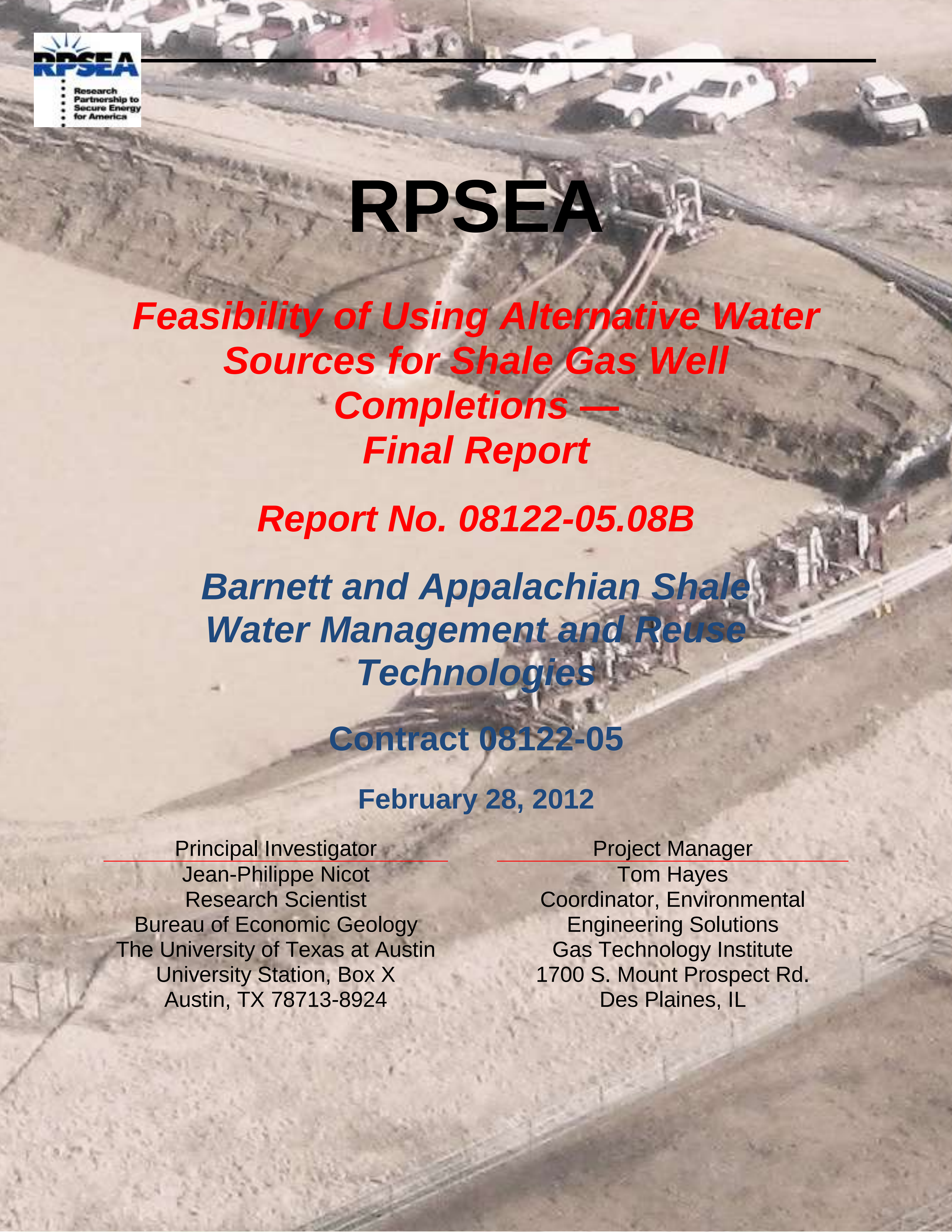

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Feasibility of Using Alternative Water Sources for Shale Gas Well Completions — Final Report

Report No. 08122-05.08B

Barnett and Appalachian Shale Water Management and Reuse Technologies

Contract 08122-05

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Feasibility of Using Alternative Water Sources for Shale Gas Well Completions

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9 Attachment D: Study of North-Central Texas Paleozoic Aquifers

This attachment details how the amount of groundwater available from local aquifers (the so-called Paleozoic aquifers) was determined. A simple numerical model, but with enough details, was built as detailed in later sections. The numerical model was built as a tool to determine the level of pumping that was sustainable according to generally accepted considerations (which, in this work, happens to be the pumping level corresponding to a 5 feet average drawdown).

9.1 How are groundwater availability and sustainability defined?

In this section we explain the reasonable choice of an average drawdown of 5 feet over 50 years as the basis to define admissible pumping levels. The subsurface holds large amounts of water but in practice only a small amount is available for withdrawal and consumption. In predevelopment conditions (that is, before any pumping occurs), aquifers are typically in steady-state conditions with relatively stable water-level and inflows (through various recharge mechanisms) balancing outflows (for example, springs, leakage to other aquifers, discharge to rivers –called base flow). When development (pumping) begins, the water comes initially from storage then typically captures some water from the discharge pathways. Recharge could increase too in what has been called captured recharge because, as the regional water levels go down, less water is discharged through streams, increasing the amount of water available for pumping. However, this may have the effect of decreasing spring flow or river base flow (important during droughts). Such processes have been observed at many locations and have two implications of interest to this work: (1) only a numerical model can capture the intricacies of the relationships between the various components of the water cycle, and (2) only a relatively small amount of the water present in an aquifer can be practically extracted from the aquifer before detrimental impacts occur. Clearly there is no single or simple answer to the how-much-pumping question but the science community can provide tools in deciding the acceptable pumping level. In Texas, various governmental bodies help in determining the pumping threshold before these detrimental impacts occur. The concept of detrimental impact is also subject to discussion because some Texas aquifers are being mined. In such case detrimental impacts involve factors outside of the hydrogeologic realm and are societal or political in nature. Typically, such levels are set indirectly by one of the 16 Regional Water Planning Groups (RWPGs, http://www.twdb.state.tx.us/wrpi/rwp/rwp.asp, http://www.twdb.state.tx.us/wrpi/rwp/3rdround/2011RWP.asp) and 16 Groundwater Management Areas (GMAs, http://www.twdb.state.tx.us/GwRD/GMA/gmahome.htm) deciding what an acceptable impact would be for the different aquifers present within their geographic boundaries. The Paleozoic aquifers are contained in 3 RWPGs (Region B, Region C, and Brazos G) and 2 GMAs (GMA 6 and mostly GMA 8). Metrics chosen by the groups vary. Some groups focus on spring flow, allowing pumping as long as it does not let flow fall below some level, other groups focus on regional drawdowns, not allowing long-term pumping levels that would translate into a regional drawdown beyond an agreed-upon threshold, others set a minimum amount of water that must stay in the aquifer. Such conditions are called *Desired Future Conditions* (DFC's) in the Water Plan. Note that it is important to know if an aquifer is unconfined (water comes from true dewatering of the aquifer) or confined (aquifer stays fully saturated and water comes from depressurization of the aquifer) to appreciate the drawdown threshold. In the TWDB jargon, the pumping level corresponding to the DFCs is called Managed Available Groundwater (MAG). Following such procedure the TWDB updates and produces a State Water Plan in 5-year cycles (http://www.twdb.state.tx.us/wrpi/swp/swp.asp), the Paleozoic aquifers of North-Central Texas are not included in such a plan (because population is sparse and also relies on surface water and because water is sometimes brackish and wells of low yield). For this reason, it is not known what an acceptable pumping level would be for the local population and economic activities, but a reasonable guess can be put forward by looking at how nearby aquifers are handled. The TWDB State Water Plan defines two closely related water volumes: “existing groundwater supplies” and “groundwater availability” (TWDB, 2011). The former describes the amount which can be immediately withdrawn from the subsurface whereas the latter represent the amount available regardless of legal or physical availability. This work discusses available groundwater from the Paleozoic aquifers.

A few DFC’s from across the state follows: GMA 11, in East Texas, includes the Northern Carrizo-Wilcox and overlying aquifers and its DFC’s are defined to allow up to 17 feet of drawdown. GMA 13, covering the southern Carrizo-Wilcox and overlying aquifers from the Mexican border to northeast of San Antonio, proposed an average drawdown of 23 ft. It also proposed an average drawdown of 2 ft on the Yegua-Jackson aquifer and an average artesian flow of 500 gpm for the Edwards aquifer in Frio County (south Texas). GMA 16 accepted an average 94 ft drawdown in the Southern Gulf Coast aquifers. Further north, GMA 15 covering the Central Gulf Coast aquifer planned a 12 ft average drawdown.

Eastern edge of GMA 6 includes Clay, Jack, and Palo Pinto counties, three western counties of the area of study. The focus of GMA 6 is mostly its western half with the Ogallala, Dockum, Blaine, and Seymour aquifers. Blaine Aquifer is also an aquifer hosted by Paleozoic rocks. DFC’s vary from 2 to 7 feet of average drawdown but also includes the possibility of pumping up to half of the water available in some unconfined areas of the Blaine aquifer. GMA 8 includes the other counties of the area of study but is mostly focused on the southeastern half of the area in the footprint of the Trinity and overlying aquifers. Unlike other GMAs that define DFC’s for their entire area, DFC’s in GMA 8 are county-based and vary from 0 to maybe 10 ft in the unconfined section to tens and sometimes hundreds of feet in the confined section.

Somewhat arbitrarily but consistent with numbers above and presented in Table 8. a maximum drawdown of 5 feet was chosen as a reasonable value for the Paleozoic aquifers.

Table 8. Desired Future Conditions drawdowns for selected GMAs.

GMA #	Location in the State and aquifer name	Aver. DD
Selected aquifers in Texas		
GMA 11	East Texas: confined and unconfined Northern CZWX and other aquifers	17 ft
GMA 13	South Texas Southern CZWZ and other aquifers	23 ft
GMA 16	South Texas Southern Gulf Coast	94 ft
GMA 15	Central Texas Central CZWX and other aquifers	12 ft
Aquifers close to and similar to the Paleozoic Aquifers		
GMA 6	Texas Panhandle: Blaine aquifer	2-7 ft
GMA 8	North-Central Texas: Trinity and overlying aquifers unconfined confined	<10 ft 100’s ft

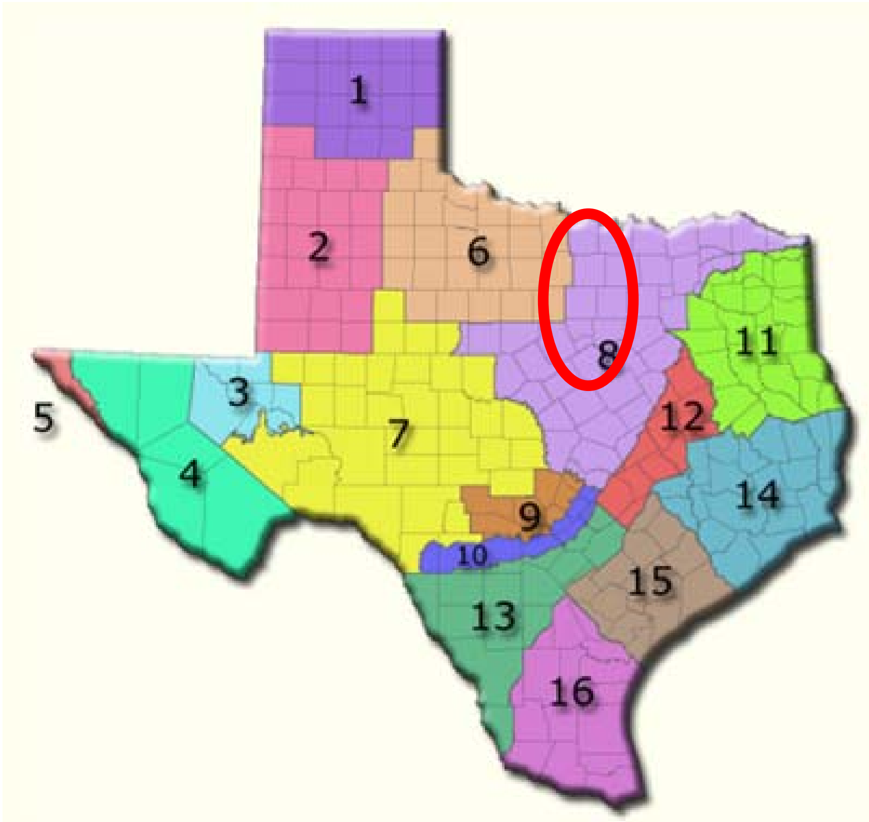


Figure 16. Map of GMAs and of area of interest (red ellipse)

9.2 How was the Pumpage Corresponding to the 5-ft Drawdown Determined?

The first step is to collect information on how much water has been withdrawn from the aquifers in the past (for all uses) and how much is projected to be withdrawn exclusive of fracing. One of the TWDB water planning databases contains historical pumping by county since 1980 (http://www.twdb.state.tx.us/wushistorical). Estimates for earlier years were made by assuming that population and groundwater use are linearly related. Census data has information about population (https://www.tsl.state.tx.us/ref/abouttx/census.html). Future water use by county is also provided in a TWDB file (http://www.twdb.state.tx.us/wrpi/data/proj/2012demandproj.asp) by county. Note that the current version of the TWDB future water use does not include fracing. In a second step, we added the fracking water use projections (Nicot et al., 2011). We conservatively assumed that all frac water would be groundwater. The annual projections were not directly used, instead the average for each county of the projections over the 30 additional years the play is projected to be active (to 2040) was used and then still used beyond the time the play was projected active (from 2040 to 2060). The county level has been determined as the most adequate for water use projections. It includes prospectivity considerations and likely general interest of the county from the oil and gas industry. In other words, it distributes the pumping across the area in a logical way instead of assuming pumping will be distributed evenly throughout the entire zone f interest. The third step was to multiply the average projections by a coefficient until the average drawdown condition of 5 ft (between 2010 and 2060) was met. The average drawdown was calculated on the cells with drawdown>0. The final frac pumping is ~7 times the projected amount suggesting the aquifers can sustain such pumping levels at the regional level (Table 9). However, locally drawdowns can be much more pronounced (maximum is >100 ft).

Table 9. Time-constant pumping level in individual cells in addition to the natural pumping owing to all uses but fracking

County	Clay	Erath	Jack	Montague	Palo Pinto	Parker	Wise
Pumping rate / cell (m^3/day)	27	14	17	27	14	19	22

Note: pumping is applied only to those cells within the 33rd high transmissivity percentage

9.3 Well Yield Estimate

In addition to knowing how much water is present (capacity), it is also important to quantify availability, that is, well yield or how much water can be produced in a given amount of time. Well yields reported to TCEQ (see document below) do not necessarily represent the maximum yield of the aquifer because those wells are drilled for domestic use. They are not screened over the entire available thickness and probably do not withdraw water to capacity over their actual screened interval. However, they represent the physical evidence that the aquifer is able to sustain at least that pumping rate. Transmissivity values are better estimates but they have not been groundtruthed by actual pumping.

9.4 Water Quality

A MS thesis partially funded by this project focused on the water quality of the Paleozoic aquifers. An excerpt of the draft is attached next and summarized in this section. According to the TWDB database, main source of information to this discussion (no samples were taken in the filed for this study), the median Total Dissolved Solid concentration is ~800 mg/L (up to 4,000 mg/L) (Table 2 of Appendix 1 of this attachment). The pH is generally relatively high, between 7 and 9, in agreement with a strong carbonate imprint. The ionic composition is very variable is likely the result of the mixing of two end members: a deeper sodium chloride and a shallower calcium bicarbonate member. Note that the database is likely biased towards fresher sections of the aquifers and not necessarily similar to the distribution resulting from sampling those aquifers according to a regular grid.

9.5 Description of Model of the Paleozoic Aquifers

The following documents (Appendix 2 and Appendix 3) describe the construction of the model.

Appendix1: Alternative Groundwater resources in North-Central Texas for the Development of the Barnett Shale Gas Play (MS thesis's excerpt) – Geochemical Analysis of Selected North-Central Texas Aquifers

Appendix 2: Evaluation of Paleozoic Aquifers of North Central Texas; Part I: Development of a Static Model for a Numerical Model

Appendix 3: Evaluation of Paleozoic Aquifers of North Central Texas; Part II: Groundwater Flow Model

(Draft) Abstract

Alternative Groundwater resources in North-Central Texas for the development of the Barnett Shale Gas Play

Edward R. McGlynn, M.S.

The University of Texas at Austin, 2012

Supervisors: Jack Sharp and J.-P. Nicot

Texas water resources are under pressure due to population growth expected in the coming decades, increasing industrial demands, and frequent periods of drought. With this increasing demand for limited water resources it is important to explore alternative water sources within the State. One of those resources that can developed are the many small aquifers which have never been characterized but could be an alternative source of fresh and brackish water for agriculture, municipal, and industrial applications.

The natural gas industry's demand for water is growing in Texas as new drilling techniques such as hydraulic fracturing have opened new reserves previously considered economically non-viable. The development of smaller aquifers containing brackish water is a viable alternative to the gas industry's current reliance on fresh (potable) groundwater resources. The aquifer sections containing brackish water need to be mapped and characterized so they can be developed as an alternative water resource by the gas industry.

The Barnett Shale in North-central Texas is one of the first major gas plays in the United States to use the technique of hydraulic fracturing in field development. This technique requires large quantities of water to create the required hydraulic pressure down the gas well to fracture the normally low permeability shale. A typical horizontal well completion consumes approximately 3.0 to 3.5 million gallons (11.4 to 13.2 million liters) of fresh water. Projections of future groundwater demand for the Barnett Shale gas play total 417,000 AF, an annual average of 22,000 AF over the expected 2007-2025 development phase (Nicot 2009). This level of water demand has the gas industry and groundwater managers in the State exploring alternative sources of water for future development of the Barnett Shale.

One alternative source of water for the expanding footprint of the Barnett Shale gas play are the smaller Pennsylvanian aquifers on the western edge of the basin. These small aquifers are underutilized and contain waters with higher levels of TDS. These levels are, however, acceptable to the drilling industry. In order to characterize theses aquifers, TWDB databases were utilized to analyze water chemistry and well productivity.

The aquifers of the study area are located primarily in Montague, Jack, Palo Pinto, Wise and Parker counties. Well depths range mostly between 30 and 500 feet (9.1 and 152.4 meters) below land surface. Yields from wells are variable, ranging from less than 5 to over 60 gpm (27.3 to over 327 m^3/day). The specific capacity of the minor aquifers range mostly between 0.10 and 5.0 gpm/ft-drawdown, which indicates significant drawdown, will be required to meeting industry pumping rate requirements of 100 gpm (545 m^3/day). To establish a pump rate of 100 gpm (545 m^3/day), the drawdown would expect to range between 20 feet and 1000 feet (6 and 305 meters). Groundwater quality in the minor aquifers generally contains between 300 and 3800 mg/L TDS, well under the industry waterflooding requirement of less than 20,000 mg/L TDS. Calcium levels generally range between 2 and 220 mg/L, well within the industry requirement of less than 350 mg/L, pH levels range between 9 and 7, which is outside the industry requirement of less than 8 for waterflooding.

Excerpts from draft thesis only

I. Study Area Description

The focus of this study is the Fort Worth basin of north-central Texas which includes 14 counties with significant gas production: Bosque, Dallas, Denton, Erath, Hill, Hood, Jack, Johnson, Montague, Palo Pinto, Parker, Somervell, Tarrant, and Wise. These 14 counties will be referred to as the Tier I & II counties relative to the development of the Barnett Shale gas play (Figure 1). The Tier I counties were the first and primary areas developed in the Barnett shale play including Denton, Tarrant, Dallas, Johnson, Hill and Bosque. While the Tier II counties encompass the new region in which the developers of the Barnett play are migrating to.

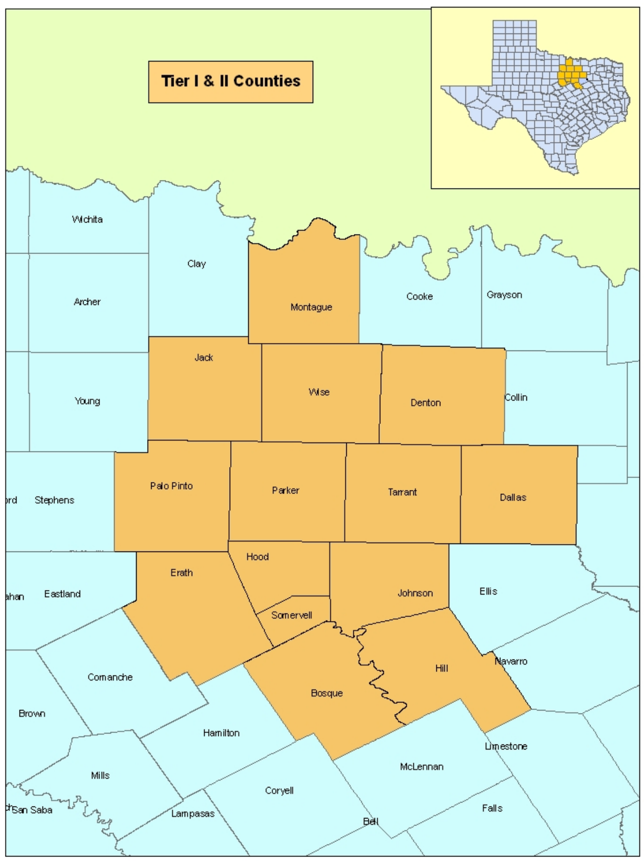


Figure 1. Study Area - Tier I & II Counties

Due to the current use and knowledge by the natural gas industry of the Cretaceous strata of the study area, the primary focus of this study is the Pennsylvanian strata. The Pennsylvanian area of north central Texas can be described as two great inliers of Carboniferous rocks that protrude through the Cretaceous strata on the east and dip beneath Permian rocks on the west and north. The two areas are separated by a narrow tongue of Cretaceous (Trinity) sand, and the southern outcrop rests against Ordovician rocks for a short distance along the Llano uplift. The total area covered by the Pennsylvanian is about 7,000 square miles. It includes the west part of Montague, the south- east part of Clay, the greater portion of Jack, Young, Stephens, Palo Pinto, Eastland, Brown, the east half of Coleman, the north part of San Saba, and the northeast of McCulloch counties. The shape and location of the Pennsylvanian area are shown on the index map (Figure 2).

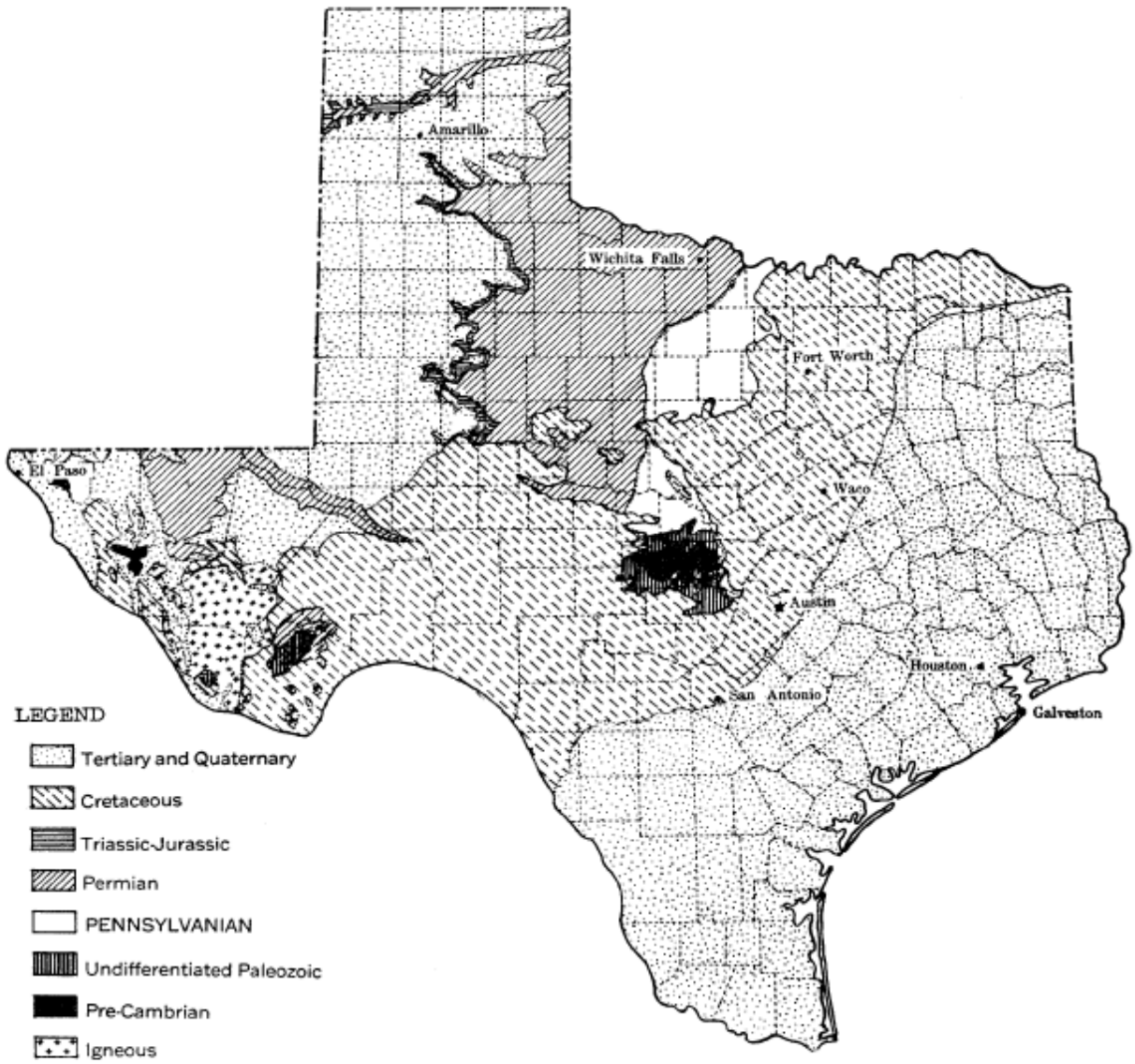


Figure 2. The Pennsylvanian area of north central Texas, Moore (1922)

II. Geological setting

Stratigraphic units that supply fresh to slightly saline water to wells in the study area range in age from Paleozoic to Recent. The North Central Texas Region includes several prominent geologic structures, which include the Pennsylvanian and Permian Paleozoic and the Cretaceous strata of the Trinity aquifer.

a. Regional Stratigraphy

The Cretaceous System is composed of two series, Gulf and Comanche, and each is divided into groups. The Gulf Series is divided into the following five groups: Navarro, Taylor, Austin, Eagle Ford, and Woodbine. The Comanche Series is divided into the following three groups: Washita, Fredericksburg, and Trinity. The Taylor and Eagle Ford Groups consist predominantly of shale, limestone, clay, and marl and yield only small amounts of water in localized areas (Nordstrom 1982). The Navarro and Austin Groups consist of chalk, limestone, marl, clay, and sand and, except for the Nacatoch and Blossom Sands, yield only small amounts of water locally. The Nacatoch Sand of the Navarro Group and the Blossom Sand of the Austin Group yield small to moderate supplies of water to limited areas. The Woodbine Group is the only important aquifer of the Gulf Series in the area covered by this report. It consists of sand, sandstone, and clay and is capable of yielding small to large amounts of water. Both the Washita and Fredericksburg Groups of the Comanche Series consist predominantly of limestone, shale, clay, and marl and yield only small amounts of water to localized areas. The Trinity Group is the principal aquifer in the region and is divided into the Paluxy, Glen Rose, Twin Mountains, and Antlers Formations. The Paluxy consists of sand and shale and is capable of yielding small to moderate amounts of water. The Glen Rose is predominantly a limestone and yields small quantities of water only to localized areas. The Twin Mountains is composed of conglomerate, sand, and shale. It is the principal aquifer formation of Cretaceous age in the region and yields moderate to large amounts of water. The name Antlers Formation is applied north of the Glen Rose pinch-out, where the Paluxy and Twin Mountains coalesce to form one unit (Nordstrom 1982).

The Trinity Group of Cretaceous age contains the largest and most prolific aquifer in the study area. The aquifer consists of the Antlers, Twin Mountains and Paluxy Formations. The Antlers is a coalescence of the Paluxy and Twin Mountains in the northern part of the study area where the Glen Rose Formation is no longer traceable. The lower sands and shales of the Twin Mountains are the hydrologic equivalent of the basal portion of the Antlers. The younger Woodbine Group overlies the Fredericksburg and Washita Groups that function as an aquitard between the Woodbine and the stratigraphically lower Paluxy Formation (Baker 1990).

b. Structure

Pennsylvanian and Permian rocks in the outcrop along the west edge of the study area dip westward and northwestward at about 40 feet per mile (7.6 m/km). Permian beds probably extend not much farther eastward than Montague County (Nordstrom 1982). The Pennsylvanian sediments, which underlie the Cretaceous rocks in most of the remaining area, thicken from the outcrop eastward into the Fort Worth basin. The Cretaceous System forms a southeastward-thickening wedge extending across the area into a structural feature known as the East Texas basin. Thickness of these rocks ranges from zero in the west to nearly 7,500 feet (2,286 m) in the southeast. Regional dip is east and southeast at rates of about 15 to 40 feet per mile (2.8 to 7.6 m/km). The dip rate increases to as much as 300 feet per mile (57 m/km) on the southeastward-plunging ridge called the Preston anticline.

Quaternary deposits occur along the flood plains of the Brazos, Red, Sulphur, and Trinity Rivers and many of their main tributaries. Terraces, which represent remnants of older floodplain deposits of these drainage systems, occur at higher elevations along some of the rivers, particularly the Red River. Alluvial deposits are reported to be as thick as 70 feet (21 m) in Fannin County. Generally, the alluvial deposits are irregular in thickness and areal extent (Nordstrom 1982).

ERA	SYSTEM	SERIES	GROUP	FORMATION	APPOXIMATE MAXIMUM THICKNESS (FT)	HYDRAULIC PROPERTIES*
Cenozoic	Quaternary	Recent	Alluvium	Alluvium	60	Yields small to large amounts of fresh water to wells along the rivers and their tributaries.
		Pleistocene	Seymour	Seymour	125	
Mesozoic	Cretaceous	Gulf	Navarro	Kemp Clay, Corsicana Marl, Nacatoch Sand	800	Upper members are not known to yield water to wells in area; lower member yields small to moderate quantities of fresh to slightly saline water near the outcrop.
			Taylor	Marlbrook Mar, Pecan Gap Chalk, Wolfe City -Ozan Formations	1500	Yields small quantities of water to shallow wells.
			Austin	Gober Chalk, Brownstown Marl, Blossom Sand, Bonham Formation	700	Yields small to moderate quantities of fresh to moderately saline water to wells in northeastern part. Limited as an aquifer.
			Eagle Ford		650	Yields small quantities of water to shallow wells.
			Woodbine		700	Yields moderate to large quantities of fresh to slightly saline water to municipal, industrial and irrigation wells.
		Comanche	Washita		1000	Yields small quantities of water to shallow wells.
			Fredericksburg		250	Yields small quantities of water to shallow wells.
			Trinity	Antlers: Paluxy	400	Yields small to moderate quantities of fresh to slightly saline water to wells.
				Antlers: Glen Rose	1500	Yields small quantities of water in localized areas.
				Antlers: Twin Mountains	1000	Yields moderate to large quantities of fresh to slightly saline water to wells.
Paleozoic	Permian	Wolfcamp	Cisco	Pueblo	100	Yields small to moderate quantities of fresh to moderately saline water for public supply, industrial, irrigation, domestic, and stock wells.
				Harpersville	200	
	Pennsylvanian	Virgil		Thrifty	300	
				Graham	600	
			Canyon	Caddo Creek	300	Yields small quantities of fresh to slightly saline water to wells in and near the outcrop.
		Missouri		Brad	400	
				Graford	600	
				Palo Pinto	300	
			Strawn	Mineral Wells	1100	Yields small quantities of slightly to moderately saline water from sandstone and conglomerate in and near the outcrop.
		DesMoines		Brazos River	1400	
				Mingus		
				Grindstone Creek		
				Lazy Bend		

*Yield of Wells: small -less than 100 gallons per minute (gpm); moderate - 100 to 1,000 gpm; large - more than 1,000 gpm
Chemical Quality of Water: fresh -less than 1,000 milligrams per liter (mg/l); slightly saline - 1,000 to 3,000 mg/l; moderately saline - 3,000 to 10,000 mg/l; very saline - 10,000 to 35,000 mg/l; brine - more than 36,000 mg/l.

Figure 3 Stratigraphy of North-Central Texas Study Area.

Modified from Nordstrom (1988), Duffin (1992) and Baker (1990)

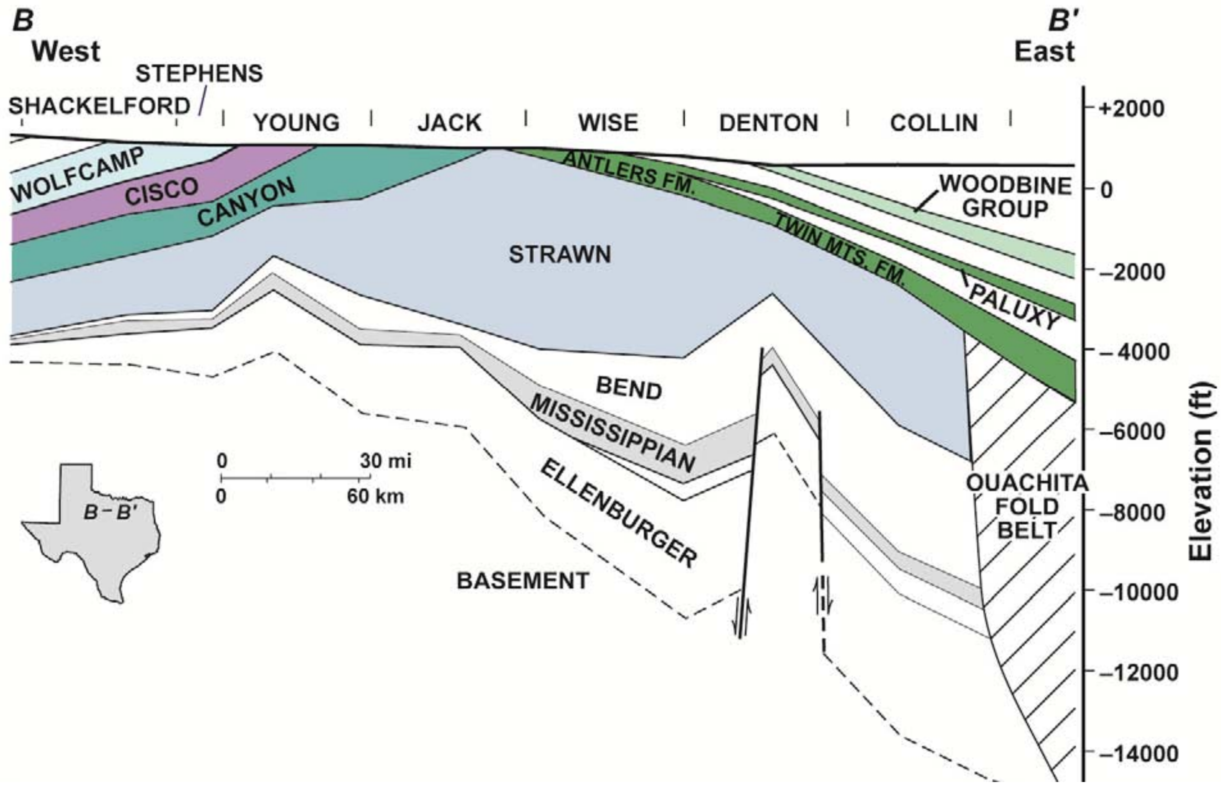


Figure 4a. Stratigraphic Section of Study Area – West to East

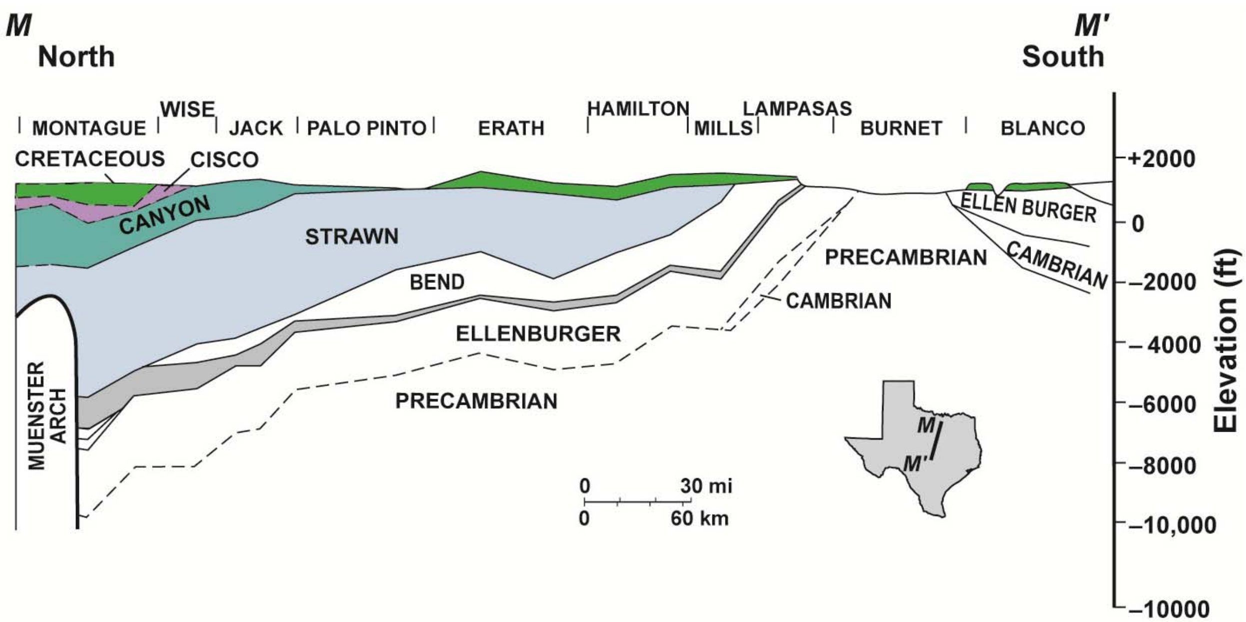


Figure 4b. Stratigraphic Section of Study Area – North to South

III. Hydrogeology

a. Major Aquifers

Trinity Aquifer

The Trinity aquifer is a major aquifer that extends across much of the central and northeastern part of the State. Located in central Texas, the aquifer extends from the Red River to the eastern edge of Bandera and Medina counties, covering a total of 61 counties in the state (Ashworth et al., 1995). The aquifer's area of outcrop is 10,652 square miles (27,588 square kilometers) along its western length and the area of subsurface is 21,308 miles (34,291 km) primarily along its eastern length (Water for Texas, 2007).

Formations comprising the Trinity Group are (from youngest to oldest) the Paluxy, Glen Rose, and Travis Peak (see Figure 5). Up dipping, where the Glen Rose thins or is missing, the Paluxy and Twin Mountains combine to form the Antlers formation. The Antlers consists of up to 900 feet (274 meters) of sand and gravel, with clay beds in the middle section. Forming the upper unit of the Trinity Group, the Paluxy Formation consists of up to 400 feet (122 meters) of predominantly fine to coarse-grained sand inter-bedded with clay and shale. The formation pinches out down dip and does not occur south of the Colorado River (Bradley, 1999). Underlying the Paluxy, the Glen Rose Formation forms a gulf-ward thickening wedge of marine carbonates consisting primarily of limestone. South of the Colorado River, the Glen Rose is the upper unit of the Trinity Group and is divisible into an upper and lower member (Nordstrom 1982).

The Trinity aquifer is comprised of sediments of the Trinity Group and is divided into lower, middle, and upper aquifers based on hydraulic characteristics of the sediments (Barker et al., 1990). The Lower Trinity aquifer consists of the Hosston and Sligo Formations in the subsurface and the Sycamore Sand in the outcrop area; the Middle Trinity aquifer consists of the Cow Creek Limestone, the Hensel Sand, and the Lower Member of the Glen Rose Limestone; and the Upper Trinity aquifer consists of the Upper Member of the Glen Rose Limestone. Low-permeable sediments in the lower and upper parts of the Glen Rose Limestone separate the Middle and Upper Trinity aquifers. The Lower and Middle Trinity aquifers are separated by the low permeability Hammett Shale (see Figure 2) (Mace et al., 2000). The basal parts of the Hosston Formation, the Sycamore Sand, and up dip parts of the Hensel Sand are mostly sand and contain some of the most permeable sediments in the Hill Country (Barker et al., 1994). The Cow Creek Limestone is highly permeable in outcrop but has relatively low permeability in the subsurface due to the precipitation of calcitic cements (Barker et al., 1994). Similarly, the lower parts of the Glen Rose Limestone are more permeable in outcrop areas than in deeper areas (Barker et al, 1994).

The most permeable sands of the Trinity aquifer can be found in the outcrop areas within Brown, Callahan, Comanche, Eastland and Erath counties. The permeability coefficients range from approximately 87 to 235 gallons per day per square foot (gpd/ft^2) (SI unit 3.8 x10^{-5} to 1.03 x10^{-4} m^3/s/m^2). Because of this extreme range in permeability in water saturated sands, transmissibility values vary widely, ranging from zero to 20,000 gpd/ft (Klemt et al. 1975). The sands within the calcareous facies of the Trinity aquifer have extremely low permeabilities due to the cementation of the sands and range from 1 to 20 gpd/ft^2, with coefficients of transmissibility ranging from zero to 1,000 gpd/ft (Klemt et al. 1975).

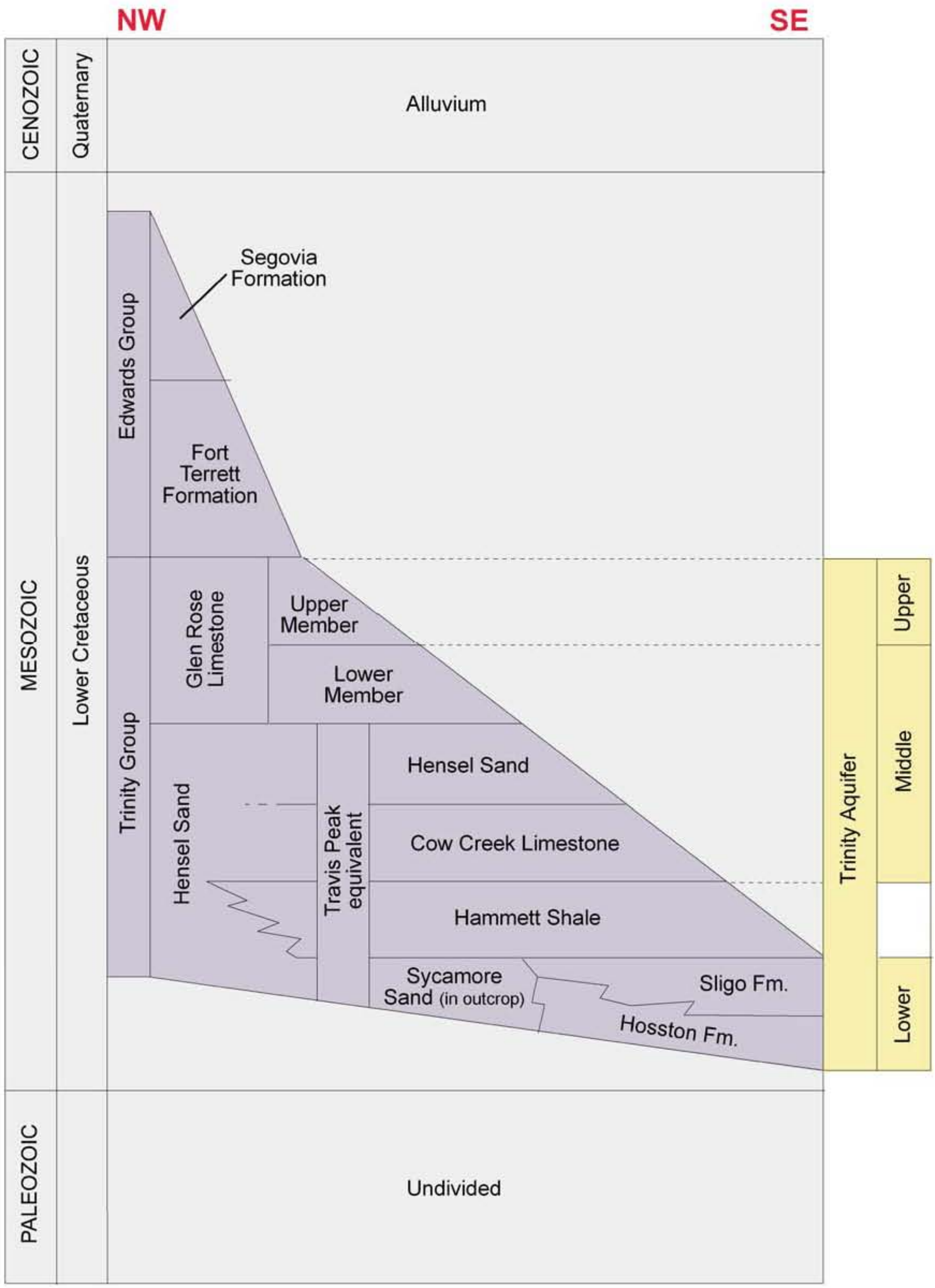


Figure 5. Trinity Aquifer Stratigraphic and Hydrostratigraphic Section (Mace 2000)

Recharge & Discharge

Recharge to the aquifer is primarily in the form of infiltration of precipitation on the outcrop areas and seepage of water from lakes, rivers, unlined earthen ponds, losing streams, and return flows of water used to irrigate crops on the aquifer's surface. A significant portion of the recharged water reemerges as springs and seeps along the contact of the Edwards Group with the Upper Member of the Glen Rose Limestone and as baseflow in gaining river and stream reaches. Discharge from the aquifer also occurs due to subsurface flow into the Edwards aquifer as well as public and private wells (Veni, 1994).

Water Quality

The Trinity aquifer water quality is generally good but very hard in the outcrop of the Trinity aquifer. Total dissolved solids increase to the east and southeast as the depth to the aquifer increases. Sulfate and chloride concentrations also tend to increase with depth (Water for Texas, 2007). Water quality ranges from fresh (less than 1,000 mg/I TOS) up to slightly saline (1,000 to 3,000 mg/I TOS). Chloride concentrations for the Trinity aquifer exceed the SCL of 300 mg/L in the western outcrop areas and the southeastern down-dip areas. Nitrate concentrations exceed the SCL of 44.3 mg /L (as nitrate) in the western outcrop. Sulfate concentrations of the Trinity aquifer exceed the SCL of 300 mg/L in the central and eastern section. High sulfate values may indicate an interconnection between the gypsum rich Glen Rose Formation and the formations it overlies (Bradley, 1999).

b. Minor Aquifers

Alluvium

The recent alluvium of Quaternary age is a minor source of groundwater used primarily in the study area for livestock purposes. Alluvial deposits are found in the floodplains of the major tributaries of streams which make up the surface drainage system in the study area. Ground water in the alluvium is generally calcium bicarbonate water, very hard, normally of neutral pH, and of greatly varying dissolved-solids content. Due to the combination of naturally occurring poor quality water in many areas and the contamination by various activities occurring in the oil and gas industry, the overall quality of ground water obtained from alluvial deposits is poor for domestic purposes.

Brazos River Alluvium

Water-bearing alluvial sediments occur in floodplain and terrace deposits of the Brazos River of southeast Texas. The Brazos River Alluvium aquifer, up to seven miles wide, stretches for 350 miles along the sinuous course of the river between southern Hill and Bosque counties and eastern Fort Bend County. Irrigation accounts for almost all of the pumpage from the aquifer (Cronin 1967). The Quaternary alluvial sediments consist of clay, silt, sand, and gravel, and generally are coarsest in the lower part of the accumulations. Saturated thickness of the alluvium is as much as 85 feet or more, with maximum thickness occurring in the central and southeastern parts of the aquifer. Some wells yield up to 1,000 gal/min, but the majority yields between 250 gal/min and 500 gal/min (Cronin 1967).

The chemical quality of the ground water varies widely. In many areas, concentrations of dissolved solids exceed 1,000 mg/l. Most of the Brazos River Valley irrigated with this ground water contains soils sufficiently permeable to alleviate any soil salinity problems. In some places, the water from the aquifer is fresh enough to meet drinking water standards (Cronin 1967).

Cisco Group

The Cisco group is comprised of fluvial-deltaic sediments of primarily sandstone with beds of limestone, shale, mudstone, and conglomerate (Kier 1979). The upper portion of the Texas Pennsylvanian included in the Cisco group is characterized by its more clastic sediments, its thin but persistent limestones, and the presence of coal. It includes all the beds between the Home Creek limestone of the Canyon and the lowermost beds containing Permian fossils. The change in the character of the rocks in passing from the Canyon to the Cisco is evidently the result of a diastrophic movement which made shallow the waters in northern Texas and which brought into them large amounts of coarse sand and gravel, chiefly from the north, for the northern portion of the Cisco is materially thicker and more clastic than the southern portion. The total thickness of the Cisco group is about 700 to 800 feet in the southern Pennsylvanian area and 1,400 to 1,500 feet in the north. Six formations have been recognized in the Cisco, as indicated in the foregoing table of stratigraphic divisions, in order from the base: Graham, Thrifty, Harpersville, and Pueblo. As a whole, the Cisco group is not more fossiliferous than other parts of the Texas Pennsylvanian, but some beds, as the upper shale of the Graham formation, are among the most fossiliferous in the mid-continent region (Moore 1922). The Cisco Group crops out in the southwest corner of Montague County and underlies the Wichita Group to the north. The Cisco Group consists of alternating beds of shale, sandstone, limestone, and conglomerate. As in the Wichita Group, there is less sand down-dip than in the outcrop. In the study area, rocks of Pennsylvanian age generally dip toward the west or northwest at a rate of approximately 50 feet per mile (9.5 m/km) and are overlain by the Trinity Group of Cretaceous age to the east (Nordstrom 1982).

The southern tip of the Cisco Group aquifers (Pennsylvanian) outcrops across northwestern Eastland County. The western edge in Eastland and Stephens Counties approaches 1,000 feet in thickness. The quality of water is variable but most wells sampled in the Cisco Group do not meet secondary drinking water standards. For the purpose of this option, a target of 1,500 mg/L TDS is assumed although this is well above the average of wells sampled as reported by Duffin and Beynon (1,014 mg/L). TDS has been measured as high as 3,700 mg/L in these aquifers (Nordstrom 1982).

The Cisco Group is the uppermost Pennsylvanian aged unit present in Central Texas. The Cisco Group outcrops in a 15 to 20 mile band in Concho, McCulloch, and Coleman Counties and rapidly dips into the subsurface away from the Llano Uplift area. The Cisco Group contains both the Thrifty and Graham Formations and is comprised of shales, sandstones, conglomerates, limestones, and coal beds. It is approximately 1,000 feet (305 meters) thick away from the outcrop, however net sand is only 10 to 15 percent of the total thickness. Porosities average 12 to 22 percent, and permeabilities range from 10 to 350 millidarcies (Core Laboratories, 1972).

The Cisco Group provides fresh to moderately saline water to wells in Coleman and Brown Counties, in and near where it outcrops. Of the water wells in the study area that are included in the TWDB database, just over half produce fresh water, with most of the remainder producing slightly saline (1,000-3,000 mg/L TDS) groundwater. A majority of these wells are less than 200 feet (61 meters) deep. In the down-dip areas, salinities of produced water from the Cisco have TDS ranging from 50,000 to 200,000 mg/L (LBG-Guyton 2004).

Because the Cisco produces groundwater with relatively low salinities, it may be considered a potential source of saline water, particularly in the eastern half of the region where the aquifer is found at shallower depths.

Thrifty Formation

The Thrifty formation consists of thick shales which are less fossiliferous and brighter in color than those of the Graham, limestones which are thicker and somewhat more massive than those of other divisions of the Cisco, and some sandstone and coal. It has been mapped from Jermyn in Jack County through Young and Stephens counties to the border of the Cretaceous in Eastland County. In the northern Pennsylvanian area its thickness is about 150 to 200 feet (46 to 61 meters), in the southern, 100 to 125 feet (31 to 38 meters) (Moore 1922).

Thrifty Formation units listed in order from oldest to youngest are the Avis Sandstone, Ivan Limestone, Blach Ranch Limestone, and Breckenridge Limestone. Interspersed between these limestone sequences are numerous unnamed sandstone and mudstone units. The Avis Sandstone and many of the unnamed sandstone units provide small quantities of potable ground water to wells in northwest Jack County. Origin and stratigraphy of the sandstone units are similar to that of the Graham Formation (Nordstrom 1988).

Graham Formation

The older or lower members of the Graham are present only in the north, pinching out southward and being overlapped by the younger or higher members. The formation is distinguished from the underlying beds by its very clastic character and thinner limestones, and from succeeding beds by its prolific and characteristic fauna (Moore 1922). Units making up the Graham Formation, listed in order from oldest to youngest, are the Finis Shale, Gonzales Creek Member, Bunger Limestone, Necessity Shale, Gunsight Limestone, and Wayland Shale. Water-bearing sandstone units within the Gonzales Creek Member constitute the major source of potable ground water in the Graham Formation. Numerous other unnamed sandstone beds occurring between major limestone sequences also provide a source of groundwater to domestic and livestock wells (Nordstrom 1988).

The Graham Formation forms the base of the Cisco Group and is overlain by the Thrifty Formation. Thicknesses of sandstone units vary considerably, due to the discontinuous nature of the beds. Sandstone origins are from two depositional systems fluvial and deltaic. Fluvial system units consist of braided facies of medium-to-coarse grained sandstones and conglomerate with cross· beds, chert pebbles, and little mud: meander belts of siltstone and fine-grained sandstones; distributary-channel fill of fine to medium grained sandstone; and valley fill fluvial of upward fining beds from coarse gravel to medium-grained sandstone with trough cross beds. Typical deltaic system facies in the Cisco Group are similar to those described in Canyon Group sequences. Bar-finger sandstones consisting of delta front, channel- mouth-bar, and distributary-channel facies are common, interspersed with mudstones of prodelta and inter-distributary origin (Nordstrom 1988).

Canyon Group

The Pennsylvanian-age Canyon Group is located stratigraphically below the Cisco. The Canyon Group outcrops west and north of the Llano Uplift in Brown and McCulloch Counties, and, as with the Cisco, rapidly dips into the subsurface, occurring at depths of 3,000 feet (914 meters) within 50 miles (81 km) of the outcrop, and much greater depths throughout the rest of the study area. Porosities of the thick limestone beds in the Canyon range from 5 to 25 percent, and the porosity of the reef facies may be as high as thirty percent locally. Permeabilities range from 1 to over 500 millidarcies (Core Laboratories, 1972).

The Canyon group includes the beds formed after the deposition of the coarse sandstones, conglomerates, shales, and coal of Strawn time, when the land to the east had been worn low, the accumulating sediments forming a series of thick limestones and fine calcareous clays, with only a few lenses of sandstone. The areal extent of the Canyon Group in Jack County occupies the southeastern half of the county except in those areas overlain by Cretaceous sediments of the Trinity Group. Groundwater is primarily obtained from the sandstone units located between major limestone sequences. Major sandstone units are found within the Palo Pinto Formation, Wolf Mountain Shale, Placid Shale, and Colony Creek Shale (Nordstrom 1988).

Groundwater occurs primarily within the sandstone units of the Canyon Group. It exists under water-table conditions along the outcrop and under artesian conditions down dip, where confining beds of limestone and shale overlie the aquifer. Groundwater flow is to the northwest and, locally, away from groundwater highs and toward the surface drainage system (Nordstrom 1988).

The Canyon provides some fresh but mostly slightly- to moderately-saline (1000 to 10,000 mg/L) water to wells that are less than 400 feet (122 meters) deep in and near the outcrop area. In down dip areas, limited quality data from Canyon produced water suggests a wide range of salinity, ranging from less than 10,000 mg/L to greater than 200,000 mg/L. As with other deeper, hydrocarbon-producing formations, the salinity of formation water may be more variable on a regional basis than the contours. Because the Canyon produces groundwater with relatively low salinities where the aquifer is found at depths of less than 5,000 feet (1524 meters), it may be a potential source of saline water (LBG-Guyton, 2004).

Colony Creek Formation

Units of the Colony Creek Shale containing potable water consist primarily of fine-grained sandstone of delta-destructional, delta front, and distributary channel origin; and coarse-grained sandstone and conglomerate of fluvial channel origin. The predominant sequence could be summed up as fine grained deltaic sandstone units overlying and flanking sandy prodelta and interdeltaic mudstone facies (Erxleben, 1975). As with the previous formations, emphasis is placed on the sandstone aquifer facies (Nordstrom 1988).

Palo Pinto Formation

The Palo Pinto limestone is a thick, crystalline, dark gray rock made up typically of beds 2 to 6 inches in thickness and having a total thickness of 50 to 100 feet (15 to 30 meters). It forms a prominent escarpment across Palo Pinto County and has been traced for a long distance in the Brazos Valley. It has not, however, been identified south of the Cretaceous overlap in Eastland County which separates the Pennsylvanian outcrops. The chief distinguishing feature of the fossils which have been found in the Palo Pinto Formation is their very robust size, many species being represented by individuals more than twice the normal size (Moore 1922).

The Palo Pinto Formation dips northwestward and in general does not yield large quantities of fresh water to wells. The Palo Pinto Limestone is the only formation of the Canyon Group that crops out in Parker County’s extreme northwest corner of the county but does not yield water to wells (Stramel 1951).

Strawn Group

The Strawn group includes all the strata between the top of the Smithwick shale and the base of the Palo Pinto limestone in the Brazos River Valley or its stratigraphic equivalent in the Colorado River Valley. The rocks of this group are distinguished chiefly by their clastic character, especially the thickness of coarse sandstones, and by their irregularity in bedding. The two main areas of Strawn outcrop, one in the valley of Colorado River and the other in the valley of the Brazos, are broadly similar, but it has not been possible to identify divisions of the one in the other. The entire section of the Strawn is observable along Colorado River, but in the Brazos Valley a considerable thickness of beds belonging to the lower portion of the Strawn are not exposed on account of the Cretaceous overlap from the east (Moore 1922).

In the Brazos River Valley two main divisions of the Strawn have been identified, the Millsap Formation below and the Mineral Wells Formation above. Only the upper portion of the Millsap Formation is exposed at the surface, outcrops being found in the eastern part of the Strawn area near Millsap and along Brazos River in southwestern Parker County. The limestones which appear in this part of the section are quite unlike any beds observed in the Mineral Wells Formation (Moore 1922).

The Strawn Group, located stratigraphically below the Canyon, is a Pennsylvanian unit found throughout the study area, and includes the Lone Camp, Millsap Lake, and Kickapoo Creek Formations. The Strawn Group outcrops in a very wide area immediately north of the Llano Uplift, including the extreme western portions of McCulloch and Brown Counties. As with the other Pennsylvanian units, the Strawn rapidly dips into the subsurface away from the Llano Uplift, occurring at significant depths throughout much of the study area. Only in the easternmost counties in the planning area does the Strawn occur at depths of less than 5,000 feet. The Strawn Group consists of sandstones, shales, conglomerates, and limestones, and due to the variations in rock types, porosities and permeabilities are highly variable, with porosity ranges of 5 to 20 percent and permeability ranges of 5 to over 500 millidarcies (Core Laboratories, 1972). The Strawn is a significant hydrocarbon-producing formation, and quality data of produced water is available from this unit in its western extent. Produced formation water in the western extent of the Strawn is highly saline, with TDS concentrations of over 200,000 mg/L being common. A trend toward lower salinity (<50,000 mg/L) occurs in the aquifer’s southeasterly extent (LBG-Guyton 2004).

Mineral Wells Formation

The Mineral Wells Formation, part of the Pennsylvanian Strawn Group, consists of shale with inter-bedded sandstone and limestone. Sandstone and limestone members are the Hog Mountain Sandstone, informal sandstone unit 1, the Village Bend Limestone, Lake Pinto Sandstone, Dog Bend Limestone, informal sandstone unit 2 (Devils Hollow Sandstone), and the Turkey Creek Sandstone (Fisher 1996).

The Mineral Wells formation includes the sandstones and shales of the upper part of the Strawn in the Brazos River Valley above the Thurber coal. It is very well exposed in the vicinity of Mineral Wells and along Brazos River, its outcrop extending in a belt 10 to 15 miles wide from Erath to Jack and Wise counties. Four prominent sandstone members produce prominent escarpments which are the chief topographic features of the region. The shales are sandy and are at least in part very fossiliferous (Moore 1922).Shale portions of the Mineral Wells Formation vary from thin-bedded and fissile to blocky and show a range of greenish, bluish, reddish, and yellowish-gray colors. The Hog Mountain Sandstone is the basal member of the Mineral Wells Formation and is about 25 ft. thick. Informal sandstone unit 1 is about 25ft above the Hog Mountain Sandstone and is conglomeratic. Village Bend Limestone is 10ft thick and is finely crystalline and weathers medium light gray to yellowish gray. The Lake Pinto Sandstone is about 50ft thick and is a medium-to fine-grained sandy shale that is pale grayish brown to reddish brown. The Dog Bend Sandstone is an algal wackestone to mudstone that is finely crystalline, locally sandy, and up to 5 ft thick (Fisher 1996).

Waters from the Mineral Wells formation are predominantly sodium bicarbonates in composition. Waters from the Strawn Group are mostly calcium bicarbonate in composition. The Texas Water Development Board (TWDB) does not consider the Mineral Wells or Strawn group to be a major source of groundwater (Fisher 1996).

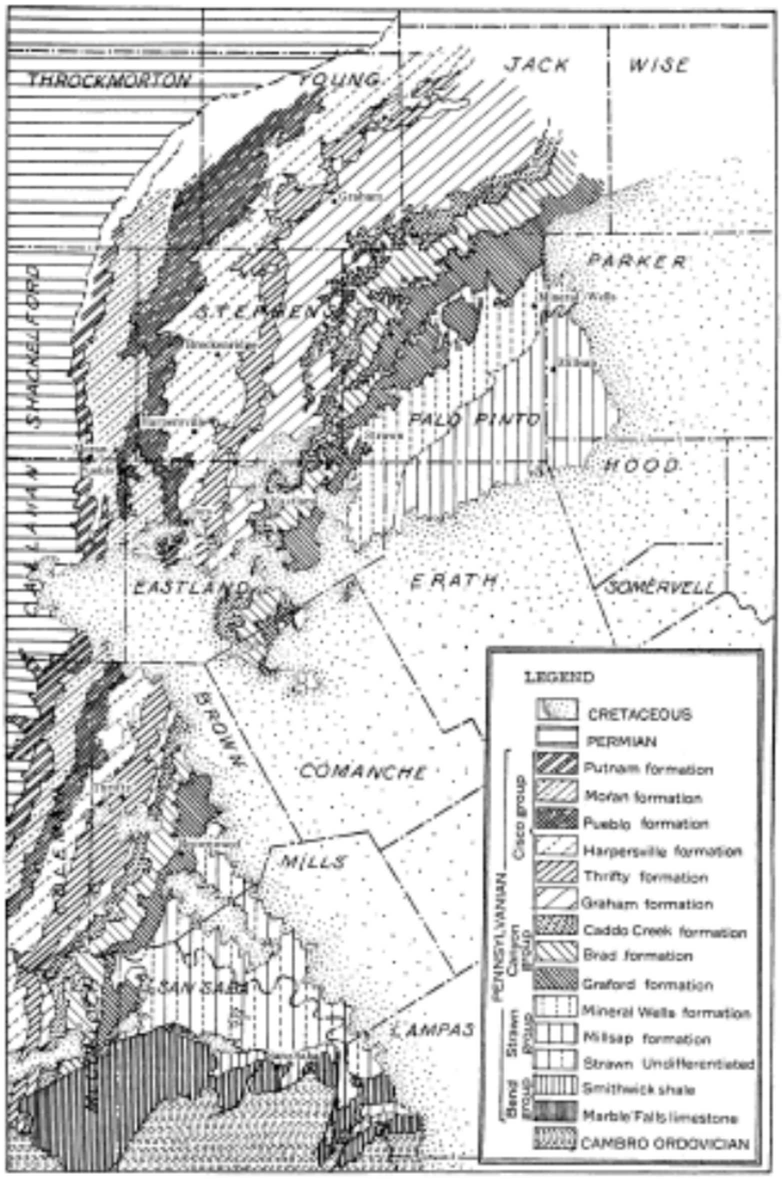


Figure 6. Outcrops of Pennsylvanian formations in north central Texas (Moore 1922)

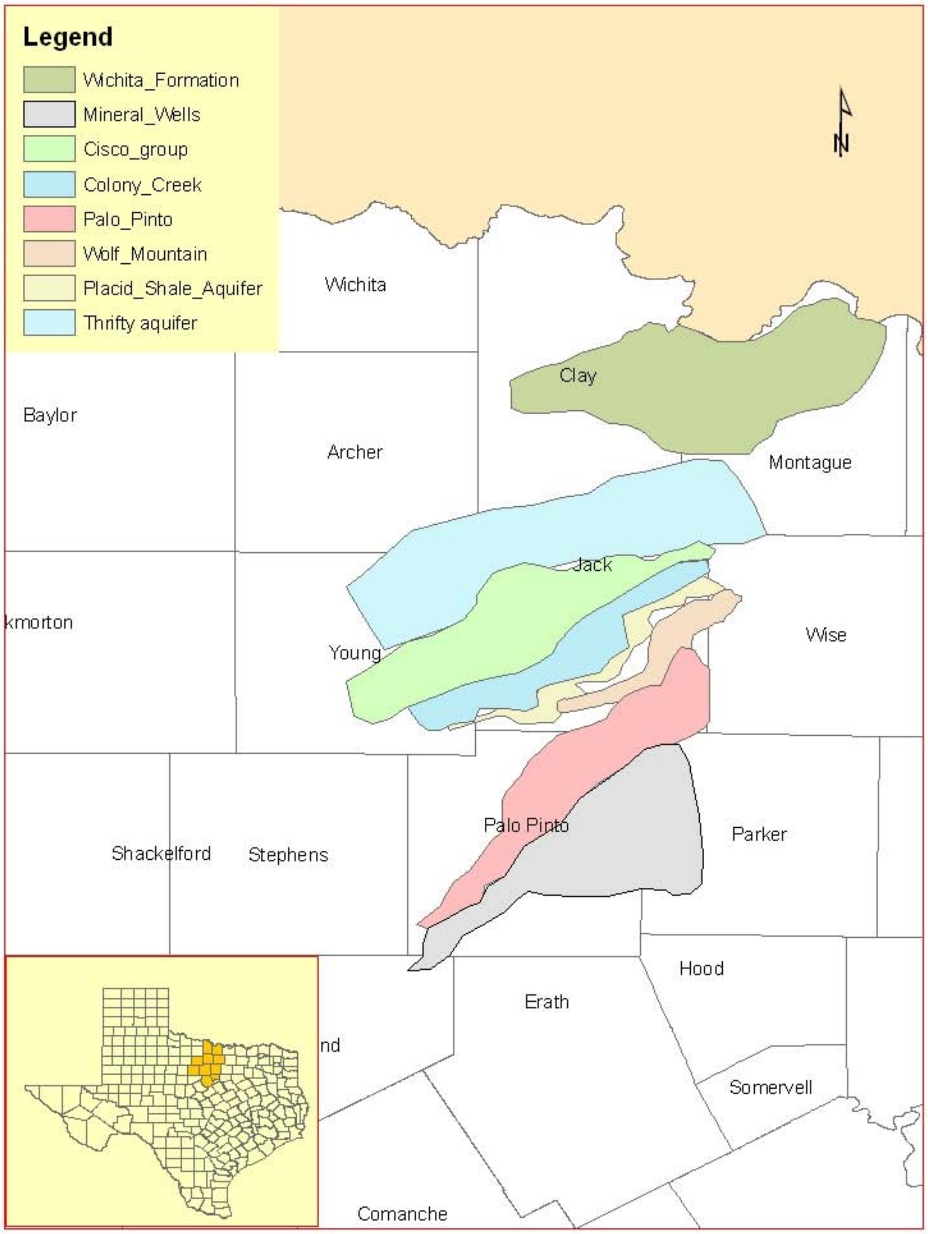


Figure 7. Minor Aquifers in Tier I & II

IV. Methods

a. Aquifer Data Analysis

i. Hydraulic Properties

The compilation of well depth, pumping rate, specific-capacity, and transmissivity for the minor aquifers in the study area included publically available data from the following sources: (1) Driller reports in the form of Access databases from the Texas Water Development Board (TWDB); and (2) Texas Public Water Supply (PWS) database from Texas Commission on Environmental Quality (TCEQ).

The TWDB groundwater database contains approximately 105,000 water quality samples from about 55,000 unique locations across the state. The well drawdown test data from the drilling reports including pumping rates, pump time and resulting drawdown were used to determine specific-capacity and transmissivity using standard Theis (1935) methods. Well drillers normally conduct a well performance test after completing drilling to determine specific-capacity. This test involves pumping the well at a constant rate for a period of time and the amount of drawdown is noted. Specific capacity, *Sc*, is then defined as the pumping rate, *Q*, divided by the amount of drawdown, *s* (Equation 1):

$$S\,c = Q\,/\,s \qquad \text{Eqn. 1}$$

Specific capacity is generally reported as discharge per unit of drawdown. For example, a well pumped at 100 gallons per minute (gpm) with 20 ft of drawdown would have specific capacity of 5 gpm/ft (Mace 1999). There is an analytical relationship between specific-capacity and transmissivity, so the specific-capacity data was used to estimate transmissivity based on the Theis (1935) nonequilibrium equation:

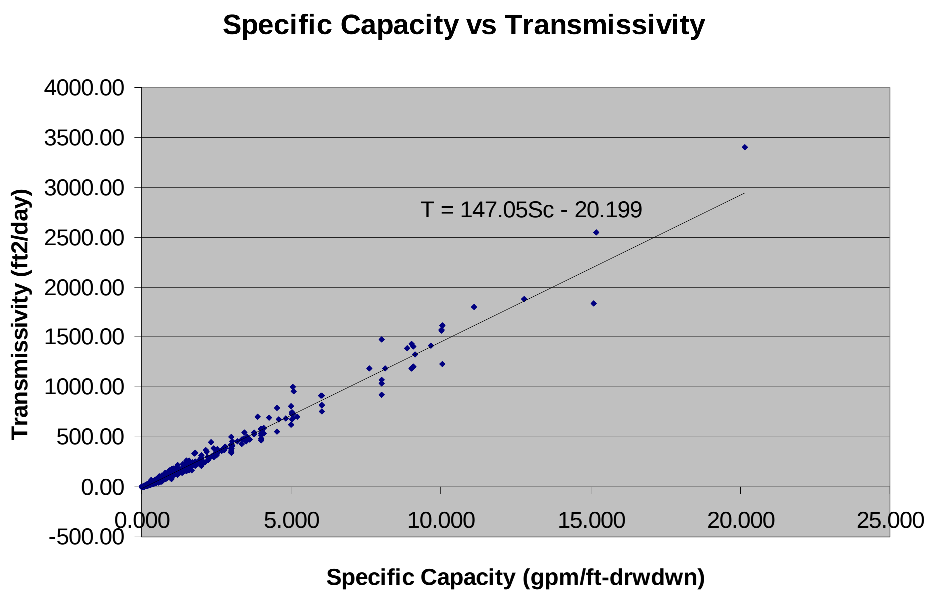
$$S_c = \frac{4\pi T}{\left[\ln\left(\frac{2.25Tt_p}{r_w^2 S}\right)\right]} \qquad \text{Eqn. 2}$$

where *S* is the storativity of the aquifer, t_p is the time of production (that is, pumping) when the drawdown was measured, and r_w is the radius of the well in the screened interval. This equation assumes (1) a fully-penetrating well; (2) a homogeneous, isotropic porous media; (3) negligible well loss; (4) and an effective radius equal to the radius of the production well (Walton, 1970). The above equation cannot be explicitly solved for transmissivity, it must be solved graphically or iteratively (Mace 1999). Equation 2 was rearranged to solve for transmissivity using Equation 3 where an initial guess for *T* was used on the right-hand side of the equation and a plausible value of *S* was used.

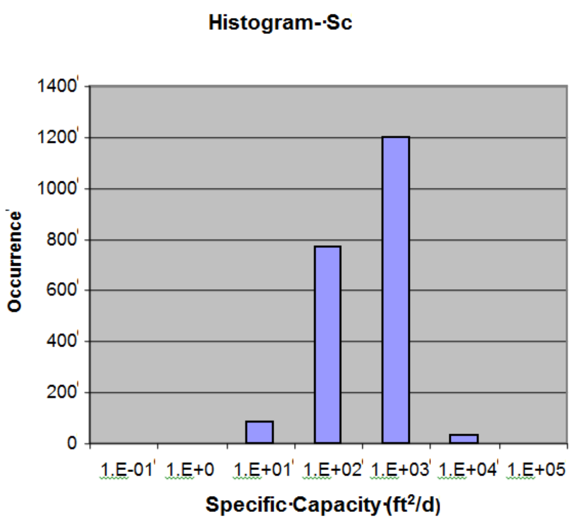
$$T = S_c/4\pi\ [\ln(2.25Tt_p) - \ln(r_w^2S)] \qquad \text{Eqn.3}$$

The database of wells in area of the minor aquifers included 2084 total wells with complete well performance data sets. General characteristics of the wells analyzed include: a mean depth of 118.5 feet with a range of 28.9 and 498.7 feet and a 50th percentile depth of 90 feet; a mean well diameter of 4.3 inches with a 50th percentile of 4.0 inches; and mean pumping rate of 21.9 gallons per minute (gpm) with a 50th percentile of 20 gpm; and a mean drawdown of 46.5 ft with a 50th percentile of 20 feet.

The specific capacity and related transmissivity for all wells appear log-normally distributed and have direct relationship as observed in the graph of specific capacity plotted against transmissivity. A best fit line using least square regression gives a relationship of $T = 147\ S_c - 20.2$ with a correlation coefficient, R^2 of 0.98. Therefore, the relationship has a 98% prediction interval, which means an estimate of transmissivity from specific capacity has a confidence factor of 98%.



The specific capacity ranges from 0.1 to 5 gpm/ft-drawdown with a mean of 1.05 gpm/ft and a 50th percentile of 0.7 gpm/ft. Transmissivity ranges from 4 to 420 ft^2/day with a mean of 133 ft^2/day and a 50th percentile of 80 ft^2/day.



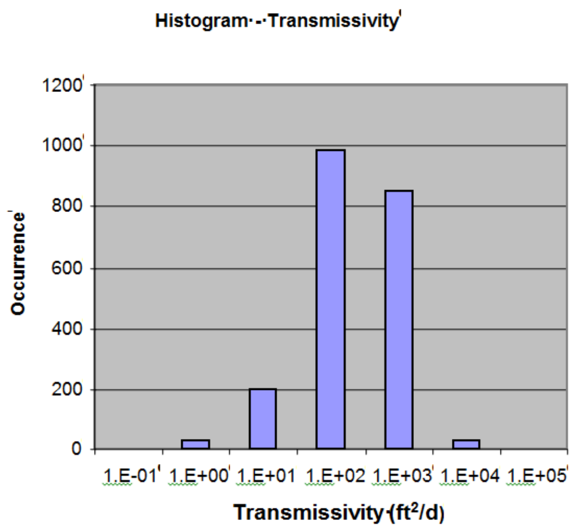


Figure 9. Histograms for specific capacity and transmissivity

The minor aquifers of the study area located primarily in the western counties of Montague, Jack, Palo Pinto, Wise and Parker. Well depths range mostly between 30 and 500 feet (9 and 152 meters) below land surface. Yields from wells are variable, ranging from less than 5 to over 60 gpm, well below the industry requirement of 100 gpm requiring the use of multiple wells. The specific capacity of the minor aquifers range mostly between 0.10 and 5.0 gpm/ft-drawdown, which indicates significant drawdown of the minor aquifers will be required to achieve the 100 gpm pumping rate required by the hydraulic fracturing industry. To establish a pump rate of 100 gpm, the drawdown would expect to range between 20 feet and 1000 feet (6 and 305 meters). Groundwater quality in the minor aquifers generally contains between 300 and 3800 mg/L TDS, well under the industry waterflooding requirement of less than 20,000 mg/L TDS. Calcium levels generally range between 2 and 220 mg/L, well within the industry requirement of less than 350 mg/L. pH levels range between 9 and 7, which is outside the industry requirement of less than 8 for waterflooding.

Rank	Well Depth (ft)	Well Diameter (in.)	Pumping Rate (gpm)	Drawdown (ft)	Pump Test Time (hr)	Specific Capacity (gpm/ft drawdown)	Specific Capacity (ft2/day)	Transmissivity (ft2/day)
95th percentile	498.65	6	60.0	170	5	3.01	578.73	421.2
70th percentile	245	4.5	25.0	50	1	1.20	231.19	149.4
50th percentile	190	4	20.0	20	1	0.67	128.61	80.5
30th percentile	112.7	4	18.0	12	1	0.33	64.26	35.8
5th percentile	28.9	4	4.6	5	0.5	0.06	11.10	4.1
Min	12	2	0.3	1	0.25	0.01	1.60	0.2
Max	1010	12	200.0	370	41	20.16	3881.08	3400.3
Mean	118.5	4.3	21.9	46.5	2.1	1.05	201.30	133.6
Industry Requirements			**> 100**	**< 350**	**< 8**			

Table 1. Well data percentile distribution, range and mean.

As the minor aquifers in the western counties (Montague, Jack, Palo Pinto, Wise and Parker) were not identified by aquifer in the driller reports from the TWDB database, the well data was mapped in GIS using the 5-digit zip codes provided for each well. Using the zip code data provides greater resolution of the well data in GIS. The following four GIS maps of Montague, Jack , Palo Pinto, Wise and Parker counties, illustrate the distribution of well characteristics across county borders.

The map of well depth illustrates that the deeper wells are along the eastern side of the study area and north towards the Red River valley. Corresponding to the well depth, the pumping rates are also higher along the eastern side of the study area and north into Montague County. Specific conductivity and the directly related transmissivity are highest on in the eastern half of the study area and decline as you move west.

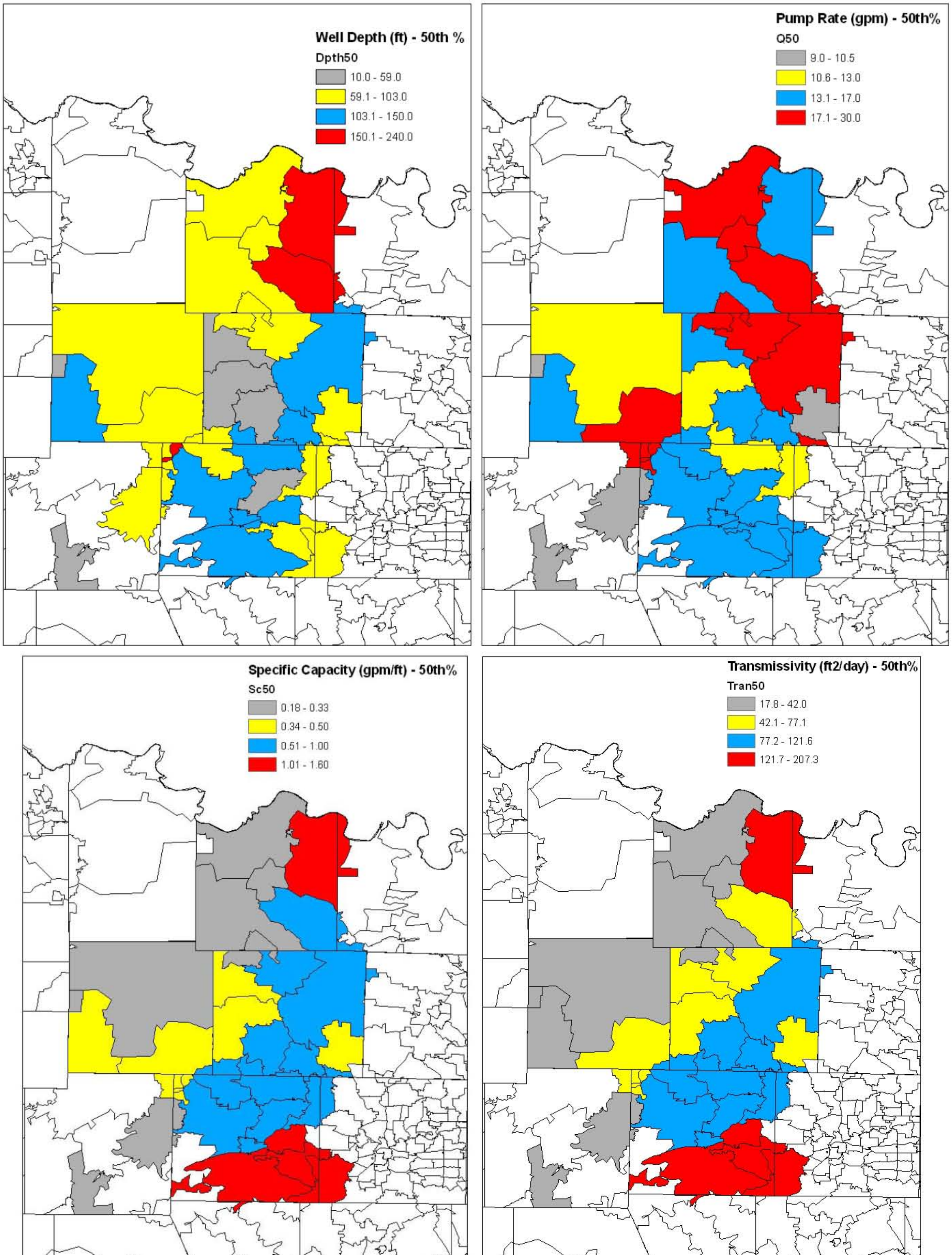


Figure 10. Depth, pump rate, specific capacity, and transmissivity by zip code for minor aquifers

ii. Water Quality

Chemical data were compiled from the TWDB's electronic Microsoft Access database of wells installed after February 5, 2001 from the Texas Water Development Board Submitted Driller's Report Database (Texas Water Development Board 2011). TWDB well data are submitted by drilling companies via the online Texas Well Report Submission and Retrieval System (Texas Department of Licensing and Regulation 2011).

Well data were collected on the concentration (in milliequivalents per liter) for all major cations and anions as well as the water's total dissolved solids (TDS) and pH. This water chemistry data was analyzed using a Durov plot. Groundwater salinity in the minor aquifers generally ranges between 300 and 3800 mg/L TDS, well under the industry waterflooding requirement of less than 20,000 mg/L TDS. Calcium levels generally range between 2 and 220 mg/L, well within the industry requirement of less than 350 mg/L. pH levels range between 9 and 7, which is outside the industry requirement of less than 8 for waterflooding.

When plotting all the minor aquifers together on a Durov plot most of the aquifers demonstrated similar water chemistry. The Durov plot showed the groundwater in the minor aquifers is predominately composed of bicarbonate and chloride anions, sodium and calcium cations, and low concentrations of dissolved solids and a pH range of 7 to 9.

Rank	Bicarb (mg/l)	Sulfate (mg/l)	Chloride (mg/l)	Calcium (mg/l)	pH	TDS	Alkalinity	Specific Conductivity
95th percentile	749	593	1700	221	8.8	3796	638	7823
70th percentile	518	151.3	235	78	8.3	1170	435	2183
50th percentile	425	78.5	120	35	8.1	758	357	1403
30th percentile	353	45	52	7	7.7	545	296	987
5th percentile	213	15	14	2	7.2	334	182	585
Min	39	4	4	1	6.3	108	40	178
Max	2026	4530	9572	920	11.5	14189	1660	34500
Industry Requirements			**< 10,000**	**< 350**	**< 8**	**< 20,000**		

Table 2. Summary of relevant information on Paleozoic aquifer water quality

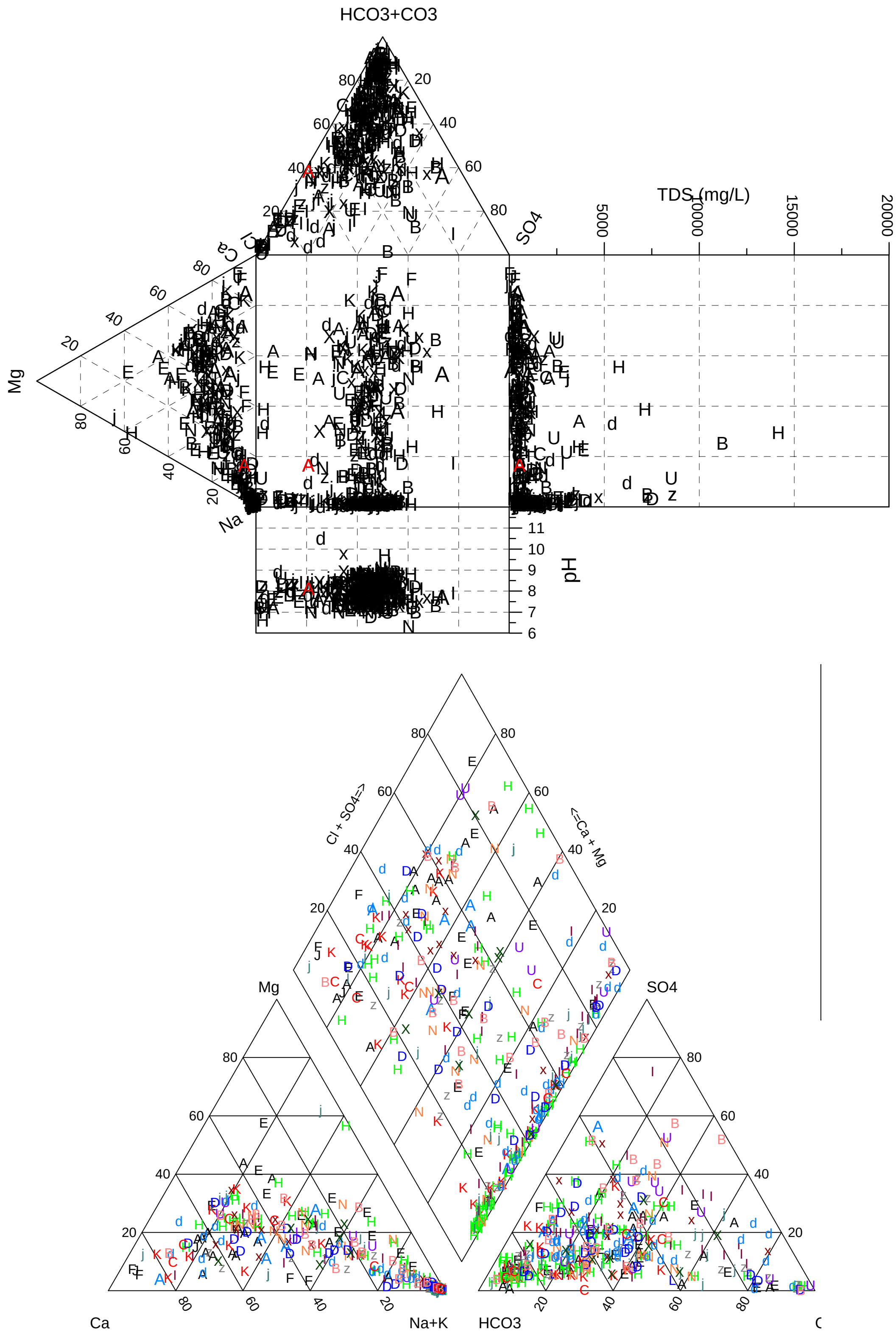


Figure 11. Chemical characteristics of all minor aquifers of the study area

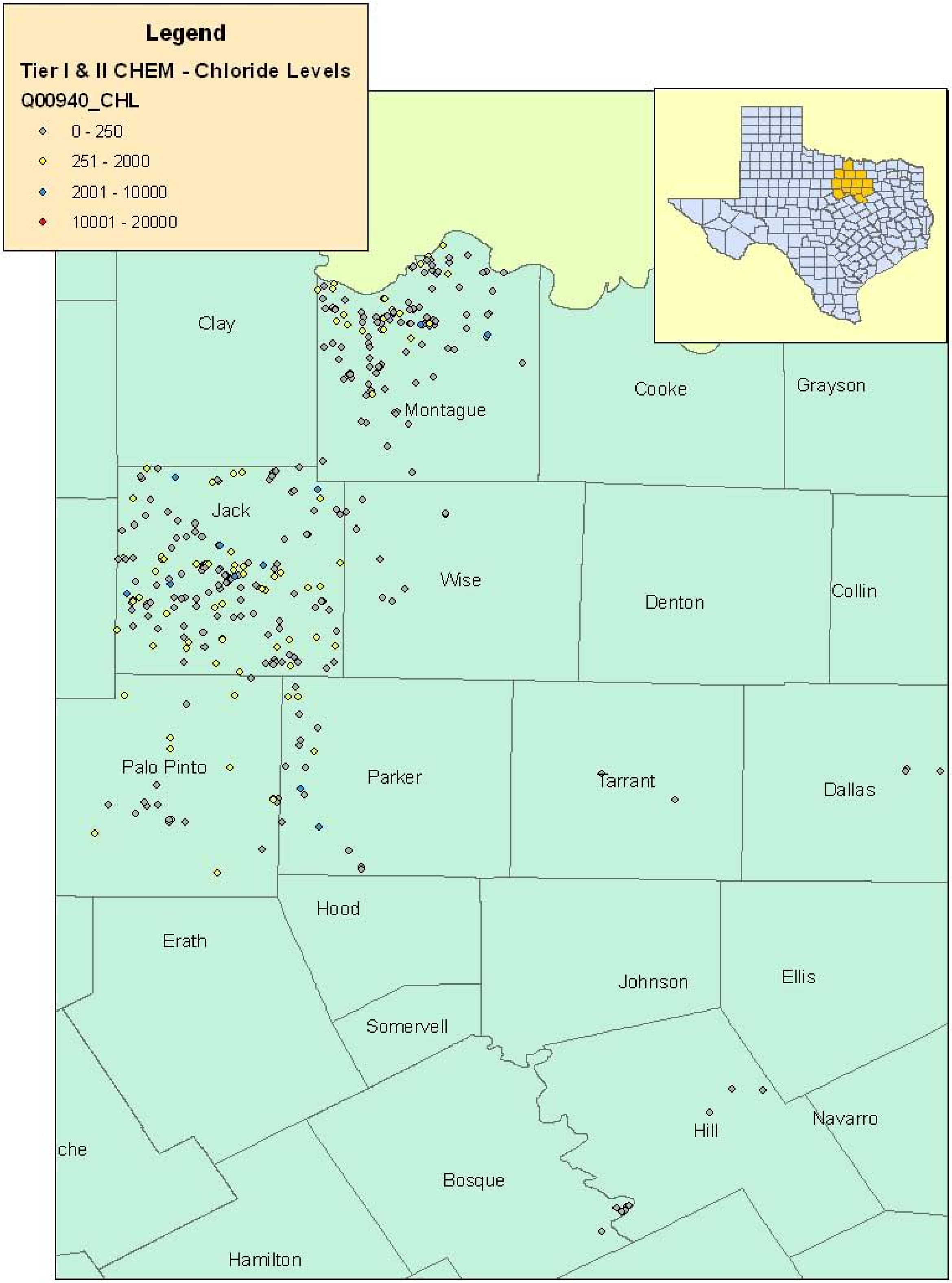
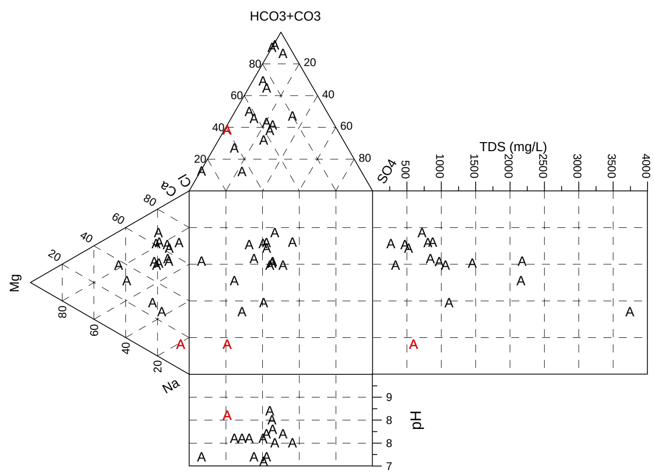
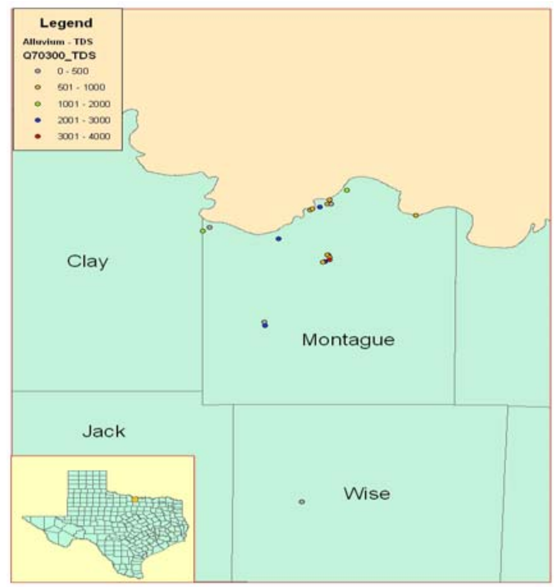


Figure 12. Chloride levels in water wells

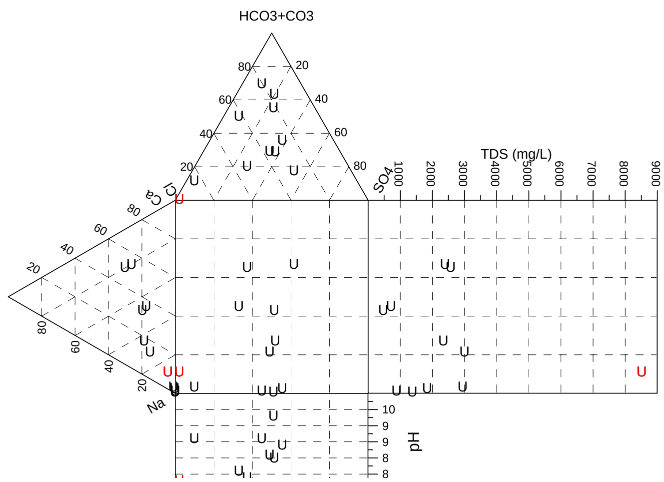
The Alluvium aquifers in the region are generally is located in northern border of Montague County along the Red river and its tributaries. Well depths are generally shallow ranging mostly between 20 and 200 feet below land surface. Groundwater quality in the Alluvium aquifers are generally good containing between 300 and 3000 mg/L TDS, well under the industry waterflooding requirement of less than 20,000 mg/L TDS. Calcium levels generally range between 2 and 260 mg/L, well within the industry requirement of less than 350 mg/L. pH levels range between 8 and 7, which is outside the industry requirement of less than 8 for waterflooding.. The Durov plot shows that the alluvium groundwater is predominately composed of bicarbonate and chloride anions, and sodium and calcium cations. The pH levels of the alluvium ground water are grouped primarily around 8 but ranges from 7 to 9. The concentrations of dissolved solids are loosely cluttered and ranges from 200 to 2000 mg/L.

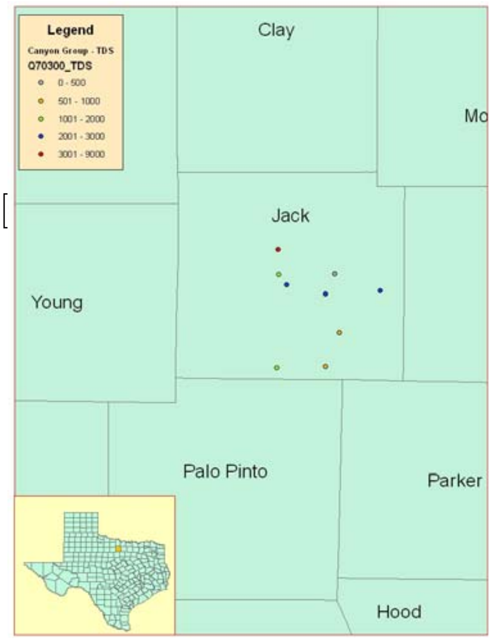




Alluvium									
Rank	**Bicarb (mg/l)**	**Sulfate (mg/l)**	**Chloride (mg/l)**	**Calcium (mg/l)**	**pH**	**TDS**	**Alkalinity**	**Spec Cond**	**Well Depth (ft.)**
95th percentile	891	257	1285	256	8	2824	730	6383	183
70th percentile	464	132	230	153	8	1131	380	2145	61
50th percentile	405	49	157	104	8	820	332	1460	52
30th percentile	336	28	86	59	8	627	275	1175	34
5th percentile	242	13	16	18	7	318	199	579	22
Min	222	12	11	2	7	247	182	434	19
Max	2026	960	1770	443	9	3998	1660	7790	212
Industry Requirements			**< 10,000**	**< 350**	**< 8**	**< 20,000**			

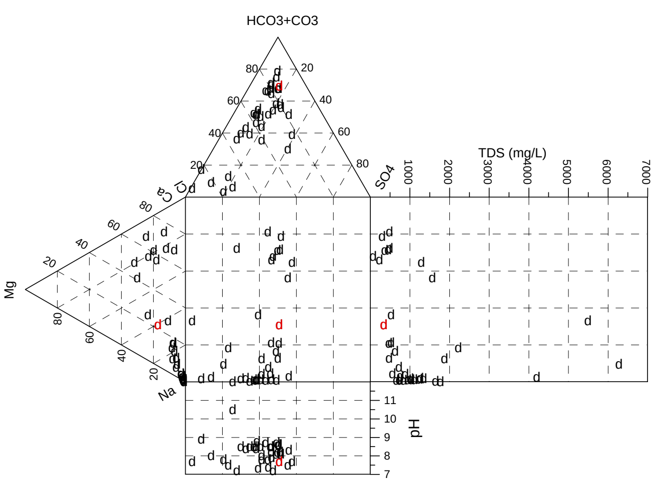
The Canyon Group aquifer is located in the eastern part of Jack County. Well depths range mostly between 50 and 600 feet below land surface. Groundwater quality in the Canyon Group generally contains between 500 and 5000 mg/L TDS, well under the industry waterflooding requirement of less than 20,000 mg/L TDS. Calcium levels generally range between 10 and 400 mg/L with 70 percentile below 140 mg/L, well within the industry requirement of less than 350 mg/L. pH levels range between 9 and 7, which is outside the industry requirement of less than 8 for waterflooding. The Durov plot shows that the Canyon Group groundwater is not well grouped with respect to sulfate, bicarbonate and chloride anions, but sodium and calcium are the predominate cations. The pH levels of the Canyon Group groundwater are loosely clustered and range from 7 to 10. The concentrations of dissolved solids are also not well grouped and ranges from 300 to 3000 mg/L.

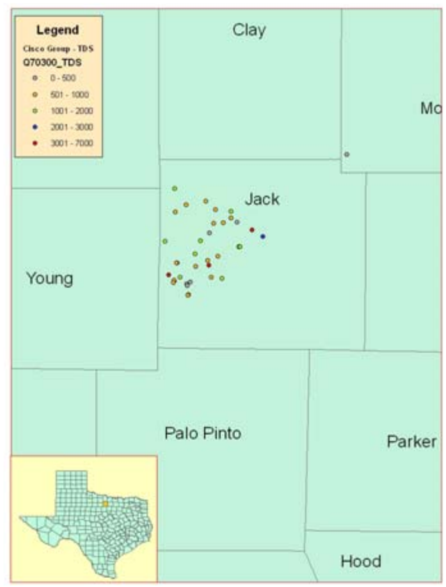




Canyon Group									
Rank	**Bicarb (mg/l)**	**Sulfate (mg/l)**	**Chloride (mg/l)**	**Calcium (mg/l)**	**pH**	**TDS**	**Alkalinity**	**Spec Cond**	**Well Depth (ft.)**
95th perc.	786	899	3305	423	9	5745	728	11856	638
70th perc.	642	526	610	142	8	2559	540	4867	320
50th perc.	428	225	415	92	8	2331	351	3500	280
30th perc.	395	95	192	27	7	1365	324	2512	105
5th perc.	185	59	79	3	7	583	152	1161	53
Min	51	47	50	3	7	462	42	882	46
Max	886	990	5107	431	9	8502	730	17808	690
Industry Requirements			**< 10,000**	**< 350**	**< 8**	**< 20,000**			

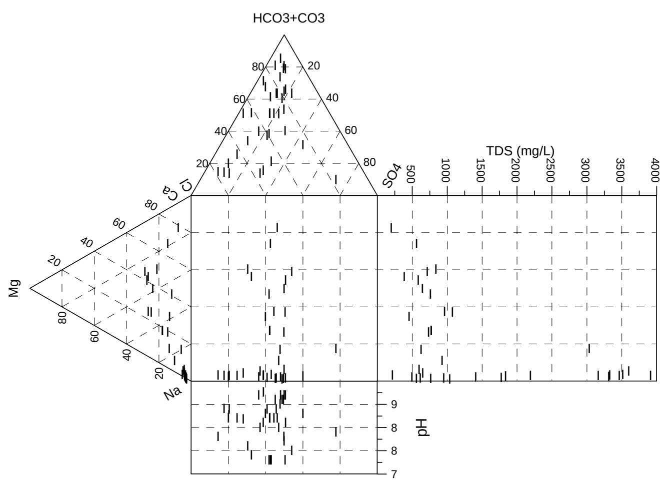
The Cisco Group aquifer is located in the western part of Jack County. Well depths range mostly between 70 and 500 feet below land surface. Groundwater quality in the Cisco Group generally contains between 300 and 4500 mg/L TDS, well under the industry waterflooding requirement of less than 20,000 mg/L TDS. Calcium levels generally range between 1 and 225 mg/L, well within the industry requirement of less than 350 mg/L. pH levels range between 9 and 7, which is outside the industry requirement of less than 8 for waterflooding. The Durov plot shows that the Cisco Group groundwater is predominately bicarbonates and chloride anions and sodium and calcium cations. The pH levels of the Canyon Group groundwater are concentrated around 8 with a range from 7 to 9. The concentrations of dissolved solids are primarily grouped at less than 1000 mg/L with a range from 100 to 2000 mg/L.

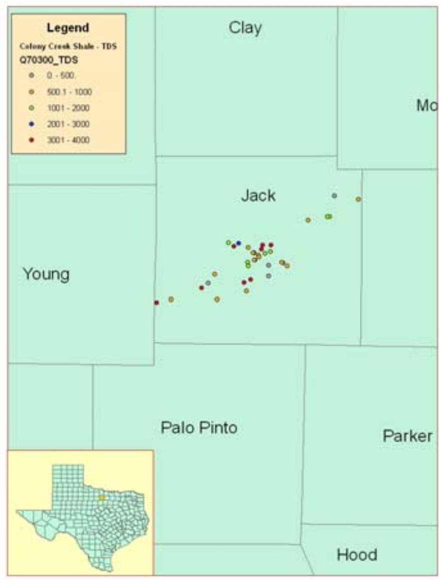




Cisco Group									
Rank	**Bicarb (mg/l)**	**Sulfate (mg/l)**	**Chloride (mg/l)**	**Calcium (mg/l)**	**pH**	**TDS**	**Alkalinity**	**Spec Cond**	**Well Depth (ft.)**
95th percentile	643	462	2230	224	9	4492	534	9324	500
70th percentile	505	141	285	56	9	1270	454	2384	280
50th percentile	403	94	164	19	8	788	337	1413	205
30th percentile	321	67	71	6	8	561	295	1004	143
5th percentile	77	25	29	1	7	320	160	592	70
Min	39	7	13	1	7	108	40	178	70
Max	696	991	3192	556	12	6310	574	13104	515
Industry Requirements			**< 10,000**	**< 350**	**< 8**	**< 20,000**			

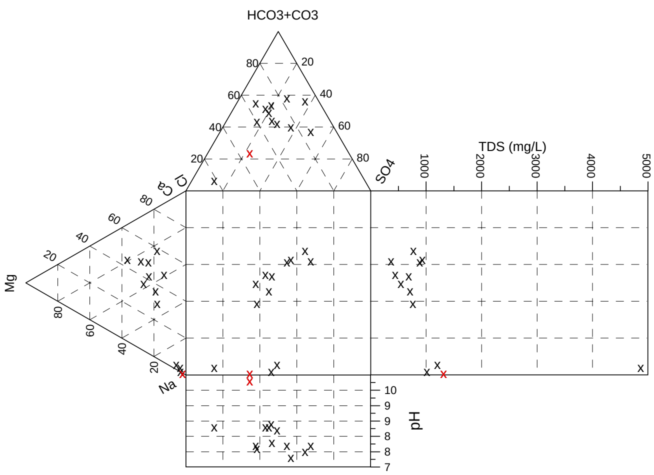
The Colony Creek aquifer is located in Jack County running along a diagonal line from the northeast to the southwest. Well depths range mostly between 90 and 400 feet below land surface. Groundwater quality in the Colony Creek generally contains between 400 and 3500 mg/L TDS, well under the industry waterflooding requirement of less than 20,000 mg/L TDS. Calcium levels generally range between 2 and 128 mg/L, well within the industry requirement of less than 350 mg/L. pH levels range between 9 and 7, which is outside the industry requirement of less than 8 for waterflooding. The Durov plot shows that the Colony Creek Shale groundwater is predominately bicarbonates and chloride anions and sodium and calcium cations. The pH levels of the Colony Creek Shale groundwater are loosely clustered and generally well distributed within a range of 7 to 10. The concentrations of dissolved solids range between 200 and 4000 mg/L but are primarily below 1000 mg/L.

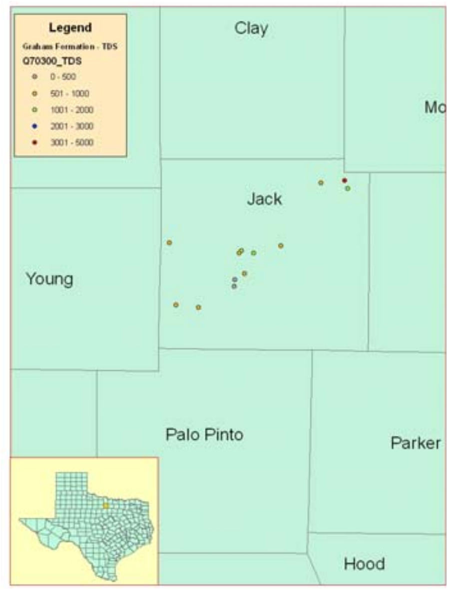




Colony Creek									
Rank	**Bicarb (mg/l)**	**Sulfate (mg/l)**	**Chloride (mg/l)**	**Calcium (mg/l)**	**pH**	**TDS**	**Alkalinity**	**Spec Cond**	**Well Depth (ft.)**
95th percentile	694	933	1385	128	9	3585	582	7211	364
70th percentile	542	252	247	56	8	1539	461	2414	252
50th percentile	503	163	156	30	8	828	412	1606	211
30th percentile	444	74	73	14	8	697	364	1244	160
5th percentile	216	29	31	2	7	406	179	805	89
Min	168	12	26	2	7	253	138	480	70
Max	744	1691	1718	161	9	3968	610	8288	424
Industry Requirements			**< 10,000**	**< 350**	**< 8**	**< 20,000**			

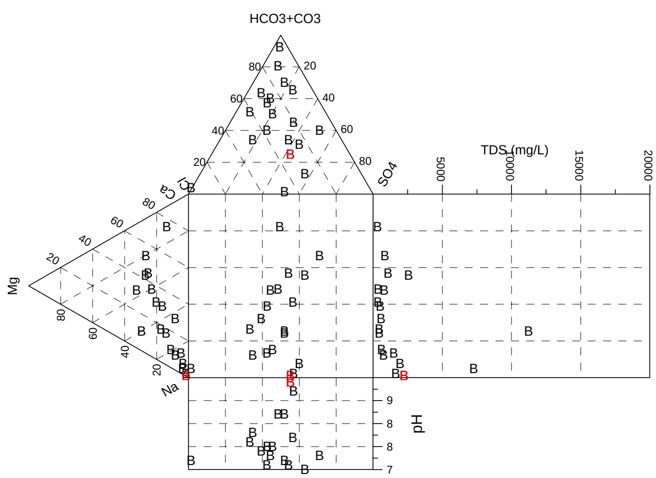
The Graham Formation is located in Jack County running along a diagonal line from the northeast to the southwest. Well depths range mostly between 20 and 300 feet below land surface. Groundwater quality in the Graham Formation generally contains between 400 and 2800 mg/L TDS, well under the industry waterflooding requirement of less than 20,000 mg/L TDS. Calcium levels generally range between 2 and 170 mg/L, well within the industry requirement of less than 350 mg/L. pH levels range between 9 and 7, which is outside the industry requirement of less than 8 for waterflooding. The Durov plot shows that the Graham Formation groundwater has generally even concentrations of bicarbonate, sulfate and chloride anions and also even concentrations of sodium, calcium and magnesium cations. The pH levels of the Graham Formation groundwater are generally well distributed between 7 and 9. The concentrations of dissolved solids are primarily below 1000 mg/L.

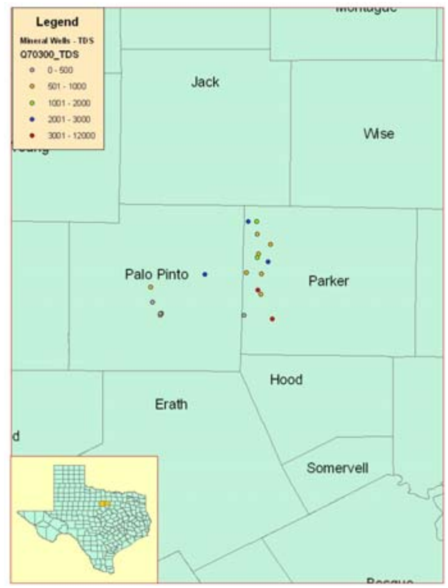




Graham Formation									
Rank	**Bicarb (mg/l)**	**Sulfate (mg/l)**	**Chloride (mg/l)**	**Calcium (mg/l)**	**pH**	**TDS**	**Alkalinity**	**Spec Cond**	**Well Depth (ft.)**
95th percentile	592	408	1129	170	9	2789	490	5573	298
70th percentile	443	235	175	106	8	1017	410	1950	161
50th percentile	373	181	131	81	8	823	327	1595	120
30th percentile	323	150	110	61	8	753	282	1470	75
5th percentile	206	67	29	4	7	464	169	877	21
Min	150	60	29	2	7	418	123	780	20
Max	597	545	2337	170	10	4923	491	9856	360
Industry Requirements			**< 10,000**	**< 350**	**< 8**	**< 20,000**			

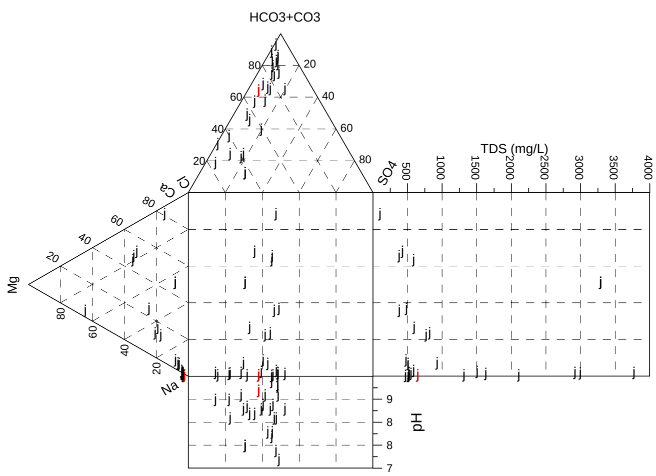
The Mineral Wells aquifer is located in western Parker County and eastern Palo Pinto County. Well depths range mostly between 30 and 400 feet below land surface. Groundwater quality in the Mineral Wells aquifer generally contains between 400 and 8000 mg/L TDS, well under the industry waterflooding requirement of less than 20,000 mg/L TDS. Calcium levels generally range between 10 and 370 mg/L, with 70 percentile less than 100 mg/L, well within the industry requirement of less than 350 mg/L. pH levels range between 9 and 7, which is outside the industry requirement of less than 8 for waterflooding. The Durov plot shows that the Mineral Wells groundwater is not well grouped but is primarily a combination of bicarbonates and chloride anions and sodium and calcium cations. The pH levels of the Mineral Wells groundwater is primarily less than 8 with a range of 7 to 10. The concentrations of dissolved solids range between 200 and 3000 mg/L.

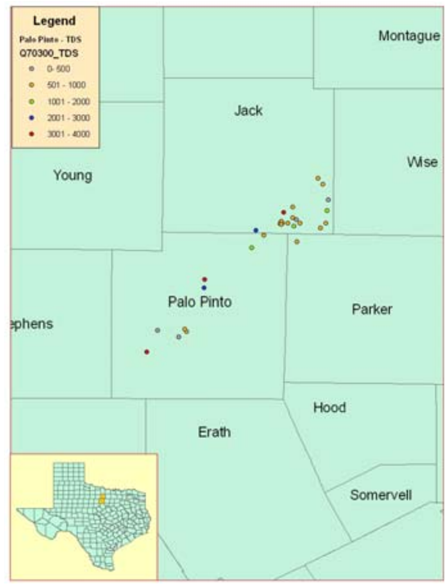




Mineral Wells									
Rank	**Bicarb (mg/l)**	**Sulfate (mg/l)**	**Chloride (mg/l)**	**Calcium (mg/l)**	**pH**	**TDS**	**Alkalinty**	**Spec Cond**	**Well Depth (ft.)**
95th percentile	671	1443	3141	365	9	7749	550	12870	403
70th percentile	462	371	258	96	8	1668	378	2758	163
50th percentile	388	120	143	60	8	879	318	1490	103
30th percentile	335	76	111	38	7	625	274	1052	94
5th percentile	279	14	26	10	7	433	229	755	35
Min	156	5	11	6	7	411	128	742	30
Max	777	4530	4320	401	9	11303	637	14400	432
Industry Requirements			**< 10,000**	**< 350**	**< 8**	**< 20,000**			

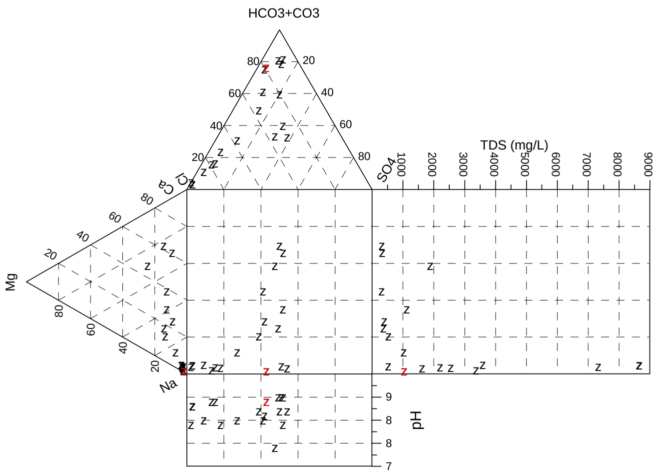
The Palo Pinto aquifer is located along a diagonal from southwest Jack County to southwest Palo Pinto County, primarily in Palo Pinto County. Well depths range mostly between 30 and 360 feet below land surface. Groundwater quality in the Palo Pinto aquifer generally contains between 400 and 3500 mg/L TDS, well under the industry waterflooding requirement of less than 20,000 mg/L TDS. Calcium levels generally range between 1 and 370 mg/L, with 70 percentile less than 50 mg/L, well within the industry requirement of less than 350 mg/L. pH levels range between 9 and 7, which is outside the industry requirement of less than 8 for waterflooding. The Durov plot shows that the Palo Pinto groundwater is predominately bicarbonate and chloride anions and sodium and calcium cations. The pH levels of the Palo Pinto groundwater are concentrated around 9 and range from 7 to 10. The concentrations of dissolved solids are grouped around 500 mg/L with a range of 300 to 3000 mg/L.

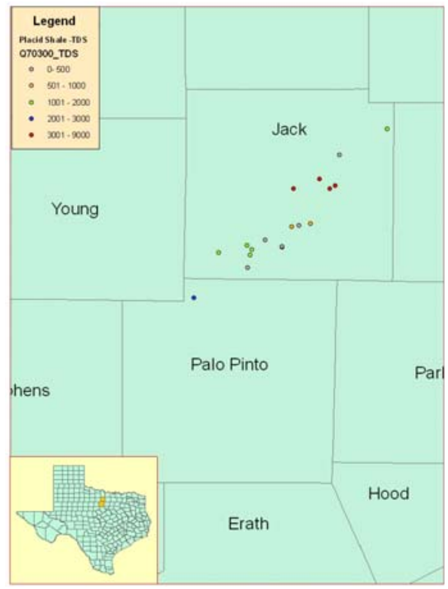




Palo Pinto Limestone									
Rank	**Bicarb (mg/l)**	**Sulfate (mg/l)**	**Chloride (mg/l)**	**Calcium (mg/l)**	**pH**	**TDS**	**Alkalinity**	**Spec Cond**	**Well Depth (ft.)**
95th percentile	732	579	1154	362	9	3344	626	6642	357
70th percentile	573	100	334	44	8	1214	470	2094	252
50th percentile	477	57	104	12	8	643	415	1200	220
30th percentile	411	43	42	6	8	566	336	1033	173
5th percentile	274	15	23	1	7	435	224	846	35
Min	172	4	4	1	7	155	141	286	35
Max	790	664	1686	526	9	3825	647	7840	450
Industry Requirements			**< 10,000**	**< 350**	**< 8**	**< 20,000**			

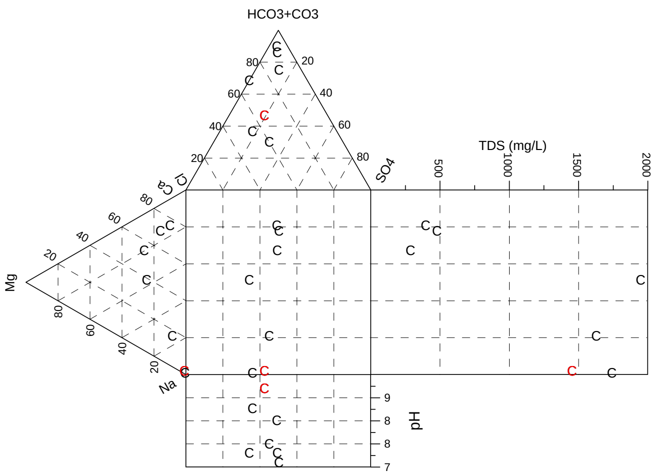
The Placid Shale aquifer is located primarily in Jack County running along a diagonal from the northeast of the county to the southwest. Well depths range mostly between 100 and 450 feet below land surface. Groundwater quality in the Placid Shale generally contains between 350 and 9000 mg/L TDS, well under the industry waterflooding requirement of less than 20,000 mg/L TDS. Calcium levels generally range between 4 and 130 mg/L, well within the industry requirement of less than 350 mg/L. pH levels range between 9 and 7, which is outside the industry requirement of less than 8 for waterflooding. The Durov plot shows that the Placid Shale groundwater is predominately bicarbonate and chloride anions and sodium and calcium cations. The pH levels of the Placid Shale groundwater are concentrated around 8 and range from 7 to 9. The concentrations of dissolved solids are grouped around 500 mg/L with a range of 400 to 4000 mg/L.

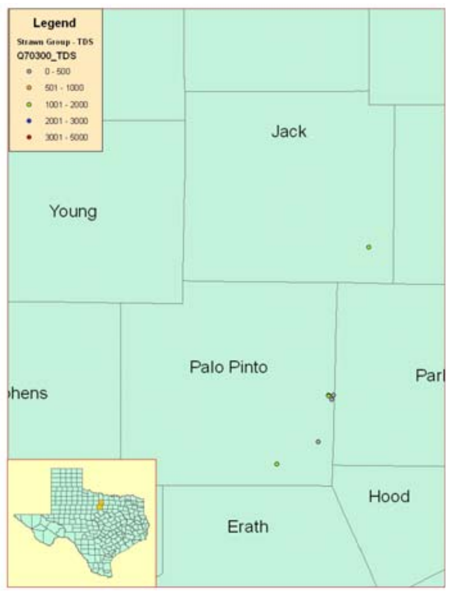




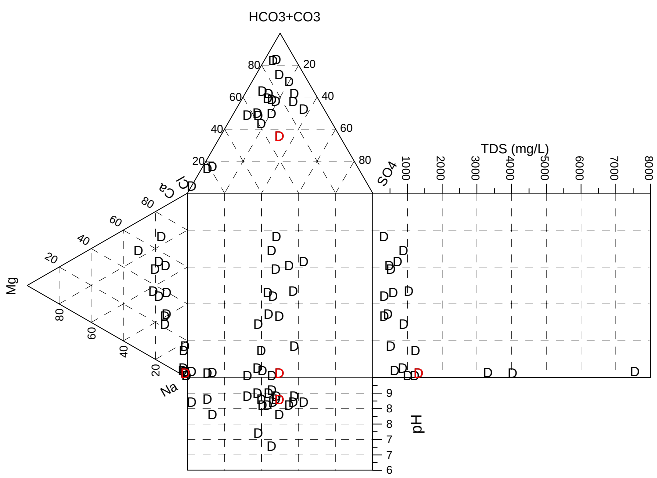
Placid Shale									
Rank	**Bicarb (mg/l)**	**Sulfate (mg/l)**	**Chloride (mg/l)**	**Calcium (mg/l)**	**pH**	**TDS**	**Alkalinity**	**Spec Cond**	**Well Depth (ft.)**
95th percentile	671	497	5008	130	9	8715	552	17920	426
70th percentile	487	168	1253	85	8	2851	406	5738	243
50th percentile	373	127	326	45	8	1432	312	2688	219
30th percentile	332	61	102	27	8	588	280	1090	197
5th percentile	234	34	25	8	8	372	192	675	119
Min	226	21	15	4	7	365	185	665	100
Max	871	505	5008	310	9	8715	758	17920	544
Industry Requirements			**< 10,000**	**< 350**	**< 8**	**< 20,000**			

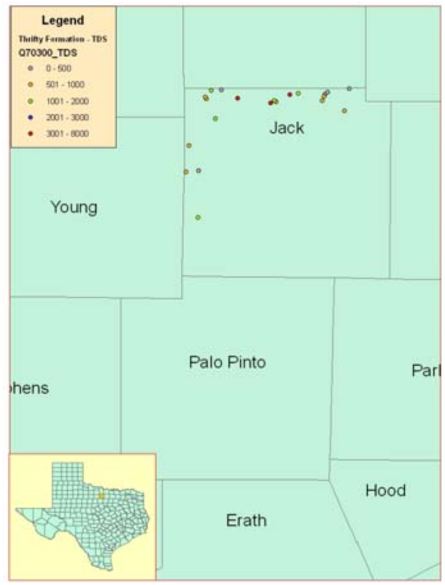
(Strawn Group)





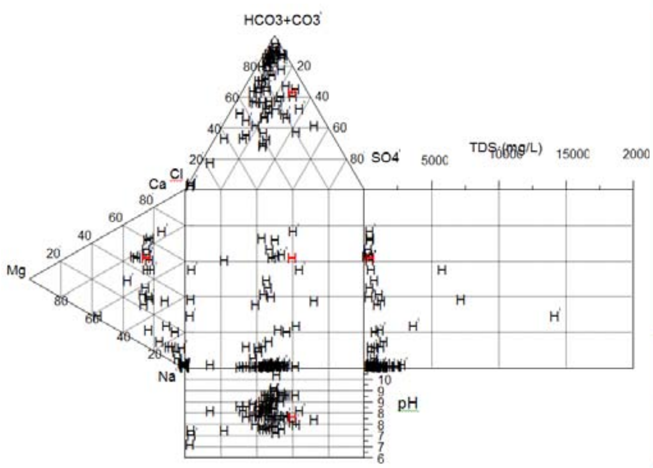
The Thrifty Formation is located along the northern and eastern border area of Jack County. Well depths range mostly between 100 and 300 feet below land surface. Groundwater quality in the Thrifty Formation generally contains between 300 and 4000 mg/L TDS, well under the industry waterflooding requirement of less than 20,000 mg/L TDS. Calcium levels generally range between 30 and 140 mg/L, well within the industry requirement of less than 350 mg/L. pH levels range between 9 and 7, which is outside the industry requirement of less than 8 for waterflooding. The Durov plot shows that the Thrifty Formation groundwater is predominately bicarbonate and chloride anions and sodium and calcium cations. The pH levels of the Thrifty Formation groundwater are concentrated around 8.5 and range from 7 to 9. The concentrations of dissolved solids are grouped around 500 mg/L with a range of 300 to 1500 mg/L.

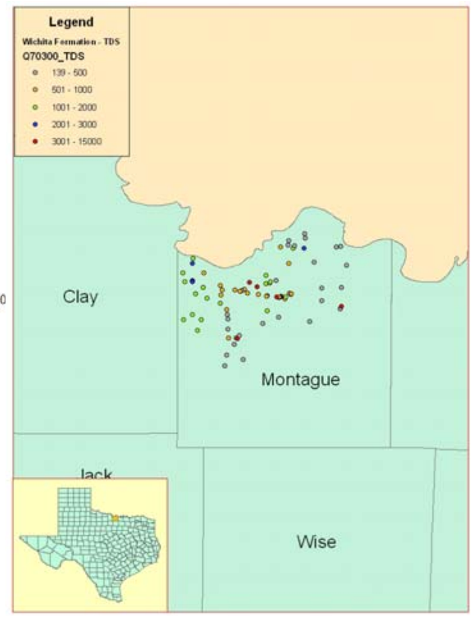




Thrifty Formation									
Rank	**Bicarb (mg/l)**	**Sulfate (mg/l)**	**Chloride (mg/l)**	**Calcium (mg/l)**	**pH**	**TDS**	**Alkalinity**	**Spec Cond**	**Well Depth (ft.)**
95th percentile	644	257	1988	136	9	4034	528	8512	285
70th percentile	500	148	212	82	8	1046	410	2024	225
50th percentile	439	94	111	46	8	872	360	1424	200
30th percentile	334	67	69	29	8	530	276	1008	180
5th percentile	290	18	28	3	7	337	249	610	98
Min	266	16	21	3	7	327	218	608	60
Max	721	326	4424	171	9	7559	625	16240	358
Industry Requirements			**< 10,000**	**< 350**	**< 8**	**< 20,000**			

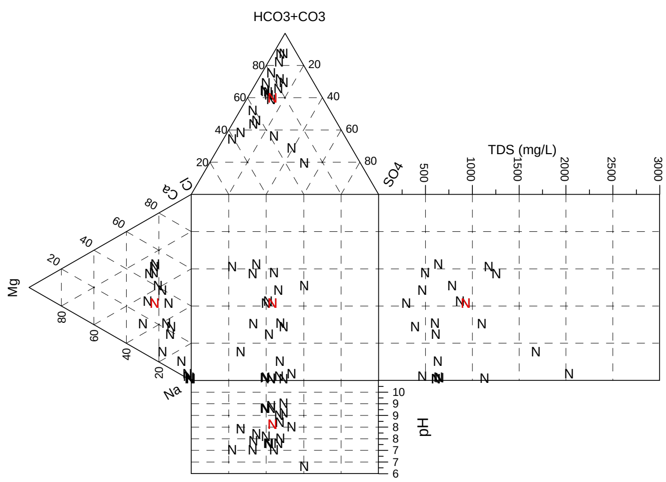
The Wichita Formation is located in central and northwestern Montague County. Well depths range mostly between 70 and 500 feet below land surface. Groundwater quality in the Wichita Formation generally contains between 300 and 3300 mg/L TDS, well under the industry waterflooding requirement of less than 20,000 mg/L TDS. Calcium levels generally range between 2 and 100 mg/L, well within the industry requirement of less than 350 mg/L. pH levels range between 9 and 7, which is outside the industry requirement of less than 8 for waterflooding. The Durov plot shows that the Wichita Formation groundwater is predominately bicarbonate and chloride anions while the cations are not well grouped relative to sodium, calcium and magnesium. The pH levels of the Wichita Formation groundwater are concentrated around 8.5 and range from 7 to 10.5. The concentrations of dissolved solids are grouped around 700 mg/L with a range of 300 to 3000 mg/L.

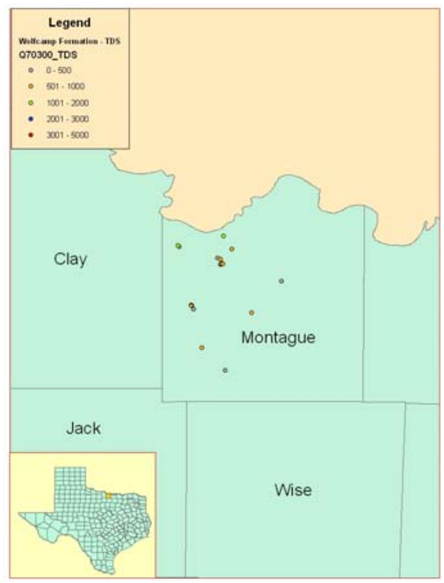




Wichita Formation									
Rank	**Bicarb (mg/l)**	**Sulfate (mg/l)**	**Chloride (mg/l)**	**Calcium (mg/l)**	**pH**	**TDS**	**Alkalinity**	**Spec Cond**	**Well Depth (ft.)**
95th percentile	870	480	1347	107	9	3254	722	6664	485
70th percentile	539	134	214	25	8	1162	464	2156	247
50th percentile	460	55	84	4	8	712	392	1250	206
30th percentile	376	32	29	2	8	493	320	886	168
5th percentile	256	15	9	2	7	350	209	627	74
Min	61	8	5	1	7	139	50	245	21
Max	1391	1260	9572	920	10	14189	1140	34500	700
Industry Requirements			**< 10,000**	**< 350**	**< 8**	**< 20,000**			

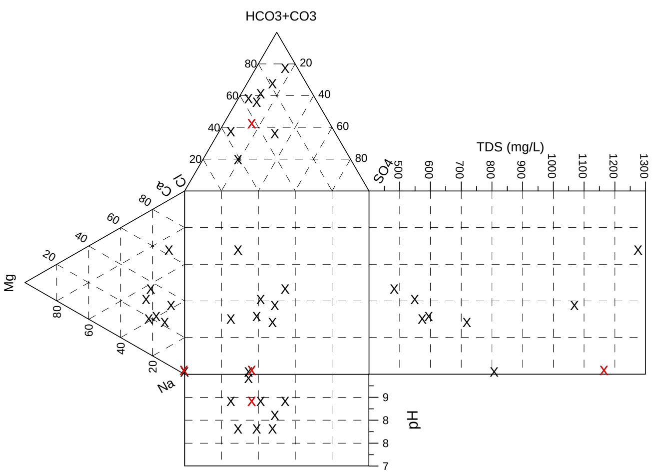
The Wolfcamp Formation is located in central and western Montague County. Well depths range mostly between 30 and 400 feet below land surface. Groundwater quality in the Wolfcamp Formation generally very good containing between 400 and 1700 mg/L TDS, well under the industry waterflooding requirement of less than 20,000 mg/L TDS. Calcium levels generally range between 1 and 210 mg/L, well within the industry requirement of less than 350 mg/L. pH levels range between 9 and 7, which is outside the industry requirement of less than 8 for waterflooding. The Durov plot shows that the Wolfcamp Formation groundwater is predominately bicarbonate and chloride anions and sodium and calcium cations. The pH levels of the Wolfcamp Formation groundwater are concentrated around 8.5 and range from 6 to 9.5. The concentrations of dissolved solids are not well grouped and are evenly distributed between 300 and 1300 mg/L.

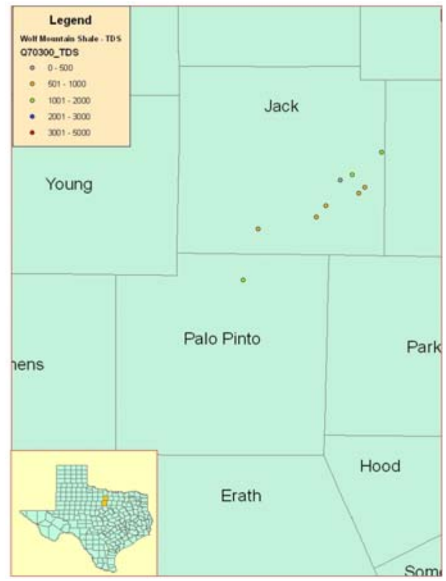




Wolfcamp Formation									
Rank	**Bicarb (mg/l)**	**Sulfate (mg/l)**	**Chloride (mg/l)**	**Calcium (mg/l)**	**pH**	**TDS**	**Alkalinity**	**Spec Cond**	**Well Depth (ft.)**
95th percentile	694	290	461	206	9	1661	592	3334	355
70th percentile	561	99	164	74	8	915	481	1718	213
50th percentile	458	61	113	40	8	640	395	1192	162
30th percentile	409	43	69	15	7	614	338	1093	80
5th percentile	192	23	35	1	7	397	157	715	18
Min	144	14	25	1	6	298	118	540	18
Max	732	620	580	219	9	2035	600	3744	393
Industry Requirements			**< 10,000**	**< 350**	**< 8**	**< 20,000**			

The Wolf Mountain Shale aquifer is located in the southeastern corner of Jack County. Well depths range mostly between 70 and 530 feet below land surface. Groundwater quality in the Wolf Mountain Shale generally very good containing between 500 and 1300 mg/L TDS, well under the industry waterflooding requirement of less than 20,000 mg/L TDS. Calcium levels generally range between 4 and 210 mg/L, well within the industry requirement of less than 350 mg/L. pH levels range between 9 and 8, which is outside the industry requirement of less than 8 for waterflooding. The Durov plot shows that the Wolf Mountain groundwater is predominately bicarbonate and chloride anions and sodium and calcium cations. The pH levels of the Wolf Mountain groundwater are concentrated around 8.5 and range from 8 to 10. The concentrations of dissolved solids are grouped around 550 mg/L with a range of 400 to 800 mg/L.





Wolf Mountain Shale									
Rank	**Bicarb (mg/l)**	**Sulfate (mg/l)**	**Chloride (mg/l)**	**Calcium (mg/l)**	**pH**	**TDS**	**Alkalinity**	**Spec Cond**	**Well Depth (ft.)**
95th percentile	510	238	402	212	9	1230	427	2493	529
70th percentile	445	117	211	58	8	963	381	1839	374
50th percentile	389	65	175	56	8	717	319	1296	175
30th percentile	366	53	111	42	8	580	302	1137	124
5th percentile	245	33	47	4	8	507	202	954	69
Min	234	31	22	3	8	481	194	872	45
Max	520	265	474	275	9	1274	428	2704	550
Industry Requirements			**< 10,000**	**< 350**	**< 8**	**< 20,000**			

V. References

Anaya, R., Conceptual model for the Edwards-Trinity aquifer system, Edwards Plateau, Texas. In: Mace, R. E.,Angle, E. S., and Mullican, W. F., III (eds.), Aquifers of the Edwards Plateau, Texas Water Development Board, Report 360, p. 21-62., 2004.

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Aquifer	System	Series	Group	Rock Characteristics	Water Bearing Characteristics	**County**													
						Bosque	*Dallas*	*Denton*	*Erath*	*Hill*	*Hood*	*Jack*	*Johnson*	*Montague*	*Palo Pinto*	*Parker*	*Somervell*	*Tarrant*	*Wise*
Edwards	Cretaceous	Comanche	Fredericksburg	hard fossiliferous limestone, reef material, shale, cherty and dolomite	Yields small to large amounts of water														
Antlers	Cretaceous	Comanche	Trinity	fine to coarse grain sand with shale and streaks of limestone	Yields small to moderate amounts of water			x						x					x
Glen Rose	Cretaceous	Comanche	Trinity	limestone, shale and anhydrite	locally yields small amounts of usable water											x	x	x	
Hensell	Cretaceous	Comanche	Trinity	conglomerate, fine to coarse grained sands, sandstone, siltstone, sandy shale and limestone	Yields small to large amounts of water	x			x	x							x		
Hosston	Cretaceous	Comanche	Trinity	conglomerate, fine to coarse grained sands, sandstone, siltstone, sandy shale and limestone	Yields moderate to large amounts of water	x			x	x			x				x		
Paluxy	Cretaceous	Comanche	Trinity	fine to medium grain sands	Yields small to medium amounts of water	x	x	x	x	x	x		x			x	x	x	x
Pearsall	Cretaceous	Comanche	Trinity	predominantly shale interbedded with sand	locally yields small amounts of water					x									
Travis peak	Cretaceous	Comanche	Trinity	calcareous sands and silts, conglomerates,				x		x			x			x	x	x	

Aquifer	System	Series	Group	Rock Characteristics	Water Bearing Characteristics	*County*													
						Bosque	*Dallas*	*Denton*	*Erath*	*Hill*	*Hood*	*Jack*	*Johnson*	*Montague*	*Palo Pinto*	*Parker*	*Somervell*	*Tarrant*	*Wise*
				and limestones.															
Twin Mountain	Cretaceous	Comanche	Trinity	medium- to coarse-grained sands, silty clays, and conglomerates		x	x	x	x		x		x		x	x	x	x	x
Washita (Wichita)	Cretaceous	Comanche	Washita	fossiliferous limestone, marl, and clay, some sand near top	yields small quantities of water to shallow wells	x								x					
Austin Chalk	Cretaceous	Gulf	Austin	chalky limestone, fine to medium sands, fossiliferous	locally yields small amounts of water		x			x									
Eagle Ford Shale	Cretaceous	Gulf	Eagle Ford	shale with thin beds of sandstone and limestone	Yields small quantities of water to shallow wells					x									
Woodbine	Cretaceous	Gulf	Woodbine	ferruginous sand, sandstone, shale, sandy shale clay	Yields small to medium amounts of water		x	x		x			x					x	
Brazos Alluvium	Quaternary/ Penn.	DesMoines	Strawn	alluvial sediments consist of clay, silt, sand, and gravel,	Yields small to medium amounts of water (250-500 gpm)	x				x									
Mineral Wells	Pennsylvanian	DesMoines	Strawn	shale with interbedded sandstone, limestone and conglomerate	small quantities of water of slightly to moderately brackish water.							x			x	x			
Graham Formation	Pennsylvanian	Missouri	Cisco	numerous lenticular sandstone deposits, thin limestone, shale and siltstone	yields small quantities of fresh to slightly saline water							x		x					

Aquifer	System	Series	Group	Rock Characteristics	Water Bearing Characteristics	County													
						Bosque	*Dallas*	*Denton*	*Erath*	*Hill*	*Hood*	*Jack*	*Johnson*	*Montague*	*Palo Pinto*	*Parker*	*Somervell*	*Tarrant*	*Wise*
Thrifty Formation	Pennsylvanian	Virgil	Cisco	Numerous lenticular sandstone deposits, thin limestone, shale and siltstone	yields small quantities of fresh to slightly saline water							**x**		**x**					
Colony Creek Shale	Pennsylvanian	Canyon	Canyon									**x**							**x**
Palo Pinto	Pennsylvanian	Canyon	Canyon	limestone and marl with some sandstone and shale	yields small quantities of fresh to slightly saline water							**x**			**x**	**x**			
Wolf Mountain Shale	Pennsylvanian	Canyon	Canyon	Shale, sandstone and limestone	yields small quantities of fresh to slightly saline water							**x**			**x**				
Taylor Marl					Yields small quantities		**x**												
Gonzalos Creek Member (Graham formation)	Pennsylvanian	Missouri	Cisco	Numerous lenticular sandstone deposits, thin limestone, shale and siltstone	yields small quantities of fresh to slightly saline water														
Paleozoic														**x**		**x**			**x**
Alluvium												**x**		**x**	**x**	**x**			**x**

Feasibility of Using Alternative Water Sources for Barnett Shale Gas Well Completions: Evaluation of Paleozoic Aquifers of North Central Texas Part I: Development of a Static Model for a Numerical Model

BY

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ABSTRACT

This report presents the first characterization of North Central Texas Paleozoic aquifers for Barnett Shale hydraulic fracturing water supply. Barnett Shale is one of the largest gas play in U.S., facilitated by hydraulic fracturing, which uses between two and six million gallons per well. Gas wells in eastern play currently use mix of surface water sources and groundwater from Trinity Aquifer. However, the western play is limited by scarce surface water resources and thin or absent Trinity aquifer. Thus, continued Barnett expansion requires new water sources. The research focuses on Barnett Shale but the approach has application to shale gas development in other water-stressed regions.

We evaluate North Central Texas Paleozoic aquifer sandstone distribution in outcrop and subsurface, evaluate aquifer properties in a 2,474-well database — including well discharge rate, specific capacity, transmissivity, hydraulic conductivity, and well characteristics (i.e., diameter, depth, screen length), compile water quality data (total dissolved solids and major ions). We integrate net sand thickness maps for Paleozoic Strawn, Canyon, Cisco, and Wichita Groups with aquifer hydraulic properties and groundwater quality. With the exception of wells completed in Canyon Group limestone near Possum Kingdom Reservoir and wells in the Trinity aquifer footprint that are likely dual completion Trinity and Paleozoic aquifer wells, transmissivity and hydraulic conductivity of most wells (25^{th} to 90^{th} percentile) range within two log cycles. Thus, our analysis generally does not suggest that wells be completed one portion of the study area favoring another: Paleozoic aquifer properties appear to be homogeneous. We do recommend that future Paleozoic aquifer hydraulic fracturing supply wells be completed in the four groups studied with screen intervals in excess of 200 feet to provide sufficient water quantity, but still avoiding saline groundwater.

INTRODUCTION

This report evaluates groundwater availability from a potential Barnett Shale hydraulic fracturing water supply source from Paleozoic sandstone aquifers in a nine-county area of North Central Texas (**Figure 1**). Continued Barnett Shale expansion depends on access to water resources of sufficient quantity and quality, as hydraulic fracturing can use over 3.5 million gallons per well completion. Traditionally, eastern Barnett wells were fraced using groundwater from Trinity aquifer wells, but as development moves west of the Dallas-Fort Worth area, the Trinity aquifer is thin or absent, and river water is difficult or expensive to acquire (**Figure 1**). Thus, resolving water supply bottleneck is critical for continued Barnett Shale development.

This work addresses the problem of increasing water available for Barnett Shale hydraulic fracturing by presenting the first evaluation of North Central Texas Paleozoic groundwater resources. This report presents previously uncompiled North Central Texas Paleozoic sandstone distribution, hydraulic parameters, and groundwater quality. Specifically, this work (1) Characterizes the spatial distribution of Paleozoic sandstone in outcrop and the subsurface; (2) Evaluates hydraulic properties of Paleozoic sandstone, including specific capacity, transmissivity, and hydraulic conductivity, using aquifer pumping test data from Texas Commission on Environmental Quality (TCEQ) and Texas Water Development Board (TWDB); (3) Compiles summary groundwater quality data; and (4) Presents a preliminary estimate of groundwater available for hydraulic fracturing using Paleozoic sandstones. These data are used to (1) support the construction of a numerical groundwater flow model to evaluate groundwater availability, and (2) run a

GIS analysis to assess the proximity and utility of different water sources to a given Barnett Shale well location – both will be completely separately.

BARNETT SHALE DEVELOPMENT AND WATER SUPPLY LIMITATIONS

Recent technological advances, especially hydraulic fracturing, have facilitated the extraction of natural gas from previously uneconomic shale formations (Curtis 2002). One such play is the Barnett Shale of North Central Texas (Pollastro, Hill et al. 2003; Montgomery, Jarvie et al. 2005; Loucks and Ruppel 2007; Pollastro, Jarvie et al. 2007). In the 1990s, Barnett Shale gas development began in southeast Wise County and rapidly expanded north into Montague Co., east into Denton Co., south into the Dallas-Fort Worth metroplex of Tarrant County and now includes sixteen counties in North Central Texas (**Figure 1**) (Railroad Commission of Texas 2011).

Each well completion by hydraulic fracturing can use over 3.5 million gallons of water in a period of hours to few days (Railroad Commission of Texas 2011). From 1993 to 2011, gas production and associated water use for hydraulic fracturing has increased, with a cumulative water use of around 130,000 acre-feet to generate a cumulative gas production of nearly 10 trillion cubic feet (TCF) (**Figure 2**). Large water volumes are required for this development and water supplies are becoming tighter. In 2005, 60 percent of the water used in North Central Texas hydraulic fracturing was sourced from groundwater in the Trinity and Woodbine aquifers (Harden & Assoc. 2007). However, as Barnett Shale development moves north, west, and south, the Trinity aquifer is thin or absent (**Figure 2**). Furthermore public and private surface water resources are highly allocated and expensive where available. As a result, novel hydraulic fracturing water sources are being developed, including capture and reuse of produced hydraulic fracturing water (Railroad Commission of Texas 2011). New groundwater sources are also being considered for Barnett Shale hydraulic fracturing. This research presents the first evaluation of North Central Texas Paleozoic sandstone aquifers for use as a Barnett Shale hydraulic fracturing resource.

DESCRIPTION OF STUDY AREA

This research evaluates groundwater availability from Paleozoic strata in a 7,545 mi^2 (19,541 km^2), nine county area of North Central Texas west of the Dallas-Fort Worth metroplex, including Clay, Erath, Jack, Hood, Palo Pinto, Parker, Montague, Somervell, and Wise Counties (**Figure 2**). No major metropolitan area is located in the study area, but smaller towns include Henrietta, Nocona, Ringgold, St. Jo, Bridgeport, Chico, Decatur, Jacksboro, Perrin, Graford, Mineral Wells, Strawn, Bowie, Weatherford, Granbury, Glen Rose, Dublin, and Stephenville.

North Central Texas average annual precipitation (1951–1983) ranges 28–32 inches per year (Larkin and Bomar 1983). Mean January low and high temperatures (1951–1983) are around 30° and 56°F (respectively) and July mean low and high temperatures are around 73° and 98°F (respectively) (Larkin and Bomar 1983). The landscape is characterized by gently rolling erosional topography (elevation 750 to 1,300 feet) with hills formed by sandstone called “cuestas” and flat valleys formed by erosion of shale (Bayha 1967; U.S. Geological Survey 2011). Brazos, Red, and Trinity Rivers and their tributaries cross the region (U.S. Geological Survey 2011). Major reservoirs include Lake Nocona, Lake Jacksboro, Lake Bridgeport, Lake Weatherford, Palo Pinto Creek Reservoir, Squaw Creek, Lake Granbury, and Possum Kingdom Lake.

Thousands relatively low yield wells (to be discussed in detail later in this report) source Paleozoic aquifers for domestic and stock uses (Bayha 1967) (Texas Commission on Environmental Quality 2011; Texas Water Development Board 2011; Texas Water

Development Board 2011). Public water supplies also use Paleozoic aquifers, including several towns in Montague, Wise, Jack, Palo Pinto, and Parker Counties (Texas Commission on Environmental Quality 2009). Groundwater is used for irrigation in Clay (61% of irrigation), Erath (49%), Palo Pinto (26%), and Montague Counties (9%) but TWDB reporting does not specify if the source is a Paleozoic, Trinity, or alluvial aquifer (Texas Water Development Board 2011). Groundwater is not used for agriculture in Jack, Hood, Somervell, and Wise Counties (Texas Water Development Board 2011).

REGIONAL GEOLOGIC SETTING

Thisreport investigates Pennsylvanian and Permian Paleozoic strata of North Central Texas (Desmoines to Leonard Series) deposited in the Eastern Shelf of the Permian Basin which overlie the Barnet Shale west of the Dallas-Fort Worth area (**Figure** 3). In the eastern half of the study area, Cretaceous strata of the Trinity aquifer are unconformably deposited upon the Paleozoic section (**Figure 4**). Geology of North Central Texas Paleozoic strata are well discussed in the open literature (Wermund, Jenkings et al. 1962; McGowen, Hentz et al. 1967; Wermund and Jenkings 1969; Barnes 1972; Brown, Cleaves et al. 1973; Galloway and L. Frank Brown 1973; Erxleben 1974; Cleaves 1975; Erxleben 1975; Kier, Brown et al. 1979; Brown, Solis-Iriarte et al. 1987; Hentz and Brown 1987; Hentz 1988; Jones and Hentz 1988; Brown, Solis-Iriarte et al. 1990; Bradshaw and Mazzullo 1996; Brown, Ambrose et al. 2009).

The entire Paleozoic section shown on **Figure 4** is comprised of fluvial-deltaic and fluvial deposits from sediment sources from the Ouachita and Arbuckle mountains to the east and north of the study areas (respectively). During Strawn group deposition, westward dipping beds of alternating sandstone and shale were deposited by deltas which prograded across the gently dipping, low accommodation Concho Shelf (Cleaves 1975;

Kier, Brown et al. 1979). As uplift decreased and erosion progressed in the Ouachita Mountains, sediment input declined and a more carbonate bank, shale-rich environment persisted throughout the deposition of the Canyon Group (Erxleben 1974; Erxleben 1975; Kier, Brown et al. 1979). Uplift of the Ouachita Mountains increased again in the upper Permian, leading to active deposition of sand-rich Cisco Group (and Bowie Group updip, continental Cisco Group equivalent) strata alternating with more shale-rich rocks (Kier, Brown et al. 1979; Brown, Solis-Iriarte et al. 1987; Brown, Solis-Iriarte et al. 1990). Sediment influx diminished during upper Cisco and Bowie Group deposition (Wolfcamp Series) as Ouachita Mountain uplift again declined. The trend in lower sediment input continued from uppermost Cisco Group deposition into Wichita-Albany Group (Wolfcamp-Leonard Series), with updip fluvial deposition along a low-relief coastal plain (Wichita Group) grading westward into a mud-rich sedimentary deposition and shallow, low-relief carbonate bank (Hentz 1988).

Paleozoic rocks crop out where not covered by Trinity aquifer strata, generally in the western half of the nine county study area (McGowen, Hentz et al. 1967; Barnes 1972; Hentz and Brown 1987) (**Figure 3**). Paleozoic strata dip westward in the southern study area and change strike to the north of the study area where they dip north. Dip is toward the Permian Basin generally around 0.5° (Wermund, Jenkings et al. 1962; Hentz 1988) (**Figure 5, Figure** 6**, and Figure** 7). In outcrop, Paleozoic strata are generally undeformed and non-faulted.

The entire Paleozoic section is comprised of alternating fine-grained coarse-grained sediments with intermittent limestone beds. Sandstone deposition is highly discontinuous and no attempt has been made by previous researchers to correlate individual sand layers (Erxleben 1974; Cleaves 1975; Erxleben 1975; Hentz 1988;

Brown, Solis-Iriarte et al. 1990). With the exception of the Winchell Limestone and Ranger Limestone, most limestone beds are only a few feet thick (Barnes 1972).

Wichita and Albany Groups

The continental Wichita Group and equivalent marine Albany Group are lower Permian age strata of Wolfcamp series comprised of highly heterogeneous marginal marine and marine facies of shale and sandstone (Hentz 1988). The Wichita Group is of fining-upwards sandstone deposited in continental conditions along the piedmont that drained the Ouachita highlands at Northeast margin of Midland Basin Eastern shelf (**Figure 8**) (Hentz 1988). Deposits of the piedmont to upper coastal plain are comprised of channel deposits, sandy braided and mixed load rivers. River deposits are have overbank mudstones, channel and crevasse splay sandstones, and marsh claystones. Upper coastal plain has mud-rich meandering rivers, sandy ephemeral streams, and mudflats. Mapable sandstone bodies are regionally discontinuous (Hentz and Brown 1987). Sandstone is interfingered along strike with limestone and mudstone. Relative Wichita sand percent decreases from sand-rich strata in the east to mud-rich strata in the western outcrop. Sand-rich braided stream systems are located in Montague County and Eastern Clay County. Mudstone-dominated, tidal flat, shallow shelf marine strata of the fluvial-deltaic Albany Group become more prevalent west of Central Clay County.

For ease of reporting, we combine and present the continental Wichita Group and marine Albany group. Both groups were deposited at the same time. The Wichita group has a higher sand percent and covers more of the study area, so were refer to the two lumped groups as the Wichita Group.

Cisco and Bowie Groups

Similarly, we combine equivalent marine, fluvial-deltaic Cisco Group and continental Bowie Group strata into one lumped group we refer to here as Cisco Group. The Cisco group is comprised of fluvial-deltaic sediments of primarily sandstone with beds of limestone, shale, mudstone, and conglomerate (Kier, Brown et al. 1979; Brown, Solis-Iriarte et al. 1987; Brown, Solis-Iriarte et al. 1990) (**Figure 9**). The Cisco Group is comprised of sixteen lithogenetic units defined with coastal onlap limestone sequences (e.g., nearshore, shelf, shelf-edge, slope systems) and progradational/aggradational terrigenous clastic sequences (fluvial-deltaic and slope/basin sequences) (Brown, Solis-Iriarte et al. 1987; Brown, Solis-Iriarte et al. 1990).

The Cisco Group was deposited from the upper Pennsylvanian to lower Permian during the Virgil to Wolfcamp Series (Brown, Solis-Iriarte et al. 1987; Brown, Solis-Iriarte et al. 1990) during four major depositional phases (1) Home Creek to Breckenridge interval, a thick fluvial-deltaic, thick shelf-margin deltaic, slope, basinal systems with thin shelf-edge limestone, (2) Breckenridge to Saddle Creek interval, a thinner platform fluvial-deltaic, thick shelf-margin deltaic, slope, and basinal system, (3) Saddle Creek to Dothan interval, a thick proximal fluvial system of thin platform fluvial-deltaic system with moderately thick shelf and shelf edge limestone, and (4) Dothan to Coleman Junction interval, a thick shelf and shelf edge limestone with poor developed platform fluvial-deltaic system.

Despite the location in the Cisco Group, sands are highly heterogeneous. No attempt was made by Brown (Brown, Solis-Iriarte et al. 1987; Brown, Solis-Iriarte et al. 1990) to correlate individual sand layers. Regionally extensive limestone marker beds, however, permit the segregation of high highstand/lowstand regressive sequences (Brown, Solis-Iriarte et al. 1990).

Canyon

The Canyon Group is a primarily marine, fluvial-deltaic and carbonate system deposited during the Missourian Series of the Pennsylvanian (Erxleben 1974; Erxleben 1975) (**Figure 10**). The Canyon Group differs from the overlying Cisco Group and underlying Strawn Group in that it was deposited during a period of decreased uplift in the Ouachita Mountains which resulted in a decreased sediment supply. Consequently, Canyon Group strata reflect a higher percentage of finer-grained (e.g., shale) and carbonate strata. Sandstone body facies include valley-fill, distributary channel-fill, and delta-front deposits. Valley-fill deposits are comprised of fining upward sequences of gravel and coarse sand. Distributary channel-fill is comprised of massive, fine- to medium-grained sand. Delta-front deposits are finest-grained, thin-bedded, sheet sandstone and siltstone.

Discontinuous sand units (Pearson 2007) are found within shale Formations that comprise the Canyon Group. Ranger Limestone and Winchell Limestone form palisades surrounding Possum Kingdom Reservoir, while other Canyon Group limestone beds are generally no more than a few feet thick.

Strawn

The Strawn Group is a primarily marine, fluvial-deltaic system (Cleaves 1975). The upper Strawn was deposited by the Perrin delta and has net sandstone <50 to >140 feet. The lower Strawn is comprised of several sandstone units. Sediments of the Strawn Group were deposited during relatively high sedimentary input during multiple delta progradations (**Figure 11**). Diagenetic cements comprise up to 47% of Strawn Group rock volume and reduced initial porosity in several ways: chlorite rim growth around quartz grains, an average of 11% syntaxial quartz overgrowth, calcite (as well as iron-calcite, ankerite, and kaolinite) cementation (Land and Dutton 1978).

HYDROGEOLOGY

A review of open literature reveals that the Texas Water Development Board has published several hydrogeology reports for Paleozoic aquifers in counties in the study area, including Jack (Nordstrom 1988), Montague (Bayha 1967), Parker (Stramel 1951; Fisher, Mace et al. 1996), and Palo Pinto Counties (Fisher, Mace et al. 1996). Reports have also been produced on the overlying Trinity aquifer (Beynon 1991; R.W. Harden & Associates 2004; Harden & Assoc. 2007). However, no report synthesizes groundwater availability for Paleozoic aquifers in North Central Texas, which is one objective of this work.

Wichita

No report is available in the open literature on the hydrogeology of the Wichita Group. However, one report discusses groundwater in Montague County (Bayha 1967), which includes work on the Wichita Group.

Cisco

Groundwater is produced primarily from numerous sandstone bodies interspersed between shale and thinner limestone beds (Nordstrom 1988). Water quality >100,000 mg/L down dip (Texas Water Development Board 1972). Most potable groundwater is produced from sandstone units ten to 50 feet thick, that thins to Northeast (Hentz and Brown 1987). Sandstone bodies are highly discontinuous in the Cisco (Nordstrom 1988) – in fact Brown et al. (1990) did not attempt to do well to well correlation of sandstones. Groundwater also has a large range in water quality laterally and vertically.

Canyon

Groundwater is produced from sandstone between limestone beds (Nordstrom 1988). The Canyon Group has three sandstone intervals found in shale in which groundwater occurs that range from 50 to 150 feet. Depth to water is approximately 100 feet, slightly to moderately saline near outcrop and >100,000 mg/L down dip (Texas Water Development Board 1972). In addition to sandstone, some wells completed in Winchell Limestone (50 to 70 feet thick) and Ranger Limestone (190 feet thick) in the vicinity of Possum Kingdom Reservoir (Barnes 1972) are artesian, suggesting significant limestone permeability (Texas Commission on Environmental Quality 2011).

Strawn

Similarly to the Wichita Group, no report focuses on the hydrogeology of the Strawn Group. However, one TWDB focuses on the Strawn Group in Parker County (Stramel 1951). We do know that groundwater produced in Palo Pinto County with Na-HCO_3 composition from sandstone beds 25 to 50 feet thick (Fisher, Mace et al. 1996).

Trinity Aquifer

While not the focus of this study, it is important to be aware that the Trinity aquifer overlies Paleozoic strata in the eastern half of the study area (Hentz and Brown 1987). Here, the Cretaceous Trinity aquifer forms a thin veneer in SE half of Montague County and majority of Wise County (except for NE corner). To learn more about the Trinity aquifer, please refer to (Bayha 1967; Nordstrom 1982; Nordstrom 1988; Beynon 1991; R.W. Harden & Associates 2004; Harden & Assoc. 2007). A groundwater availability model (GAM) was constructed for the Trinity aquifer, but it did not include Paleozoic strata (R.W. Harden & Associates 2004; Harden & Assoc. 2007). In fact, the Trinity GAM considers the base of Cretaceous as an impermeable boundary with now Trinity-Paleozoic cross-formational flow. However, Paleozoic sediments are unconformably overlain by basal Trinity aquifer sands and hydraulic communication is likely, but not investigated by this research.

Existing Hydrogeologic Data

Some hydrogeologic data are available for Paleozoic aquifers in the study area. In particular, selected aquifer tests have been conducted in Palo Pinto and Montague Counties (Meyers 1969; Fisher, Mace et al. 1996). Paleozoic strata were included in the groundwater availability model for the Seymour aquifer west of the study area (Ewing, Jones et al. 2004).

Groundwater quality data are available in the county reports (Bayha 1967; Nordstrom 1988), in addition to a report on saline groundwater (Texas Water Development Board 1972), and also from water well databases (Texas Commission on Environmental Quality 2011; Texas Water Development Board 2011; Texas Water Development Board 2011).

METHODS

This research addresses the questions of (1) Where are Paleozoic sands in North Central Texas; and (2) How much groundwater is available? To this end, this work (1) Reviews of literature, (2) Compiles well pumping test data for hydraulic parameter estimation, (3) Develops a conceptual hydrogeologic model of North Central Texas Paleozoic aquifers in the Barnett Shale Play using a GIS framework by (3a) Delineating Paleozoic aquifer sands using surface geology maps, subsurface well log data, (3b) Constraining the groundwater flow systems using hydraulic conductivity data and well discharge rates from aquifer pumping tests from TCEQ and TWDB databases and Groundwater total dissolved solid data to infer where Paleozoic sands are currently recharged, and (4) Developing structural maps.

LITERATURE REVIEW

Our literature review included searches of the online databases GeoRef, Google Scholar, and ISI Web of Knowledge. We also searched catalogues of Bureau of Economic Geology and University of Texas Walter Geology libraries. Search terms included: Paleozoic, North Central Texas, Bowie Group, Canyon Group, Cisco Group, Strawn Group, Wichita Group, and also Clay, Erath, Jack, Hood, Montague, Palo Pinto, Parker, Somervell, and Wise Counties. The references were initially organized into general groups of geochemistry, hydrogeology, stratigraphy, and structure.

DATA COMPILATION

We compiled data from publically available sources related to groundwater quality, groundwater wells, hydraulic parameters, and water supply type. We reviewed

TWDB hydrogeology reports available online (Texas Water Development Board 2011), BEG open file reports, and theses and dissertations from The University of Texas at Austin and Baylor University.

During our compilation of pumping test data, we evaluated publicly available well completion reports from two sources, TCEQ (2011) and TWDB (2011). TCEQ well completion reports are available as scanned PDF documents of wells installed prior to February 5, 2001. Texas Water Development Board Submitted Driller's Report Database contains wells installed after February 5, 2001 and contains wells submitted on an entirely optional basis via the online Texas Well Report Submission and Retrieval System maintained by the Texas Department of Licensing and Regulation (Texas Department of Licensing and Regulation 2011) and also TWDB permit applications. We downloaded and inspected paper copies of well completion reports in the TCEQ database and downloaded the TWDB database.

Well completion reports were entered into Excel spreadsheet. Significant editing of the TWDB "Casing, Blank Pipe, and Well Screen Data" was required. Spreadsheet information includes: well ID no., data source, County, 2.5-minute U.S. Geologic Survey quad in which the well is located, well depth, screened interval (which used to estimate hydraulic conductivity), depth to water (relative to ground level datum), diameter of borehole, casing, and screen, discharge rate, drawdown, pumping duration, test type (i.e., jetted, pumped, bailed, etc.), specific capacity (calculated with discharge rate and drawdown), transmissivity (estimated analytically using specific capacity, discharge rate, pumping duration, well diameter, and drawdown), and hydraulic conductivity.

The majority of wells in the study area are small diameter domestic wells and step-drawdown tests data to estimate hydraulic properties are unavailable. Thus an analytical approach was used to estimate hydraulic parameters (Mace and Smyth 2003).

Latitude and longitude presented in TCEQ and TWDB well completion report databases is often too unreliable to plot. Thus, well locations were plotted at the centroid of the 2.5-minute U.S.G.S. quad in which the well is located. Wells in either database do not provide information as to the aquifer in which the well is completed. Thus, the elevation of the screen midpoint is used compared with structural maps generated by this work to assign an aquifer to the well (i.e., Strawn, Canyon, Cisco, or Wichita).

HYDROGEOLOGIC CONCEPTUAL MODEL DEVELOPMENT

Maps of Paleozoic Sand Distribution: Strawn, Canyon, Cisco, and Wichita Groups

We delineated sandstone bodies likely to host groundwater in extractable quantities by integrating outcrop sand maps and subsurface well log data within a structural context. Initially, the four groups that comprise the Paleozoic section of North Central Texas (i.e., Strawn, Canyon, Cisco, and Wichita) were delineated in GIS from the 1:250,000 digital Geologic Atlas of Texas (Pearson 2007). We combined contemporaneously deposited predominantly non-marine Bowie Group with the predominantly down-dip marine equivalent Cisco Group and we subsequently refer the combined group as the Cisco Group. Similarly, we combined predominantly non-marine Wichita Group with the predominantly down-dip marine equivalent Albany Group into one Wichita Group. Sand distribution within each of the four major groups was mapped independently.

Delineation of Group Tops

Next, we delineated subsurface tops of each group using GIS to integrate net sand thickness into a three-dimensional framework suitable for conversion to numerical groundwater flow model layers.

Strawn Group posed the greatest challenge to map in the subsurface for a number of reasons. First, rocks of the Cretaceous age Trinity aquifer unconformably overlie the Strawn Group and limits outcrop area to a roughly 40 by 80 kilometer portion of Southeast Palo Pinto County, far north Erath County, and far west Parker County (**Figure** 3). Second, Cleaves (Cleaves 1975) limited subsurface mapping to the west of the outcrop zone; thus, no subsurface data were available for the subcrop east of the outcrop. To address these challenges, the Strawn Group layer top was delineated using a variety of methods. Where Strawn crops out, the layer top was assumed to be ground surface extracted from the one arc-second (approximately 30-meter resolution) National Elevation Dataset (U.S. Geological Survey 2011). Strawn subcrop top to the west and northwest of the outcrop was estimated using a structural contour map of the regionally extensive Dog Bend Limestone marker bed (**Figure 12**) located in the Upper Strawn Group (Wermund, Jenkings et al. 1962). We use the Dog Bend Limestone Base to infer the dip of the Strawn top. So that the eastern extent of the Dog Bend Limestone map coincided with the western limit of the Strawn Group outcrop, we added 170 meters to the Dog Bend Limestone structural map. Where the Strawn is found unconformably below Cretaceous strata of the Trinity aquifer east of eastern Montague and Wise county — and east of the area shown on the Dog Bend Limestone structure map — we infer top of the Strawn Group using structural contours of the base of the Cretaceous (**Figure 13**) (Nordstrom 1982).

The Canyon Group layer top was delineated using National Elevation Data (U.S. Geological Survey 2011) for the outcrop zone and structural contours of the base of the Cretaceous (Nordstrom 1982) for the portion of the Canyon underlying the Trinity aquifer. The subcrop of the Canyon to the west of the outcrop zone was extrapolated using a structural contour map of the Home Creek Limestone top (**Figure 14**) (Wermund and Jenkings 1969) which Erxleben (Erxleben 1974; Erxleben 1975) defines as the top of the Canyon Group.

The Cisco Group layer top was chosen using National Elevation Data (U.S. Geological Survey 2011) for the outcrop zone, structural contours of the base of the Cretaceous (Nordstrom 1982) for the portion of the Cisco underlying the Trinity aquifer. The Cisco subcrop to the west of the outcrop was computed using trigonometry considering the width of the outcrop assuming a regional dip. A dip of 0.5 degrees was estimated using the Home Creek Limestone top structural contour map (Wermund and Jenkings 1969). The bed perpendicular Cisco thickness of the Cisco was calculated using Equation 1, where:

$$L = \tan(\sigma) * W , \qquad \text{(Eqn. 1)}$$

where, L = bed-perpendicular thickness, σ = bed dip, and W = outcrop width.
Thus, the top of the Cisco was calculated by adding the computed Cisco thickness to the top of the Canyon.

The Wichita Group layer top was compiled from National Elevation Data (U.S. Geological Survey 2011) for the outcrop zone and structural contours of the base of the Cretaceous (Nordstrom 1982) for the portion of the Cisco underlying the Trinity aquifer. In the subsurface, the Wichita top was delineated using the same trigonometric approach of the Cisco Group (Equation 1) using a regional dip of 0.5 degrees and the outcrop width.

Sand Distribution in Outcrop

Outcrop sand distribution was delineated using Geologic Atlas of Texas sandstone member polygons (Pearson 2007). Within each of the four groups, all polygons in the MemberPoly250K feature class in the MEMBER_CD field that started with “ss” (indicating an undifferentiated sandstone member) or that were specifically listed in the Geologic Atlas of Texas map sheet notes as a sandstone member were plotted to create the sandstone outcrop map show in (**Figure 3**). For example, regionally correlable sandstone bodies such as, |Pa, the Avis Sandstone and |Pgc, the Gonzales Creek Member, both of the undivided Thrifty and Graham Formations of the Cisco Group were included as specifically named sandstone members. All polygons in the “MEMBER_CD” field that were shale based on the GAT map sheet notes were omitted. Similarly, limestone beds were omitted because they are typically only a few feet thick in the study area. However, we plotted Winchell Limestone and Ranger Limestone of the Canyon Group, which form outcrops in the vicinity of Possum Kingdom Reservoir and have a total thickness of ~240 feet (McGowen, Hentz et al. 1967). An evaluation of well pumping tests (discussed later) shows that some wells in the TCEQ database (Texas Commission on Environmental Quality 2011) completed in limestone near Possum Kingdom Reservoir are artesian, suggesting significant permeability in these two limestone formations (**Figure 3**).

Sand Distribution in Subsurface

Subsurface sand distribution for Strawn, Canyon, and Cisco Groups was compiled from maps done by previous researchers using well log analyses (Cleaves 1975; Erxleben 1975; Brown, Solis-Iriarte et al. 1987) (**Figure 15, Figure** 16**, and Figure** 17). The Wichita group lacked subsurface data, so subsurface sand distribution was inferred from surface sand mapping (Hentz and Brown 1987) and a conceptual sedimentary depositional model (Hentz 1988). Initial sand mapping was refined based on conceptual sedimentary depositional models (Cleaves 1975; Erxleben 1975; Brown, Solis-Iriarte et al. 1987; Hentz 1988) and Geologic Atlas of Texas map sheet notes (McGowen, Hentz et al. 1967; Barnes 1972; Hentz and Brown 1987).

Previous studies of the Strawn, Canyon, and Cisco Groups (Cleaves 1975; Erxleben 1975; Brown, Solis-Iriarte et al. 1990) mapped subsurface sand distribution using an extensive petroleum well log database of ~5,000 geophysical logs. We scanned sand maps for: (1) Strawn Group (Cleaves 1975) **–** Plate XVII is already a net sand map **–** of individual sand facies, including Dobbs Valley, Ada, Brazos River, Hog Mountain, Lake Pinto, Devil's Hollow, and Turkey Creek Fluvial-Deltaic Facies; (2) Canyon Group (Erxleben 1975) – Plates IV, VI, and VIII – net sandstone thicknesses of the Wolf Mountain Shale, Placid Shale, and Colony Creek Shale Intervals; and (3) sandstone isoliths for sixteen cyclic sequences of the Cisco Group (Brown, Solis-Iriarte et al. 1987). No subsurface sand distribution data are available for the Wichita Group.

All scanned subsurface sand distribution maps were georeferenced in ArcMap version 10 geographic information system (GIS) to North American Albers Equal Area Conic projection (Environmental Systems Research Institute 2010). Sand thickness contours were digitized in GIS. ArcMap Spatial Analyst Topo to Raster command used to interpolate sand thickness to a grid. Sand thickness improperly interpolated less than zero were replaced with zero-foot values using ArcMap Spatial Analyst Reclassify command. Cleaves (1975) presented Strawn Group subsurface sand distribution as a net sandstone isopach map that was digitized directly (**Figure 15**). In contrast, Canyon and Cisco Groups have multiple sand intervals (three and sixteen, respectively); thus, individual gridded rasters of sand thickness were summed in ArcMap Spatial Analyst Add command to create a net sand thickness raster (**Figure 16 and Figure** 17).

As subsurface sand distribution data are unavailable for the Wichita Group, we relied on general trends in sandstone and sand grain size distribution (Hentz 1988). At the eastern border of Montague County, we assumed a sand content of 40 percent which graded smoothly to 10 percent at the western border of Clay County (Hentz 1988). We assumed a 20 percent subsurface sand content and smoothly graded into the higher sand content to the east (Hentz 1988).

Constraining Aquifers Using Groundwater Total Dissolved Solids

We use maps of total dissolved solids (TDS) concentration in Strawn, Canyon, and Cisco Groups groundwater (Texas Water Development Board 1972) to make inferences into groundwater recharge pathways from the outcrop into the subsurface. No groundwater TDS data are available in the open literature for the Wichita Group, so we do not use a groundwater TDS constraining approach for this group. We assume that the subsurface is being recharge only where groundwater TDS is relatively low. Report 157 by the Texas Water Development Board (1972) uses TDS inferred from borehole geophysical logs in a relatively sparse well network to delineate 50,000 and 100,000 milligram per liter (mg/L) TDS groundwater contours (**Figure 18, Figure 19, and Figure** 20). We assume that groundwater >50,000 mg/L TDS is not actively recharged. Thus, portions of the study area with elevated groundwater TDS are omitted from the active groundwater flow system and not considered part of the hydrogeologic conceptual model.

Evaluation of Aquifer Hydraulic Properties from Well Pumping Tests

With the goal of evaluating aquifer hydraulic parameters, we present a preliminary database of well pumping tests compiled from well completion reports in publicly available TCEQ and TWDB databases (Texas Commission on Environmental Quality 2011; Texas Water Development Board 2011) for a rectangular region that encompasses the nine county study area. We manually entered PDF scans of TCEQ well completion reports downloaded from the website (Texas Commission on Environmental Quality 2011). TCEQ database includes wells installed prior to February 5, 2001. We downloaded the electronic Microsoft Access database of wells installed after February 5, 2001 from the Texas Water Development Board Submitted Driller's Report Database (Texas Water Development Board 2011). TWDB well data are submitted by drilling companies via the online Texas Well Report Submission and Retrieval System (Texas Department of Licensing and Regulation 2011). Because well completion data (e.g., screen top and bottom, casing start and end depth, borehole diameter, well screen and casing diameter, etc.) are entered into one field of the database by the drilling company, we edited database records considerably to put it into a usable format for spreadsheet analysis.

We initially constructed a database with pumping test data from 7,614 wells, 4,559 of which we entered from TCEQ and 3,055 from the TWDB. Next, we deleted 2,619 wells obviously screened in the Trinity aquifer or alluvium (i.e., based on location, depth, and lithology encountered during drilling), had mislabeled location outside of the study area, dry holes, artesian (e.g., 71 wells screened in limestone near Possum Kingdom Reservoir), or incomplete data, resulting in a preliminary database of 4,995 wells. Of the 4,995 wells in the preliminary database, 1,524 did not have well borehole data. However, 3,471 wells have well borehole radius. Thus, in order to increase the number of wells in the database from which we can calculate aquifer hydraulic properties, we use a well borehole radius mode of 7.875 inches to populate wells without well borehole radius data. A total of 820 wells in the preliminary database did not have drawdown data needed to estimate aquifer hydraulic properties.

Wells screened in alluvial aquifers were removed from the database. The Red River forms the northern boundary of Clay and Montague Counties. Along with its tributaries, the Red River has a large alluvial aquifer. Alluvial aquifers are also associated with the Trinity and Brazos Rivers. Wells screened in alluvium were eliminated from the database by comparing the well location with surface geology. Alluvium, terrace deposits, and windblown deposits from the Geologic Atlas of Texas (Pearson 2007) was plotted in GIS with well location. Wells lacked latitude and longitude and were plotted at the centroid of an approximately seven square mile, 2.5-minute quadrangle (approximately 2.9 miles east-west by 2.4 miles north-south). The lithologic log of each well located in a quadrangle with Alluvium, terrace deposits, and windblown deposits was evaluated. Wells located along the Red River in Clay County are completed primarily in alluvium with a total depth generally less than 50 feet. Conversely, wells in Montague County along the Red River are deeper (i.e., greater than 80 feet), screened at depths below unconsolidated sands (i.e., strata described as "surface sand" in well lithologic logs), and completed in sands bounded by shale indicative of Paleozoic strata that is absent in alluvium. A similar approach identified wells screened in the alluvial aquifers of the Trinity and Brazos Rivers. A total of 144 well were identified as completed in alluvium are not considered in the evaluation of Paleozoic aquifers.

Wells screened in the Trinity aquifer were also removed from the database. Every county in the study area, except Clay County, has Trinity aquifer outcrop (**Figure 3**). We eliminate Trinity aquifer wells from the preliminary well database by assigning each well to one of the four geologic groups (e.g., Strawn, Canyon, Cisco, Wichita Group) based on well depth and geologic structure of the four groups. We compare the well screen midpoint, which is computed as the average of the top most and bottom most screen, with the top of each Group layer that we generated in GIS. A well screen midpoint elevation that is located between the top and bottom elevation of a certain layer is assigned to that layer. To account for uncertainty in our analysis, wells likely screened in the Trinity aquifer that did not have well depth more than approximately ten percent deeper than the base Trinity were omitted from the database. Based on this analysis, we refined the preliminary database (which contained alluvial and Trinity aquifer wells), resulting in a final Paleozoic well database comprised of 2,474 wells, with 434 wells in Strawn Group, 496 wells in Canyon Group, 1,340 wells in Cisco Group, and 204 wells in Wichita Group.

While the final well database includes 2,474 wells screened in Paleozoic strata, not all of the wells have complete data. In order to understand the characteristics of wells in the database, we evaluate the wells using standard statistics (**Table 1** and **Table 2 and Figure 21**). The database is almost entirely comprised of narrow domestic wells with a median diameter of 4.5 inches and a 90th percentile depth value of 370.4 feet. Most of the wells are shallow, with a median depth of around 200 feet. As many of the wells are domestic, median screen length is 35 feet. Median discharge rate for the entire database is 11 gallons per minute, with a 90th percentile value of 30 gallons per minute (**Table 1**). The respective median pumping rates for the Strawn, Canyon, Cisco, and Wichita Groups are 14, 10, 12, and 7 gallons per minute (**Table 2**). Most well pumping tests lasted one hour, as is typical for domestic water well construction.

We also compiled water quality results from TWDB (2011), which are shown in **Table 3**. Water quality for the wells in the database is potable, with median values for pH=8.1, bicarbonate = 425 mg/L, sulfate = 78 mg/L, chloride = 120 mg/L, total dissolved solids = 758 mg/L, and alkalinity = 357 mg/L.

Estimation of Transmissivity from Specific Capacity

The well pumping test database was analyzed for transmissivity (T) and hydraulic conductivity (K). Ideally, T, K and storativity (S) can be estimated by analyzing time-drawdown data collected during multi-well aquifer pumping test (Theis 1935). However, TWDB and TCEQ data are primarily for domestic wells with simple one-well tests. We estimate T and K from specific capacity data because the TCEQ and TWDB databases do not have multi-well aquifer pumping test data for the study area. Furthermore, only five tests were available in open literature in Montague County (Meyers 1969) and four in Fort Wolter on the Palo Pinto-Parker County border (Fisher, Mace et al. 1996). Estimating T and K from specific capacity data is not as accurate as multi-well time-drawdown data analysis, but because of the lack of multi-well aquifer pumping tests we generate aquifer hydraulic properties from specific capacity data.

Several approaches are available in the open literature to estimate T from specific capacity data, which are summarized in Mace and Smyth (2003). We use the iterative analytical solution presented by Mace and Smyth (2003). Well performance tests done by drillers of domestic wells typically pump or bail a well at a constant discharge rate (*Q*), and measure drawdown (*s*) from static, pre-development groundwater level to get specific capacity (S_c) using Equation 2, where:

$$S_C = \frac{Q}{s} \qquad \text{(Eqn. 2)}$$

We use the analytical relationship presented by Theis (1935) shown in Equation 3

$$S_C = \frac{4\pi T}{\left[ln\left(\frac{2.25 T t_p}{r_w^2 S} \right) \right]} \qquad \text{(Eqn. 3)}$$

Where *ln* is the natural logarithm, t_p is the time of production (i.e., pumping or bailing time), r_w is the radius of the well in the screen interval (measured as the borehole radius), and *S* is the storativity of the aquifer.

We rearrange Equation 3 and solve Equation 4 iteratively in spreadsheet

$$T = \left(\frac{S_c}{4\pi}\right)\left[ln\left(2.25Tt_p\right) - ln\left(r_w^2 S\right)\right] \quad . \qquad \text{(Eqn. 4)}$$

We use an initial guess for *T* on the right-hand side of the equation and assume a plausible value of *S*.

All 2,474 wells in our database had all the information required for estimating *T* iteratively using the Theis (1935) analytical relationship. However, 25 well had zero drawdown and 465 wells failed to converge on a solution, resulting in 1,984 wells for which *T* was estimated. Hydraulic conductivity (*K*) was calculated from T using Equation 5:

$$K = \frac{T}{b} \quad , \qquad \text{(Eqn. 5)}$$

where *b* is total screened interval. Of 1,984 wells, 998 had total screen length data needed to calculate *K*. Thus, we used the median screen length of 35 feet for wells without screen length data to increase the number of calculated hydraulic conductivity values possible (**Figure 22**).

Comparing Population Density with Well Density

We evaluate the location of Paleozoic wells in the database to answer the question if well location is a function of population density or unfavorable geology. To address this question we created a map of relative population density using year 2000 U.S. Census Data (U.S. Census Bureau 2000), as 2010 Census results were not available yet online and we would not expect North Central Texas population density to change appreciably from 2000 to 2010. First, Arc GIS TIGER/Line® Shapefiles of U.S. Census blocks were downloaded from the U.S. Census Bureau (2000) for Clay, Erath, Hood, Jack, Montague, Palo Pinto, Parker, Somervell, and Wise Counties. Then, year 2000 population data (P.1 Total Population table) for was downloaded from the U.S. Census (2000) for each Census block for the counties of interest, for a total of 17,234 Census blocks. Optional geographic identifiers (G001. Geographic Identifiers) were selected during Excel file downloading so that the file contained population and land and water area (and other values not pertinent). Because land and water area are provided in square meters, population density per square mile of total surface area was calculated in Excel for each census block (University of Georgia Libraries 2004) using Equation 6:

population density = total population / ((land area + water area) / 2589988 .(Eqn. 6)

Text format latitude and longitude were converted to numbers using the Excel concatenate, left, and right expressions. Finally, block data shapefiles were loaded into ArcMap version 10. The spreadsheet of population density was added to ArcMap, plotted as X-Y data with NAD 1983 Geographic projection and exported as a new shape file of population density at a point that is situated inside of a Census block shapefile polygon, and added back into ArcMap. The spatial join command with target = polygon blocks, join = point population density, join option = one-to-one, and match = intersect was used to create new shapefile that presented population density for each year 2000 U.S. Census block for the nine counties in the study area.

We find that population density is highest in Southeast Montague County, Wise, Parker, Hood, Somervell, and Erath Counties (**Figure 23**). Coincidentally, the highest population density is also located along the outcrop zone of the Trinity aquifer. Higher population density in Clay, Jack, and Palo Pinto Counties is limited to a few towns. The spatial distribution of 2.5-minute quadrangles with wells screened in the Paleozoic are located primarily in the western two-thirds of the study area both in higher and lower population density zones. Thus, well locations do not appear to be influenced by zones of favorable geology. Gaps in domestic well coverage also correspond to low population density; thus, if wells are not present in an area, it does not necessarily mean that hydraulic conductivity is low in that location.

NUMERICAL GROUNDWATER FLOW MODEL SIMULATIONS

Conceptual Groundwater Flow Model of North Central Texas Paleozoic Strata

In support of groundwater development (which will be discussed in more detail in a later report), here we discuss how the hydrogeologic conceptual model is translated into groundwater model layers and properties.

Layers and Grid

We convert our hydrogeologic conceptual model of four Groups into layers that can be used for simulating groundwater flow by considering sand fraction, groundwater TDS, and permeability distribution.

Sand Fraction

Net sand thickness was calculated for the Strawn, Canyon, and Cisco Groups using data from the open literature (Erxleben 1974; Cleaves 1975; Erxleben 1975; Brown, Solis-Iriarte et al. 1990). For the Strawn group, Cleaves (1975) presents a net sandstone isolith map. Net sandstone maps for the Colony Creek Formation, Placid Formation, and Wolf Mountain Formation of the Canyon Group were contoured and summed in GIS (Erxleben 1974; Erxleben 1975). Sands deposited during sixteen cyclic cycles of the Cisco Group were contoured and summed in GIS (Brown, Solis-Iriarte et al. 1990). For the Strawn, Canyon, and Cisco Groups, the sand fraction, or percent of a Group layer comprised of sandstone, was calculated by dividing net sand thickness of a Group by the total thickness of a Group. For the Wichita Group, sand fraction was extrapolated in GIS assuming a sand fraction of 40 percent on the eastern portion of the outcrop of the Nocona Formation grading smoothly to a sand fraction of 10 percent in the western portion of the outcrop in the study area based on field mapping by Hentz (1988). For the Canyon, Cisco, and Wichita Groups, the thickness of the Group was calculated in GIS using the model layer tops calculated previously. However, net sand thickness evaluated by Cleaves (1975) is less than the total thickness of the Strawn Group because of dip to the west and east. Thus, we calculated sand fraction for the Strawn Group by assuming a false layer bottom elevation of -1,697 meters.

Delineation of Percent of Model Layer Active

We used an approach that mapped zero and one lines, representing the percent of a given cell that is active (from 0 to 100) in order to account for the fact that groundwater TDS increases down dip, caused by a lesser degree of groundwater circulation (**Figure** 24). Thus, we placed a one line to trace the eastern extent of the outcrop. We then drew a zero line to the west of the outcrop zone that generally paralleled the 50,000 mg/L TDS line (Texas Water Development Board 1972). The zero and one line could also be moved to capture areas of high or low sand fraction. The area between the zero and one lines was then interpolated in GIS using inverse distance weighting (IDW). The Strawn followed a similar approach but it was given two zero lines on both sides of the outcrop whose central axis corresponded to the one line: one to the west in the downdip direction similar to the other formations and one to the East underneath the Trinity to account for likely hydraulic connection between the aquifers.

Permeability Distribution

Similarly, permeability (in the form of hydraulic conductivity) also needs to be populated in the model layers. Thus, we plotted log hydraulic conductivity on the sand fraction maps. We contoured hydraulic conductivity values following the data and also general sand depositional patterns from the literature (Erxleben 1974; Cleaves 1975; Erxleben 1975; Hentz 1988; Brown, Solis-Iriarte et al. 1990) following the principle that higher sand fraction also means larger sand bodies and higher hydraulic conductivity (**Figure 8, Figure 9, Figure 10, and Figure 11**). During Strawn Group deposition, sand was deposited in two major deltas: Bowie and Perrin. The Bowie Delta deposited sands in East North East-West South West trend across Clay and Montague Counties. The Perrin Delta deposited sands roughly East-West across Jack, Parker, Palo Pinto, and Wise Counties. Several smaller bayhead deltas deposited sands in a South East-North West direction in South East Palo Pinto, Hood, and Erath Counties. During Canyon deposition the Henrietta Fan Delta System deposited sand sloughed off the Arbuckle Mountains in Oklahoma in a North-South direction in Clay and Montague Counties. The Perrin Delta System persisted and deposited sands in a roughly East-West to Southeast-Northwest orientation primarily in Jack County and also Southwest Wise and Northwest Parker

Counties. A carbonate-rich lagoon dominated Palo Pinto County (and further Southwest). Sands were deposited in sixteen cyclical sequences of the Cisco Group; however, the general trend was deposition from Northeast-Southwest and East-West from Bowie Complex (delta) and other sediment sources along the Ouachita Mountain front. For Wichita Group, sand was deposited from East-West from Ouachita Foldbelt and also North-South from Arbuckle Mountains giving trend of higher sand to the East in piedmont and coastal plain fluvial deposition, and lower sand content in West in tidal flats with more mud.

RESULTS AND DISCUSSION

We present the first North Central Texas Paleozoic aquifer characterization, in an area where water supply for hydraulic fracturing constrains Barnett Shale expansion. We include the following results in this report: (1) Characteristics of wells and water quality in our database, (2) Distribution of sand in outcrop and subsurface, (4) An evaluation of aquifer hydraulic parameters, and (5) An initial assessment of groundwater availability from Paleozoic aquifers.

DATA COMPILATION

In this report, we present a database of wells in the nine county study area of North Central Texas compiled from TCEQ (2011) and TWDB (2011) (**Table 1** and **Table 2**)

HYDROGEOLOGIC CONCEPTUAL MODEL

Paleozoic Sandstone Distribution in Outcrop

Sandstone is distributed irregularly in outcrop (**Figure 3**) and forms small hills called "cuestas" surrounded by more shale-rich valleys. Strawn Group sandstone is found in roughly two southwest-northeast trending bands separated by a larger area dominated by siltstone. Canyon Group sandstone is scarce in outcrop and limited to updip (i.e., eastern) portions of the northern outcrop. Outcrops of Ranger and Winchell Limestone (**Figure 4**) dominate about half the down dip extent of Canyon Group outcrop. By visual inspection, the Cisco Group has the highest percent of sandstone in outcrop, which is found interspersed with more shale-rich areas. In general, two strike-oriented bands of shale are found in the east-center and far west of the outcrop. Also, Cisco Group sandstone in outcrop is slightly greater to the north. Wichita Group has comparatively low sandstone in outcrop, and a higher percentage in the east.

Paleozoic Sand Distribution in Subsurface

Here we present maps of net sand and sand fraction for each of the four groups. Net sandstone thickness in the Strawn Group ranges from around 450 to >600 meters in the study area (**Figure 25**). Sand fraction appears evenly spaced because of the high overall thickness of the layer in excess of 1,700 meters. Canyon Group net sandstone thickness ranges from around 50 to >250 meters in the study area; however near the outcrop zone maximum sandstone thickness is >100 meters (**Figure 26**). Sand fraction is variable from <10 to >30 percent near the outcrop zone. Cisco Group net sandstone thickness ranges from around 50 to >150 meters in the study area (**Figure 27**). Cisco Group Sand fraction is variable from <10 to >30 percent near the outcrop zone and is less heterogeneous than Canyon Group sand distribution. Wichita Group Sand fraction decreases from around 20 percent in the east to <10 in the west (**Figure 28**).

Evaluation of Aquifer Hydraulic Parameters From Well Pumping Tests

Most wells discharge at a rate between six and 30 gallons per minute (25^{th} and 90^{th} percentile, respectively) (**Figure 29**). Elevated discharge rates appear primarily in the southeastern half of the Cisco Group outcrop, far eastern Wichita Group, irregularly throughout the Strawn Group, and in the vicinity of Possum Kingdom Reservoir, where limestone strata of the Canyon Group (Winchell and Ranger Limestone) appear to be in hydraulic communication with the Brazos River. Some wells have elevated discharge rates — 750 gpm (maximum), 40 gpm (95^{th} percentile), and 90 gpm (99^{th} percentile) — which are most likely wells with dual completion in the Paleozoic and Trinity aquifer. Wells in the database were selected based on screen interval and our geologic model to be completed in Paleozoic strata; however, uncertainties may have included some wells in the Trinity aquifer footprint to be included that are screened across homogeneous, indistinguishable sands at the base of the Trinity and top of the Paleozoic.

Specific capacity results highest overall in the Strawn Group. Isolated, elevated specific capacity regions are also found in Canyon Group limestone, portions of the Cisco Group, and western Wichita Group (**Figure 30**). Transmissivity values are variable across the study area, but are high in the Strawn Group, portions of the Canyon Group, and also the southeast outcrop area of the Cisco Group and easternmost Wichita Group (**Figure 31**). Hydraulic conductivity appears relatively homogeneous when presented in the log scale (**Figure 32**). Median log transmissivity value for all four groups is 1.1 (**Table 4**). Strawn Group has the highest median value of log transmissivity (1.4), followed by Canyon (1.3), Wichita (1.1), and Cisco (1.0). However, given the uncertainties in our analysis, the results suggest a relatively homogeneous spatial distribution of relatively low transmissivity across the study area. Median log hydraulic conductivity for all four groups is around -0.2 (**Table 6**). Strawn Group has the highest median value of log hydraulic conductivity (0.41), followed by Canyon (0.31), Wichita (0.45), and Cisco (0.42). As with transmissivity, hydraulic conductivity values are generally uniform, with all wells between 25th and 90th percentile within two log cycles.

CONCLUSIONS

Despite heterogeneity in Paleozoic aquifer surface and subsurface sand distribution, hydraulic properties of wells in our database are remarkably uniform (and also meager, when compared to the Trinity aquifer). Transmissivity and hydraulic conductivity values for 25^{th} to 90^{th} percentile wells are within two log cycles. Well discharge rates are generally low, but typical for domestic wells (25^{th} to 90^{th} percentile wells range from six to 30 gpm). Wells with discharge rate greater than 40 gpm (95^{th} percentile) are possible completed in both Trinity and Paleozoic aquifers, reflecting uncertainties in our geologic model and also screen length assumption of 35 feet for wells lacking these data. Other high-discharge wells are completed in Canyon Group limestone strata around Possum Kingdom Reservoir, suggesting hydraulic communication with Brazos River in these wells. Elsewhere in the study area, wells are not typically completed in limestone. Future hydraulic fracturing wells should have a screen length longer than the median value of 35 feet in order to produce sufficient water. Groundwater quality in wells completed in the first 300 feet is generally potable (90^{th} percentile well depth of around 370 feet). However, groundwater salinity increases rapidly downdip to >100,000 mg/L TDS, suggesting limited recharge and poor hydraulic communication of deep sand bodies with sand in outcrop. Thus, we recommend that future hydraulic fracture supply generally have a total depth less that X,XXX feet to produce groundwater of suitable quality.

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FIGURES

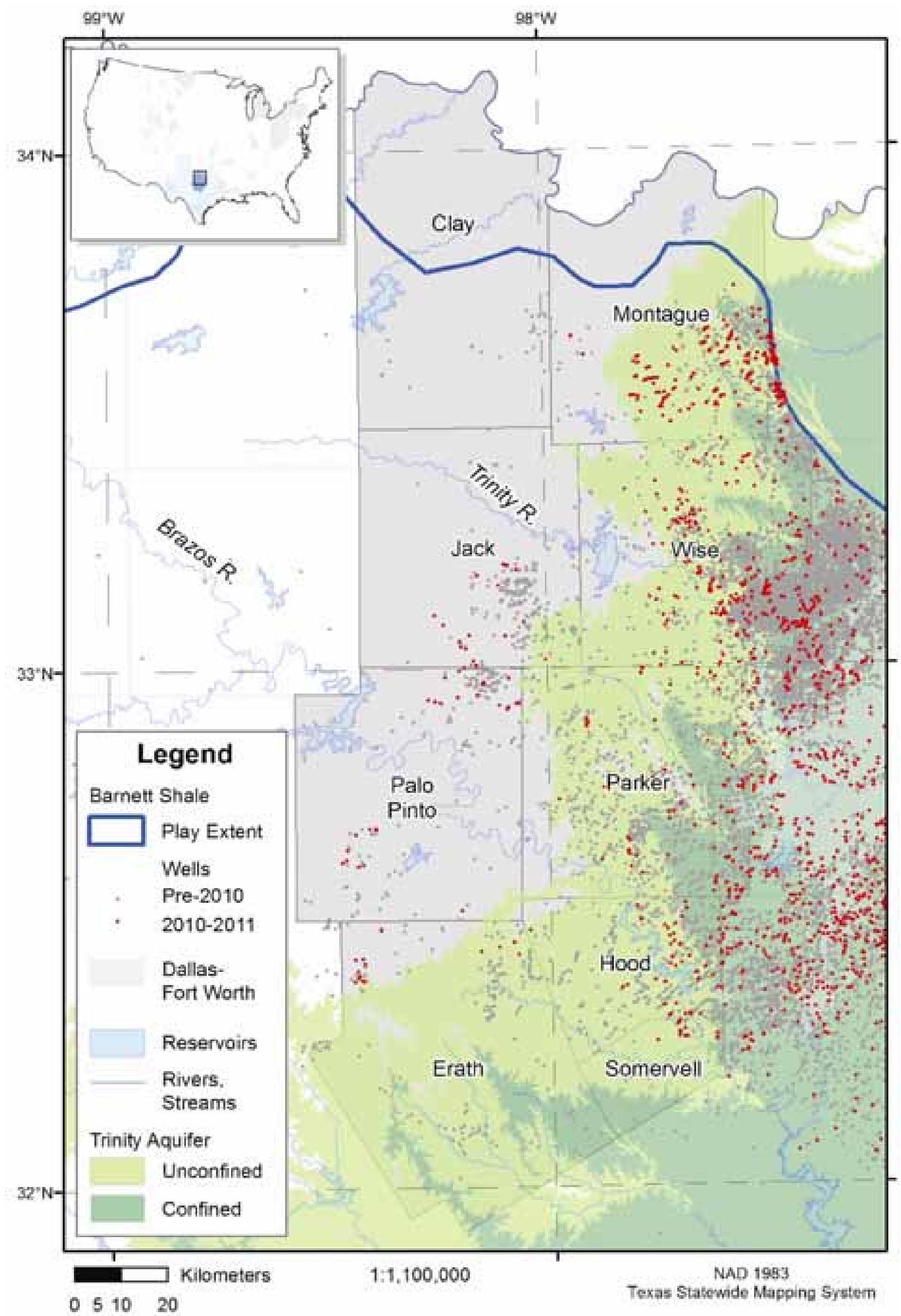

Figure 1. Regional Geologic Setting: Barnett Shale Play, Gas Well Locations, Trinity Aquifer, and Study Area Location

Barnett Shale Play wells from 1993 to 2010 (IHS Energy 2011). Inset map shows study location and unconventional shale gas plays in the United States (U.S. Energy Information Administration 2011). The study area is focused in nine county area of North Central Texas to the west of Dallas-Fort Worth.

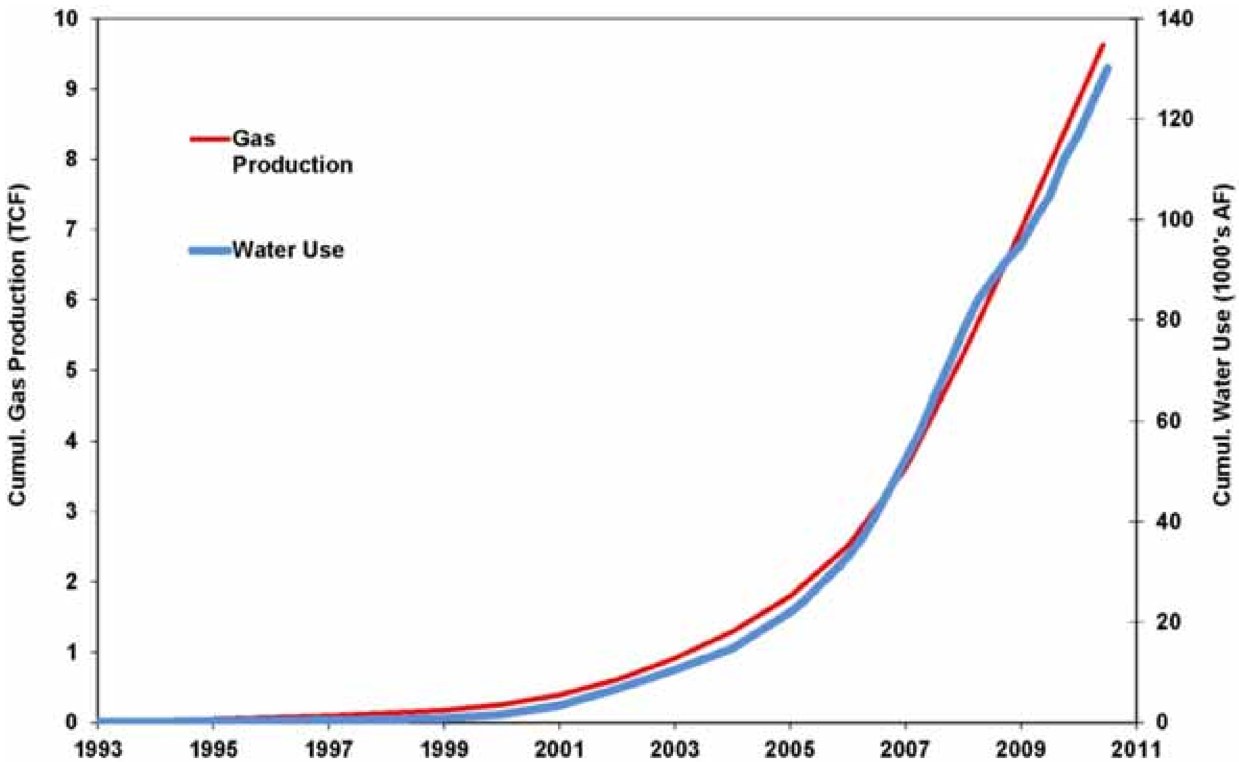

Figure 2. Barnett Shale Gas Production and Water Use: 1993 to 2011

Figure is compiled from IHS Energy (2011) and Railroad Commission of Texas (2011) databases.

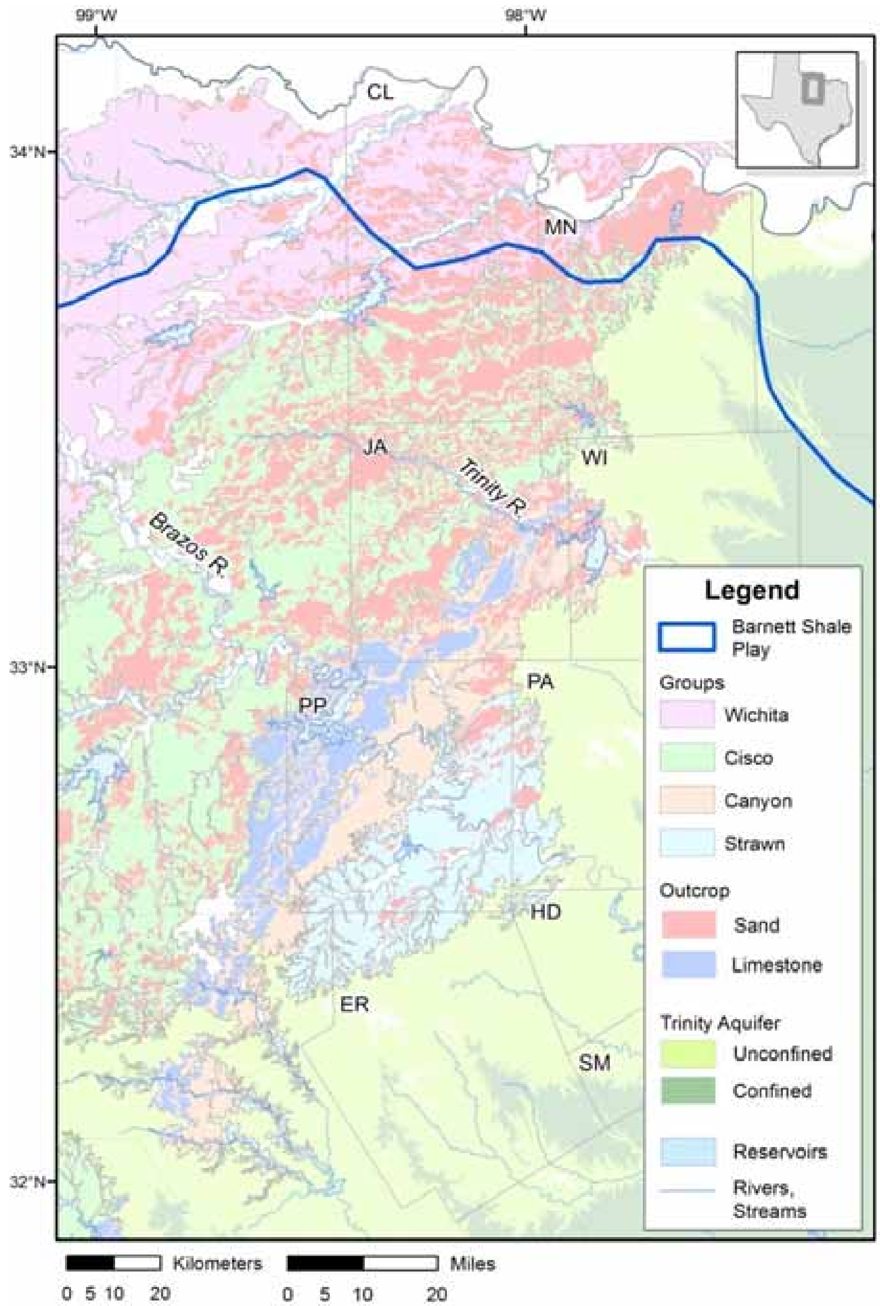

Figure 3. Geologic Map of the Study Area

Geology is compiled from digial Geologic Atlas of Texas and geologic map sheets (McGowen, Hentz et al. 1967; Barnes 1972; Hentz and Brown 1987; Pearson 2007).

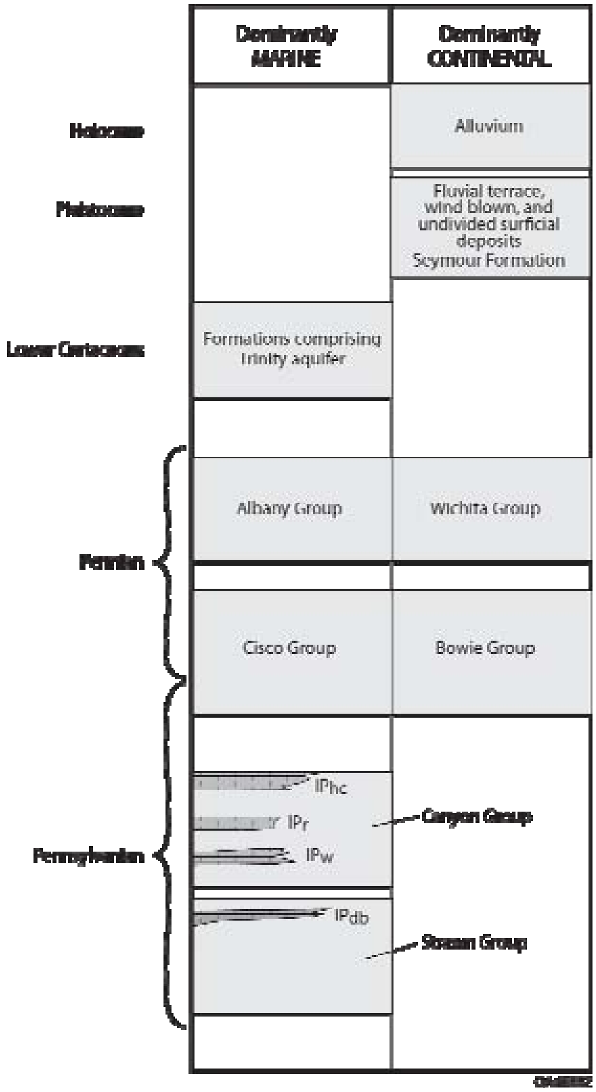

Figure 4. Generalized Chronostratigraphic Colum

Stratigraphy is synthesized from severl publications (Wermund, Jenkings et al. 1962; McGowen, Hentz et al. 1967; Wermund and Jenkings 1969; Barnes 1972; Brown, Cleaves et al. 1973; Galloway and L. Frank Brown 1973; Erxleben 1974; Cleaves 1975; Erxleben 1975; Kier, Brown et al. 1979; Brown, Solis-Iriarte et al. 1987; Hentz and Brown 1987; Hentz 1988; Jones and Hentz 1988; Brown, Solis-Iriarte et al. 1990; Bradshaw and Mazzullo 1996; Brown, Ambrose et al. 2009) . $|P_{hc}$ is Home Creek Limestone, $|P_r$ is Ranger Limestone, $|P_w$ is Winchell Limestone, and $|P_{db}$ is Dog Bend Limestone.

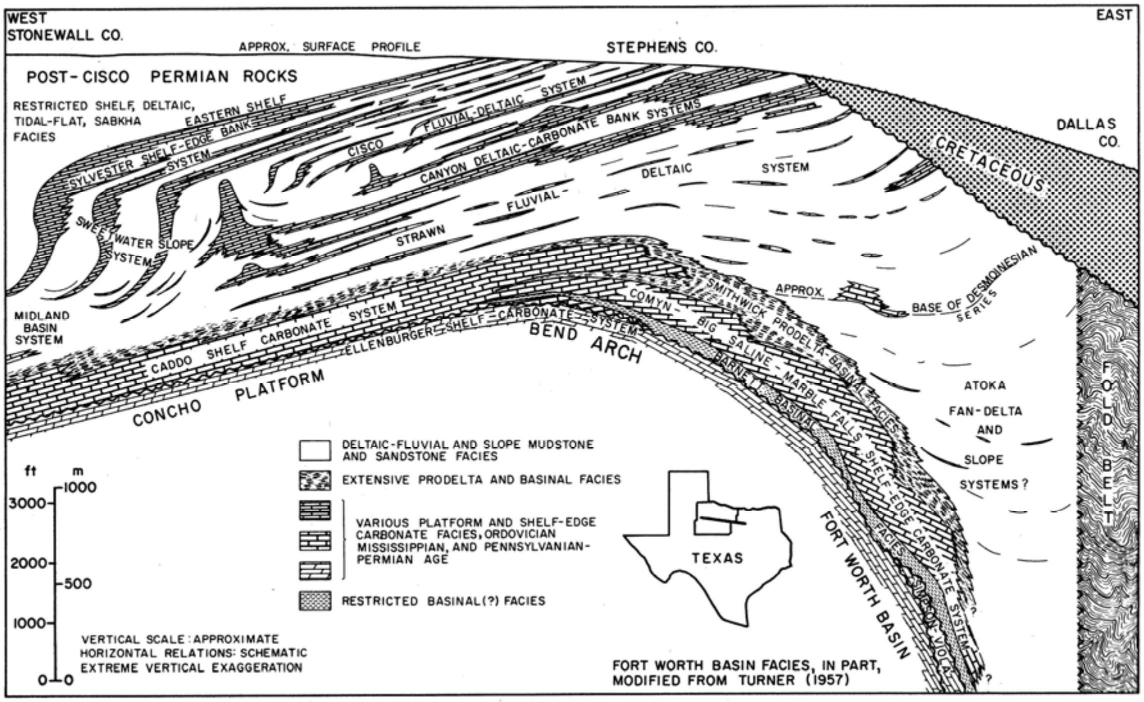

Figure 5. Generalized Depositional Systems Tracts of North Central Texas

The Paleozoic of North Central Texas is comprised of four generalized groups: Strawn Group, Canyon Group, Cisco Group, and post-Cisco Permian rocks of the Wichita Group (Brown, Cleaves et al. 1973).

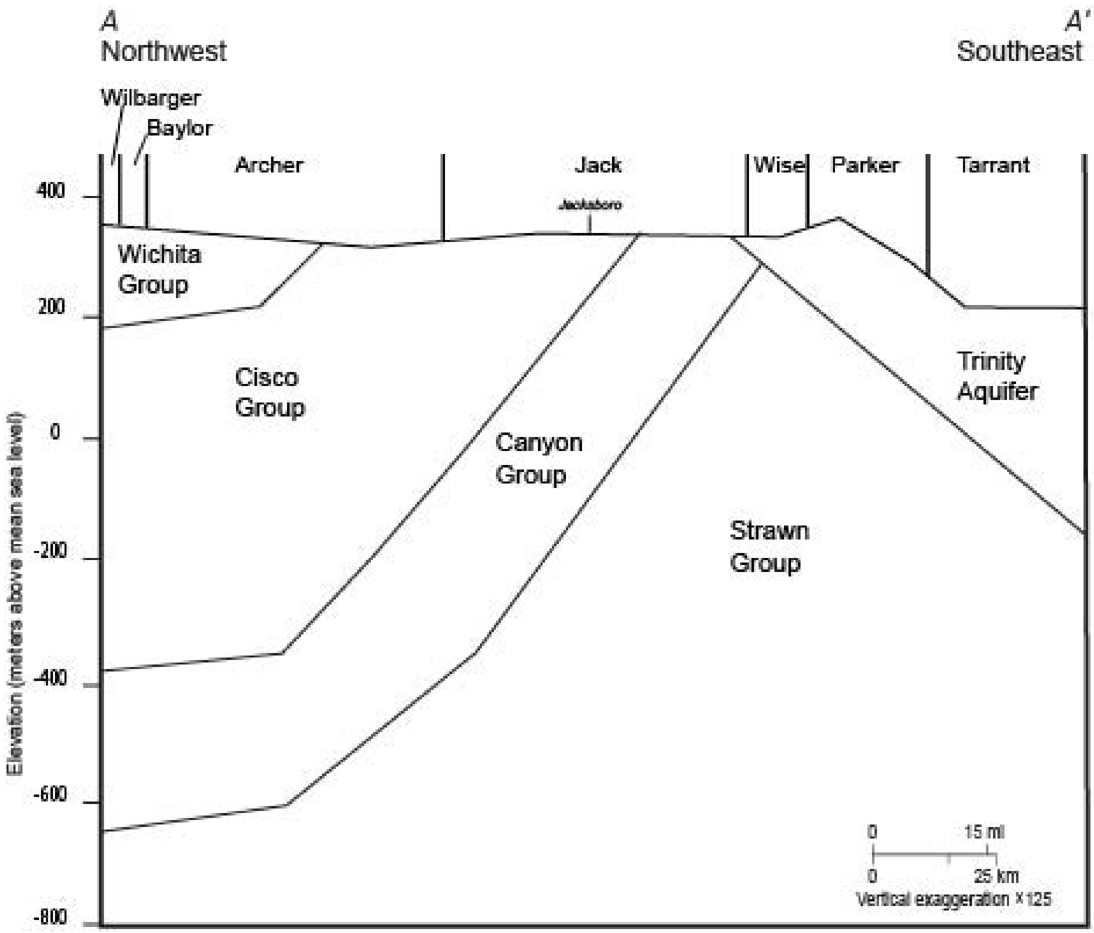

Figure 6. Hydrogeologic Cross Section A-A'

Cross section is a synthesis of existing outcrop and subsurface data (Wermund, Jenkings et al. 1962; Wermund and Jenkings 1969; Erxleben 1974; Cleaves 1975; Erxleben 1975; Nordstrom 1982; Hentz 1988; Brown, Solis-Iriarte et al. 1990; Pearson 2007; U.S. Geological Survey 2011).

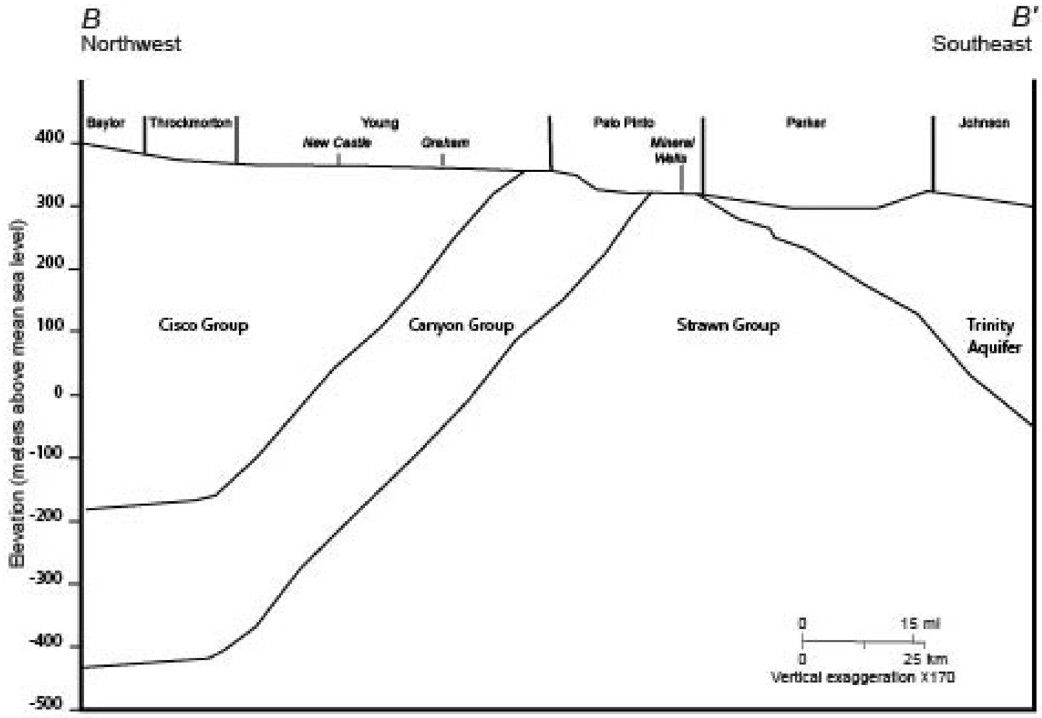

Figure 7. Hydrogeologic Cross Section B-B'

Cross section is a synthesis of existing outcrop and subsurface data (Wermund, Jenkings et al. 1962; Wermund and Jenkings 1969; Erxleben 1974; Cleaves 1975; Erxleben 1975; Nordstrom 1982; Hentz 1988; Brown, Solis-Iriarte et al. 1990; Pearson 2007; U.S. Geological Survey 2011).

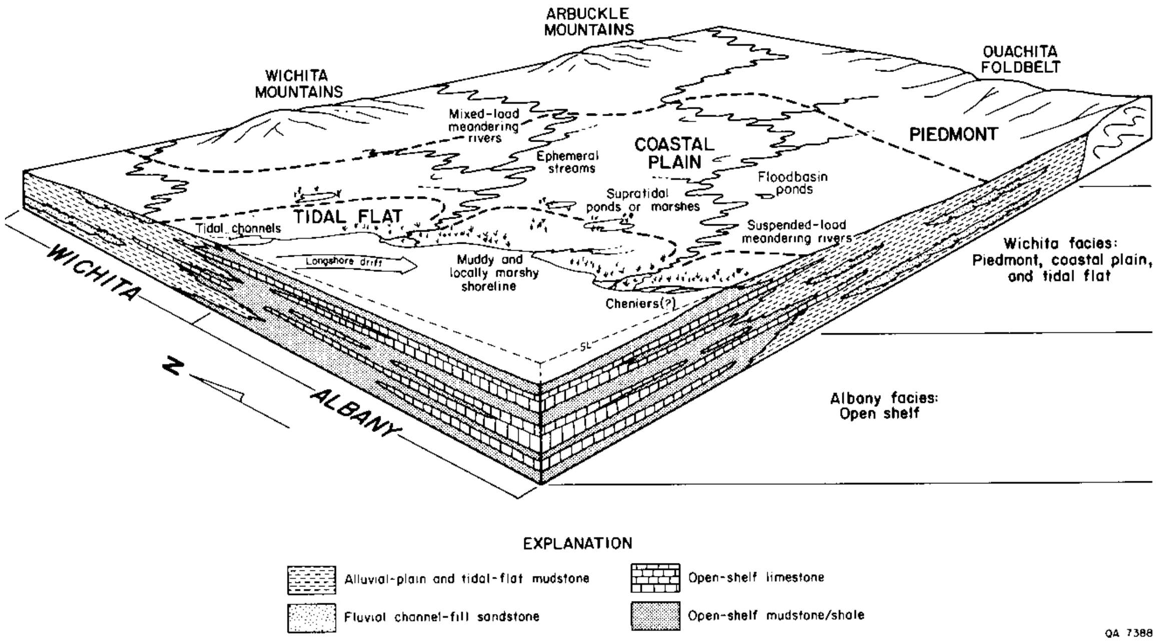

Figure 8. Schematic Paleoenvironment of Wichita and Albany Groups

Wichita Group was deposited in prodominantly in fluvial settings of piedmont and coastal plain and Albany Group was deposited in predominantly marine tidal flats (Hentz 1988).

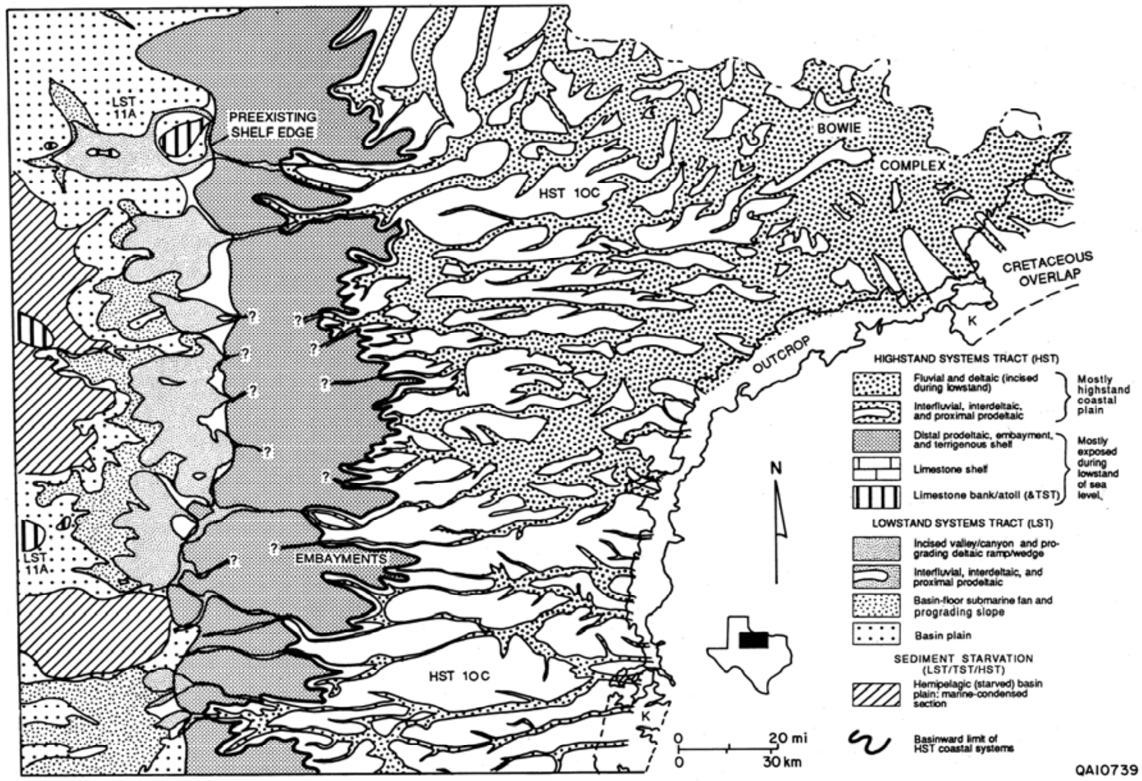

Figure 9. Generalized Depositional Systems Cisco Group

Cisco Group is comprised of highly heterogeneous sandstone and shale deposited in prodominantly marine, fluvial-delatic settings with sediment sourced from the Ouachita and Arbuckle Mountains and deposited on the Eastern Shelf of the Permian Basin (Brown, Solis-Iriarte et al. 1990).

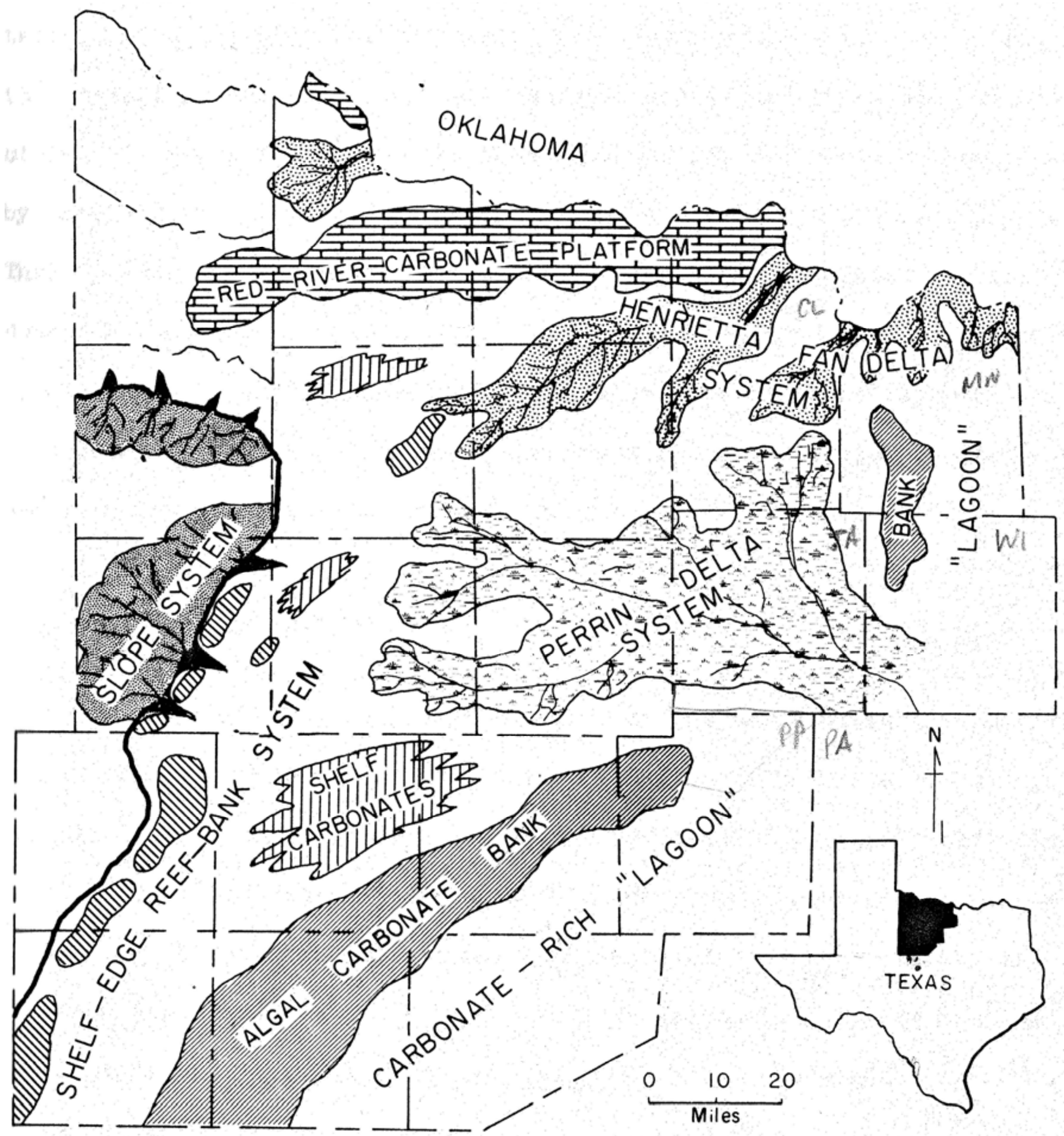

Figure 10. Generalized Depositional Systems of Canyon Group

Canyon Group is a prodominantly marine, fluvial-delatic and carbonate bank setting resulting from a reduced sediment input sourced from the Ouachita and Arbuckle Mountains comprised of heterogeneous sandstone and siltstone, in addition to limestone beds (Erxleben 1974; Erxleben 1975).

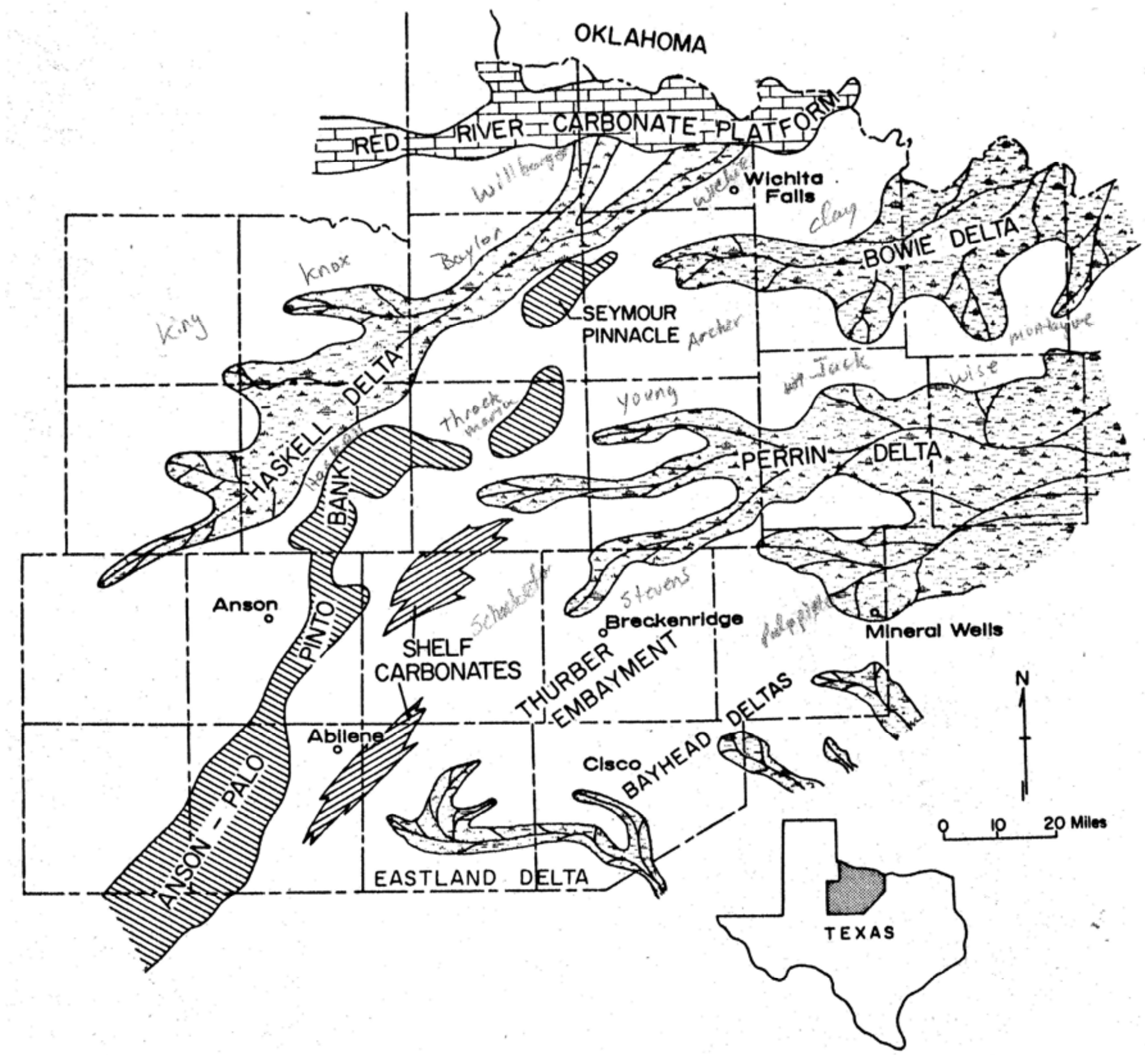

Figure 11. Generalized Depositional Systems of Strawn Group

Similarly to the Cisco Group, the Strawn Group is comprised of highly heterogeneous sandstone and shale deposited in prodominantly marine, fluvial-delatic settings with sediment sourced from the Ouachita and Arbuckle Mountains and deposited on the Eastern Shelf of the Permian (Cleaves 1975).

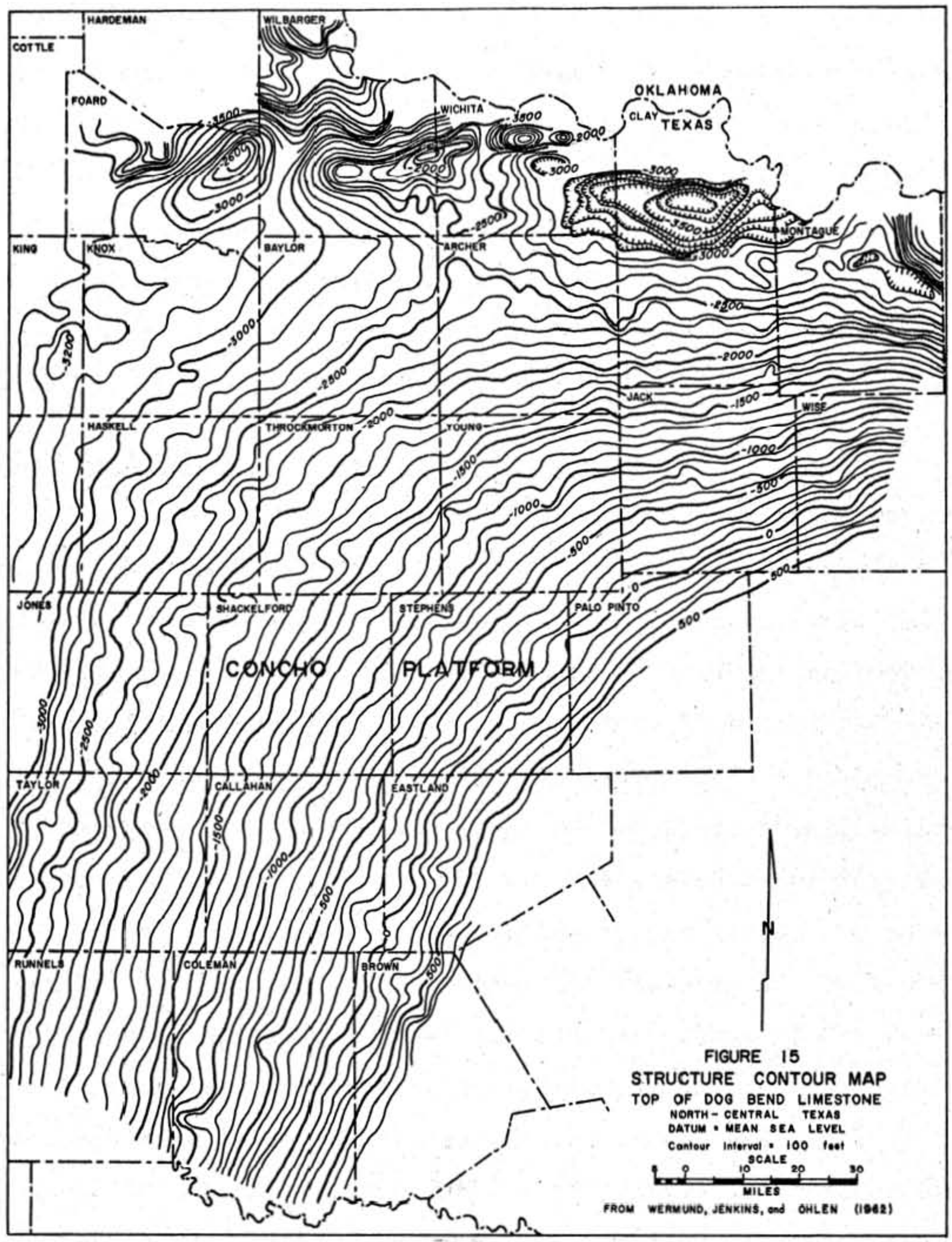

Figure 12. Structural Contour Map of the Dog Bend Limestone

The Dog Bend Limestone is used to delineate the upper Strawn Group. Figure after Wermund et al. (1962).

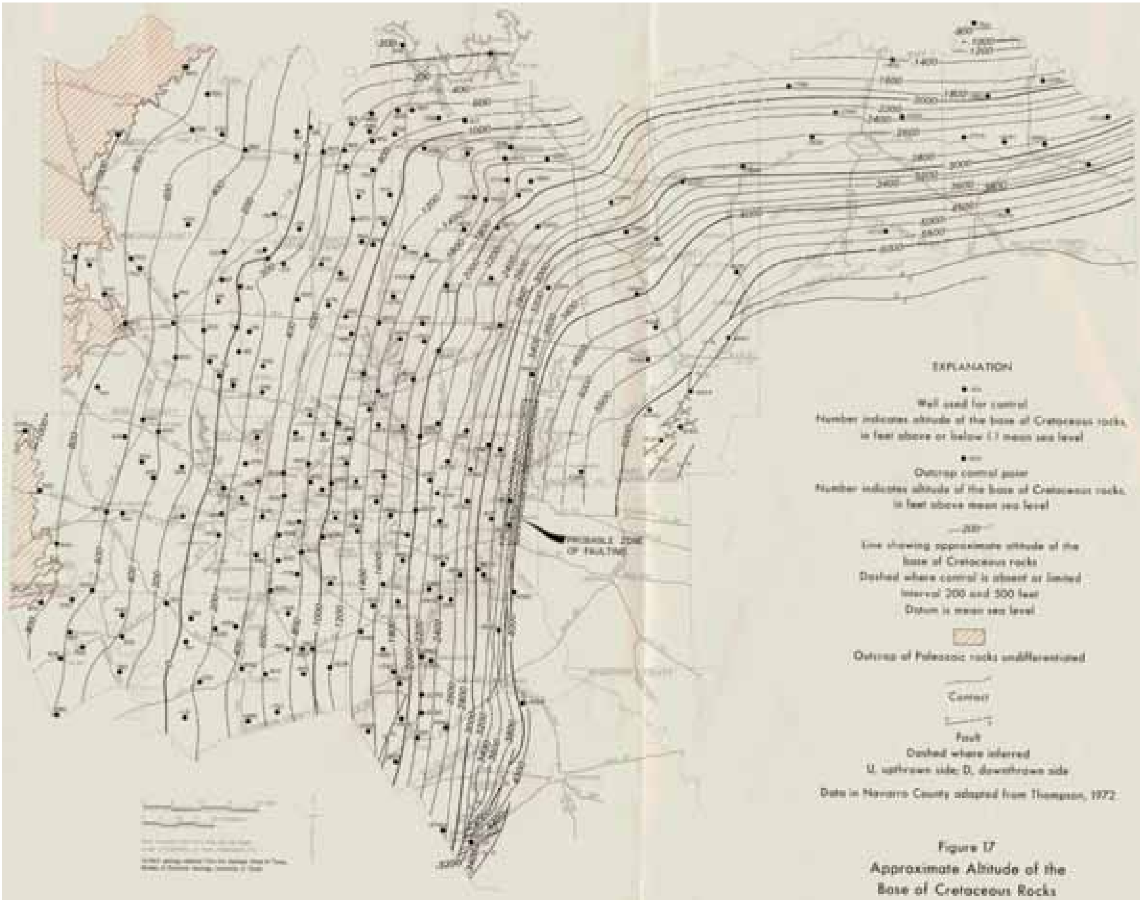

Figure 13. Approximate Altitude of the Base of Cretaceous Rocks

The base of the Cretaceous (i.e., Trinity aquifer) is used to infer the top of the Strawn, Canyon, and Cisco Groups where overlain by Trinity Aquifer. Figure after (Nordstrom 1982).

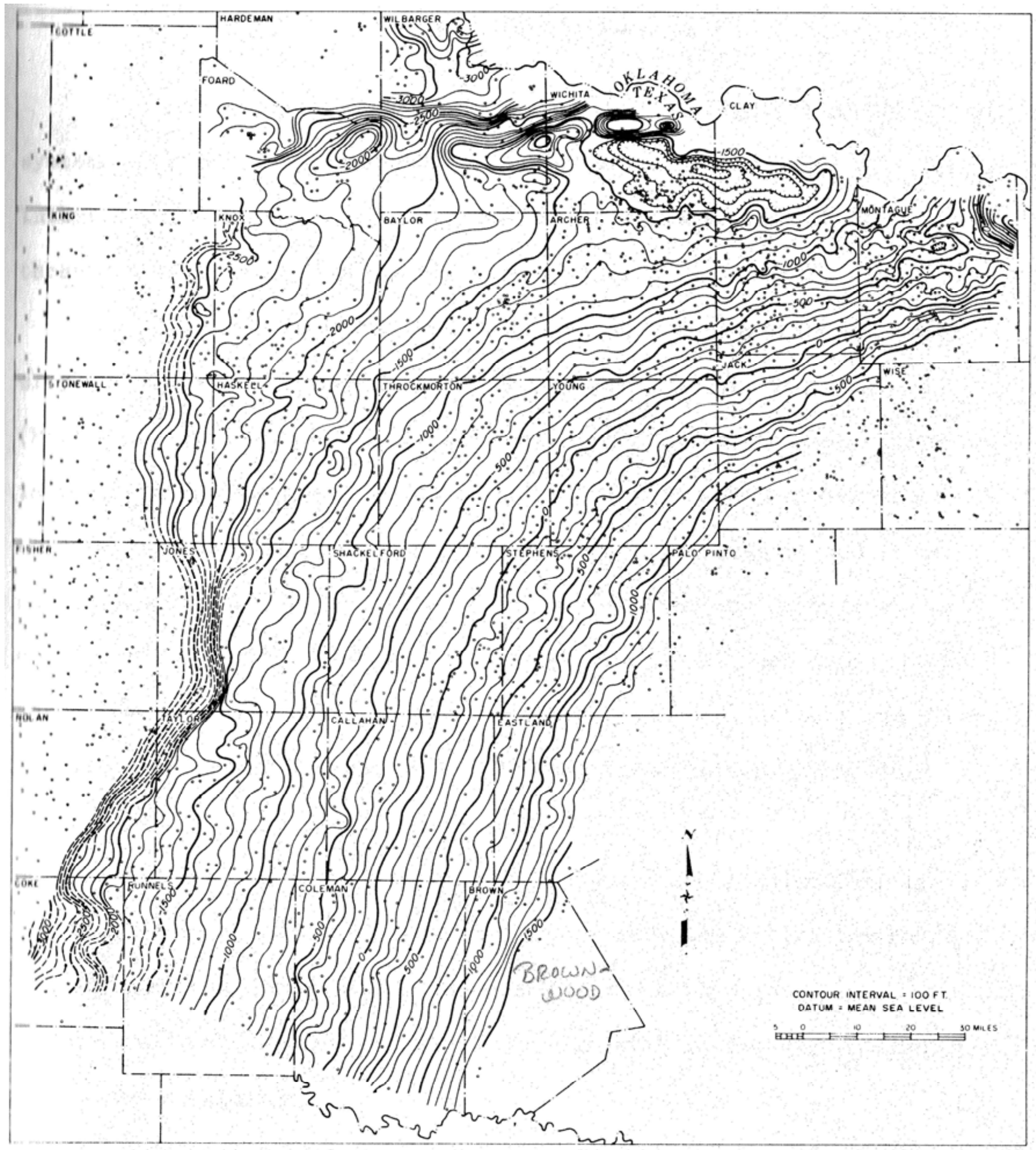

Figure 14. Structural Contour Map of Home Creek Limestone

The Home Creek Limestone is used to delineate top of the Canyon Group. Figure after Wermund and Jenkins (1969).

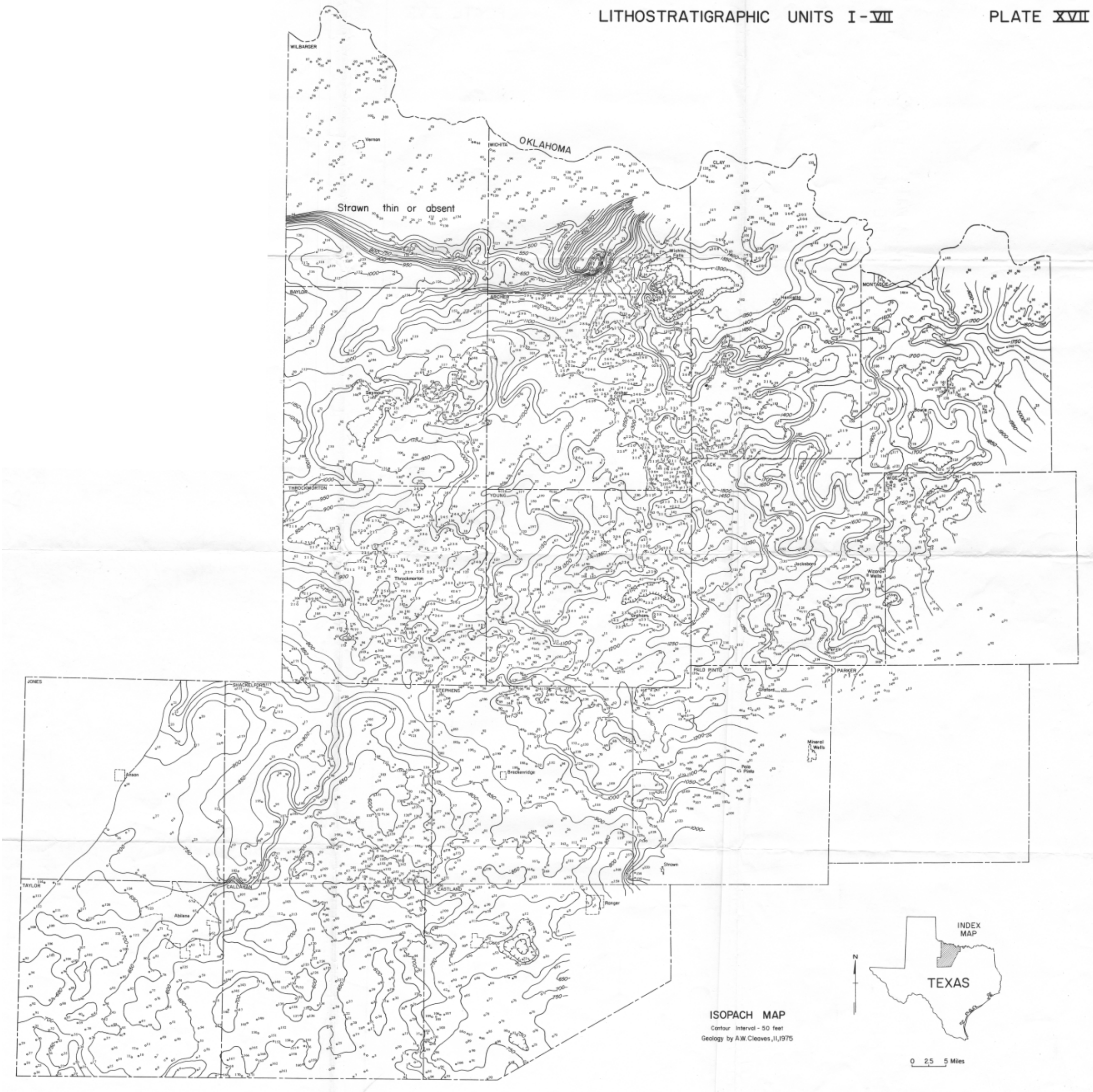

Figure 15. Subsurface Sand Distribution: Strawn Group

Net sand map for the Strawn Group after Cleaves (1975).

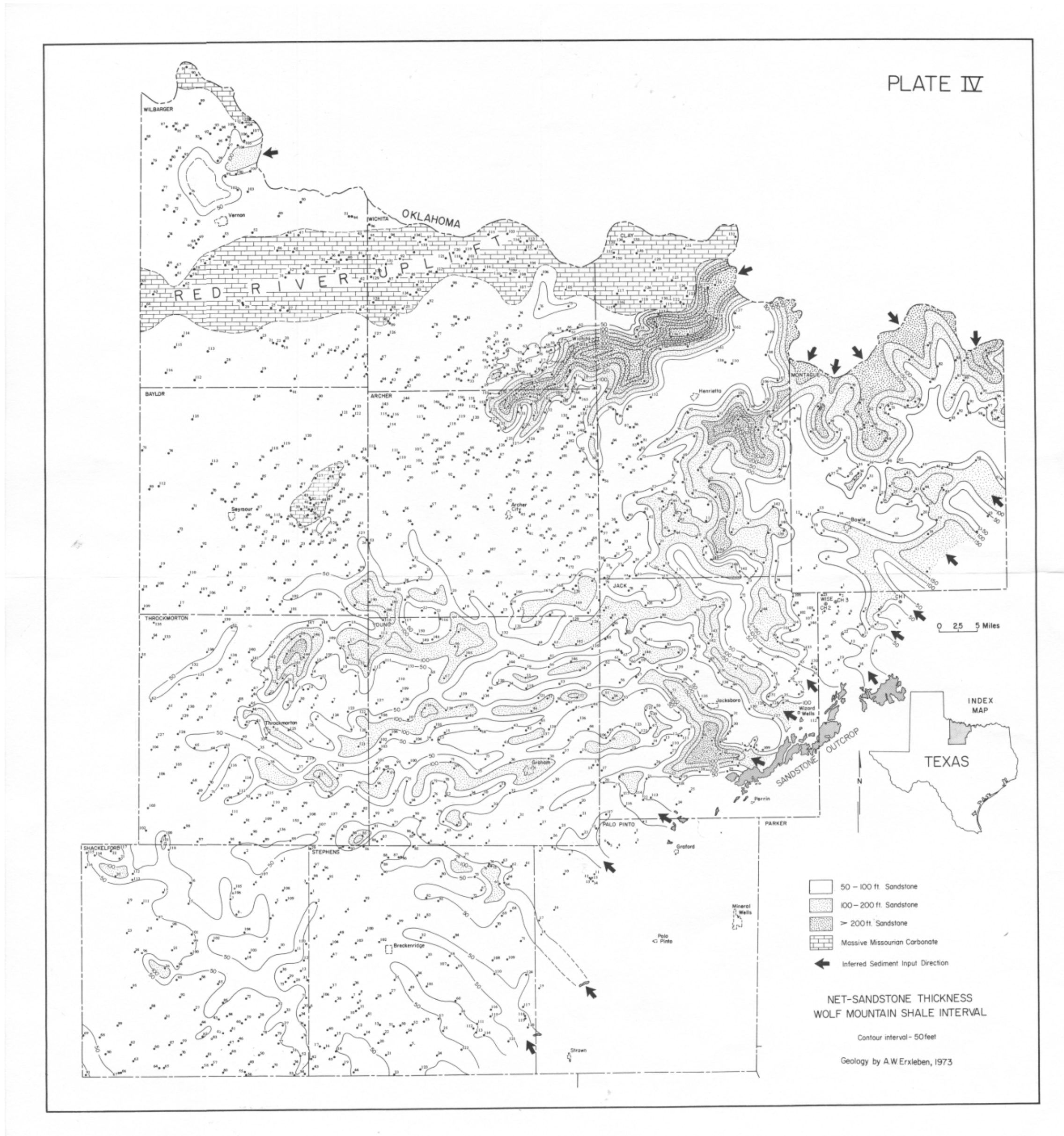

Figure 16. Representative Subsurface Sand Distribution: Canyon Group

Net sand map for one of three sandstone intervals of the Canyon Group after Erxleben (1975).

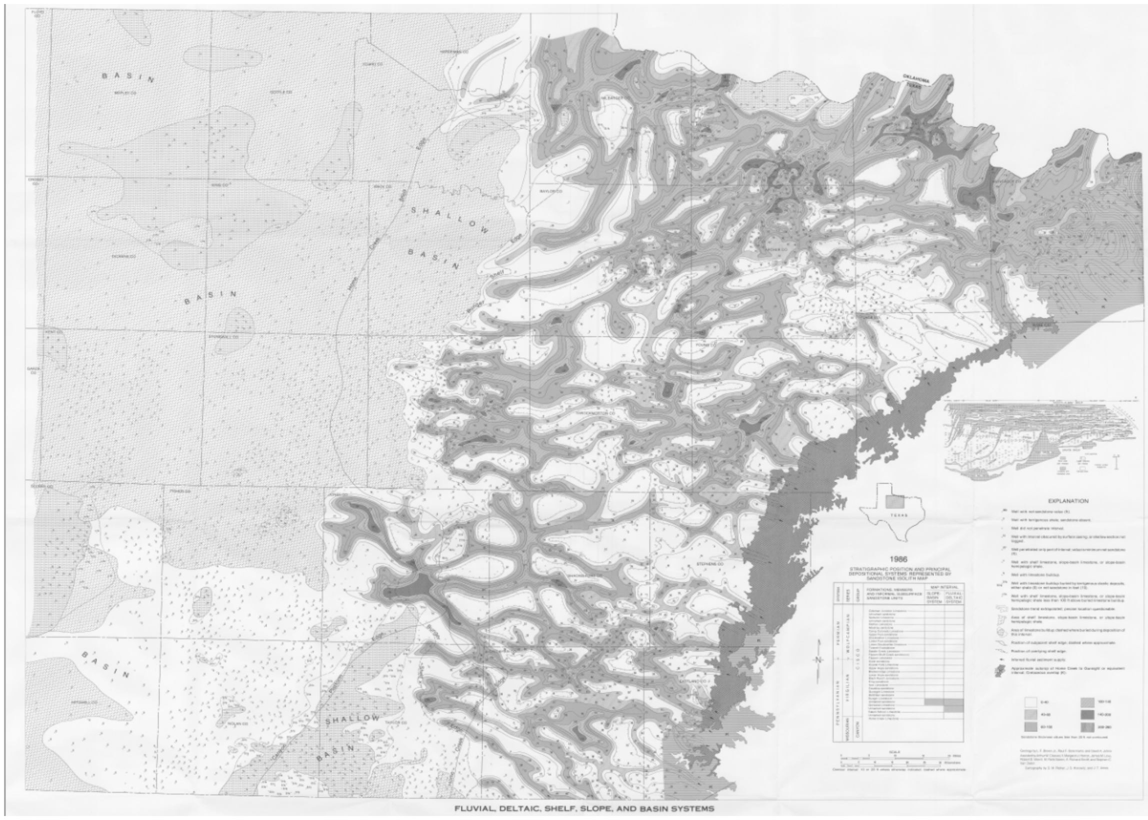

Figure 17. Representative Subsurface Sand Distribution: Cisco Group

Net sand map for one of sixteen sandstone intervals of the Cisco Group (from the sandstone-rich lower Cisco Group) after Brown (1990).

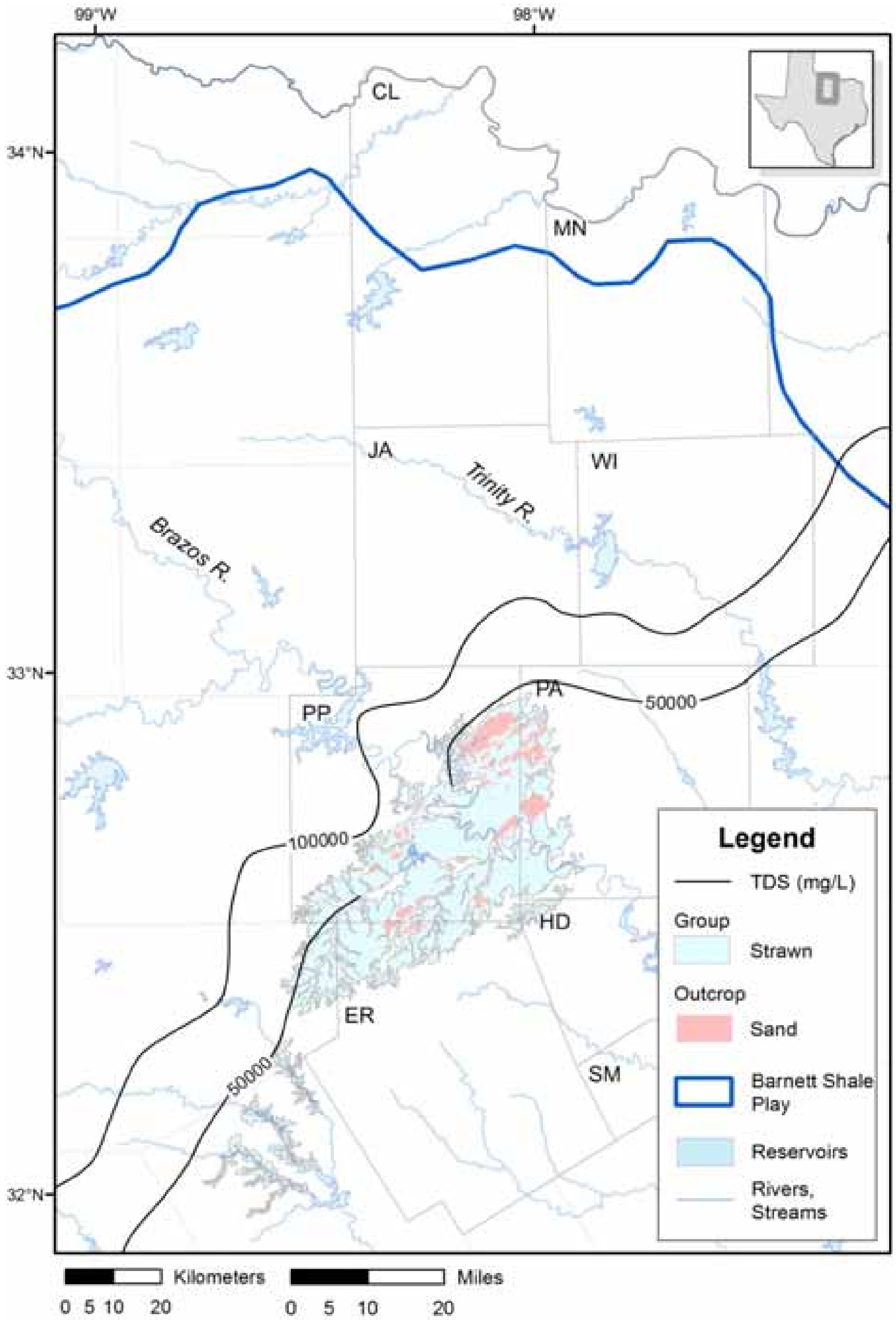

Figure 18. Groundwater Total Dissolved Solids: Strawn Group

Groundwater salinity from Texas Water Development Board (1972).

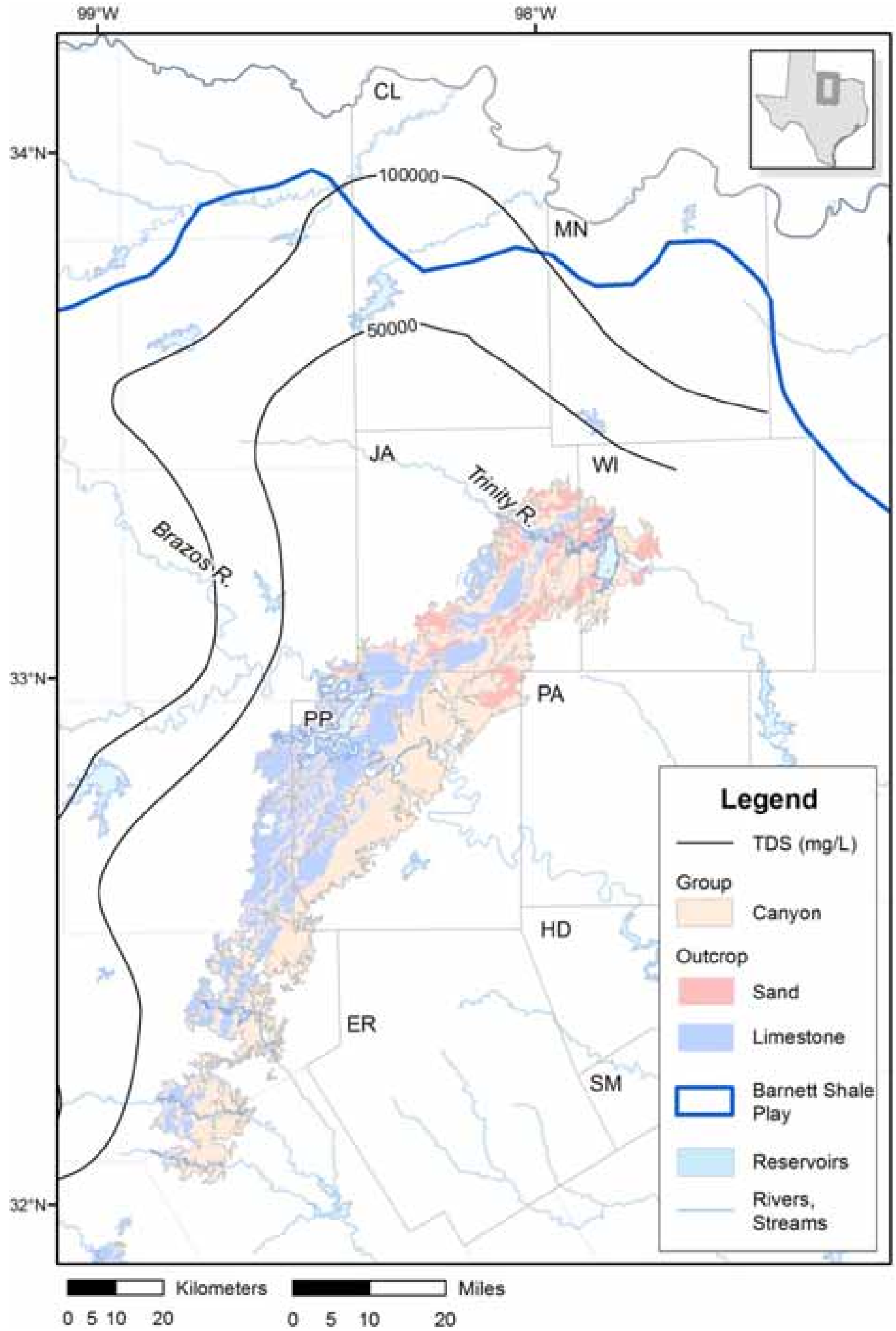

Figure 19. Groundwater Total Dissolved Solids: Canyon Group

Groundwater salinity from Texas Water Development Board (1972).

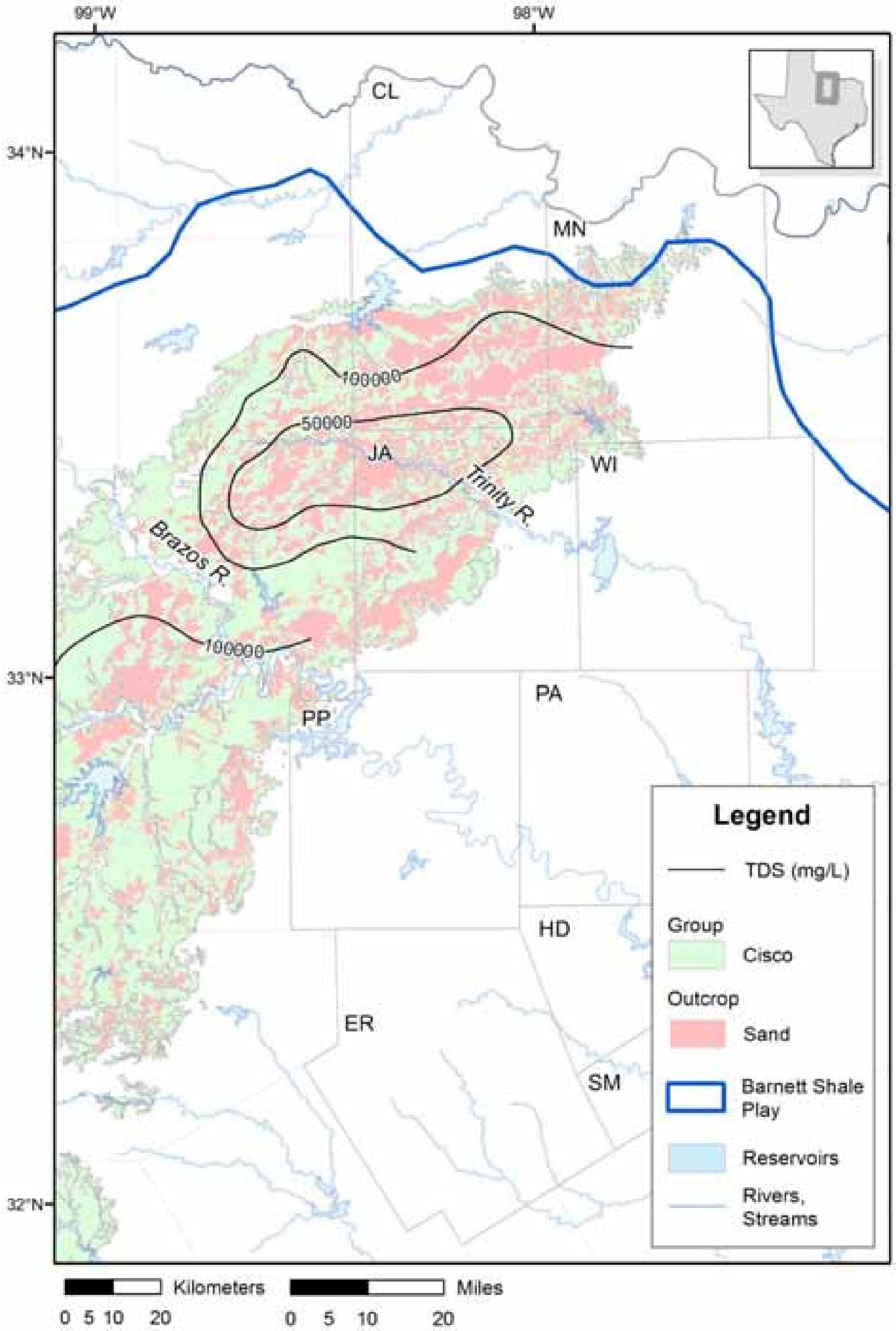

Figure 20. Groundwater Total Dissolved Solids: Cisco Group

Groundwater salinity from Texas Water Development Board (1972).

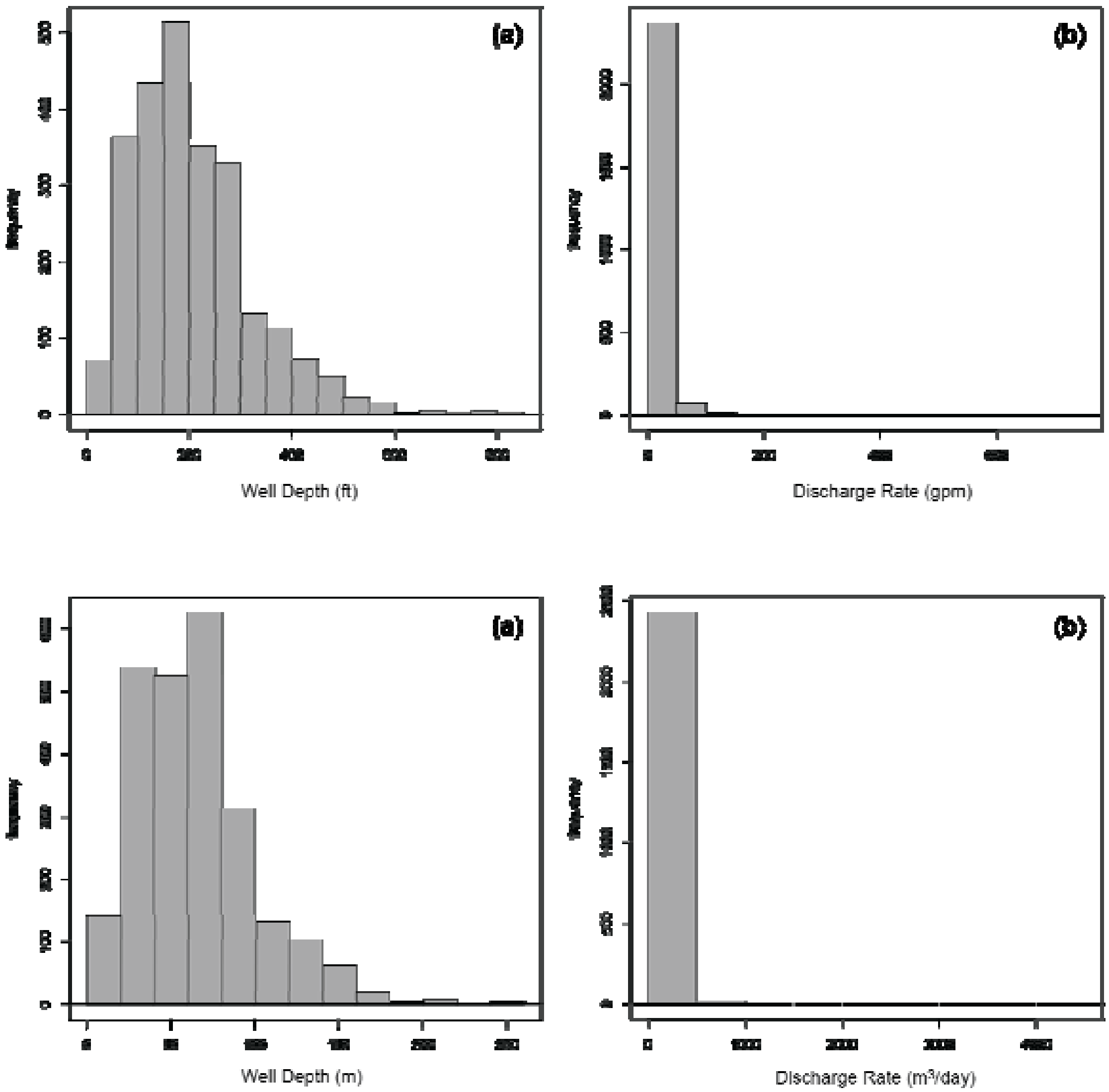

Figure 21. General Characteristics of Well Depth and Discharge Rate

(a) Well depth, (b) Discharge rate; in english and SI units

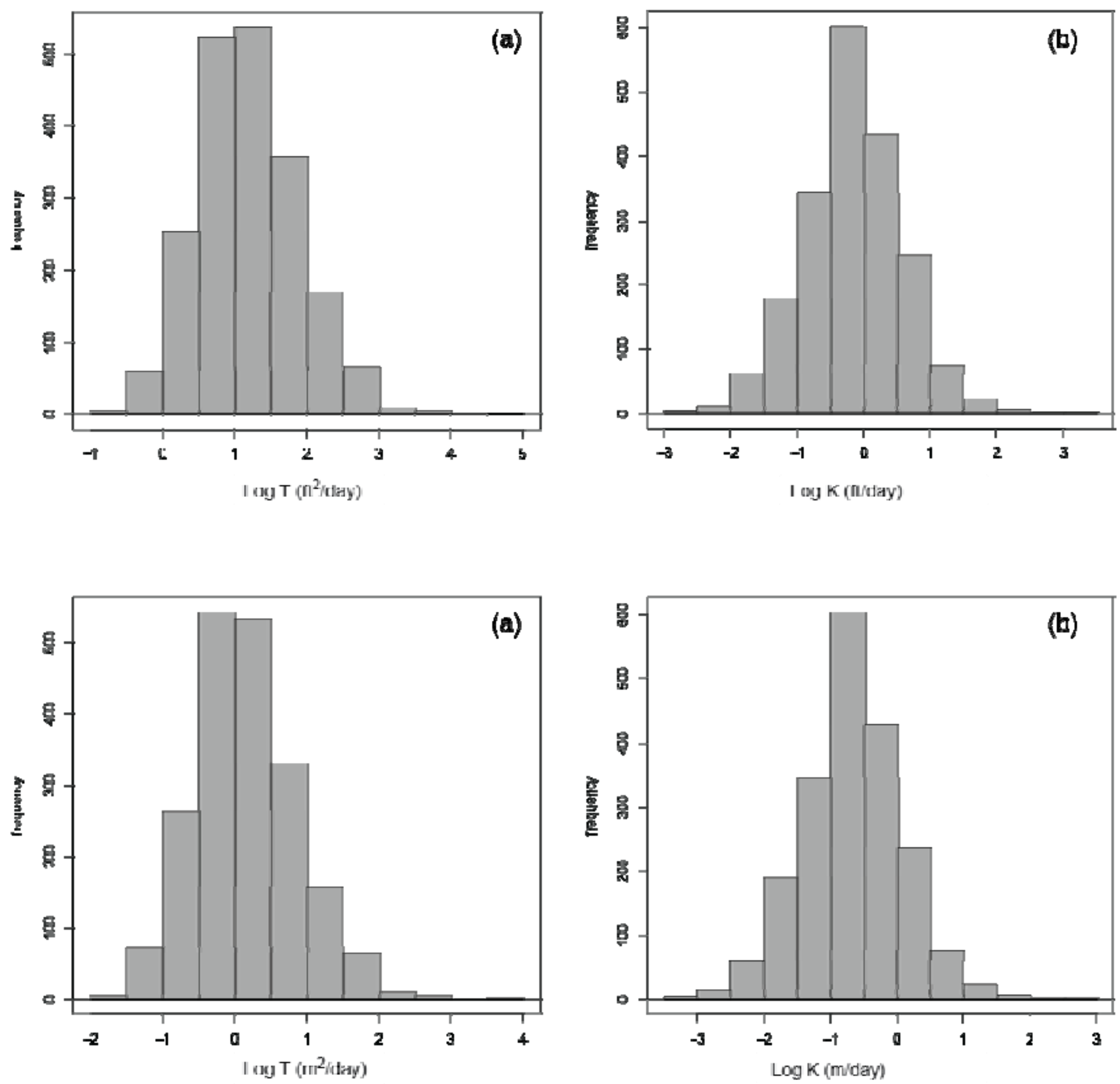

Figure 22. General Characteristics of Transmissivity and Hydraulic Conductivity

(a) Transmissivity, (b) Hydraulic conductivity; in english and SI units

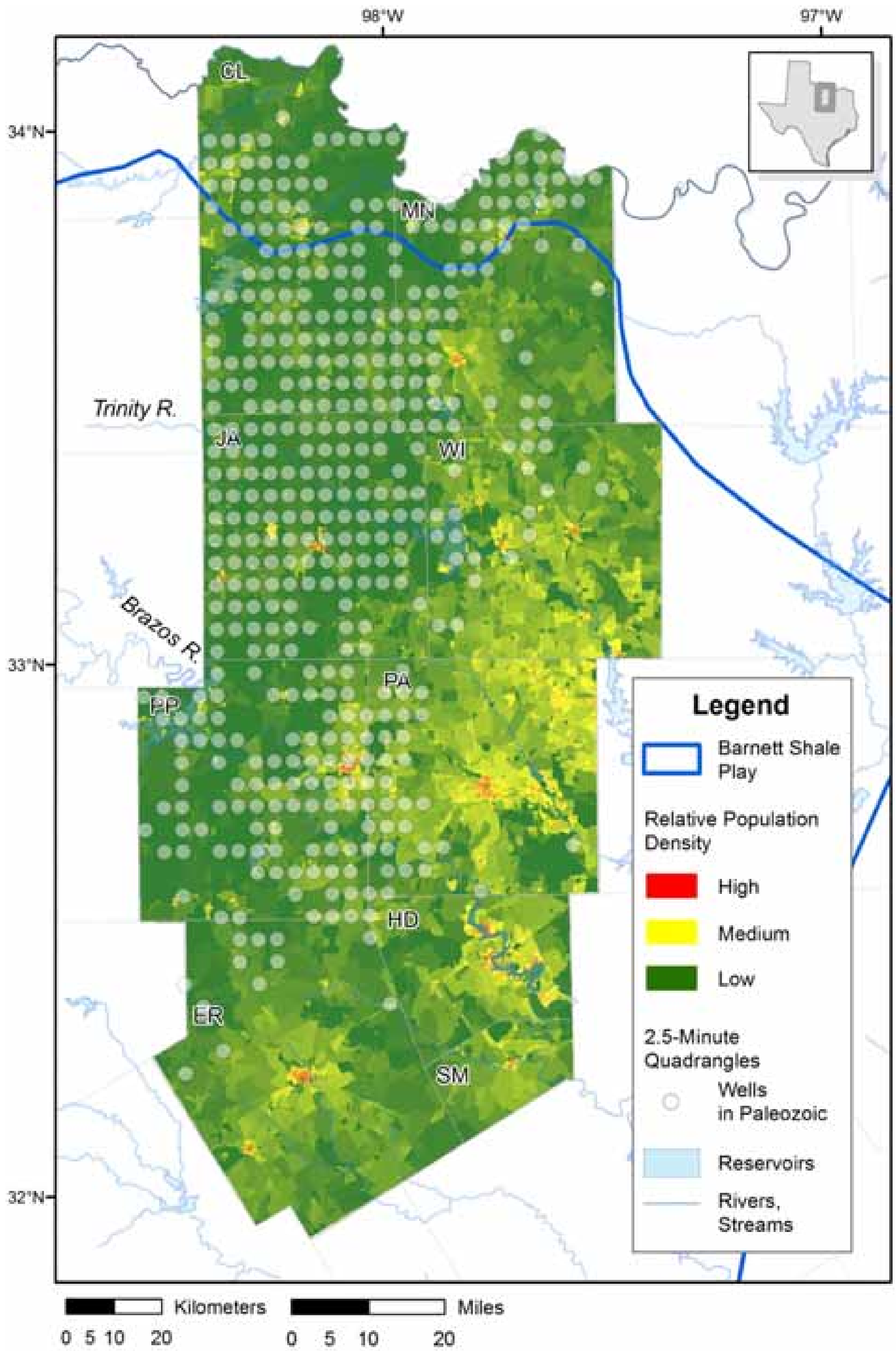

Figure 23. Population Density and Quadrangles with Paleozoic Wells

Population density data are from U.S. Census Bureau (2000).

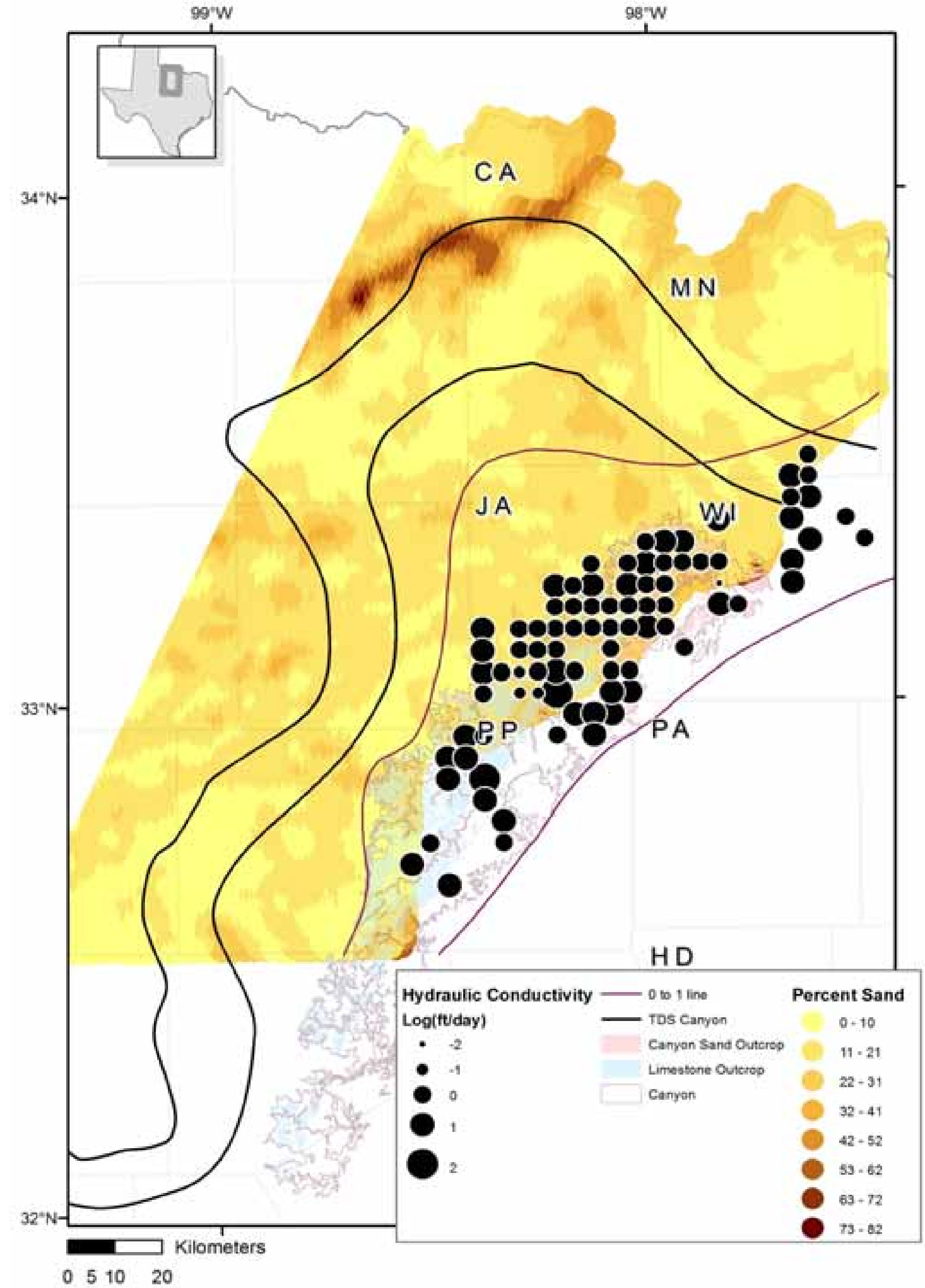

Figure 24. Interpolation Method for Hydraulic Conductivity

Zero and one lines reflect spatial distribution of groundwater salinity from Texas Water Development Board (1972) and outcrop from (Pearson 2007).

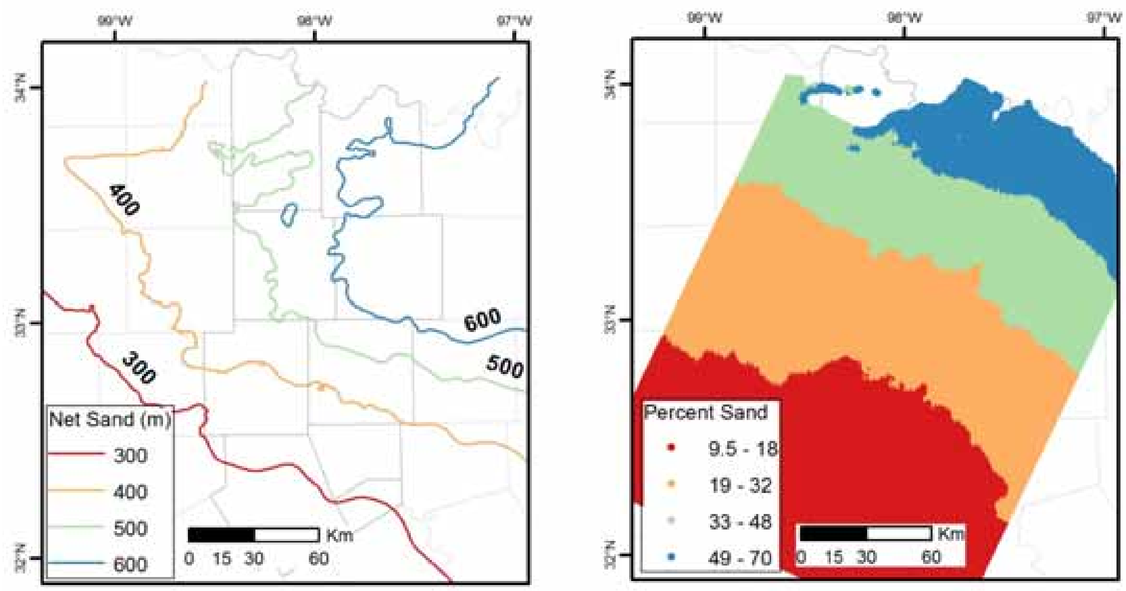

Figure 25. Subsurface Sand Distribution: Strawn Group

(A) Net sand thickness, (B) Sand fraction. Net sand thickness indicated by countours from Cleaves (1975). Sand fraction is net sand thickness divided by layer thickness.

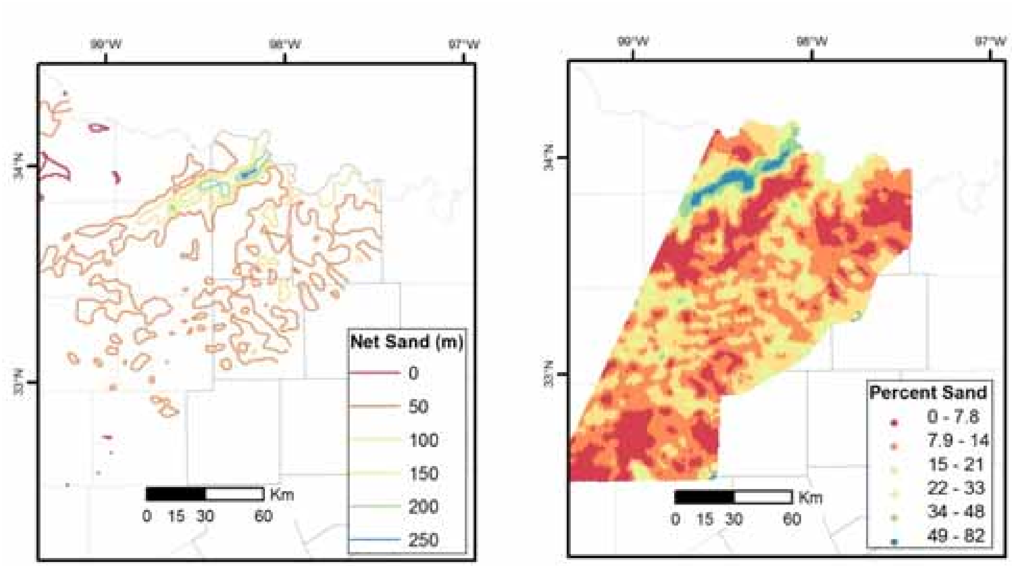

Figure 26. Subsurface Sand Distribution: Canyon Group

(A) Net sand thickness, (B) Sand fraction. Net sand thickness indicated by countours from Erxleben (1975). Sand fraction is net sand thickness divided by layer thickness.

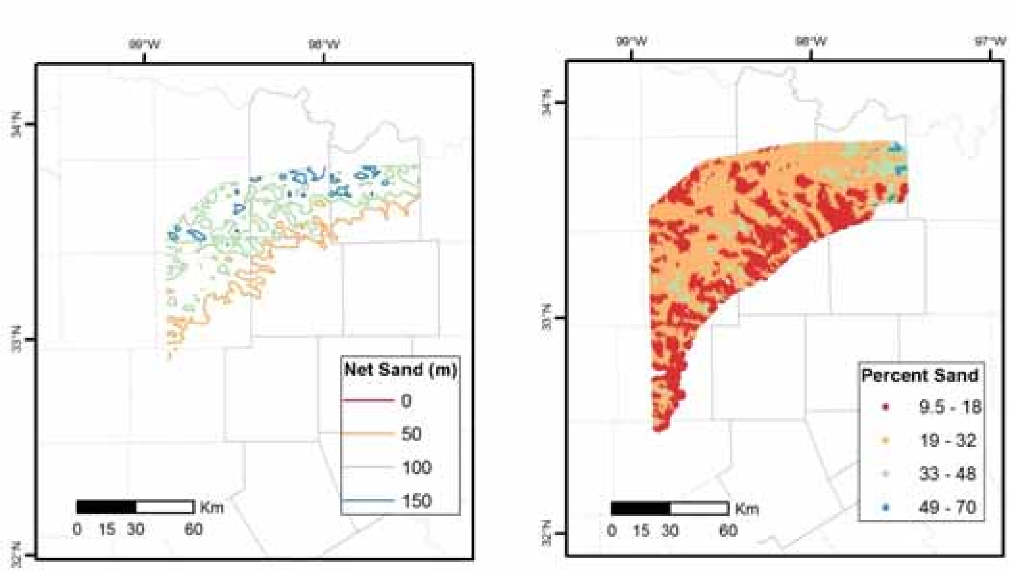

Figure 27. Subsurface Sand Distribution: Cisco Group

(A) Net sand thickness, (B) Sand fraction. Net sand thickness indicated by countours from Brown (1990). Sand fraction is net sand thickness divided by layer thickness.

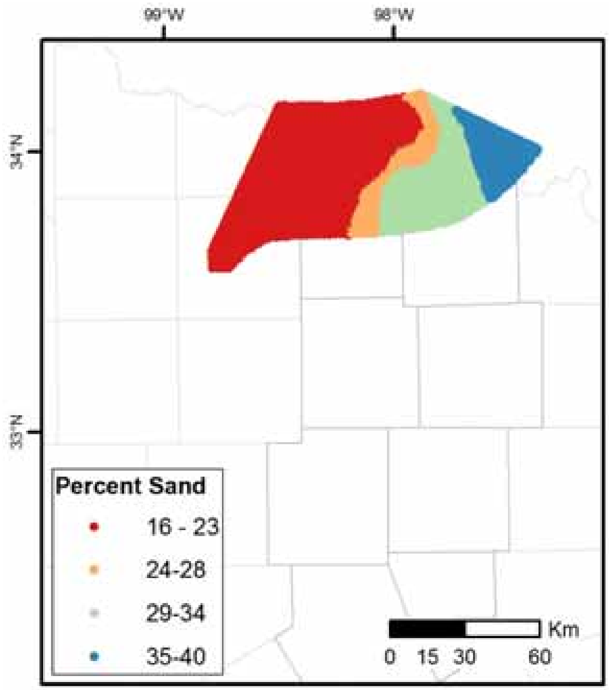

Figure 28. Subsurface Sand Distribution: Wichita Group

Sandstone net sand maps are not available for the Wichita Group. Sand fraction estimated following Hentz (1988).

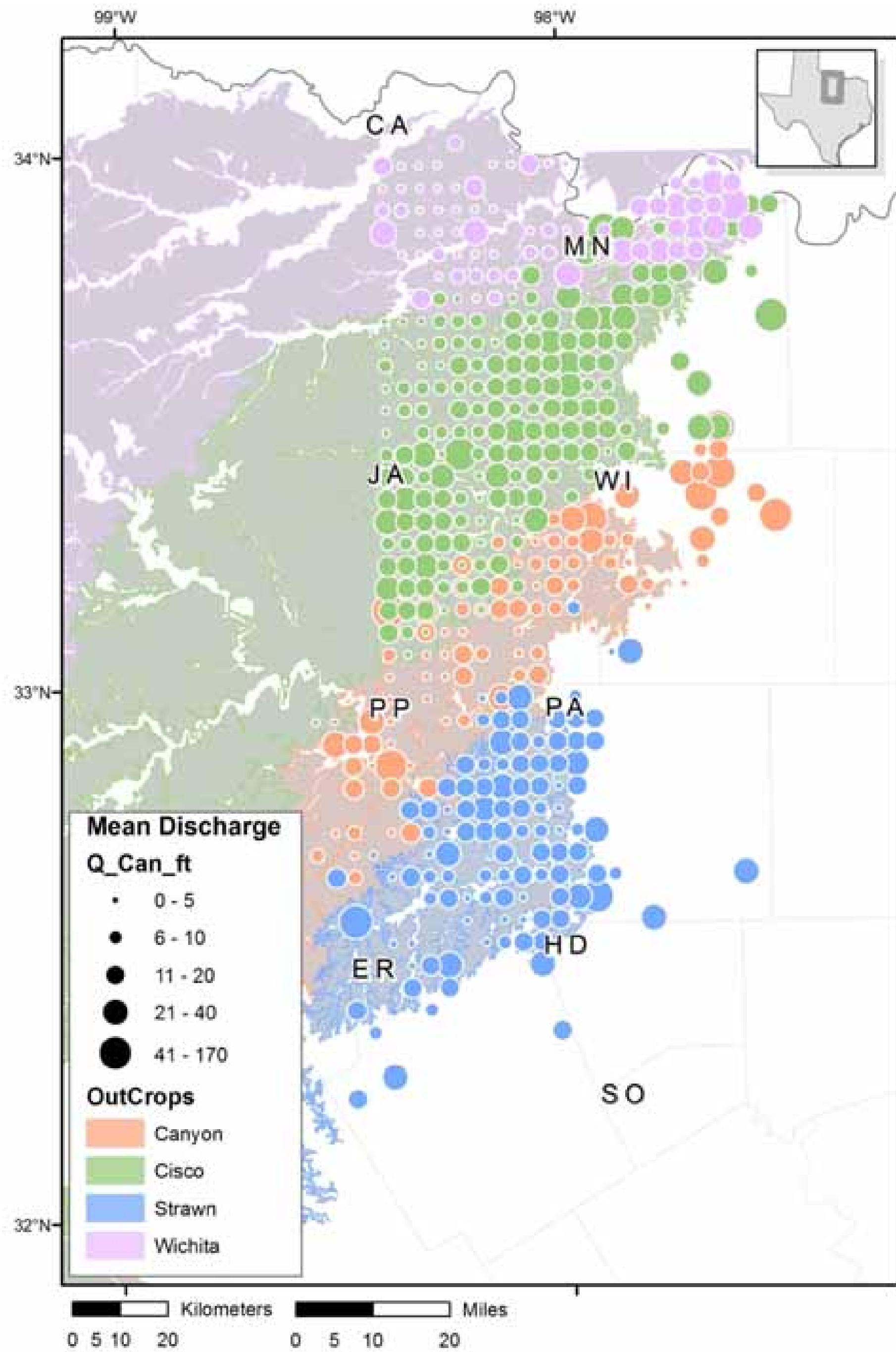

Figure 29. Spatial Distribution of Discharge Rate

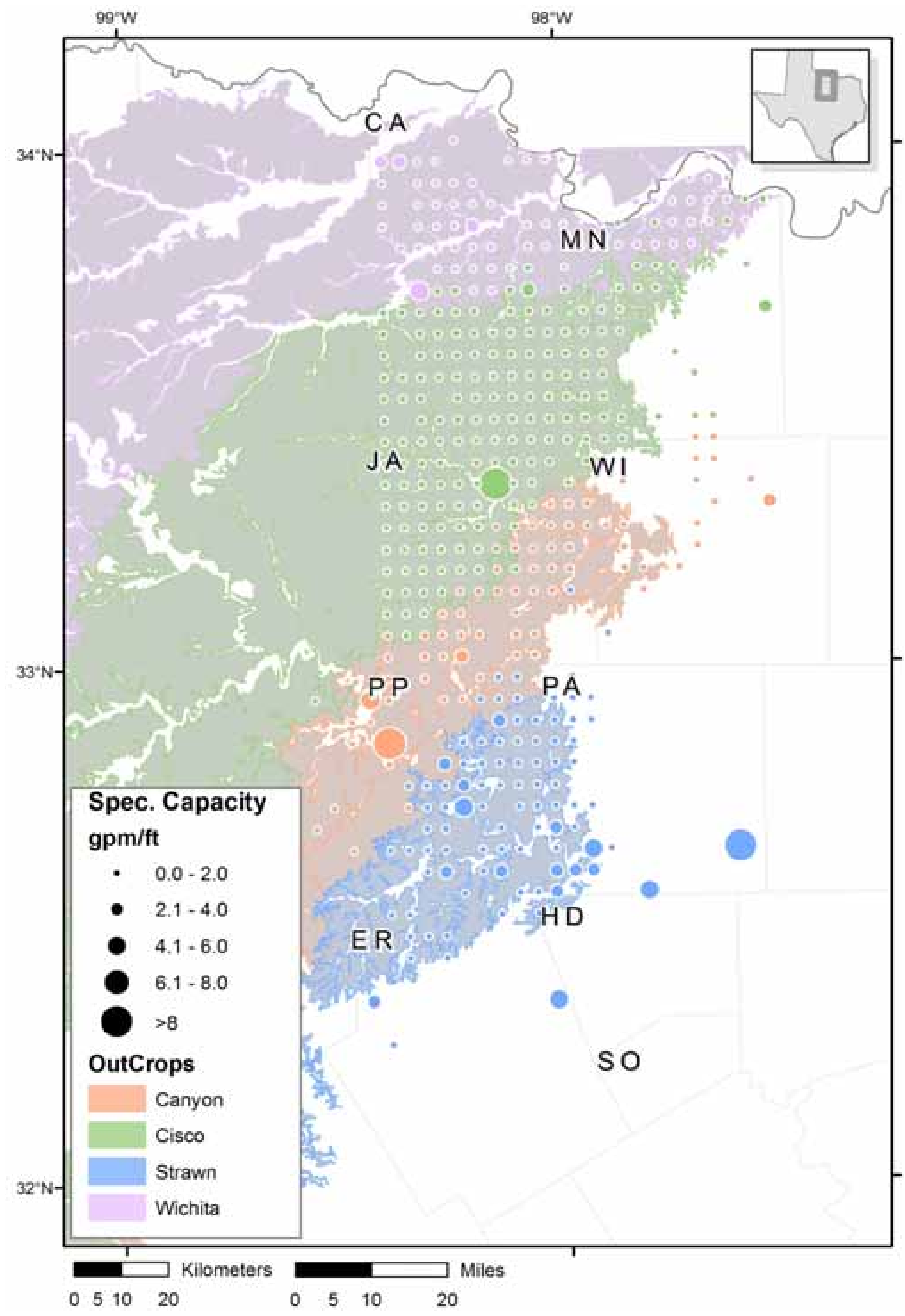

Figure 30. Spatial Distribution of Specific Capacity

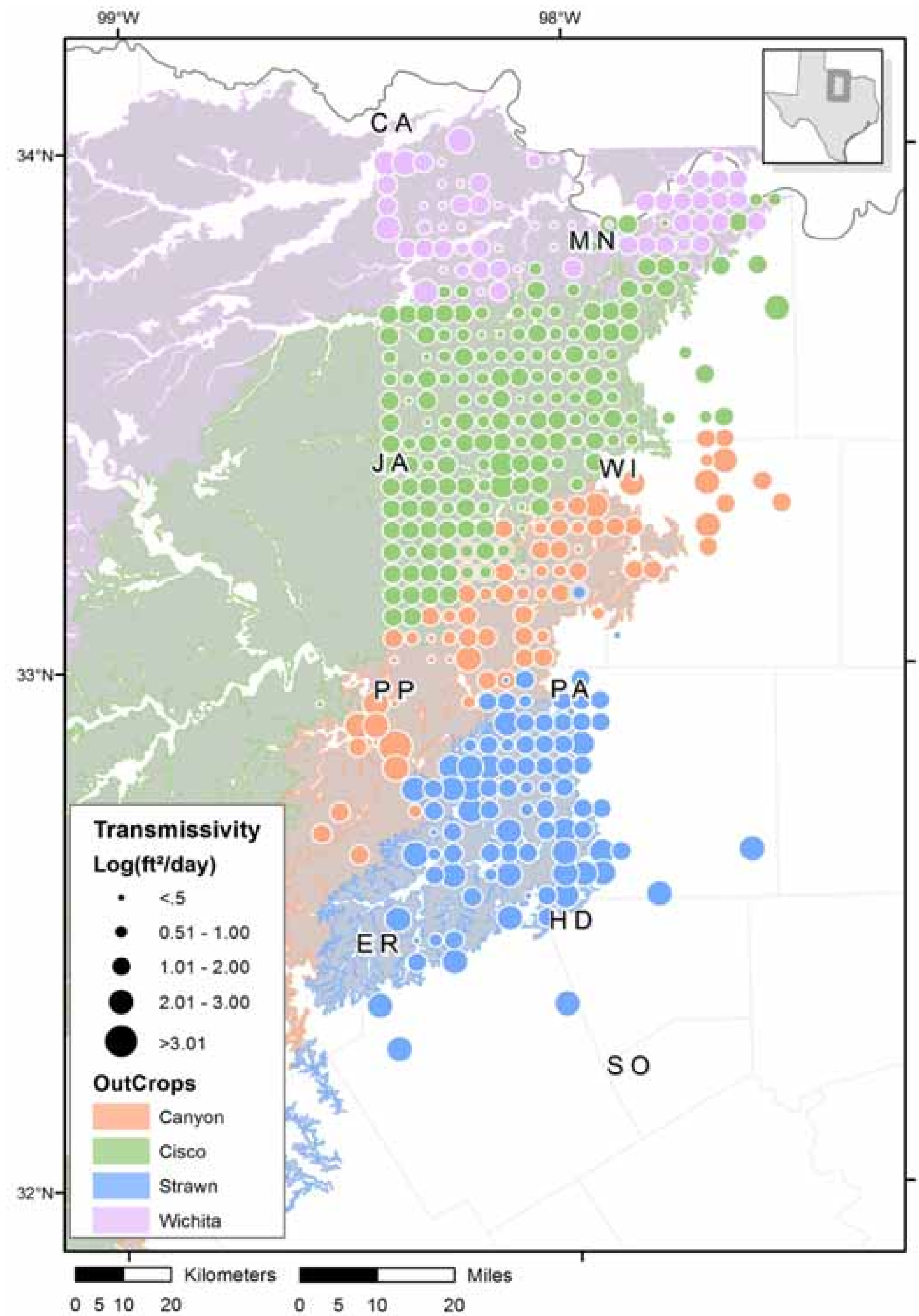

Figure 31. Spatial Distribution of Transmissivity

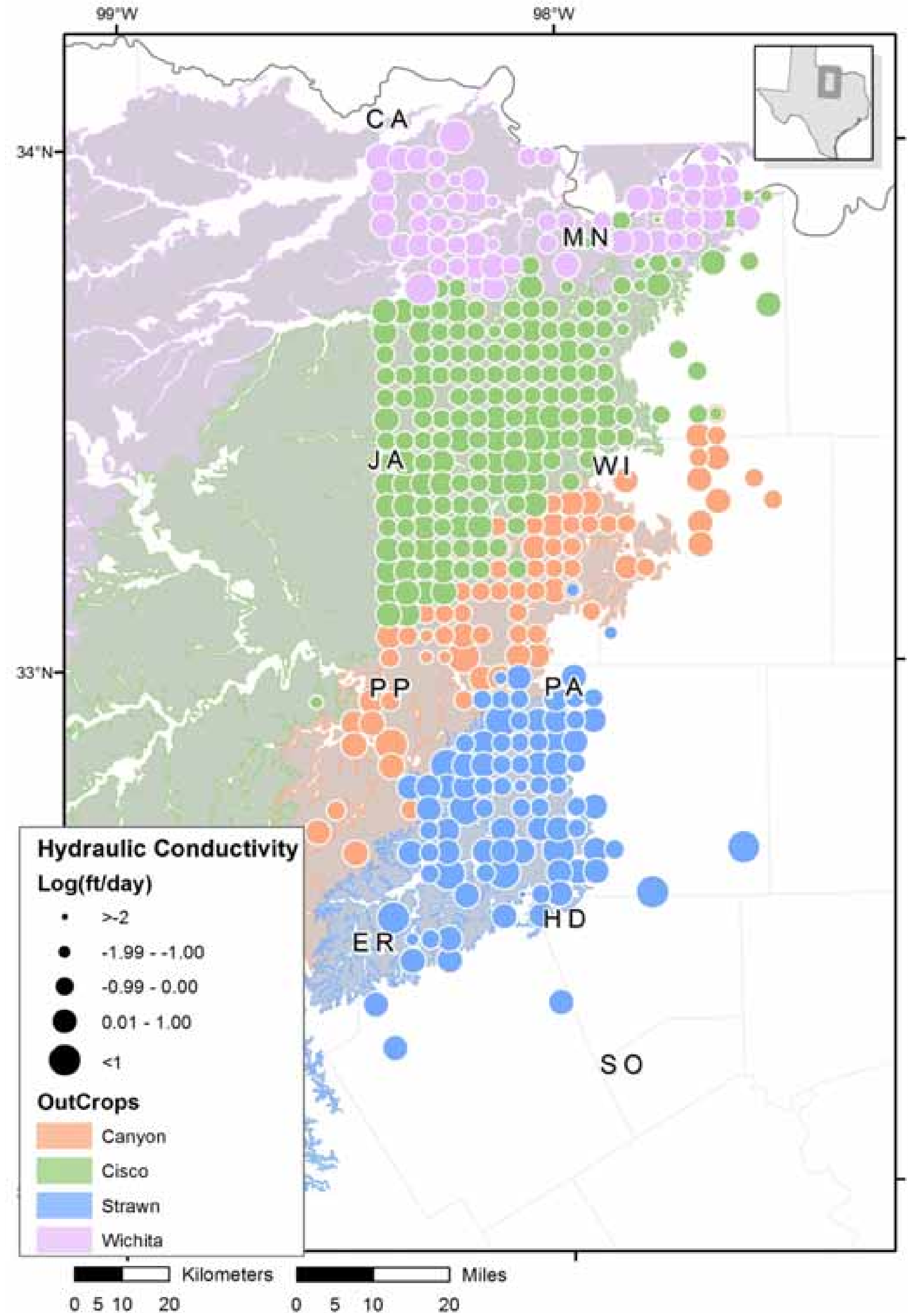

Figure 32. Spatial Distribution of Hydraulic Conductivity

TABLES

Table 0. Characteristics of Initial, Preliminary, and Final Well Databases

Sources of data: TCEQ (2011) and TWDB (2011).

	Total	Percent
Initial Well Database	**7,614**	-
Trinity aquifer wells (1st pass), dry holes, wells mislocated outside study area	2,548	33
Artesian wells screened in limestone near Possum Kingdom Reservoir	71	1
Preliminary Well Database	**4,995**	-
Wells without borehole radius	1,524	31
Wells without drawdown data	820	16
Alluvial aquifer wells	144	3
Trinity aquifer wells (2nd pass)	2,377	48
Final Well Database	**2,474**	-
Strawn Group	434	18
Canyon Group	496	20
Cisco Group	1,340	54
Wichita Group	204	8

Table 1. Characteristics of Wells and Tests in the Database

n: number of values, 25th: 25th percentile, 50th percentile (median), 75th percentile, 90th percentile, [a] geometric mean,

Parameter	Units	n	25th	50th	75th	90th	Mean	Std. Dev.
Diameter	Inches	2,441	4.0	4.5	5.0	5.0	4.6	0.8
Depth	Feet	2,469	120.0	200.0	270.0	370.4	182.3[a]	114.7
Screen length	Feet	2,474	20.0	35.0	40.0	100.0	37.2[a]	59.8
Discharge rate	gpm	2,449	6.0	11.0	20.0	30.0	9.8[a]	23.4
Pumping time	Hours	2,409	1	1	1	2	1.1[a]	15.5

Parameter	Units	n	25th	50th	75th	90th	Mean	Std. Dev.
Diameter	cm	2,441	10.2	11.4	12.7	12.7	11.6	2.0
Depth	m	2,469	36.6	61.0	82.3	112.9	55.6[a]	35.0
Screen length	m	2,474	6.1	10.7	12.2	30.5	11.4[a]	18.2
Discharge rate	m^3/day	2,449	32.7	60.0	109.0	163.5	53.6[a]	127.5
Pumping time	Hours	2,409	1	1	1	2	1.1[a]	15.5

Table 2. Discharge Rate of Wells in the Database

n: number of values, gpm: gallons per minute, 25th: 25th percentile, 50th percentile (median), 75th percentile, 90th percentile, [a] geometric mean.

Parameter	Units	n	25th	50th	75th	90th	Mean [a]	Std. Dev.
Strawn	gpm	432	8	14	20	35	11.4	22.2
Canyon	gpm	476	4	10	20	30	8.1	40.4
Cisco	gpm	1337	7	12	20	30	10.7	15.4
Wichita	gpm	204	3	7	20	30	6.4	11.5

n: number of values, ft^3/day: cubic feet per day, 25th: 25th percentile, 50th percentile (median), 75th percentile, 90th percentile, [a] geometric mean.

Parameter	Units	n	25th	50th	75th	90th	Mean [a]	Std. Dev.
Strawn	ft^3/day	432	1540.0	2695.0	3850.0	6737.5	2194.5	4271.9
Canyon	ft^3/day	476	577.5	1925.0	3465.0	5775.0	1559.3	7654.4
Cisco	ft^3/day	1337	134735	2310.0	3850.0	5775.0	2059.8	2961.4
Wichita	ft^3/day	204	577.5	1347.5	3850.0	5775.0	1232.0	2219.3

Table 3. Groundwater Quality Summary Statistics

Wells from the Texas Water Development Board Groundwater Database (2011) that are located ouside of Trinity aqufer footprint are assumed to be screened in Paleozoic aquifers. Water quality results are reported in milligrams per liter, with the exception of dimensionless pH values.

Percentile	pH	Bicarbonate	Sulfate	Chloride	Total Dissolved Solids (TDS)	Alkalinity
95th	8.8	749	593	1,700	3,796	638
70th	8.3	518	151	235	1,170	434
50th	8.1	425	78	120	758	357
30th	7.7	353	45	52	545	296
5th	7.2	213	15	14	334	182
Max	11.5	2,026	4,530	9,572	14,189	1,660

Table 4. Log Transmissivity Values Estimated from Pumping Test Analysis (ENGLISH UNITS)

Hydarulic conductivity in feet per day (feet^2/day). n: number of values, 25th: 25th percentile, 50th percentile (median), 75th percentile, 90th percentile.

	n	25th	50th	75th	90th	Mean	Std. Dev.
All Tests	1984	0.72	1.1	1.6	2.1	1.2	0.70
Strawn	329	1.0	1.4	2.2	2.6	1.5	Ab
Canyon	352	0.81	1.3	1.7	2.1	1.3	Ab
Cisco	1152	0.67	1.0	1.5	1.9	1.1	Ab
Wichita	151	0.58	1.1	1.5	2.1	1.1	Cb

Table 5. Log Transmissivity Values Estimated from Pumping Test Analysis (SI UNITS)

Hydarulic conductivity in feet per day (m^2/day). n: number of values, 25th: 25th percentile, 50th percentile (median), 75th percentile, 90th percentile.

	n	25th	50th	75th	90th	Mean	Std. Dev.
All Tests	1984	-0.31	0.096	0.59	1.1	0.15	0.70
Strawn	329	-0.011	0.41	1.2	1.6	0.50	Ab
Canyon	352	-0.22	0.31	0.69	1.1	0.26	Ab
Cisco	1152	-0.36	-0.029	0.42	0.83	0.029	Ab
Wichita	151	-0.45	0.072	0.45	1.1	0.055	Cb

Table 6. Log Hydraulic Conductivity Values Estimated from Pumping Test Analysis (ENGLISH UNITS)

Hydarulic conductivity in feet per day (feet/day). n: number of values, 25th: 25th percentile, 50th percentile (median), 75th percentile, 90th percentile.

	n	25th	50th	75th	90th	Mean	Std. Dev.
All Tests	1984	-0.62	-0.16	0.30	0.74	-0.17	0.74
Strawn	329	-0.46	0.10	0.66	1.1	0.097	0.82
Canyon	352	-0.52	-0.073	0.36	0.79	-0.098	0.68
Cisco	1152	-0.69	-0.24	0.14	0.63	-0.27	0.69
Wichita	151	-0.78	-0.11	0.37	0.80	-0.14	0.82

Table 7. Log Hydraulic Conductivity Values Estimated from Pumping Test Analysis (SI UNITS)

Hydarulic conductivity in feet per day (m/day). n: number of values, 25th: 25th percentile, 50th percentile (median), 75th percentile, 90th percentile.

	n	25th	50th	75th	90th	Mean	Std. Dev.
All Tests	1984	-1.1	-0.68	-0.22	0.22	-0.68	0.74
Strawn	329	-0.97	-0.41	0.14	0.59	-0.42	0.82
Canyon	352	-1.0	-0.59	-0.16	0.27	-0.61	0.68
Cisco	1152	-1.2	-0.76	-0.37	0.11	-0.78	0.69
Wichita	151	-1.3	-0.63	-0.15	0.29	-0.66	0.82