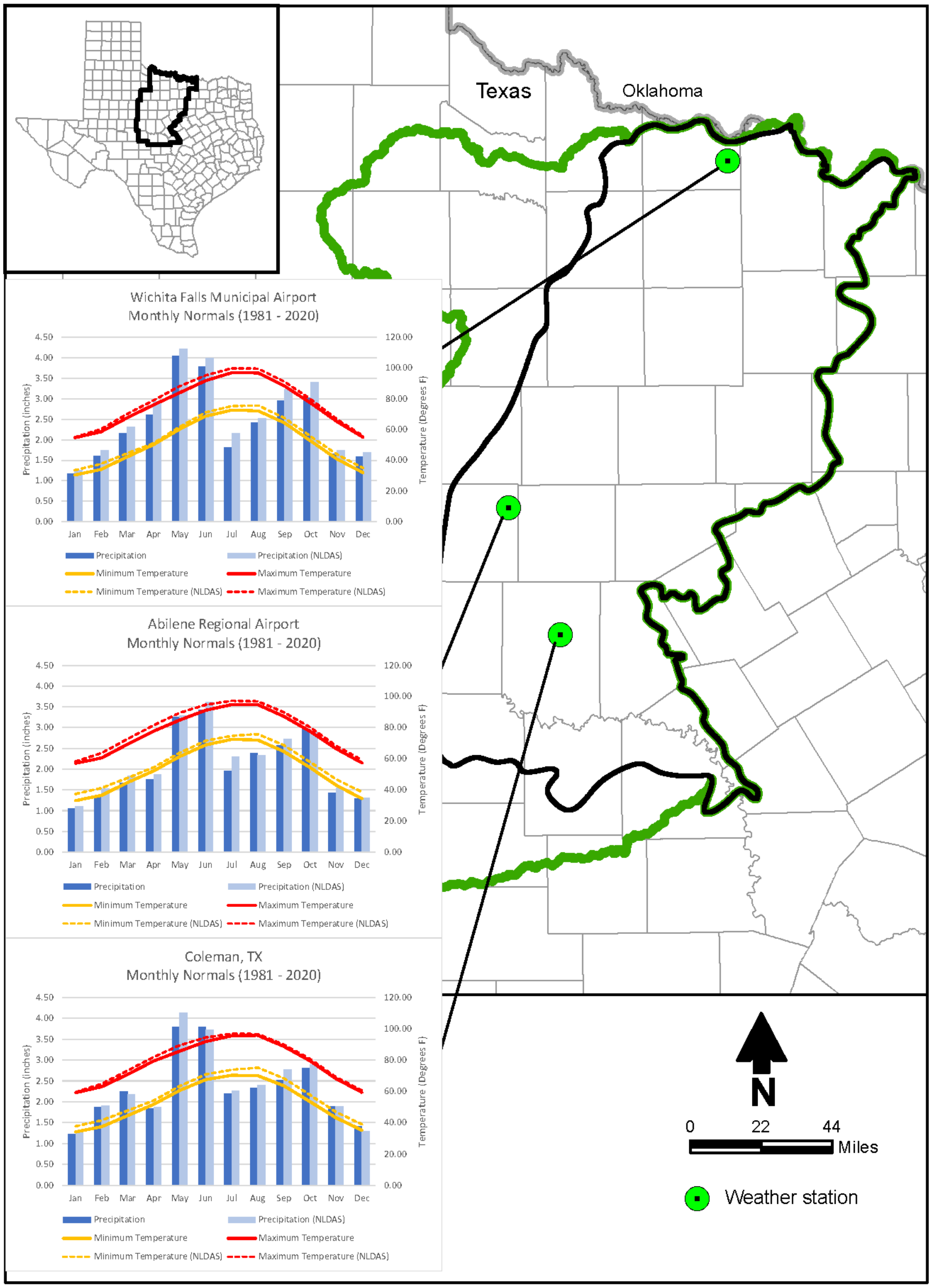


Figure 7-4. Comparison of North American Land Data Assimilation System precipitation at selected weather stations.

7.2.3.2. Soils

Soils data used by the Distributed Parameter Watershed Model include saturated hydraulic conductivity, soil depth to bedrock, saturated and residual water contents, and the van Genuchten curve parameters. These data were obtained directly or estimated based on soils data published by the U. S. Department of Agriculture SSURGO database (Natural Resources Conservation Service, 2020), which contains electronic data from field surveys conducted by the U. S. Department of Agriculture for the model domain.

The SSURGO database provides texture data (percent sand, silt, and clay), saturated hydraulic conductivity, dry bulk density, saturated water content, and water contents at ⅓ bar and 15 bars for each soil horizon. The SSURGO database also reported the soil depth to bedrock where bedrock was within 2 meters of the ground surface. A weighted average for soil texture, saturated water content, and the saturated hydraulic conductivity was estimated within a SSURGO map unit based on the soil horizon thickness. The residual water contents and van Genuchten curve parameters were estimated based on soil texture for each SSURGO map unit using the Rawls and Brakensiek pedotransfer method (Rawls and Brakensiek, 1985; Rawls and others, 1992; Carsel and Parrish, 1988; Lee, 2005).

Within the recharge model area, there were 2,487 map units in the SSURGO database. In order to make model input and simulations more tractable, SSURGO map units were grouped based on soil texture descriptions, a process that led to 61 categories of grouped soils. The soil parameters reported and estimated for each SSURGO map unit were averaged for the grouped soils. These are the soil categories presented in Figure 2-13. Grid cells were assigned a soil type based on the predominant SSURGO map units present at each recharge model cell centroid.

The SSURGO database reports depth to bedrock for depths up to 2 meters. For soils with thickness greater than 2 meters, the soil depths were assumed to be equal to the maximum vegetation rooting depth of 4 meters. Soil vertical hydraulic conductivity is one of the model inputs adjusted during the recharge model simulations; these adjustments along with the initial estimates are presented in Section 7.2.4.

7.2.3.3. Bedrock Vertical Hydraulic Conductivity

Bedrock data used in the Distributed Parameter Watershed model are the saturated hydraulic conductivities of the bedrock underlying the soils. The bedrock geology for each grid cell is based on the 1:250,000 scale Geologic Atlas of Texas sheets (Bureau of Economic Geology, 2014). Bedrock underlying soils in the study area may restrict net infiltration when the saturated hydraulic conductivity of the bedrock is less than the infiltration rate and where soils are shallow. The bedrock hydraulic conductivities were initially estimated based on the unit lithology (e.g., sandstone or shale) and professional judgment. In addition, it was known that about 60 percent of the horizontal hydraulic conductivity values (Section 9) were less than 1 foot per day, and for most geologic units the vertical hydraulic conductivity would be expected be lower than the horizontal hydraulic conductivity by at least a factor of 10, and more likely by a factor of 100 or even 1,000 based on the layering of sediments. Using this reasoning, initial estimates of bedrock hydraulic conductivities ranged from 1.5 x 10^{-4} feet per day for the Dockum Group, Blaine Formation, and several Cambrian and Precambrian hard rock units up to 2.5 feet per day for Quaternary alluvium and the Seymour Formation. Note that although some geologic units, such as the Dockum and the Blaine, do not occur within the boundaries of the Cross Timbers Aquifer, they occur as outcrop in portions of the watershed models that extend west of the western aquifer boundary.

Bedrock geologies with similar estimated vertical hydraulic conductivity were grouped during the model simulations to reduce the number of bedrock geology groups from 108 to 35. The Distributed Parameter Watershed Model inputs contain all 108 geology groups as mapped directly from the Geologic Atlas of Texas sheets.

Bedrock vertical hydraulic conductivity is one of the model inputs adjusted during the recharge model simulations; these adjustments along with the full range of initial estimates are presented in Section 7.2.4.

7.2.3.4. Vegetation

Vegetation data used in the Distributed Parameter Watershed Model include the rooting depth and plant height for each class of vegetation and the density of vegetation in each model grid cell. Vegetation classes were obtained from the National Land Cover Database (Homer and others, 2012) (Figure 2-12). The dominant vegetation types are shrub/scrub, herbaceous, and cultivated crops. Table A-2 (Appendix A) summarizes the rooting depths and maximum plant height for vegetation class in the Cross Timbers Aquifer region.

Rooting depths were estimated from similar vegetation classes described in Canadell and others (1996) and Westenbroek and others (2010), and range from 0.30 meter (1 foot) for barren land to 3.90 meters (13 feet) for evergreen forests. Plant heights were estimated from similar vegetation classes described in Allen and others (1998). Plant heights range from 0.10 meter (0.33 foot) for developed areas to 10 meters (33 feet) for evergreen forests. The vegetation density was obtained from monthly MODIS satellite observations of the leaf area index for the representative wet water year of 2005 (U.S. Geological Survey, 2016b). The monthly leaf area index data were provided as input to the Distributed Parameter Watershed Model.

7.2.3.5. Topography

Topography data used in the Distributed Parameter Watershed Model includes the slope, azimuth, and elevation of the land surface for each model grid cell. The topography is part of the recharge model calculations of reference evapotranspiration (also known as potential evapotranspiration). For example, south-facing slopes will typically have higher evapotranspiration than north-facing slopes in the northern hemisphere due to increased solar radiation. The routing of surface runoff in the recharge models is also based on averaged grid cell elevations.

Topography data in the model were derived from the U.S. Geological Survey 30-meter digital elevation model (Accessed January 20, 2020) (Figure 2-5) by averaging elevations, slopes, and azimuth onto the ¼-mile square grid cells.

7.2.4. Comparison of Simulated Recharge to Observed Data

Because groundwater flow in the Cross Timbers Aquifer is topographically driven, and the main discharge mechanism for groundwater is to streams in relatively close proximity to points of recharge (Section 6), simulation results from the Distributed Parameter Watershed Model were compared to estimates of base flow at selected stream gauges, which is interpreted to be an indicator of the quantity of groundwater recharge upstream of the gauge. Initially, all U.S. Geological Survey stream gauge locations with mean daily discharge data (U.S. Geological Survey, 2016a) in the model area were considered as potential comparison points. Stream gauges were initially excluded if they were immediately downstream of a dam. If several gauges remained in a given sub-basin, additional locations were excluded if there was a dam anywhere in their drainage area (with two exceptions described below). Other criteria used to exclude a gauge include (1) if their drainage area was very small relative to other available gauges or (2) if there was only a small number of years for comparison. This process led to selection of 22 gauge locations where simulated recharge was compared to estimated base flow (Figure 7-2).

The Middle Colorado sub-basin contains two comparison stream gauges. Both gauges have reservoirs in their drainage area, although for gauge 8127000, the upstream reservoir is small. Comparison at these gauges was conducted as an approximate check on the magnitude of recharge in this basin, although estimated base flow at these gauges should be considered with caution.

Base flow separation was performed using the local minimum method (Pettyjohn and Henning, 1979) implementation in HYSEP (Sloto and Crouse, 1996). The local minimum method estimates a surface runoff duration based on drainage area and then selects "moving minimums" within that duration. Interpolation is performed between minimum points; an example figure of this process is provided in Section 8.

Comparisons were performed between observed annual base flow at each stream gauge and the modeled annual recharge across the associated drainage area. Estimated riparian evapotranspiration was considered as a potential component to be added to base flow, but this approach did not significantly affect results.

When the initial model runs were compared to the base flow estimates, it was clear that the simulated recharge was almost universally too high. To reduce recharge, the soil hydraulic conductivities were reduced by a factor of 5 to better mimic the magnitude of the observed data. Conceptually, the estimated soil properties do not account for layering and other anisotropy expected to commonly occur, so this adjustment was viewed as reasonable. To refine the models further, the hydraulic conductivities of selected individual soil groups were further adjusted up or down, with the underlying constraint that the values had to be maintained within the minimum and maximum reported hydraulic conductivities from SSURGO within each soil group divided by 5. The initial and final adjusted soil hydraulic conductivities are provided in Table A-3 (Appendix A), and the final adjusted soil hydraulic conductivity is plotted in Figure 7-5.

In addition to soil hydraulic conductivity, bedrock hydraulic conductivity was also selectively adjusted in some basins. The adjustments were constrained to be between 1/100 and 10 times the initial estimated value. The initial and final adjusted bedrock hydraulic conductivities are provided in Table A-4 (Appendix A), and are illustrated in Figure 7-6. Adjusted bedrock vertical hydraulic conductivities went as low as 5 x 10^{-4} feet per day.

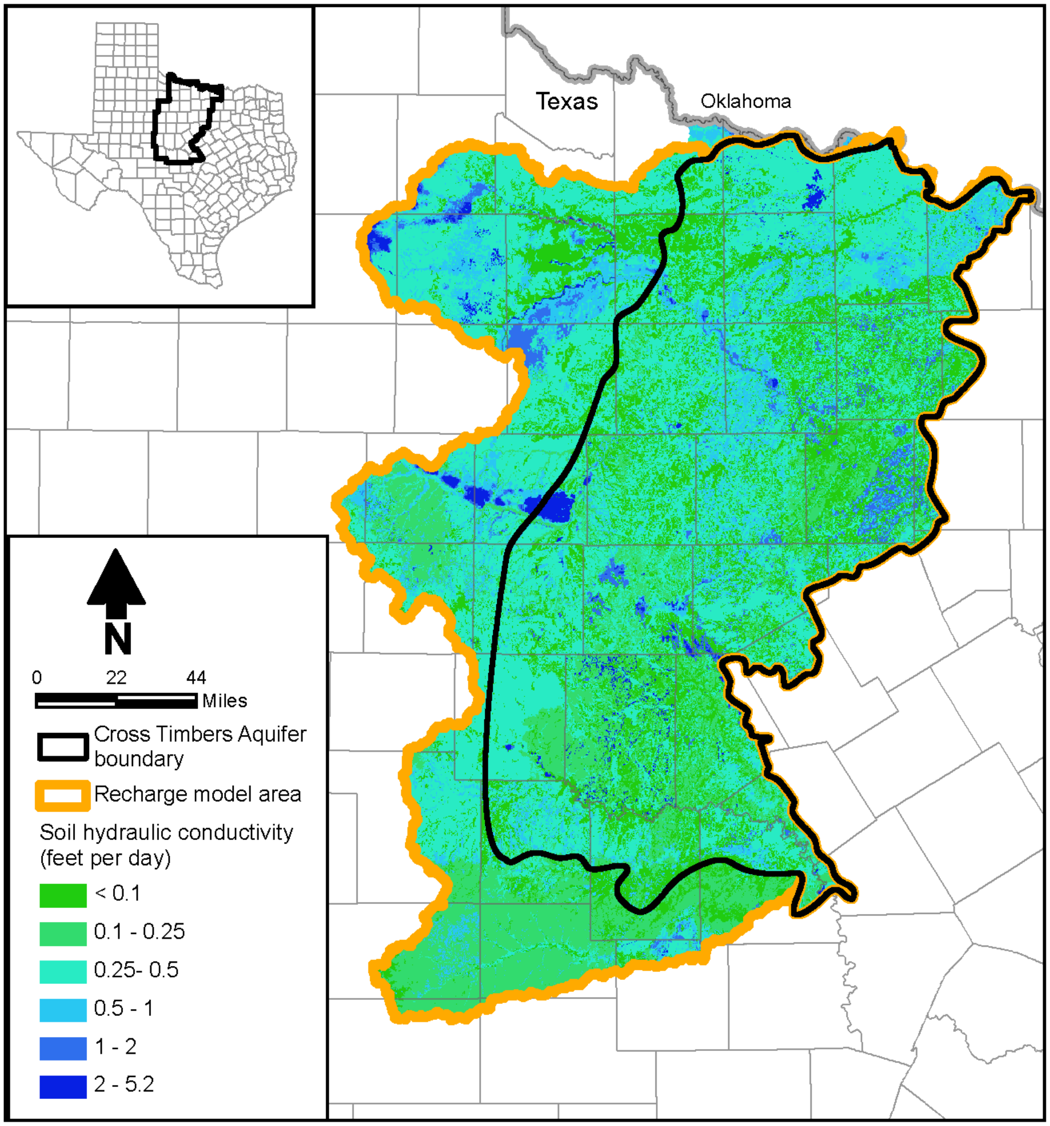


Figure 7-5. Final soil hydraulic conductivity used the Distributed Parameter Watershed Model simulations.

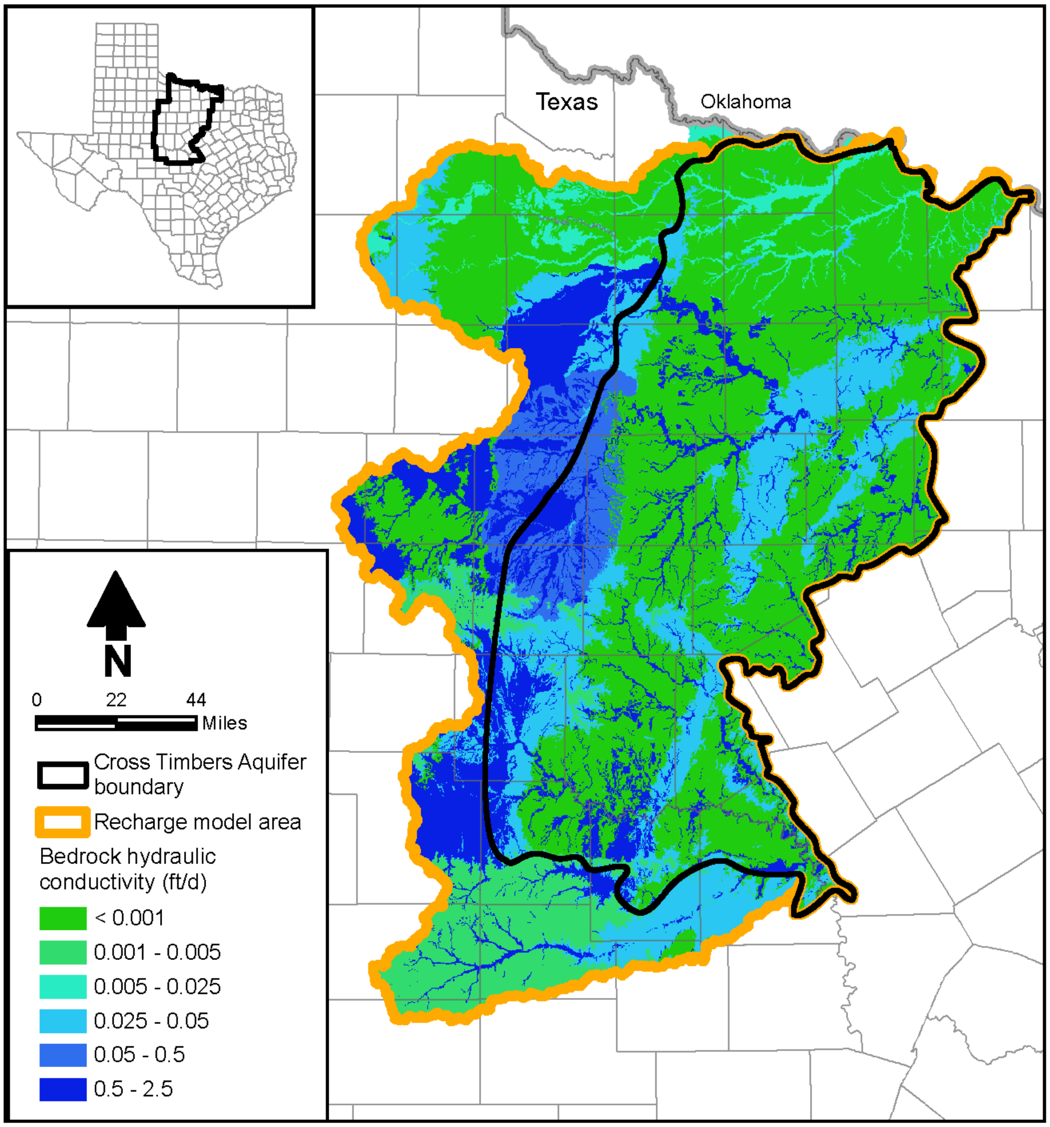


Figure 7-6. Final bedrock hydraulic conductivity used the Distributed Parameter Watershed Model simulations.

7.2.5. Simulation Results

Figures of the final Distributed Parameter Watershed Model recharge estimates compared to estimated base flow at the 22 selected stream gauges are provided in Appendix B. Figures 7-7 through 7-10 are example comparisons for gauges in the Little Wichita, Middle Brazos-Millers, Middle Colorado, and San Saba sub-basins, respectively. Most gauges show reasonable agreement between observed base flow and simulated recharge volumes in terms of magnitude and timing, particularly given that (1) estimated base flows have some inherent uncertainty because they are based on an imperfect analysis of total stream flow and (2) watershed model adjustments were kept to a small number of model inputs.

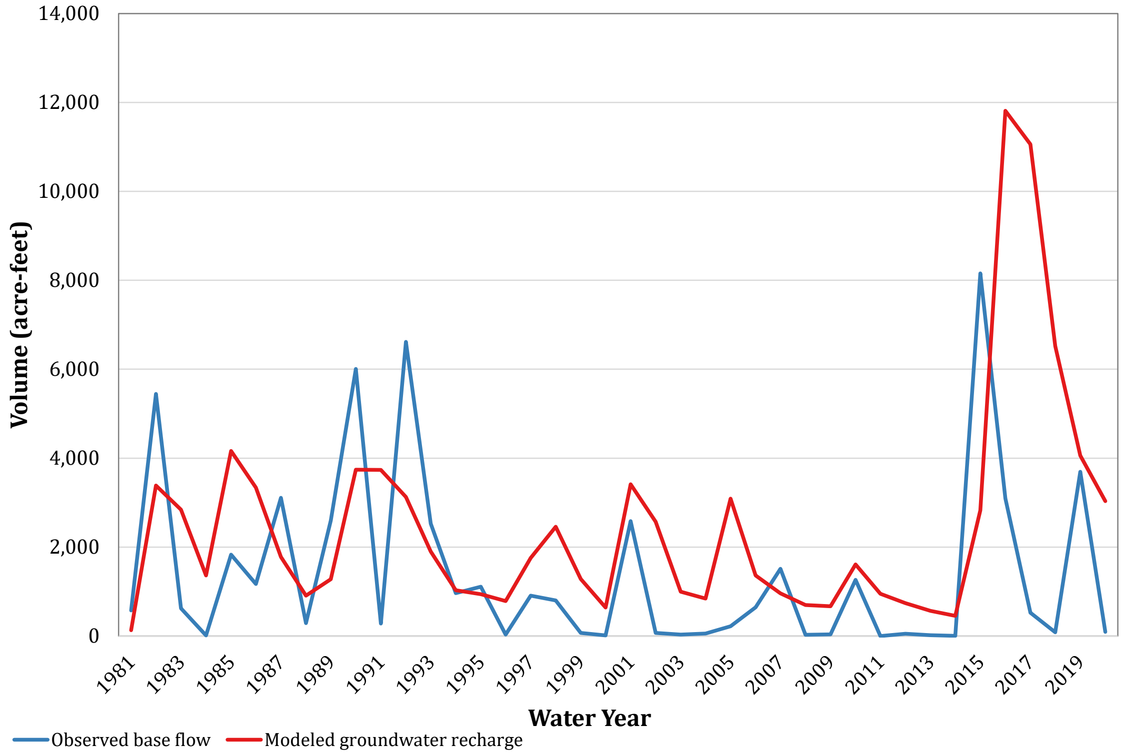


Figure 7-7. **Comparison of recharge simulation results to observed base flow for gauge 07315200 (Little Wichita).**

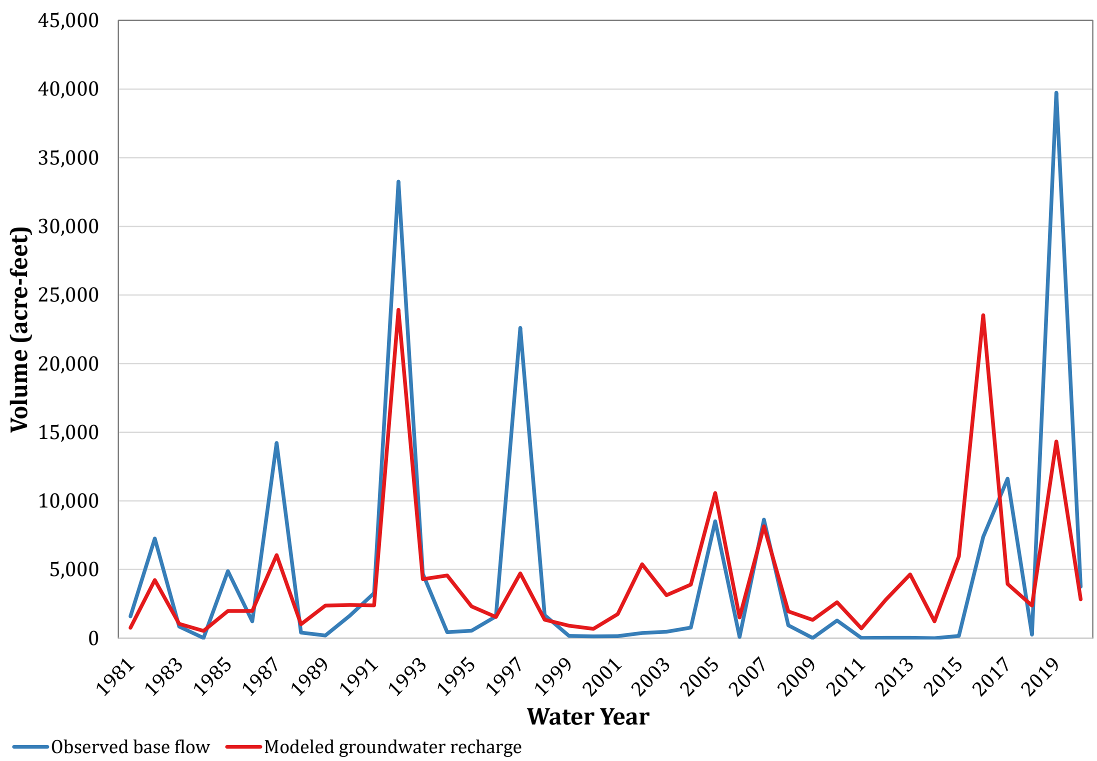


Figure 7-8. **Comparison of recharge simulation results to observed base flow for gauge 08086212 (Middle Brazos-Millers).**

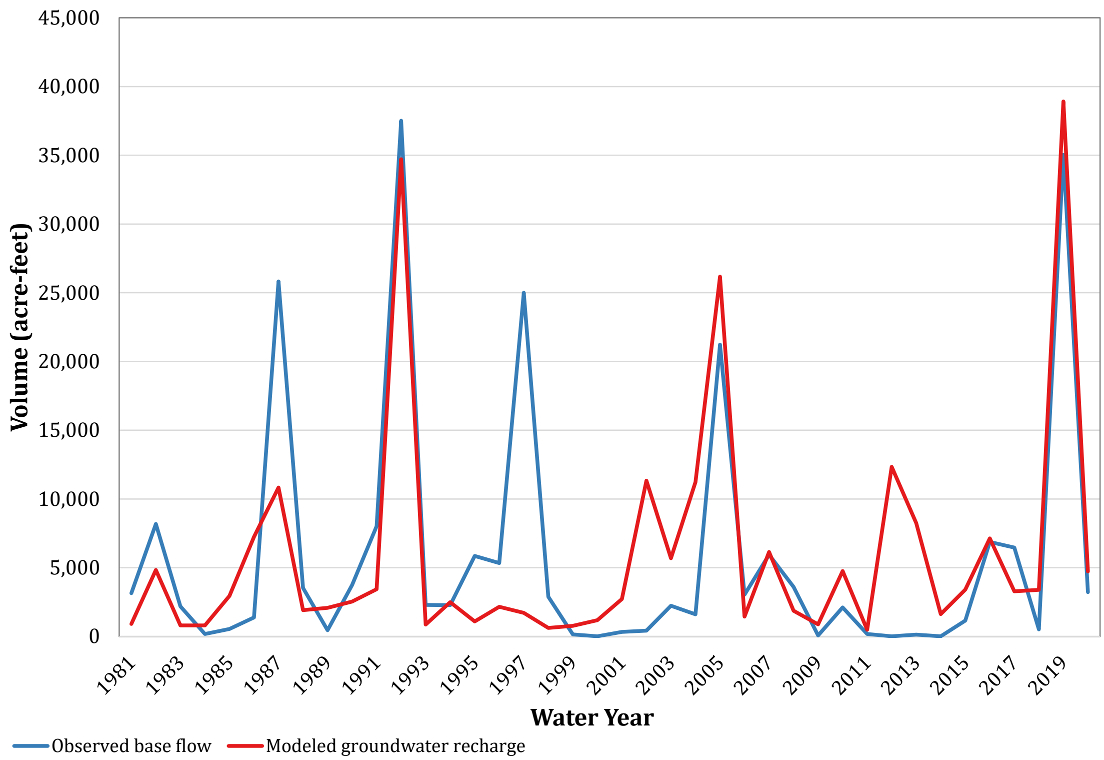


Figure 7-9. Comparison of recharge simulation results to observed base flow for gauge 08127000 (Middle Colorado).

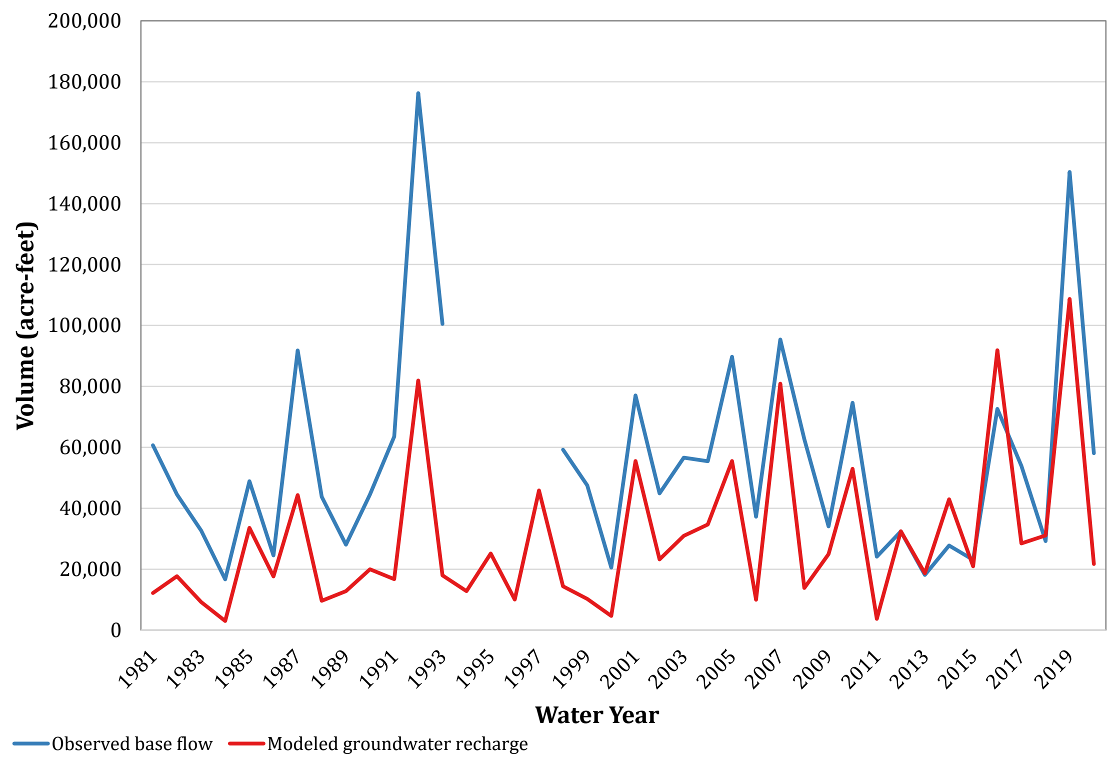


Figure 7-10. Comparison of recharge simulation results to observed base flow for gauge 08146000 (San Saba).

The final estimated groundwater recharge is presented for mean annual conditions (i.e., 1981 through 2020), example "dry" conditions (water year 2011), and example "wet" conditions (water year 2016). Figure 7-11 illustrates mean annual precipitation over the watershed model study area and Figure 7-12 presents the mean simulated recharge. As indicated in Figure 7-12, higher recharge generally occurs where soil hydraulic conductivity and bedrock hydraulic conductivity are highest, as would be expected. In addition, higher rates of recharge occur along drainages because (1) the drainages occur in alluvial sediments (bedrock at those locations), which has high permeability, and (2) storm flows are collected in the drainages and provide water to be recharged.

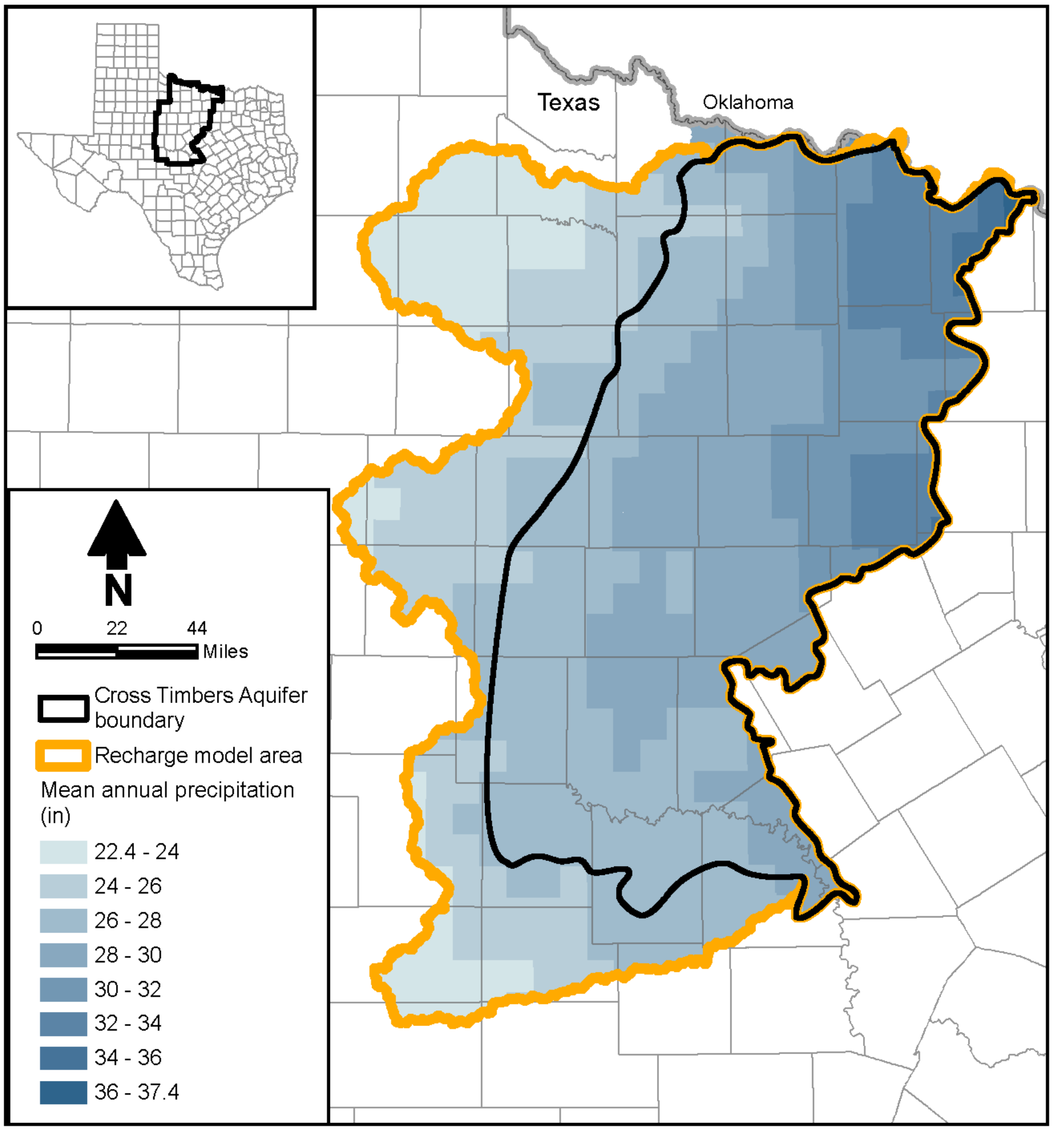


Figure 7-11. Mean annual precipitation 1981 through 2020 used in Distributed Parameter Watershed Model simulations.

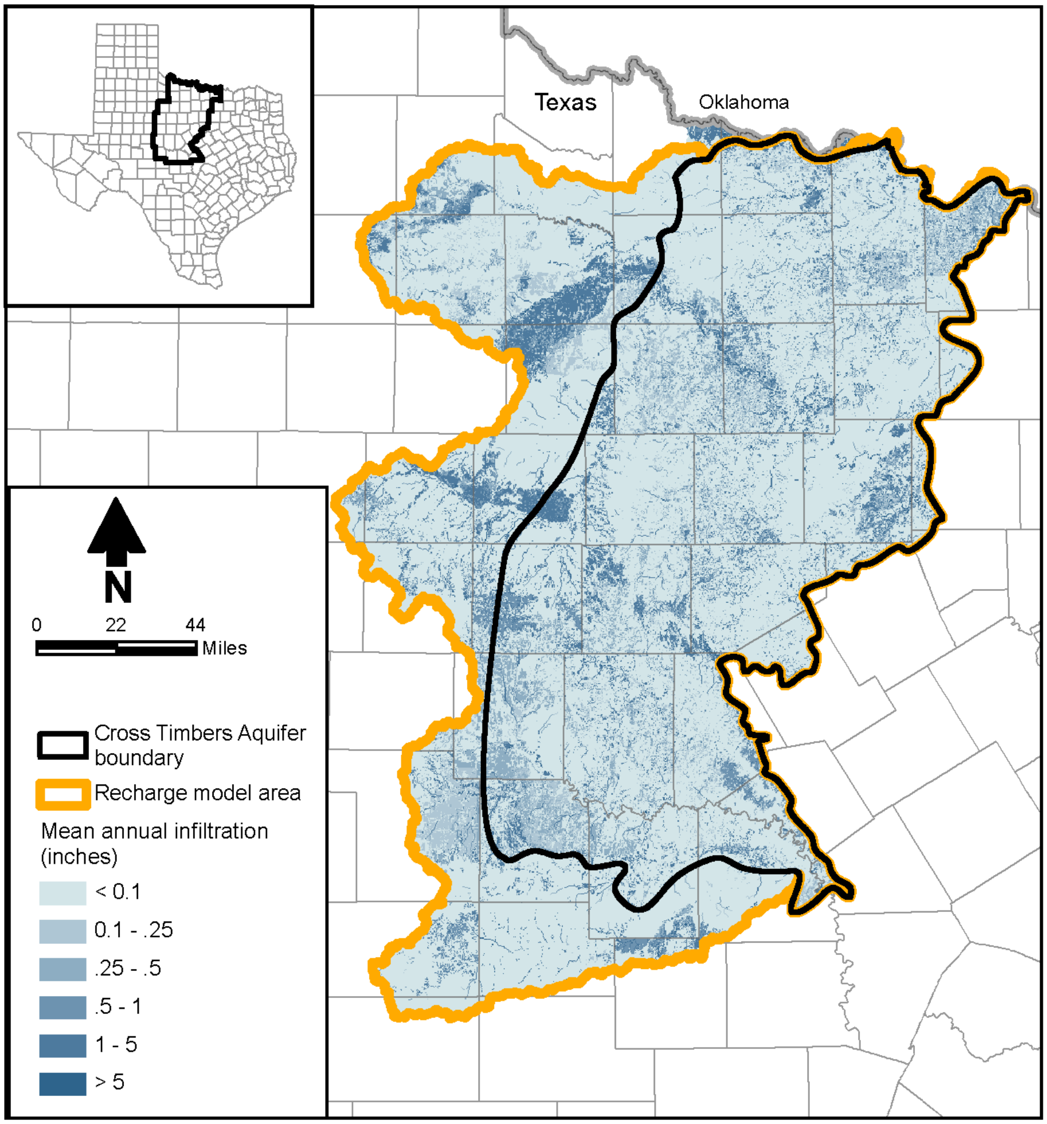


Figure 7-12. Mean annual simulated recharge, 1981 through 2020.

Table 7-1 provides the mean annual precipitation amounts and recharge by sub-basin. As indicated in the table, the mean annual recharge ranges from 0.19 to 0.45 inch per year, or about 0.73 to 1.62 percent of average annual precipitation. Note that the values provided in the first three columns of Table 7-1 are for the entire watershed model area, including streams that occur in alluvium filled valleys and drainages. However, the majority of water that infiltrates into alluvium likely discharges farther downstream and never enters the underlying Paleozoic (Cross Timbers Aquifer) rocks. To approximate recharge to the Paleozoic rocks only, recharge at the watershed model cells that have alluvium as the bedrock type were subtracted from the computations; these recharge numbers are provided in the last two columns of Table 7-1. As indicated in the table, using this approach, the mean annual recharge ranges from 0.16 to 0.32 inch per year, or about 0.62 to 1.18 percent of average annual precipitation.

Table 7-1. Simulated mean annual recharge for 1981 through 2020.

Sub-basin	Precipitation (inches)	Recharge (inches)	Percent of Average Annual Precipitation	Recharge Excluding Alluvium (inches)	Percent of Average Annual Precipitation
Little Wichita, Upper Clear Fork-Brazos	27.68	0.35	1.28	0.22	0.81
Middle Brazos-Millers	27.45	0.45	1.62	0.32	1.18
Middle Brazos-Palo Pinto	30.91	0.33	1.06	0.25	0.80
Middle Colorado	27.25	0.33	1.21	0.28	1.03
San Saba	25.47	0.19	0.73	0.16	0.62
Upper Clear Fork-Brazos	25.83	0.36	1.38	0.31	1.19

Figure 7-13 illustrates the annual precipitation over the watershed model study area for the year 2011, and Figure 7-14 presents the simulated recharge. Comparison of Figures 7-14 and 7-12 illustrates the significantly reduced recharge due to the dry conditions.

Table 7-2 provides the annual precipitation amounts and recharge corresponding recharge estimates by sub-basin for 2011. As indicated in the table, the estimates recharge rate for this dry year from 0.22 to 0.11 inch per year, or about 0.27 to 1.25 percent of average annual precipitation. If recharge to the alluvium is subtracted out, all simulated recharge rates are on the order of hundredths of an inch, and less than 1 percent of the annual precipitation.

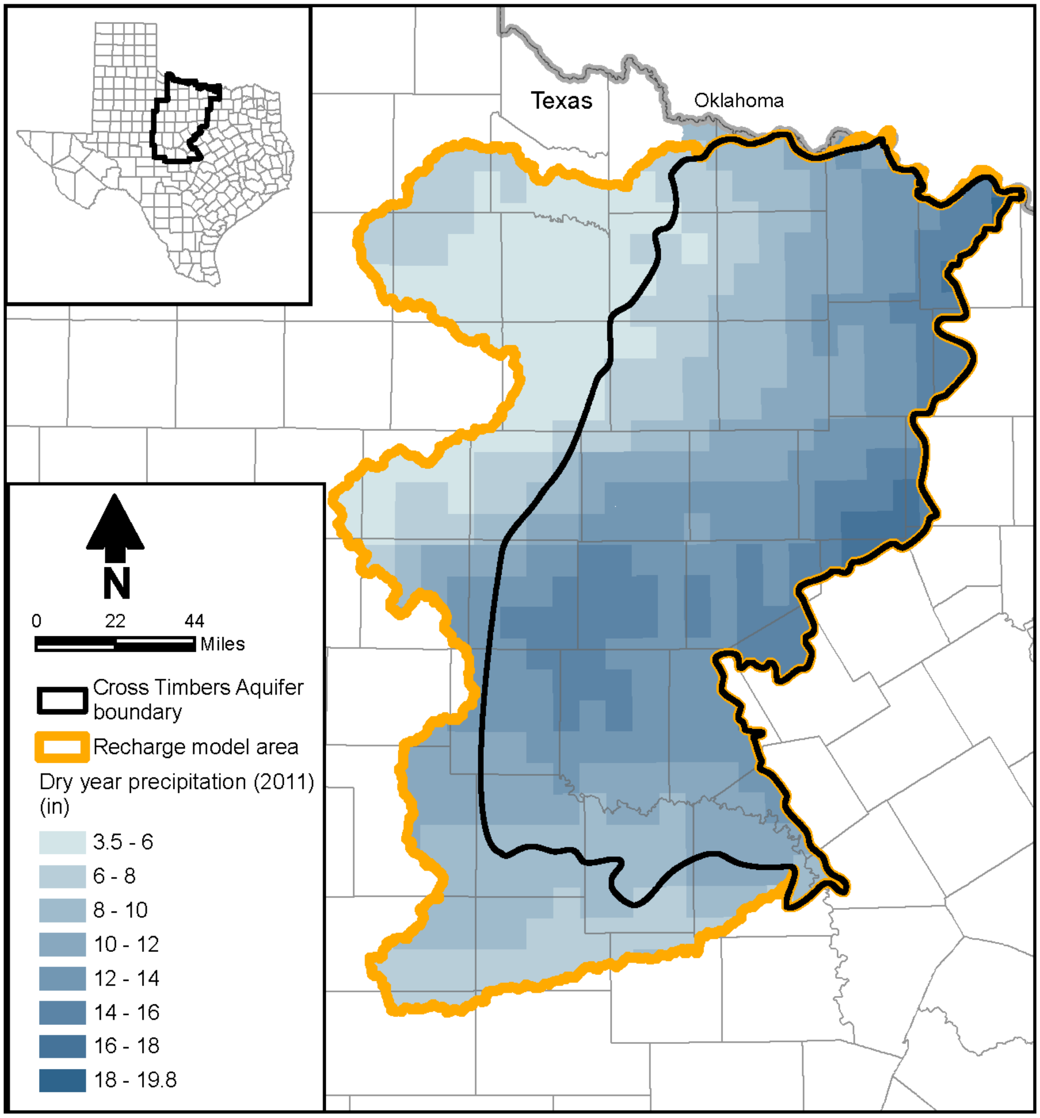


Figure 7-13. Dry year (2011) annual precipitation used in Distributed Parameter Watershed Model simulations.

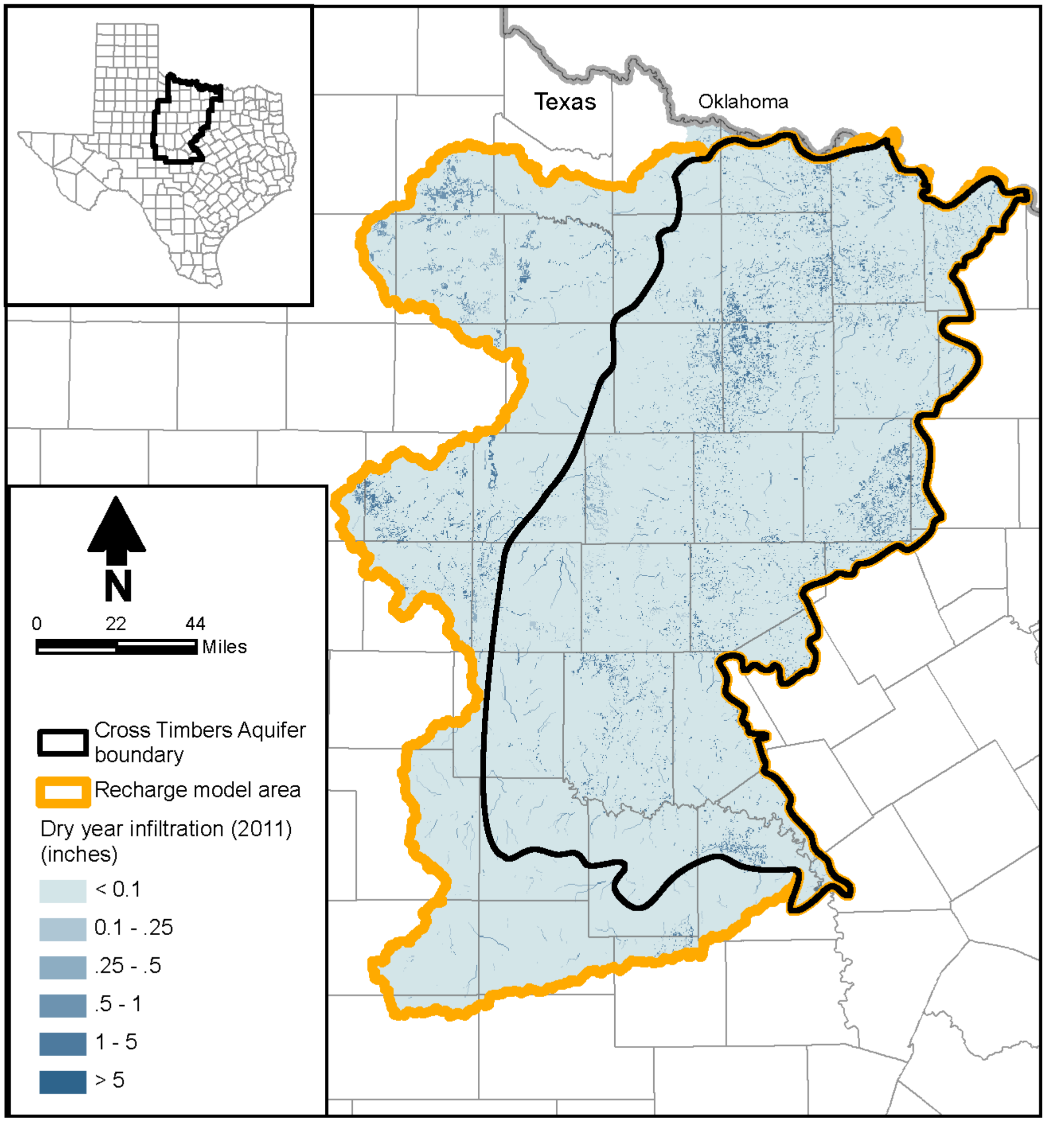


Figure 7-14. Dry year (2011) simulated annual recharge.

Table 7-2. Simulated recharge for dry year (2011) conditions.

Sub-basin	Precipitation (inches)	Recharge (inches)	Percent of Average Annual Precipitation	Recharge Excluding Alluvium (inches)	Percent of Average Annual Precipitation
Little Wichita, Upper Clear Fork-Brazos	8.59	0.11	1.25	0.06	0.75
Middle Brazos-Millers	8.57	0.07	0.87	0.06	0.75
Middle Brazos-Palo Pinto	13.47	0.09	0.69	0.08	0.58
Middle Colorado	11.93	0.06	0.46	0.04	0.36
San Saba	8.25	0.02	0.27	0.02	0.23
Upper Clear Fork-Brazos	8.36	0.06	0.70	0.05	0.57

Figure 7-15 illustrates the annual precipitation over the watershed model study area for the year 2016 and Figure 7-16 presents the simulated recharge. Comparison of Figures 7-16 and 7-12 illustrates the increased recharge due to the wet conditions.

Table 7-3 provides the annual precipitation amounts and recharge corresponding recharge estimates by sub-basin for 2016. As indicated in the table, the estimates recharge rate for this wet year from 0.56 to 1.2 inches per year, or about 1.42 to 2.84 percent of average annual precipitation. If recharge to the alluvium is subtracted out, all simulated recharge rates are less than 1 inch per year.

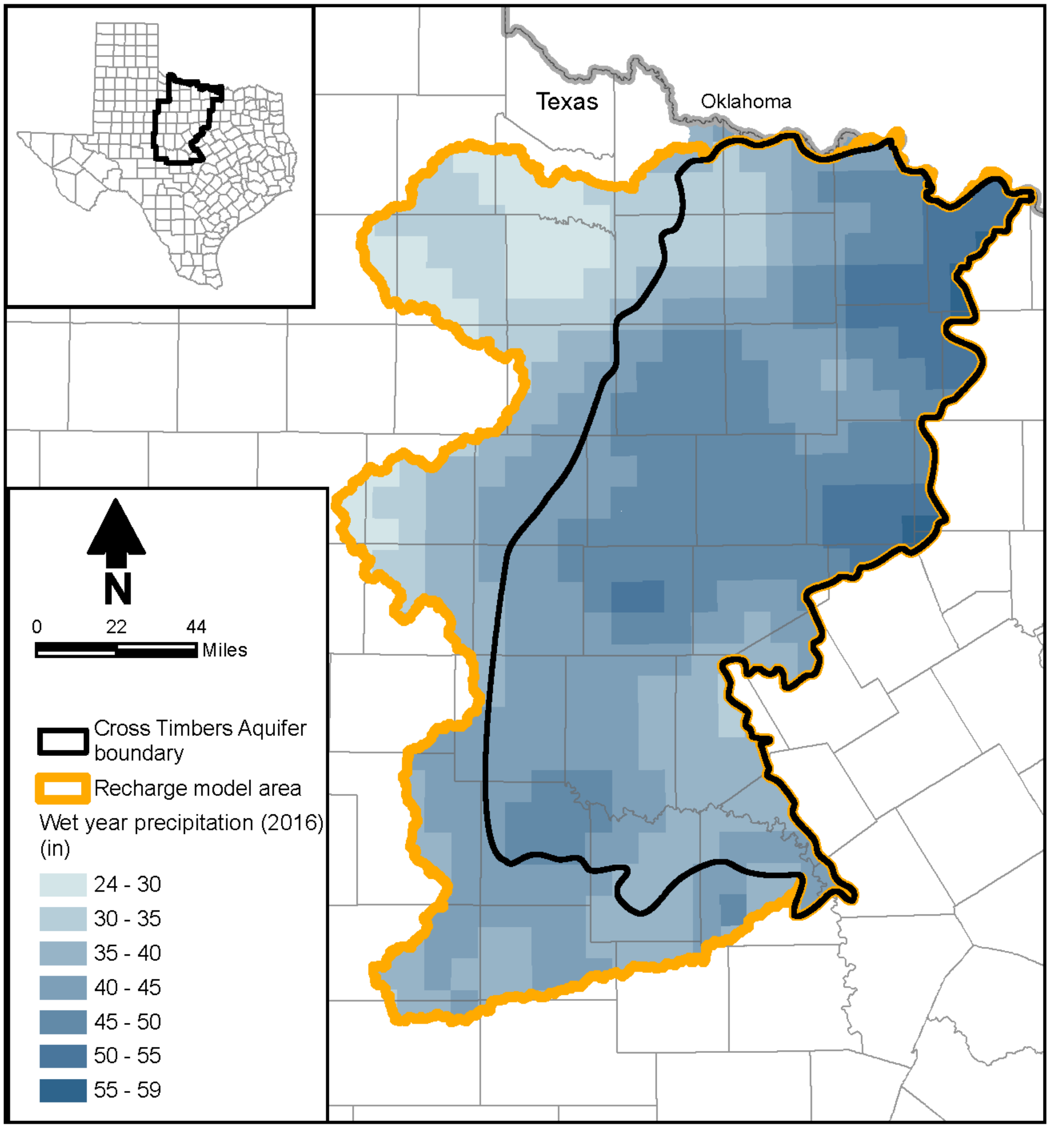


Figure 7-15. Wet year (2016) annual precipitation used in Distributed Parameter Watershed Model simulations.

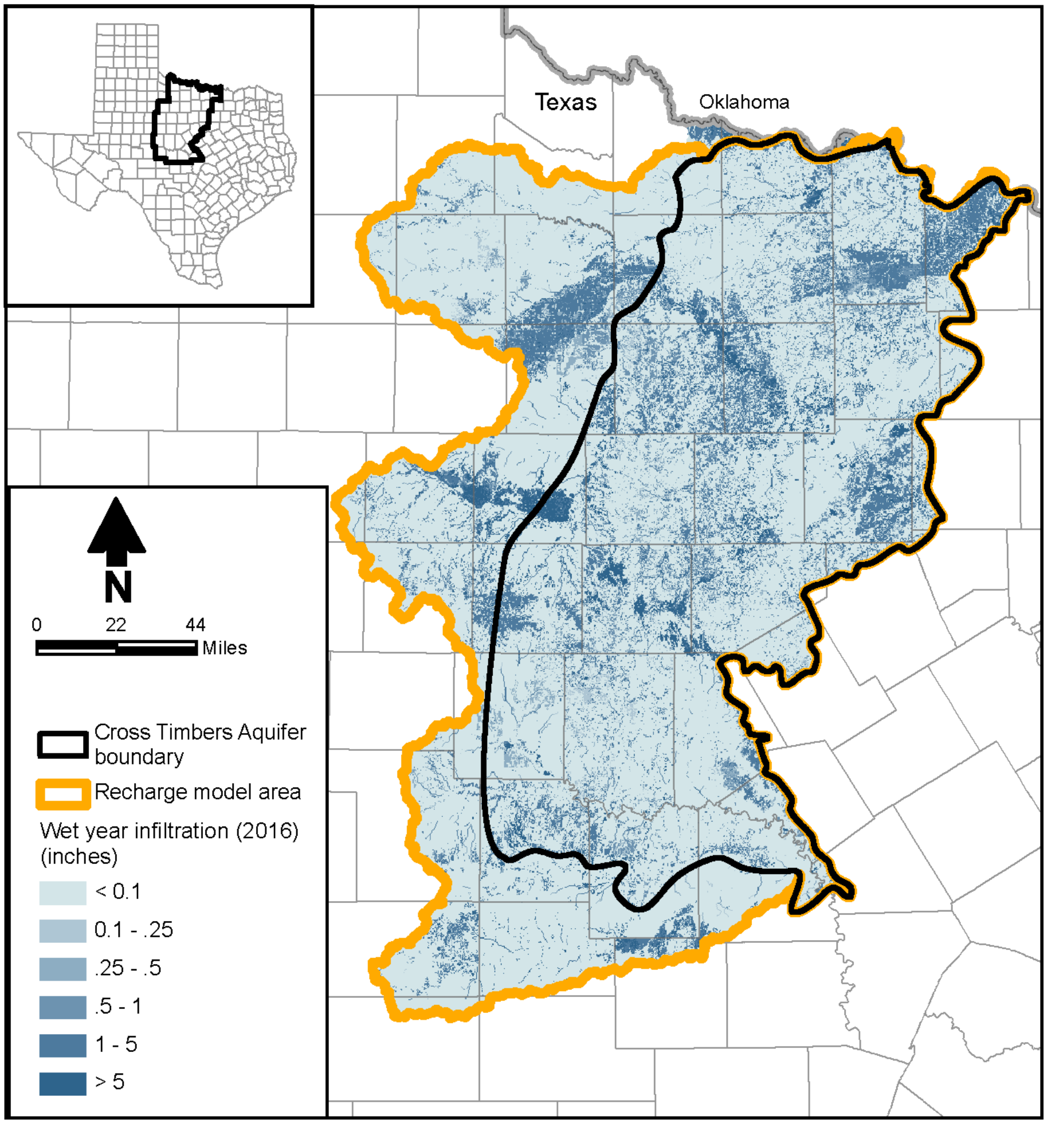


Figure 7-16. Wet year (2016) simulated annual recharge.

Table 7-3. Simulated recharge for wet year (2016) conditions.

Sub-basin	Precipitation (inches)	Recharge (inches)	Percent of Average Annual Precipitation	Recharge Excluding Alluvium (inches)	Percent of Average Annual Precipitation
Little Wichita, Upper Clear Fork-Brazos	37.08	0.75	2.03	0.53	1.43
Middle Brazos-Millers	42.29	1.20	2.84	0.92	2.18
Middle Brazos-Palo Pinto	47.21	0.95	2.02	0.74	1.56
Middle Colorado	41.56	0.62	1.48	0.53	1.28
San Saba	39.71	0.56	1.42	0.49	1.24
Upper Clear Fork-Brazos	39.47	0.94	2.38	0.85	2.16

The estimates of recharge made using the Distributed Parameter Watershed Model are within the range of values estimated by others working in adjoining regions using a variety of methods, as summarized at the beginning of this section.

8. Surface Water Features

The Cross Timbers Aquifer study area encompasses portions of the watersheds of the Red, Trinity, Brazos, and Colorado Rivers (Figure 8-1); each of these river systems is a major perennial stream. In addition, 34 significant reservoirs also occur within the study area (Figure 8-1). The reservoirs are an important source of public water supply for populations inside, and in some cases outside, the study area. For example, O.H. Ivie Reservoir supplies water for the Colorado River Municipal Water District, which has member cities west of the study area.

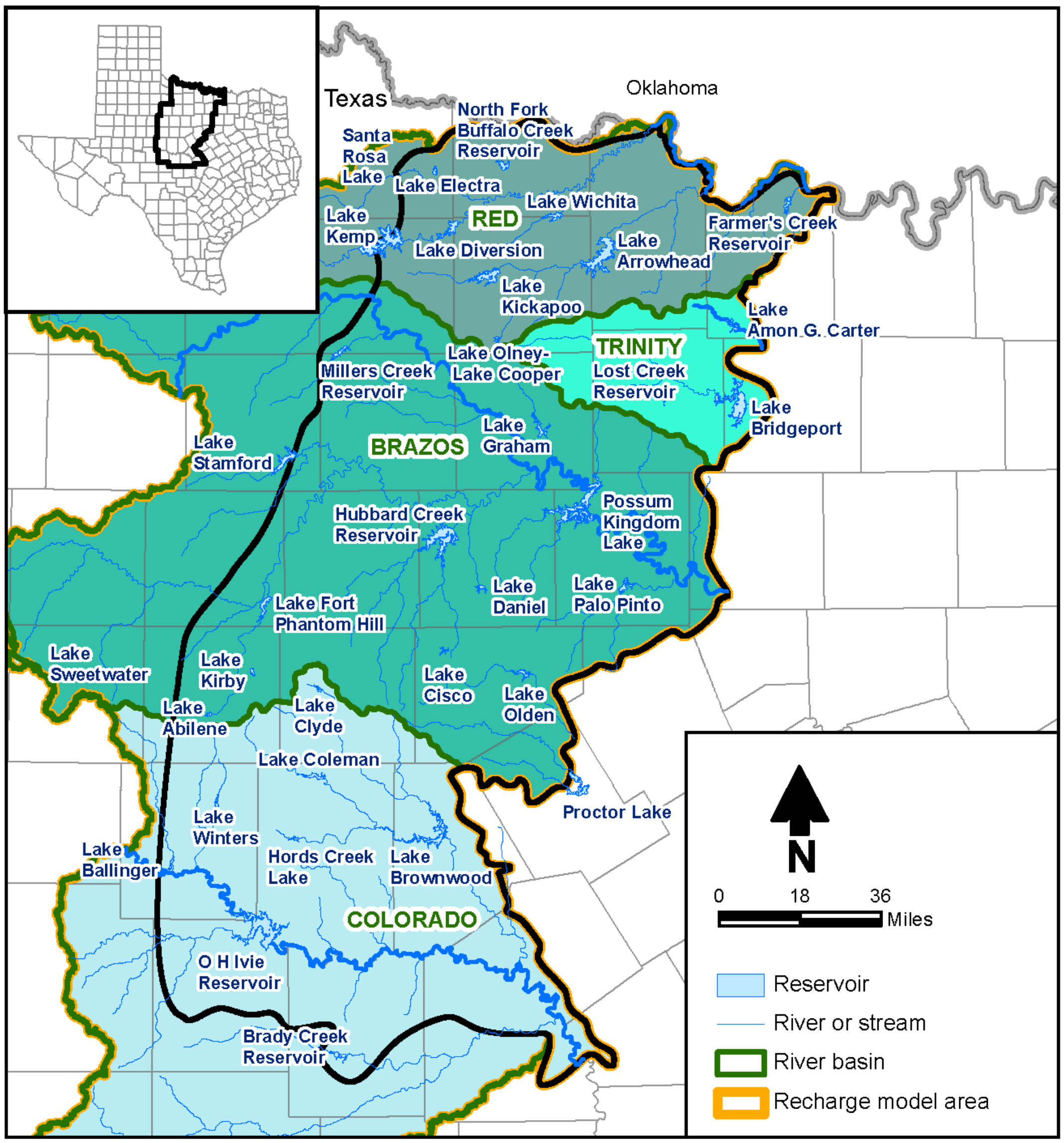


Figure 8-1. Significant reservoirs in the study area.

A list of the reservoirs with some summary information developed from the 2012 State Water Plan (TWDB, 2012) is provided in Table 8-1. Dates of reservoir impoundment range from 1901 to 1991. Figure 8-2 provides the change in volume and stage for several of the reservoirs in the region. Impoundment of the reservoirs and changes in reservoir stage will affect groundwater levels in the vicinity of each reservoir.

Table 8-1. Major reservoirs within the Cross Timbers Aquifer study area.

Reservoir Name	Type	River Basin	Year Impounded	2010 Firm Yield (acre-feet)	Full Capacity (acre-feet)
Brady Creek Reservoir	Water supply	Colorado	1963	0	30,430
Farmer's Creek Reservoir	Water supply	Red	1960	1,260	26,000
Hords Creek Lake	Water supply	Colorado	1948	0	8,640
Hubbard Creek Reservoir	Water supply	Brazos	1962	27,708	317,750
Lake Abilene	Water supply	Brazos	1921	1,141	7,900
Lake Amon G Carter	Water supply	Trinity	1956	2,107	20,050
Lake Arrowhead	Water supply	Red	1966	26,000	262,100
Lake Ballinger / Lake Moonen	Water supply	Colorado	1984	30	6,850
Lake Bridgeport	Water supply	Trinity	1931	System Operation	386,420
Lake Brownwood	Water supply	Colorado	1933	47,200	149,925
Lake Cisco	Water supply	Brazos	1923	1,138	26,000
Lake Clyde	Water supply	Colorado	1970	500	5,748
Lake Coleman	Water supply	Colorado	1966	5	40,000
Lake Daniel	Water supply	Brazos	1948	230	9,515
Lake Diversion	Water supply	Red	1924	System Operation	40,000
Lake Electra	Water supply	Red	1950	462	8,730
Lake Fort Phantom Hill	Water supply	Brazos	1938	11,816	74,310
Lake Graham	Water supply	Brazos	1958	5,335	53,680
Lake Kemp	Water supply	Red	1923	100,983	319,600
Lake Kickapoo	Water supply	Red	1945	19,800	106,000
Lake Kirby	Water supply	Brazos	1928	533	7,620
Lake Leon	Water supply	Brazos	1954	5,938	27,290
Lake Mineral Wells	Water supply	Brazos	1920	2,508	6,760
Lake Olney / Lake Cooper	Water supply	Red	1935	960	6,650
Lake Palo Pinto	Water supply	Brazos	1964	9,658	44,100
Lake Stamford	Water supply	Brazos	1953	5,667	57,632
Lake Wichita	Water supply	Red	1901	System Operation	14,000
Lake Winters/New Lake Winters	Water supply	Colorado	1983	0	8,374
Lost Creek Reservoir	Water supply	Trinity	1991	1,597	11,961
Millers Creek Reservoir	Water supply	Brazos	1974	50	33,000
North Fork Buffalo Creek Reservoir	Water supply	Red	1964	840	15,400
O H Ivie Reservoir	Water supply	Colorado	1989	85,150	554,340
Possum Kingdom Lake	Water supply	Brazos	1941	230,750	724,739
Proctor Lake	Water supply	Brazos	1963	19,467	59,400

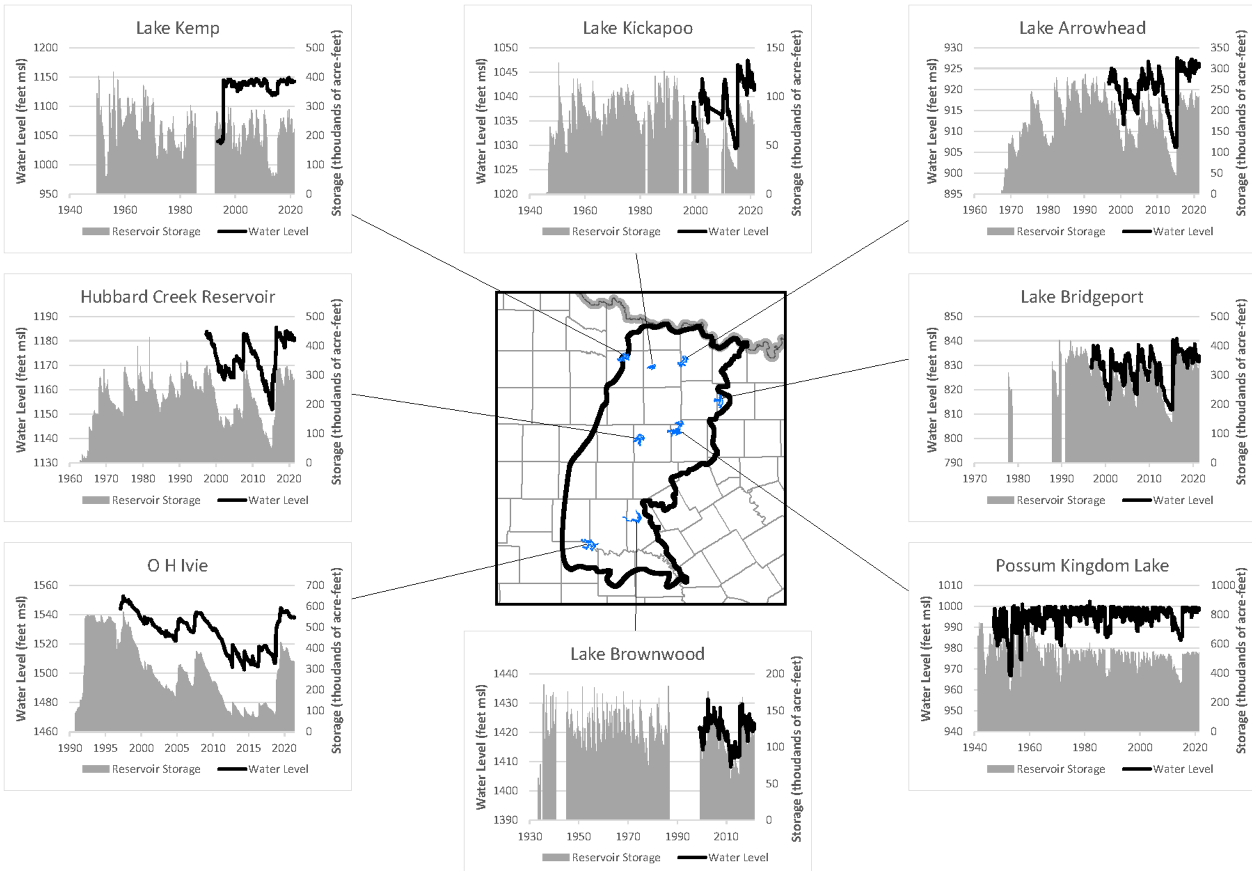


Figure 8-2. Change in volume and stage for selected reservoirs in the region.

8.1. Base Flow Analysis

In developing an understanding the Cross Timbers Aquifer groundwater system, the primary item of interest relative to surface water is the groundwater/surface water interaction. To assist with this, the stream flow records for stream gauges within the study area were analyzed to assess base flow using the U.S. Geological Survey code HYSEP, which implements the method developed by Pettyjohn and Henning (1979). Base flow separation was done using the local minimum method available in HYSEP. The gauges analyzed for base flow are plotted in Figure 8-3, and summary information about the analysis is provided in Table 8-2.

The stream gauges selected for comparison of recharge model results are also identified in Figure 8-3. As discussed in Section 7, these gauges are upstream of major reservoirs, except for gauge 8143600 in Mills County, which is a significant distance downstream of Lake Brownwood. The locations of the gauges relative to reservoirs are shown in Figure 8-3. An example of the HYSEP analysis is provided in Figure 8-4.

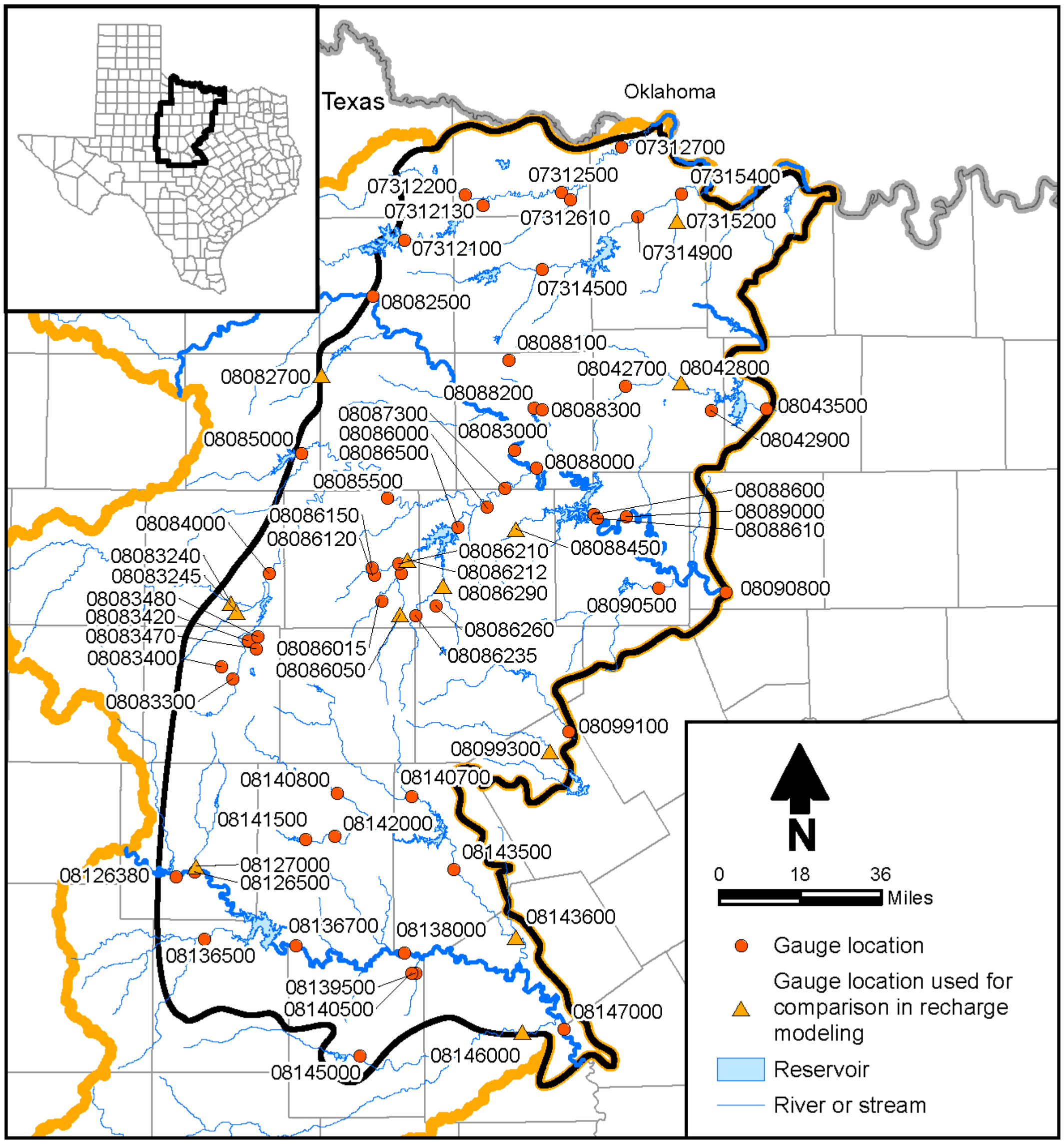


Figure 8-3. Stream gauges selected for comparison of recharge model results.

Table 8-2. Summary of annual base flow.

USGS Site No.	USGS Site Name	Annual Base Flow (acre-feet)				Years of Complete Data	% Days with Flow	Remark
		Mean	Median	Minimum	Maximum			
07312100	Wichita Rv nr Mabelle, TX	37,636	31,429	516	145,436	61	100.00%	Downstream from dam/structure
07312130	Wichita Rv at SH 25 nr Kamay, TX	5,423	4,624	1,552	11,885	6	100.00%	Downstream from dam/structure
07312200	Beaver Ck nr Electra, TX	7,252	4,448	83	36,265	60	98.51%	Downstream from dam/structure
07312500	Wichita Rv at Wichita Falls, TX	68,481	46,762	4,212	346,212	82	100.00%	Downstream from dam/structure
07312610	Holliday Ck at Wichita Falls, TX	2,418	1,262	93	8,780	10	95.26%	Downstream from dam/structure
07312700	Wichita Rv nr Charlie, TX	90,088	73,554	12,051	311,146	51	100.00%	Downstream from dam/structure
07314500	Little Wichita Rv nr Archer City, TX	2,997	265	12	77,485	64	63.61%	Downstream from dam/structure
07314900	Little Wichita Rv abv Henrietta, TX	5,499	276	1	118,177	67	37.57%	Downstream from dam/structure
07315200	E Fk Little Wichita Rv nr Henrietta, TX	1,192	552	1	8,155	56	62.51%	Comparison point
07315400	Little Wichita Rv nr Ringgold, TX	1,533	1,088	743	3,641	6	74.03%	Before 1981 only
08042700	North Ck nr Jacksboro, TX	183	41	1	1,600	24	36.92%	Before 1981 only
08042800	W Fk Trinity Rv nr Jacksboro, TX	7,518	1,406	0	75,882	64	69.99%	Comparison point
08042900	Beans Ck at Wizard Wells, TX	13,947	13,947	13,947	13,947	1	91.63%	Three or fewer years of data
08043500	W Fk Trinity Rv at Bridgeport, TX	5,883	4,239	326	16,336	5	82.58%	Before 1981 only
08082500	Brazos Rv at Seymour, TX	36,431	27,434	662	207,362	96	91.42%	Drainage area covers multiple basins
08082700	Millers Ck nr Munday, TX	265	15	0	3,533	57	29.94%	Comparison point
08083000	Brazos Rv nr Graham, TX	3,098	3,098	366	5,830	2	74.13%	Before 1981 only
08083240	Clear Fk Brazos Rv at Hwy 83 nr Hawley, TX	13,415	8,865	1,437	52,986	26	49.25%	Comparison point
08083245	Mulberry Ck nr Hawley, TX	812	296	3	5,271	21	60.00%	Comparison point
08083300	Elm Ck nr Abilene, TX	1,943	680	15	15,095	16	54.95%	Before 1981 only
08083400	Little Elm Ck nr Abilene, TX	93	15	0	885	16	20.89%	Before 1981 only
08083420	Cat Claw Ck at Abilene, TX	74	64	1	225	28	16.27%	Downstream from dam/structure
08083470	Cedar Ck at Abilene, TX	682	174	36	6,351	14	84.83%	Downstream from dam/structure

Table 8-2 (continued)

USGS Site No.	USGS Site Name	Annual Base Flow (acre-feet)				Years of Complete Data	% Days with Flow	Remark
		Mean	Median	Minimum	Maximum			
08083480	Cedar Ck at IH 20, Abilene, TX	797	195	2	5,271	19	73.38%	Downstream from dam/structure
08084000	Clear Fk Brazos Rv at Nugent, TX	11,990	6,893	78	117,582	96	96.05%	Downstream from dam/structure
08085000	Paint Ck nr Haskell, TX	2,629	2,629	2,629	2,629	1	33.39%	Before 1981 only
08085500	Clear Fk Brazos Rv at Ft Griffin, TX	24,972	11,671	246	289,720	96	88.68%	Drainage area covers multiple basins
08086000	Clear Fk Brazos Rv at Crystal Falls, TX	12,377	9,071	3,010	28,357	4	72.93%	Before 1981 only
08086015	Hubbard Ck nr Sedwick, TX	329	6	2	979	3	14.27%	Before 1981 only
08086050	Deep Ck at Moran, TX	1,686	219	1	22,190	30	37.67%	Comparison point
08086100	Hubbard Ck nr Albany, TX	2,096	317	6	10,983	13	48.11%	Before 1981 only
08086120	Salt Prong Hubbard Ck at US Hwy 380 nr Albany, TX	505	74	26	1,910	5	45.07%	Before 1981 only
08086150	N Fk Hubbard Ck nr Albany, TX	710	395	54	4,161	27	95.98%	Small drainage area
08086210	Snailum Ck nr Albany, TX	125	112	22	241	3	14.55%	Before 1981 only
08086212	Hubbard Ck bl Albany, TX	4,321	886	1	39,741	54	70.03%	Comparison point
08086235	Battle Ck nr Moran, TX	1,285	1,285	9	2,561	2	42.31%	Before 1981 only
08086260	Pecan Ck nr Eolian, TX	143	46	0	657	9	34.58%	Before 1981 only
08086290	Big Sandy Ck abv Breckenridge, TX	953	103	0	22,483	58	61.86%	Comparison point
08086500	Hubbard Ck nr Breckenridge, TX	2,898	75	3	25,667	31	62.63%	Downstream from dam/structure
08087300	Clear Fk Brazos Rv at Eliasville, TX	27,859	14,007	595	145,662	47	67.44%	Drainage area covers multiple basins
08088000	Brazos Rv nr South Bend, TX	103,842	71,193	3,025	734,482	78	92.82%	Drainage area covers multiple basins
08088100	Salt Ck at Olney, TX	58	38	1	238	19	39.66%	Before 1981 only
08088200	Salt Ck nr Newcastle, TX	70	70	50	91	2	32.24%	Before 1981 only
08088300	Briar Ck nr Graham, TX	137	35	0	1,373	31	26.37%	Small drainage area
08088450	Big Cedar Ck nr Ivan, TX	224	50	1	1,208	24	58.01%	Comparison point

Table 8-2 (continued)

USGS Site No.	USGS Site Name	Annual Base Flow (acre-feet)				Years of Complete Data	% Days with Flow	Remark
		Mean	Median	Minimum	Maximum			
08088600	Brazos Rv at Morris Sheppard Dam nr Graford, TX	87,260	49,166	18,149	466,295	19	100.00%	Downstream from dam/structure
08088610	Brazos Rv nr Graford, TX	97,117	62,678	20,454	505,749	30	96.82%	Downstream from dam/structure
08089000	Brazos Rv nr Palo Pinto, TX	122,618	82,628	17,047	614,058	95	97.98%	Drainage area covers multiple basins
08090500	Palo Pinto Ck nr Santo, TX	4,424	1,919	1	17,585	26	36.76%	Before 1981 only
08090800	Brazos Rv nr Dennis, TX	161,012	112,713	17,323	816,002	49	94.28%	Drainage area covers multiple basins
08099100	Leon Rv nr De Leon, TX	3,389	1,206	0	24,121	39	41.73%	Downstream from dam/structure
08099300	Sabana Rv nr De Leon, TX	2,006	1,396	2	7,560	47	60.83%	Comparison point
08126380	Colorado Rv nr Ballinger, TX	16,688	9,551	81	149,990	113	94.34%	Drainage area covers multiple basins
08126500	Colorado Rv at Ballinger, TX	18,199	12,430	81	70,308	72	93.58%	Before 1981 only
08127000	Elm Ck at Ballinger, TX	4,499	1,964	3	37,514	88	63.73%	Comparison point
08136500	Concho Rv at Paint Rock, TX	18,250	15,160	71	194,092	105	92.21%	Drainage area covers multiple basins
08136700	Colorado Rv nr Stacy, TX	28,637	12,130	1,155	282,733	52	97.76%	Downstream from dam/structure
08138000	Colorado Rv at Winchell, TX	46,597	28,002	452	304,267	77	85.53%	Drainage area covers multiple basins
08139500	Deep Ck nr Mercury, TX	324	22	0	3,033	20	17.71%	Before 1981 only
08140500	Dry Prong Deep Ck nr Mercury, TX	162	24	0	1,222	20	14.62%	Before 1981 only
08140700	Pecan Bayou nr Cross Cut, TX	3,993	1,086	11	19,395	10	13.68%	Before 1981 only
08140800	Jim Ned Ck nr Coleman, TX	3,429	172	0	15,510	15	32.27%	Before 1981 only
08141500	Hords Ck nr Valera, TX	296	77	1	2,577	43	54.83%	Downstream from dam/structure
08142000	Hords Ck nr Coleman, TX	817	130	0	4,197	35	21.58%	Downstream from dam/structure
08143500	Pecan Bayou at Brownwood, TX	17,429	5,831	115	89,710	58	86.54%	Downstream from dam/structure
08143600	Pecan Bayou nr Mullin, TX	23,023	8,250	475	248,913	53	96.64%	Comparison point
08145000	Brady Ck at Brady, TX	977	107	1	13,327	66	50.29%	Downstream from dam/structure

Table 8-2 (continued)

USGS Site No.	USGS Site Name	Annual Base Flow (acre-feet)				Years of Complete Data	% Days with Flow	Remark
		Mean	Median	Minimum	Maximum			
08146000	San Saba Rv at San Saba, TX	62,532	56,605	10,393	176,272	101	95.84%	Comparison point
08147000	Colorado Rv nr San Saba, TX	165,596	122,581	19,847	679,695	101	98.55%	Drainage area covers multiple basins

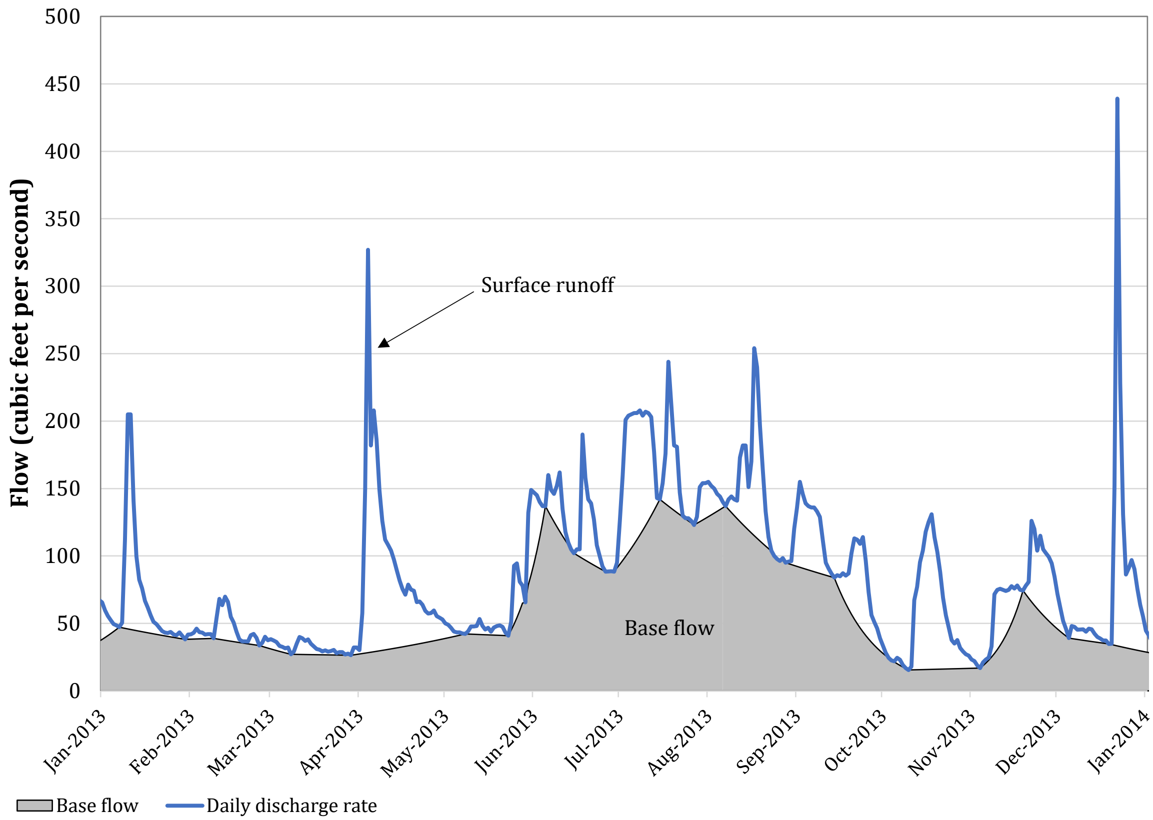


Figure 8-4. Example of HYSEP base flow analysis (gauge 08090800).

It should be noted that stream routing analysis was not conducted during this study; therefore, for gauges downstream of reservoirs, the amount of water attributable to reservoir releases is not accounted for. Consequently, the base flow amounts provided for these gauges should be viewed with caution, but the information is provided to give an idea of the magnitude of typical stream flows (not flood flows) that occur through the region.

As indicated in Table 8-2, a number of the gauges have recorded flow less than 100 percent of the time. Even for days that surface flow is not occurring at the gauge, subflow (shallow groundwater flow) will occur in the high permeability alluvium beneath the stream channels. For the recharge model comparison gauges, the months with the least days of flow are typically July, August, and September, and this pattern occurs at a number of other gauges as well. This result is not surprising, as water losses through evapotranspiration will be highest during the summer period. In drainages and tributaries where there is consistent flow for a portion of the year, the water table likely occurs near the base of the stream bed, and rises to form base flow during wet periods or during the winter months when evapotranspiration is reduced.

8.2. Springs

A total of 51 springs were identified as emanating from the Cross Timbers Aquifer; 50 were identified from the TWDB groundwater database and 1 was identified in Heitmuller and Reece (2003). The spring locations are shown in Figure 8-5. Available information on spring discharge and other noteworthy comments are summarized in Table 8-3. None of the springs have large flow rates; most seem to be perennial, but some are noted as wet weather springs. Spring 2145201 in Throckmorton County is noted to have begun flowing in 1960, which would indicate a rising water table at that location.

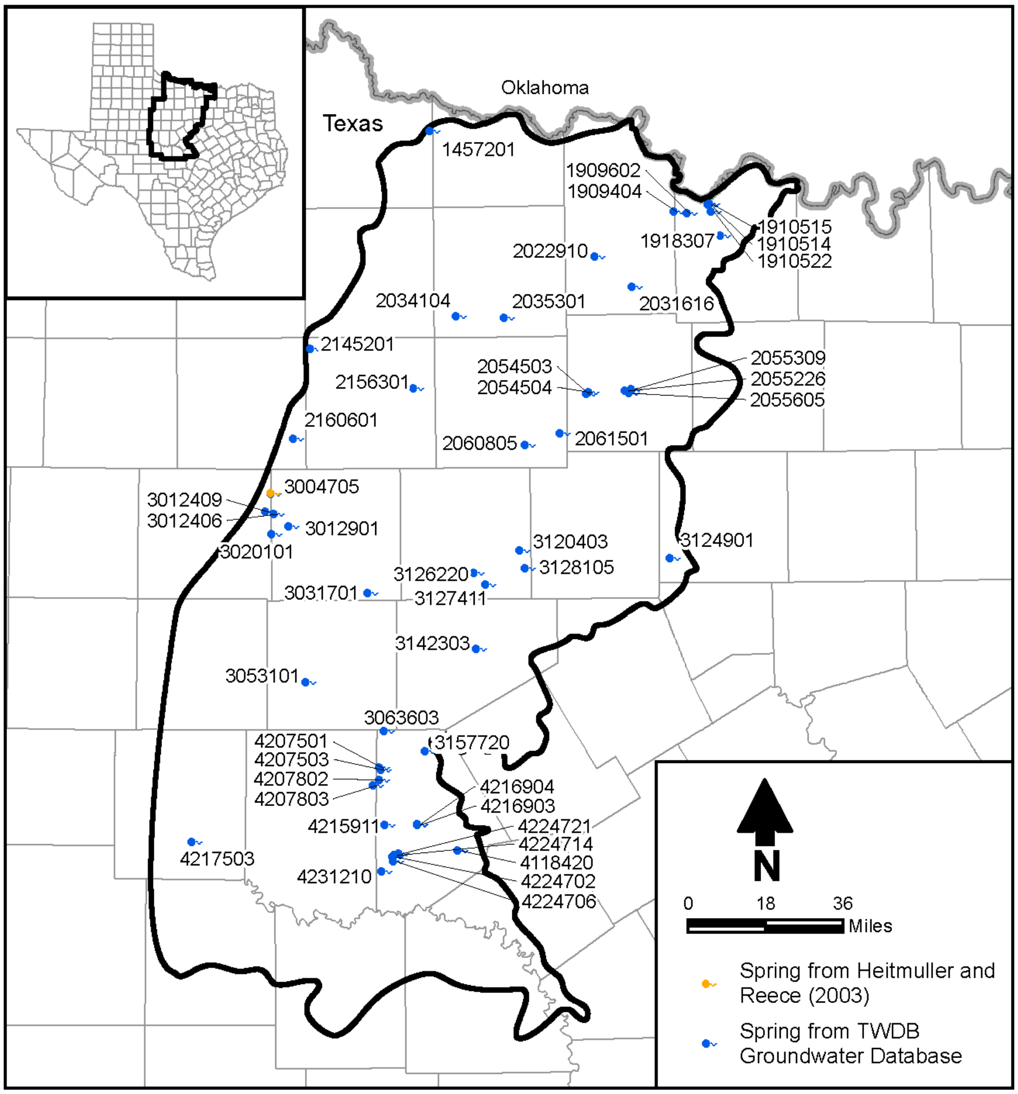


Figure 8-5. Springs identified as emanating from the Cross Timbers Aquifer.

Table 8-3. Summary of Cross Timbers Aquifer springs.

State Well Number [a]	County	Aquifer Unit Description	Remarks
1457201	Wichita	Wichita Formation or Group	
1909404	Montague	Wichita Formation or Group	Reportedly flowed during drought of the 1950s.
1909602	Montague	Wichita Formation or Group	
1910514	Montague	Wichita Formation or Group	
1910515	Montague	Wichita Formation or Group	
1910522	Montague	Wolfcamp Formation	Very slow seep. Flows into creek about 20 yards north of spring. Estimated flow 1 gallon per hour on 6/22/1977.
1918307	Montague	Archer City Formation	Spring M-1 in TWDB Report 189.
2022910	Clay	Cisco Group	
2031616	Clay	Cisco Group	
2034104	Archer	Wichita Formation or Group	
2035301	Archer	Archer City Formation	
2054503	Jack	Cisco Group	
2054504	Jack	Cisco Group	
2055226	Jack	Thrifty and Graham Formations	
2055309	Jack	Colony Creek Shale	McConnel Spring. Flow estimated at 10 to 20 gallons per minute on 11/12/1975. Formerly used as a domestic supply and springhouse.
2055605	Jack	Colony Creek Shale	Flows from crevices in massive limestone. Not flowing on 11/12/1975.
2060805	Young	Graham Formation	Issues from sandy, jointed limestone outcrop along creek. Reported to flow year round on 2/13/1963.
2061501	Young	Graham Formation	
2145201	Throckmorton	Lueders Limestone	Flow began in 1960.
2156301	Throckmorton	Putnam Formation	Known locally as "Mexican Springs." Flowing as of 12/11/1967.
2160601	Haskell	Lueders Limestone	
3012105	Shackelford	Lueders Limestone	Tank dug out below spring. Previously 3012101.
3012406	Shackelford	Lueders Limestone	
3012409	Jones	Lueders Limestone	Flows from gray porous limestone. Discharge estimated greater than 20 gallons per minute.
3012901	Shackelford	Lueders Limestone	Dug down to 20 feet. Concrete curb. Rock walled. Sometimes supplies water for drilling rigs. Reported water level declines as much as 5 feet during droughts.
3020101	Shackelford	Lueders Limestone	Located just south of an old rock house and is flowing from a massive limestone.
3031701	Shackelford	Putnam Formation	Dug out for tank in February 1967; shallow water table encountered.
3053101	Callahan	Wichita Formation or Group	Dug out to 8 feet. Estimated flow rate 8 gallons per minute.

Table 8-3 (continued)

State Well Number [a]	County	Aquifer Unit Description	Remarks
3063603	Brown	Wichita Formation or Group	Water is pumped from spring to house. Tank has been dozered out.
3120403	Stephens	Home Creek Limestone	Estimated discharge 0.5 to 3 gallons per minute in May, 1960. Conductance 560 μmhos/cm on 3/21/1991.
3124901	Parker	Strawn Group	
3126220	Stephens	Graham Formation	Seep
3127411	Stephens	Graham Formation	Seven holes drilled, 9 feet into rock. Five holes produce flowing water. Dam put in to collect water, but also collects surface runoff, 4/26/1962.
3128105	Stephens	Ranger Limestone	Wet weather spring.
3142303	Eastland	Canyon Group	20 gallons per minute per Heitmuller and Reece (2003).
3157720	Brown	Cisco Group	Water is pumped from spring to house.
4118420	Brown	Strawn Group	
4207501	Brown	Wichita Formation or Group	
4207503	Brown	Wichita Formation or Group	
4207802	Brown	Wichita Formation or Group	
4207803	Brown	Wichita Formation or Group	
4215911	Brown	Cisco Group	
4216903	Brown	Canyon Group	
4216904	Brown	Canyon Group	
4217503	Runnels	Alluvium	Ecological Recovery Foundation inventoried spring on TWDB contract 2005-001-059. Biota descriptions and flow history available as scanned images.
4224702	Brown	Cisco Group	Excavated to limestone aquifer in 1959.
4224706	Brown	Cisco Group	
4224714	Brown	Cisco Group	Excavated to 10 feet.
4224721	Brown	Canyon Group	Excavated to 10 feet in 1959.
4231210	Brown	Cisco Group	
3004705 [b]	Shackelford	Lueders Limestone	

[a] Source is TWDB groundwater database unless otherwise noted.
[b] Source is Heitmuller and Reece (2003).

9. Aquifer Hydraulic Properties

This section presents data and analysis on Cross Timbers Aquifer hydraulic properties, specifically hydraulic conductivity and storage coefficient.

9.1. Previous Reports

Most existing reports that address the Cross Timbers Aquifer do not provide aquifer properties such as hydraulic conductivity and storage coefficient. There are three adjacent groundwater availability models that include some of the geologic units that comprise the Cross Timbers Aquifer; these studies are for the Seymour Aquifer (Ewing and others, 2004), the minor aquifers of the Llano Uplift region (Shi and others, 2016a), and the Lipan Aquifer (Beach and others, 2004).

Ewing and others (2004) used a horizontal hydraulic conductivity of 0.82 and 0.52 feet per day for the Clear Fork Group and Wichita Group rocks, respectively. For vertical hydraulic conductivity, they used an anisotropy ratio of 10,000, and the corresponding vertical hydraulic conductivities for these units are 8.2×10^{-5} and 5.2×10^{-5} feet per day, respectively. Jigmund and others (2014) provide an updated groundwater availability model of the Seymour Aquifer in Haskell, Knox, and Baylor Counties; in their model, they consider the underlying Clear Fork Group rocks to be an aquitard that they do not include in the simulations. Ewing and others (2004) used a storage coefficient of 0.15 for the Permian rocks beneath the Seymour Aquifer, identifying this value as a literature estimate (there were no measurements).

In the Llano Uplift groundwater availability model of Shi and others (2016b), the Wichita-Albany, Cisco, Canyon, and Strawn Groups that underlie the Cretaceous rocks are considered as one low-permeability hydrogeologic unit (aquitard or confining unit). The horizontal hydraulic conductivity of these units ranges from 0.01 to 0.3 feet per day, with a geometric mean of 0.08 feet per day. The vertical hydraulic conductivity ranges from about 3×10^{-5} to about 3×10^{-4} feet per day in Coleman, Concho, and McCulloch Counties, and to about 2.5×10^{-3} feet per day in Mills County. The storage coefficient applied for confined conditions is 2×10^{-6} feet per day, and the specific yield applied is 0.002.

In their groundwater availability model of the Lipan Aquifer, Beach and others (2004) consider the main aquifer unit, the Leona Formation (gravel) as hydraulically connected with the underlying Clear Fork Group rocks; therefore, in most of their model, the aquifer properties are representative of a single, combined unit. In southern Runnels County and northwestern Concho County, where the Leona Formation is absent or thin, they use a horizontal hydraulic conductivity of 4 feet per day. Beach and others (2004) use a storage coefficient of 0.005 throughout most of their model domain, which is representative of semi-confined conditions.

Reported aquifer tests in Christian and Wuerch (2012) were reviewed, and there were no Cross Timbers Aquifer pumping tests reported. Myers (1969) was also reviewed, and there were five aquifer tests identified for Montague County for wells completed in units "of Carboniferous (Pennsylvanian) age." The results of these tests are summarized in Table 9-1; the hydraulic conductivity was calculated for tests where the screened interval could be determined.

Table 9-1. Summary of available aquifer test results for the Cross Timbers Aquifer from Myers (1969); all wells are in Montague County.

Latitude	Longitude	Type of Test	Transmissivity (gpd/ft^2)	Hydraulic Conductivity (ft/d)	Storage Coefficient
33°47'24"	97°43'13"	Recovery of observation well	109	—	2×10^{-6}
33°46'57"	97°42'56"	Recovery of pumped well	400	2.1	—
33°47'25"	97°43'10"	Recovery of pumped well	163	—	—
33°46'56"	97°42'57"	Recovery of observation well	349	—	4×10^{-6}
33°47'24"	97°43'12"	Recovery of pumped well	169	0.48	—

gpd/ft^2 = Gallons per day per square foot
ft/d = Feet per day

9.2. Determination of Hydraulic Conductivity from Specific Capacity

Specific capacity is the pumping rate of a well divided by the water-level decline (drawdown) at the well that occurs due to pumping. Specific capacity data are available for many wells in the Texas Department of Licensing and Registration online database. Aquifer transmissivity can be estimated from specific capacity data using a modified form of the Cooper-Jacob solution for drawdown in a pumping well (Walton, 1970; Mace, 2001). The Cooper and Jacob solution for drawdown in a pumping well (Cooper and Jacob, 1946) can be written assuming consistent units as follows:

$$s = (Q/(4\pi T)) \times \ln(2.25Tt/r^2S) \qquad \text{Equation 1}$$

where s = drawdown in the well
Q = pumping rate of the well
T = aquifer transmissivity
t = time since pumping began
r = radius of the well
S = aquifer storage coefficient

Equation 1 can be rearranged to solve for the specific capacity as follows:

$$Q/s = 4\pi T/(\ln(2.25Tt/r^2S)) \qquad \text{Equation 2}$$

Where all terms in the above equation are known except for transmissivity, the transmissivity can be solved for iteratively. Once the aquifer transmissivity is determined, the average hydraulic conductivity across the interval of aquifer that produced water to the well during the pumping period can be determined by dividing the transmissivity by the producing interval thickness.

Cross Timbers Aquifer specific capacity data were obtained from two sources and analyzed as described in the following subsections.

9.2.1. Texas Department of Licensing and Registration Dataset

The Texas Department of Licensing and Registration online database of wells for the Cross Timbers Aquifer area as downloaded on January 4, 2019 was used to develop estimates of aquifer hydraulic conductivity. In order to initially screen for shallow alluvial wells, wells with a total depth of 50 feet or less were omitted from the dataset. Of the remaining wells, those with pumping rates, duration of pumping, drawdown during the pumping, and well diameter were identified.

Next, wells where the screened or open interval of the well could be determined were considered, which is a total of 665 wells. There were very few wells where multiple screened intervals were identified, and the vertical distance of blank casing between the open intervals was not large. Therefore, in these limited cases the open interval was assumed to be the distance from the top of the first open interval to the bottom of the deepest open interval. In addition, the static depth to water at each well was compared to the top of screen, and where the water level was below the top of screen, the open interval was reduced accordingly in the computations of hydraulic conductivity. It is noteworthy that numerous wells completed in the Cross Timbers Aquifer have depths significantly deeper than the bottommost open interval of the well, presumably to provide well-bore storage due to limited well yield. Therefore, well depth is often not a good indicator of certain aquifer properties, such as depth of producing units.

Once the specific capacity dataset was developed, aquifer transmissivity was estimated using Equation 2. All of the variables in Equation 2 were known except for the aquifer storage coefficient, which was assumed to be 0.0001. This storage coefficient is representative of confined aquifer conditions, and even though many wells completed in the Cross Timbers Aquifer may occur in unconfined or semi-confined portions of the aquifer, the confined aquifer storage coefficient assumption is appropriate due to the limited duration of pumping represented in the data. A total of 88 percent of the wells had pumping durations of two hours or less, and only 2 percent of the wells were pumped for more than a day. During early periods of drawdown (short pumping duration) at a pumping well, water levels in unconfined aquifers respond as though the pumping occurred in a confined aquifer (e.g., Neuman, 1975).

Finally, Equations 1 and 2 assume that the well is 100 percent efficient, meaning that it is assumed that the water level within the well casing is the same as that in the aquifer material adjacent to the well casing. It is well known that most water wells do not exhibit 100 percent efficiency, particularly small-diameter wells in generally low-yield aquifers such as the Cross Timbers Aquifer. Well efficiency is not known for the wells in the dataset, but a general range of 60 to 90 percent is a reasonable assumption. In estimating hydraulic conductivity from the specific capacity data, a 75 percent well efficiency was therefore assumed, and the reported drawdown was multiplied by 0.75 to approximate the drawdown in the aquifer unit adjacent to the well casing.

These steps were followed to determine the aquifer transmissivity from specific capacity for the dataset of 665 wells. The calculated transmissivity was plotted against screen interval and well depth, and both plots indicated no correlation in these parameters. This result implies that wells are typically completed within a specific (likely the shallowest) producing unit, and increased yield is not obtained by extending the screened interval or the well depth. Next, aquifer hydraulic conductivity was calculated by dividing transmissivity by the thickness of open interval for each well.

Unlike wells in the TWDB groundwater database, wells in the Texas Department of Licensing and Registration database do not have an assigned aquifer code. Once the hydraulic conductivity was estimated for each well location, each well was assigned to one of the hydrostratigraphic units outlined in Sections 4 and 5. To accomplish this, the hydrostratigraphic layer surfaces in the three-dimensional geologic model were exported into the geographic information system, and the layer surfaces were compared to the top and bottom of open interval at each well to determine in which hydrostratigraphic unit the open interval occurred. Because shallow layers in the geologic model (Layers 1A and 1B, corresponding to the Seymour and Trinity Aquifers, respectively) were not the focus of the study, and because Quaternary alluvium at many places along streams is not incorporated in the geologic model, additional checks for shallow wells were completed as follows:

1. The surface geologic unit that occurs at each well location was determined by overlaying the well locations on the Geologic Atlas of Texas surface geology coverage.
2. The driller's logs for wells that occur within Cretaceous units, the Seymour Formation, or any type of designated Quaternary unit were reviewed to evaluate if the producing interval was within one of these units or beneath these units in a Paleozoic unit.
3. Wells were plotted on the surface geology map, and wells with a bottom of open interval of 80 feet or less near streams were reviewed to determine the producing geologic unit. Selected wells between streams were reviewed to confirm that they were producing from the Cross Timbers Aquifer.

These steps led to identification of 499 wells determined to be screened in the Cross Timbers Aquifer.

Summary results of the hydraulic conductivity analysis are provided in Table 9-2 and Figures 9-1 through 9-8. Figure 9-1 illustrates the results for wells that fall in hydrostratigraphic Layers 1A and 1B (Seymour or Trinity Aquifers) and Quaternary alluvium. These units are not the focus of this study, but the results are provided because the calculations were made. As illustrated in Table 9-2, the Cross Timbers Aquifer units generally have low hydraulic conductivity; 36 to 66 percent of the wells per unit have hydraulic conductivity less than 1 foot per day. Layer 8 (Strawn and Atoka Groups) appears to have the highest overall hydraulic conductivity. Layers 5 (Lower Cisco Group) and 8 (Strawn and Atoka Groups) have a small number of wells with high hydraulic conductivity of over 100 feet per day. These values were kept in the dataset because they are reflective of the values reported to the Texas Department of Licensing and Registration by well drillers, but errors in either the reported pumping rate and/or the reported drawdown are suspected. If the data are not in error, they indicate that limited zones of highly permeable aquifer material can occur locally.

Table 9-2. Summary of Cross Timbers Aquifer horizontal hydraulic conductivity determined from Texas Department of Licensing and Registration well data.

Hydrostratigraphic Layer	Number of Wells	Hydraulic conductivity (ft/d)			Percent of values less than 1 ft/d	Percent of values greater than 10 ft/d
		5th percentile	95th percentile	Median		
2	5	—	—	0.83	—	—
3	46	0.014	20.6	0.48	59	9
4	207	0.08	16	0.78	66	9
5	75	0.03	16	1.9	36	12
6	75	0.023	12.1	0.93	52	8
7	31	0.06	18.5	0.89	55	13
8	60	0.013	78.2	5.0	25	38

ft/d = Feet per day

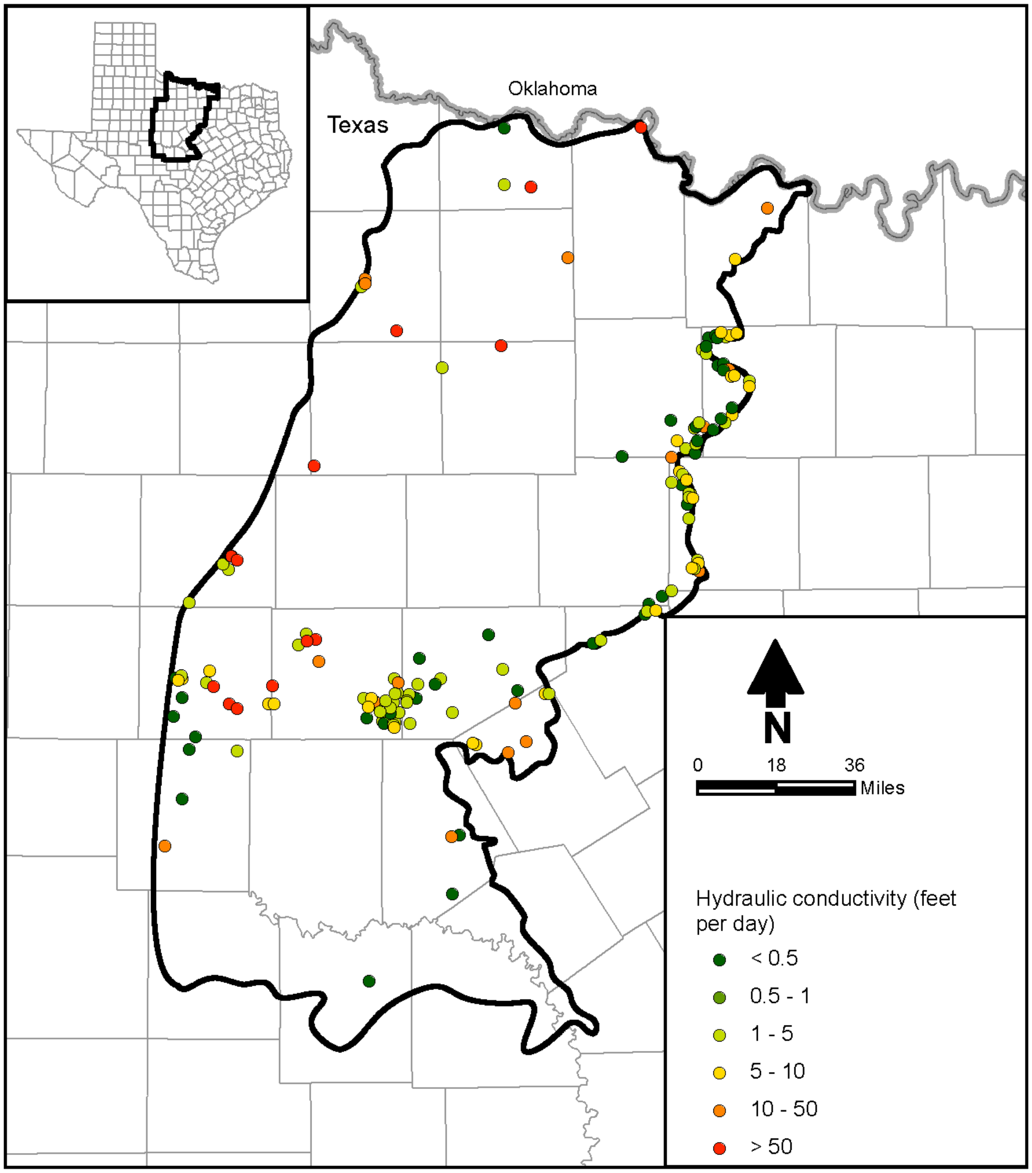


Figure 9-1. **Estimated Seymour, Trinity and Quaternary alluvium hydraulic conductivity from Texas Department of Licensing and Registration specific capacity data.**

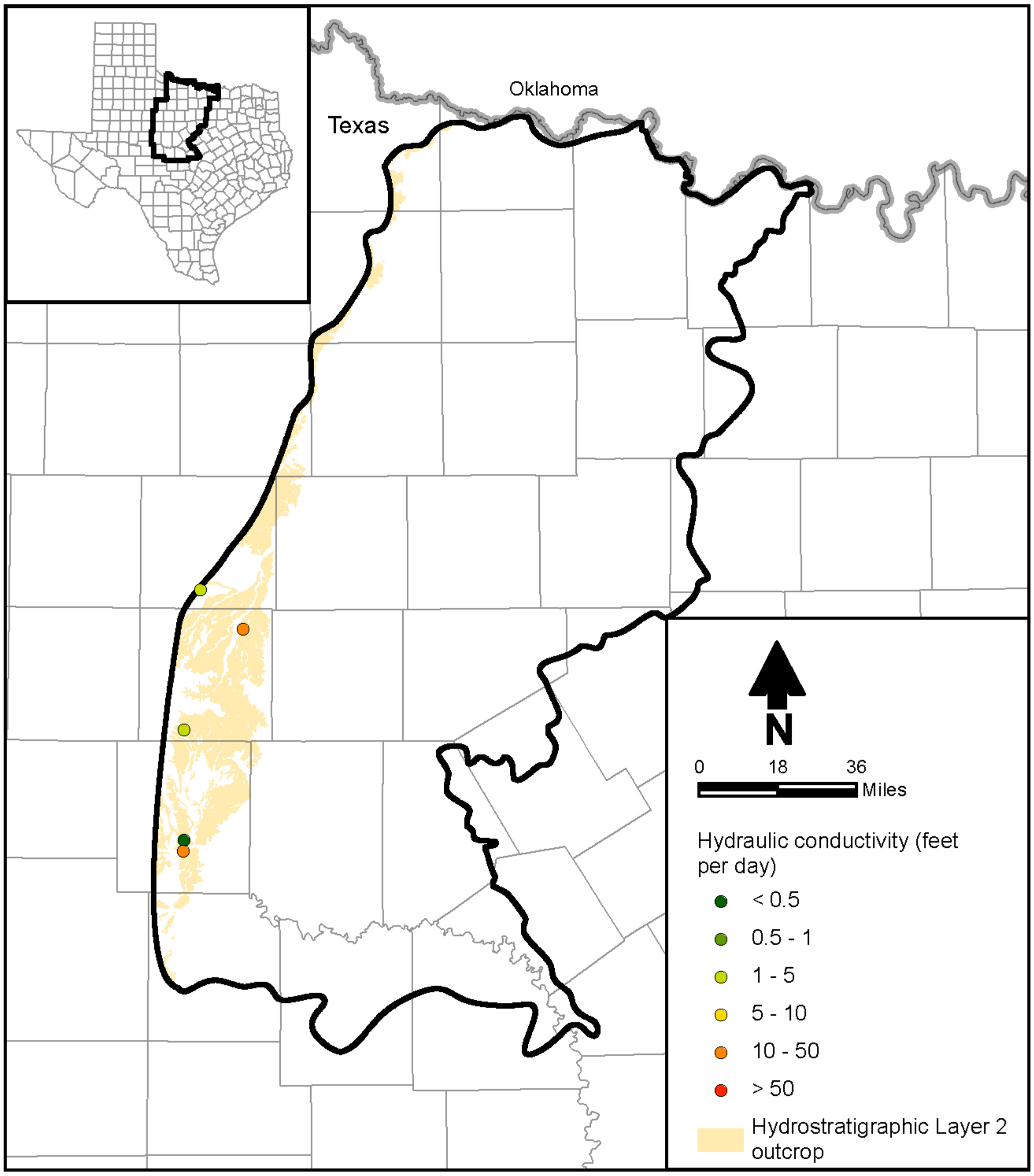


Figure 9-2. Estimated hydrostratigraphic Layer 2 (Clear Fork Group) hydraulic conductivity from Texas Department of Licensing and Registration specific capacity data.

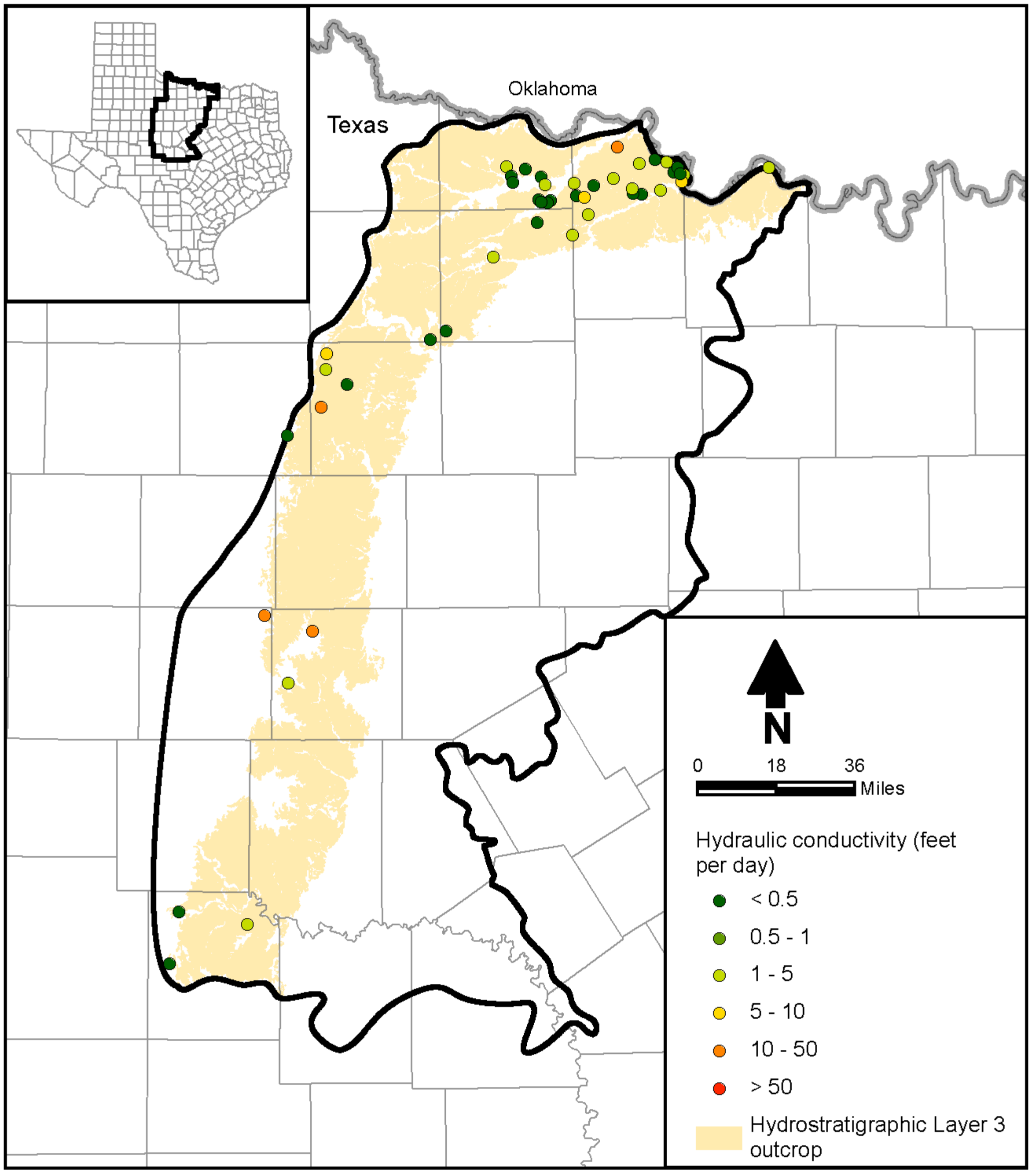


Figure 9-3. Estimated hydrostratigraphic Layer 3 (Wichita-Albany Group) hydraulic conductivity from Texas Department of Licensing and Registration specific capacity data.

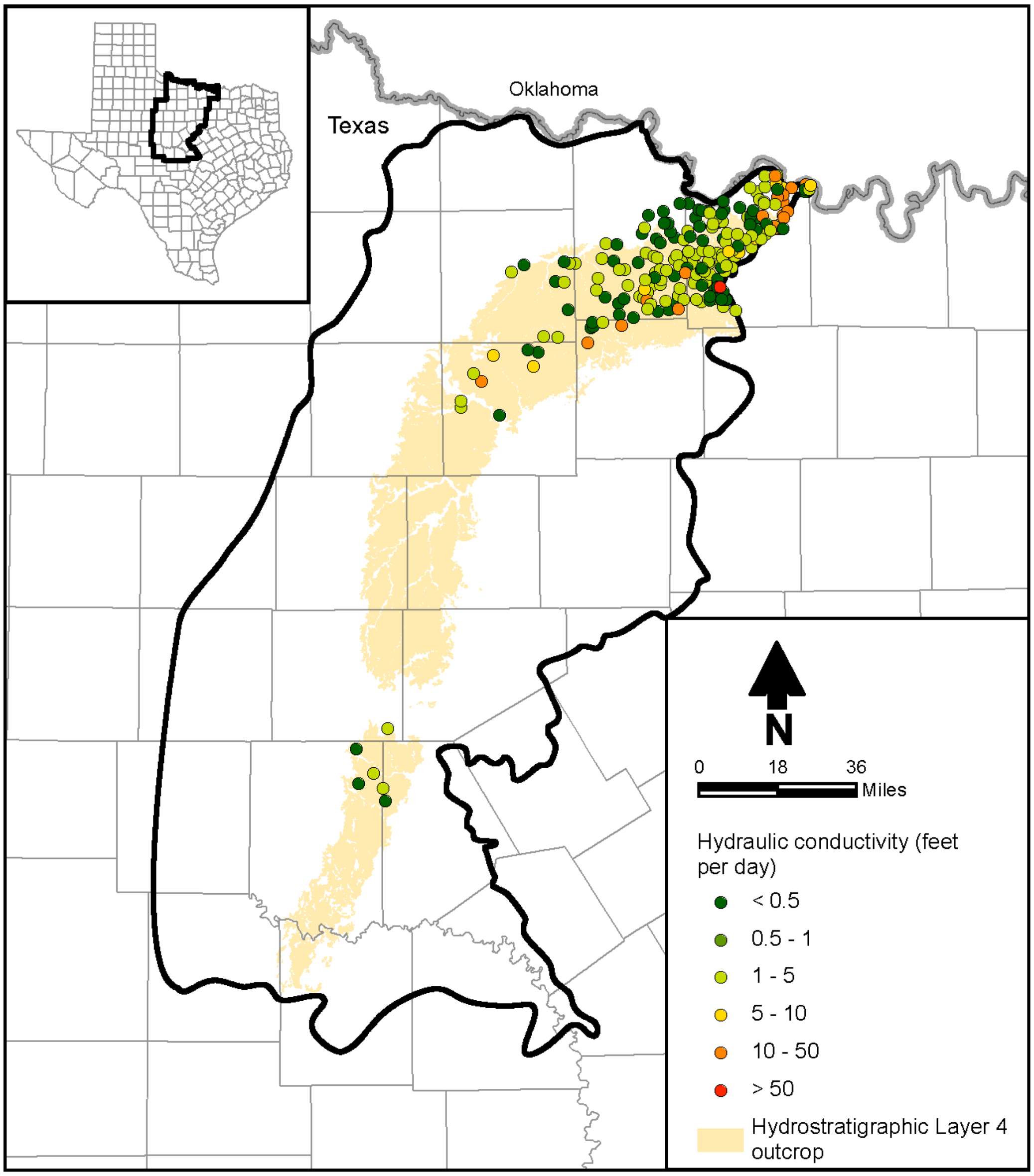


Figure 9-4. **Estimated hydrostratigraphic Layer 4 (Upper Cisco Group) hydraulic conductivity from Texas Department of Licensing and Registration specific capacity data.**

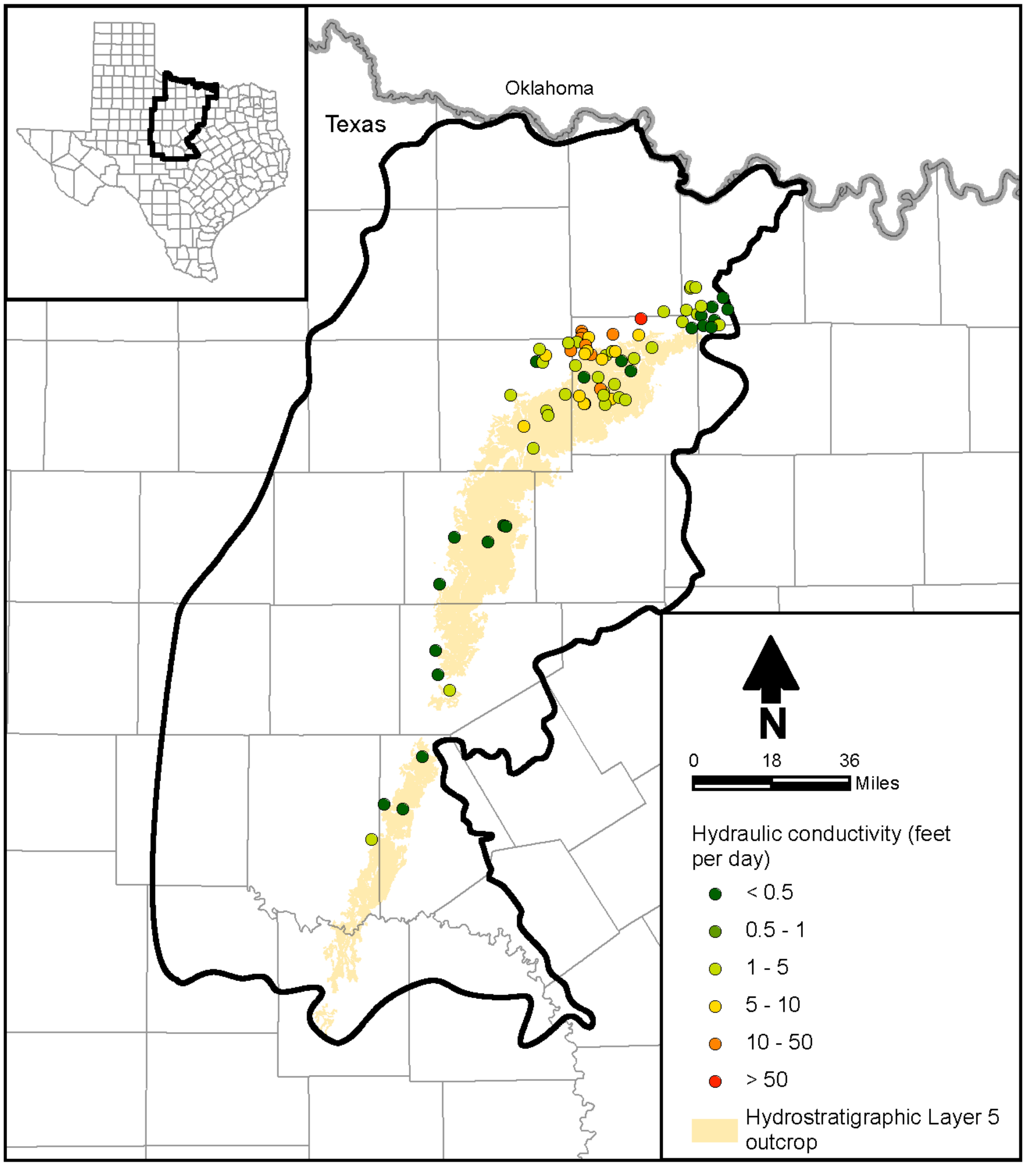


Figure 9-5. Estimated hydrostratigraphic Layer 5 (Lower Cisco Group) hydraulic conductivity from Texas Department of Licensing and Registration specific capacity data.

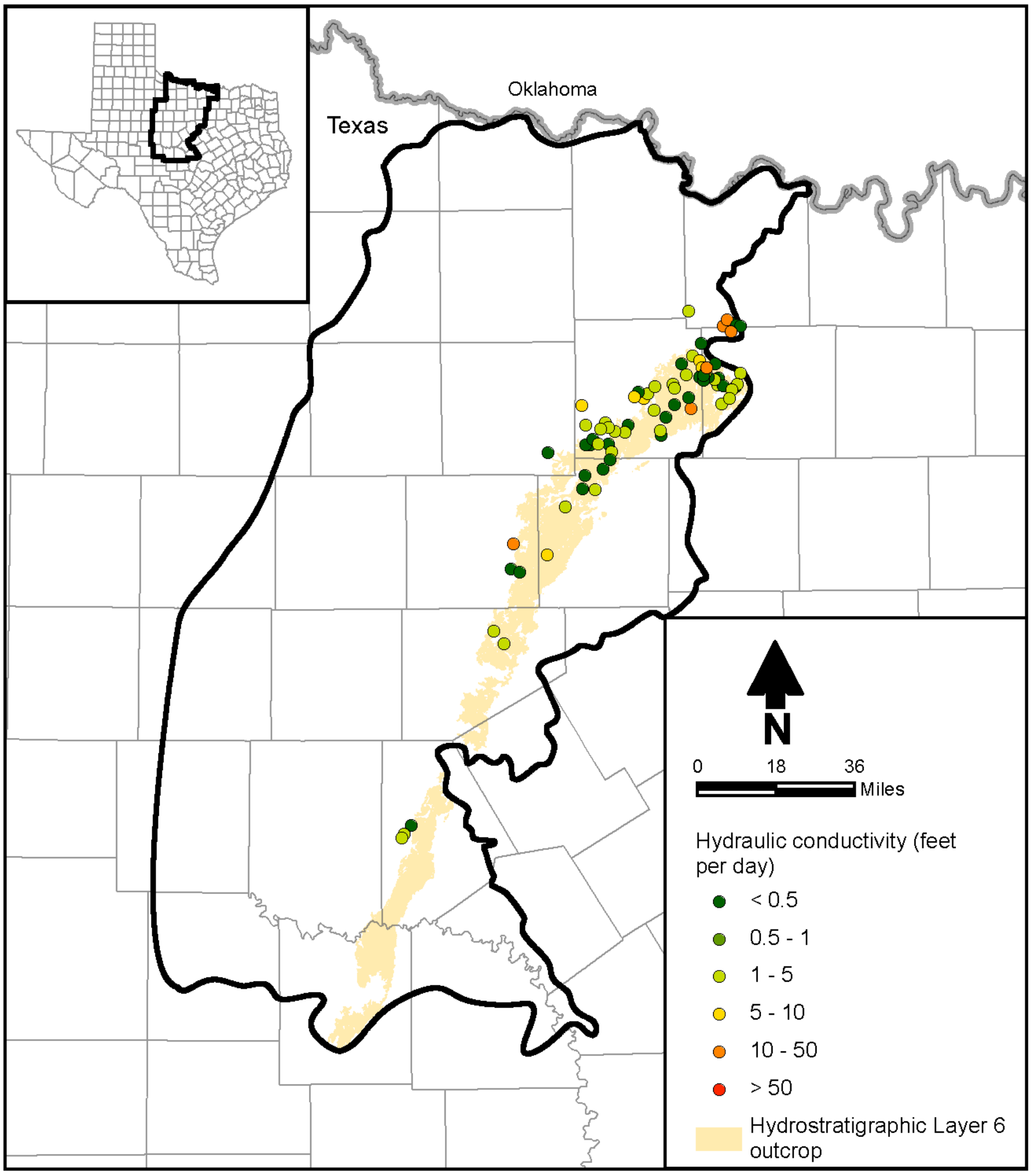


Figure 9-6. **Estimated hydrostratigraphic Layer 6 (Upper Canyon Group) hydraulic conductivity from Texas Department of Licensing and Registration specific capacity data.**

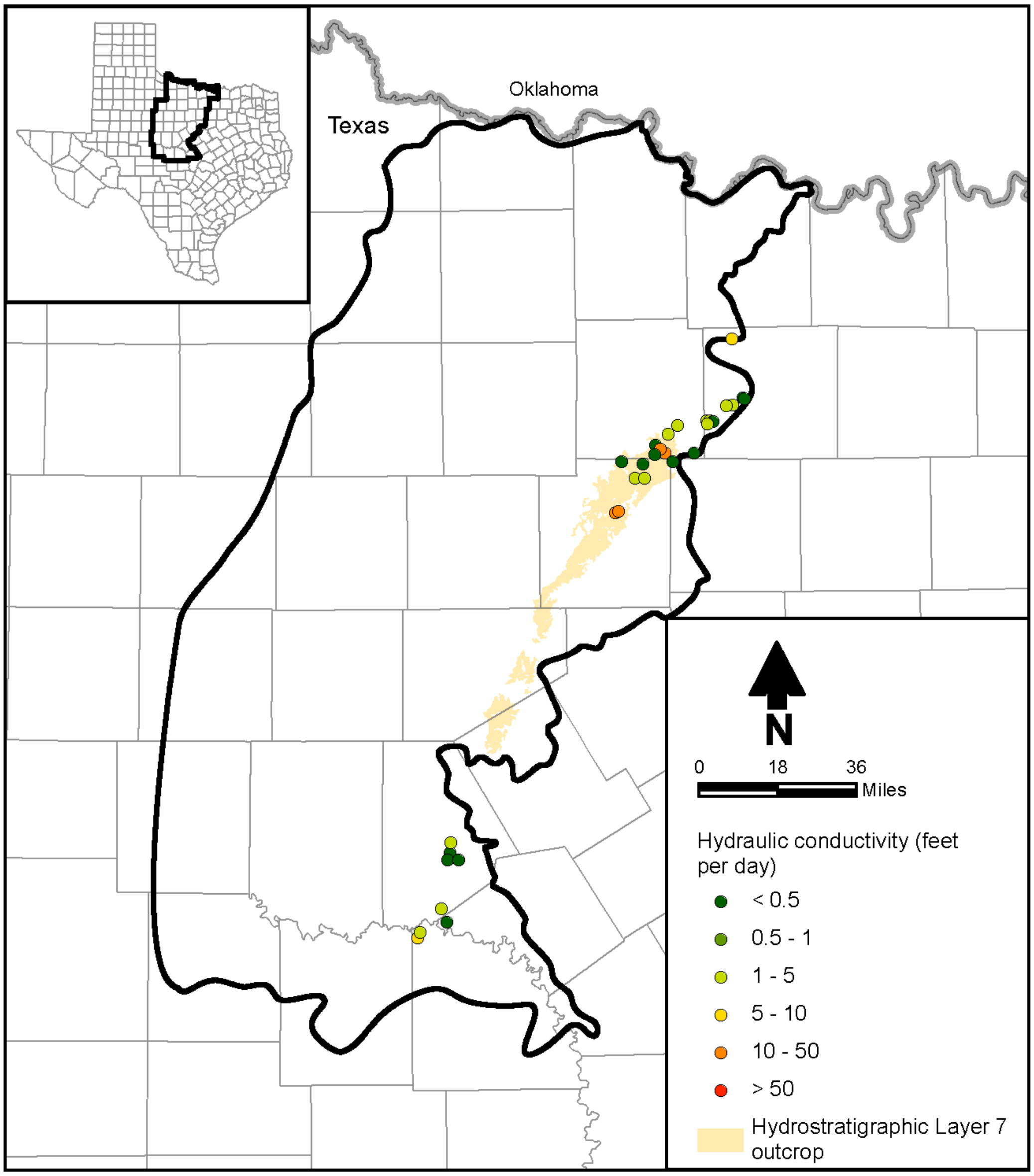


Figure 9-7. **Estimated hydrostratigraphic Layer 7 (Lower Canyon Group) hydraulic conductivity from Texas Department of Licensing and Registration specific capacity data.**

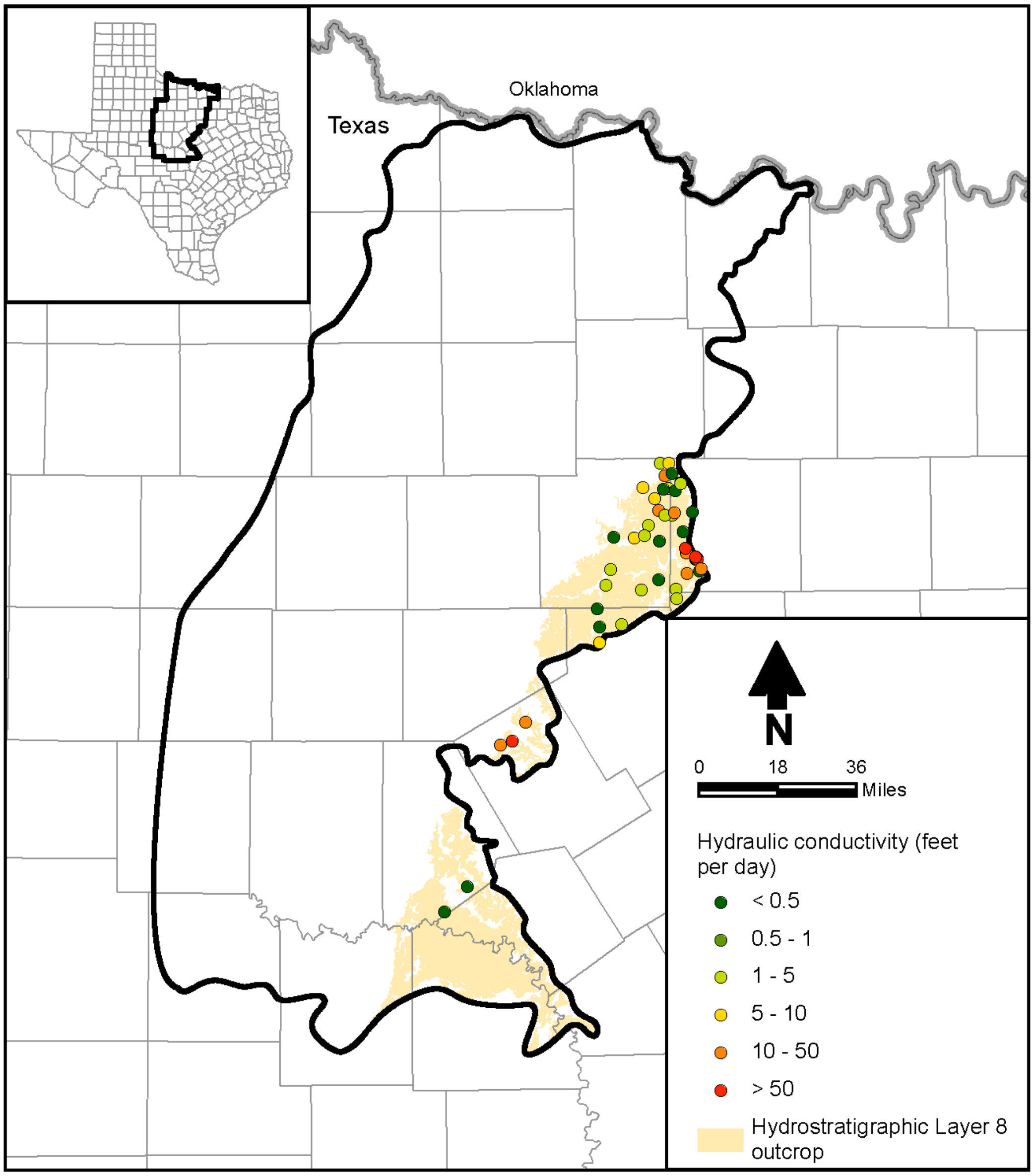


Figure 9-8. Estimated hydrostratigraphic Layer 8 (Strawn and Atoka Groups) hydraulic conductivity from Texas Department of Licensing and Registration specific capacity data.

9.2.2. Nicot and Others (2013) Dataset

Nicot and others (2013) analyzed 2,474 specific capacity tests obtained from written and scanned records from the Texas Commission on Environmental Quality. They report a wide variation in results, but 90 percent of the data points fell between 0.03 and 10 feet per day, with a median value of 0.6 feet per day. Other median values of interest were a well diameter of about 4.5 inches, a screen length of 35 feet, a test pumping rate of about

11 gallons per minute, and well depth of 200 feet. The wells were divided into the Strawn, Canyon, Cisco, and Wichita Group outcrops, and the data were interpolated to provide contours of hydraulic conductivity. Nicot and others (2013) also note that groundwater flow will occur preferentially along the strike of the permeable geologic units.

The specific capacity data points used in the Nicot and others (2013) study were obtained from J.P. Nicot of the Bureau of Economic Geology on May 4, 2021. Because well locations are frequently uncertain in the older Texas Commission on Environmental Quality data, the well locations were assigned to the centroid of the state well grid to which they belonged (Nicot and others, 2013). The dataset provided did not include an estimate of hydraulic conductivity. For this reason and to be consistent with the analysis presented in Section 9.2, the specific capacity data were analyzed using the same approach described above, except that wells identified as Paleozoic in the dataset were assumed to be correct because the determination of aquifer unit (i.e., Paleozoic or shallow) was already conducted by Nicot and others (2013). Once wells with no screen interval or other inputs required to compute hydraulic conductivity were removed from the dataset, there were 1,186 wells remaining. Of these, 529 wells are inside the aquifer extent and 657 are west of the aquifer extent, beneath the adjacent Northern Trinity Aquifer.

The median hydraulic conductivity for the Nicot and others (2013) wells within the Cross Timbers Aquifer boundary is 2.6 feet per day. The 5th and 95th percentiles are 0.08 and 40 feet per day, respectively.

Figure 9-9 illustrates the hydraulic conductivity distribution of the Nicot and others (2013) dataset processed as explained above. Multiple data points within the same state well grid were averaged to create a single point; this process yielded 441 datapoints—216 inside the Cross Timbers Aquifer boundary and 225 outside the Cross Timbers Aquifer boundary. As indicated in Figure 9-9, Cross Timbers Aquifer units to the east that occur beneath the Northern Trinity Aquifer appear to have permeability as high as those within the Cross Timbers Aquifer west of the Trinity outcrop.

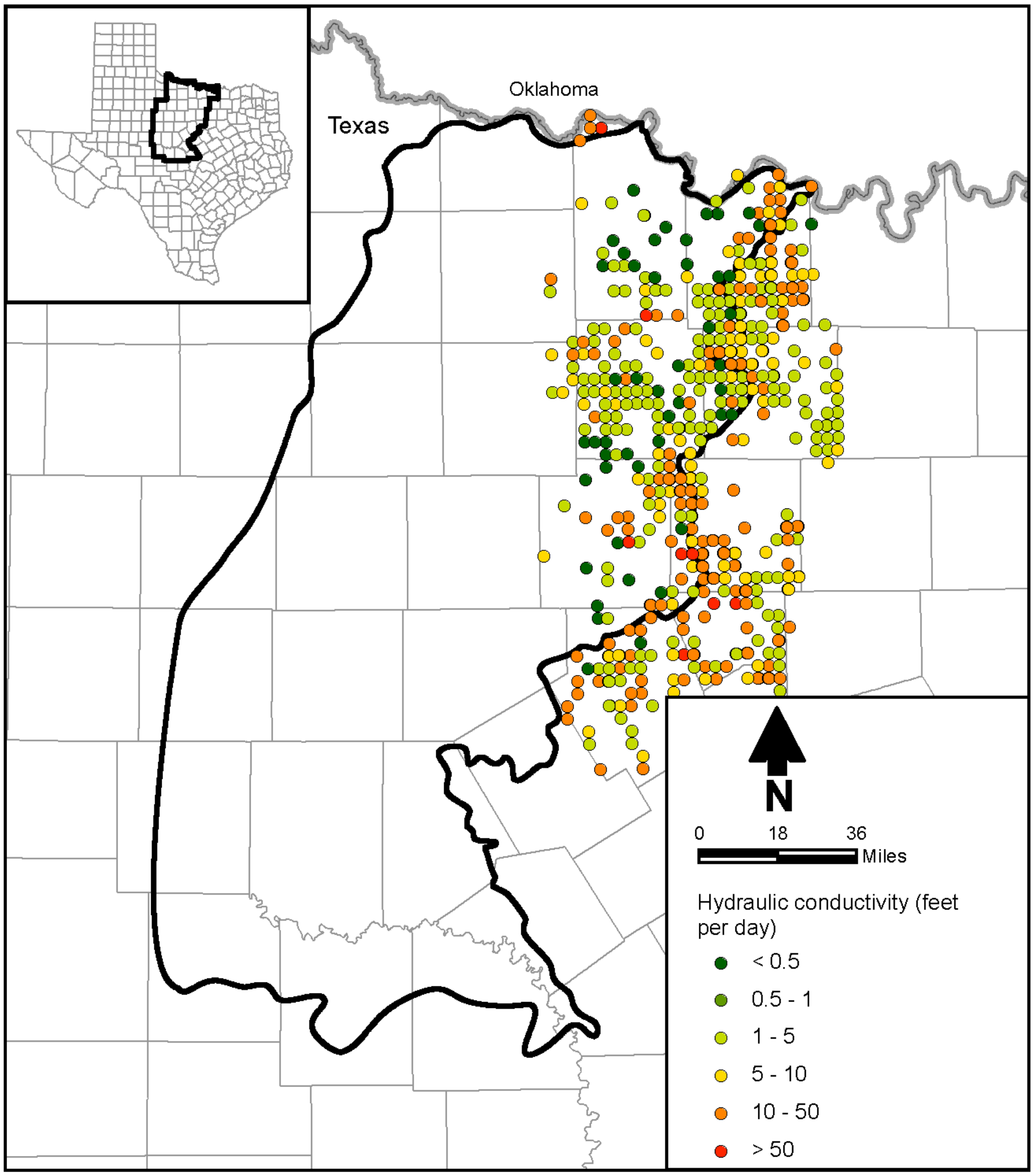


Figure 9-9. Estimated Cross Timbers Aquifer hydraulic conductivity from Texas Department of Licensing and Registration specific capacity data compiled by Nicot and others (2013).

9.3. Aquifer Storage Coefficient

There are very few measured storage coefficients; available values are provided in Table 9-1. Both of the values in Table 9-1 are small and representative of confined aquifer conditions. Groundwater in the Cross Timbers Aquifer occurs under confined and unconfined conditions, although conditions are believed to be predominantly unconfined (Ballew and French, 2019; Nicot and others, 2013). Where wells are completed in outcrop and the permeable units (sandstone or fractured rock) occur near surface, the aquifers will be unconfined, with a storage coefficient that may range from 1 or 2 percent to maybe 10 percent (i.e. 0.01 to 0.1). Where wells are screened in deeper portions of a producing unit downdip of the outcrop, the aquifer will be confined and the storage coefficient will be more on the order of 1×10^{-4} to 1×10^{-6} feet per day.

10. Groundwater Discharge

Groundwater discharge occurs through groundwater pumping from wells (pumpage) and natural groundwater discharge to streams and springs. This section discusses groundwater discharge by pumpage. Spring flow and base flow to streams are discussed in Section 8. .

Because the Cross Timbers Aquifer was only formally designated as a minor aquifer in 2017 (Ballew and French, 2019), historical groundwater pumpage estimates for this aquifer do not exist. Prior to being designated as a minor aquifer, historical pumpage from the Cross Timbers Aquifer would likely be classified as “Other Aquifer” in the TWDB data sources.

Ballew and French (2019) evaluated the number of wells in each county in the Cross Timbers Aquifer area to determine the number known to be completed in the Strawn, Canyon, Cisco, and Wichita Groups. This evaluation provides good insight into the role the Cross Timbers Aquifer plays in groundwater use within each county. Figure 10-1 shows the percentage of wells within each county known to be completed in the Cross Timbers Aquifer based on the data from Ballew and French (2019). In eight counties in the northern portion of the study area (Archer, Clay, Jack, Montague, Palo Pinto, Shackelford, Stephens, and Young), about two-thirds or more of all of the wells within the county are completed in the Cross Timbers Aquifer. In several counties within the study area, between one-quarter and one-half of all of the wells in the TWDB database are completed in the Cross Timbers Aquifer. Two of these counties—Brown and Coleman—are located in the southern portion of the study area, which is also where the Cross Timbers is either the only or the predominant designated aquifer present. In most of the other counties in the study area, officially designated major or minor aquifers other than the Cross Timbers Aquifer occur over significant portions of the county. In these counties, less than 10 percent of the wells are completed in the Cross Timbers Aquifer.

Ballew and French (2019) estimated that between 1984 and 2016, annual pumping from all aquifers classified as “Other Aquifers” ranged from 9,546 to 25,024 acre-feet, averaging 14,716 acre-feet. Even during the severe drought that occurred between 2010 and 2016, pumping from “Other Aquifers” averaged only 21,346 acre-feet per year. Although this amount of pumping during the drought is about a 50 percent increase relative to overall average conditions, the overall amount of pumping from the “Other Aquifers” is small.

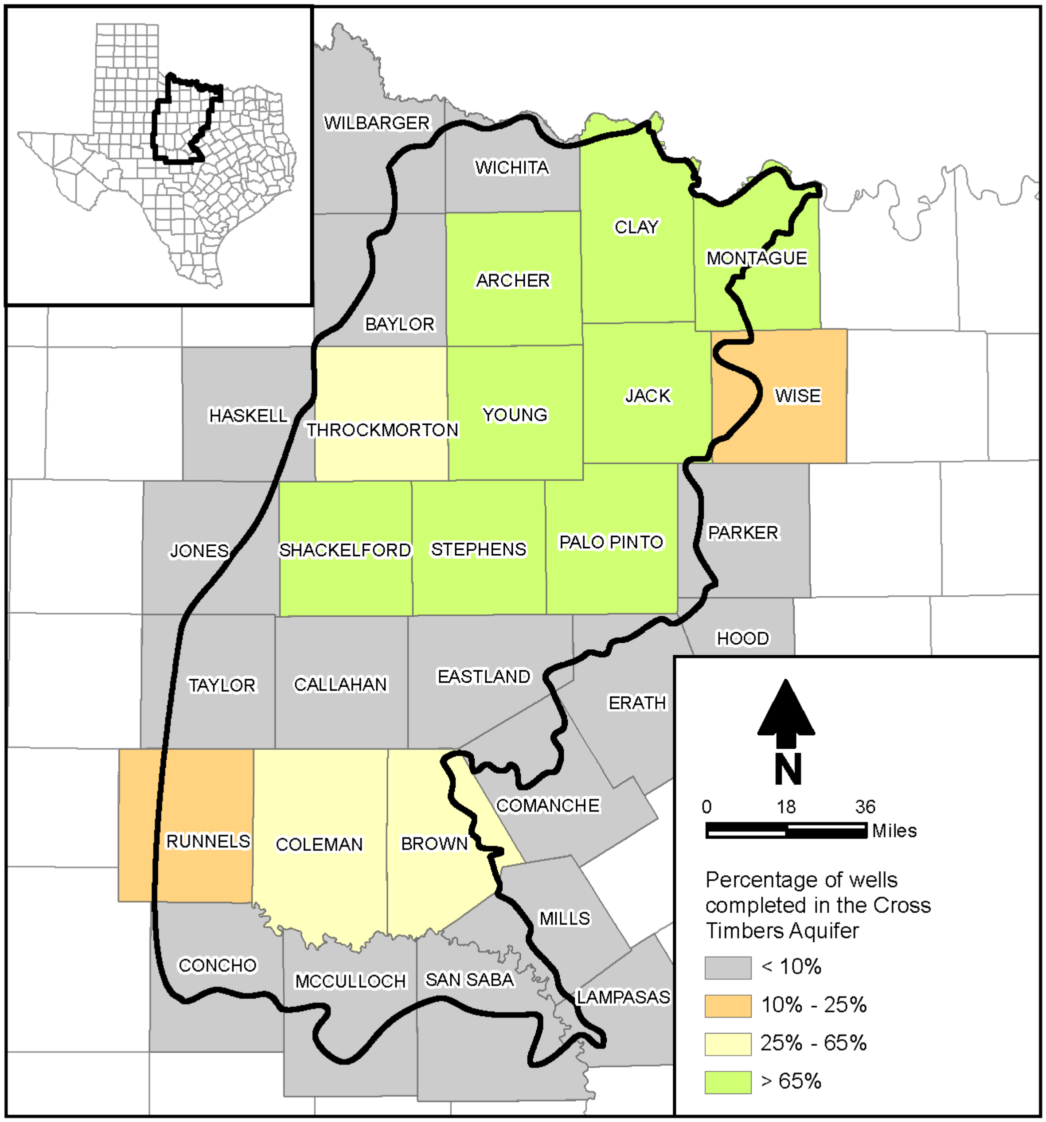


Figure 10-1. Percentage of total wells completed in the Cross Timbers Aquifer.

In order to estimate groundwater pumping from the Cross Timbers Aquifer, we followed the general approach of Ballew and French (2019) with some modification. Like Ballew and French (2019), unused and plugged/destroyed wells were removed from the dataset of wells downloaded from the TWDB groundwater database. In addition, wells with no aquifer code assigned (unassigned wells) were also removed from the dataset, as were monitor wells. It appeared that the TWDB aquifer codes 318ARRY (Arroyo), 318BLGN (Bullwagon), 318CHOZ (Choza), 318CLFK (Clear Fork), 318CZVL (Choza/Vale), 318LDRS (Leuders), 318VALE (Vale), and 320PSLV (Pennsylvanian) were not included in the Cross Timbers Aquifer in Ballew and French (2019), but wells with these codes were included in the current analysis. Finally, in order to estimate the component of “Other Aquifer” pumpage attributed to the Cross Timbers Aquifer, the percentage of “Other Aquifer” wells screened in the Cross Timbers Aquifer was calculated. Table 10-1 and Figure 10-2 provide the results of this analysis on a county-by-county basis. It is important to note that the exclusion of wells in other major and minor aquifers in this analysis significantly changed the percentages of wells in the Cross Timbers Aquifer compared to those of Ballew and French (2019).

Table 10-1. Percentage of "Other Aquifer" wells completed in the Cross Timbers Aquifer in each county in the study area.

County	Total Wells	Total Cross Timbers Aquifer Wells	Total "Other" Wells	Percentage of "Other Aquifer" Wells in Cross Timbers Aquifer
Archer	200	200	0	100%
Baylor	385	7	63	10%
Brown	1345	395	7	98%
Callahan	426	12	6	67%
Clay	325	269	42	86%
Coleman	489	229	254	47%
Comanche	1035	73	4	95%
Concho	307	44	30	59%
Eastland	807	40	3	93%
Erath	462	3	0	100%
Haskell	845	51	3	94%
Jack	369	363	1	100%
Jones	880	276	177	61%
Lampasas	146	4	11	27%
McCullough	394	4	37	10%
Mills	72	3	1	75%
Montague	521	340	37	90%
Palo Pinto	62	58	2	97%
Parker	589	36	13	73%
Runnels	315	280	24	92%
San Saba	393	15	23	39%
Shackelford	72	56	15	79%
Stephens	261	234	26	90%
Taylor	369	61	218	22%
Throckmorton	83	36	46	44%
Wichita	146	3	15	17%
Wilbarger	749	6	76	7%
Wise	236	33	4	89%
Young	413	406	7	98%

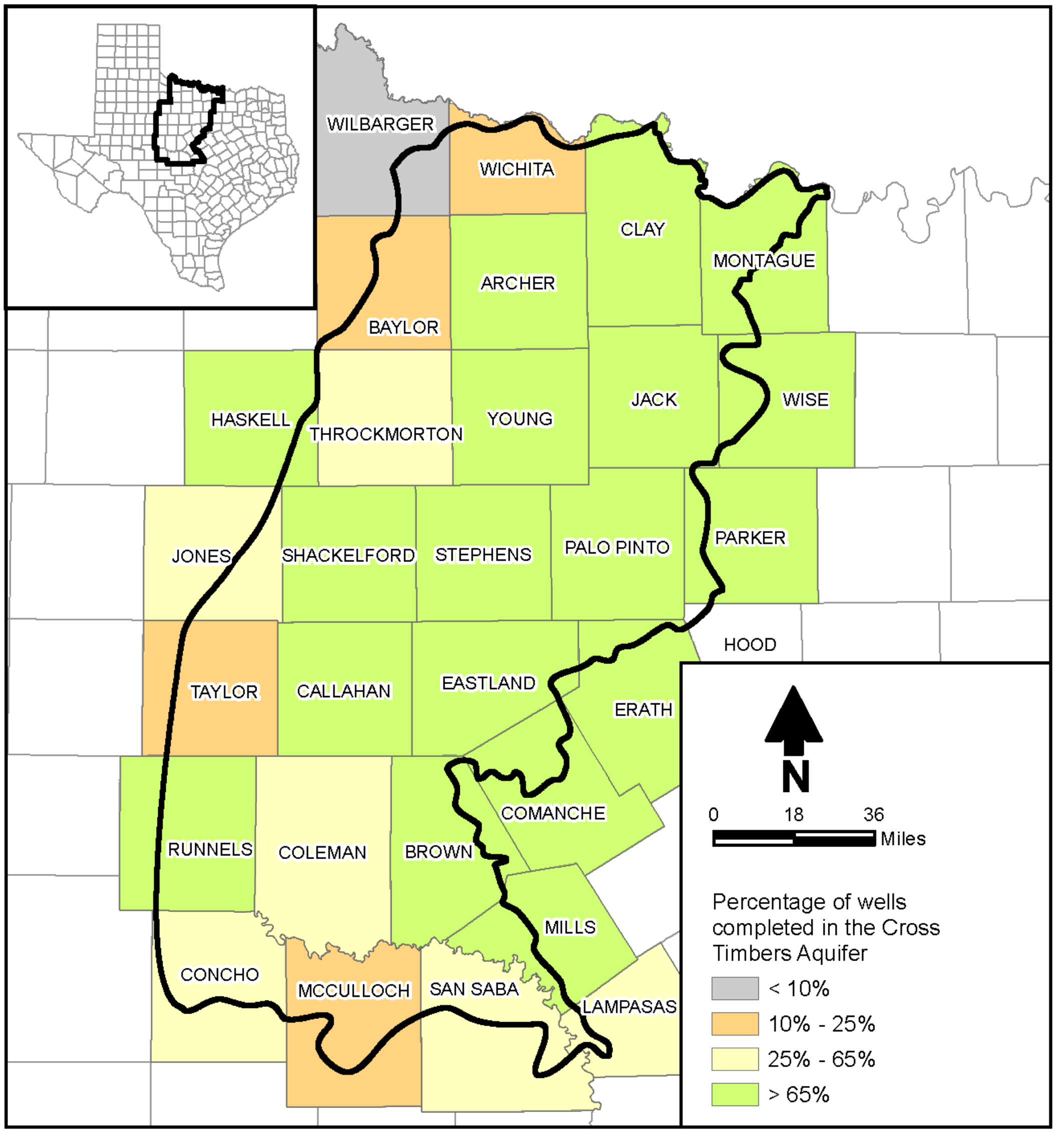


Figure 10-2. Percentage of "Other Aquifer" wells completed in the Cross Timbers Aquifer.

Groundwater pumping estimates were obtained from several sources. First, county totals of groundwater pumpage for each aquifer were obtained from the TWDB water planning historical groundwater pumpage estimates. This dataset provides estimates of groundwater by aquifer and by use (municipal, irrigation, livestock, manufacturing/ industrial, mining, and steam-electric power) from 1980 to 2018. Second, groundwater pumpage detail was obtained from the TWDB water planning pumpage detail estimates. This dataset provides pumpage detail for each county, including estimates of non-surveyed municipal (rural domestic), irrigation, and livestock pumpage for each aquifer in every county in the state. Finally, industrial and municipal water intake data was obtained from the TWDB water planning section, which provides intake survey data for specific municipal and industrial entities back to 1955, and includes whether these intake data are for surface water or groundwater. This dataset, combined with information from the groundwater database on individual wells, can provide additional historical detail on groundwater pumpage from the Cross Timbers Aquifer. All of these data sources were accessed on May 6, 2021.

Based on these datasets, the amount of pumping for the Cross Timbers Aquifer was determined based on the percentages listed in Table 10-1, and specific detail for non-surveyed pumpage and pumpage for specific entities for each county in the study area was estimated. A summary of total estimated Cross Timbers Aquifer pumping is provided in Section 10.1.1. Summaries of estimated pumping by county are provided in Section 10.1.2.

10.1. Total Groundwater Pumping

The majority of pumpage from the Cross Timbers Aquifer is for municipal, mining, irrigation, and livestock purposes. Groundwater pumping for manufacturing use accounts for less than 50 acre-feet per year of the total pumping, and there is no estimated steam-electric power use of groundwater from the Cross Timbers Aquifer. Evaluation of the pumpage detail in the study area indicates that the vast majority of the pumpage estimated to have occurred from "Other Aquifers," which will include the Cross Timbers Aquifer, is assigned to non-surveyed estimates of municipal (i.e., rural domestic), irrigation, and livestock pumpage, and not to specific entities or wells. Ballew and French (2019) identified 52 public supply wells completed in the Cross Timbers Aquifer. Virtually all of the pumpage totals for individual entities identified through the pumpage detail dataset, as well as historical municipal and industrial intake data dating back to 1955, are for very small volumes.

Total estimated pumpage from the Cross Timbers Aquifer is shown in Figure 10-3; it ranges from 7,570 acre-feet in 2004 to 28,780 acre-feet in 2010, and averages 11,690 acre-feet per year from 1984 to 2018. A good portion of the variability in estimated total annual pumpage arises from the variability in the annual mining pumpage. For an aquifer the size of the Cross Timbers Aquifer (approximately 17,800 square miles), this is a very small amount of pumpage, and is reflective of the limited well production capacity and freshwater saturated thickness intrinsic to the aquifer.

Annual groundwater pumpage for municipal use from the Cross Timbers Aquifer is shown in Figure 10-4. Total municipal pumping ranges from 1,926 to 5,525 acre-feet per year, with an average of 2,979 acre-feet per year. Municipal pumping has remained relatively constant since 1980, other than a significant increase that occurred during the drought period 2010 to 2013.

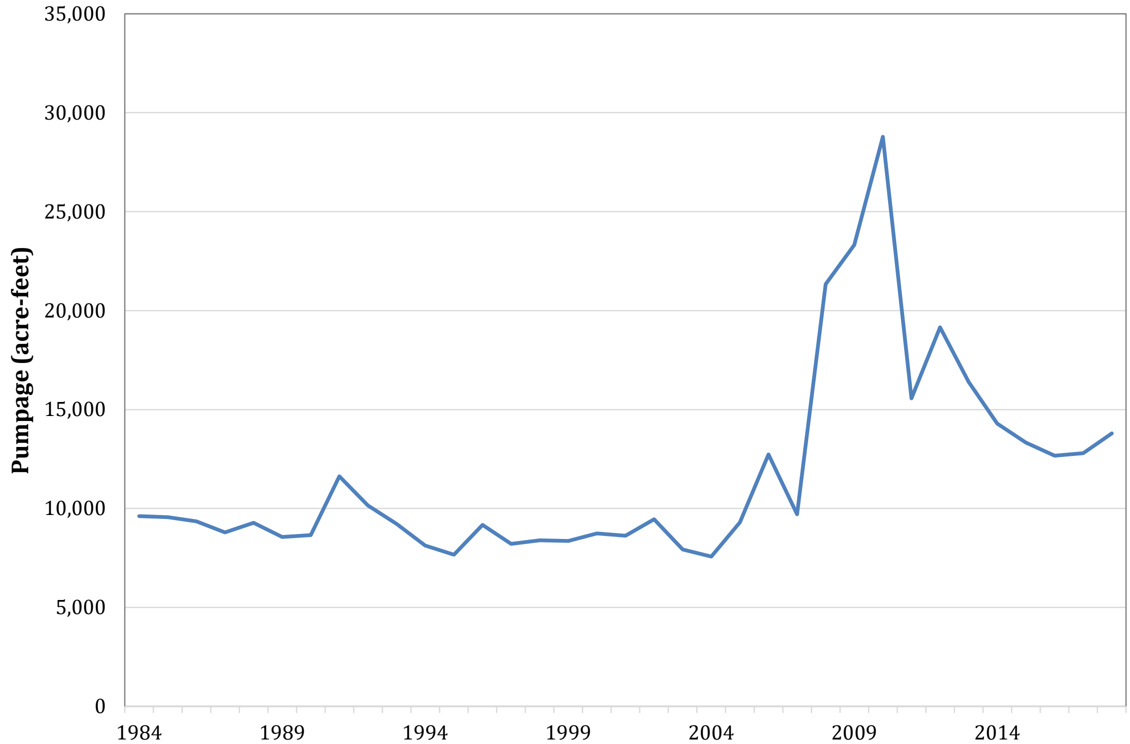


Figure 10-3. Estimated total annual pumpage from the Cross Timbers Aquifer.

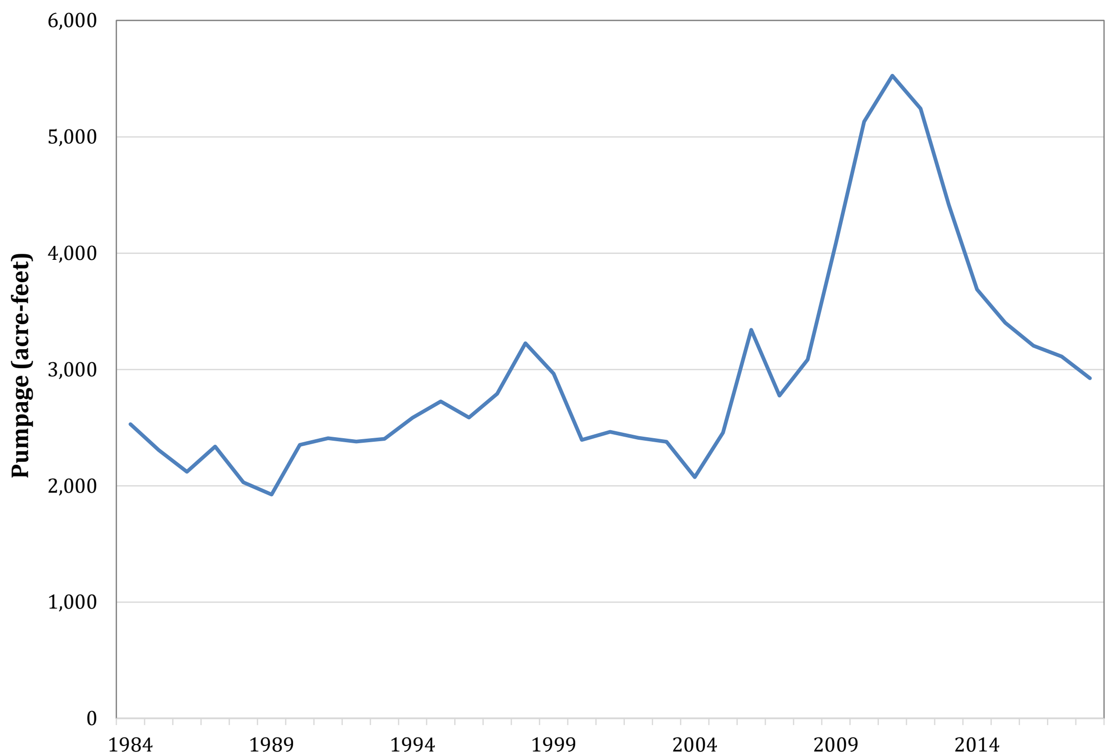


Figure 10-4. Estimated annual municipal pumpage from the Cross Timbers Aquifer.

Figure 10-5 presents the annual groundwater pumpage for mining purposes for the Cross Timbers Aquifer. This water use has ranged from 0 to 13,950 acre-feet in 2010, with an average of 1,200 acre-feet per year. A large peak in pumpage occurred in 2008 and 2009, likely caused by increased oil and gas well drilling activity.

Annual irrigation pumpage from the Cross Timbers Aquifer is shown in Figure 10-6. Estimated annual irrigation pumping ranges from 1,653 to 10,828 acre-feet, with an average of 5,072 acre-feet per year. Irrigation pumpage remained fairly constant from 1980 to about 2005, since which time it has generally increased. The most recent estimated irrigation pumpage is about twice that of years prior to 2005.

Annual livestock pumpage from the Cross Timbers Aquifer is shown in Figure 10-7, and ranges from 1,270 to 2,196 acre-feet, with an average of 1,679 acre-feet per year. Livestock pumpage has been relatively steady since 1980, with annual variations of approximately 500 acre-feet.

The overall annual pumpage from the Cross Timbers Aquifer excluding mining use is provided in Figure 10-8. This amount ranges from 5,947 to 17,589 acre-feet, with an average of 9,759 acre-feet per year. The total non-mining pumpage has remained fairly constant from 1980 through the 1990s, but has generally increased since that time due to increases in municipal and irrigation pumpage.

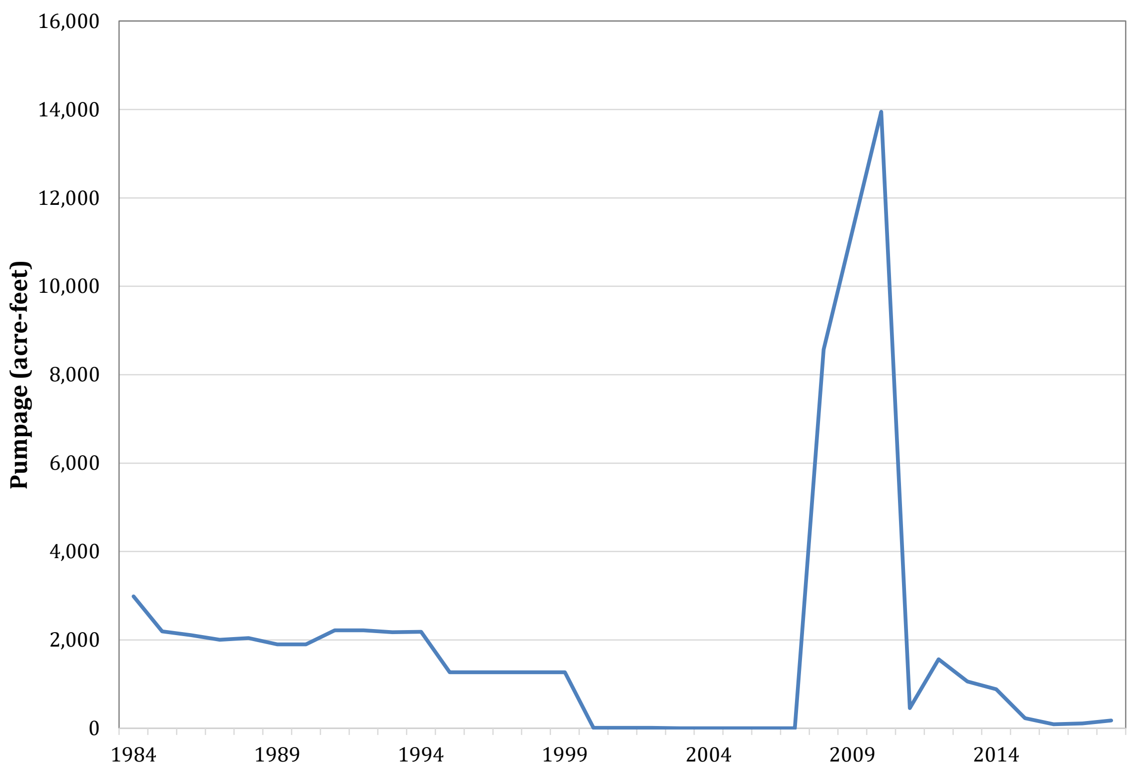


Figure 10-5. Estimated annual mining pumpage from the Cross Timbers Aquifer.

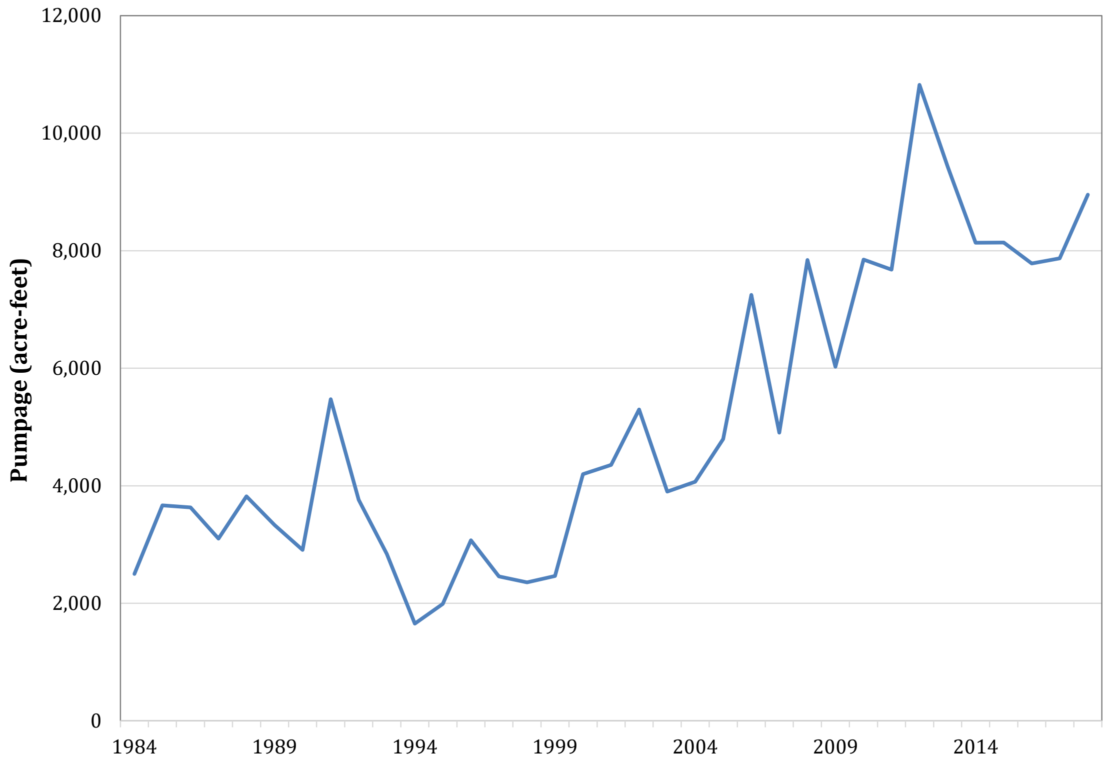


Figure 10-6. Estimated annual irrigation pumpage from the Cross Timbers Aquifer.

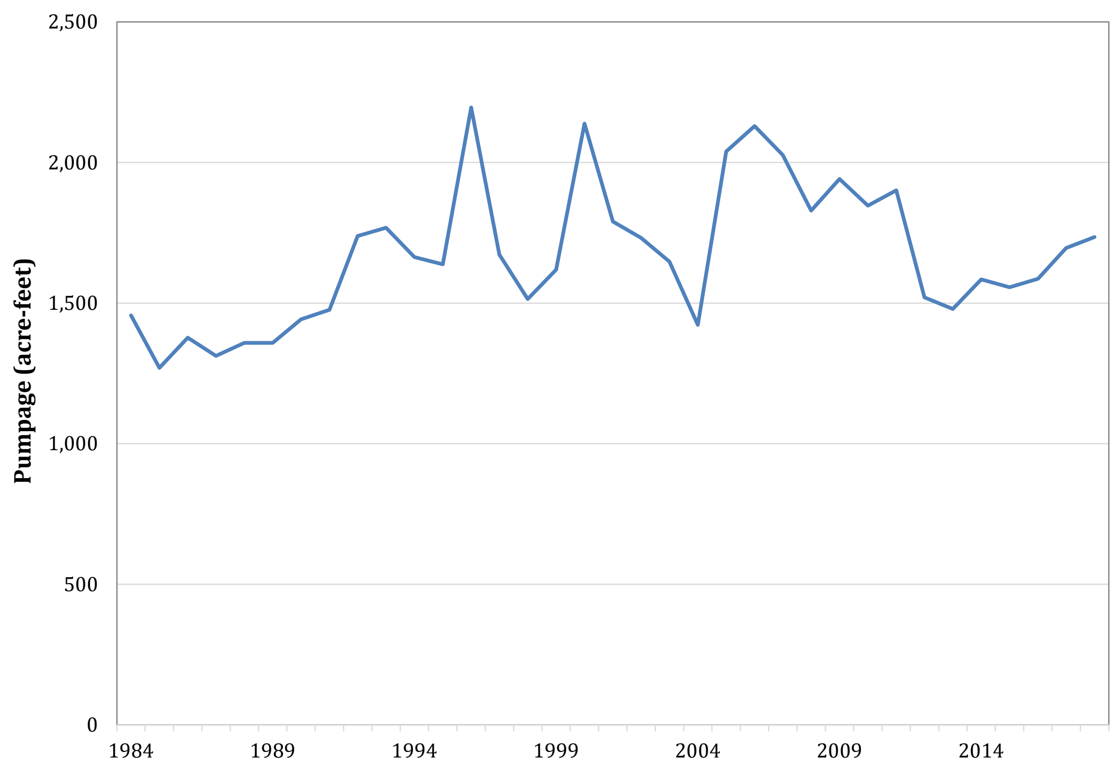


Figure 10-7. Estimated annual livestock pumpage from the Cross Timbers Aquifer.

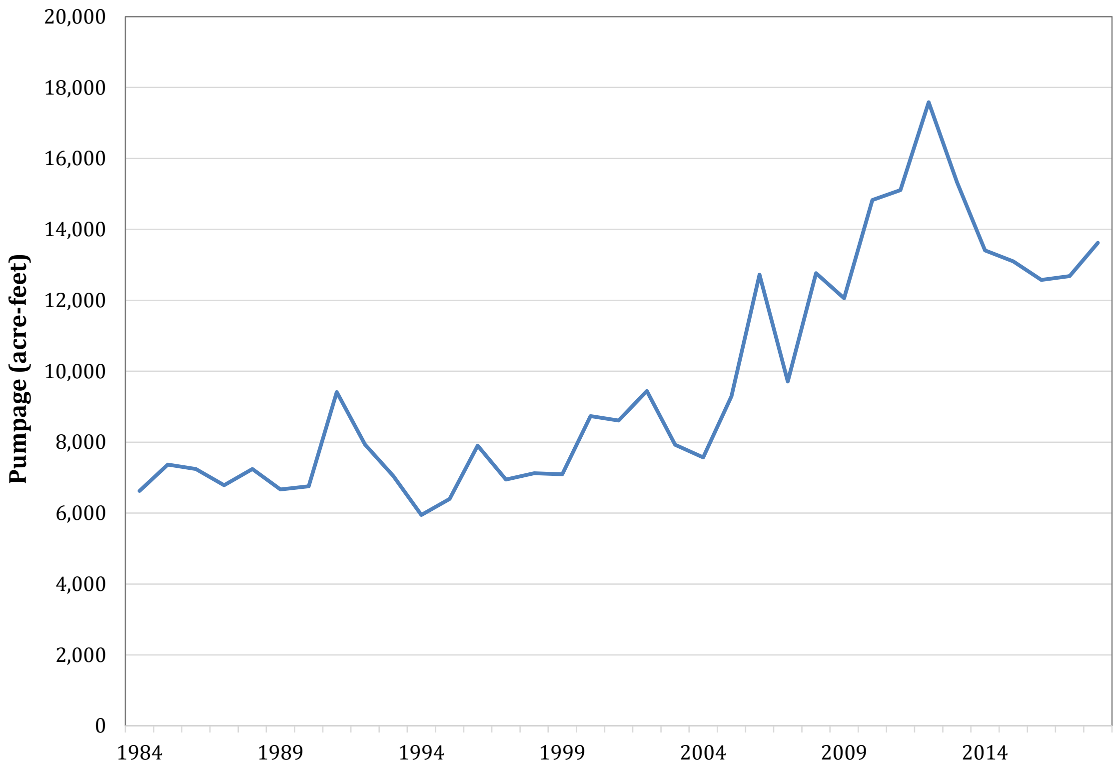


Figure 10-8. Estimated annual non-mining pumpage from the Cross Timbers Aquifer.

10.2. County Groundwater Pumping Summaries

The TWDB has collected groundwater pumping detail for each county starting in the year 2000. These data were used to provide insight into the amount of total estimated pumping that is occurring as non-surveyed estimates, as well as for specific entities that provided survey data to the TWDB. Because this region is generally sparsely populated, it was anticipated that the majority of pumpage that occurs from the Cross Timbers Aquifer is from non-surveyed estimates of municipal, irrigation, and livestock pumpage. The pumpage detail also provides specifics on surveyed entities within the study area, which would primarily be municipal and industrial users. However, as expected, very few specific entities were identified in the pumpage detail for the Cross Timbers Aquifer within the study area. In addition to the pumpage detail from 2000 and later, historical municipal and industrial intake amounts were used to estimate pumpage for specific entities back to the 1950s. As with the pumpage detail from 2000 and later, very few entities were identified in this dataset.

Archer County

In Archer County, 100 percent of the wells included in the "Other Aquifers" pumpage (total of 200 wells) are completed in the Cross Timbers Aquifer. Total pumpage in the county in "Other Aquifers" estimated to be from the Cross Timbers Aquifer has increased from about 200 acre-feet in 2001 to nearly 400 acre-feet in 2018, with a significant increase in response to the drought that occurred in the region in 2011 to 2014 (Figure 10-9). There are no identified individual entities producing groundwater in Archer County.

Baylor County

In Baylor County, 10 percent of the wells included in the "Other Aquifers" pumpage (a total of 7 wells) are completed in the Cross Timbers Aquifer. Total pumpage in the county in "Other Aquifers" estimated to be from the Cross Timbers Aquifer has increased from about 10 acre-feet in 2001 to about 40 acre-feet in 2018, with an increase in response to the drought that occurred in the region in 2011 to 2014 (Figure 10-10). There are no identified individual entities producing groundwater in Baylor County.

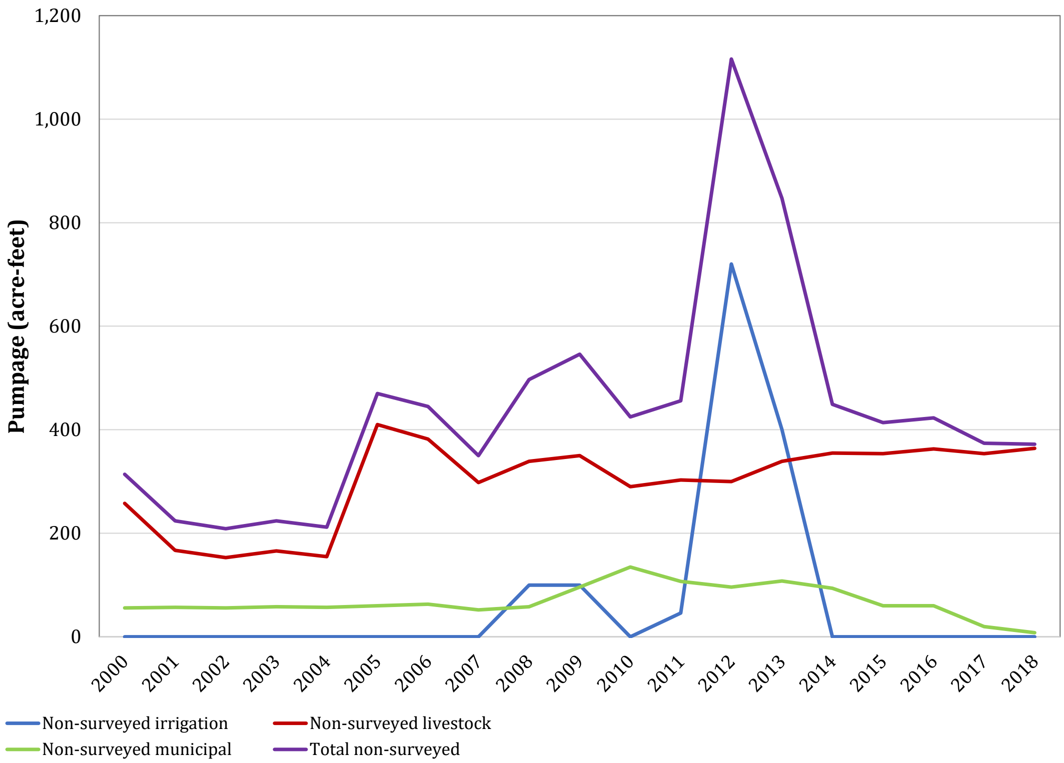


Figure 10-9. Estimated non-surveyed pumpage for the Cross Timbers Aquifer from 2000 to 2018 in Archer County.

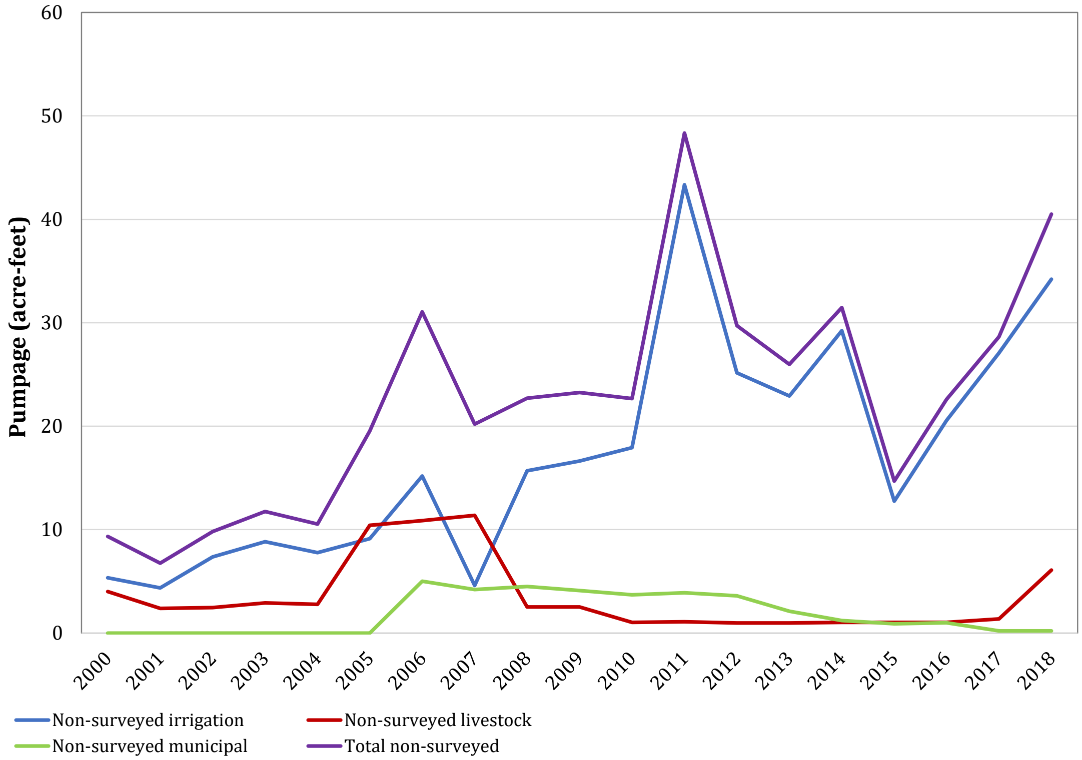


Figure 10-10. Estimated non-surveyed pumpage for the Cross Timbers Aquifer from 2000 to 2018 in Baylor County.

Brown County

In Brown County, 98 percent of the wells included in the "Other Aquifers" pumpage (total of 395 wells) are completed in the Cross Timbers Aquifer. Total pumpage in the county in "Other Aquifers" has remained fairly constant at about 100 acre-feet from 2000 to 2018, with an increase in response to the drought that occurred in the region in 2009 to 2013 (Figure 10-11). In addition to the non-surveyed pumpage shown in Figure 10-11, the Lake Brownwood Christian Retreat had surveyed pumpage of less than 10 acre-feet per year within the county (Table 10-2).

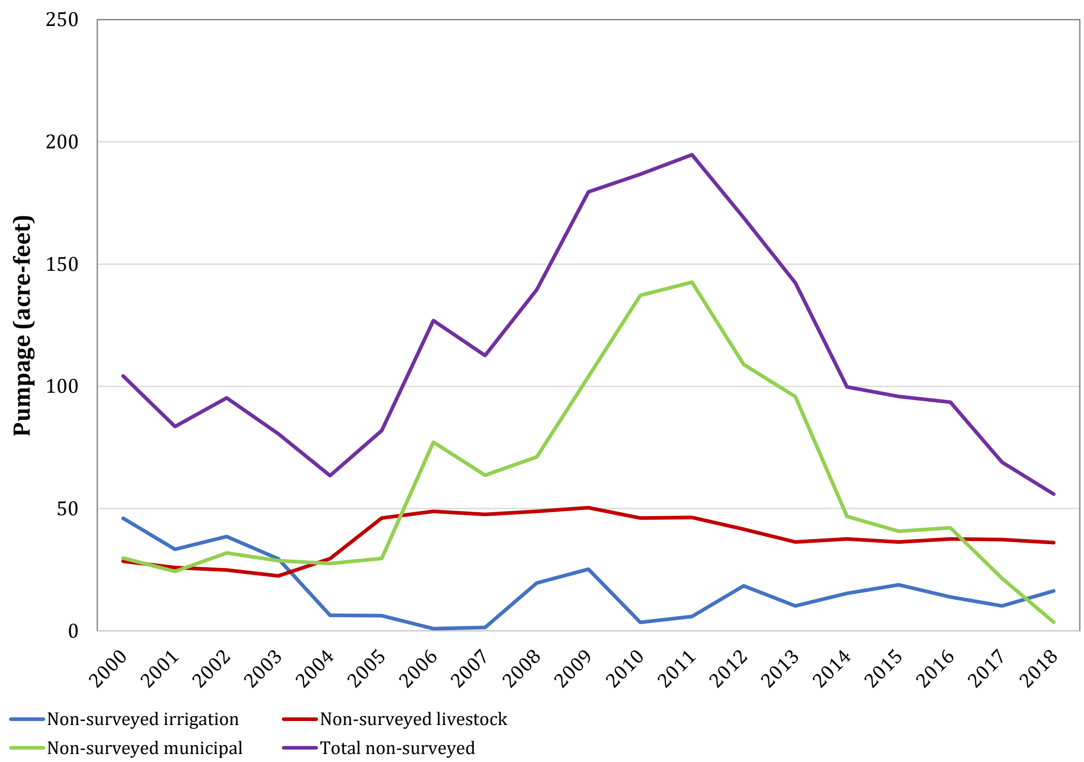


Figure 10-11. Estimated non-surveyed pumpage for the Cross Timbers Aquifer from 2000 to 2018 in Brown County.

Table 10-2. Surveyed pumpage from 2001 to 2015 in Brown County (no data for 2000 or 2016 through 2018.

Year	Lake Brownwood Christian Retreat Surveyed Pumpage (acre-feet)
2001	3.0
2002	3.0
2003	3.0
2004	5.0
2005	4.7
2006	3.1
2007	4.3
2008	4.8
2009	6.0
2010	6.9
2011	6.7
2012	7.9
2013	7.9
2014	4.7
2015	4.3

Callahan County

In Callahan County, 67 percent of the wells included in the "Other Aquifers" pumpage (total of 12 wells) are completed in the Cross Timbers Aquifer. Total pumpage in the county in "Other Aquifers" has increased slightly from 2000 to 2018, but has always been less than 20 acre-feet per year (Figure 10-12). There are no identified individual entities producing groundwater in Callahan County.

Clay County

In Clay County, 86 percent of the wells that will be included in the "Other Aquifers" pumpage (total of 269 wells) are completed in the Cross Timbers Aquifer. Total pumpage in the county in "Other Aquifers" has remained fairly constant at about 1,000 acre-feet from 2000 to 2018, with an increase in response to the drought that occurred in the region in 2009 to 2014 (Figure 10-13).

In addition to the non-surveyed pumpage shown in Figure 10-13, three individual entities had surveyed pumpage from 2000 to 2018 and historical municipal intake pumpage back to 1961: the Bluegrove Water supply Corporation, the City of Bellvue, and the Midway Independent School District. The combined pumpage from these entities is less than 50 acre-feet per year (Table 10-3).

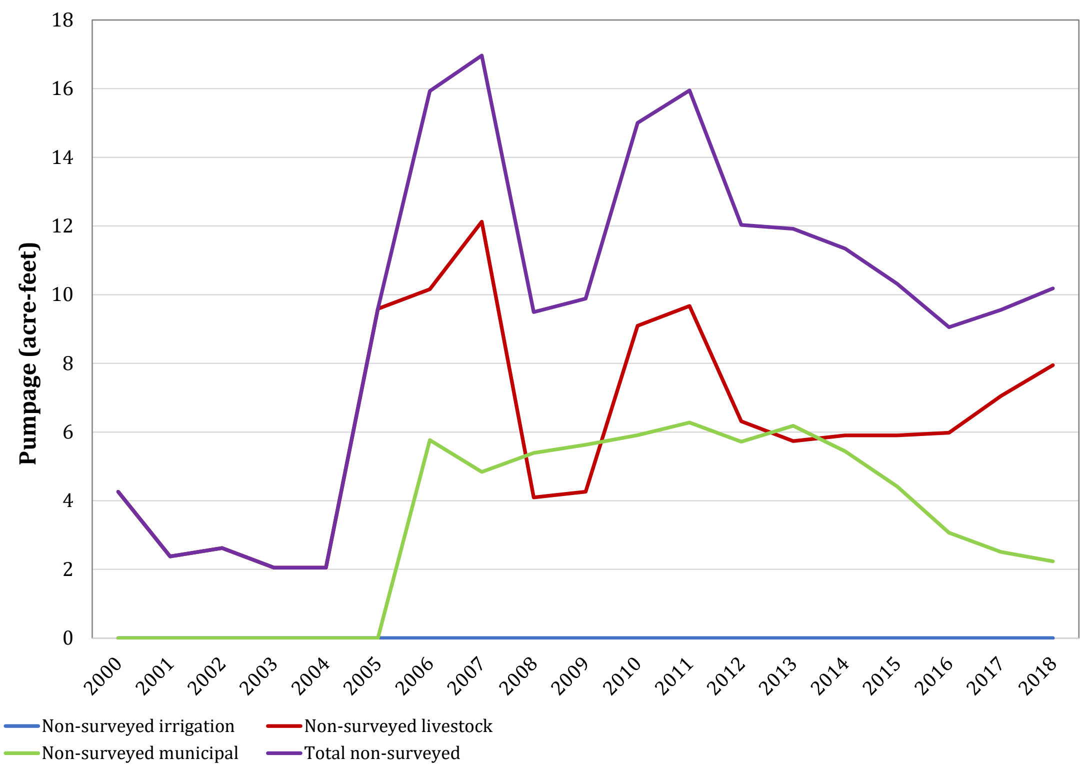


Figure 10-12. Estimated non-surveyed pumpage for the Cross Timbers Aquifer from 2000 to 2018 in Callahan County.

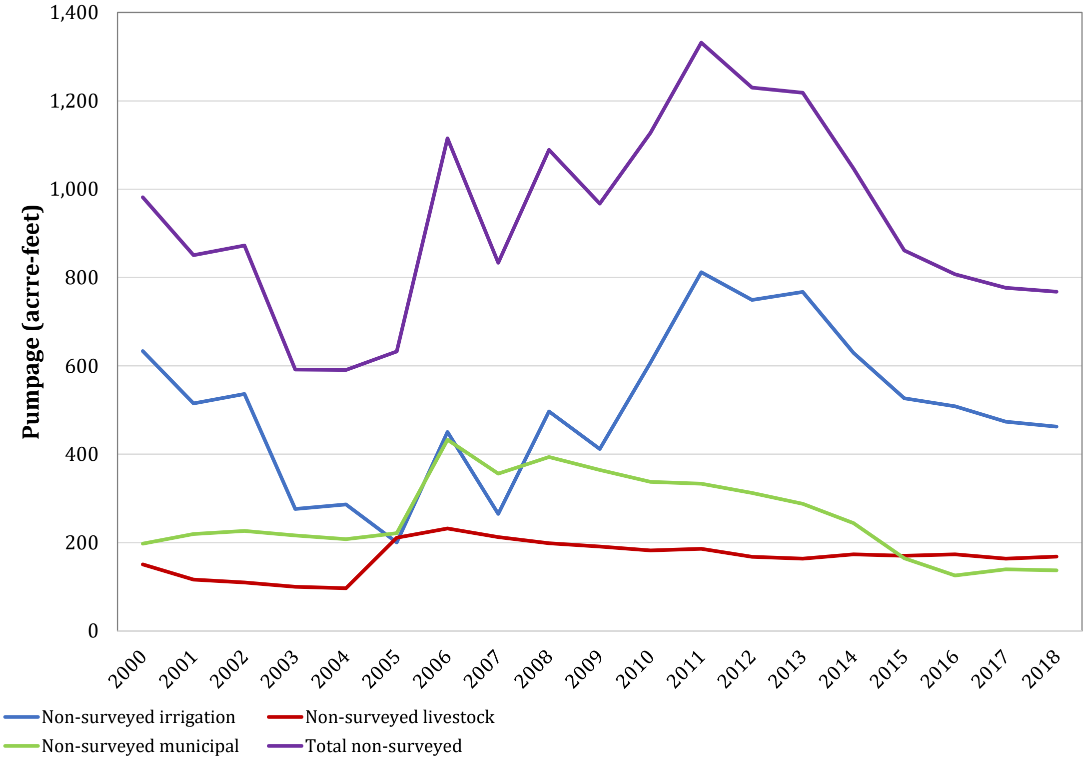


Figure 10-13. Estimated non-surveyed pumpage for the Cross Timbers Aquifer from 2000 to 2018 in Clay County.

Table 10-3. Historical and surveyed pumpage in Clay County.

Year	Pumpage (acre-feet)		
	Bluegrove Water Supply Corporation	City of Bellevue	Midway Independent School Distict
1961		16.6	
1962		16.6	
1963			
1964		15.1	
1965		20.5	
1966		30.8	
1967			
1968		30.8	
1969		21.0	
1970	1.1	21.0	
1971	3.2		
1972	3.5	27.7	
1973	3.7	20.8	
1974	4.5	20.9	
1975	4.1		
1976	5.1	38.4	

Table 10-3 (continued)

Year	Pumpage (acre-feet)		
	Bluegrove Water Supply Corporation	City of Bellevue	Midway Independent School Distict
1977	5.8	45.2	
1978	6.5	42.6	
1979	7.3	42.5	
1980	7.3	48.0	
1981	8.1	44.2	
1982	8.1	44.8	
1983	8.1	46.9	
1984	8.4	46.9	
1985	7.9	45.2	
1986	8.1	45.2	
1987	8.2	45.1	
1988	8.1	45.0	
1989	8.0	44.1	
1990	7.5	42.0	
1991	7.6	41.0	
1992	6.9	40.8	
1993	7.1	44.7	
1994	7.2	41.1	
1995	6.9	42.2	
1996	6.9	42.2	
1997	6.9	42.2	
1998	6.9	42.2	
1999		42.2	
2000	7.4	42.2	
2001	7.4	42.2	
2002	7.4	42.2	
2003	7.4	42.2	
2004	7.4	42.2	
2005	7.2	42.2	
2006	8.6	42.2	
2007	7.4	42.2	
2008	7.1		
2009	7.4		
2010	7.8		
2011	7.1		
2012	6.2		
2013	5.6		1.2
2014	5.4		1.5
2015	6.3	27.7	1.1
2016	5.9	26.3	
2017	5.2	26.6	
2018	4.3	26.6	

Coleman County

In Coleman County, 47 percent of the wells included in the “Other Aquifers” pumpage (total of 229 wells) are completed in the Cross Timbers Aquifer. Total pumpage in the county in “Other Aquifers” has remained fairly constant from 2000 to 2018, and has always been less than 50 acre-feet per year (Figure 10-14). There are no identified individual entities producing groundwater in Coleman County.

Comanche County

In Comanche County, 95 percent of the wells included in the “Other Aquifers” pumpage (total of 73 wells) are completed in the Cross Timbers Aquifer. Total pumpage in the county in “Other Aquifers” has increased from about 800 acre-feet in 2000 to about 1,200 acre-feet in 2018, with an increase in during 2010 to 2019 due to drought (Figure 10-15). There are no identified individual entities producing groundwater that are considered to be producing from the Cross Timbers Aquifer in Comanche County.

Concho County

In Concho County, 59 percent of the wells included in the “Other Aquifers” pumpage (total of 44 wells) are completed in the Cross Timbers Aquifer. Total pumpage in the county in “Other Aquifers” has been somewhat erratic from 2000 to 2018, ranging from 500 acre-feet per year to over 2,000 acre-feet per year (Figure 10-16). There are no identified individual entities producing groundwater that are considered to be producing from the Cross Timbers Aquifer in Concho County.

Eastland County

In Eastland County, 93 percent of the wells included in the “Other Aquifers” pumpage (total of 40 wells) are completed in the Cross Timbers Aquifer. Total pumpage in the county in “Other Aquifers” has varied from 2000 to 2018, but has always been less than 150 acre-feet per year (Figure 10-17). There are no identified individual entities producing groundwater that are considered to be producing from the Cross Timbers Aquifer in Eastland County.

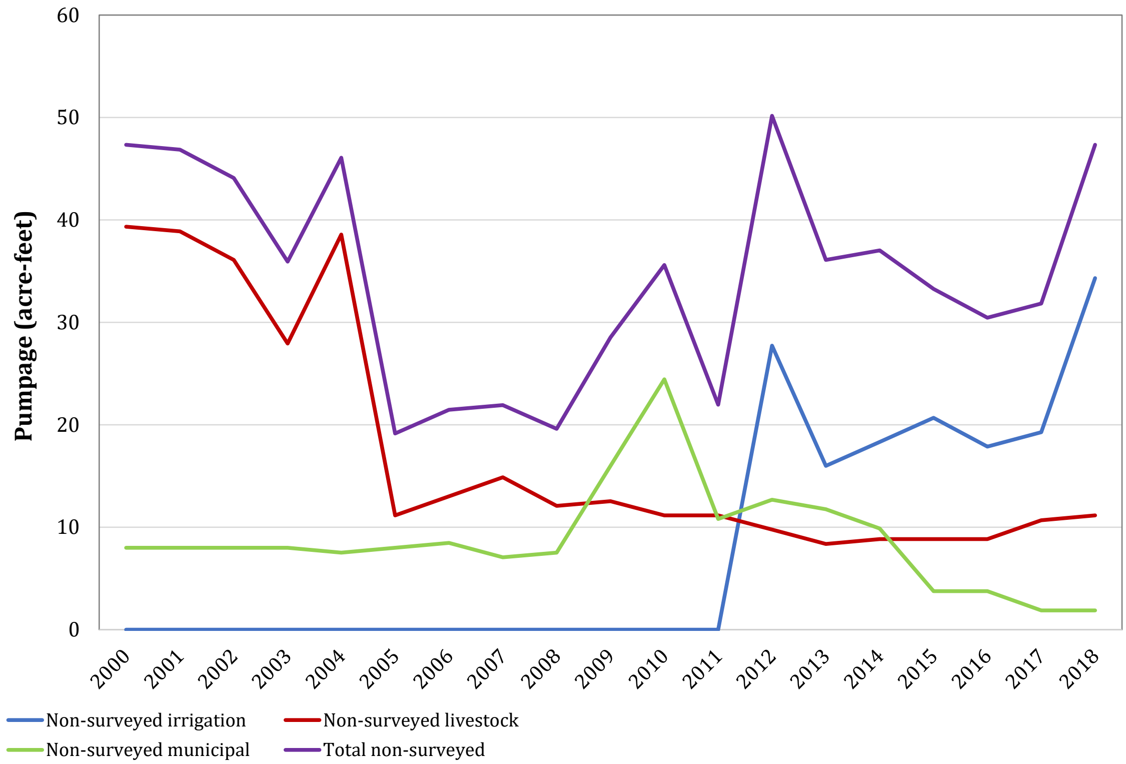


Figure 10-14. Estimated non-surveyed pumpage for the Cross Timbers Aquifer from 2000 to 2018 in Coleman County.

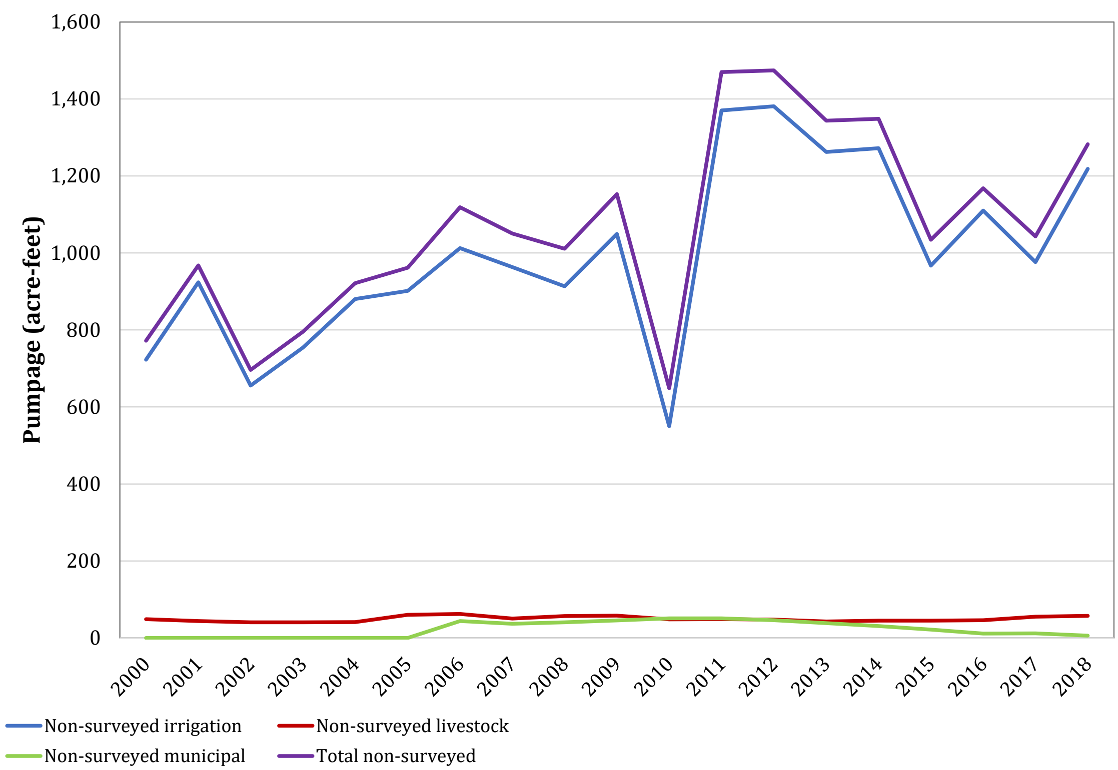


Figure 10-15. Estimated non-surveyed pumpage for the Cross Timbers Aquifer from 2000 to 2018 in Comanche County.

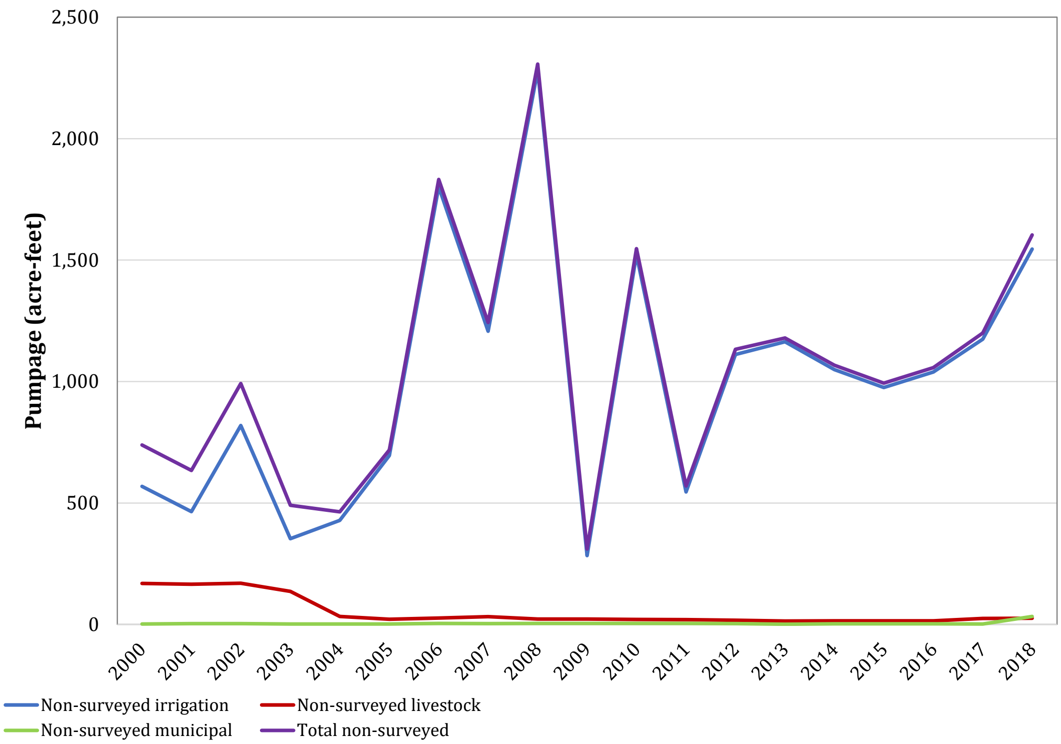


Figure 10-16. Estimated non-surveyed pumpage for the Cross Timbers Aquifer from 2000 to 2018 in Concho County.

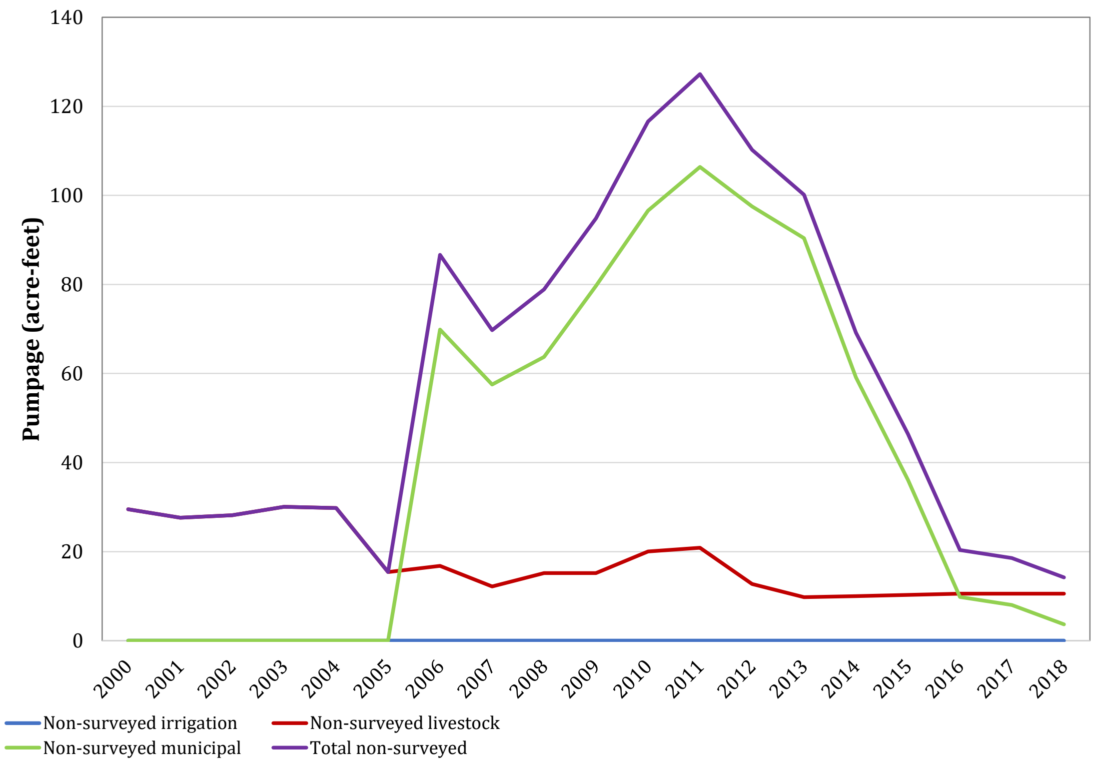


Figure 10-17. Estimated non-surveyed pumpage for the Cross Timbers Aquifer from 2000 to 2018 in Eastland County.

Erath County

In Erath County, 100 percent of the wells that will be included in the “Other Aquifers” pumpage (total of 3 wells) are completed in the Cross Timbers Aquifer. However, there is no surveyed or non-surveyed pumpage in Erath County that is potentially from the Cross Timbers Aquifer.

Haskell County

In Haskell County, 94 percent of the wells that will be included in the “Other Aquifers” pumpage (total of 51 wells) are completed in the Cross Timbers Aquifer. Total pumpage in the county in “Other Aquifers” has remained fairly constant from 2000 to 2018, at about 300 acre-feet per year, with an increase between 2011 and 2014 during the drought that occurred in the region (Figure 10-18). There are no identified individual entities producing groundwater in Haskell County.

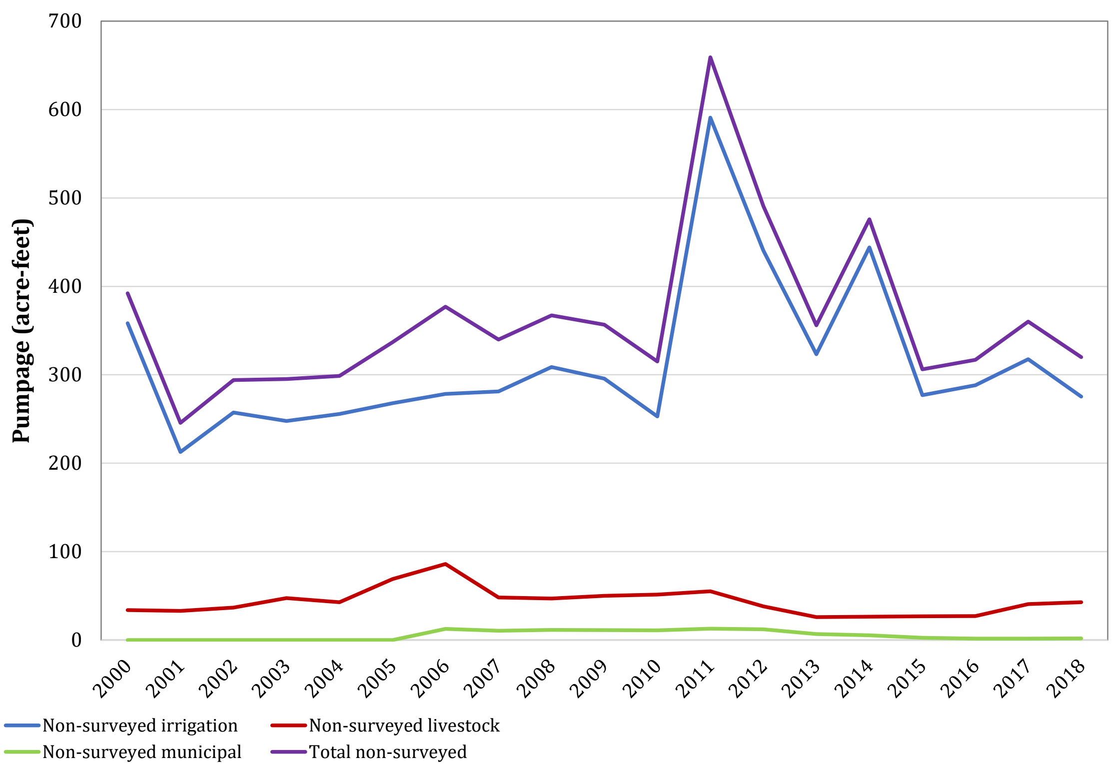


Figure 10-18. Estimated non-surveyed pumpage for the Cross Timbers Aquifer from 2000 to 2018 in Haskell County.

Jack County

In Jack County, 100 percent of the wells that will be included in the “Other Aquifers” pumpage (total of 363 wells) are completed in the Cross Timbers Aquifer. Total pumpage in the county in “Other Aquifers” has increased slightly from about 100 acre-feet in 2000 to nearly 400 acre-feet in 2018, with an increase in response to the drought that occurred in the region in 2009 to 2014 (Figure 10-19). In addition to the non-surveyed pumpage shown in Figure 10-19, three individual entities had surveyed pumpage from 2000 to 2018. These are the City of Bryson, the Perrin Water System, and the Perrin Whitt Independent School District. Total pumpage from these entities is less than 50 acre-feet per year (Table 10-4).

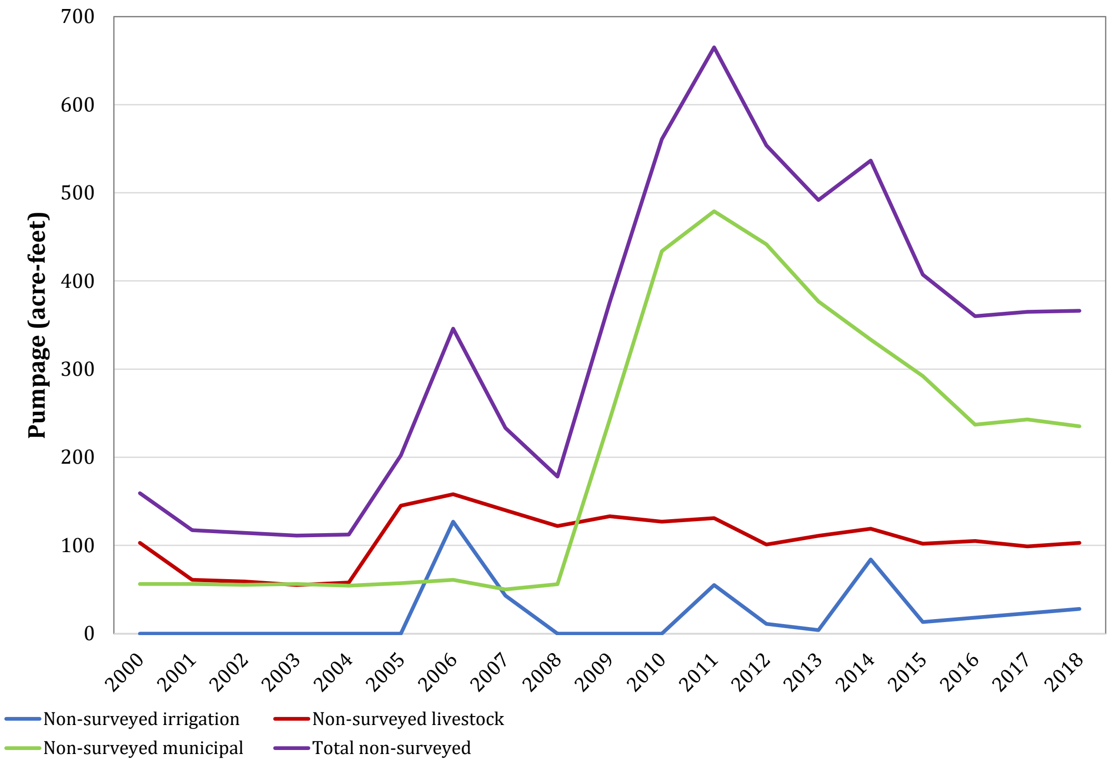


Figure 10-19. Estimated non-surveyed pumpage for the Cross Timbers Aquifer from 2000 to 2018 in Jack County.

Table 10-4. Surveyed pumpage from 2000 to 2018 in Jack County

Year	Surveyed Pumpage (acre-feet)		
	City of Bryson	Perrin Water System	Perrin Whitt Independent School District
2000			3.1
2001		28.8	3.1
2002		26.4	2.8
2003		21.7	3.1
2004		22.7	2.5
2005		23.3	3.1
2006		24.3	3.0
2007			2.7
2008			2.7
2009		27.7	2.6
2010		17.6	3.1
2011		21.7	3.1
2012		19.0	3.4
2013		23.2	2.6
2014		18.5	2.6
2015		27.7	3.0
2016	15.4	28.2	
2017	17.0	34.7	
2018	19.0	46.4	

Jones County

In Jones County, 61 percent of the wells included in the “Other Aquifers” pumpage (total of 276 wells) are completed in the Cross Timbers Aquifer. Total pumpage in the county in “Other Aquifers” has been variable from 2000 to 2018, ranging from about 500 to 1,600 acre-feet per year (Figure 10-20). There are no identified individual entities producing groundwater in Jones County.

Lampasas County

In Lampasas County, 27 percent of the wells included in the “Other Aquifers” pumpage (total of 4 wells) are completed in the Cross Timbers Aquifer. Total pumpage in the county in “Other Aquifers” has remained fairly constant from 2000 to 2018, but has always been less than 35 acre-feet per year (Figure 10-21). There are no identified individual entities producing groundwater in Lampasas County.

In addition to the Cross Timbers Aquifer, non-surveyed pumpage was identified for the Marble Falls Aquifer in Lampasas County (Figure 10-22). This pumpage has appeared to decline over time, and is less than 100 acre-feet per year for the entire time period (Figure 10-22).

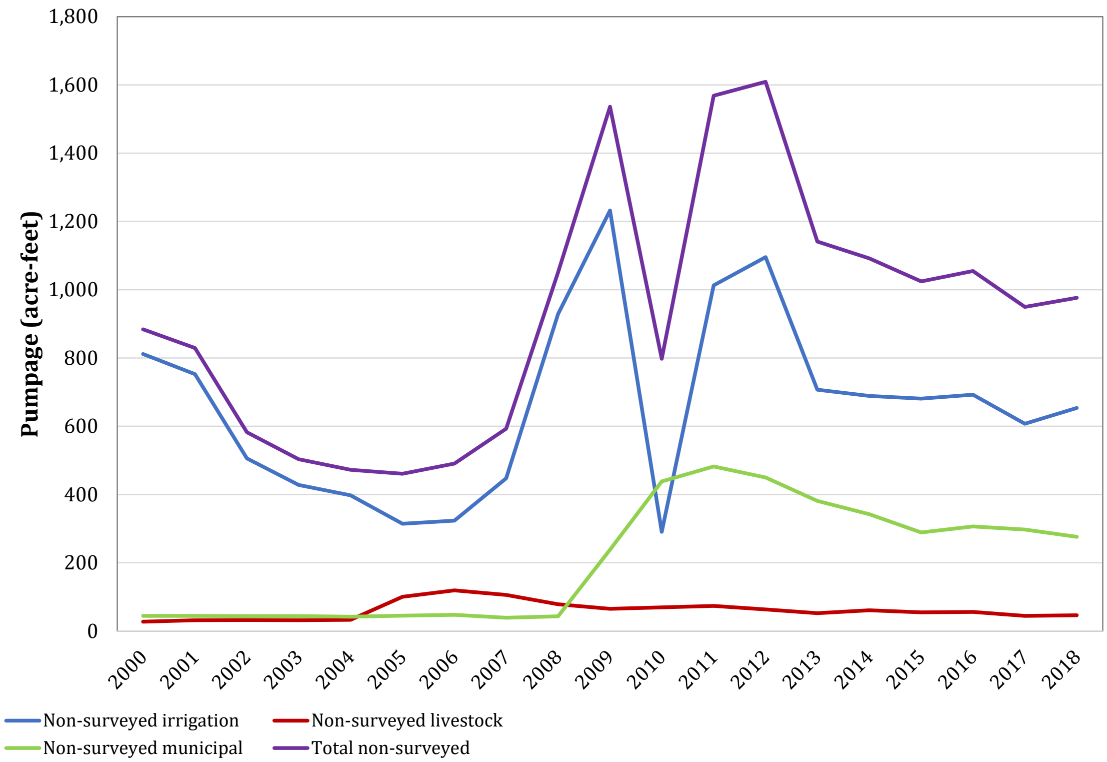


Figure 10-20. Estimated non-surveyed pumpage for the Cross Timbers Aquifer from 2000 to 2018 in Jones County.

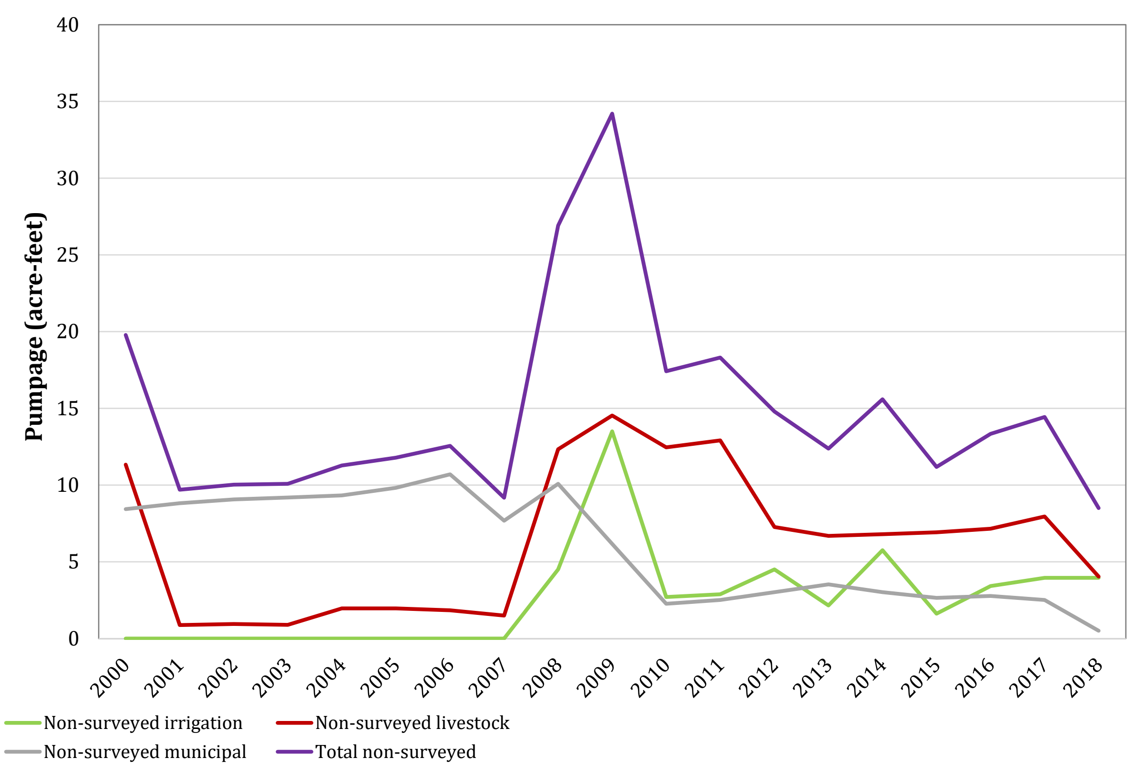


Figure 10-21. Estimated non-surveyed pumpage for the Cross Timbers Aquifer from 2000 to 2018 in Lampasas County.

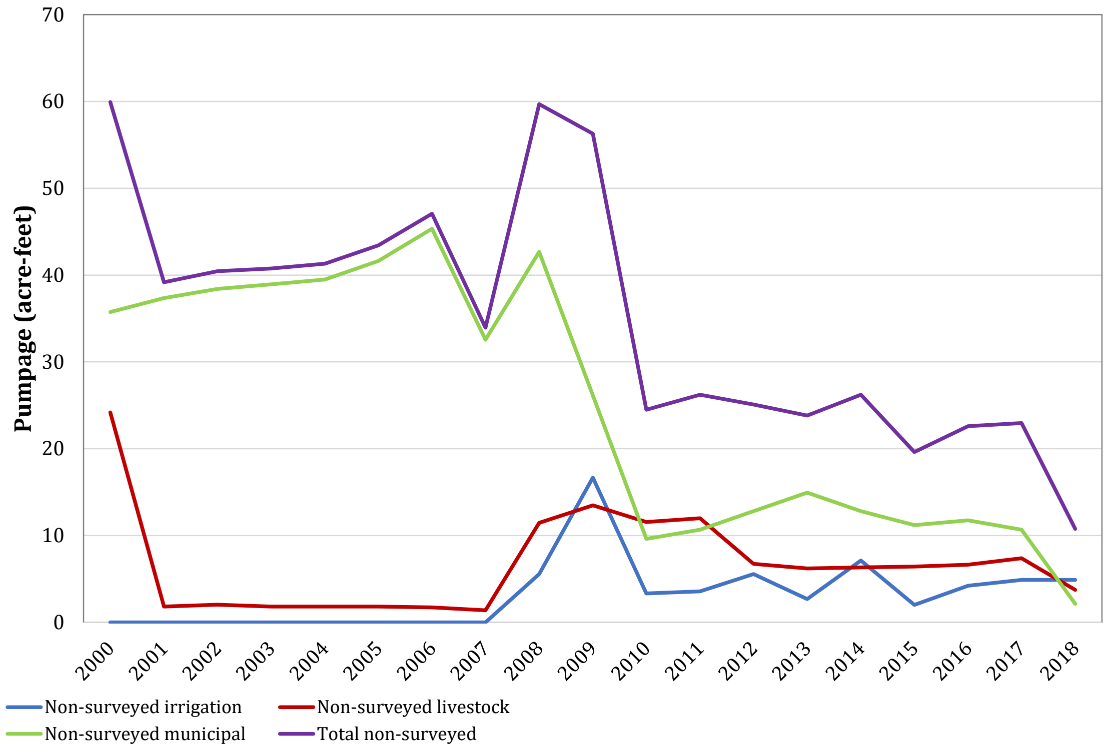


Figure 10-22. Estimated non-surveyed pumpage for the Marble Falls Aquifer from 2000 to 2018 in Lampasas County.

McCulloch County

In McCulloch County, 10 percent of the wells included in the "Other Aquifers" pumpage (total of 4 wells) are completed in the Cross Timbers Aquifer. Total pumpage in the county in "Other Aquifers" has decreased from 2000 to 2018, but has been less than 15 acre-feet per year (Figure 10-23). The only identified individual entity that has produced groundwater in McCulloch County is the City of Mercury, which had a Cross Timbers Aquifer well that was pumped from 1955 to 1980 (Table 10-5).

In addition to the Cross Timbers Aquifer, non-surveyed pumpage was identified for the Marble Falls Aquifer in McCulloch County. This pumpage has declined over time, and is less than 60 acre-feet per year for the entire time period (Figure 10-24).

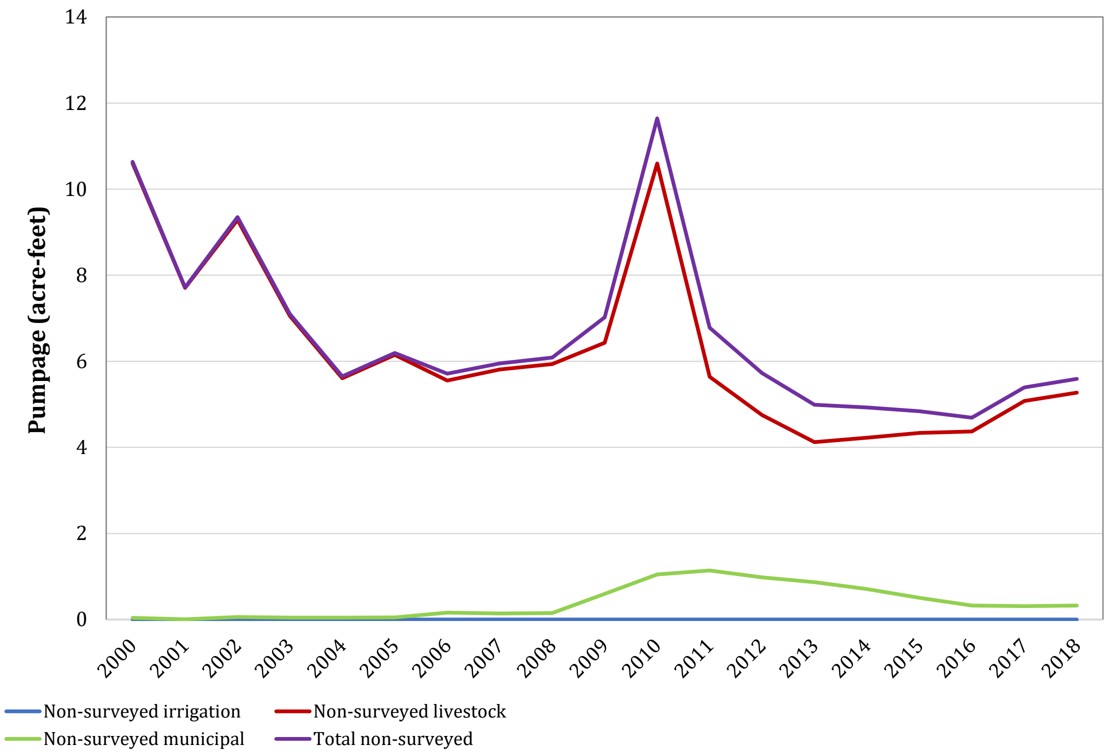


Figure 10-23. Estimated non-surveyed pumpage for the Cross Timbers Aquifer from 2000 to 2018 in McCulloch County.

Table 10-5. Historical pumpage in McCulloch County

Year	City of Mercury Historical Pumpage (acre-feet)
1955	11.8
1963	8.1
1966	11.5
1967	5.5
1970	1.5
1971	1.3
1972	1.1
1973	1.6
1974	1.7
1975	1.3
1976	1.9
1977	0.8
1979	1.5
1980	1.8

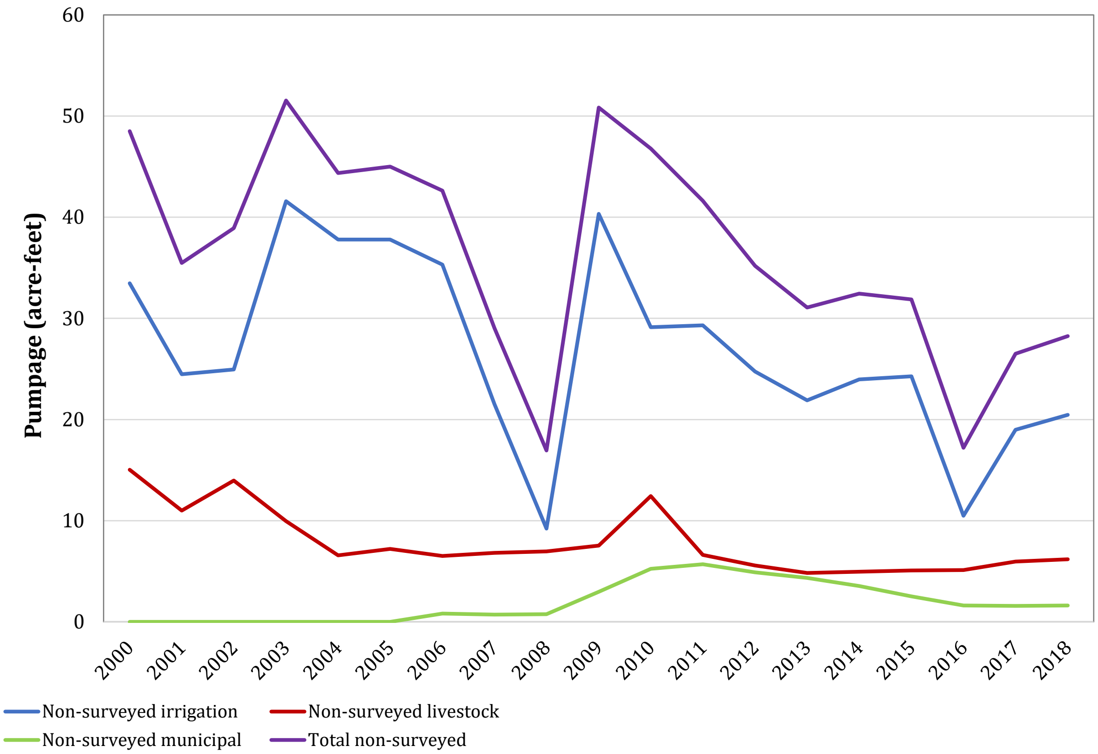


Figure 10-24. Estimated non-surveyed pumpage for the Marble Falls Aquifer from 2000 to 2018 in McCulloch County.

Mills County

In Mills County, 75 percent of the wells included in the "Other Aquifers" pumpage (total of 3 wells) are completed in the Cross Timbers Aquifer. Total pumpage in the county in "Other Aquifers" has decreased from about 140 acre-feet in 2000 to about 20 acre-feet in 2018 (Figure 10-25). There are no identified individual entities producing groundwater in Mills County.

Montague County

In Montague County, 90 percent of the wells included in the "Other Aquifers" pumpage (total of 340 wells) are completed in the Cross Timbers Aquifer. Total pumpage in the county in "Other Aquifers" has remained fairly constant from 2000 to 2018 at around 800 acre-feet per year, with an increase from 2009 to 2013 due to drought conditions that occurred in the region (Figure 10-26).

Three entities were identified as having produced from the Cross Timbers Aquifer prior to 2000 from the historical municipal intake estimates: the City of Saint Jo, the Nocona Hills Water Supply Corporation, and the Red River Authority–Ringold facility. This pumpage is shown in Table 10-6.

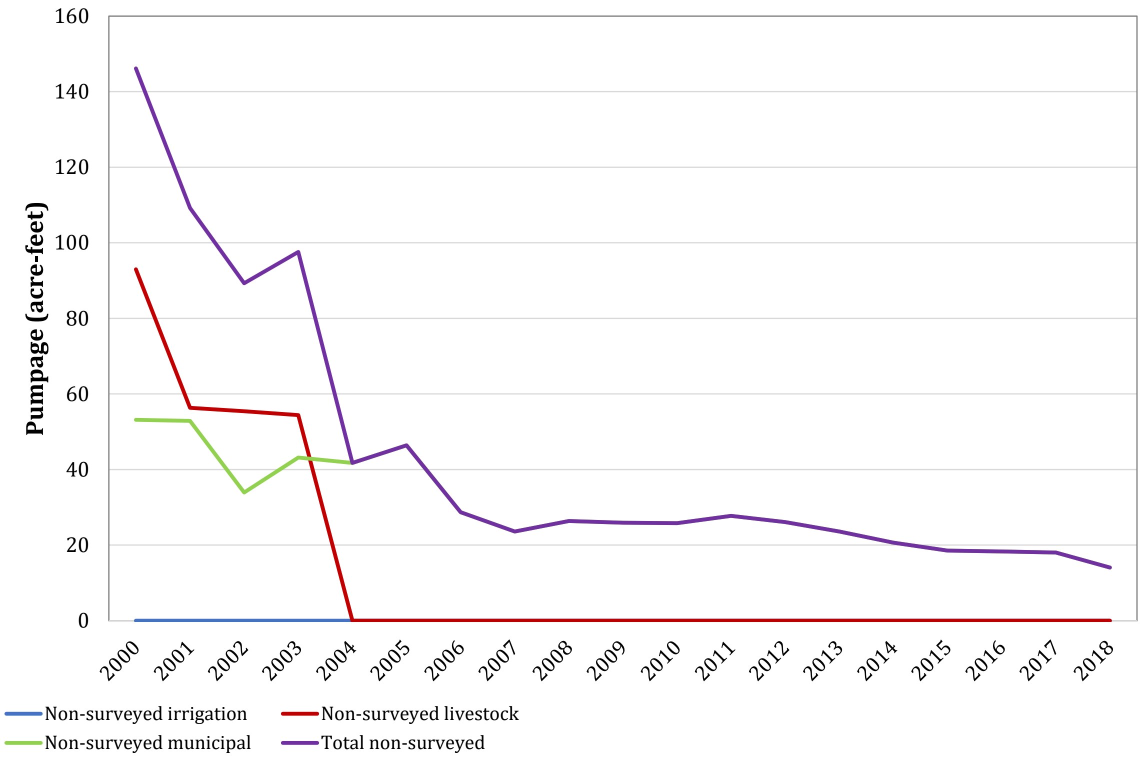


Figure 10-25. Estimated non-surveyed pumpage for the Cross Timbers Aquifer from 2000 to 2018 in Mills County.

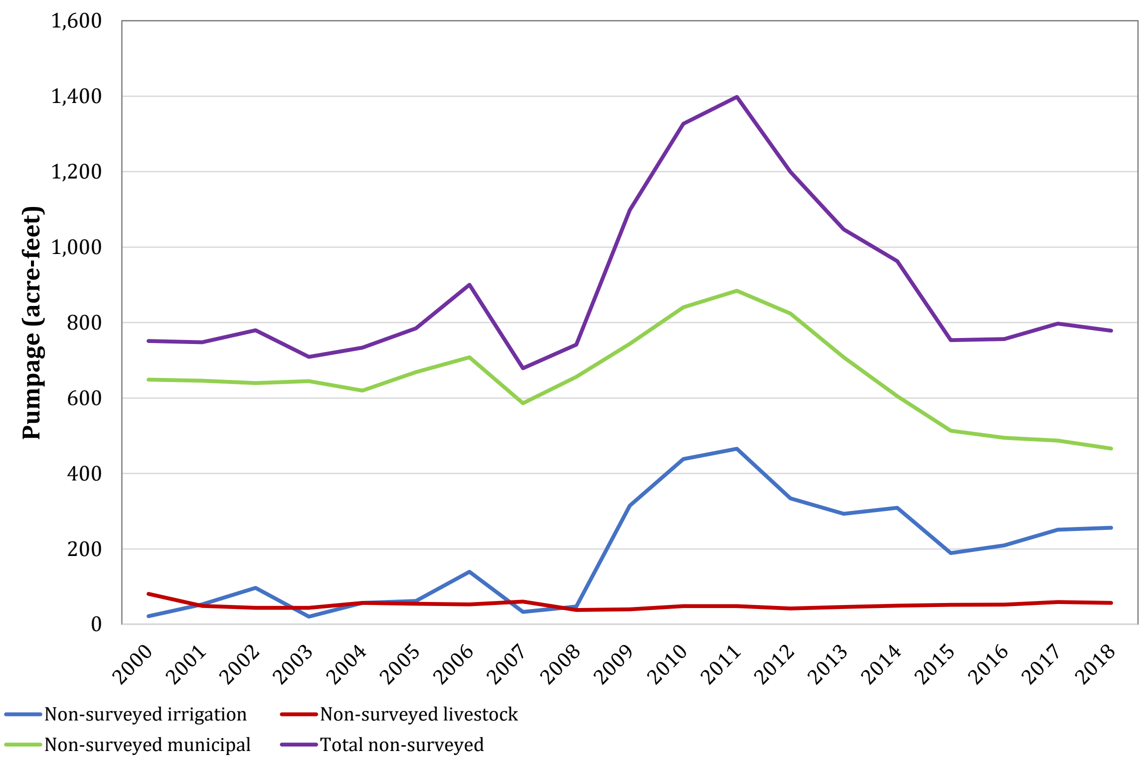


Figure 10-26. Estimated non-surveyed pumpage for the Cross Timbers Aquifer from 2000 to 2018 in Montague County.

Table 10-6. Historical pumpage in Montague County

Year	Historical Pumpage (acre-feet)		
	City of Saint Jo	Nocona Hills Water Supply Corporation	RRA - Ringold
1955			
1956			
1957			
1958	69.1		
1959	83.8		
1960	87.0		
1961	95.9		
1962	95.8		
1963	116.8		
1964			
1965	93.2		
1966	102.9		
1967	112.4		
1968	116.6		5.5
1969	124.5		8.8
1970	129.6		9.3
1971	123.9		9.3
1972	142.3		9.4
1973	132.3		28.1
1974	133.5		9.6
1975	121.3		9.8
1976	134.8		11.2
1977	139.5	55.9	16.9
1978	146.6	55.4	22.3
1979	139.8	55.2	19.7
1980	174.6	89.3	21.2
1981	148.7	76.2	18.4
1982	135.2	67.7	18.6
1983	135.8	82.4	18.8
1984	149.0	99.2	17.9
1985	143.3	65.3	19.6
1986	147.2	58.9	21.9
1987	143.7	54.7	20.6
1988	156.2	67.8	24.3
1989	148.5	58.6	23.9
1990	151.6	55.1	20.2
1991	142.0	59.6	24.6
1992	126.1	53.6	19.7

Table 10-6 (continued)

Year	Historical Pumpage (acre-feet)		
	City of Saint Jo	Nocona Hills Water Supply Corporation	RRA - Ringold
1993	148.6	60.7	17.8
1994	147.0	73.8	18.0
1995	135.9	69.9	19.1
1996	186.6	76.7	21.1
1997	186.2	83.4	19.5
1998	230.3	102.4	20.7
1999	178.4	91.4	19.5

Palo Pinto County

In Palo Pinto County, 97 percent of the wells that will be included in the "Other Aquifers" pumpage (a total of 58 wells) are completed in the Cross Timbers Aquifer. Total pumpage in the county in "Other Aquifers" has remained fairly constant from 2000 to 2018, at between 400 and 600 acre-feet per year, with a significant increase from 2010 to 2013 during the drought that occurred in the region (Figure 10-27). There are no identified individual entities producing groundwater in Palo Pinto County.

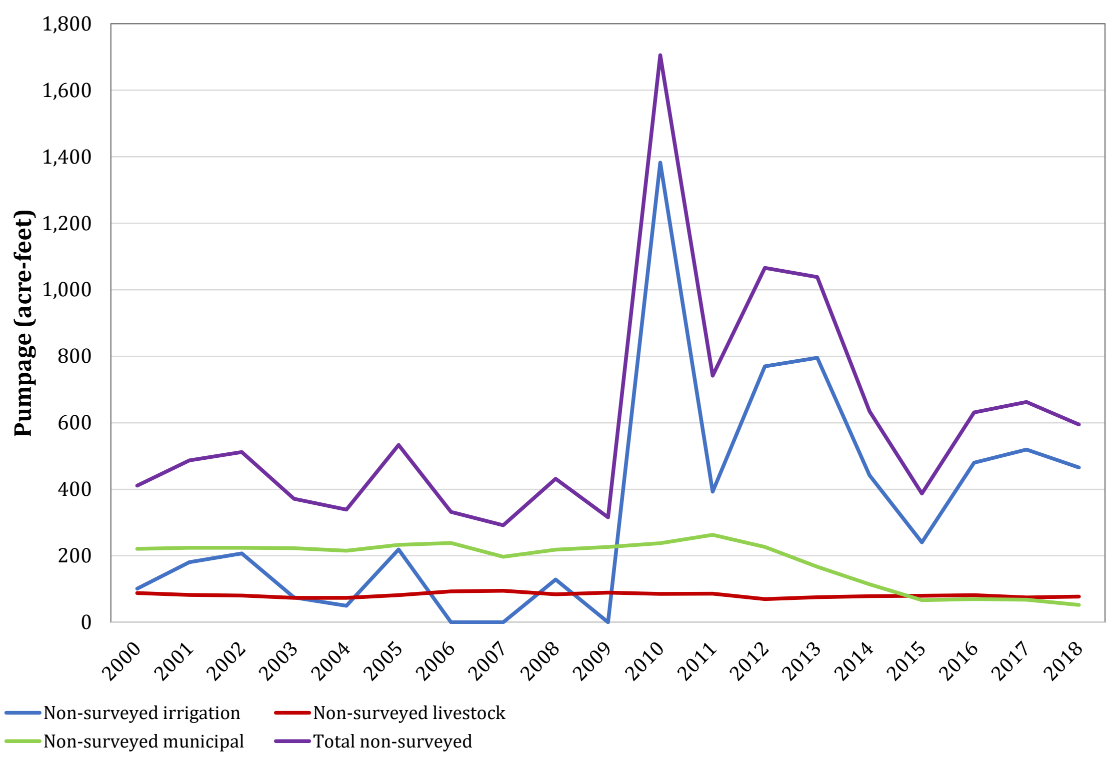


Figure 10-27. Estimated non-surveyed pumpage for the Cross Timbers Aquifer from 2000 to 2018 in Palo Pinto County.

Parker County

In Parker County, 73 percent of the wells included in the “Other Aquifers” pumpage (a total of 36 wells) are completed in the Cross Timbers Aquifer. Total pumpage in the county in “Other Aquifers” has increased from about 50 acre-feet in 2000 to 400 acre-feet in 2018, with a slight increase in response to the drought that occurred in the region in 2009 to 2014 (Figure 10-28). One entity was determined to have produced from the Cross Timbers Aquifer historically: the Whitt Water Supply Corporation produced small amounts of groundwater from 1967 to 1999 (Table 10-7).

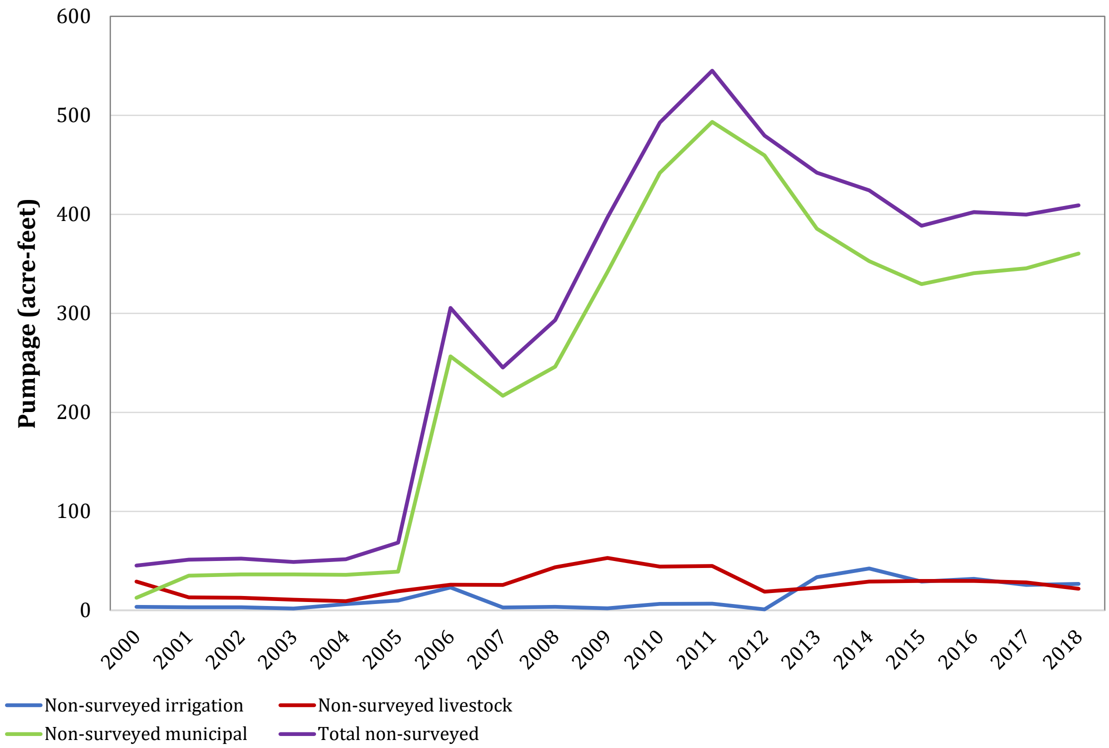


Figure 10-28. Estimated non-surveyed pumpage for the Cross Timbers Aquifer from 2000 to 2018 in Parker County.

Table 10-7. Historical pumpage in Parker County

Year	Historical Pumpage for Whitt Water Supply Corporation (acre-feet)
1967	6.1
1969	4.9
1970	6.5
1971	5.9
1972	6.6
1973	7.2
1974	6.8
1975	5.8
1976	8.7
1977	7.5
1978	5.3
1979	5.7
1981	8.2
1982	7.7
1983	9.7
1984	7.2
1985	12.7
1986	7.7
1987	8.2
1988	8.8
1989	7.6
1990	7.4
1991	7.4
1992	7.7
1993	8.0
1994	7.5
1995	9.0
1996	8.5
1997	7.4
1998	9.4
1999	7.8

Runnels County

In Runnels County, 92 percent of the wells included in the "Other Aquifers" pumpage (a total of 280 wells) are completed in the Cross Timbers Aquifer. Total pumpage in the county in "Other Aquifers" has increased from about 500 acre-feet in 2000 to 3,500 acre-feet in 2018 (Figure 10-29). There are no identified individual entities producing groundwater in Runnels County.

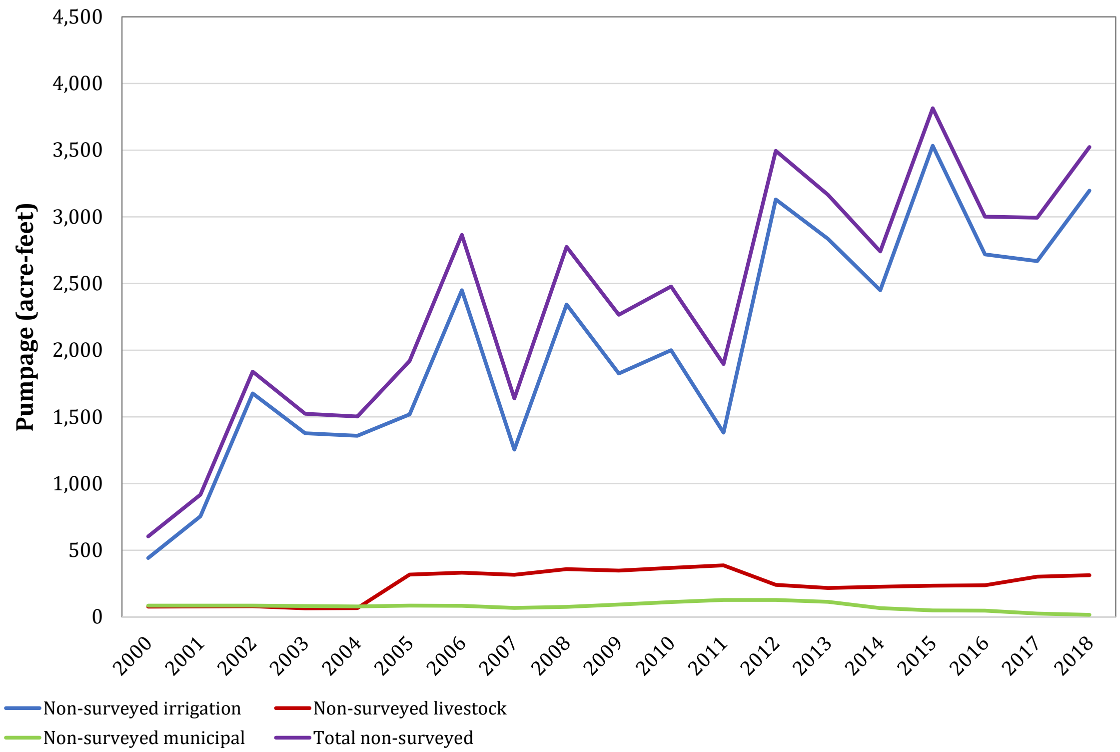


Figure 10-29. Estimated non-surveyed pumpage for the Cross Timbers Aquifer from 2000 to 2018 in Runnels County.

San Saba County

In San Saba County, 39 percent of the wells that will be included in the "Other Aquifers" pumpage (a total of 15 wells) are completed in the Cross Timbers Aquifer. Total pumpage in the county in "Other Aquifers" has increased from about 30 acre-feet in 2000 to 50 acre-feet in 2018 (Figure 10-30). There are no identified individual entities producing groundwater in San Saba County.

In addition to the Cross Timbers, non-surveyed pumpage was identified for the Marble Falls Aquifer in San Saba County. This pumpage has declined significantly over this time period, from approximately 400 acre-feet per year to less than 50 acre-feet per year after 2006 (Figure 10-31).

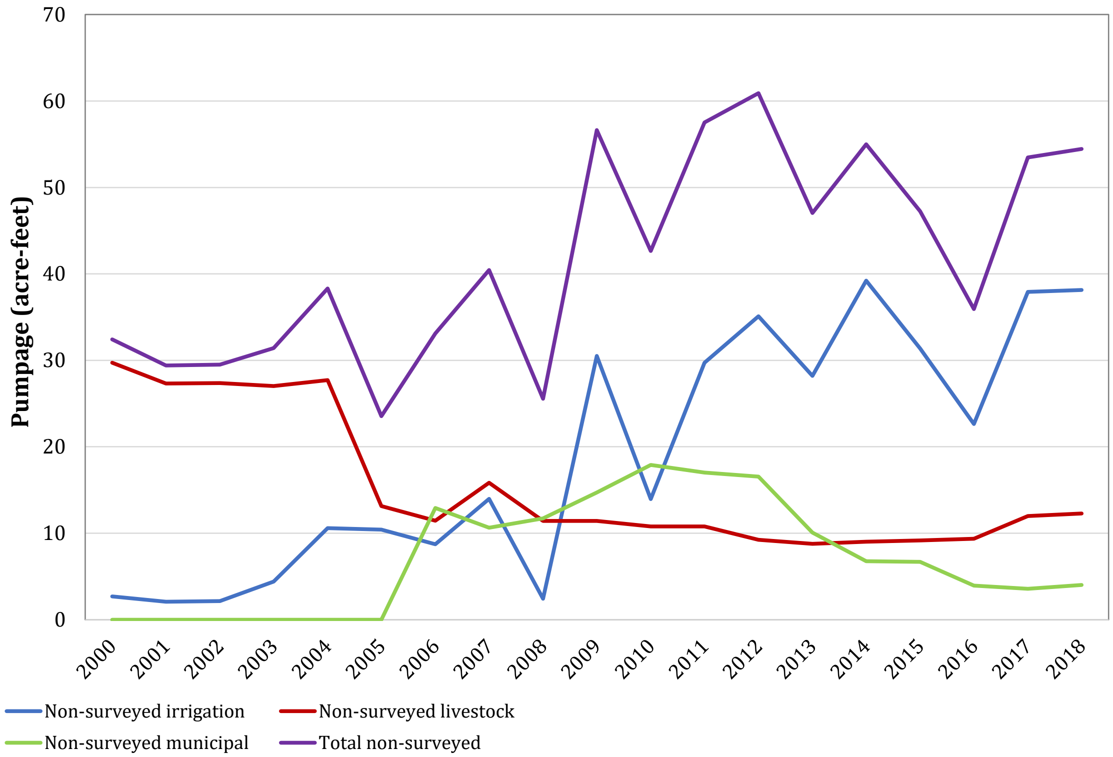


Figure 10-30. Estimated non-surveyed pumpage for the Cross Timbers Aquifer from 2000 to 2018 in San Saba County.

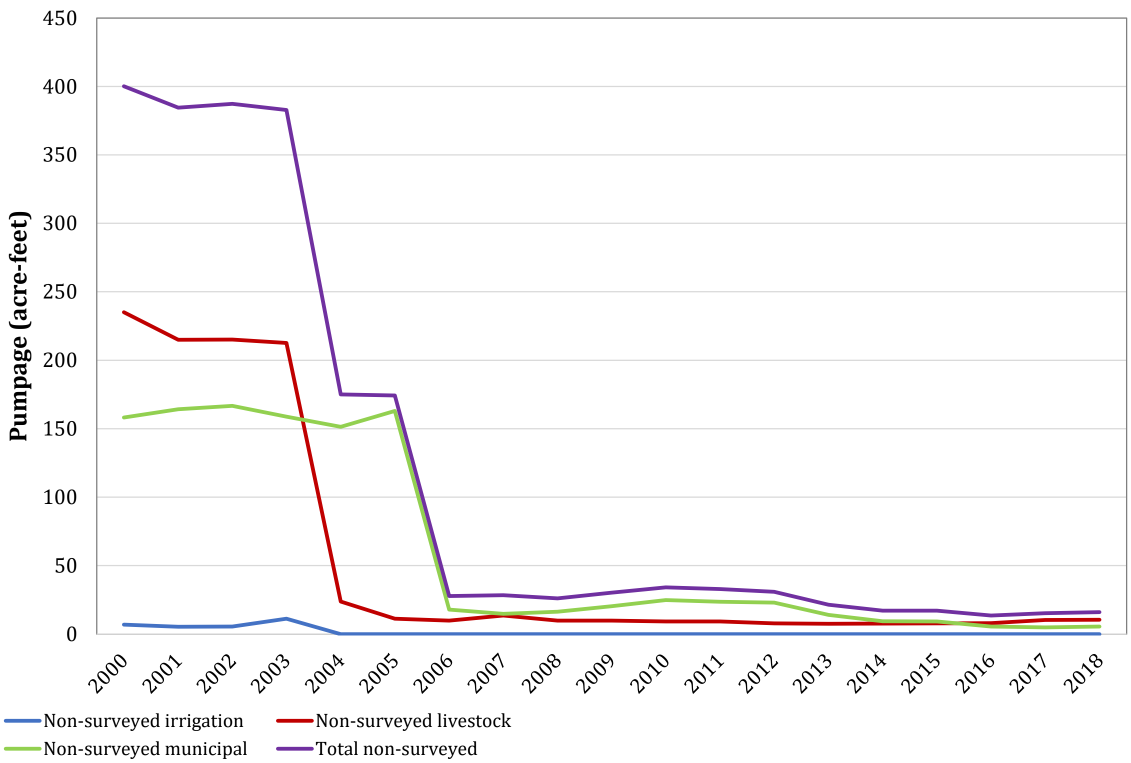


Figure 10-31. Estimated non-surveyed pumpage for the Marble Falls Aquifer from 2000 to 2018 in San Saba County.

Shackelford County

In Shackelford County, 79 percent of the wells included in the “Other Aquifers” pumpage (a total of 56 wells) are completed in the Cross Timbers Aquifer. Total pumpage in the county in “Other Aquifers” has been fairly erratic from 2000 to 2018, but has always been less than 300 acre-feet per year (Figure 10-32). There are no identified individual entities producing groundwater in Shackelford County.

Stephens County

In Stephens County, 90 percent of the wells that will be included in the “Other Aquifers” pumpage (a total of 234 wells) are completed in the Cross Timbers Aquifer. Total pumpage in the county in “Other Aquifers” has decreased slightly from 2000 to 2018, but has always been less than 200 acre-feet per year (Figure 10-33). There are no identified individual entities producing groundwater in Stephens County.

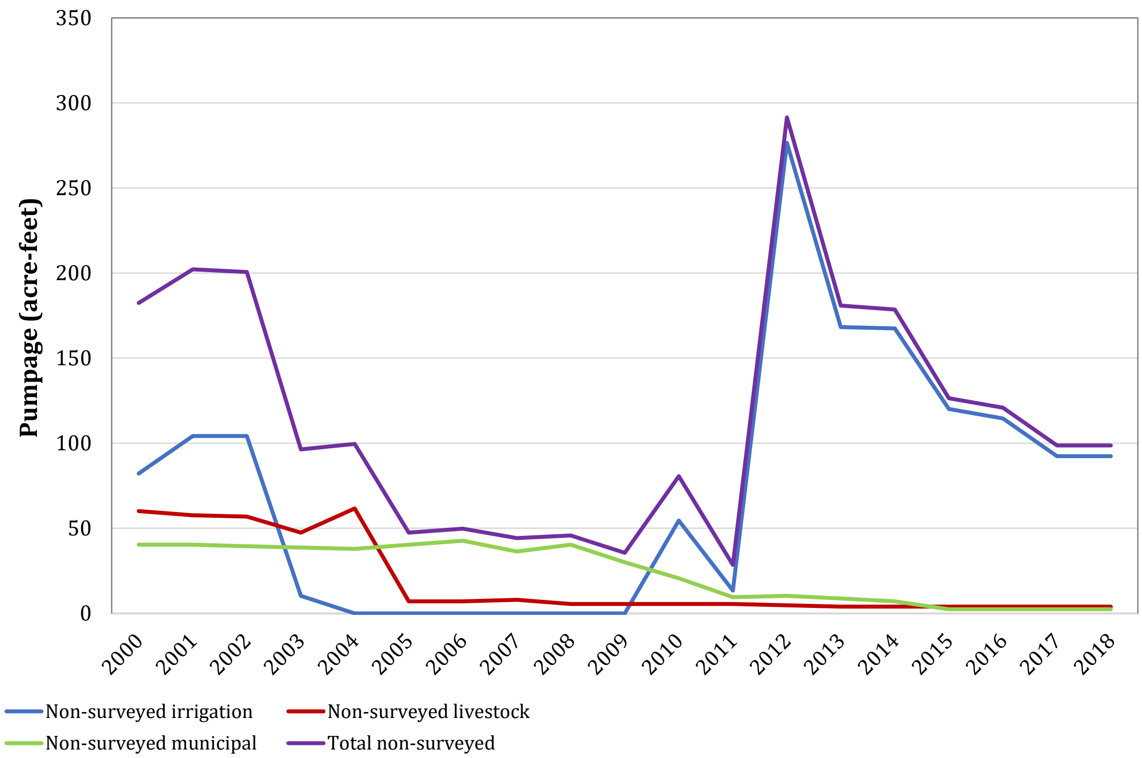


Figure 10-32. Estimated non-surveyed pumpage for the Cross Timbers Aquifer from 2000 to 2018 in Shackelford County.

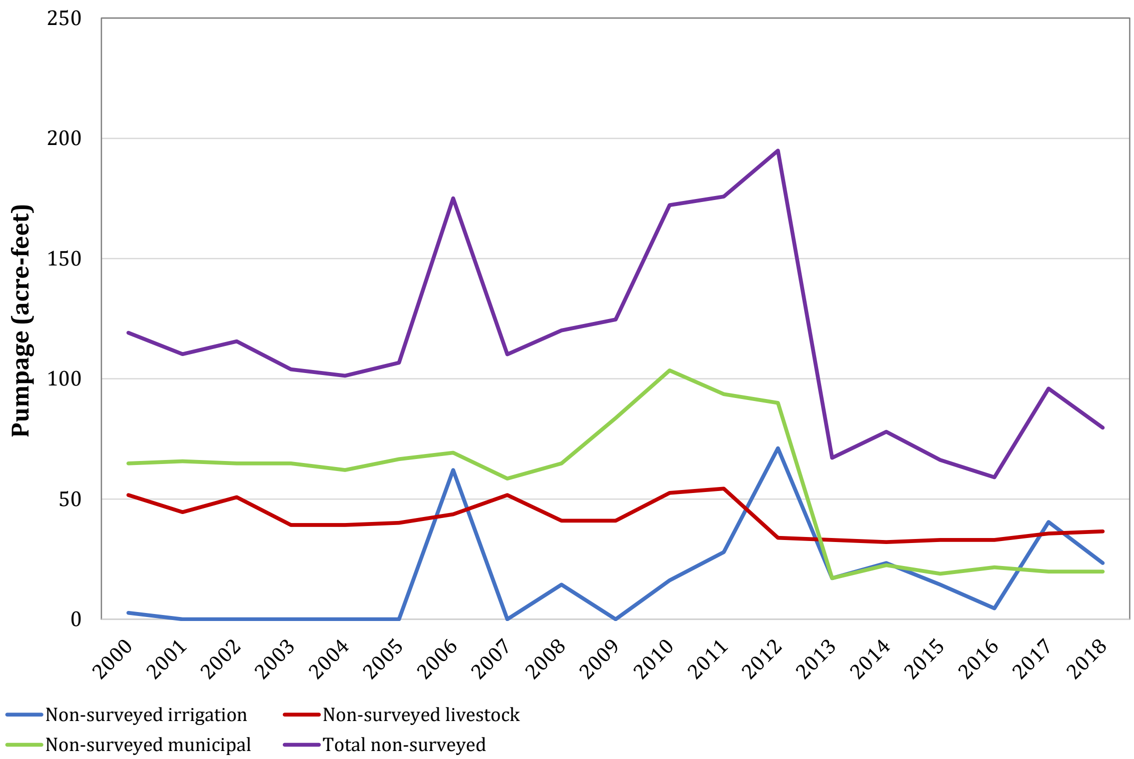


Figure 10-33. Estimated non-surveyed pumpage for the Cross Timbers Aquifer from 2000 to 2018 in Stephens County.

Taylor County

In Taylor County, 22 percent of the wells included in the "Other Aquifers" pumpage (a total of 61 wells) are completed in the Cross Timbers Aquifer. Total pumpage in the county in "Other Aquifers" has remained fairly constant from 2000 to 2018, at between 100 and 200 acre-feet per year, with a significant increase from 2010 to 2013 during the drought that occurred in this region (Figure 10-34). There are no identified individual entities producing groundwater in Taylor County.

Throckmorton County

In Throckmorton County, 44 percent of the wells included in the "Other Aquifers" pumpage (a total of 36 wells) are completed in the Cross Timbers Aquifer. Total pumpage in the county in "Other Aquifers" decreased significantly from 2000 to 2018, but has always been less than 45 acre-feet per year (Figure 10-35). There are no identified individual entities producing groundwater in Throckmorton County.

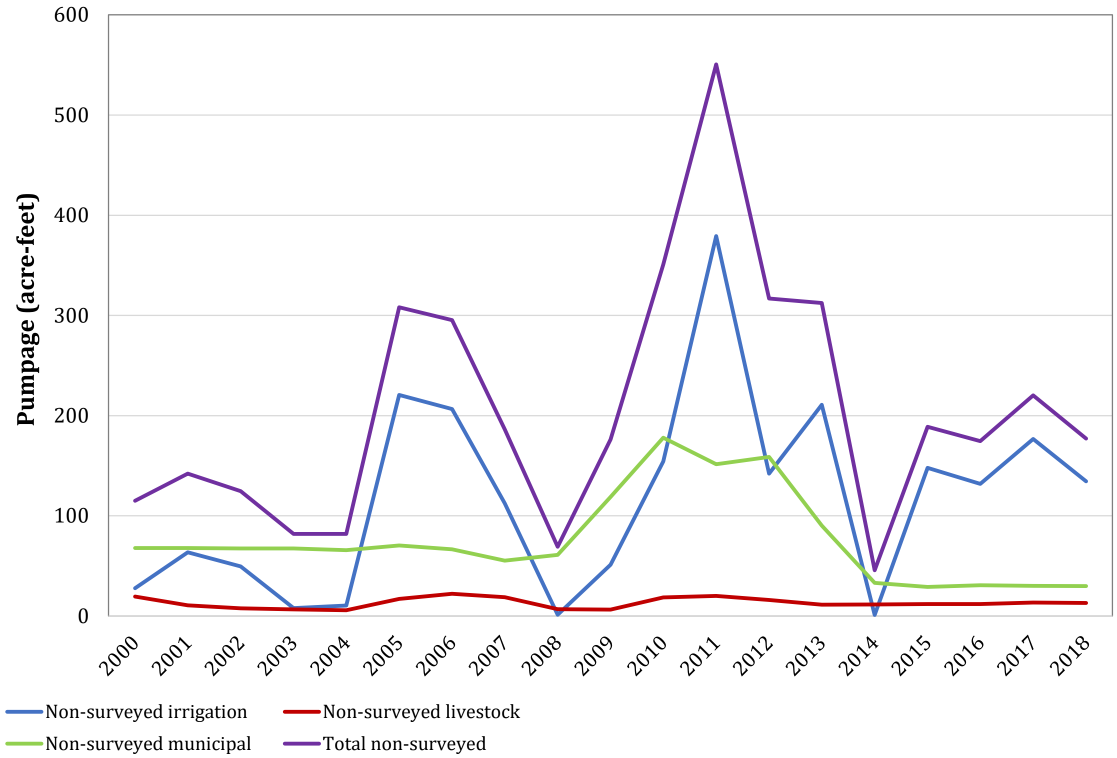


Figure 10-34. Estimated non-surveyed pumpage for the Cross Timbers Aquifer from 2000 to 2018 in Taylor County.

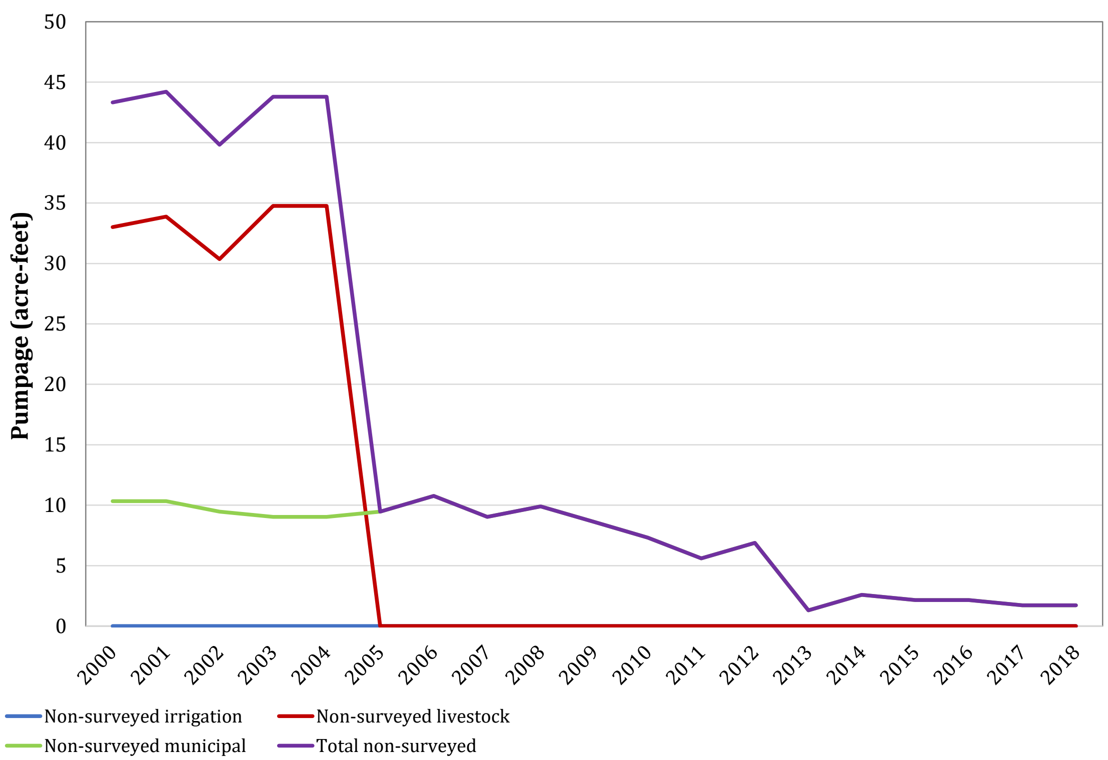


Figure 10-35. Estimated non-surveyed pumpage for the Cross Timbers Aquifer from 2000 to 2018 in Throckmorton County.

Wichita County

In Wichita County, 17 percent of the wells that will be included in the “Other Aquifers” pumpage (a total of 3 wells) are completed in the Cross Timbers Aquifer. Total pumpage in the county in “Other Aquifers” has decreased slightly, from about 150 acre-feet in 2000 to 100 acre-feet in 2018, with a distinct increase in 2010 during the drought period (Figure 10-36). There are no identified individual entities producing groundwater in Wichita County.

Wilbarger County

In Wilbarger County, 7 percent of the wells included in the “Other Aquifers” pumpage (a total of 6 wells) are completed in the Cross Timbers Aquifer. Total pumpage in the county in “Other Aquifers” has remained fairly constant from 2000 to 2018, but has always been less than 350 acre-feet per year (Figure 10-37). There are no identified individual entities producing groundwater in Wilbarger County.

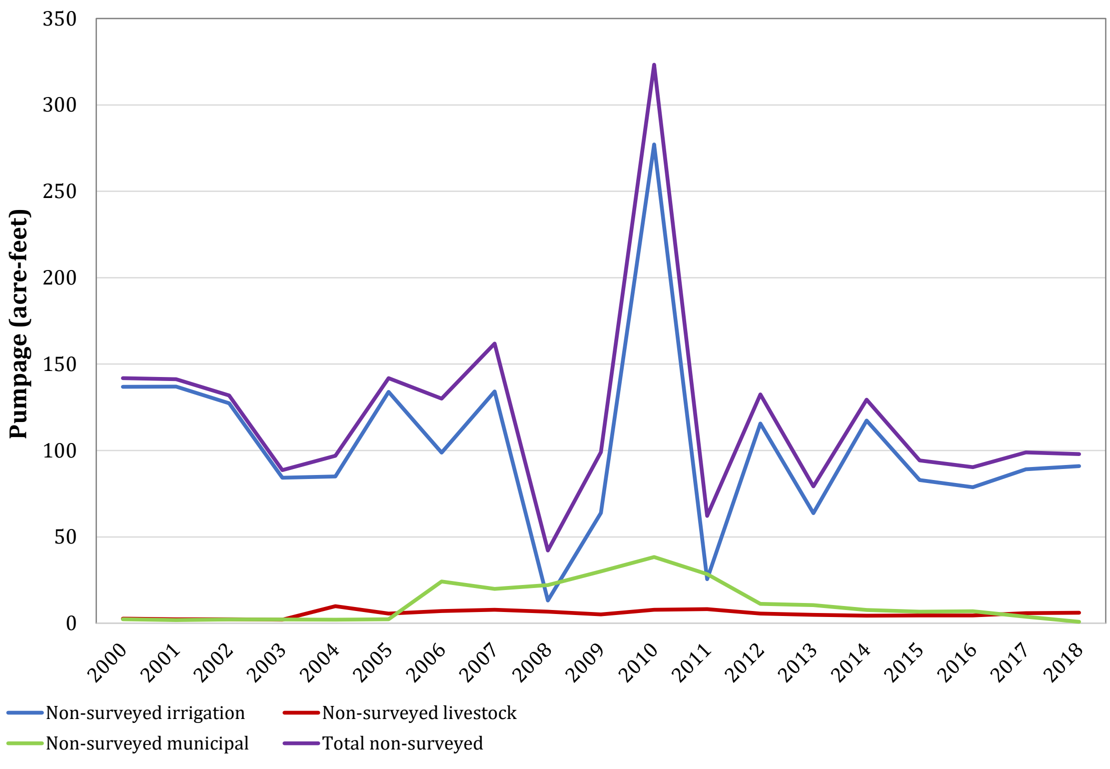


Figure 10-36. Estimated non-surveyed pumpage for the Cross Timbers Aquifer from 2000 to 2018 in Wichita County.

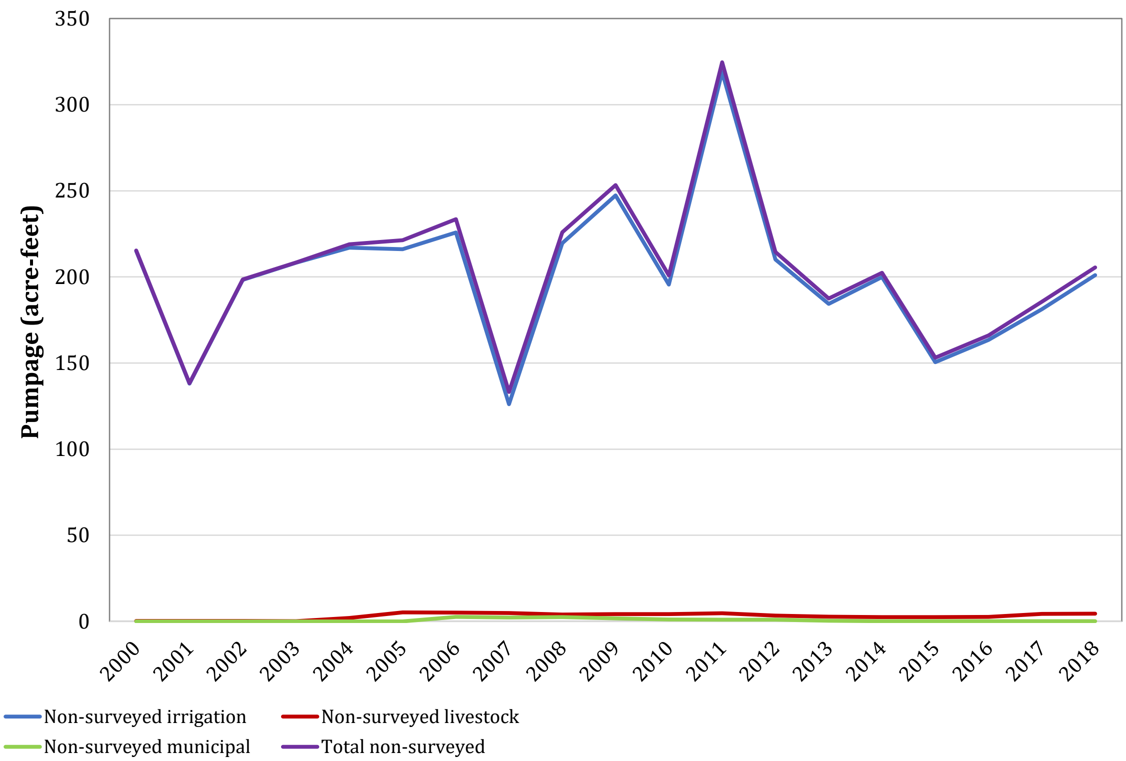


Figure 10-37. Estimated non-surveyed pumpage for the Cross Timbers Aquifer from 2000 to 2018 in Wilbarger County.

Wise County

In Wise County, 89 percent of the wells included in the "Other Aquifers" pumpage (a total of 33 wells) are completed in the Cross Timbers Aquifer. Total pumpage in the county in "Other Aquifers" has been variable from 2000 to 2018, but has always been less than 650 acre-feet per year (Figure 10-38). There are no identified individual entities producing groundwater in Wise County.

Young County

In Young County, 98 percent of the wells included in the "Other Aquifers" pumpage (a total of 406 wells) are completed in the Cross Timbers Aquifer. Total pumpage in the county in "Other Aquifers" has remained fairly constant at about 300 acre-feet from 2000 to 2018, with an increase in response to the drought that occurred in the region in 2009 to 2014 (Figure 10-39). In addition to the non-surveyed pumpage shown in Figure 10-39, the Loving Water Supply Corporation had surveyed and historical pumpage of 10 to 30 acre-feet per year from 1955 to 2018, and the Jean Water Suppply Corporation had historical pumpage of less than 11 acre-feet per year from 1955 to 1994 (Table 10-8).

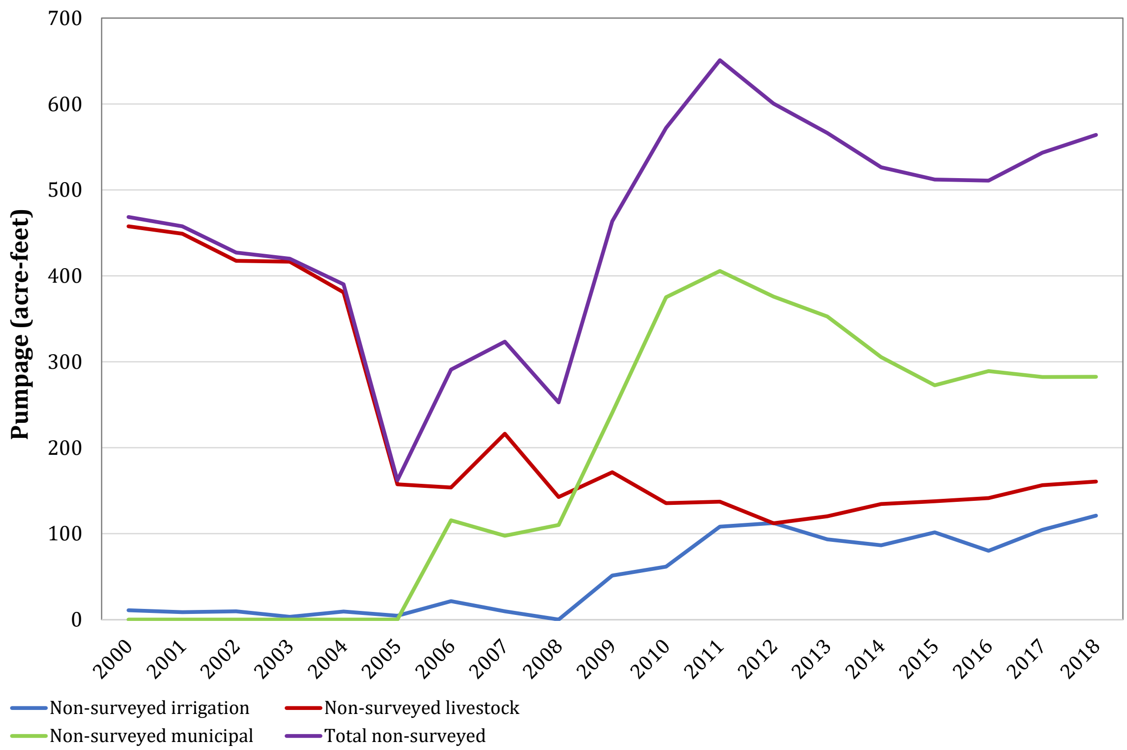


Figure 10-38. Estimated non-surveyed pumpage for the Cross Timbers Aquifer from 2000 to 2018 in Wise County.

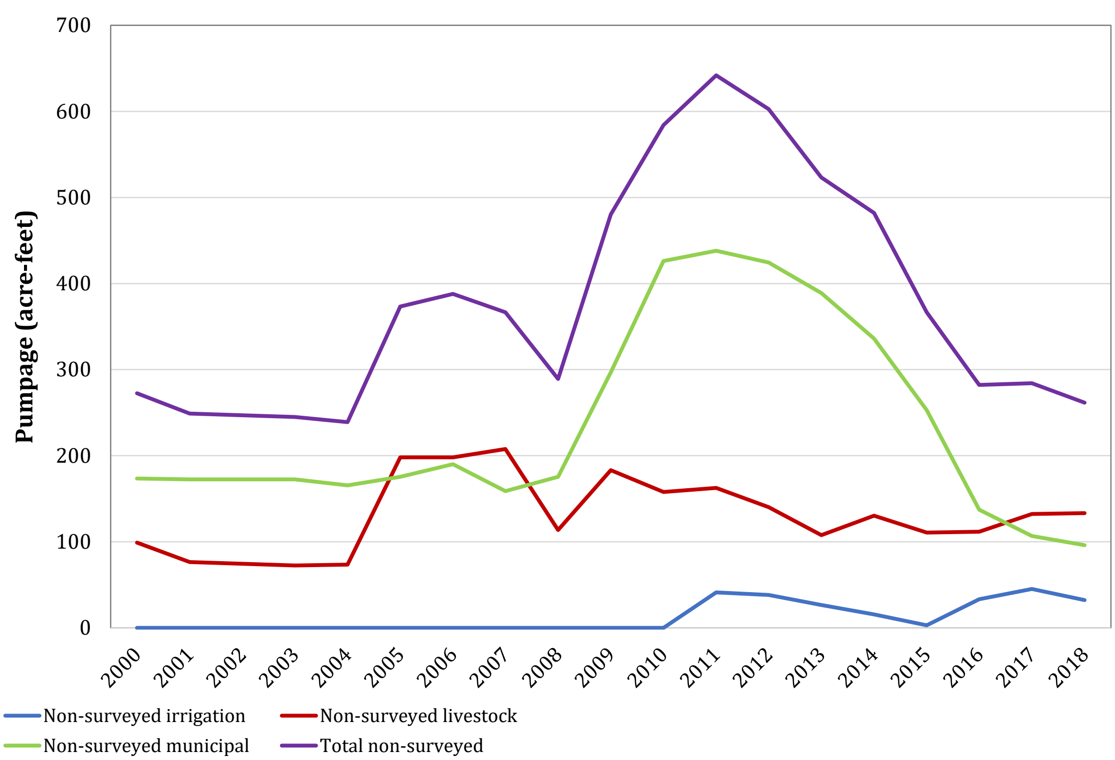


Figure 10-39. Estimated non-surveyed pumpage for the Cross Timbers Aquifer from 2000 to 2018 in Young County.

Table 10-8. Surveyed and historical pumpage from 2000 to 2018 in Young County.

Year	Pumpage (acre-feet)	
	Loving Water Supply Corporation	Jean Water Supply Corporation
1955	29.5	4.7
1956	29.5	4.7
1957	29.5	5.0
1958		4.7
1959		
1960		5.4
1961		
1962		
1963		
1964		
1965		7.3
1966	7.0	7.1
1967		7.5
1968	7.6	
1969	8.4	7.4
1970	10.4	8.7
1971	10.7	3.6
1972	10.6	3.6
1973	9.1	3.6
1974	11.1	3.6
1975	10.4	3.6
1976	13.7	
1977	14.6	4.3
1978	15.2	3.6
1979	14.9	3.6
1980	20.5	3.4
1981	19.3	6.1
1982	17.0	8.7
1983	18.9	10.8
1984	22.7	10.2
1985	18.2	9.0
1986	19.1	8.1
1987	16.0	7.3
1988	15.2	8.4
1989	13.8	6.3
1990	15.3	5.6
1991	15.9	6.4
1992	12.7	5.8
1993	15.3	5.7
1994	16.3	5.3
1995	15.8	

Table 10-8 (continued)

Year	Pumpage (acre-feet)	
	Loving Water Supply Corporation	Jean Water Supply Corporation
1996	17.9	
1997	15.9	
1998	20.8	
1999	18.7	
2000	18.8	
2001	17.6	
2002	14.8	
2003	16.7	
2004	15.6	
2005	16.8	
2006	19.9	
2007	17.5	
2008	18.6	
2009	18.1	
2010	16.1	
2011	22.3	
2012	18.4	
2013	18.3	
2014	16.7	
2015	15.8	
2016	14.6	
2017	13.9	
2018	14.3	

11. Water Quality

This section provides an overview of Cross Timbers Aquifer water quality in terms of total dissolved solids and chloride. Discussion of the high salinity water and brine that occurs at the base of fresh groundwater system is provided in Section 6.3, and is not covered here. The groundwater salinity classification developed by Winslow and Kister (1956) for TWDB brackish aquifer studies (Table 11-1) was used to guide the total dissolved solids concentration plots for Cross Timbers Aquifer wells.

Table 11-1. Groundwater salinity classification summary.

Groundwater Salinity Classification	Salinity Zone Code	Range in TDS Concentration (mg/L)
Fresh	FR	0 to 1,000
Slightly saline	SS	1,000 to 3,000
Moderately saline	MS	3,000 to 10,000
Very saline	VS	10,000 to 35,000
Brine	BR	Greater than 35,000

TDS = Total dissolved solids
mg/L = Milligrams per liter

Ballew and French (2019) provide an analysis of the number of wells by water quality category (Table 11-1) for wells completed in the Wichita, Cisco, Canyon, and Strawn Groups. Despite the difference in total number of water quality samples for wells in each group, the water quality breakdown in terms of total dissolved solids is generally consistent. For the Wichita, Cisco, and Strawn Groups, approximately 60 percent of the wells yield fresh water, about 35 percent yield slightly saline water, and the remainder (about 5 percent) yield moderately saline water. Only a very small number of wells yield saline water, and these wells are likely for industrial use or are impacted by oil and gas field activities. The Canyon Group results were similar to those for the Wichita, Cisco, and Strawn Groups, but water appeared overall more saline, with about 52, 37, and 11 percent of the wells classified as fresh, slightly saline, and moderately saline, respectively.

These results make sense, as approximately 95 percent of the Cross Timbers Aquifer wells analyzed by Ballew and French (2019) are for domestic, stock, public supply, and irrigation uses (Ballew and French, 2019). These uses will not tolerate high salinity without treatment. About 3 percent of the wells are for industrial use, which is generally less sensitive to higher salinity. Reading through the literature, it is clear that local drillers long ago developed an understanding of well depths required to avoid high salinity water, whatever that means in a local context for water supply. For example, Richter and Kreitler (1985, p. 7) note in their study that included Runnels and Concho Counties that "[t]he base of fresh water is defined by local water-well drillers as the first occurrence of blue shale, which normally occurs between 100 and 200 feet below land surface."

The distribution of total dissolved solids for Cross Timbers Aquifer wells is provided in Figure 11-1. The minimum, maximum, mean and median total dissolved solids values are 56, 147,034, 1,432, and 869 milligrams per liter, respectively. Consistent with Ballew and French (2019), the percentage of total wells that exhibit fresh, slightly saline, and moderately saline water are 57, 35, and 8 percent, respectively. Note that the current dataset also includes Clear Fork Group wells, which were not included in Ballew and French (2019).

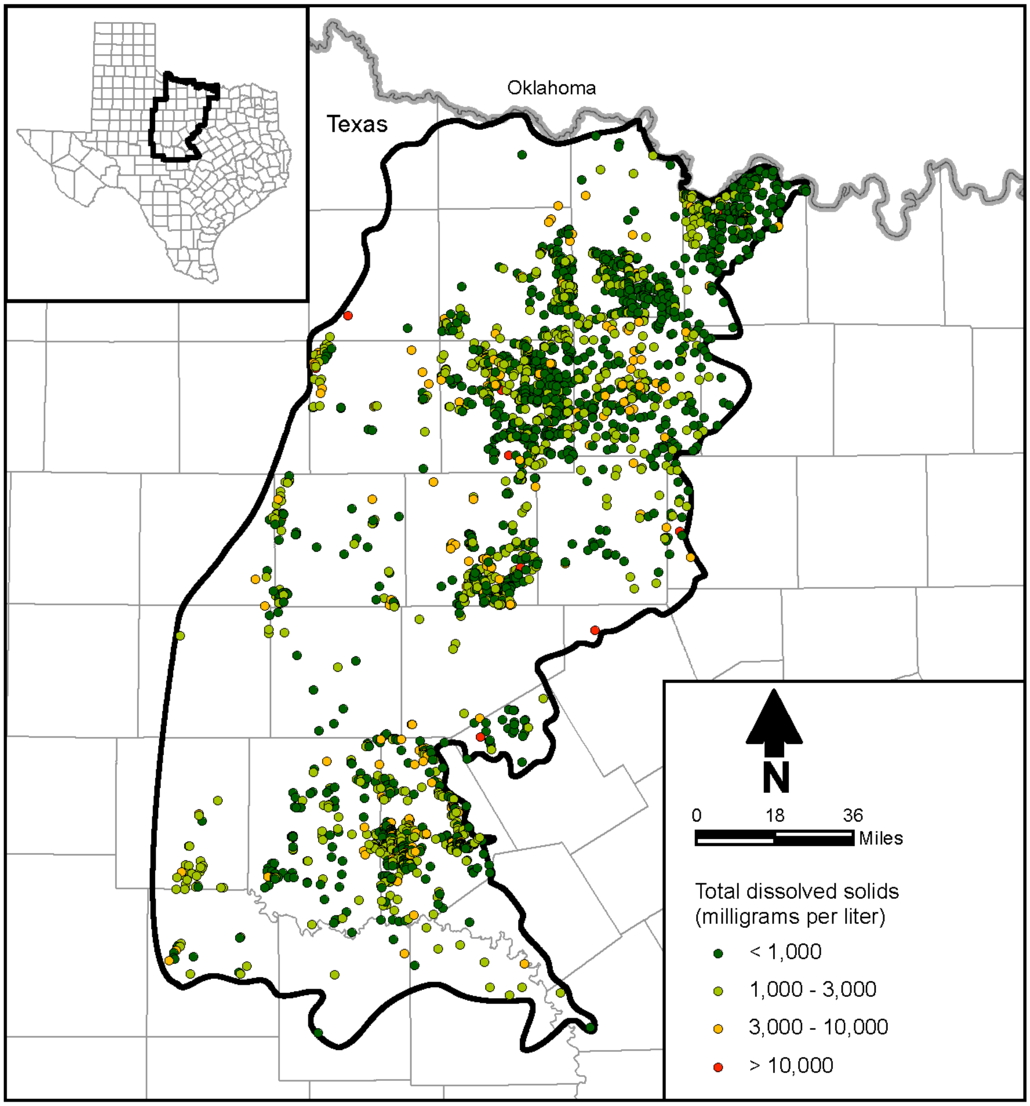


Figure 11-1. Total dissolved solids concentration for Cross Timbers Aquifer wells.

The distribution of total chloride for Cross Timbers Aquifer wells is provided in Figure 11-2. The minimum, maximum, mean, and median chloride values are 1.8, 90,400, 467, and 156 milligrams per liter, respectively. Comparison of Figure 11-2 with Figure 6-13, which shows the locations where the shallowest injection well zone is 500 feet or less below surface, indicates that the corresponding regions tend to have either higher chloride concentrations or a small number of wells. These regions include, from south to north, Brown County and county line for Brown and Coleman Counties, eastern Callahan and Shackelford Counties, southeastern Throckmorton County, northeastern Young County and northwestern Jack County, and Wichita and northwestern Clay Counties. No claim is made or implied that the injection wells are not constructed or operated properly; rather, only that the base of aquifer, formed by high salinity water and brine, is closer to the surface in these regions and that overall water quality is therefore not as good as might be found in some adjacent areas. Other regions that appear to have water with predominantly higher chloride concentrations are Mills and Runnels Counties.

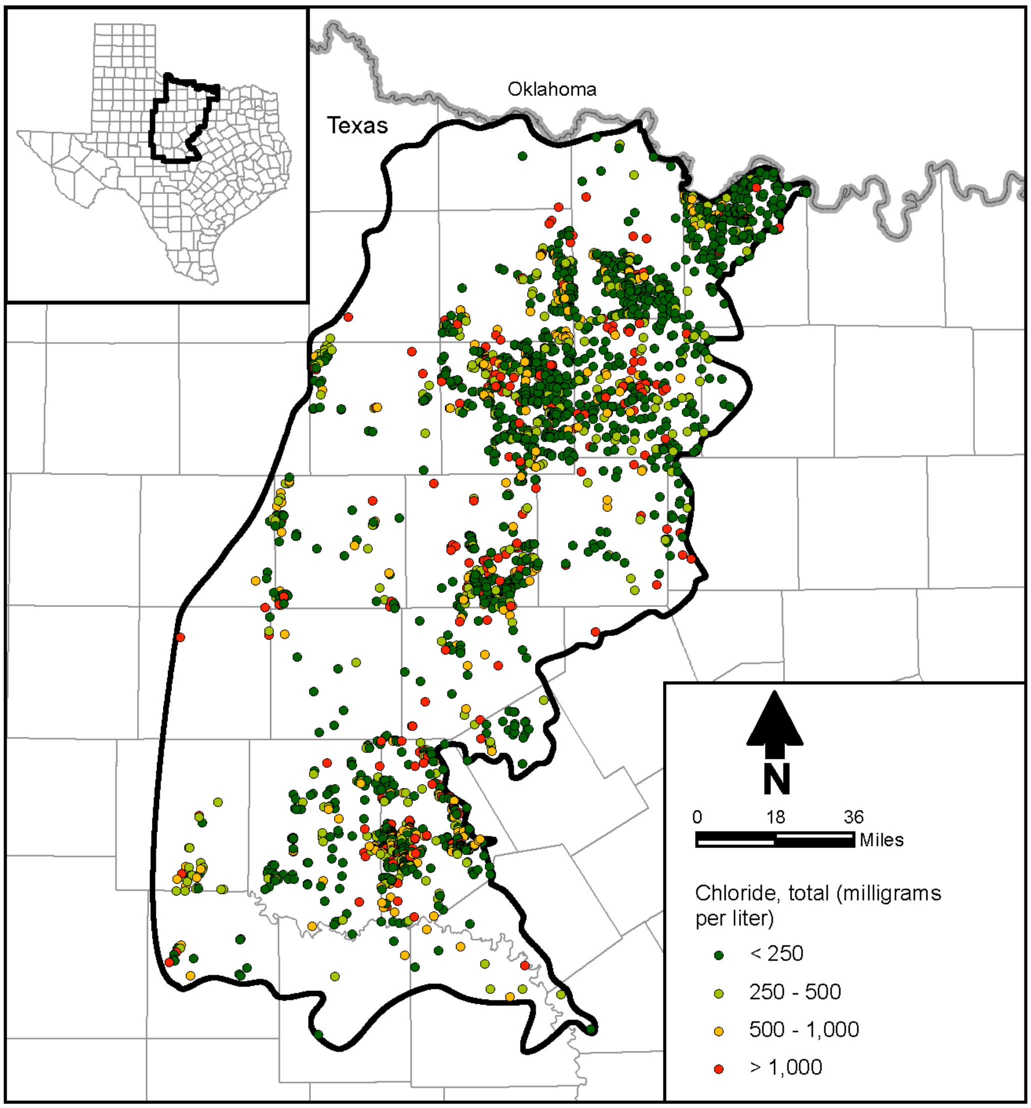


Figure 11-2. Total chloride concentration for Cross Timbers Aquifer wells.

A summary of the water quality data points is provided in Table 11-2.

Table 11-2. Summary of water quality by concentration range.

Total dissolved solids (mg/L)			Total Chloride (mg/L)		
Concentration Range (mg/L)	Number of wells	Percent (rounded)	Concentration Range (mg/L)	Number of wells	Percent (rounded)
<1,000	1,489	57	<250	1,619	62
1,000–3,000	893	35	250–500	433	17
3,000–10,000	203	8	500-1,000	280	11
>10,000	13	<1	>1,000	258	10
Total	**2,598**	**100**		**2,590**	**100**

mg/L = Milligrams per liter

The values plotted in Figures 11-1 and 11-2 are for the most recent data points available in the TWDB groundwater database, most recently downloaded on May 15, 2021. In nearly all cases, the most recent value is the only value; time series of water quality data for Cross Timbers Aquifer wells are virtually non-existent. The highest total dissolved solids and chloride concentrations were not excluded from the data, but spot checking of data indicated that the highest values are likely associated with deeper industrial wells related to oil and gas production; these wells are not intended to produce fresh water. In addition, some of the higher chloride and total dissolved solids values are likely due to groundwater contamination from oil and gas operations, a condition commonly discussed and reported in the historical TWDB county reports.

12. Conceptual Model of Groundwater Flow

Based on the data and analyses documented in the prior sections, the following conceptual model of groundwater flow is presented. The general conceptual model is illustrated schematically in Figure 12-1.

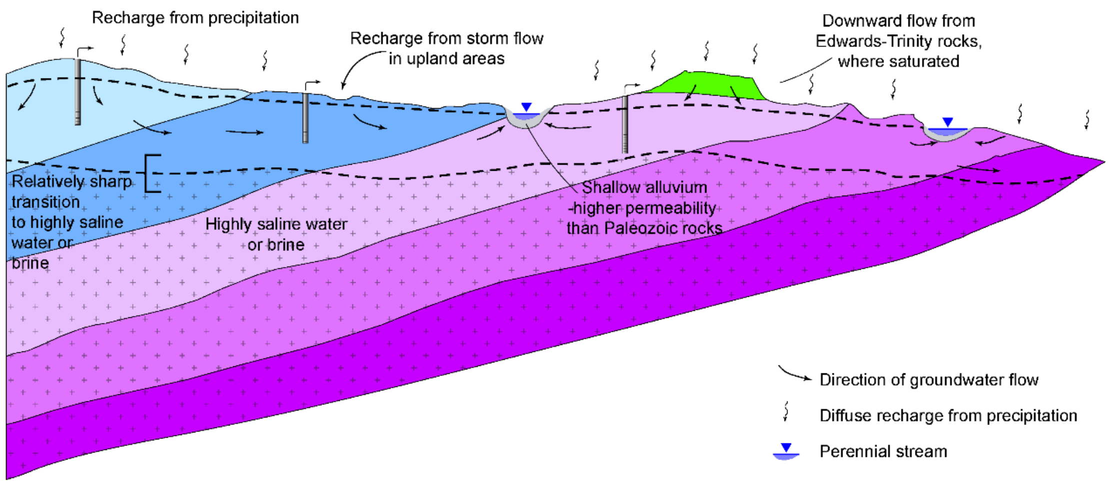


Figure 12-1. Schematic conceptual model of groundwater flow in the Cross Timbers Aquifer.

The Cross Timbers Aquifer consists of a shallow groundwater flow system, bounded below by a high salinity/brine water interface that occurs at relatively shallow depth (several hundred feet), and in some locations very shallow depths (i.e., 100 feet or less). The transition from fresh or slightly saline water to highly saline water or brine appears to be abrupt, meaning that it occurs over a short vertical distance. The brine interface at depth appears to be in equilibrium with the overlying fresh water system (Nicot and others, 2013), an observation that is supported by the lack of reported widespread groundwater degradation due to upconing, or the upward flow of poor-quality water caused by groundwater pumping. The limited yield of the Cross Timbers Aquifer rocks has probably assisted with the maintenance of this condition because there is a natural limitation on well pumping rates.

Groundwater flow is driven primarily by groundwater recharge and topography. Groundwater recharge occurs on the outcrop of the various aquifer units, and discharges primarily to stream channels (Figure 12-1). Although the Cross Timbers Aquifer rocks consist of alternating sequences of more permeable and less permeable lithologies, there appears to be sufficient primary or secondary permeability such that groundwater can migrate through the low-permeability units, at least in the near surface. Groundwater underflow between surface water basins may occur in places, but the amount is unknown and is likely relatively small. Groundwater level contour maps developed based on existing data tend to line up with the extent of surface water drainage basins; in addition, the overall aquifer saturated thickness is limited, favoring groundwater discharge to streams in relatively close proximity to areas of recharge. The high-permeability saturated alluvial sediments adjacent to stream channels act as conduits to transmit water from the Cross Timbers Aquifer to the streams or along the stream channels in the subsurface. At the eastern edge of the aquifer, groundwater recharged to the west that has not discharged into stream channels or reservoirs will flow laterally into the subcrop of Paleozoic rocks that occurs beneath the Northern Trinity Aquifer; these Paleozoic rocks are hydraulically connected to the Cross Timbers Aquifer, but are not formally part of it. Information obtained from Nicot and others (2013) indicates that there are a number of wells completed in the subcrop—likely for mining or industrial purposes—but this has not been confirmed.

The interaction of the Cross Timbers Aquifer with other aquifers is also governed primarily by topography. Trinity Aquifer outcrops occur (and actually form) areas of high topography, such as along the Callahan Divide. Consequently, groundwater in the Trinity Aquifer that is not pumped or does discharge to streams or springs will eventually seep downward to recharge the Cross Timbers Aquifer. The same is true for the Seymour Aquifer where it occurs in topographically high areas, but where saturated Seymour Formation sediments occur along stream channels, Cross Timbers Aquifer water discharges into the Seymour Aquifer, meaning that groundwater flow is upward from the Cross Timbers Aquifer into the Seymour Aquifer.

Overall groundwater pumping from the Cross Timbers Aquifer is small: only about 14,000 to 18,000 acre-feet per year (excluding mining, which is often very low depending on economic conditions) over an aquifer area of 17,790 square miles. On average, the pumping therefore equates to about 0.0014 inch per year over the aquifer area, or less than 1 percent of the average annual recharge of approximately 0.35 inch per year. Of course, recharge and pumping do not occur as an average rate across the aquifer extent, but these numbers provide some context to understand magnitude.

Where other aquifer units, such as the Seymour or Trinity, are available for groundwater supply, they are used preferentially to the Cross Timbers Aquifer. About 40 percent of total water use in the area is from groundwater and 60 percent is from surface water, with the percentage of groundwater use increasing during drought periods (Ballew and French, 2019). Multiple TWDB reports on county groundwater resources discuss towns and municipalities that had public supply wells early on but switched to surface water supplies from reservoirs, generally due to limited well yield.

Groundwater in the outcrop areas generally occurs under unconfined conditions, but groundwater can be confined in places where permeable units are overlain by less permeable units. Groundwater is obtained for limited uses (mainly stock and domestic) from whatever formations yield water near surface at a given location; overall aquifer permeability and well yield are generally small. Nicot and others (2013) identify preferential groundwater flow along strike, which may cause regional-scale anisotropy within the groundwater system. This concept is illustrated conceptually in Figure 12-2.

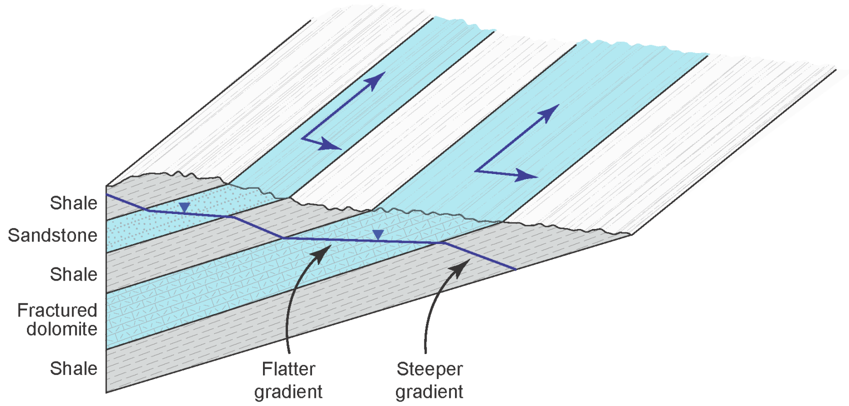


Figure 12-2. Illustration of regional-scale anisotropy within layered formation of alternating higher and lower hydraulic conductivity. Magnitudes of permeability indicated conceptually by the lengths of the arrows.

As illustrated in Figure 12-2, the hydraulic gradient (slope of the water table) will be lower, or flatter, in geologic formations or units of higher hydraulic conductivity, and steeper within units of lower hydraulic conductivity. This pattern was not observed at the regional scale when developing the water level contour maps, but the available data are relatively coarse.

The TWDB requested that a two-dimensional model grid be constructed for the Cross Timbers Aquifer to serve as a master grid (snap grid) for the project. The model grid outline is provided in Figure 12-3; the cell sizes used are ¼ mile by ¼ mile. The grid is aligned with the adjacent Northern Trinity Aquifer groundwater availability model grid (Kelly and others, 2014). The rotated model grid was selected so that the principal axes would generally coincide with the overall strike and dip of the Cross Timbers Aquifer geologic units across much of the aquifer extent, and also coincide with the general orientation of major streams to the extent possible. The selected grid orientation should facilitate groundwater availability model development in the future.

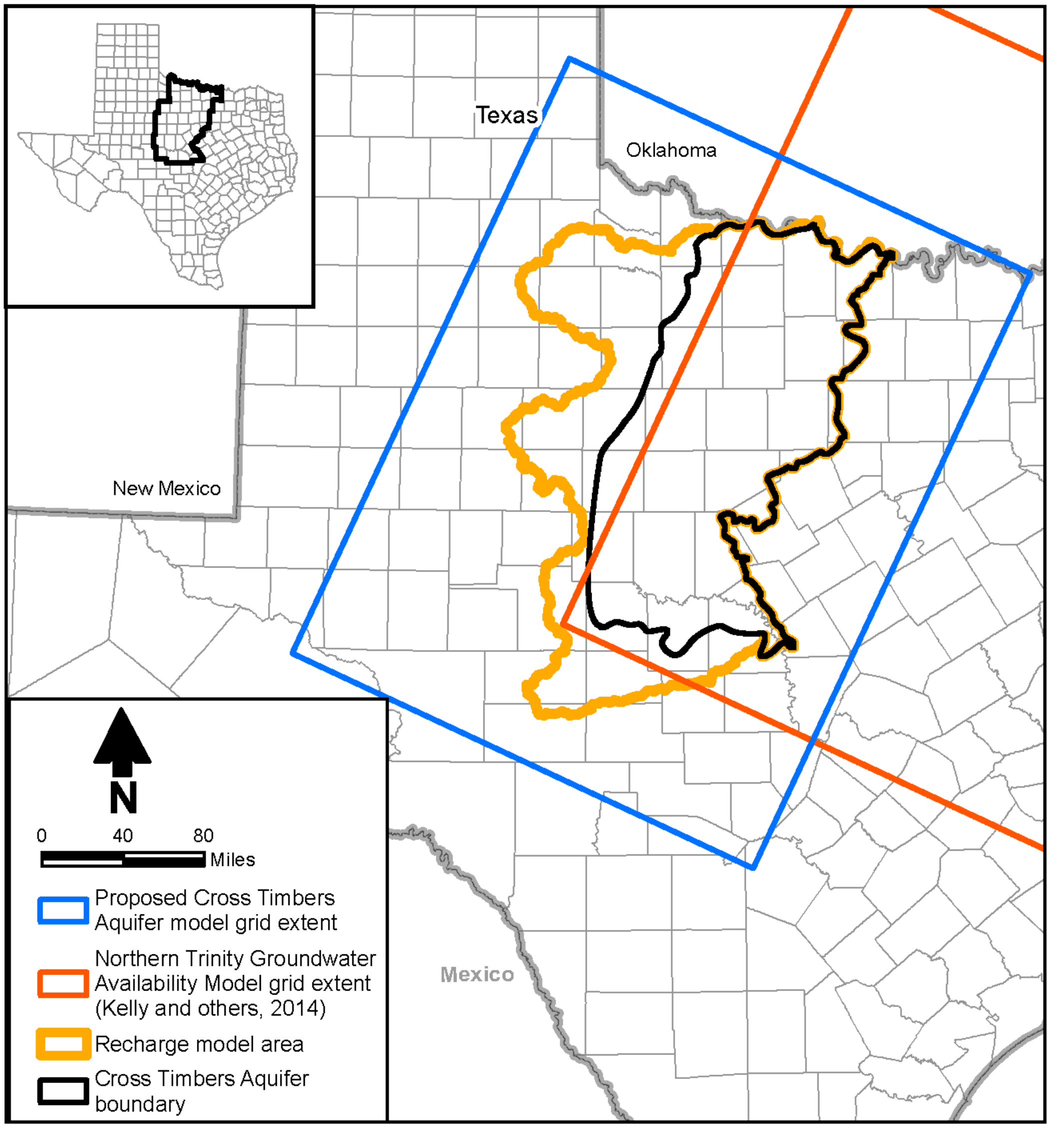


Figure 12-3. Proposed grid for Cross Timbers Aquifer groundwater modeling.

13. Future Improvements and Considerations

Future considerations and recommended next steps prior to, or perhaps as part of, developing a groundwater availability model can be organized into categories of aquifer extent. In addition, the TWDB requested input regarding modification of the Cross Timbers Aquifer boundaries if appropriate. These observations, and in some cases recommendations, are summarized in the following subsections.

13.1. Top of Aquifer

The top of the Cross Timbers Aquifer (youngest geologic unit) as defined in Ballew and French (2019) is the Wichita Group. In this study the uppermost formations in the western portion of the study area also include the Clear Fork Group rocks. In addition, throughout the study area, surficial deposits of Quaternary alluvium line the stream courses, with Seymour Formation sediments along some drainages in the north. These sediments are in direct hydraulic communication with the underlying Paleozoic rocks, and hydrologically serve as high-permeability conduits to transmit water beneath and adjacent to stream courses (Figure 12-1). Furthermore, these shallow alluvial sediments, although limited for the most part in saturated thickness, are important sources of water in many counties due to the limited and often sporadic yield of the Paleozoic units. From a hydrologic, water supply, and groundwater modeling standpoint, it would make sense to formally include these units as part of the Cross Timbers Aquifer.

13.2. Base of Aquifer

As presented in detail in Section 6.3, the base of the Cross Timbers Aquifer is determined by the occurrence of highly saline water or brine, the location of which appears to be in equilibrium with groundwater recharge. This base of aquifer has been estimated explicitly for only a couple of counties, and anecdotal information such as surface casing depths and uppermost injection interval provides useful information for other areas. Furthermore, although base of aquifer is generally shallow at several hundred feet, there are instances where the depth of fresh water is deeper. Estimating the base of the Cross Timbers Aquifer as is done in the TWDB Brackish Resources Aquifer Characterization System studies (e.g., Finch and others, 2016) would fill a significant data gap that exists for the Cross Timbers Aquifer.

13.3. Northern Aquifer Extent

The northern Cross Timbers Aquifer extent as currently delineated approximately follows the Red River, forming the state boundary with Oklahoma. Although the Cross Timbers Aquifer units continue into Oklahoma, there is no need to extend the model boundary north of the state line. This is for the following several reasons:

1. The Red River is a major perennial stream and a natural hydrologic boundary for the Cross Timbers Aquifer. The Quaternary sediments adjacent to the river are significantly more permeable than those of the underlying and adjacent Paleozoic rocks. This condition, combined with the condition that pumping from the Paleozoic rocks in Oklahoma is likely small, as it is in Texas, implies that hydrologic conditions in Oklahoma are unlikely to significantly affect Cross Timbers Aquifer conditions in Texas.
2. As also observed in Texas, the fresh to slightly saline water saturated thickness of permeable sediments is likely limited by highly saline water and brine at shallow depths, creating a situation where groundwater pumping in one state or the other is unlikely to significantly affect water levels in the adjacent state.
3. Although there are several major faults in the northwestern portion of the study area (compare Figures 4-3 and 6-6), these faults do not appear to affect groundwater flow, although data are relatively limited in this region. The apparent lack of effects on groundwater flow is most likely due to the shallow nature of the groundwater flow system; these faults likely do affect the flow of highly saline water and brine at depth.
4. Whether or not it may make sense for the TWDB to make the northern Cross Timbers Aquifer boundary coincident with the Red River perennial channel is subject to considerations raised in Section 12.

13.4. Eastern Aquifer Extent

There is no reason to adjust the eastern aquifer extent unless the TWDB wishes to more closely follow the mapped outcrop of the Northern Trinity Aquifer. For example, Figure 4-2 illustrates that there are portions of the eastern aquifer boundary that include Trinity aquifer outcrop, and wells completed in this unit were identified and had to be screened out from the hydraulic conductivity analysis (Figure 9-1). For portions of the Cross Timbers Aquifer east of the Trinity Aquifer outcrop, it would be useful to have a formal aquifer sub-crop designation.

13.5. Western Aquifer Extent

There are a number of places where groundwater in Paleozoic rocks west of the Cross Timbers Aquifer boundary is in hydraulic continuity with groundwater within the Cross Timbers Aquifer as currently delineated. One such example where detailed analysis was conducted is Jones County (Figure 6-16). Other regions where this situation was noted during the water level contouring are portions of Runnels, Baylor, and Wilbarger Counties west of the Cross Timbers Aquifer extent. In addition, Ewing and others (2004) included the Clear Fork Group as the base of the Seymour Aquifer to the west of the current Cross Timbers Aquifer extent, essentially to the western edge of the Blaine Aquifer System, which is coincident with the outcrop of the Permian Blaine Formation (Finch and others, 2016).

Extension of the Cross Timbers Aquifer western boundary would include a "strip" of Paleozoic aquifers about ½ to 1 county wide from Jones County north that are currently not designated as minor aquifers. Although groundwater flow in these rocks is likely similar to that in the Cross Timbers Aquifer, and in some cases is in direct hydraulic continuity with the Cross Timbers Aquifer as currently defined, there are other factors that the TWDB must consider in making aquifer designations (e.g., Ballew and French, 2019). These other factors are not considered here.

13.6. Southwestern and Southern Aquifer Extent

No comments or suggestions are provided regarding the southwestern and southern extent of the Cross Timbers Aquifer.

14. Acknowledgements

The project team would like to acknowledge the assistance of the Upper Trinity Groundwater Conservation District and the District Manager, Mr. Doug Shaw, for providing information relevant to this investigation and for hosting a stakeholder advisory forum. We would also like to thank Dr. J.P. Nicot of the Texas Bureau of Economic Geology for providing the compiled specific capacity data used in Nicot and others (2013).

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Appendix A

Distributed Parameter Watershed Model Inputs

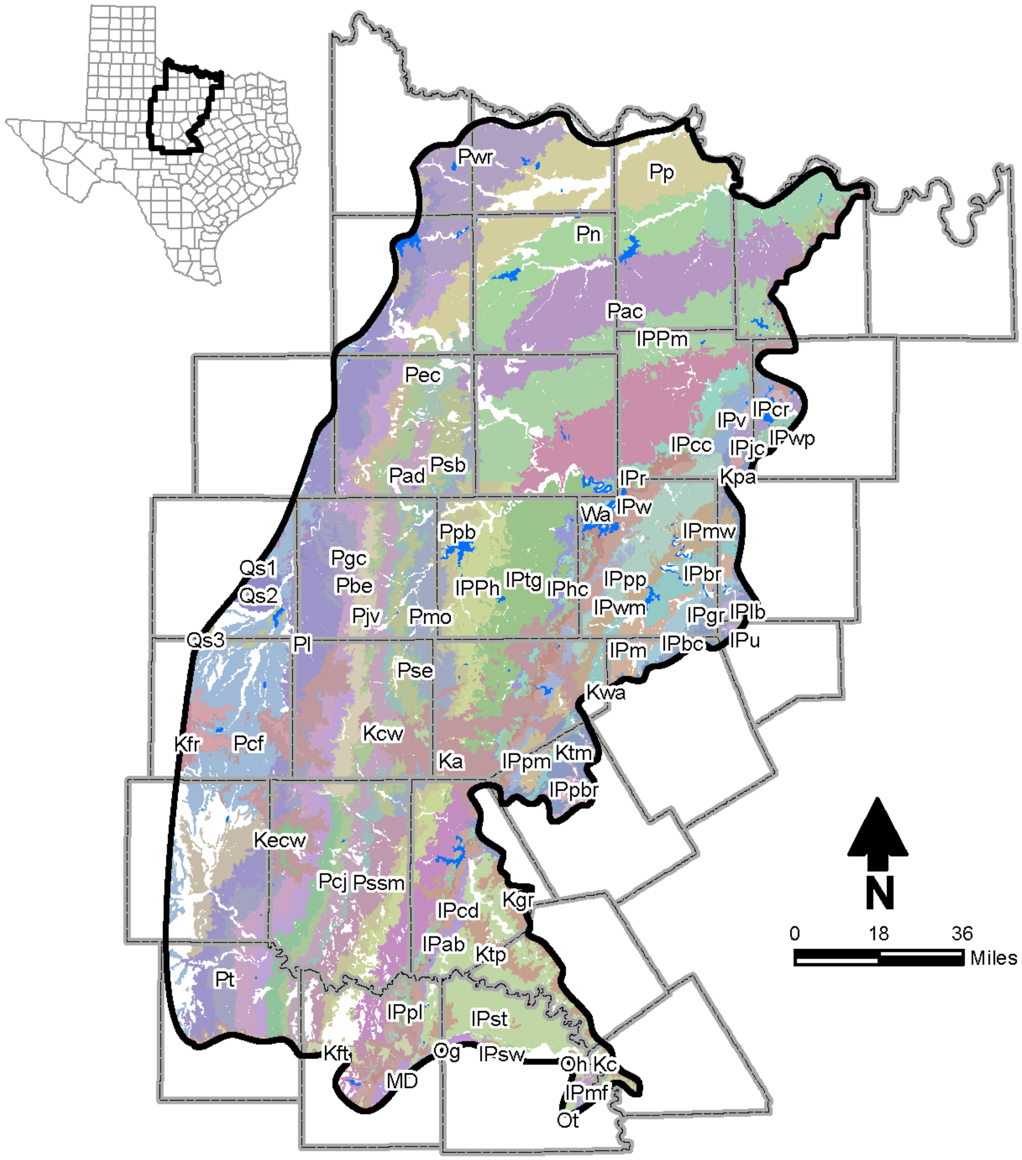

Figure A-1a. Geology used for Distributed Parameters Watershed Model.

Geology

- IPPh - Harpersville Formation
- IPPm - Markley Formation
- IPPm - Markley Formation (new)
- IPab - Adams Branch Limestone
- IPbc - Buck Creek Sandstone
- IPbr - Brazos River Formation expanded
- IPcc - Colony Creek Shale
- IPcd - Cedarton Shale
- IPcr - Chico Ridge Limestone (revised)
- IPgr - Grindstone Creek Formation
- IPhc - Home Creek Limestone
- IPhc - Home Creek lImestone
- IPjc - Jasper Creek Formation (revised)
- IPlb - Lazy Bend Formation
- IPm - Mingus Formation
- IPmf - Marble Falls Formation
- IPmw - Mineral Wells Formation
- IPpbr - Pre-Brazos River Formation rocks undivided
- IPpl - Placid Shale
- IPpm - Palo Pinto and Mineral Wells Formations
- IPpp - Palo Pinto Formation
- IPr - Ranger Limestone
- IPst - Strawn Group undivided including Pre-Brazos River Formation undivided
- IPsw - Smithwick Shale
- IPtg - Thirfty and Graham Formations undivided Correlation with area south of Brady Mountains uncertain
- IPtg - Thrifty Graham Formations undivided
- IPtg - Thrifty and Graham Formations undivided
- IPu - Unnamed Pennsylvanian rocks
- IPv - Ventioner Formation (revised)
- IPw - Winchell Limestone
- IPwm - Wolf Mountain Shale
- IPwp - Willow Point Formation (revised)
- Ka - Antlers
- Ka - Antlers Sand (Basal Cretaceous or "Trinity Sand)
- Kc - Comanche Peak Limestone
- Kcw - Comanche Peak Limestone and Walnut Formation
- Kecw - Edwards Limestone, Comanche Peak Limestone, and Walnut Formation undivided
- Kecw - Edwards and Comanche Peak Limestones and Walnut Formation
- Ked - Edwards Limestone
- Kfr - Edwards Limestone, Comanche Peak Limestone, and Walnut Formation undivided
- Kft - Fort Terrett Formation
- Kgr - Glen Rose Formation
- Kgr - Glen Rose Limestone
- Kpa - Paluxy Formation
- Ktm - Twin Mountains Formation
- Ktp - Travis Peak Formation
- Kwa - Walnut Formation
- MD - Barnett Formation, Chappel Limestone, and Houy Formation undivided
- Og - Gorman Formation
- Oh - Honeycut Formation
- Ot - Tanyard Formation
- Pac - Archer City
- Pac - Archer City Formation (new)
- Pad - Admiral
- Pad - Admiral Formation restricted
- Pbe - Bead Mountain Formation
- Pcf - Clear Fork Group
- Pcf - Clear Fork Group undivided
- Pcj - Coleman Junction Formation
- Pcj - Coleman Junction Formation expanded
- Pec - Elm Creek Formation
- Pgc - Grape Creek Formation
- Pjv - Jagger Bend Formation and Valera Formation undivided
- Pjv - Jagger Bend and Valera Formation undivided
- Pjv - Jagger Bend and Valera Formations undivided
- Pl - Lueders Formation
- Pmo - Moran Formation
- Pn - Nacona Formation
- Pn - Nocona Formation (new)
- Pp - Petrolia Formation
- Ppb - Pueblo Formation
- Psb - Santa Anna Branch
- Pse - Sedwick Formation
- Pssm - Santa Anna Branch, Sedwick, and Moran Formations undivided except in northernmost area
- Pt - Talpa Formation
- Pwr - Waggoner Ranch Formation
- Qs1 - Seymour Formation
- Qs2 - Seymour Formation
- Qs2 - Seymour Formation: thick deposits
- Qs3 - Seymour Formation
- Wa - water

Figure A-1b. Legend for geology map (Figure A-1a).

Table A-1. General distributed parameter watershed model input values.

Parameter	Variable	Units	Little Wichita	Middle Brazos-Millers	Middle Brazos-Palo Pinto	Middle Colorado	San Saba	Upper Clear Fork Brazos	Comment
Field capacity	head_fc	centimeters	341	341	341	341	341	341	1/3 bar
Wilting point	head_wp	centimeters	15,353	15,353	15,353	15,353	15,353	15,353	15 bar
Average elevation for basin	elevavg	meters	388	434	359	524	600	570	Average of model grid cells in the sub-basin
Average latitude for basin	Latavg	degrees	33.81	33.08	32.85	31.68	30.99	32.68	Approximate basin midpoint
Adjustment coefficient in Hargreaves' radiation formula	Krs	$°C^{-0.5}$	0.16	0.16	0.16	0.16	0.16	0.16	0.16 is recommended for "interior" (non-coastal) locations where land mass dominates and air masses are not strongly influenced by a large water body (Allen and others, 1998, p. 60)
Depletion factor	p	—	0.5	0.5	0.5	0.5	0.5	0.5	Varies 0 to 1 but typically ranges from 0.30 for shallow rooted plants at high values of ET_c (>8 mm/d) to 0.70 for deep rooted plants at low values of ET_c (<3 mm/d) with 0.5 in common use.
Dew point offset	Kdew_Yoff	°C	0	0	0	0	0	0	Zero assumes dew point and minimum daily air temperature are the same
Evaporation layer depth	Ze	meters	0.15	0.15	0.15	0.15	0.15	0.15	Depth of the surface soil layer that is subject to drying by way of evaporation. Upper end of range in Allen and others, 1998, p. 144 (ranges 0.10 to 0.15 meters)
Fraction of reference ET for sublimation above freezing	SUBPAR1	—	1	1	1	1	1	1	1 assumes sublimation is equal to reference evapotranspiration
Fraction of reference ET for sublimation below freezing	SUBPAR2	—	1	1	1	1	1	1	1 assumes sublimation is equal to reference evapotranspiration
Readily evaporable water	REW	millimeters	8	8	8	8	8	8	Upper end of range for loamy sand (Allen and others, 1998, Table 19)
Initial capillary head node 1	IC1	centimeters	15,353	15,353	15,353	15,353	15,353	15,353	Set to wilting point (15 bar)
Initial capillary head node 2	IC2	centimeters	15,353	15,353	15,353	15,353	15,353	15,353	Set to wilting point (15 bar)
Initial capillary head node 3	IC3	centimeters	15,353	15,353	15,353	15,353	15,353	15,353	Set to wilting point (15 bar)
Initial capillary head node 4	IC4	centimeters	341	341	341	341	341	341	Set to field capacity (1/3 bar)
Minimum air temperature for transpiration	TETMIN	°C	5	5	5	5	5	5	There is no transpiration when the average daily temperature is below 5°C
Maximum air temperature for transpiration	TETMAX	°C	40	40	40	40	40	40	There is no transpiration when the average daily temperature is above 40°C
Minimum snow melt factor	MFMIN	millimeters per day per °C	2.0	2.0	2.0	2.0	2.0	2.0	Minimum expected to occur on December 21 (Schroeder and others, 1994)
Maximum snow melt factor	MFMAX	millimeters per day per °C	5.2	5.2	5.2	5.2	5.2	5.2	Maximum expected to occur on June 21 (Schroeder and others, 1994)
Minimum transpiration coefficient (Kc) for dry surface soil (upper 0.10 to 0.15 meter) with no vegetation cover	Kc_min	—	0.15	0.15	0.15	0.15	0.15	0.15	Lower end of 0.15-0.20 range recommended by Allen and others (1998).
Turbidity coefficient for solar radiation	Kcln	—	0.57	0.57	0.57	0.57	0.57	0.57	Average annual value published for Fort Worth, TX (https://www.homerenergy.com/products/pro/docs/latest/_hm_print_window.htm?published_solar_data.htm

Table A-2. Vegetation input values for Distributed Parameter Watershed Model.

Vegetation Name	NLCD Code	Mean Maximum Rooting Depth (meters)	Mean Maximum Plant Height (meters)
Open Water	11	0.15	0.003
Developed, Low Intensity	21a	2.60	0.10
Developed, Medium Intensity	21b	2.60	0.10
Developed, High Intensity	22	2.60	0.10
Barren Land	31	0.30	0.10
Deciduous Forest	41	2.90	4.00
Evergreen Forest	42	3.90	10.00
Mixed Forest	43	3.40	4.00
Shrub/Scrub	51	1.10	1.50
Emergent Herbaceous Wetlands	71a	1.40	0.30
Herbaceous	71b	2.60	0.70
Hay/Pasture	81	2.60	0.30
Cultivated Crops	83	0.60	0.70
Developed, Open Space	85	2.60	0.10
Woody Wetlands	92	1.40	2.00

Table A-3. Soil input values for distributed parameter watershed model.

Soil Description	DPWM Code	Saturated Hydraulic Conductivity (feet per day)							van Genuchten alpha (centimeters^{-1})	van Genuchten N (unitless)	Saturated Water Content (unitless)	Residual Water Content (unitless)	Soil Depth (meters)
		Initial Estimate	Little Wichita	Middle Brazos-Millers	Middle Brazos-Palo Pinto	Middle Colorado	San Saba	Upper Clear Fork Brazos					
Unlabeled	Unlabeled	3.18×10^{-2}							5.42×10^{-2}	1.457	0.723	0.018	3.77
Bedrock	Bedrock	3.22							5.75×10^{-2}	1.479	0.750	0.011	0.30
Bouldery clay	BD_clay	1.19×10^{-2}							3.01×10^{-3}	1.044	0.302	0.055	0.41
Clay	Clay	4.80×10^{-2}	1.77×10^{-2}		3.57×10^{-3}				1.18×10^{-2}	1.132	0.431	0.097	2.19
Clay loam	CL	2.72×10^{-1}		4.08×10^{-1}		4.08×10^{-1}	5.44×10^{-2}		1.63×10^{-2}	1.210	0.445	0.101	2.95
Coarse sandy loam	COSL	6.59×10^{-1}							1.04×10^{-1}	1.366	0.411	0.080	0.36
Cobbly clay	CB_clay	1.98×10^{-1}							1.50×10^{-2}	1.171	0.520	0.117	0.30
Cobbly clay loam	CB_CL	4.23×10^{-1}							2.87×10^{-2}	1.261	0.461	0.099	0.30
Cobbly loam	CB_loam	7.97×10^{-1}				4.79×10^{-1}			2.78×10^{-2}	1.325	0.449	0.078	0.61
Cobbly silty clay	CB_SIC	2.01×10^{-1}							1.54×10^{-2}	1.222	0.528	0.113	0.35
Extremely gravelly coarse sandy loam	EGR_COSL	5.22							6.65×10^{-2}	1.466	0.434	0.027	4.00
Extremely gravelly loam	EGR_loam	3.04×10^{-1}							4.32×10^{-2}	1.303	0.547	0.089	0.43
Extremely stony clay loam	EST_CL	4.51×10^{-1}							1.95×10^{-2}	1.340	0.483	0.052	0.36
Extremely stony fine sandy loam	EST_FSL	8.62×10^{-1}							8.70×10^{-3}	1.310	0.357	0.058	0.30
Extremely stony loam	EST_loam	2.10×10^{-1}							8.30×10^{-3}	1.179	0.430	0.097	0.41
Fine sand	FS	3.12			2.74×10^{-1}				6.13×10^{-2}	1.341	0.408	0.057	4.00
Fine sandy loam	FSL	7.30×10^{-1}	5.47×10^{-1}		6.09×10^{-2}	7.31×10^{-2}			3.42×10^{-2}	1.266	0.410	0.083	3.15
Flaggy clay loam	FL_CL	4.59×10^{-1}							2.92×10^{-2}	1.272	0.453	0.097	0.30
Flaggy fine sandy loam	FL_FSL	4.72×10^{-1}							2.68×10^{-2}	1.228	0.445	0.100	0.75
Flaggy loam	FL_loam	3.82×10^{-1}							1.32×10^{-2}	1.229	0.462	0.097	0.34
Gravelly clay loam	GR_CL	3.36×10^{-1}					9.33×10^{-2}		2.48×10^{-2}	1.245	0.462	0.097	0.37
Gravelly fine sandy loam	GR_FSL	5.65×10^{-1}							1.03×10^{-2}	1.252	0.422	0.073	0.55
Gravelly loam	GR_loam	5.38×10^{-1}							3.34 x 10–2	1.289	0.423	0.083	0.45
Gravelly sandy clay loam	GR_SCL	1.50×10^{-1}							4.41 x 10–2	1.148	0.438	0.115	0.79
Gravelly sandy loam	GR_SL	1.21							2.12 x 10–2	1.221	0.408	0.077	2.32
Gravelly silty clay loam	GR_SICL	4.36×10^{-1}							1.83 x 10–2	1.279	0.487	0.091	0.33
Loam	Loam	4.82×10^{-1}						1.20×10^{-1}	1.93 x 10–2	1.262	0.430	0.086	2.71
Loamy fine sand	LFS	1.86							3.71 x 10–2	1.301	0.415	0.069	3.84
Loamy sand	LS	1.63			3.00×10^{-1}				3.01 x 10–2	1.245	0.401	0.080	2.82
Sand	Sand	1.59							1.28 x 10–2	1.353	0.408	0.024	4.00
Sandy loam	SL	1.43					2.86×10^{-1}		7.47 x 10–2	1.269	0.438	0.091	2.43
Silt loam	SIL	3.42×10^{-1}							1.32 x 10–2	1.243	0.451	0.091	3.86
Silty clay	SIC	1.98×10^{-1}		3.97×10^{-1}					1.33 x 10–2	1.187	0.477	0.107	2.36
Silty clay loam	SICL	2.90×10^{-1}				2.89×10^{-2}			1.29 x 10–2	1.203	0.449	0.100	3.50
Stony clay	ST_clay	9.89×10^{-2}							1.13 x 10–2	1.135	0.434	0.099	0.91

Table A-3 (continued)

		Saturated Hydraulic Conductivity (feet per day)											
Soil Description	DPWM Code	Initial Est.	Little Wichita	Middle Brazos-Millers	Middle Brazos-Palo Pinto	Middle Colorado	San Saba	Upper Clear Fork Brazos	van Genuchten alpha (centimeters^{-1})	van Genuchten N (unitless)	Qs (unitless)	Qr (unitless)	Soil Depth (meters)
Stony clay loam	ST_CL	1.85×10^{-1}							1.50×10^{-2}	1.185	0.441	0.101	0.51
Stony fine sandy loam	ST_FSL	2.90×10^{-1}							1.39×10^{-2}	1.206	0.420	0.090	1.70
Stony loam	ST_loam	2.54×10^{-1}			1.45×10^{-1}				1.88×10^{-2}	1.213	0.445	0.100	0.38
Stony loamy fine sand	ST_LFS	8.82×10^{-1}							6.17×10^{-2}	1.311	0.423	0.077	0.70
Stony loamy sand	ST_LS	9.97×10^{-1}							2.94×10^{-2}	1.165	0.374	0.101	1.32
Stony sandy loam	ST_SL	3.71×10^{-1}							1.57×10^{-2}	1.181	0.405	0.096	2.21
Stony silty clay	ST_SIC	6.94×10^{-2}							7.13×10^{-3}	1.120	0.396	0.093	0.97
Stony silty clay loam	ST_SICL	1.77×10^{-1}							1.29×10^{-2}	1.201	0.457	0.104	0.38
Variable	Variable	3.26							4.93×10^{-2}	1.447	0.695	0.017	3.57
Very cobbly clay	VCB_clay	2.01×10^{-1}				1.53×10^{-1}	1.53×10^{-1}		1.63×10^{-2}	1.181	0.527	0.118	0.33
Very cobbly clay loam	VCB_CL	4.52×10^{-1}							2.61×10^{-2}	1.283	0.507	0.094	0.30
Very cobbly loam	VCB_loam	4.79×10^{-1}							3.61×10^{-2}	1.282	0.457	0.093	0.43
Very fine sandy loam	VFSL	8.67×10^{-1}							1.78×10^{-2}	1.318	0.423	0.056	3.46
Very flaggy fine sandy loam	VFL_FSL	2.95×10^{-1}							6.56×10^{-2}	1.336	0.434	0.083	0.30
Very flaggy silty clay loam	VFL_SICL	3.14×10^{-1}							1.75×10^{-2}	1.251	0.472	0.099	0.30
Very gravelly clay loam	VGR_CL	3.59×10^{-1}							2.18×10^{-2}	1.248	0.465	0.096	0.93
Very gravelly fine sandy loam	VGR_FSL	1.23							4.84×10^{-2}	1.289	0.459	0.085	1.98
Very gravelly loam	VGR_loam	8.86×10^{-1}							3.64×10^{-2}	1.307	0.460	0.085	1.69
Very gravelly sandy loam	VGR_SL	1.32							1.52×10^{-2}	1.271	0.435	0.077	2.78
Very paragravelly loam	VPG_loam	4.82×10^{-1}							3.75×10^{-2}	1.288	0.475	0.095	0.65
Very stony clay	VST_clay	1.61×10^{-1}							1.19×10^{-2}	1.124	0.443	0.096	0.30
Very stony clay loam	VST_CL	2.35×10^{-1}					1.34×10^{-1}		1.74×10^{-2}	1.245	0.471	0.094	0.34
Very stony fine sandy loam	VST_FSL	3.15×10^{-1}							2.40×10^{-2}	1.217	0.438	0.100	1.22
Very stony loam	VST_loam	2.38×10^{-1}							1.31×10^{-2}	1.228	0.451	0.093	0.33
Very stony sandy loam	VST_SL	3.57×10^{-1}							9.15×10^{-3}	1.198	0.445	0.097	4.00
Water	Water	0.00							5.75×10^{-2}	1.479	0.430	0.011	4.00
Perennial wash	Wash_Per	0.00							1.45×10^{-1}	2.680	0.430	0.045	0.30
Ephemeral wash	Wash_Eph	4.68							1.45×10^{-1}	2.680	0.430	0.045	0.30

Table A-4. Bedrock input values for distributed parameter watershed model.

DPWM Name	Description	Saturated Hydraulic Conductivity (feet per day)						
		Initial Estimate	Little Wichita	Middle Brazos-Millers	Middle Brazos-Palo Pinto	Middle Colorado	San Saba	Upper Clear Fork Brazos
Crc	Moore Hollow Group - Lion Mtn, Hickory, Morgan Creek, Point Peak, San Saba	5.00 x 10^{-2}						
Crh	Moore Hollow Group - Lion Mtn, Hickory, Morgan Creek, Point Peak, San Saba	5.00 x 10^{-2}						
Crlc	Moore Hollow Group - Lion Mtn, Hickory, Morgan Creek, Point Peak, San Saba	5.00 x 10^{-2}						
Cwm	Moore Hollow Group - Lion Mtn, Hickory, Morgan Creek, Point Peak, San Saba	5.00 x 10^{-2}						
Cwmw	Moore Hollow Group - Lion Mtn, Hickory, Morgan Creek, Point Peak, San Saba	5.00 x 10^{-2}						
Cwp	Moore Hollow Group - Lion Mtn, Hickory, Morgan Creek, Point Peak, San Saba	5.00 x 10^{-2}						
Cwpp	Moore Hollow Group - Lion Mtn, Hickory, Morgan Creek, Point Peak, San Saba	5.00 x 10^{-2}						
Cws	Moore Hollow Group - Lion Mtn, Hickory, Morgan Creek, Point Peak, San Saba	5.00 x 10^{-2}						
IPab	Canyon Group Except for Palo Pinto	5.00 x 10^{-4}			1.00 x 10^{-5}			
IPbc	Strawn Group	5.00 x 10^{-4}						
IPbr	Strawn Group	5.00 x 10^{-4}						
IPcc	Colony Creek Shale	5.00 x 10^{-4}						
IPcd	Canyon Group Except for Palo Pinto	5.00 x 10^{-4}			1.00 x 10^{-5}			
IPcn	Moore Hollow Group - Lion Mtn, Hickory, Morgan Creek, Point Peak, San Saba	5.00 x 10^{-2}						
IPcr	Canyon Group Except for Palo Pinto	5.00 x 10^{-4}			1.00 x 10^{-5}			
IPgr	Strawn Group	5.00 x 10^{-4}						
IPhc	Canyon Group Except for Palo Pinto	5.00 x 10^{-4}			1.00 x 10^{-5}			
IPjc	Canyon Group Except for Palo Pinto	5.00 x 10^{-4}			1.00 x 10^{-5}			
IPlb	Strawn Group	5.00 x 10^{-4}						
IPm	Strawn Group	5.00 x 10^{-4}						
IPmf	Marble Falls Limestone	5.00 x 10^{-2}						
IPmw	Mineral Wells (shale)	5.00 x 10^{-4}						
IPpbr	Strawn Group	5.00 x 10^{-4}						
IPPh	Harpersville	5.00 x 10^{-4}			2.50 x 10^{-4}			
IPpl	Placid Shale	5.00 x 10^{-4}			5.00 x 10^{-6}			
IPPm	Upper part of Cisco Group - all low K	5.00 x 10^{-4}			2.50 x 10^{-4}			
IPpm	Palo Pinto Formation	5.00 x 10^{-2}			1.00 x 10^{-3}			5.00 x 10^{-4}
IPpp	Palo Pinto Formation	5.00 x 10^{-2}						5.00 x 10^{-4}
IPr	Canyon Group Except for Palo Pinto	5.00 x 10^{-4}			1.00 x 10^{-5}			
IPst	Strawn Group	5.00 x 10^{-4}						
IPsw	Strawn Group	5.00 x 10^{-4}						
IPtg	Thrifty and Graham Formations	5.00 x 10^{-2}						5.00 x 10^{-1}
IPu	Strawn Group	5.00 x 10^{-4}						
IPv	Canyon Group Except for Palo Pinto	5.00 x 10^{-4}			1.00 x 10^{-5}			
IPw	Canyon Group Except for Palo Pinto	5.00 x 10^{-4}			1.00 x 10^{-5}			
IPwm	Canyon Group Except for Palo Pinto	5.00 x 10^{-4}			1.00 x 10^{-5}			
IPwp	Canyon Group Except for Palo Pinto	5.00 x 10^{-4}			1.00 x 10^{-5}			
Ka	Antlers	5.00 x 10^{-2}			5.00 x 10^{-4}			
Kbu	Cretaceous units	5.00 x 10^{-3}						
Kc	Cretaceous units	5.00 x 10^{-3}						

Table A-4 (continued)

DPWM Name	Description	Saturated Hydraulic Conductivity (feet per day)						
		Initial Estimate	Little Wichita	Middle Brazos-Millers	Middle Brazos-Palo Pinto	Middle Colorado	San Saba	Upper Clear Fork Brazos
Kcw	Cretaceous units	5.00×10^{-3}						
Kecw	Edwards/Comanche peak/Walnut	5.00×10^{-3}						
Ked	Cretaceous units	5.00×10^{-3}						
Kfr	Cretaceous units	5.00×10^{-3}						
Kft	Cretaceous units	5.00×10^{-3}						
Kgr	Cretaceous units	5.00×10^{-3}						
Kh	Hensell	5.00×10^{-2}						
Kpa	Antlers	5.00×10^{-2}						
Ks	Cretaceous units	5.00×10^{-3}						
Ksf	Cretaceous units	5.00×10^{-3}						
Ktm	Twin Mountains	5.00×10^{-2}			5.00×10^{-4}			
Ktp	Travis Peak (Hosston)	5.00×10^{-2}						
MD	MD - Barnett Formation, Chappel Limestone, Houy Formation	5.00×10^{-3}						5.00×10^{-2}
Og	Ellenburger Group	5.00×10^{-2}						
Oh	Ellenburger Group	5.00×10^{-2}						
Ot	Ellenburger Group	5.00×10^{-2}						
P	Permian Rocks Undivided	5.00×10^{-4}						2.50×10^{-4}
Pac	Upper part of Cisco Group - all low K	5.00×10^{-4}			2.50×10^{-4}			
Pad	Wichita Albany Group (Leuders is separate, below)	5.00×10^{-4}						
Pb	Dockum, Blaine Formation, and 4 Cambrian/PreCambrian hard rocks - low K	1.42×10^{-4}		5.00×10^{-4}	5.00×10^{-4}	5.00×10^{-4}	5.00×10^{-4}	2.50×10^{-4}
Pbe	Wichita Albany Group (Leuders is separate, below)	5.00×10^{-4}						
Pcf	Clear Fork Group	5.00×10^{-2}	1.00×10^{-3}					5.00×10^{-1}
Pcj	Wichita Albany Group (Leuders is separate, below)	5.00×10^{-4}						
pClc	Dockum, Blaine Formation, and 4 Cambrian/PreCambrian hard rocks - low K	1.42×10^{-4}		5.00×10^{-4}	5.00×10^{-4}	5.00×10^{-4}	5.00×10^{-4}	2.50×10^{-4}
pCps	Dockum, Blaine Formation, and 4 Cambrian/PreCambrian hard rocks - low K	1.42×10^{-4}		5.00×10^{-4}	5.00×10^{-4}	5.00×10^{-4}	5.00×10^{-4}	2.50×10^{-4}
pCtm	Dockum, Blaine Formation, and 4 Cambrian/PreCambrian hard rocks - low K	1.42×10^{-4}		5.00×10^{-4}	5.00×10^{-4}	5.00×10^{-4}	5.00×10^{-4}	2.50×10^{-4}
pCvs	Dockum, Blaine Formation, and 4 Cambrian/PreCambrian hard rocks - low K	1.42×10^{-4}		5.00×10^{-4}	5.00×10^{-4}	5.00×10^{-4}	5.00×10^{-4}	2.50×10^{-4}
Pec	Wichita Albany Group (Leuders is separate, below)	5.00×10^{-4}						
Pgc	Wichita Albany Group (Leuders is separate, below)	5.00×10^{-4}						
Pjv	Wichita Albany Group (Leuders is separate, below)	5.00×10^{-4}						
Pl	Leonardian/Leuters	5.00×10^{-2}						5.00×10^{-1}
Pmo	Upper part of Cisco Group - all low K	5.00×10^{-4}			2.50×10^{-4}			
Pn	Wichita Albany Group (Leuders is separate, below)	5.00×10^{-4}						
Po-M-o	Ogallala Formation	2.50						
Pp	Wichita Albany Group (Leuders is separate, below)	5.00×10^{-4}						
Ppb	Upper part of Cisco Group - all low K	5.00×10^{-4}			2.50×10^{-4}			
Pq	Dockum, Blaine Formation, and 4 Cambrian/PreCambrian hard rocks - low K	1.42×10^{-4}		5.00×10^{-4}	5.00×10^{-4}	5.00×10^{-4}	5.00×10^{-4}	2.50×10^{-4}
Psa	Dockum, Blaine Formation, and 4 Cambrian/PreCambrian hard rocks - low K	1.42×10^{-4}		5.00×10^{-4}	5.00×10^{-4}	5.00×10^{-4}	5.00×10^{-4}	2.50×10^{-4}
Psb	Upper part of Cisco Group - all low K	5.00×10^{-4}			2.50×10^{-4}			
Pse	Upper part of Cisco Group - all low K	5.00×10^{-4}			2.50×10^{-4}			

Table A-4 (continued)

DPWM Name	Description	Saturated Hydraulic Conductivity (feet per day)						
		Initial Estimate	Little Wichita	Middle Brazos-Millers	Middle Brazos-Palo Pinto	Middle Colorado	San Saba	Upper Clear Fork Brazos
Pssm	Upper part of Cisco Group - all low K	5.00×10^{-4}			2.50×10^{-4}			
Pt	Wichita Albany Group (Leuders is separate, below)	5.00×10^{-4}						
Pwh	Cloud Chief Gypsum and Whitehorse Sandstone	5.00×10^{-2}						5.00×10^{-4}
Pwr	Wichita Albany Group (Leuders is separate, below)	5.00×10^{-4}						
Qal	Quaternary	2.50	2.50×10^{-2}					
Qao	Quaternary	2.50	2.50×10^{-2}					
Qau	Quaternary	2.50	2.50×10^{-2}					
Qc	Quaternary	2.50	2.50×10^{-2}					
Qds	Quaternary	2.50	2.50×10^{-2}					
Qg	Quaternary	2.50	2.50×10^{-2}					
Qhg	Quaternary	2.50	2.50×10^{-2}					
Qli	Lingos Formation	2.50						
Qp	Quaternary	2.50	2.50×10^{-2}					
Qs	Quaternary	2.50	2.50×10^{-2}					
Qs1	Quaternary	2.50	2.50×10^{-2}					
Qs2	Quaternary	2.50	2.50×10^{-2}					
Qs3	Quaternary	2.50	2.50×10^{-2}					
Qsd	Dune and dune ridges	2.50						
Qse1	Seymour Formation	2.50						
Qse2	Seymour Formation	2.50						
Qse3	Seymour Formation	2.50						
Qsh	Quaternary	2.50	2.50×10^{-2}					
Qt	Quaternary	2.50	2.50×10^{-2}					
Qt1	Quaternary	2.50	2.50×10^{-2}					
Qt2	Quaternary	2.50	2.50×10^{-2}					
Qu	Quaternary	2.50	2.50×10^{-2}					
TRd	Dockum, Blaine Formation, and 4 Cambrian/PreCambrian hard rocks - low K	1.42×10^{-4}		5.00×10^{-4}	5.00×10^{-4}	5.00×10^{-4}	5.00×10^{-4}	2.50×10^{-4}
Wa	Water	5.00×10^{-2}						

Appendix B

Comparison of Recharge Simulation Results to Observed Base Flow

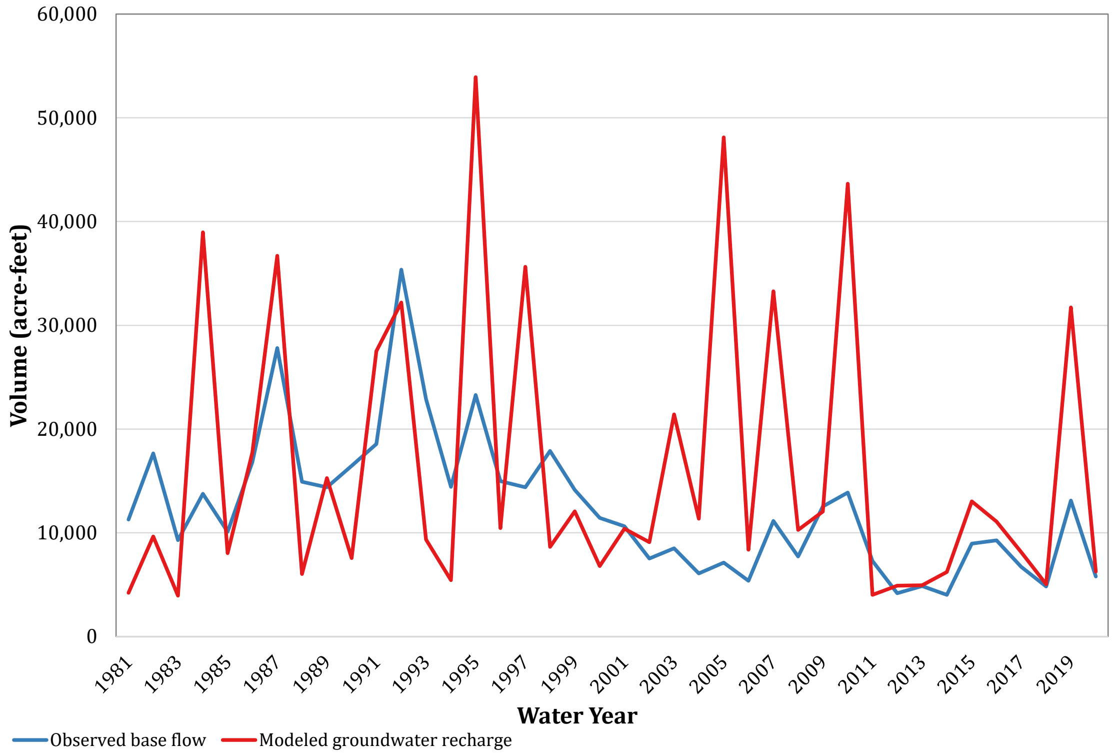

Figure 7-?. Comparison of recharge simulation results to observed base flow for gauge 07311700 (Little Wichita).

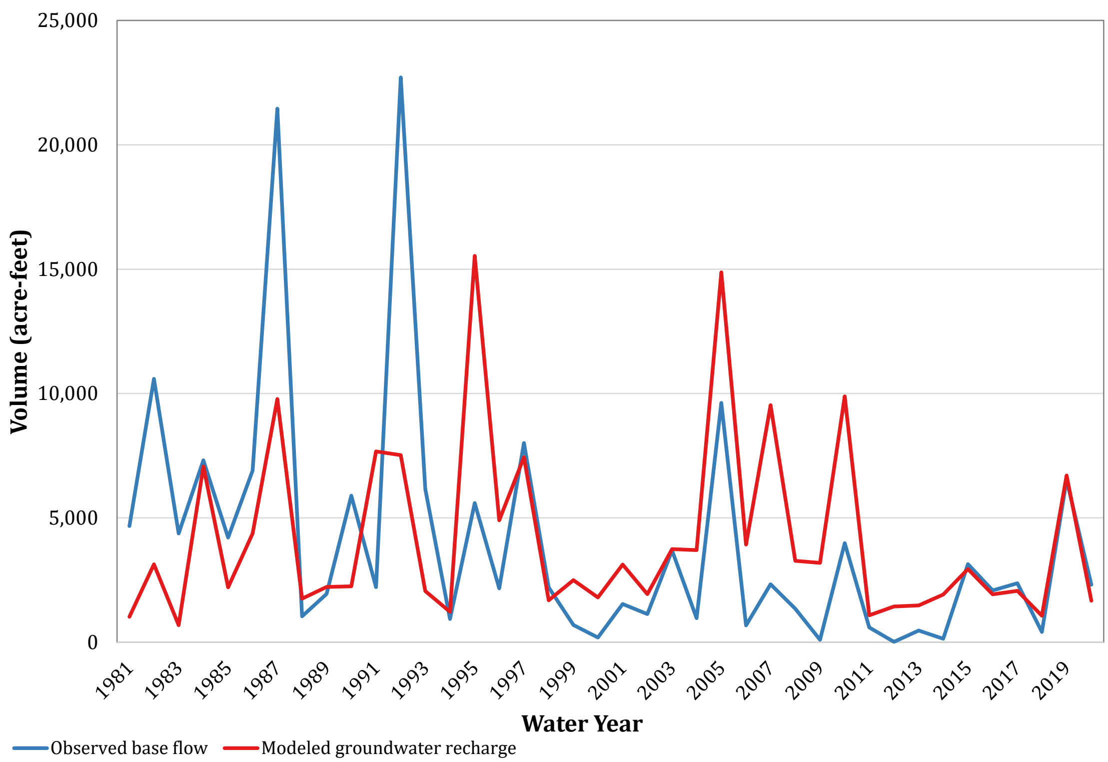

Figure 7-?. Comparison of recharge simulation results to observed base flow for gauge 07311800 (Little Wichita).

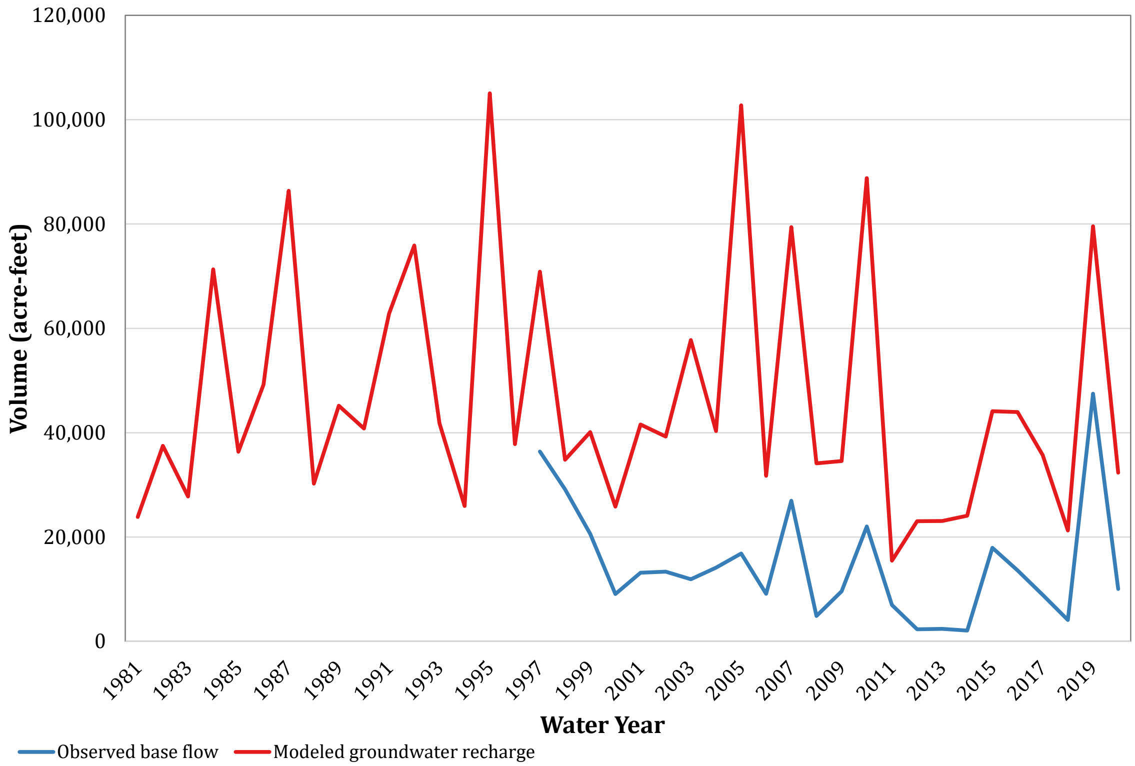

Figure 7-?. **Comparison of recharge simulation results to observed base flow for gauge 07311900 (Little Wichita).**

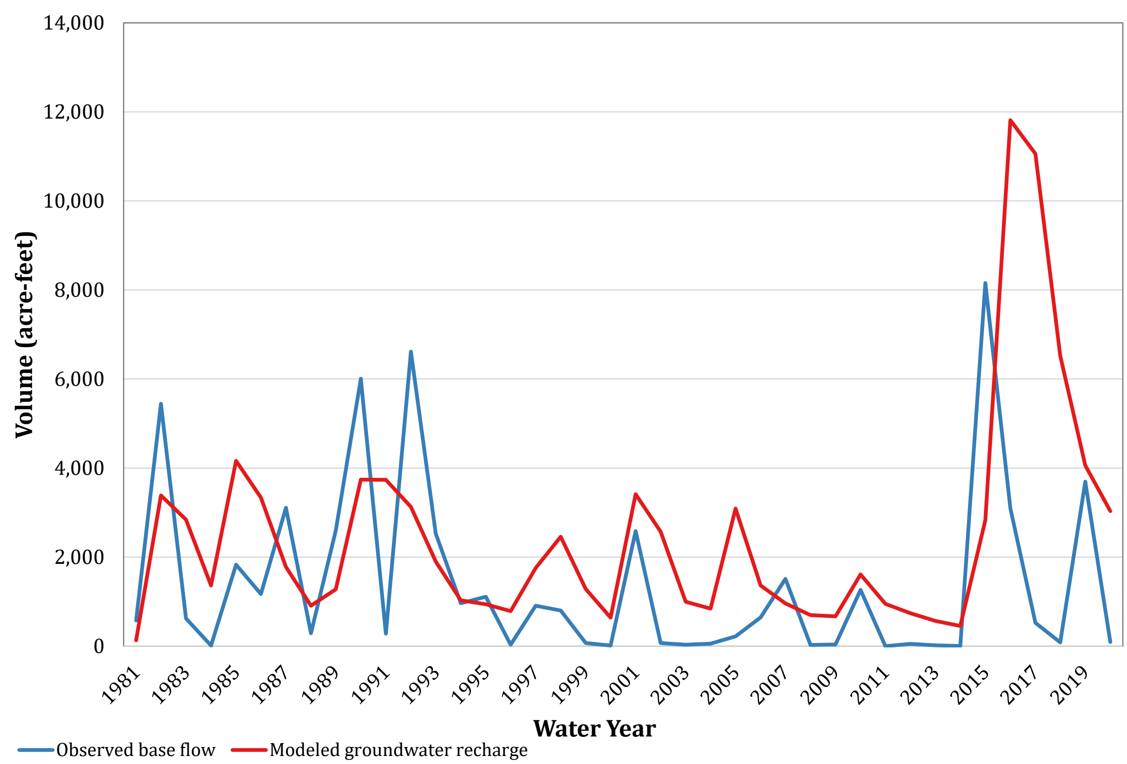

Figure 7-?. **Comparison of recharge simulation results to observed base flow for gauge 07315200 (Little Wichita).**

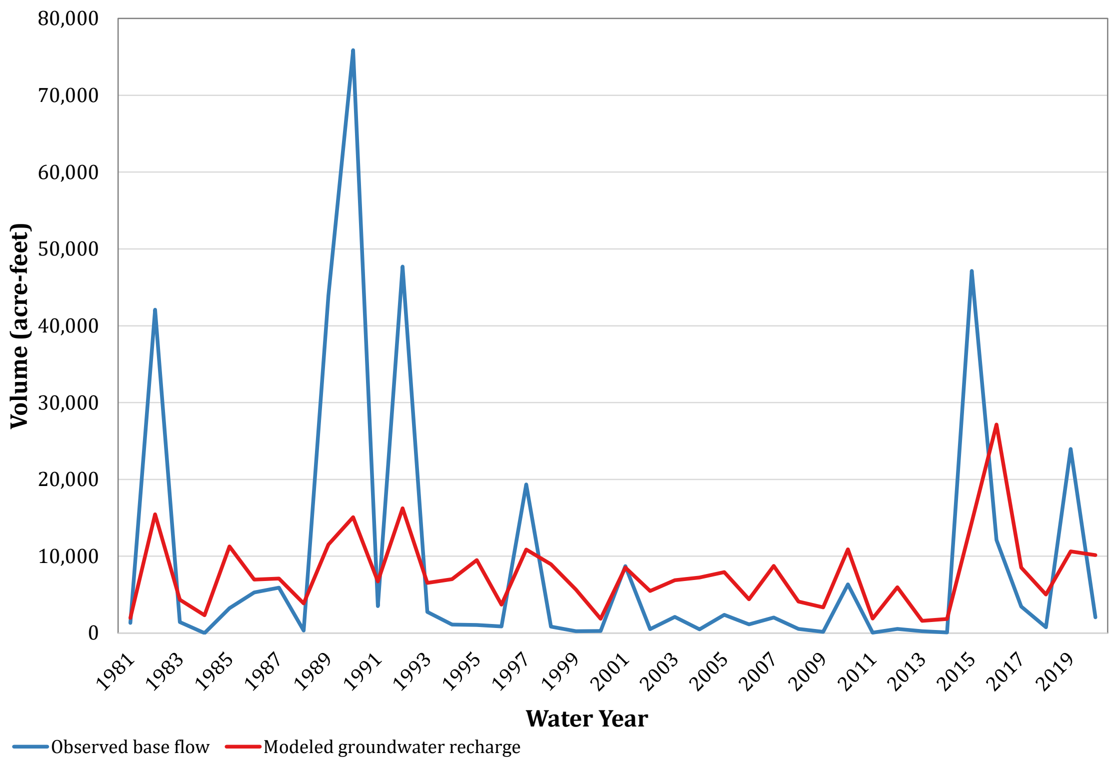

Figure 7-?. Comparison of recharge simulation results to observed base flow for gauge 08042800 (Middle Brazos-Palo Pinto).

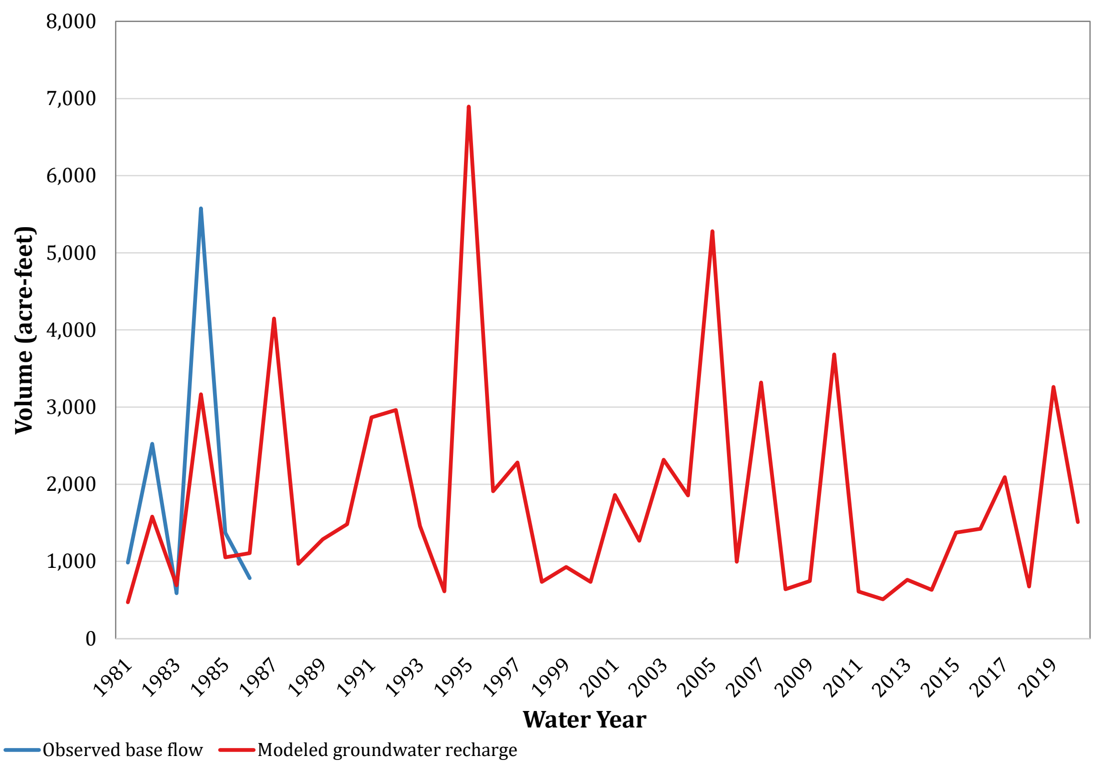

Figure 7-?. Comparison of recharge simulation results to observed base flow for gauge 08082180 (Middle Brazos-Millers).

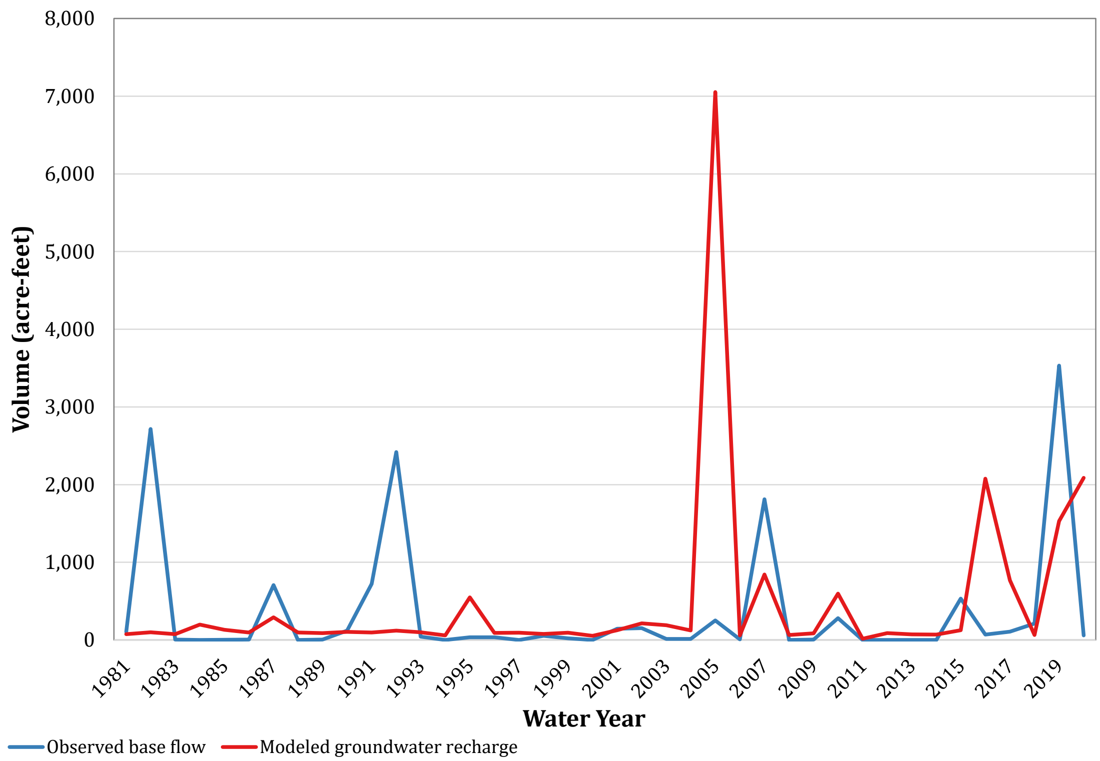

Figure 7-?. **Comparison of recharge simulation results to observed base flow for gauge 08082700 (Middle Brazos-Millers).**

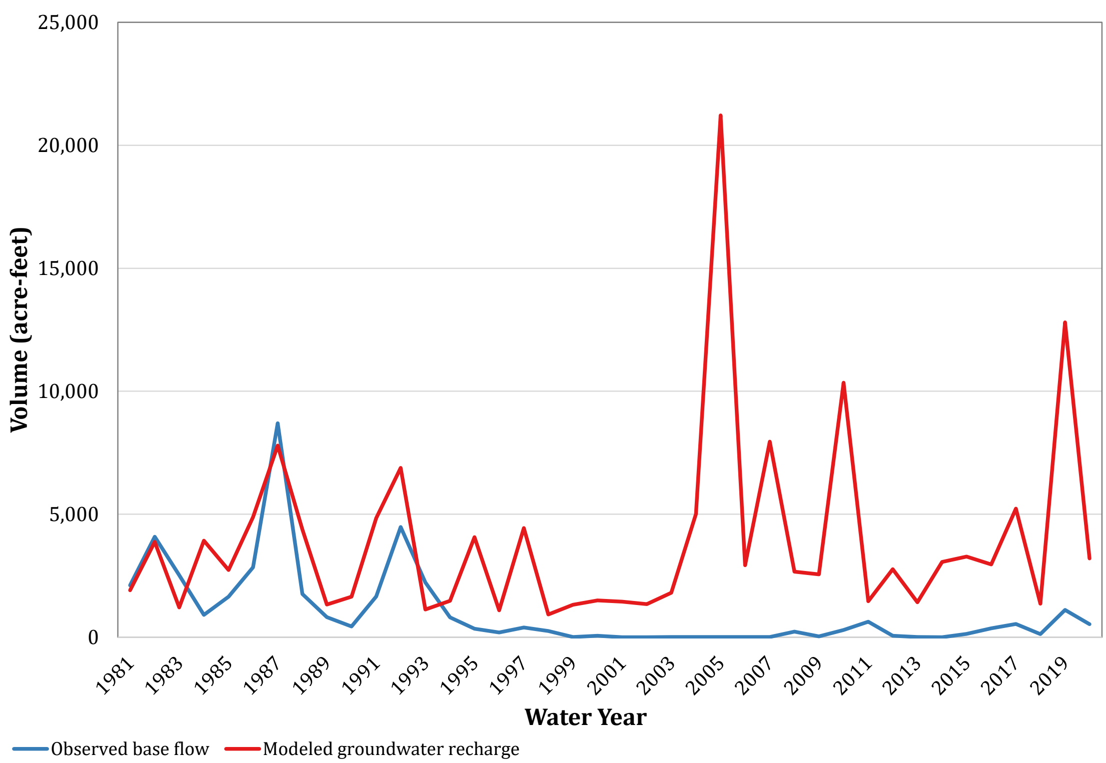

Figure 7-?. **Comparison of recharge simulation results to observed base flow for gauge 08083100 (Upper Clear Fork-Brazos).**

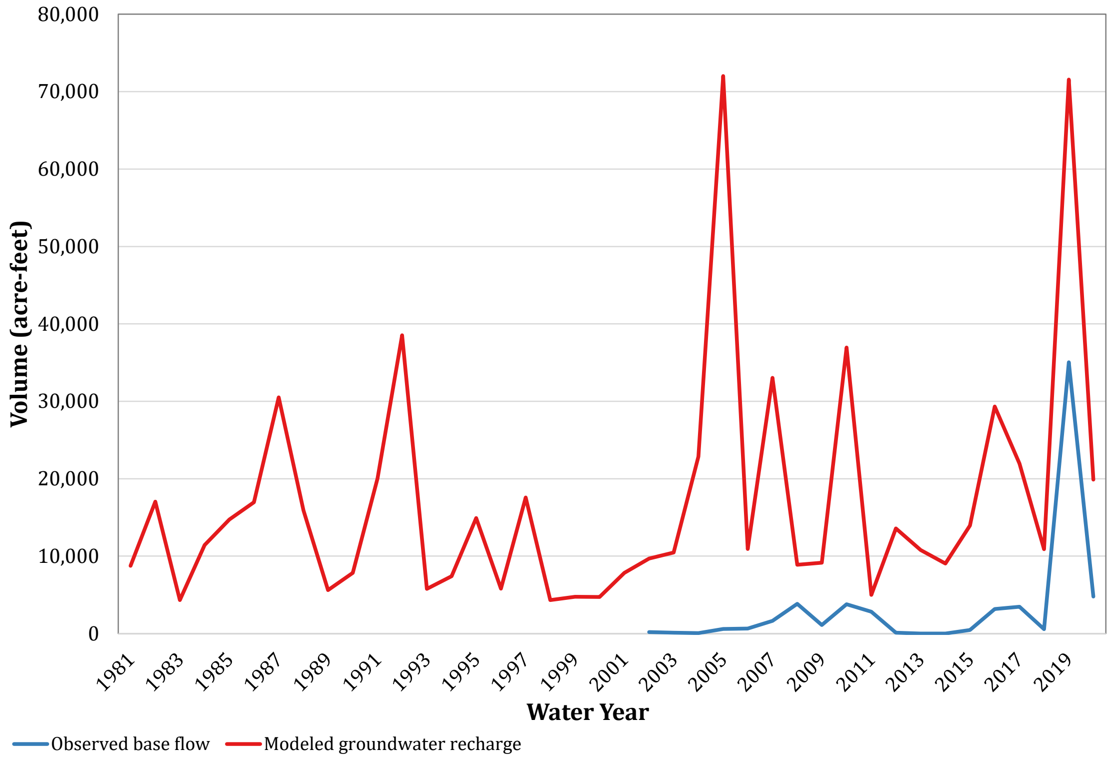

Figure 7-?. **Comparison of recharge simulation results to observed base flow for gauge 08083230 (Upper Clear Fork-Brazos).**

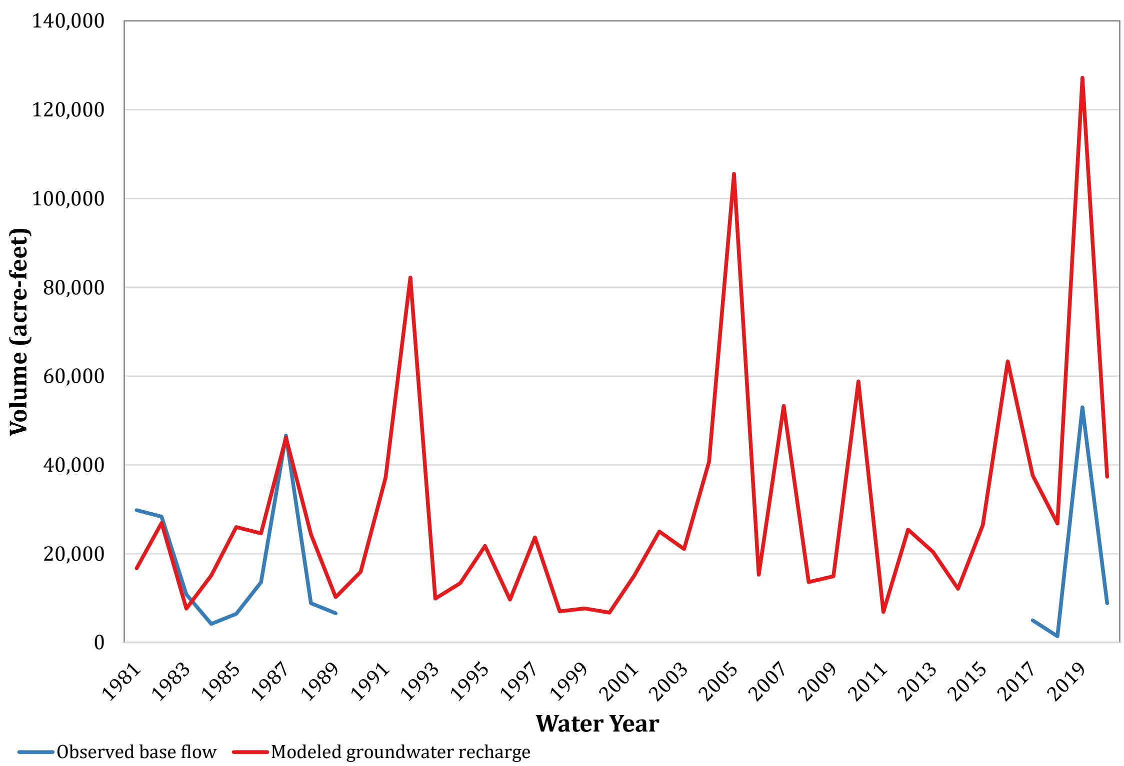

Figure 7-?. **Comparison of recharge simulation results to observed base flow for gauge 08083240 (Upper Clear Fork-Brazos).**

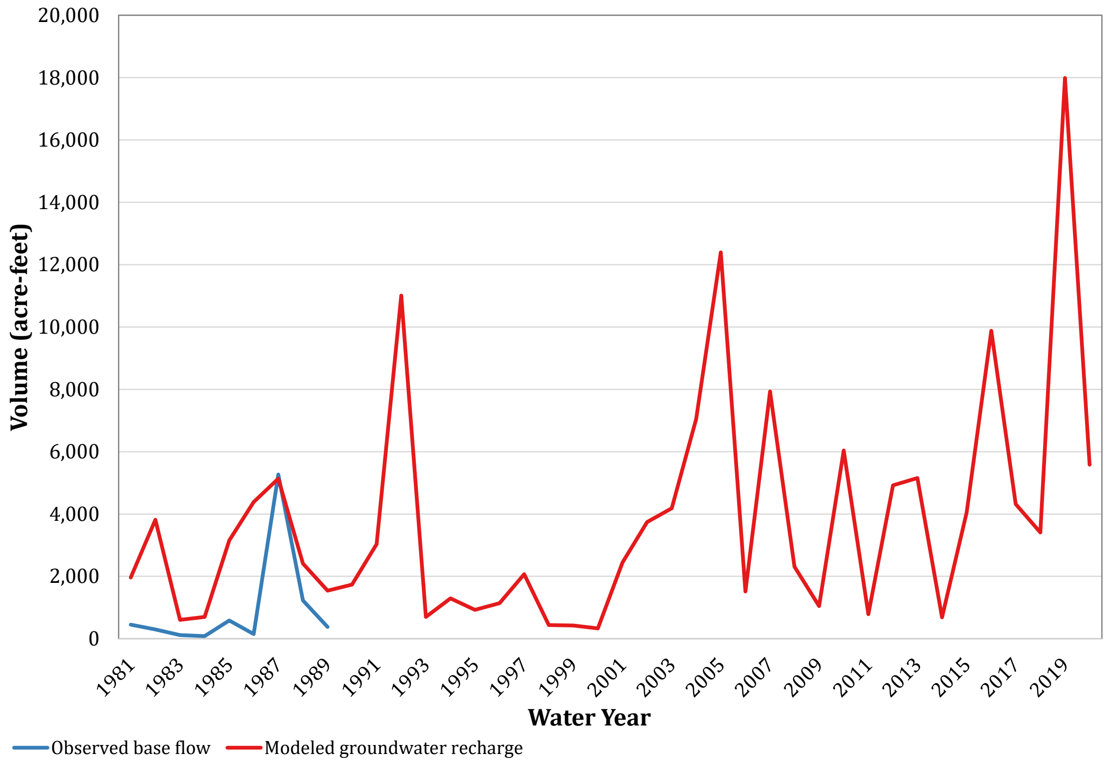

Figure 7-?. **Comparison of recharge simulation results to observed base flow for gauge 08083245 (Upper Clear Fork-Brazos).**

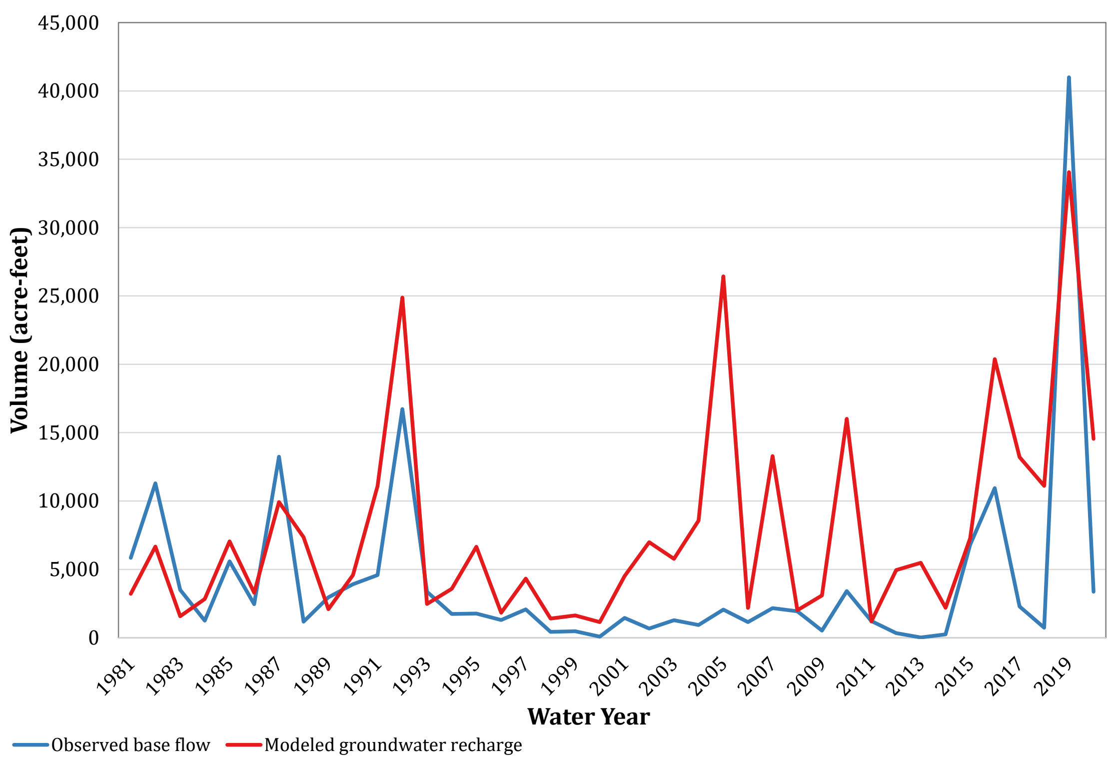

Figure 7-?. **Comparison of recharge simulation results to observed base flow for gauge 08084800 (Upper Clear Fork-Brazos).**

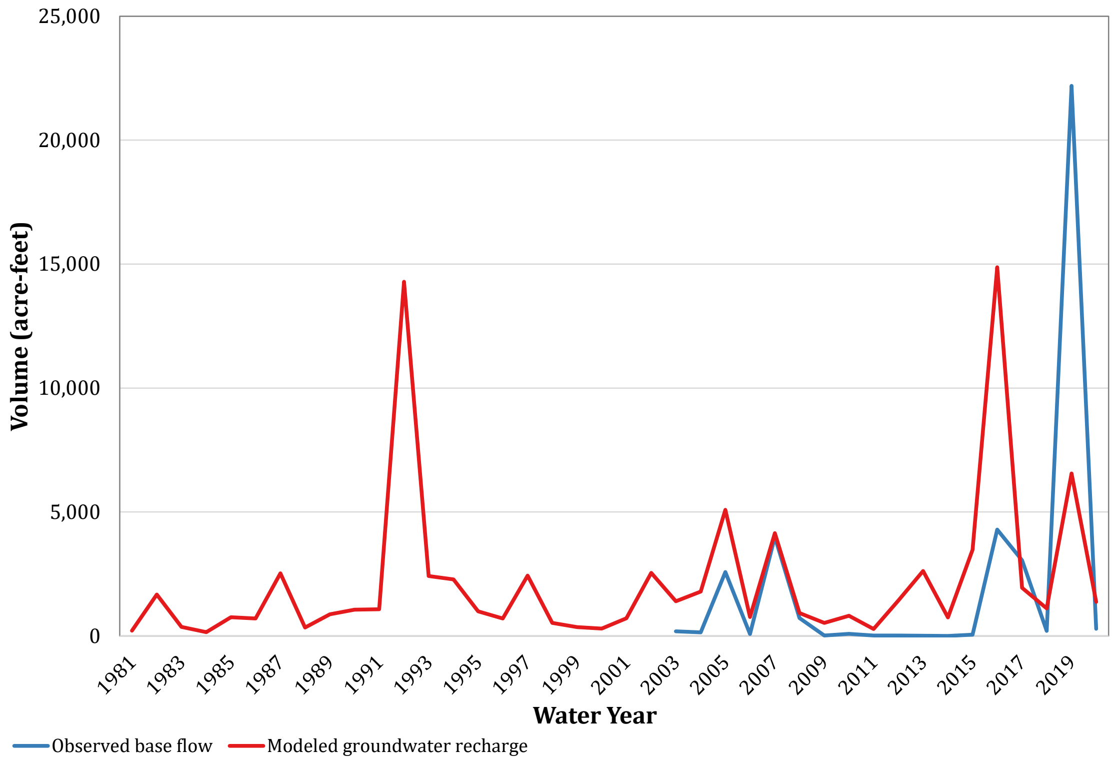

Figure 7-?. Comparison of recharge simulation results to observed base flow for gauge 08086050 (Middle Brazos-Millers).

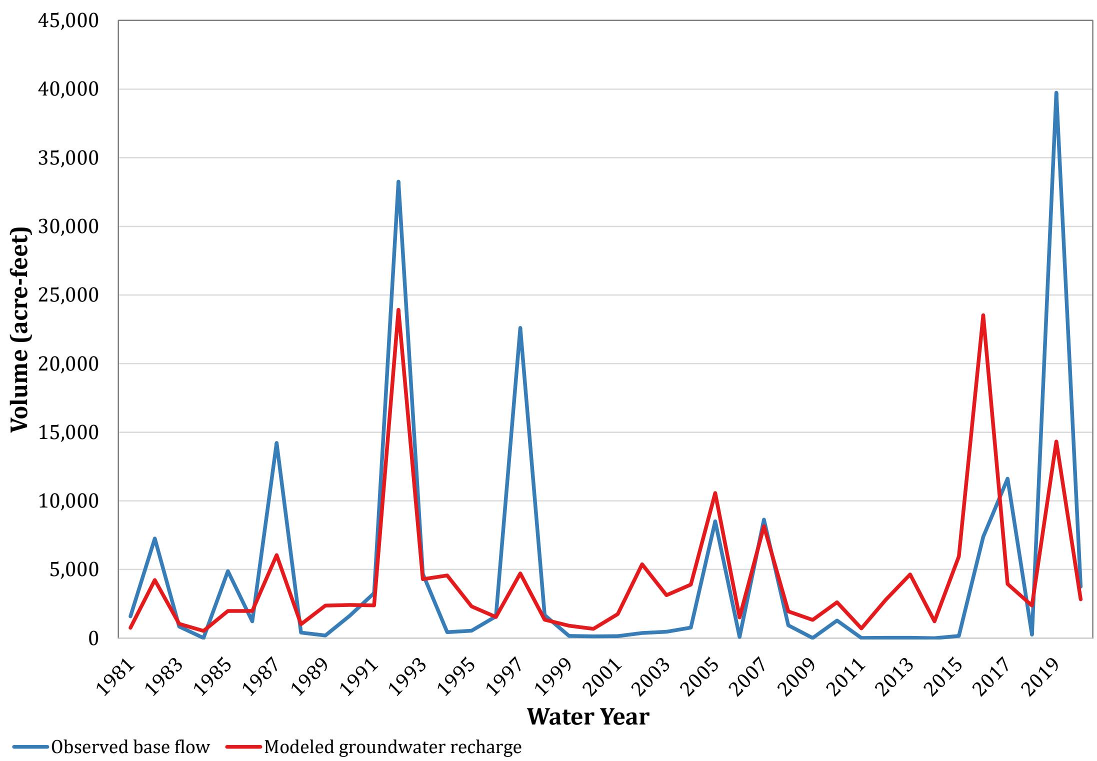

Figure 7-?. Comparison of recharge simulation results to observed base flow for gauge 08086212 (Middle Brazos-Millers).

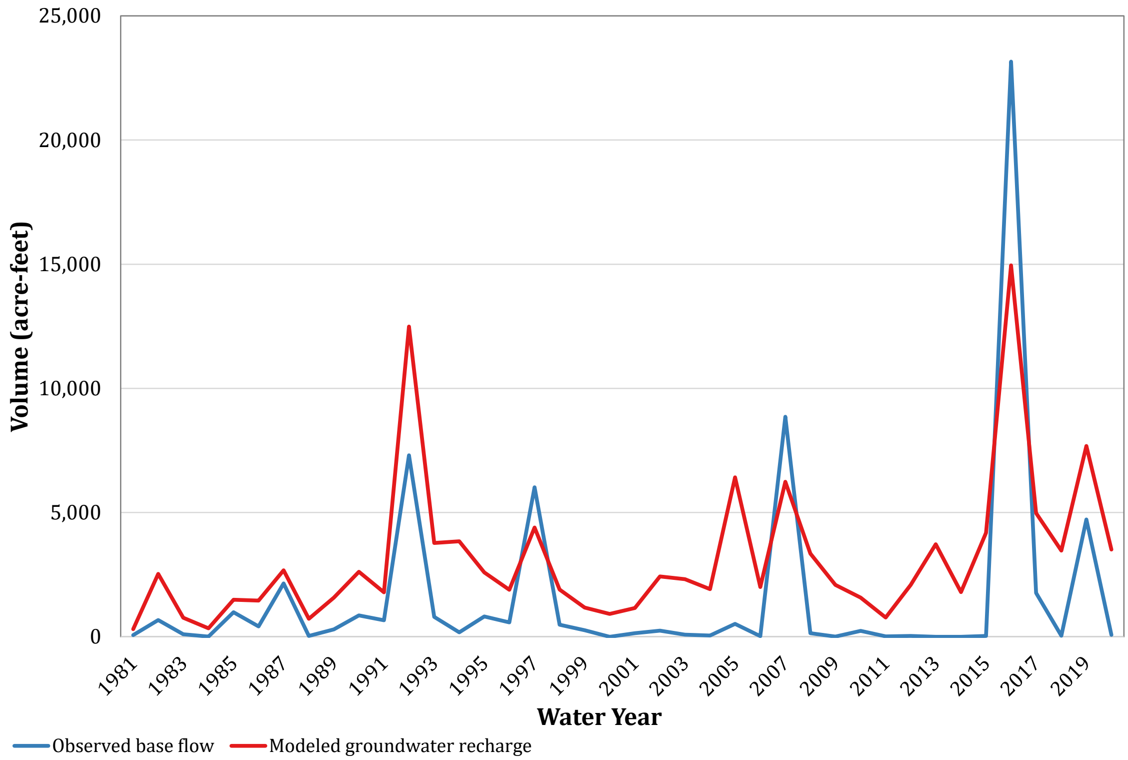

Figure 7-?. Comparison of recharge simulation results to observed base flow for gauge 08086290 (Middle Brazos-Millers).

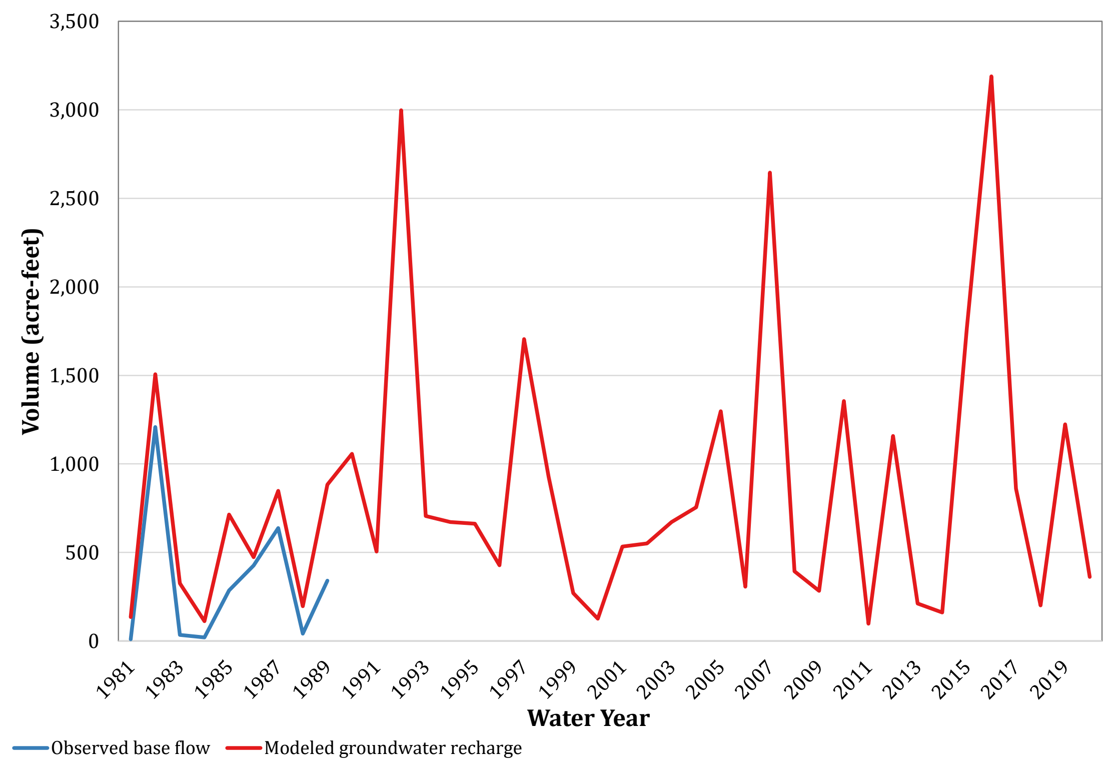

Figure 7-?. Comparison of recharge simulation results to observed base flow for gauge 08088450 (Middle Brazos-Palo Pinto).

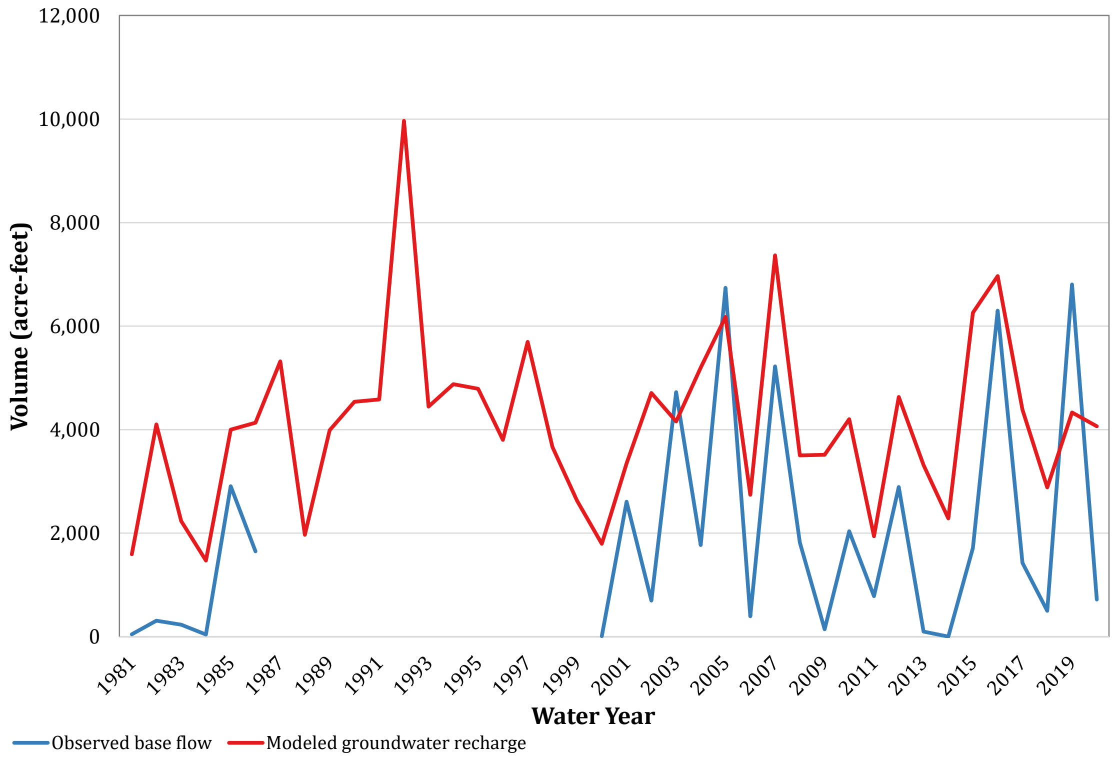

Figure 7-?. **Comparison of recharge simulation results to observed base flow for gauge 08099300 (Middle Brazos-Palo Pinto).**

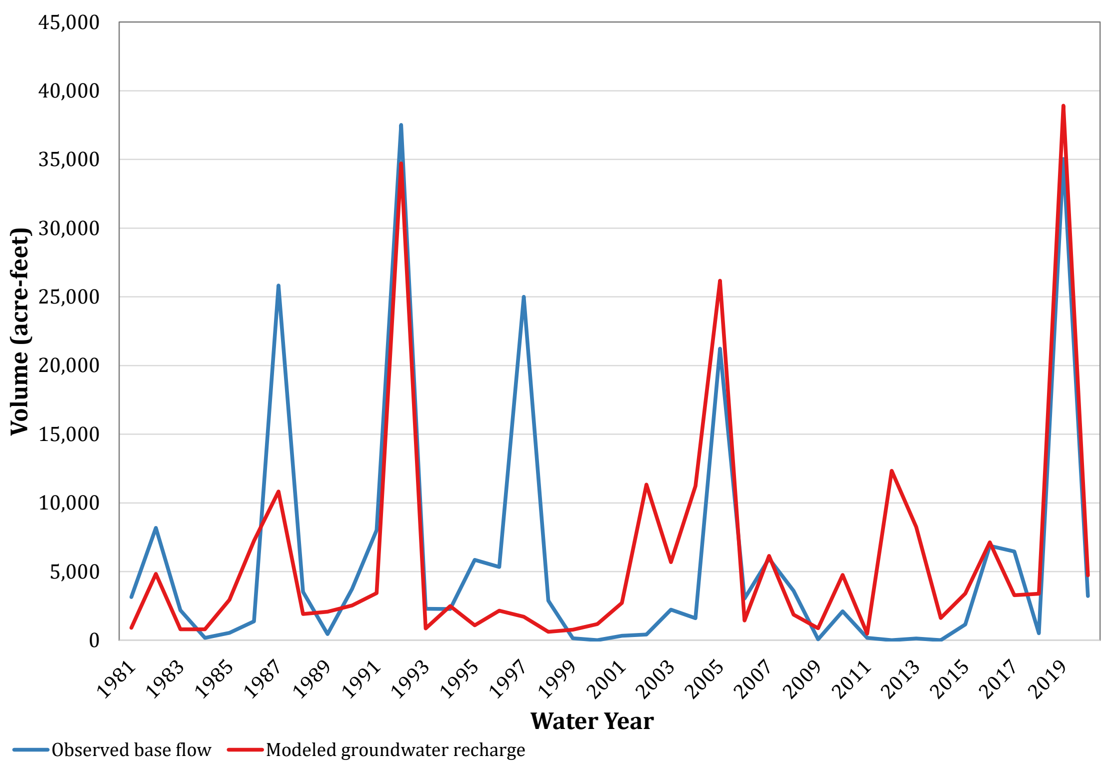

Figure 7-?. **Comparison of recharge simulation results to observed base flow for gauge 08127000 (Middle Colorado).**

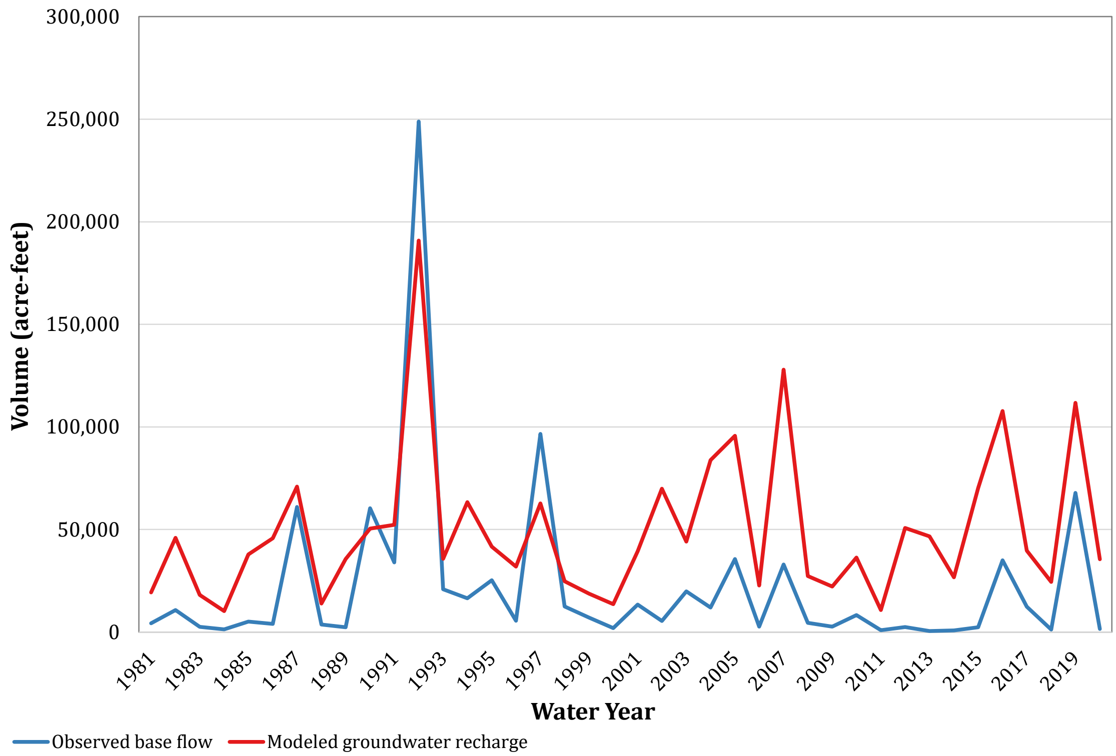

Figure 7-?. Comparison of recharge simulation results to observed base flow for gauge 08143600 (Middle Colorado).

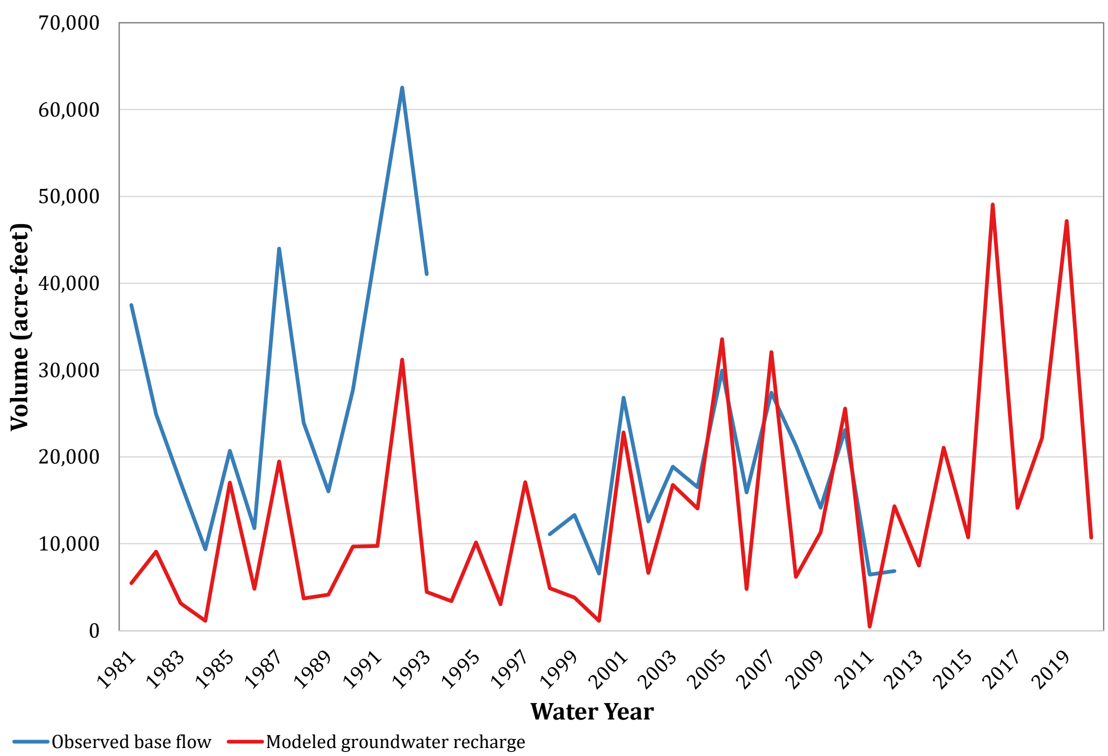

Figure 7-?. Comparison of recharge simulation results to observed base flow for gauge 08144600 (San Saba).

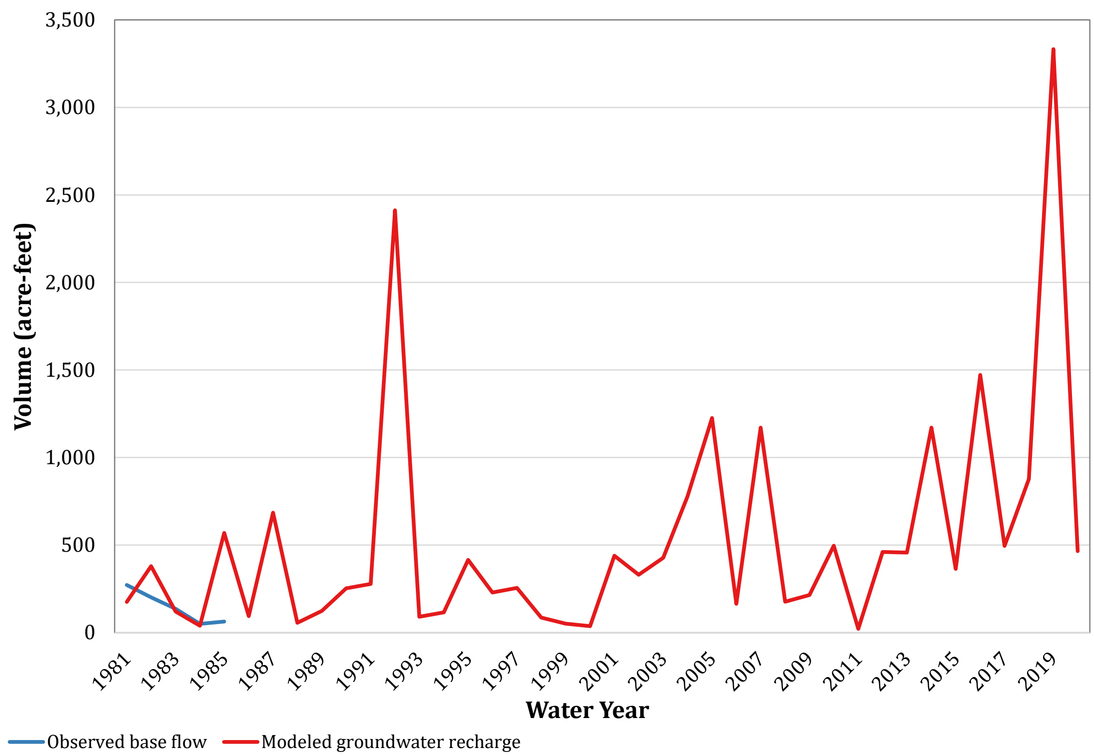

Figure 7-?. Comparison of recharge simulation results to observed base flow for gauge 08144800 (San Saba).

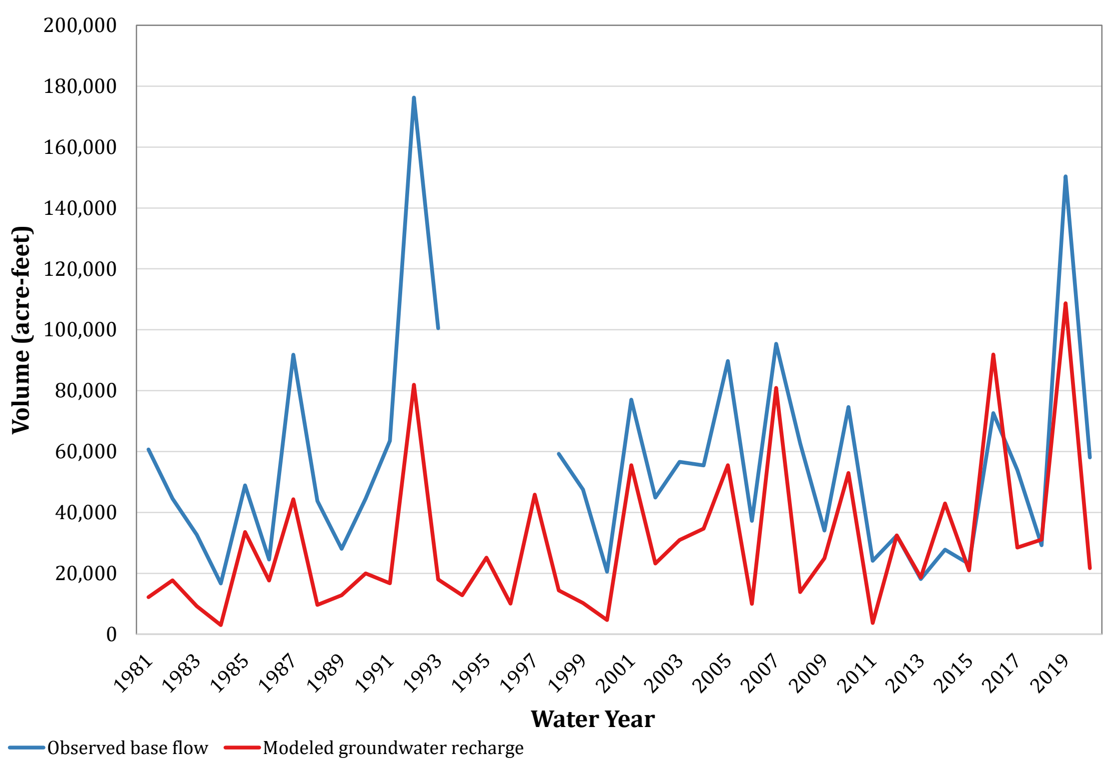

Figure 7-?. Comparison of recharge simulation results to observed base flow for gauge 08146000 (San Saba).