The Report Committee for Edward R. McGlynn
Certifies that this is the approved version of the following report:

Alternative Groundwater Resources in North-Central Texas for the Development of the Barnett Shale Gas Play

APPROVED BY
SUPERVISING COMMITTEE:

Supervisor:

John M. Sharp

Co-Supervisor:

Jean Philippe Nicot

Alternative Groundwater Resources in North-Central Texas for the Development of the Barnett Shale Gas Play

by

Edward R. McGlynn, B.Geo.E.; M.B.A.

Report

Presented to the Faculty of the Graduate School of

The University of Texas at Austin

in Partial Fulfillment

of the Requirements

for the Degree of

Masters of Art

The University of Texas at Austin

August 2012

Abstract

Alternative Groundwater Resources in North-Central Texas for the Development of the Barnett Shale Gas Play

Edward R. McGlynn, M.A.

The University of Texas at Austin, 2012

Supervisors: John M. 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 be developed is the many small aquifers which have never been well-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 a 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 (11,400 to 13,200 m^3) of fresh water. Projections of future groundwater demand for the Barnett Shale gas play total 417,000 AF (5.1×10^8 m^3), an annual average of 22,000 AF (2.7×10^7 m^3) over the expected 2007-2025 development phase. This level of water demand has the gas industry and groundwater managers 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 local Paleozoic aquifers on the western edge of the play. 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.

Table of Contents

List of Tables

List of Figures

List of Illustrations

List of Acronyms

AF	Acre-foot
DFC	Desired Future Conditions
GAM	Groundwater Availability Model
GCD	Groundwater Conservation District
GIS	Geographic Information System
gpm	Gallons per minute
MAG	Managed Available Groundwater
MCL	Maximum Contaminant Level
PGMA	Priority Groundwater Management Area
PWS	Public Water System
TCEQ	Texas Commission on Environmental Quality
TDS	Total dissolved solids
TWDB	Texas Water Development Board
USGS	United States Geological Survey

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. 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 fracked using surface water or 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. 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 sandstones 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.

Literature Review

BARNETT SHALE PLAY

The Mississippian Barnett Shale serves as source, seal, and reservoir to a world-class unconventional natural-gas accumulation in the Fort Worth basin of north-central Texas (Figure 1). The formation is a lithologically complex interval of low permeability that requires artificial stimulation to produce. At present, production is mainly confined to a limited portion of the northern basin where the Barnett Shale is relatively thick (>300 ft; >90 m), organic rich, thermally mature, and enclosed by dense limestone units able to contain induced fractures. The most actively drilled area is Newark East field, currently the largest gas field in Texas.

The Barnett Shale of the Fort Worth Basin is presently the largest producing natural gas field in Texas and the second largest in the United States. The field covers 23 counties in North Texas, including the Fort Worth metropolitan area (Figure 1). In 2009 there were more than 12,000 wells in the field producing nearly 5 billion cubic feet (1.4×10^8 m^3) per day or roughly 7.5% of U.S. natural gas production (EIA, 2009; Powell, 2009). According to the most recent data from the Texas Railroad Commission, by the end of 2011 there were more than 15,870 wells producing over 1,937 billion cubic feet (5.5×10^{10} m^3) of gas per year or approximately 31% of total gas production in Texas (RRC, 2012). An assessment by the U.S. Geological Survey (USGS) suggests a mean volume of 26.2 trillion cubic feet (7.4×10^8 m^3) of undiscovered, technically recoverable gas in the central Fort Worth basin (Montgomery, 2005). There are sufficient gas reserves in the Fort Worth basin to heat 10 million homes for 27 years (USGS, 2004).

Efforts to extend the current Barnett gas play beyond the field limits have encountered several challenges, including westward and northward increases in oil saturation and the absence of lithologic barriers to induced fracture growth. Additionally, the water resources to support the required hydraulic fracturing have been seen as a growing challenge as development has expanded beyond the footprint of the Trinity Aquifer group.

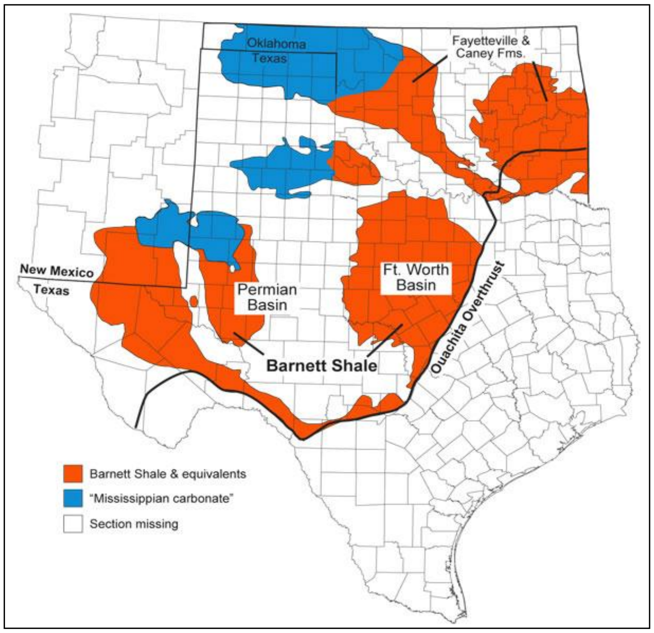


Figure 1: Location of Barnett Shale (Source: USGS, 2004)

HYDRAULIC FRACTURING

Before 1997, Barnett Shale wells (mostly vertical) were completed with massive hydraulic-fracture treatments consisting of cross-linked gelled fluids and large amounts of proppant. Because of difficulties with effectively cleaning up fracture damage caused by the cross-linked gel and the high cost of these massive stimulation treatments, the wells were not as economical as desired. In 1997, large-volume, high-rate slick water fracture-stimulation treatments were sought as a less-expensive alternative. Although well performance was not increased drastically with slick water, completion costs were reduced by approximately 65%. In 2002, horizontal wells were installed to increase the wellbore's exposure to the reservoir. The results of the first horizontal wells compared to vertical wells were three times the estimated ultimate recovery at twice the well cost. Horizontal wells offered an economic solution to areas outside the core and reduced the number of surface locations needed near populated areas (Ketter, 2008).

WATER USE ESTIMATES

Gas production in the Barnett Shale has increased in the past decade due in large part to improvements in hydraulic fracture stimulation (frac) technologies. The frac process uses water to generate and improve fracturing within the shale matrix. The fracturing improves the gas production from a well, but the use of fresh water is an added cost to the development of a well. Thus, there is incentive to use only the amount of water necessary for satisfactory completion of the process (Bene, 2007). A typical vertical and horizontal well completion consumes approximately 1.2 and 3.0 million gallons (4500 and 11,000 m^3) of fresh water, respectively. Projections made in 2007 for the high water use scenario yields a total groundwater use of 417,000 AF (5.1×10^8 m^3), an annual average groundwater use of 22,000 AF (2.7×10^7 m^3) over the 2007-2025 period for the whole Barnett Shale play (Nicot, 2009).

Previous forecasts indicated that the fraction of total freshwater (from both surface and groundwater sources in the Fort Worth Basin) would likely be less than 2% of total reserves over the course of drilling the Barnett Shale, and for the years before and after peak drilling would be substantially less. A study by the TWDB in 2007 indicated that the projected fraction of fresh water use by Barnett natural gas producers may be something less than 1.5% of regional supplies during the "peak" (if a distinguishable single peak actually occurs) and would subsequently decline from this fraction (Galusky, 2009; TWDB, 2007).

Of considerable concern to TWDB and local water resource planners in recent years has been the potential effect of Barnett drilling on groundwater supplies. Early forecasts indicated that the maximum likely peak demand (under a high drilling activity scenario) for groundwater resources from Barnett drilling would represent approximately 10% of total usage, and that this level of usage would be broadly sustainable on a regional basis (TWDB, 2007). However, most recently as a substantial fraction of Barnett drilling intensity has migrated eastward into Fort Worth and nearby communities, natural gas producers have come to rely almost entirely on purchased municipal surface water supplies. It is likely, therefore, that the fraction of groundwater supplies which will be used to develop the Barnett Shale completely will be considerably less than the 10% figure originally projected by TWDB (Galusky, 2009).

The Trinity Aquifer thins out toward the western part of the basin, indicating that there will be less groundwater available for extraction. Therefore, near the western margin of the Trinity Aquifer, and in localized areas of the counties where well yields are limiting, projected increases in the proportional groundwater demand for natural gas drilling and completion indicate the need for due diligence and pro-active water resource planning. Where water well yields are below a certain threshold (50 gallons per minute - gpm), these areas will likely not have the groundwater supplies necessary to support substantial natural gas development; thus, gas operators will of necessity look to other sources (Galusky, 2009).

Table 1 below illustrates the time required, in days and weeks, for a gas operator to pump the required 3 million gallons (11,364 m^3) of groundwater required for a horizontal well completion. The minimum acceptable pump rate of 50 gallons (0.2 m^3) per minute would require a total of 6 weeks of continuous pumping while low yield pump rate of 5 to 20 gpm would require 60 to 15 weeks respectively. A highly productive well of 200 gpm would require 1.5 weeks to pump the required 3 million gallons.

Pump Rates & Time Required for 3 million gallons (11,364 m^3)		
Pump Rate (gpm)	Time Required (days)	Time Required (weeks)
5	416.7	60
20	104.2	15
40	52.1	7.4
50	41.6	6.0
100	20.8	3.0
200	10.4	1.5

Table 1: Pump rate and time required for horizontal fracturing (1 million gallons = 3785.4 m^3)

GAS INDUSTRY REQUIREMENTS FOR FRACKING

Each drilling operator in the Barnett Shale will have different techniques for hydraulic fracturing and their requirements for the fracking will vary accordingly. However, there can be determined a general set of guidelines for the minimum water quality requirements for reliable and effective fracturing operations for the industry.

On September 26, 2007, a panel of hydraulic fracturing experts met at the XTO Facilities in Fort Worth, Texas (GTI, 2007). Based on input from industry experts, key hydraulic fracturing fluid properties include:

- Low Viscosity
- Non-reactive
- Non-Flammable
- Minimal residuals

- Minimal potential for scale and corrosion
- Low entrained solids
- Around Neutral pH (pH 6.5 – 7.5)

Industry panel group inputs:

pH can affect the formation of carbonate based scale. Biocide effectiveness is the main concern with regards to pH. Most biocides work best below pH 7, though many biocides will still work between pH 7 and 8. Highly alkaline frac waters (above pH 8) should be avoided.

Chlorides levels should be no greater than 10,000 mg/l to be acceptable. Chloride increase demand for friction reducers and scale inhibitors. Soluble calcium levels should be no greater than 350 mg/l.. Anything above this level will trigger greater demand for friction reducer during the fracking job procedure.

GROUNDWATER MANAGEMENT

In Texas the general law managing groundwater is that the resource belongs to the landowner under the rule of capture. However, most major and some minor aquifers are managed by Groundwater Conservation Districts (GCDs), often times corresponding to a county. If the property is not part of any GCD, the rule of capture fully applies and the landowner is free to first pump and then sell as much water as they desire. Within the confines of a GCD, wells are required to be registered and some pumping restriction may apply.

The Texas Water Development Board (TWDB), in 2006, identified several counties in north-central Texas as either currently experiencing or expected to experience within the next 25 years critical groundwater problems with the quality and or the quantity of groundwater available to provide for the demands of the residents within the area. The population of the north-central Texas region, including the Dallas-Fort Worth metro area, is projected to increase from approximately 5.5 million in 2000 to over 9.5 million by 2030. As a consequence the total water use is projected to increase from 1.36 million acft/yr to over 1.85 million acft/yr. Groundwater level declines and reduction of artesian pressure caused by continued removal of water from aquifer storage is a regional problem (Figure 2). Some of the state's largest water level declines, ranging from 350 to 1,000 feet (107 to 305 meters), have occurred in this region (TWDB, 2007). This determination caused the TWDB to start in motion the designation of a Priority Groundwater Management Area (PGMA) for the counties of Montague, Wise, Parker, Hood, Cooke, Denton, Tarrant, Dallas, and others in the region (Figure 3). A PGMA is an area of the state, designated by the TCEQ, which is experiencing or is expected to experience critical groundwater problems in the next 25 years. Critical groundwater problems can include; a shortage of surface water or groundwater, land subsidence resulting from the withdrawal of groundwater or contamination of groundwater supplies.

Upon completion of the PGMA designation process every county within the specified area would have a maximum of two years to either create a GCD, join an existing GCD or face the certainty that the State of Texas would either create a District for them or place them in an existing district of the State's choosing. The Commission designated the North Central Texas-Trinity and Woodbine Aquifers PGMA in Collin, Cooke, Dallas, Denton, Ellis, Fannin, Grayson, Hood, Johnson, Montague, Parker, Tarrant, and Wise counties by order on February 18, 2009.

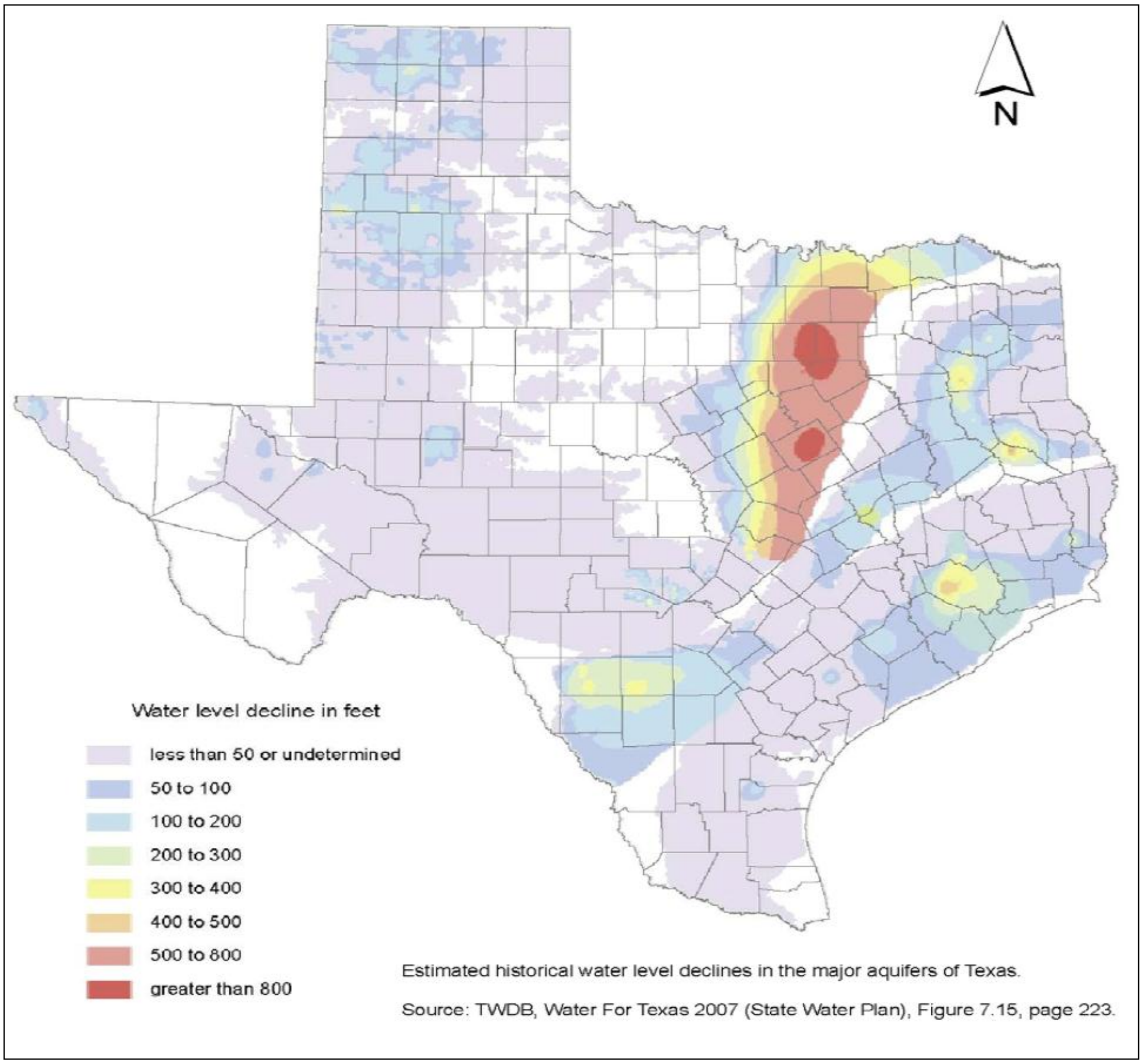


Figure 2: Texas historic water level declines

Some of the study area counties are part of a local GCD while others are not currently part of an established GCD.

Upper Trinity GCD – Montague, Wise, Parker, and Hood

Northern Trinity GCD – Tarrant

North Texas GCD – Denton

Prairielands CGD – Johnson, Hill, and Somerville

In an effort to develop a more regional planning model that took into account aquifer boundaries, not just geopolitical boundaries Groundwater Management Areas (GMA) where established by the State. The Upper and Middle Trinity is encompassed in GMA 8 and the Lower Trinity in GMA 9. With the passage of Texas HB 1763 in 2005, GCDs are required to plan for common groundwater resources jointly as a unified GMA. This system requires each GCD within a GMA to work together to set Desired Future Conditions (DFCs) that are consistent with the DFCs of other GCDs within the GMA. This process was determined to be more appropriate for a shared resource such as groundwater that has no regard for geopolitical boundaries. After a GMA has agreed on DFCs, a written decision is provided to the Texas Water Development Board (TWDB). The TWDB then calculates a Managed Available Groundwater (MAG) for each GCD by inputting the agreed upon DFCs into a Groundwater Availability Model (GAM). The MAG is then used by each GCD for permitting purposes and when updating district rules and management plans. The TCEQ is currently conducting GAM runs for the DFCs agreed upon by the GMA 9 member GCDs, as a result no finalized MAGs based on these DFCs have been released to the public.

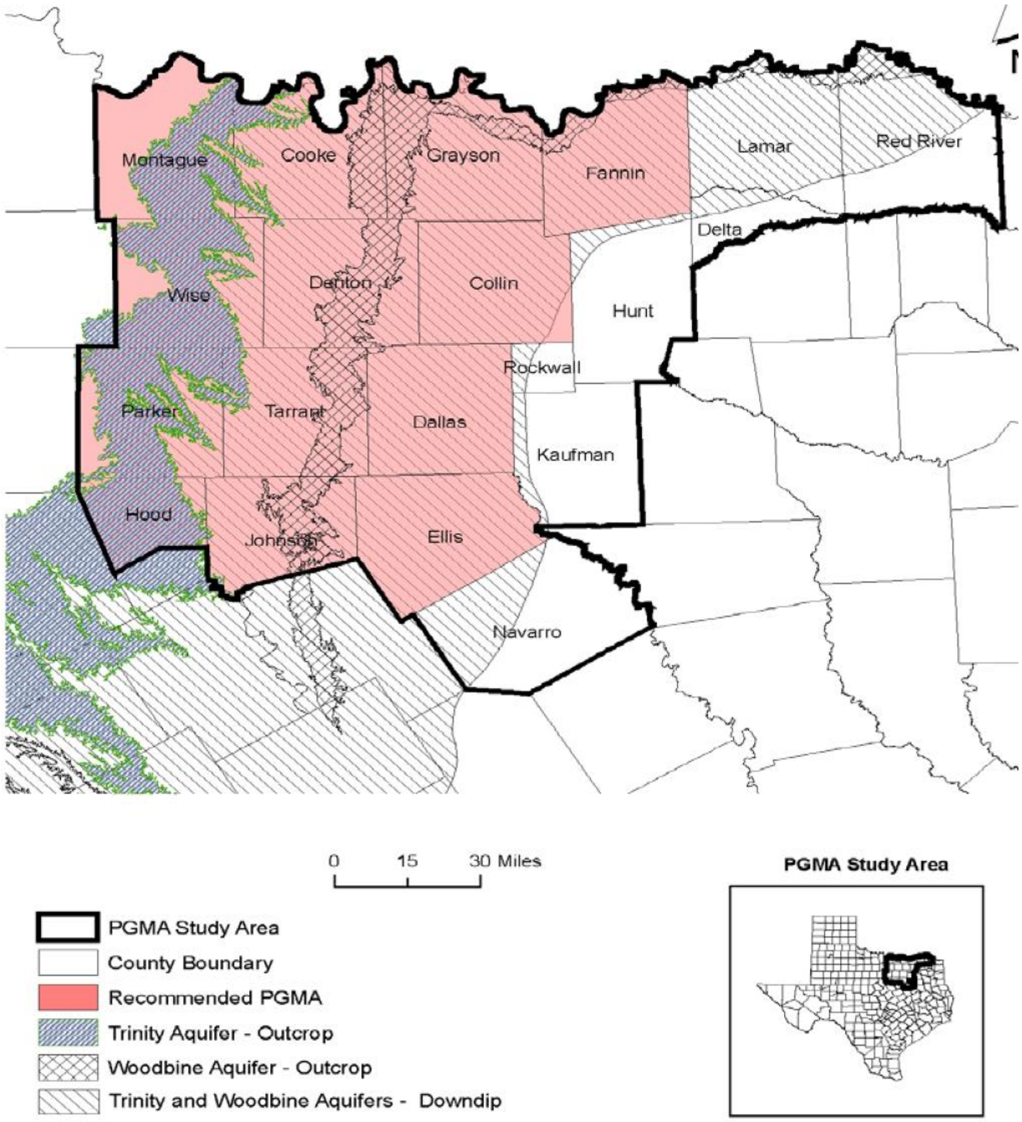


Figure 3: Recommended PGMA for North-Central Texas (Mills and Byrd, 2007)

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 4). 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.

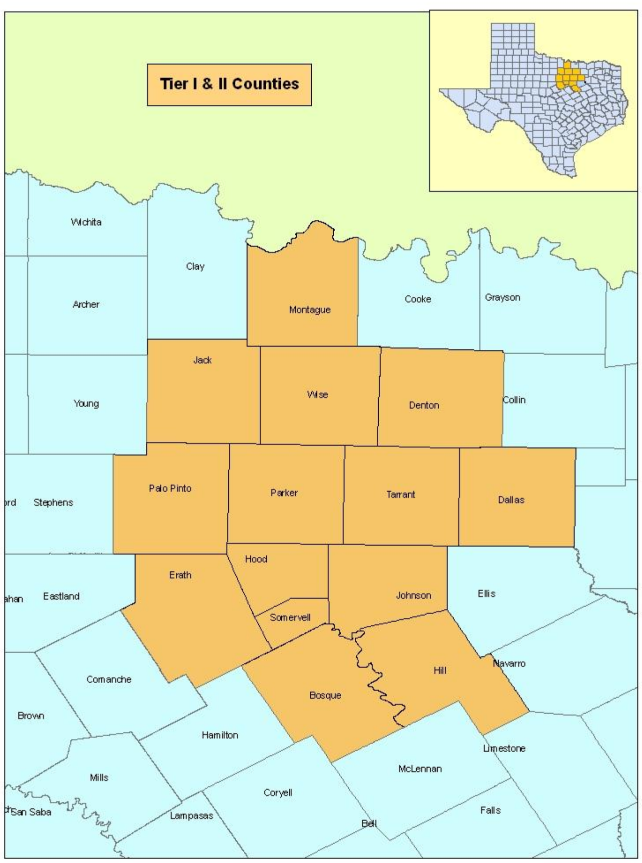


Figure 4: Study Area - Tier I & II counties

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 and the groundwater resources within these formations. 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. 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. The shape and location of the Pennsylvanian area are shown on the index map (Figure 5) (Moore and Plummer, 1922).

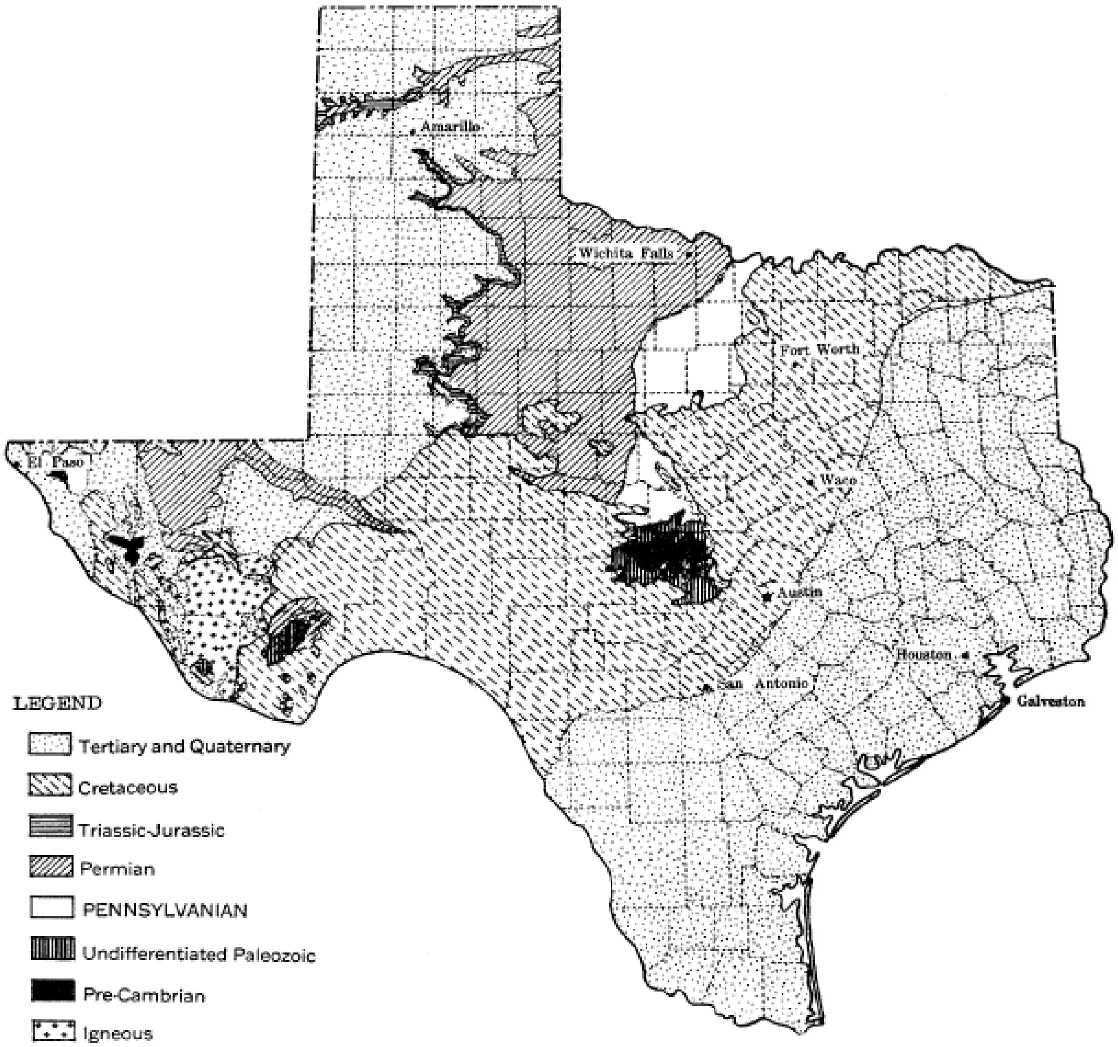


Figure 5: The Pennsylvanian area of north central Texas (Moore and Plummer, 1922)

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 (Table 2).

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).

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 (Figure 6). 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.

<table>
<tr><th>ERA</th><th>SYSTEM</th><th>SERIES</th><th>GROUP</th><th colspan="2">FORMATION</th><th>APPOXIMATE MAXIMUM THICKNESS (FT)</th><th>HYDRAULIC PROPERTIES*</th></tr>
<tr><td rowspan="2">Cenozoic</td><td rowspan="2">Quaternary</td><td>Recent</td><td>Alluvium</td><td colspan="2">Alluvium</td><td>60</td><td rowspan="2">Yields small to large amounts of fresh water to wells along the rivers and their tributaries.</td></tr>
<tr><td>Pleistocene</td><td>Seymour</td><td colspan="2">Seymour</td><td>125</td></tr>
<tr><td rowspan="10">Mesozoic</td><td rowspan="10">Cretaceous</td><td rowspan="5">Gulf</td><td>Navarro</td><td colspan="2">Kemp Clay, Corsicana Marl, Nacatoch Sand</td><td>800</td><td>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.</td></tr>
<tr><td>Taylor</td><td colspan="2">Marlbrook Mar, Pecan Gap Chalk, Wolfe City -Ozan Formations</td><td>1500</td><td>Yields small quantities of water to shallow wells.</td></tr>
<tr><td>Austin</td><td colspan="2">Gober Chalk, Brownstown Marl, Blossom Sand, Bonham Formation</td><td>700</td><td>Yields small to moderate quantities of fresh to moderately saline water to wells in northeastern part. Limited as an aquifer.</td></tr>
<tr><td>Eagle Ford</td><td colspan="2"></td><td>650</td><td>Yields small quantities of water to shallow wells.</td></tr>
<tr><td>Woodbine</td><td colspan="2"></td><td>700</td><td>Yields moderate to large quantities of fresh to slightly saline water to municipal, industrial and irrigation wells.</td></tr>
<tr><td rowspan="5">Comanche</td><td>Washita</td><td colspan="2"></td><td>1000</td><td>Yields small quantities of water to shallow wells.</td></tr>
<tr><td>Fredericksburg</td><td colspan="2"></td><td>250</td><td>Yields small quantities of water to shallow wells.</td></tr>
<tr><td rowspan="3">Trinity</td><td rowspan="3">Antlers</td><td>Paluxy</td><td>400</td><td>Yields small to moderate quantities of fresh to slightly saline water to wells.</td></tr>
<tr><td>Glen Rose</td><td>1500</td><td>Yields small quantities of water in localized areas.</td></tr>
<tr><td>Twin Mountains</td><td>1000</td><td>Yields moderate to large quantities of fresh to slightly saline water to wells.</td></tr>
<tr><td rowspan="13">Paleozoic</td><td rowspan="2">Permian</td><td rowspan="2">Wolfcamp</td><td rowspan="4">Cisco</td><td colspan="2">Pueblo</td><td>100</td><td rowspan="4">Yields small to moderate quantities of fresh to moderately saline water for public supply, industrial, irrigation, domestic, and stock wells.</td></tr>
<tr><td colspan="2">Harpersville</td><td>200</td></tr>
<tr><td rowspan="11">Pennsylvanian</td><td rowspan="3">Virgil</td><td colspan="2">Thrifty</td><td>300</td></tr>
<tr><td colspan="2">Graham</td><td>600</td></tr>
<tr><td rowspan="4">Canyon</td><td colspan="2">Caddo Creek</td><td>300</td><td rowspan="4">Yields small quantities of fresh to slightly saline water to wells in and near the outcrop.</td></tr>
<tr><td rowspan="4">Missouri</td><td colspan="2">Brad</td><td>400</td></tr>
<tr><td colspan="2">Graford</td><td>600</td></tr>
<tr><td colspan="2">Palo Pinto</td><td>300</td></tr>
<tr><td rowspan="5">Strawn</td><td colspan="2">Mineral Wells</td><td>1100</td><td rowspan="5">Yields small quantities of slightly to moderately saline water from sandstone and conglomerate in and near the outcrop.</td></tr>
<tr><td rowspan="4">DesMoines</td><td colspan="2">Brazos River</td><td rowspan="4">1400</td></tr>
<tr><td colspan="2">Mingus</td></tr>
<tr><td colspan="2">Grindstone Creek</td></tr>
<tr><td colspan="2">Lazy Bend</td></tr>
<tr><td colspan="8">*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.</td></tr>
</table>

Table 2: Stratigraphy of North-Central Texas Study Area. Modified from Nordstrom (1988), Duffin (1992) and Baker (1990)

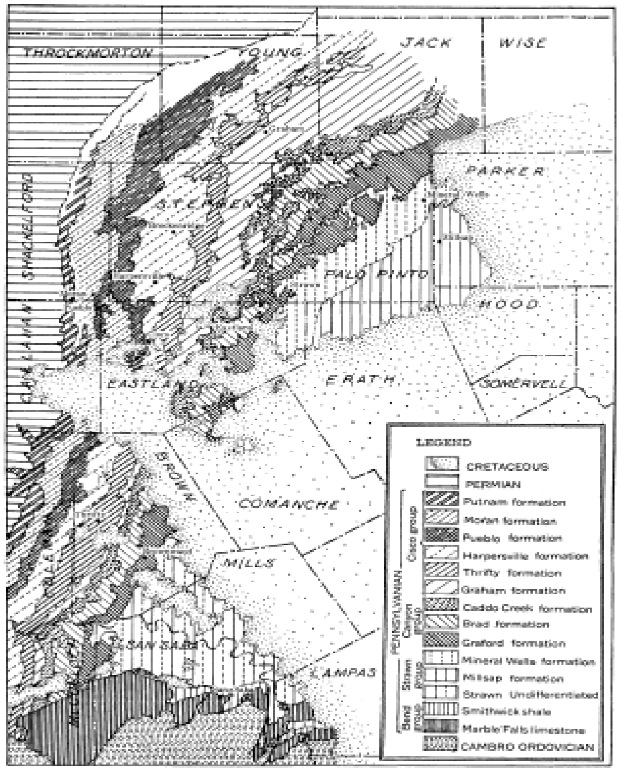


Figure 6: Outcrops of Pennsylvanian formations in north central Texas (Moore and Plummer, 1922)

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).

REGIONAL HYDROLOGY

The primary aquifers in the region include the Trinity and Woodbine aquifers with minor amounts of water produced from the Paleozoic aquifers in the western counties of the study area, including; Jack, Montague, Parker and Palo Pinto Counties. The groundwater flow in the Cretaceous age Trinity and Woodbine aquifers are both generally in the east-southeast direction (Langley, 1999). A general pattern of groundwater flows in the Paleozoic aquifers can be summarized as from high elevation to low elevation and discharges to the rivers (Nicot, 2012).

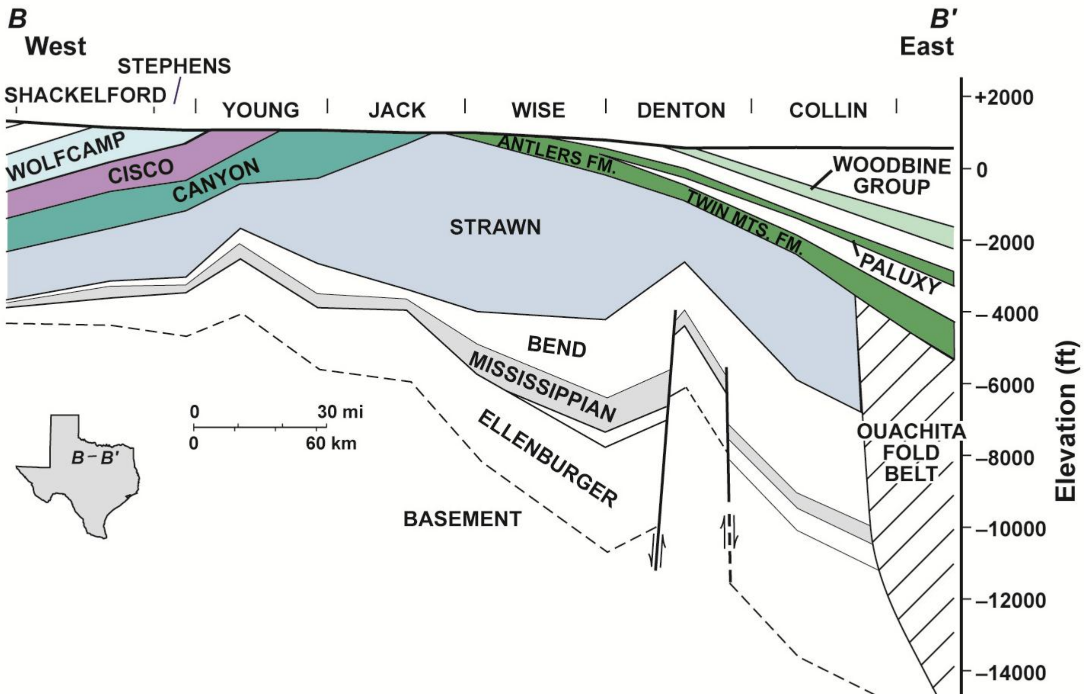


Figure 7: Stratigraphic Section of Study Area – West to East (BEG-UT 1972)

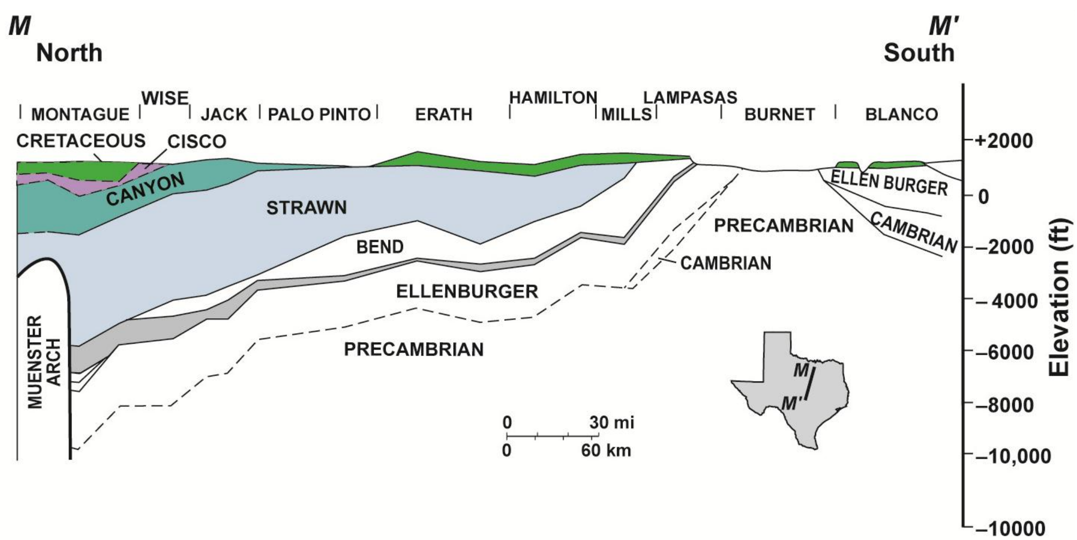


Figure 8: Stratigraphic Section of Study Area – North to South (BEG-UT 1972)

Regional Groundwater Resources

MAJOR AQUIFERS

Major aquifers are defined by the TWDB as aquifers that produce large amounts of water over large areas (TWDB, 2007). The TWDB recognizes a total of nine major aquifers in Texas. The only major aquifer in the study area in North-Central Texas is the Trinity Aquifer. The Woodbine Aquifer is considered by the TWDB to be a minor aquifer, which is defined as an aquifer which produces minor amounts of water over large areas or large amounts of water over small areas (TWDB, 2007). The TWDB recognizes 21 minor aquifers in the State. Since the Woodbine is primarily located to the east and outside of the study area, the focus of this report, as it relates to major or minor aquifers, will be limited to the Trinity Aquifer.

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, 1995). The aquifer's area of outcrop is 10,652 square miles (27,588 square kilometers) along its western length and the area of the confined section is 21,308 miles (34,291 kms) primarily along its eastern length (TWDB, 2007).

Formations comprising the Trinity Group are (from youngest to oldest) the Paluxy, Glen Rose, and Travis Peak (Figure 9). 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 (300 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 (Bradely, 1999). Underlying the Paluxy, the Glen Rose Formation forms a gulf-ward thickening wedge of marine carbonates consisting primarily of limestone (Nordstrom, 1982).

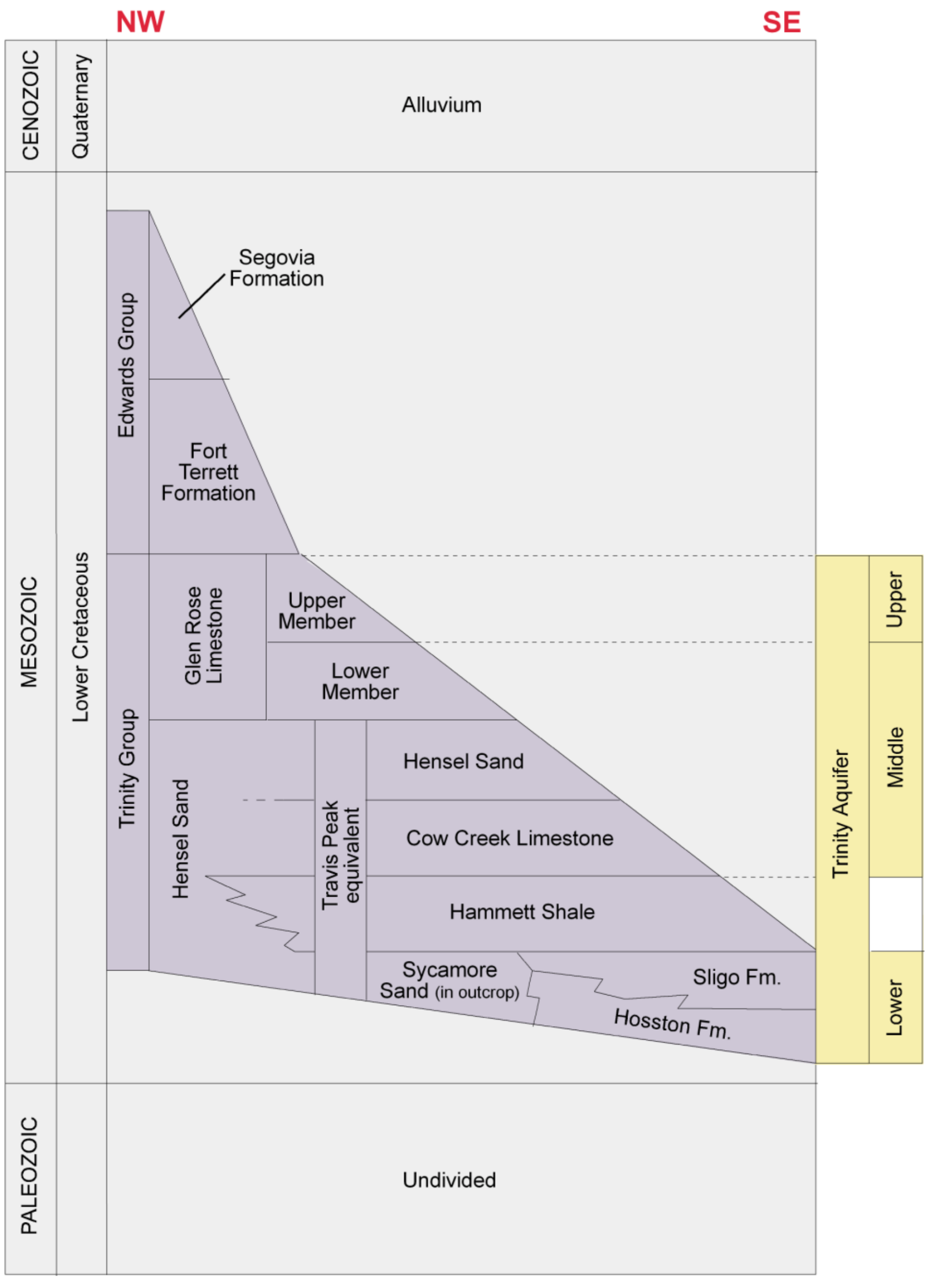


Figure 9: Trinity Aquifer stratigraphic and hydrostratigraphic section (Mace, 2000)

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, 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 (Figure 2) (Mace, 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, 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, 1994). Similarly, the lower parts of the Glen Rose Limestone are more permeable in outcrop areas than in deeper areas (Barker, 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 hydraulic conductivity ranges from approximately 87 to 235 gallons per day per square foot (gpd/ft^2) (SI unit 3.8 x 10^{-5} to 1.03 x 10^{-4} m/s). Because of this extreme range in permeability in water saturated sands, transmissibility values vary widely, ranging from zero to 20,000 gpd/ft (2.9 x10^{-3} m^2/s) (Klemt, 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 (4.4 x 10^{-7} to 8.7 x 10^{-6} m/s) with coefficients of transmissibility ranging from zero to 1,000 gpd/ft (1.4 x 10^{-4} m^2/s) (Klemt, 1975).

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).

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 (TWDB, 2007). Water quality ranges from fresh (less than 1,000 mg/I TDS) up to slightly saline (1,000 to 3,000 mg/I TDS). Chloride concentrations for the Trinity Aquifer exceed the Maximum Contaminant Level (MCL) of 300 mg/I in the western outcrop areas and the southeastern down-dip areas. Nitrate concentrations exceed the MCL of 44.3 mg/I (as nitrate) in the western outcrop. Sulfate concentrations of the Trinity Aquifer exceed the MCL of 300 mg/I 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).

LOCAL PALEOZOIC AND ALLUVIUM AQUIFERS

The Texas Water Development Board does not consider the local Paleozoic and alluvium aquifers located in north-central Texas to be significant sources of groundwater and, therefore, they are not classified as either major or minor aquifers by the state. As a result, there is very little published information about these local aquifers that are located above the western portion of the Barnett Shale gas play. Although part of a larger hydrological system, most of them are small in size barely covering a fraction of a county. It is important to characterize the aquifers as they might be the only water source in large sections of the Barnett Shale footprint, with no surface water bodies and no water treatment plant in those sparsely populated areas (Nicot, 2012).

The main sources of information on these local Paleozoic aquifers are a few published reports on water resources in North-Central Texas and well data from the original driller reports for the area maintained by the TWDB. Based on these sources the primary Paleozoic aquifers in Tier I and II of the study area include; Thrifty and Graham formations of the Cisco Group, Colony Creek, Placid, Wolf Mountain and Palo Pinto formations of the Canyon Group, Mineral Wells Formation of the Strawn Group and the Wichita Group (Figure 10). The rock and water bearing characteristics of each of the aquifers in the study area are summarized by county in Appendix 2.

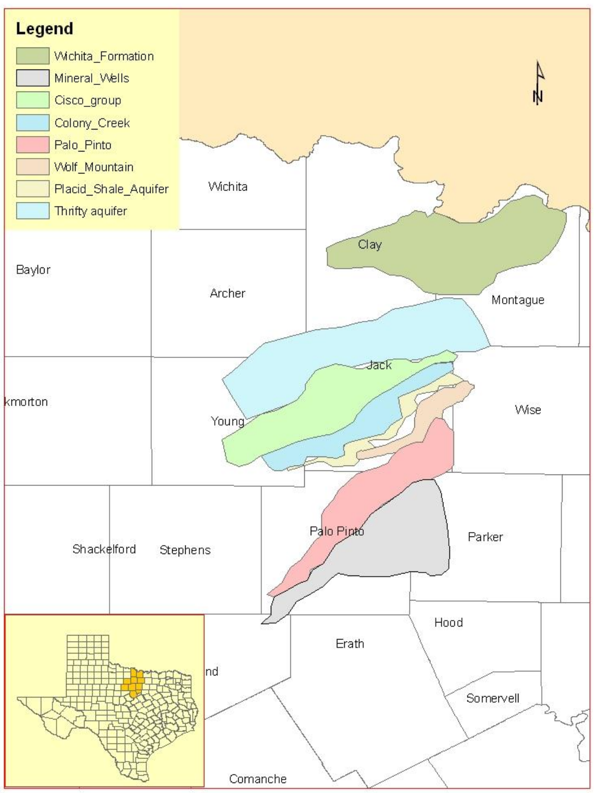


Figure 10: Local Paleozoic aquifers in Tier I & II (Figure is compiled from TWDB (2010) database).

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. Groundwater 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 groundwater 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 (560 kms) 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 (26 meters) or more, with maximum thickness occurring in the central and southeastern parts of the aquifer. Some wells yield up to 1,000 gal/min (4 m^3/min), but the majority yield between 250 gal/min (1 m^3/min) and 500 gal/min (2m^3/min) (Cronin, 1967).

Illustration 1: Brazos River Conglomerate, Palo Pinto County (See Appendix 1 for location)

The chemical quality of the groundwater varies widely. In many areas, concentrations of dissolved solids exceed 1,000 mg/l. Most of the Brazos River Valley irrigated with this groundwater 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 folding and faulting movement which lowered the ancient sea water levels during the time of deposition 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 (213 to 243 meters) in the southern Pennsylvanian area and 1,400 to 1,500 feet (427 to 457 meters) in the north. Four 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 (Moore and Plummer, 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 (300 meters) in thickness. The quality of water is variable but most wells sampled in the Cisco Group do not meet secondary drinking water standards. 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 (24 to 32 km) 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 ft (300 m) 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 (10^{-10} to $3.5x10^{-9}$ cm^2) (Moore and Plummer, 1922).

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 ft (60 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, 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 and Plummer, 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 groundwater to wells in northwest Jack County. Origin and stratigraphy of the sandstone units are similar to that of the Graham Formation (Nordstrom, 1988).

Illustration 2: Breckenridge Limestone of the Cisco Group capping Blach Ranch Limestone of the Thrifty Group, Jack County. (See Appendix 1 for location)

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 and Plummer, 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 groundwater 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).

Illustration 3: Avis Sandstone capping Wayland Shale, Jack County (See Appendix 1 for location)

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 deltafront, 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 (10^{-11} to over $5x10^{-9}$ cm^2) (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 downdip, 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).

Illustration 4: Ranger Limestone capping Placid Shale, Jack County (See Appendix 1 for location)

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 downdip 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 (1500 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. As with the previous formations, emphasis is placed on the sandstone aquifer facies (Nordstrom, 1988).

Illustration 5: Colony Creek Shale capped by Home Creek Limestone, Palo Pinto County (See Appendix 1 for location)

Palo Pinto Formation

The Palo Pinto Limestone is a thick, crystalline, dark gray rock made up typically of beds 2 to 6 inches (5 to 15 cms) in thickness and having a total thickness of 50 to 100 feet (15 to 30 m). It forms a prominent escarpment across Palo Pinto County and has been traced for a long distance in the Brazos Valley (Moore and Plummer, 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, located stratigraphically below the Canyon, 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 does the Strawn occur at depths of less than 5,000 feet (1500 meters). 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 ($5x10^{-11}$ to over $5x10^{-9}$ cm^2) (Core Laboratories, 1972).

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 and Plummer, 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 and Plummer, 1922).

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).

Illustration 6: Turkey Creek Sandstone, Palo Pinto County (See Appendix 1 for location)

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 (16 to 24 kms) 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 and Plummer, 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 (8 meter) thick. Village Bend Limestone is 10 ft (3 meter) thick and is finely crystalline and weathers medium light gray to yellowish gray. The Lake Pinto Sandstone is about 50ft (15 meter) 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 (1.5 meter) thick (Fisher, 1996).

Illustration 7: Lake Pinto Sandstone, Palo Pinto County (See Appendix 1 for location).

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).

Wichita Group

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 on the Northeast margin of the Midland Basin Eastern shelf (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. Mapped sandstone bodies are regionally discontinuous (Hentz and Brown, 1987).

Methods and Results

LOCAL AQUIFER CHARACTERIZATION

Because the local aquifers in the study area are not defined as either major or minor aquifers by the TWDB, there is a very limited amount of aquifer characterization data available. This report will attempt to characterize the local aquifers in the study area by analysis the hydraulic properties and examining the water quality. The hydraulic and water quality properties of the local Paleozoic aquifers in this report are based upon publicly available data for private and public wells drilled in the study area.

Hydraulic Properties Methods

The compilation of well depth, pumping rate, specific-capacity, and transmissivity for the local Paleozoic aquifers in the study area included publically available data from the following sources:

- Driller reports in the form of Access databases from the Texas Water Development Board (TWDB);
- 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) (0.38 m^3/min) with 20 ft (6 meter) of drawdown would have specific capacity of 5 gpm/ft (0.073 m^3/meter) (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:

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

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. 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.

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

Hydraulic Properties Results

The database of wells in area of the local Paleozoic 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 (35 meters) with a range of 28.9 and 498.7 feet (9 and 152 meters) and a 50th percentile depth of 90 feet (27 meters); 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 (0.083 m^3/min) with a 50th percentile of 20 gpm (0.076 m^3/min); and a mean drawdown of 46.5 feet (13 meters) with a 50th percentile of 20 feet (6 meters).

The specific capacity and related transmissivity for all wells are log-normally distributed and have a 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%.

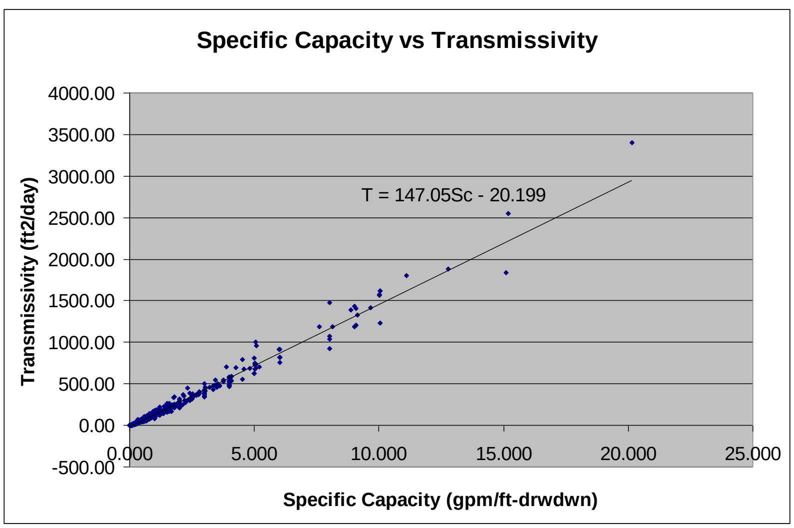
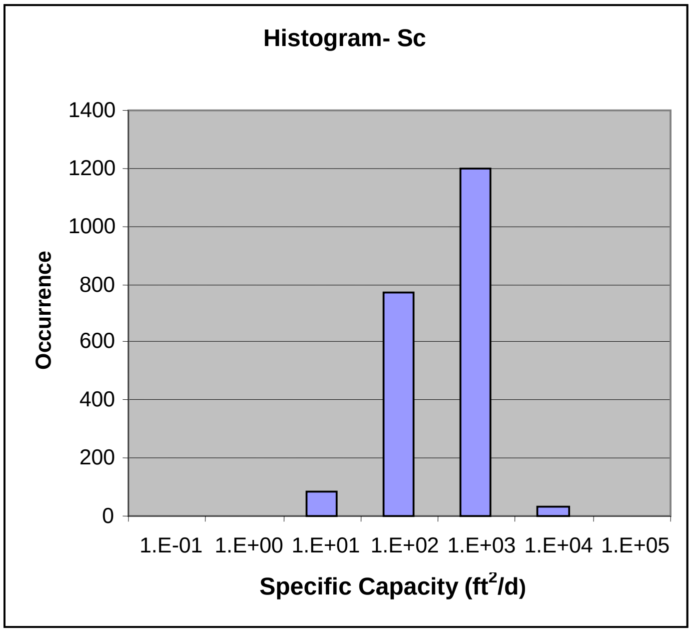


Figure 11: Specific Capacity vs. Transmissivity

The specific capacity ranges from 0.1 to 5 gpm/ft-drawdown (3.8×10^{-4} to 2×10^{-2} m^2/min) with a mean of 1.05 gpm/ft (4×10^{-3} m^2/min) and a 50th percentile of 0.7 gpm/ft

(2.6×10^{-3} m^2/min). Transmissivity ranges from 4 to 420 ft^2/day (0.37 to 39 m^2/day) with a mean of 133 ft^2/day (12.4 m^2/day) and a 50th percentile of 80 ft^2/day (7.4 m^2/day).



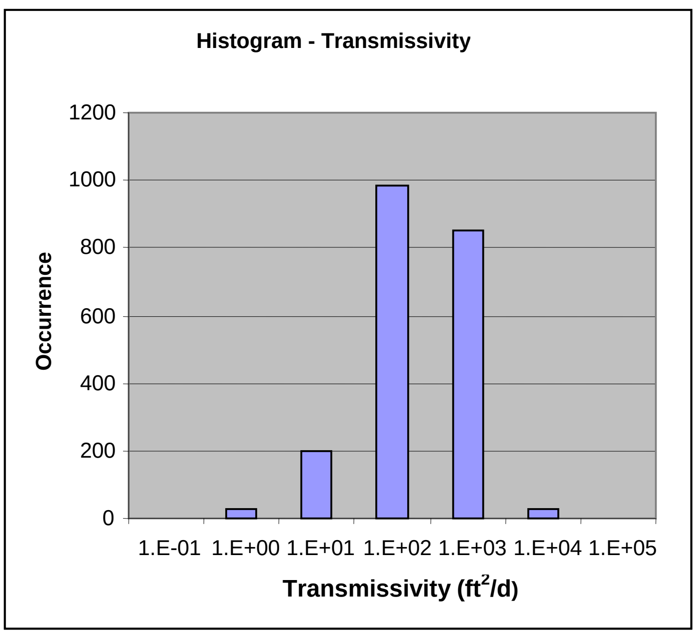


Figure 12: Histograms for specific capacity and transmissivity

Rank	Well Depth (ft)	Well Dia. (in.)	Pumping Rate (gpm)	Draw-down (ft)	Pump Test Time (hr)	Specific Capacity (gpm/ft drawdown)	Specific Capacity (ft2/day)	Transmissi-vity (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 Require-ments			**> 50**					

Table 3: Study area well data percentile distribution, range and mean.

The Paleozoic aquifers of the study area are 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 (0.38 m^3/min) requiring the use of multiple wells. The specific capacity of the local Paleozoic aquifers range mostly between 0.10 and 5.0 gpm/ft-drawdown ($3.8x10^{-4}$ to $2x10^{-2}$ m^2/min), which indicates significant drawdown of the local Paleozoic aquifers will be required to achieve the 100 gpm (0.38 m^3/min) pumping rate preferred by the hydraulic fracturing industry. To establish a pump rate of 100 gpm (0.38 m^3/min), the drawdown would expect to range between 20 feet and 1000 feet (6 and 305 meters). Groundwater quality in the local Paleozoic aquifers generally contains between 300 and

3800 mg/L TDS, well under the industry fracking 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 fracking.

As the local Paleozoic 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 Geographic Information System (GIS) using the 5-digit zip codes provided for each well (Figures 13-16). 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.

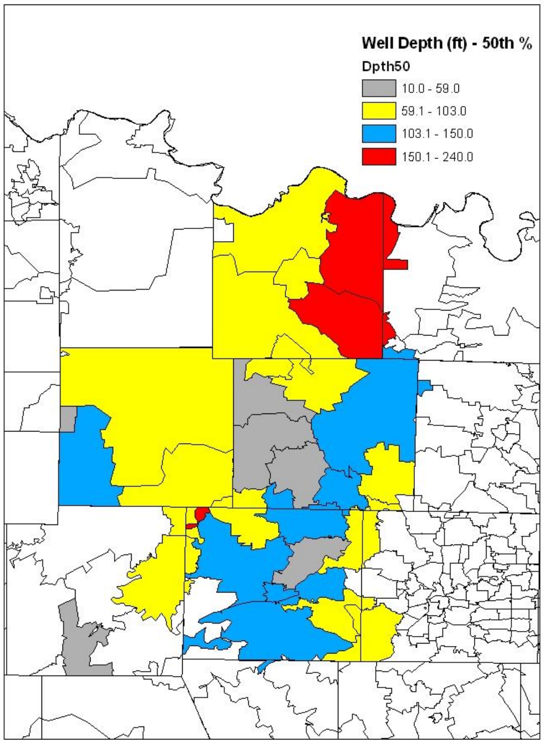


Figure 13: Well depth by zip code for local Paleozoic aquifers

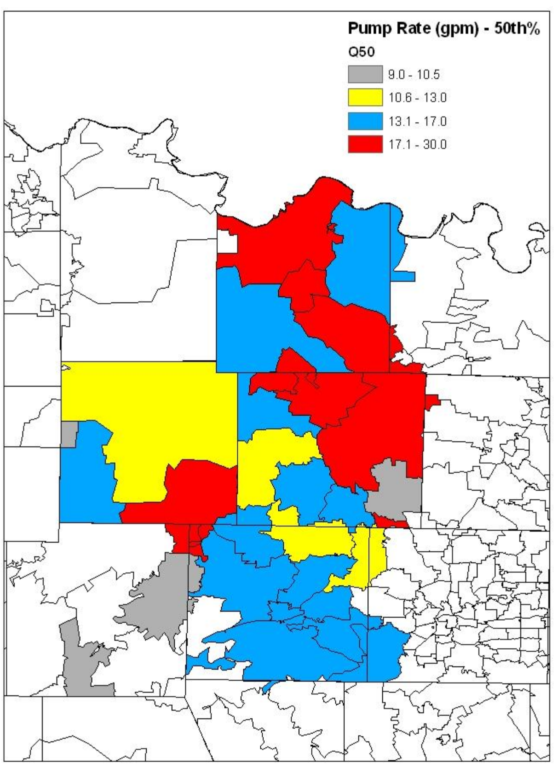


Figure 14: Pump rate by zip code for local Paleozoic aquifers

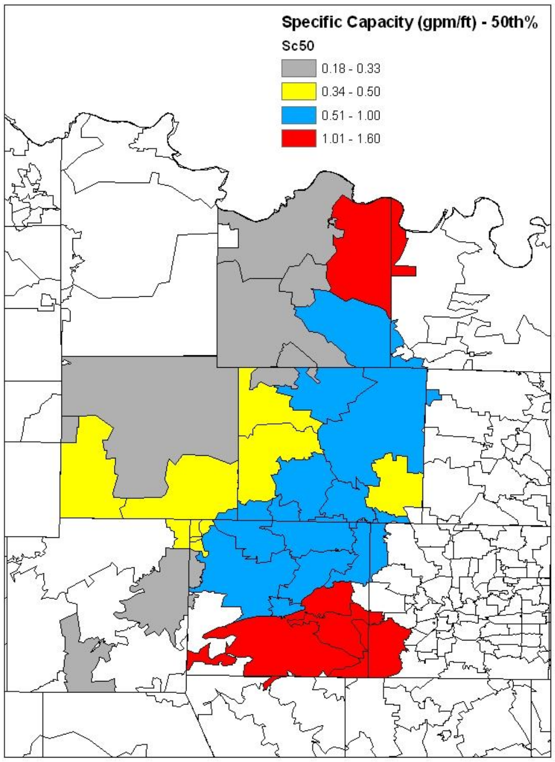


Figure 15: Specific capacity by zip code for local Paleozoic aquifers

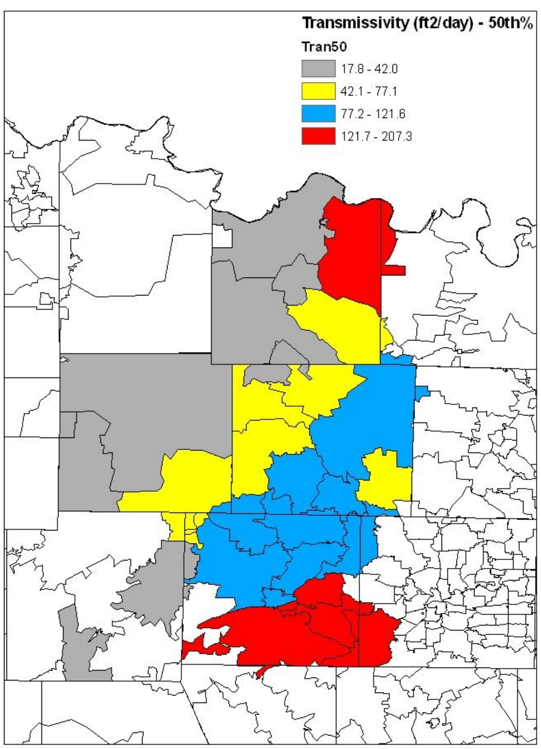


Figure 16: Transmissivity by zip code for local Paleozoic aquifers

Water Quality Methods

Water quality data for the local Paleozoic aquifers was 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 (TWDB, 2011). TWDB well data is submitted by drilling companies via the online Texas Well Report Submission and Retrieval System (Texas Department of Licensing and Regulation, 2011).

Well data was collected on the concentration (in milligrams per liter) for all major cations and anions as well as the water's total dissolved solids (TDS) and pH. The groundwater chemistry of the local Paleozoic aquifers were analyzed using Durov plots. The Durov plot is used to represent the dissolved constituents (major cations and major anions) of local aquifer groundwater and to demonstrate the hydro-chemical processes occurring within the hydrological systems.

Water Quality Results

The groundwater chemistry data was collected for all the local Paleozoic and alluvium aquifers in the study area and summarized for the key water quality components of concern for hydraulic fracturing operators, including; bicarbonate, sulfate, chloride and calcium levels, pH, TDS, alkalinity and specific conductivity (Table 4). The data was sorted by five percentile rank levels, including 5th, 30th, 50th, 70th and 95th percentiles, as well as minimum and maximum values for each water chemistry component. These results where compared against the hydraulic fracturing industry requirements as discussed earlier in this report.

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 4: Local Paleozoic aquifers water quality

Groundwater salinity in the local Paleozoic aquifers generally ranges between 300 and 3800 mg/L TDS, well under the industry fracking requirement of less than 20,000 mg/L TDS. pH levels range between 9 and 7, which is outside the industry requirement of less than 8 for fracking, however, pH levels can be easily adjusted by adding acid.

When plotting all the local Paleozoic aquifers together on a Durov plot many of the aquifers demonstrated similar water chemistry. The Durov plot showed the groundwater in the local Paleozoic 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.

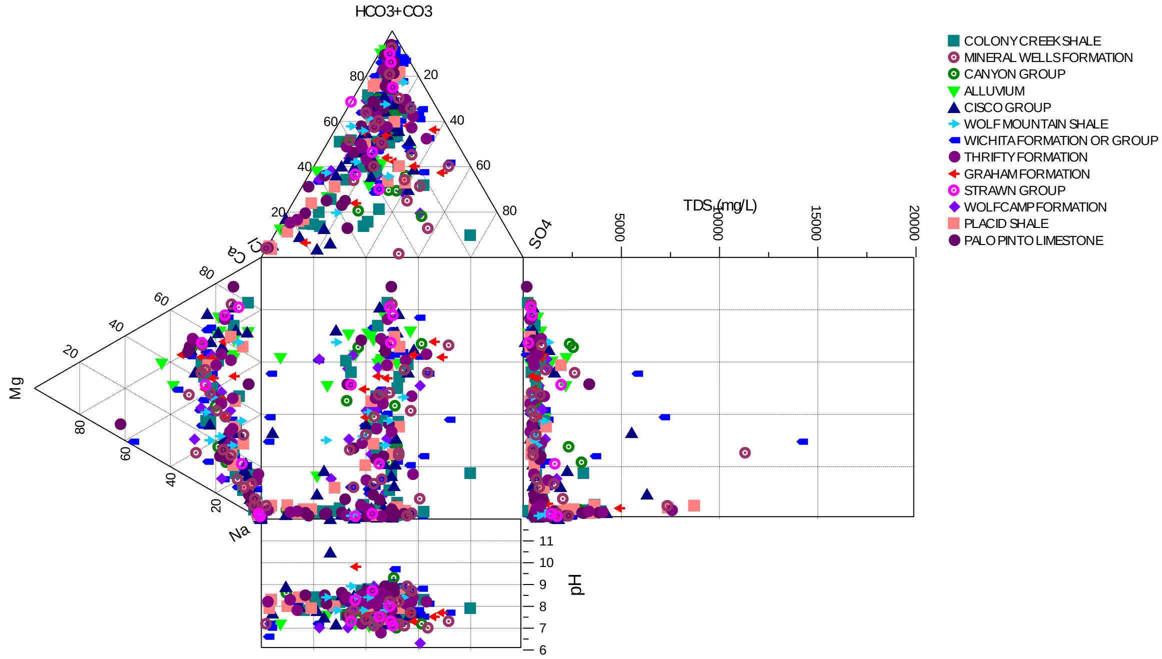


Figure 17: Durov plot of all local Paleozoic aquifers in study area

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 (6 and 60 meters) below land surface. Groundwater quality in the Alluvium aquifers are generally good containing between 300 and 3000 mg/L TDS, well under the industry fracking 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 within the industry requirement of less than 8 for fracking.

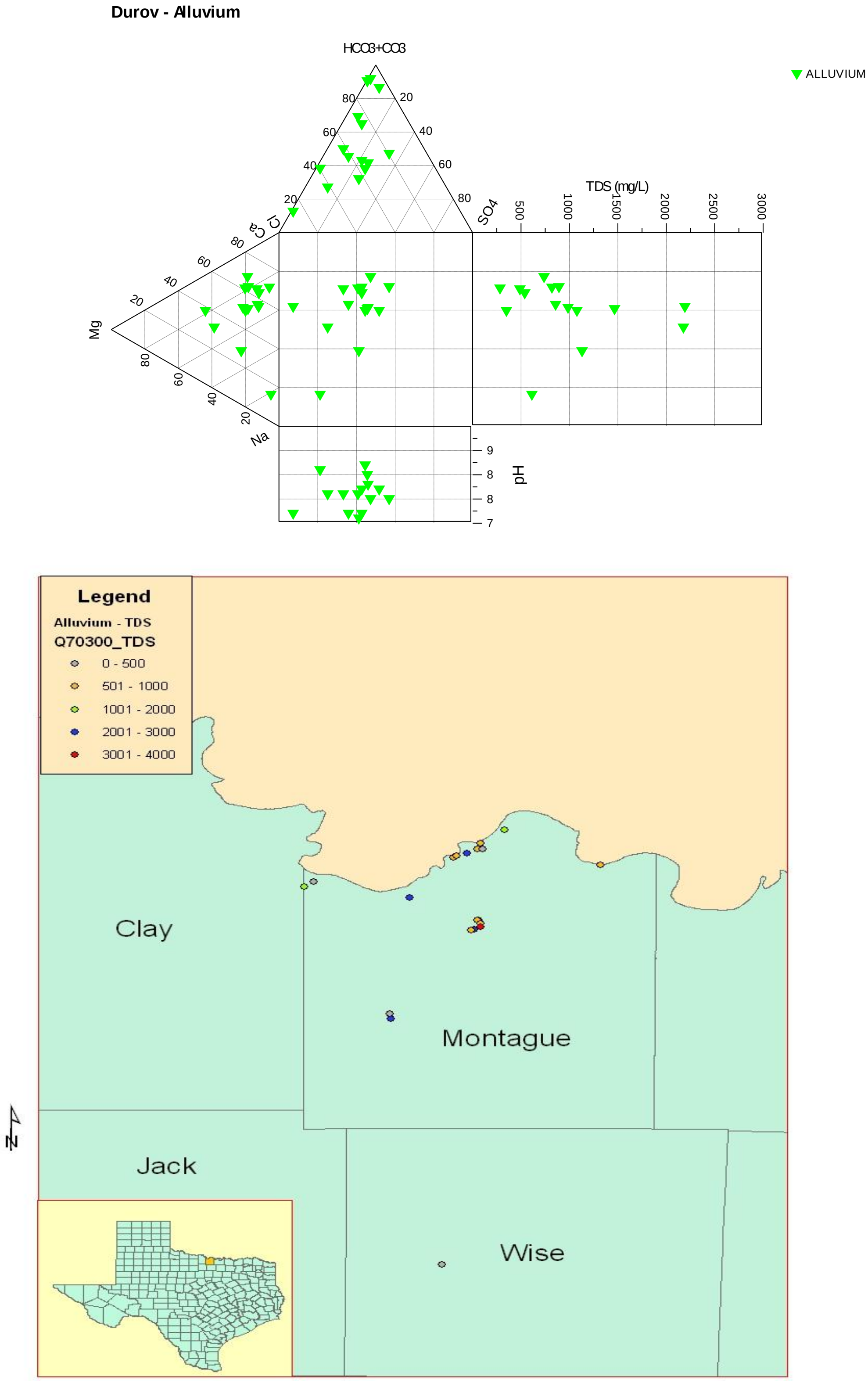


Figure 18: Alluvium Durov plot and TDS levels

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**			

Table 5: Alluvium wells water chemistry

The Durov plot (Figure 18) shows that the alluvium groundwater is predominately composed of bicarbonate and chloride anions, and sodium and calcium cations. The pH levels of the alluvium groundwater 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.

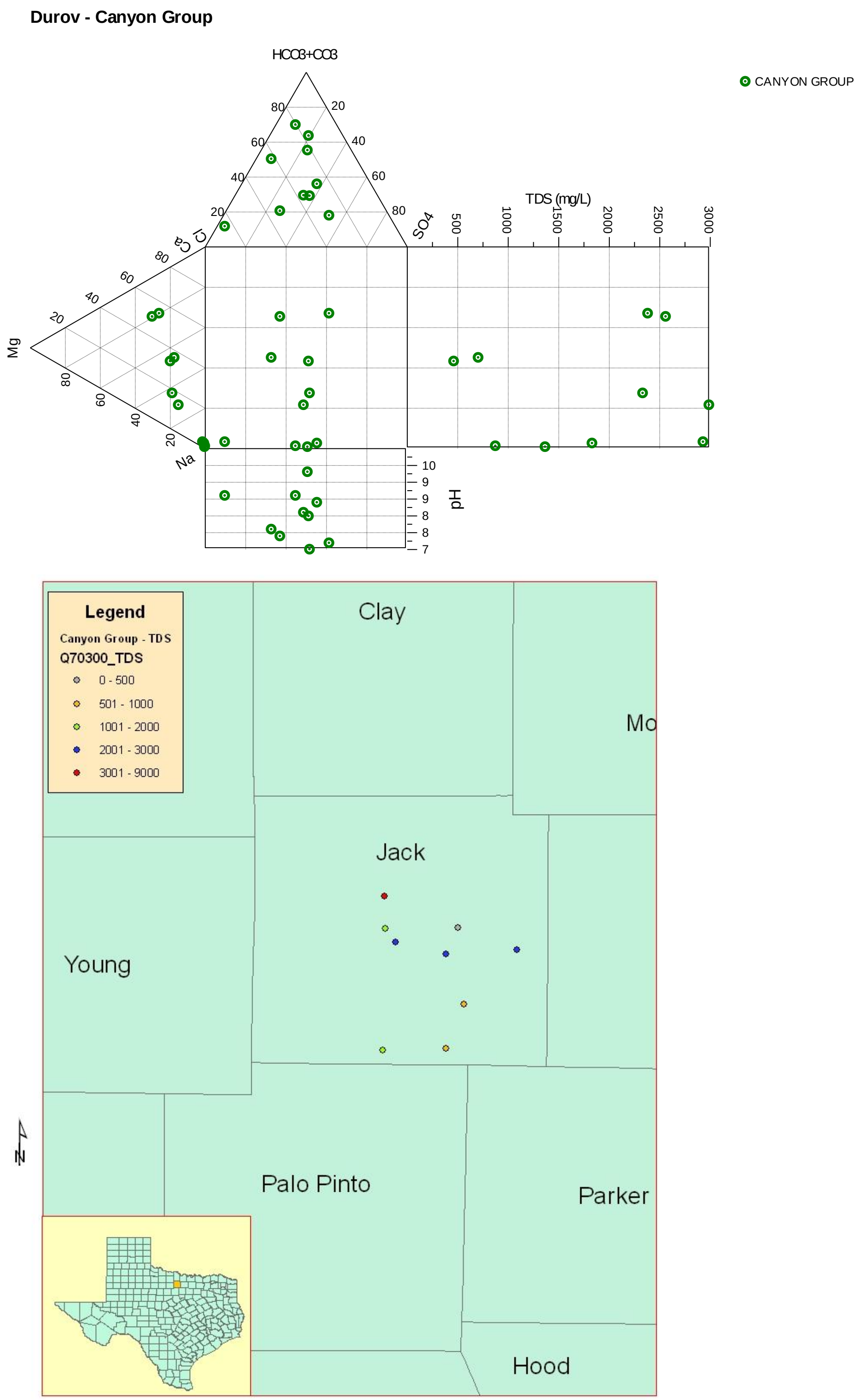


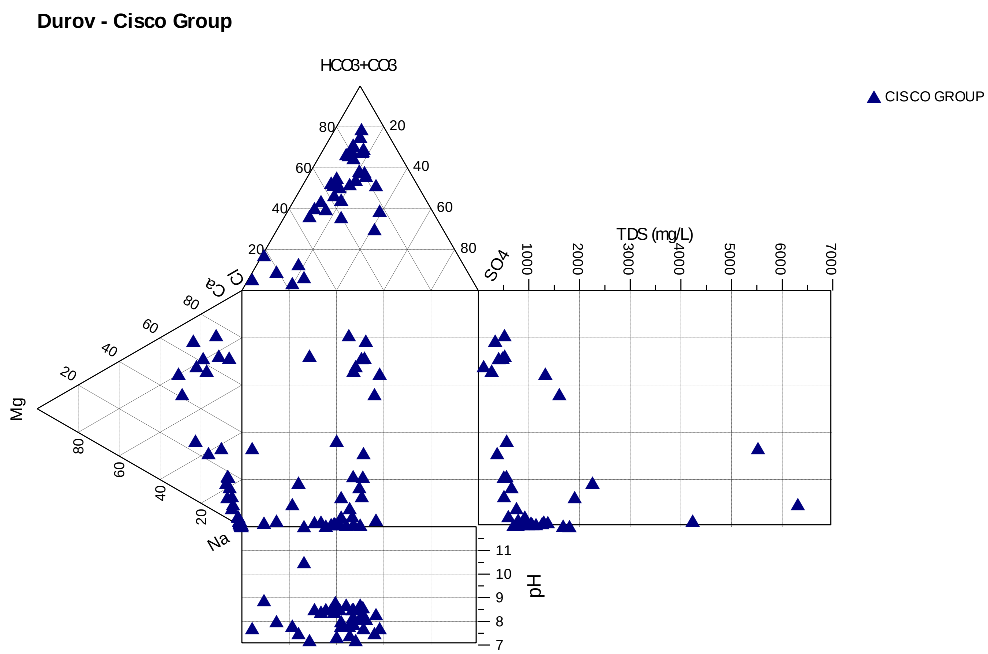
Figure 19: Canyon Group Durov plot and TDS levels

Canyon Group									
Rank	**Bicarb (mg/l)**	**Sulfate (mg/l)**	**Chloride (mg/l)**	**Calcium (mg/l)**	**pH**	**TDS**	**Alkalinity**	**Spec Cond**	**Well Depth (ft.)**
95th percentile	786	899	3305	423	9	5745	728	11856	638
70th percentile	642	526	610	142	8	2559	540	4867	320
50th percentile	428	225	415	92	8	2331	351	3500	280
30th percentile	395	95	192	27	7	1365	324	2512	105
5th percentile	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**			

Table 6: Canyon Group water chemistry

The Canyon Group aquifer is located in the eastern part of Jack County. Well depths range mostly between 50 and 600 feet (15 and 180 meters) below land surface. Groundwater quality in the Canyon Group generally contains between 500 and 5000 mg/L TDS, well under the industry fracking 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 fracking.

The Durov plot (Figure 19) 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.



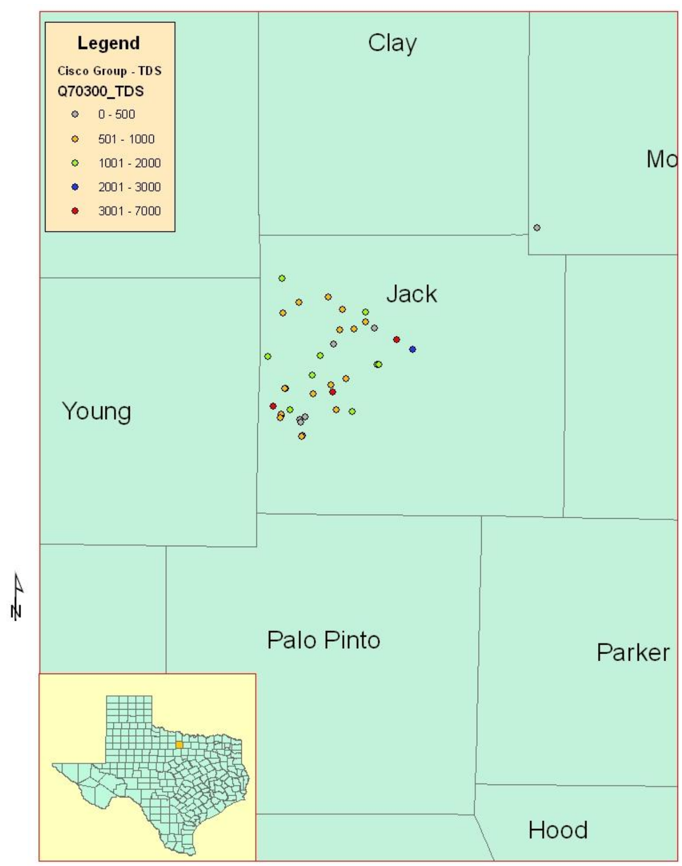


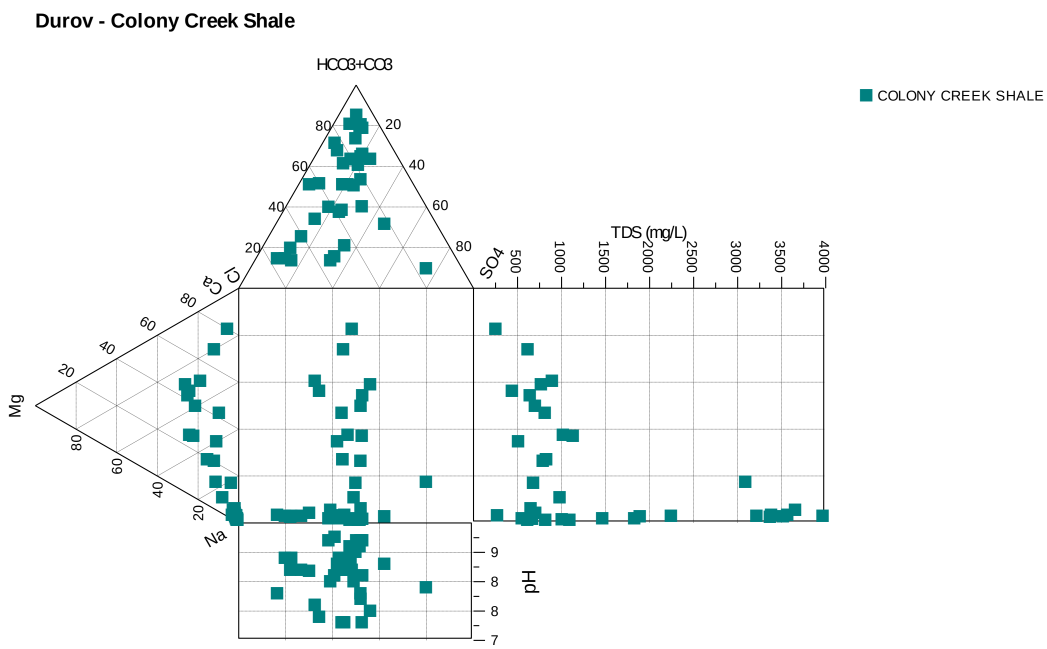
Figure 20: Cisco Group Durov plot and TDS levels

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			

Table 7: Cisco Group water chemistry

The Cisco Group aquifer is located in the western part of Jack County. Well depths range mostly between 70 and 500 feet (20 and 150 meters) below land surface. Groundwater quality in the Cisco Group generally contains between 300 and 4500 mg/L TDS, well under the industry fracking 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 fracking.

The Durov plot (Figure 20) 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.



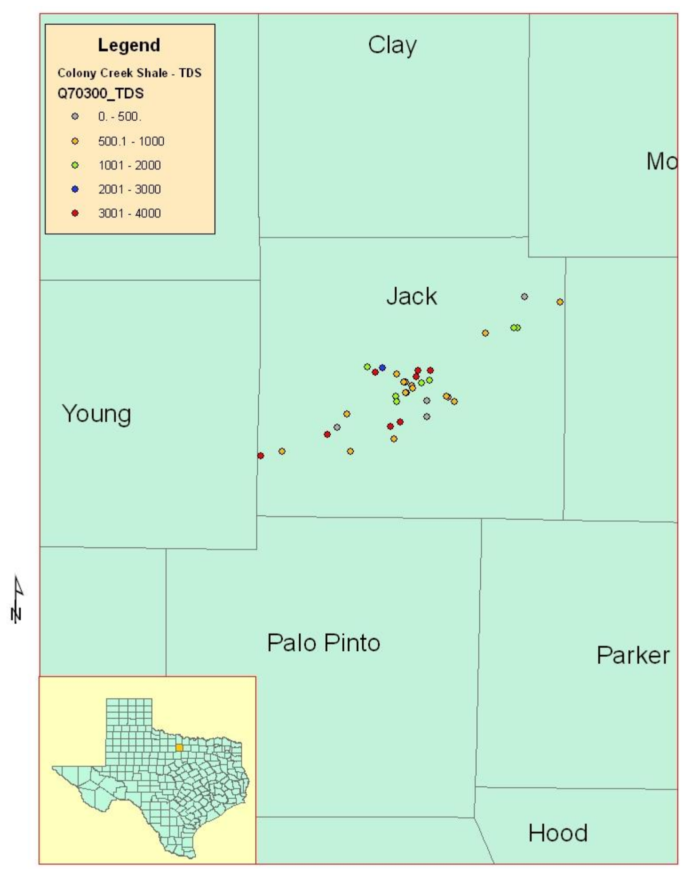


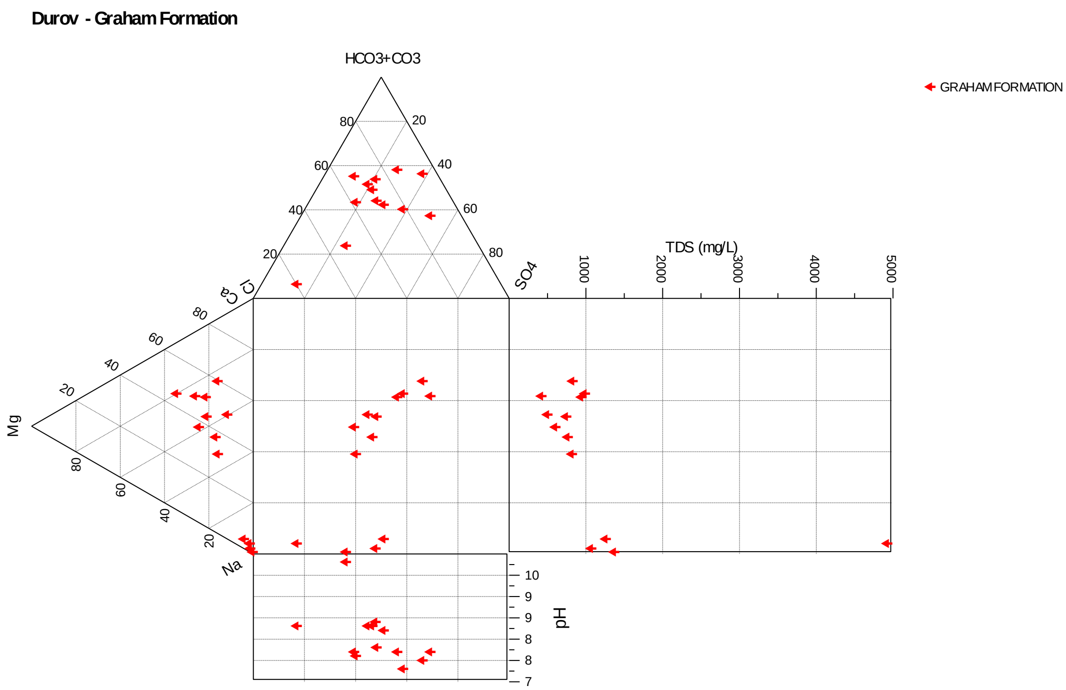
Figure 21: Colony Creek Shale Durov plot and TDS levels

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**			

Table 8: Colony Creek water chemistry

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 (25 and 120 meters) below land surface. Groundwater quality in the Colony Creek generally contains between 400 and 3500 mg/L TDS, well under the industry fracking 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 fracking.

The Durov plot (Figure 21) 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.



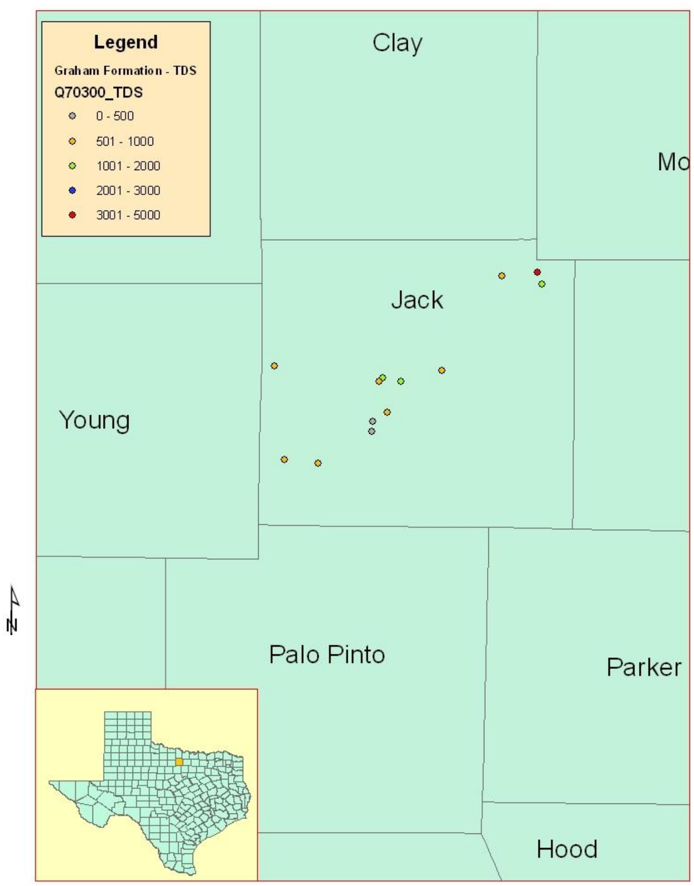


Figure 22: Graham Formation Durov plot and TDS levels

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**			

Table 9: Graham Formation water chemistry

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 (6 and 90 meters) below land surface. Groundwater quality in the Graham Formation generally contains between 400 and 2800 mg/L TDS, well under the industry fracking 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 fracking.

The Durov plot (Figure 22) 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.

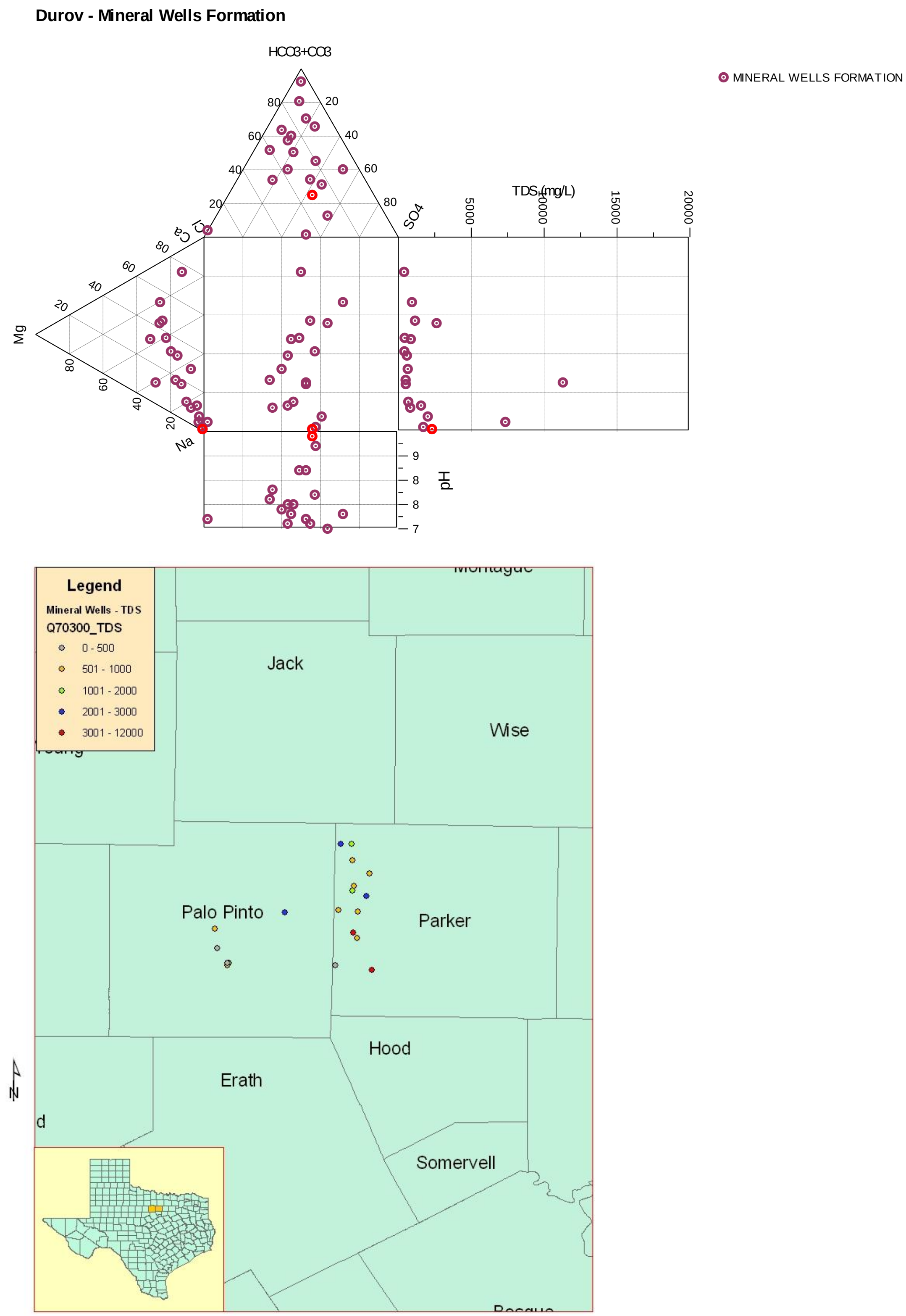


Figure 23: Mineral Wells Durov plot and TDS levels

Mineral Wells									
Rank	Bicarb (mg/l)	Sulfate (mg/l)	Chloride (mg/l)	Calcium (mg/l)	pH	TDS	Alkalinity	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			

Table 10: Mineral Wells water chemistry

The Mineral Wells aquifer is located in western Parker County and eastern Palo Pinto County. Well depths range mostly between 30 and 400 feet (9 and 120 meters) below land surface. Groundwater quality in the Mineral Wells aquifer generally contains between 400 and 8000 mg/L TDS, well under the industry fracking 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 fracking.

The Durov plot (Figure 23) 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.

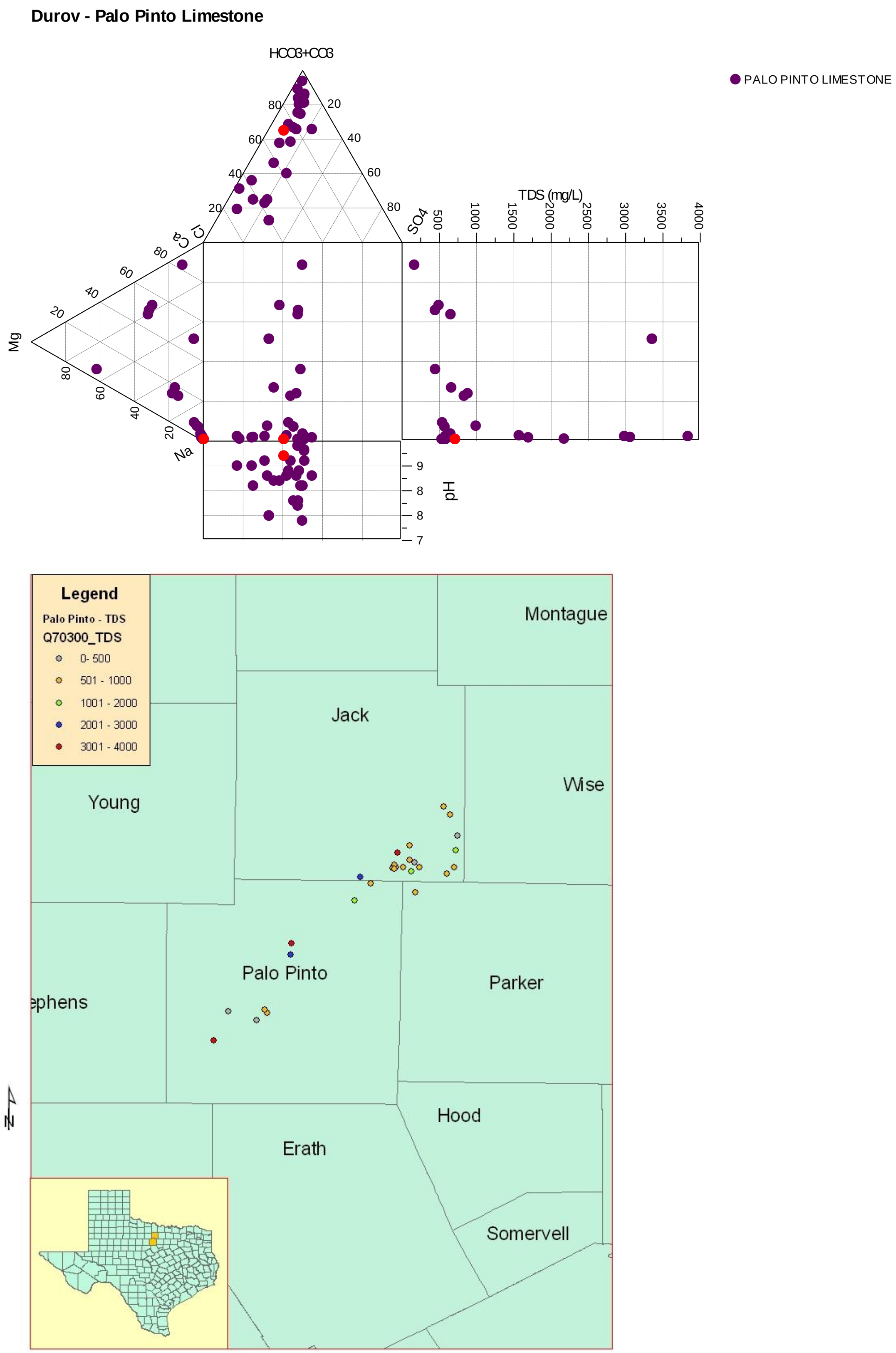


Figure 24: Palo Pinto Durov plot and TDS levels

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**			

Table 11: Palo Pinto Limestone water chemistry

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 (9 and 110 meters) below land surface. Groundwater quality in the Palo Pinto aquifer generally contains between 400 and 3500 mg/L TDS, well under the industry fracking 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 fracking.

The Durov plot (Figure 24) 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.

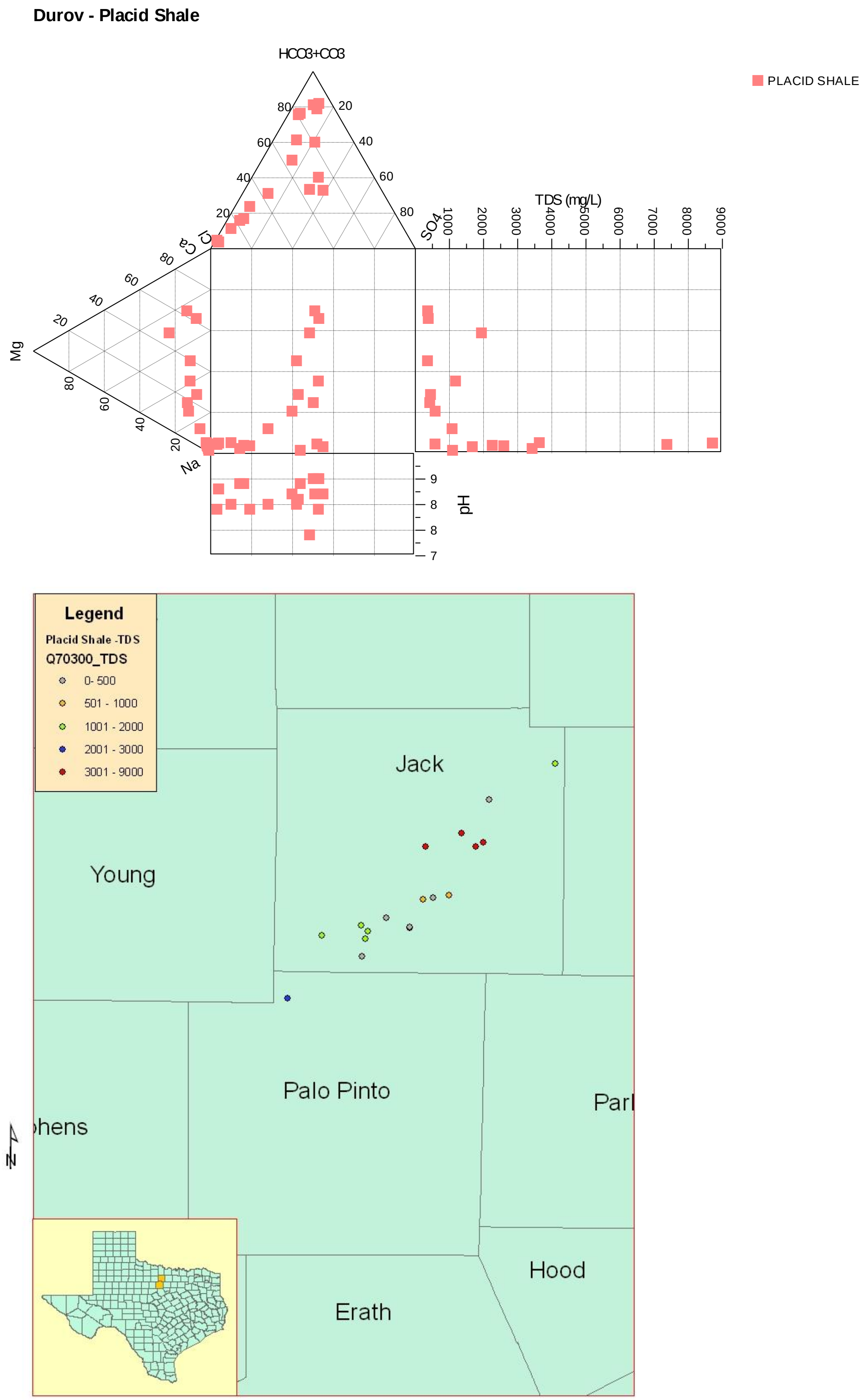


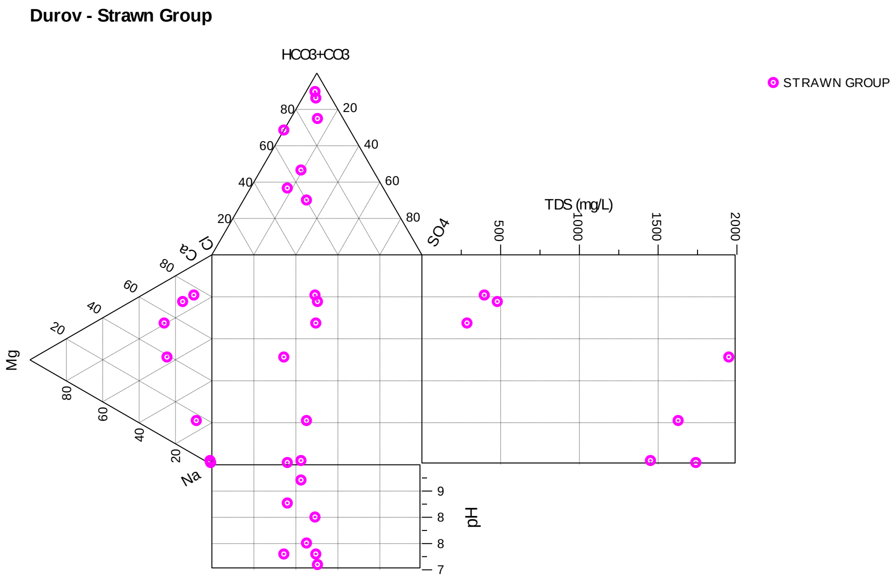
Figure 25: Placid Shale Durov plot and TDS levels

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**			

Table 12: Placid Shale water chemistry

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 (30 and 135 meters) below land surface. Groundwater quality in the Placid Shale generally contains between 350 and 9000 mg/L TDS, well under the industry fracking 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 fracking.

The Durov plot (Figure 25) 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.



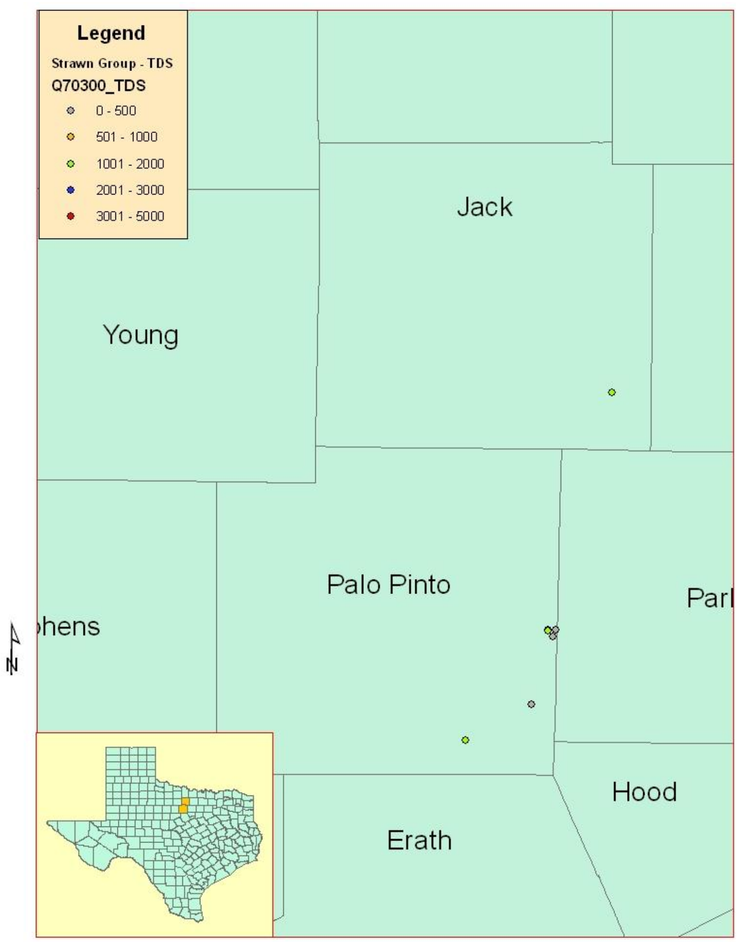
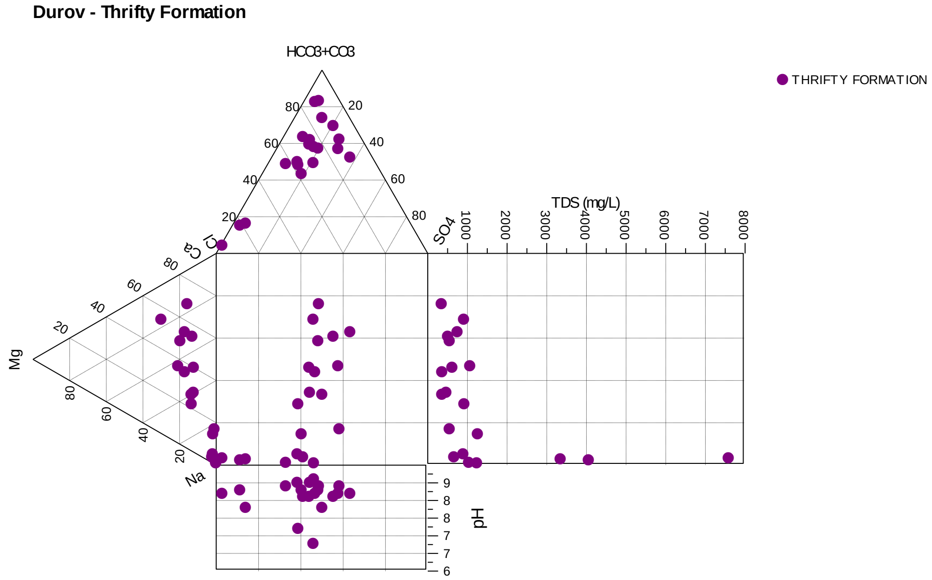


Figure 26: Strawn Group Durov plot and TDS levels

The Strawn Group is located primarily in southeast Jack and Palo Pinto Counties running along a diagonal from the southwest to northeast. The Durov plot (Figure 26) shows that the Strawn Group groundwater is predominately bicarbonate and chloride anions and sodium and calcium cations. The pH levels of the Strawn Group groundwater ranges from 7 to 9. The concentrations of dissolved solids are grouped around 500 mg/L with a range of 400 to 2000 mg/L.



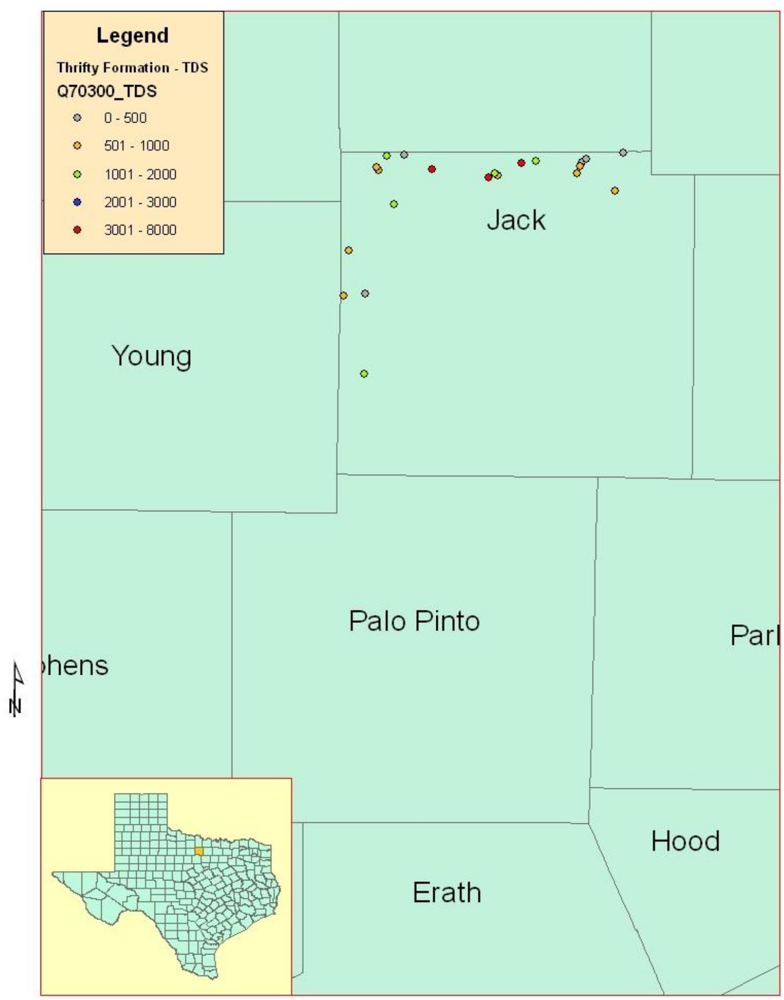


Figure 27: Thrifty Formation Durov plot and TDS levels

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			

Table 13: Thrifty Formation water chemistry

The Thrifty Formation is located along the northern and eastern border area of Jack County. Well depths range mostly between 100 and 300 feet (30 and 90 meters) below land surface. Groundwater quality in the Thrifty Formation generally contains between 300 and 4000 mg/L TDS, well under the industry fracking 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 fracking.

The Durov plot (Figure 27) 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.

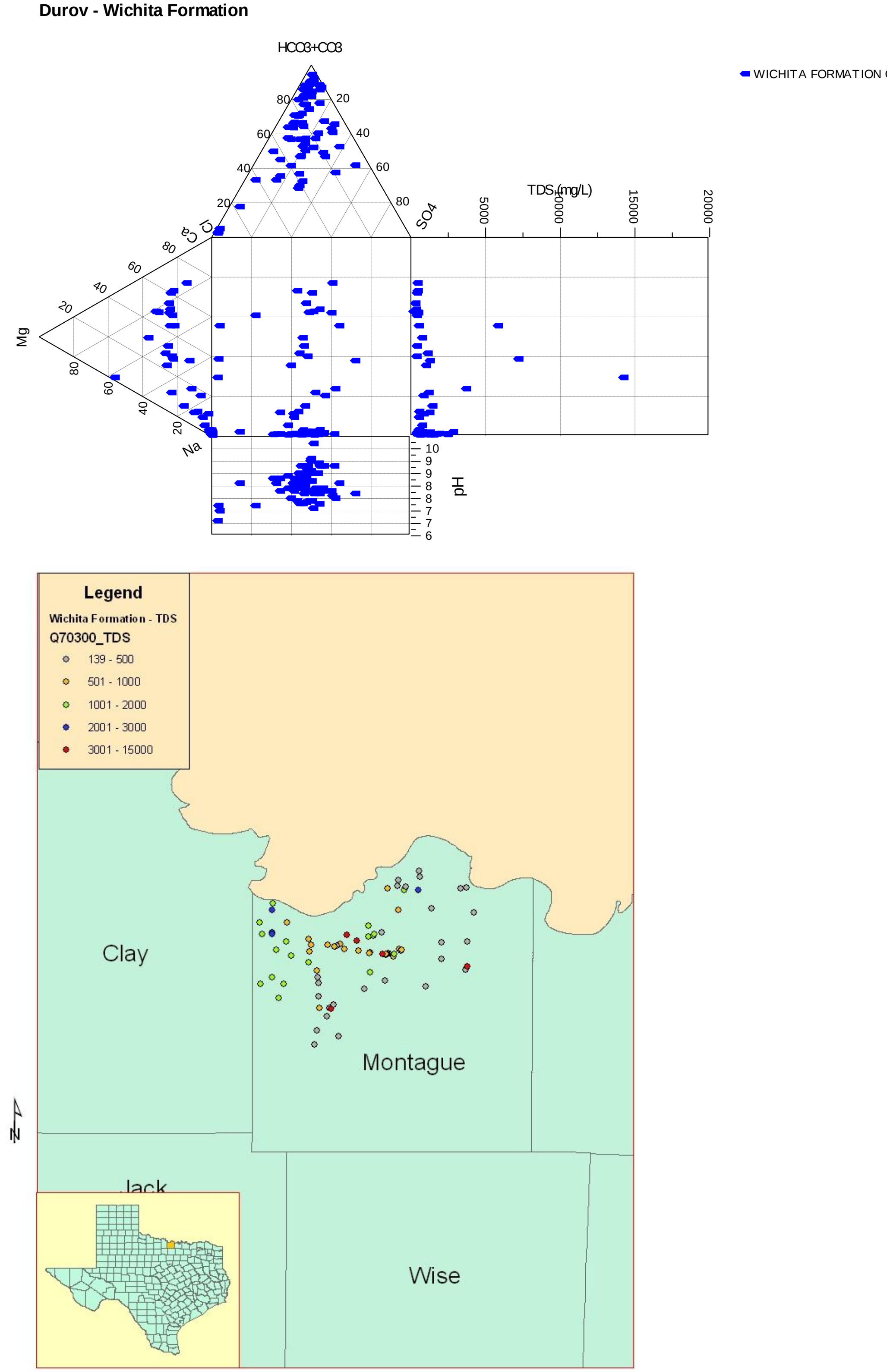


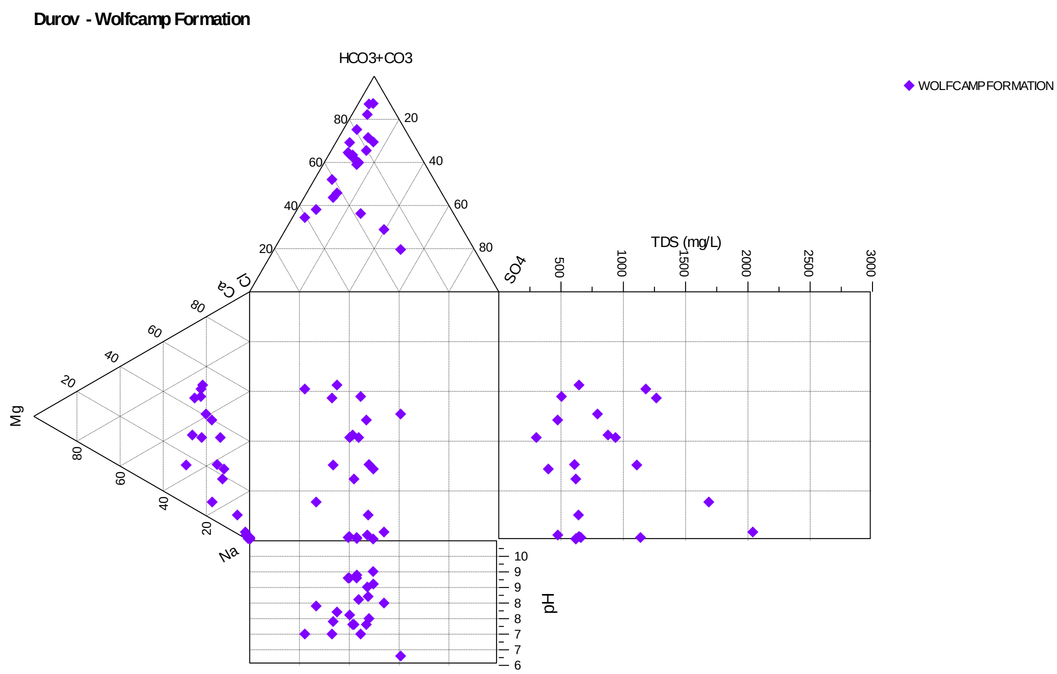
Figure 28: Wichita Formation Durov plot and TDS levels

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**			

Table 14: Wichita Formation water chemistry

The Wichita Formation is located in central and northwestern Montague County. Well depths range mostly between 70 and 500 feet (20 and 150 meters) below land surface. Groundwater quality in the Wichita Formation generally contains between 300 and 3300 mg/L TDS, well under the industry fracking 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 fracking.

The Durov plot (Figure 28) 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.



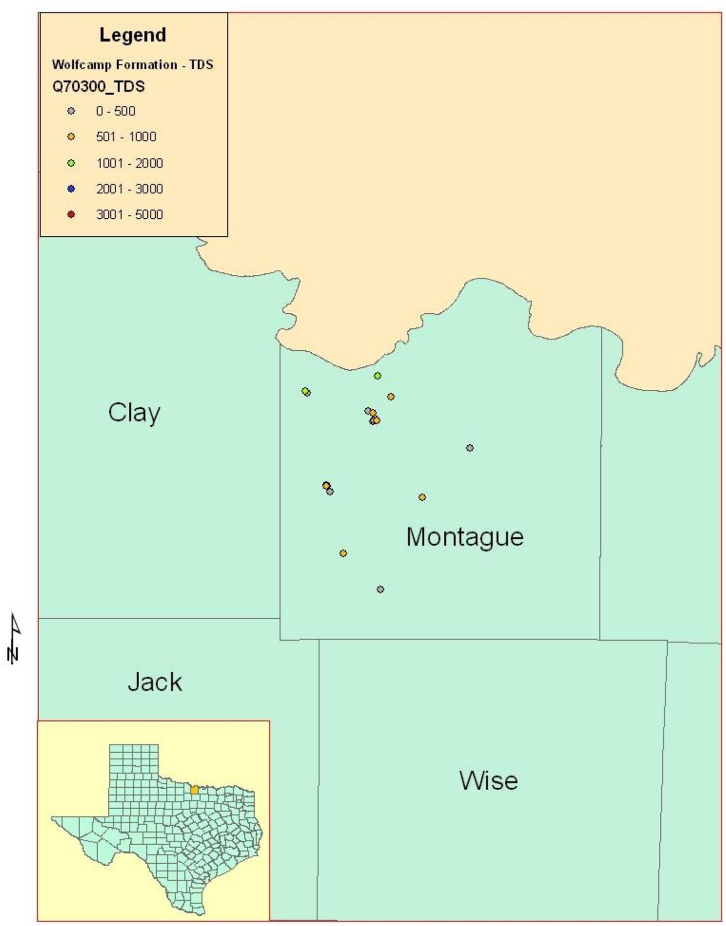


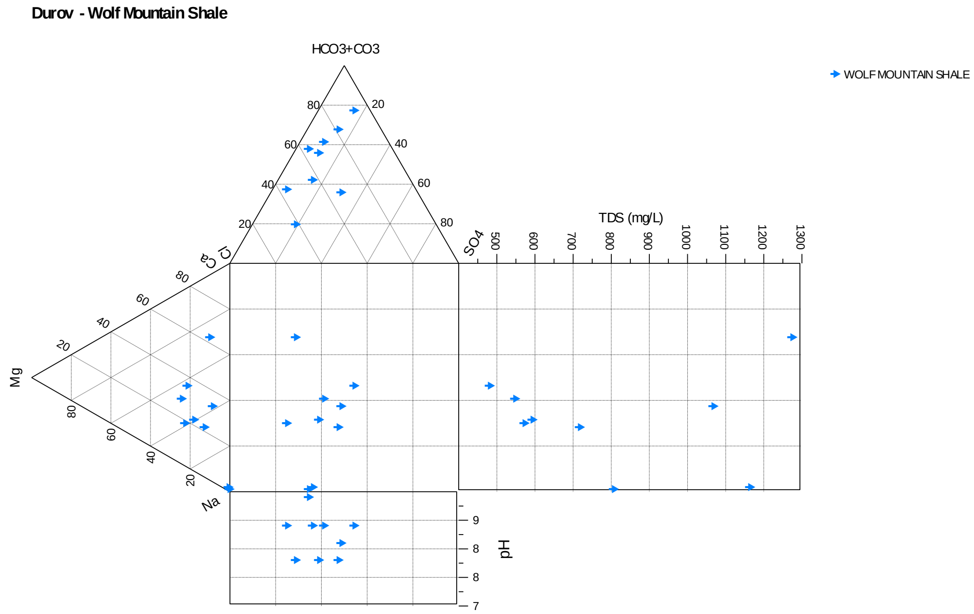
Figure 29: Wolfcamp Formation Durov plot and TDS levels

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**			

Table 15: Wolfcamp Formation water chemistry

The Wolfcamp Formation is located in central and western Montague County. Well depths range mostly between 30 and 400 feet (10 and 120 meters) below land surface. Groundwater quality in the Wolfcamp Formation generally very good containing between 400 and 1700 mg/L TDS, well under the industry fracking 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 fracking.

The Durov plot (Figure 29) 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.



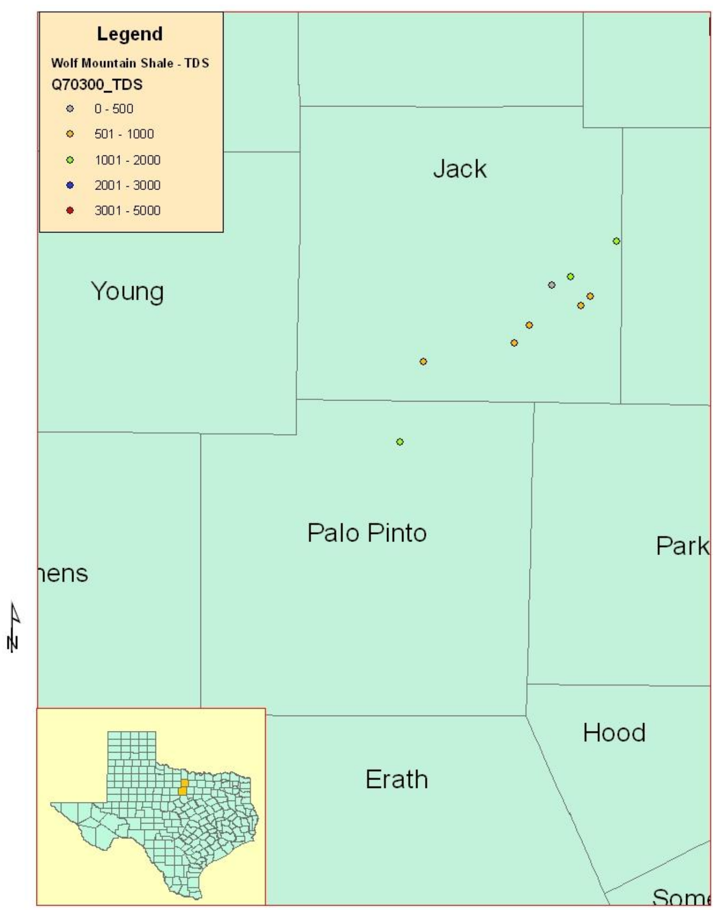


Figure 30: Wolf Mountain Shale Durov plot and TDS levels

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			

Table 16: Wolf Mountain Shale water chemistry

The Wolf Mountain Shale aquifer is located in the southeastern corner of Jack County. Well depths range mostly between 70 and 530 feet (20 and 160 meters) 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 fracking 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 fracking.

The Durov plot (Figure 30) 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.

IMPLICATIONS FOR LOCAL GROUNDWATER RESOURCE MANAGEMENT

As the Barnett Shale gas play expands west beyond the reach of the Cretaceous aquifers including the Trinity, gas operators will have to utilize multiple alternative sources for frac water including recycle produced water, surface water, transported water and regional minor aquifers. With regards to the local minor aquifers the operators will need to work closely with local groundwater management stakeholders to assure that this limited resource is maintained.

Aquifers, even small ones, do contain large volumes of water. However, most of it is not accessible without the potential for severe consequences including the drying-up of springs, decreasing base flow to streams, the disappearance of phreatophytes, subsidence, and the need to lower well pumps (Nicot, 2012). Local groundwater conservation districts responsible for the Paleozoic minor aquifers in North Central Texas and their respective GMA’s need to meet with all stakeholders including ranchers, local municipalities and the oil and gas industry to developed a manageable set of Desired Future Conditions (DFC’s). One key element of the DFC’s for the local Paleozoic minor aquifers will be the acceptable water volumes to withdraw for each aquifer which would result in an agreed-upon average drawdown.

A recent study by the Bureau of Economic Geology (Nicot, 2012) computed the pumping level, including hydraulic fracturing operations and all other regular pumping demands, corresponding to an average drawdown of 5 feet (1.5 meters) in 50 years (in 2060). However, as displayed in Table 17 and depicted in Figures 31-34, drawdowns are not constant throughout the area (Nicot, 2012). The drawdown by group layer ranges from a minor amount of only 3 feet (1 meter) over 50 years for the Strawn Group and a more significant and potentially consequential drawdown of over 14 feet (4 meters) for the Wichita Group.

Summary of simulated drawdown by group layer

Layer#	Layer Name	Mean Drawdown (ft)	Maximum Drawdown (ft)	Cell Count
1	Wichita	14.1	72	3168
2	Cisco	6.2	174	15,703
3	Canyon	3.9	95	8773
4	Strawn	3.0	633*	17,695
Weighted Average (ft)		**5.06**		45,339

*: the presence of dry cells in the model towards the end of the runs makes this maximum dubious and not necessarily realistic

Table 17: Summery of simulated drawdown by group layer (Nicot, 2012)

The greatest potential for significant drawdown was identified for the Wichita Group located primarily in Montague County of the study area and Clay County west of the study area and south of the Red River with a mean drawdown of over 14 feet (4 meters) and a maximum drawdown of 72 feet (23 meters). This level of drawdown could have a potential impact on local wells and springs over time, including the need to lower well pumps and decreased spring flow.

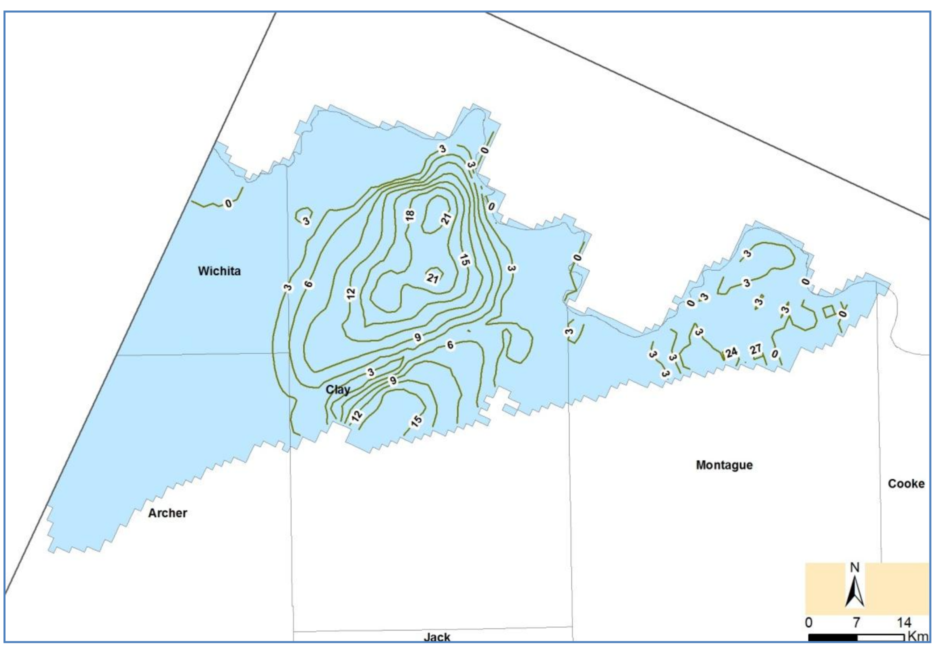


Figure 31: Simulated drawdown between 2010 and 2060 (3 m contour interval) for Wichita Group layer (Nicot, 2012).

The Cisco Group's potential for drawdown was close to the mean for all local Paleozoic Aquifers at just over 6 feet (2 meters) and a very significant maximum of 174 feet (55 meters). The area of maximum potential drawdown is concentrated in southwest Montague County of the study area and to a less extent in southeast Clay County west of the study area. While the mean drawdown is not significant, the maximum drawdown could have a significant negative impact on local wells and springs in a very limited area of Montague County.

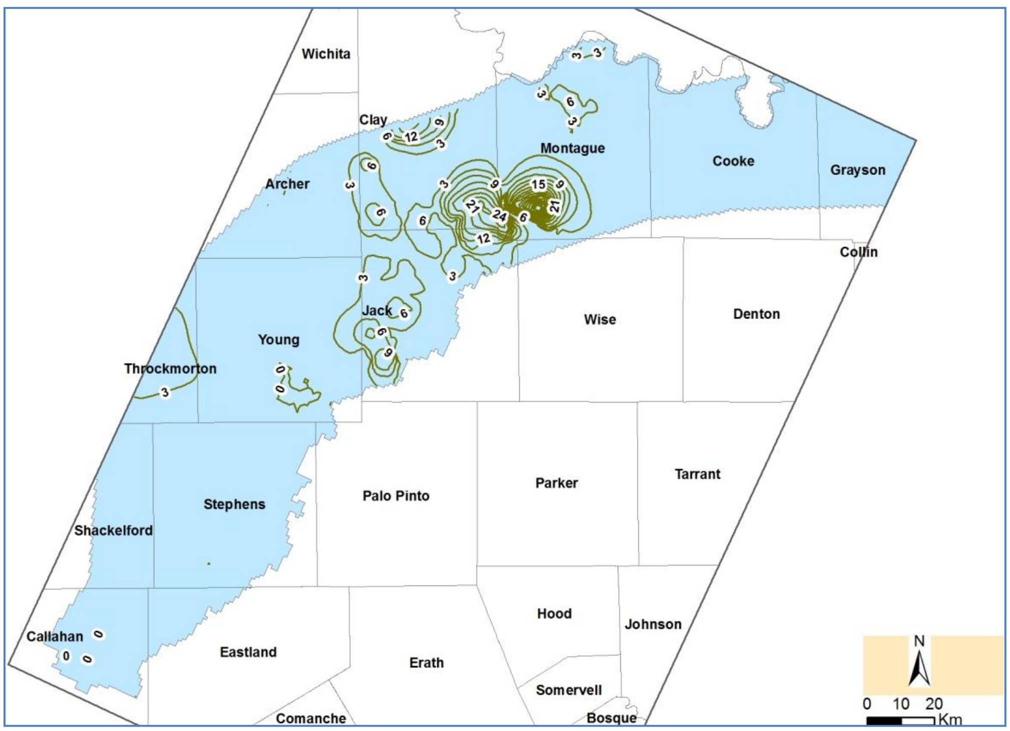


Figure 32: Simulated drawdown between 2010 and 2060 (3 m contour interval) for Cisco Group layer (Nicot, 2012)

The mean drawdown potential of 4 feet (1 meter) for the Canyon group is not significant over 50 years and is well distributed over the extent of the aquifer in Jack, Palo Pinto, and Wise counties of the study area.

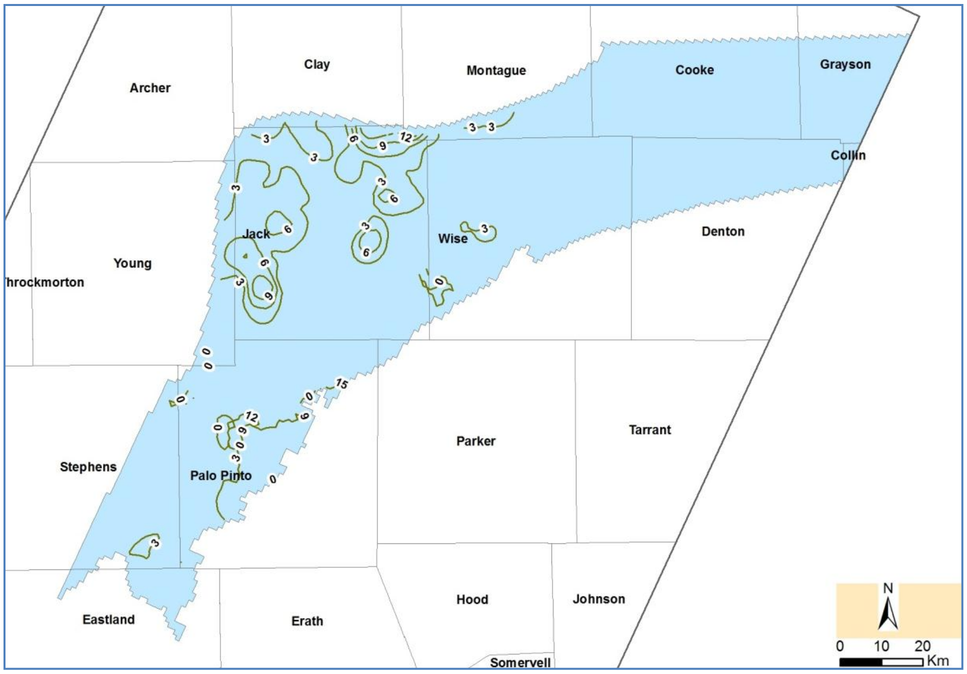


Figure 33: Simulated drawdown between 2010 and 2060 (3 m contour interval) for Canyon Group layer (Nicot, 2012).

The mean drawdown potential of 3 feet (1 meter) for the Strawn group is not significant over 50 years and is concentrated primarily in Palo Pinto and Erath counties of the study area. The very high potential maximum drawdown for the Strawn Group is due to the presence of dry cells in the model resulting in a unrealistic value.

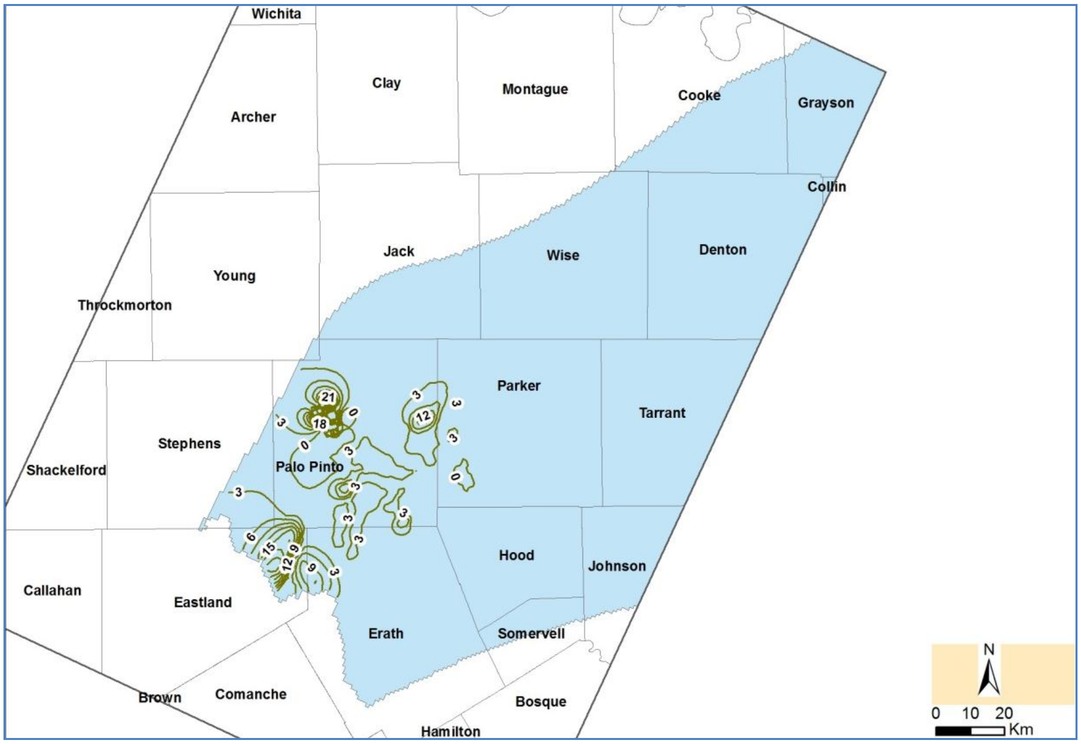


Figure 34: Simulated drawdown between 2010 and 2060 (3 m contour interval) for Strawn Group layer (Nicot, 2012).

Conclusion

The local Paleozoic aquifers of North-Central Texas, on the western edge of the Barnett Shale gas play (located primarily in Montague, Jack, Palo Pinto, Wise, and Parker counties), can provide an alternative source of water for oil and gas development in the area. While the hydraulic properties of the Paleozoic aquifers are considerably less productive than the Barnett Shale gas developers have experienced with the Trinity Aquifer, they can still yield sufficient volumes of water to support hydraulic fracturing operations when combined with other water resources such as surface reservoirs and recycling.

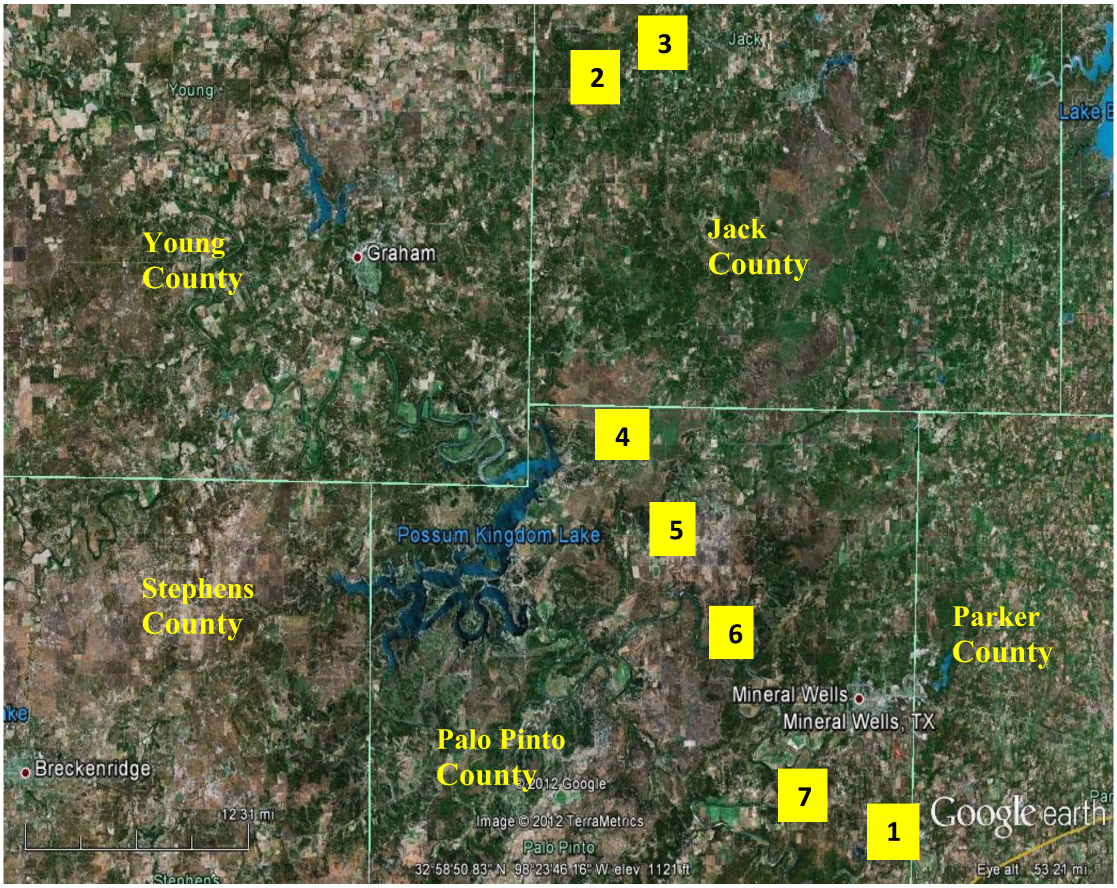
The hydraulic properties of the Paleozoic aquifers are relatively heterogeneous despite the lack of uniformity in the underlying geology of the formations. The transmissivity of the aquifers ranges from 4 to 420 ft^2/day (0.37 to 39 m^2/day) with a mean of 133 ft^2/day (12.4 m^2/day) and a 50th percentile of 80 ft^2/day (7.4 m^2/day). The specific capacities of the aquifers range from 0.1 to 5 gpm/ft-drawdown (1.8 to 90 m^3/day/meter-drawdown) with a mean of 1.05 gpm/ft (20 m^3/day/meter) and a 50th percentile of 0.7 gpm/ft (13 m^3/day/meter), indicating that a 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). Such a high drawdown would not be realistic considering the relative thicknesses of the Paleozoic formations are normally only a few hundred feet or less. Yields from wells in the Paleozoic aquifers are relatively low, ranging from less than 5 to over 60 gpm (27.3 to over 327 m^3/day) with a mean of 22 gpm (120 m^3/day). Pump rates at this level would require over 13 weeks of pumping time to accumulate in storage ponds the 3 million gallons (11,364 m^3) of water required for a gas well horizontal fracturing operation. Well depths range mostly between 30 and 500 feet (9.1 and 152.4 meters) below land surface. Groundwater quality in the local

Paleozoic aquifers generally contains between 300 and 3800 mg/L TDS, well under the industry fracking 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 hydraulic fracturing but manageable with the use of additives.

The modeled drawdown of the local Paleozoic Aquifers, based on increased levels of pumping due to hydraulic fracturing development in the study area, identified a mean drawdown of 5 feet (1.5 meters) over 50 years. While not significant over the total study area, there were concentrated pockets of concern in the study area. Particularly in Montague County, were potential mean and maximum drawdowns could have a significantly negative impact on local wells and springs over time, including the need to lower well pumps and decreased spring flow.

The small local Paleozoic aquifers of North-Central Texas are a limited resource and will have to be managed as such. The stakeholders for the aquifers, including ranchers, local municipalities, and industry will need to work together to decide of the how to manage this resource for the future and assure economic development while maintaining future sustainability.

Appendix



Appendix 1: Approximate location of Illustrations 1-7

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

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
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.	Des Moines	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	Des Moines	Strawn	shale with interbedded sandstone, limestone and conglomerate	Small quantities of water of slightly to moderately brackish water.							X			X	X			

Aquifer	System	Series	Group	Rock Characteristics	Water Bearing Characteristics	Bosque	Dallas	Denton	Erath	Hill	Hood	Jack	Johnson	Montague	Palo Pinto	Parker	Somervell	Tarrant	Wise
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					
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				
Alluvium												X		X	X	X			X

Appendix 2: Aquifer characteristics by county summary

Bibliography

Anaya, R., 2004, 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.

Ashworth, J.B., and Hopkins, J., 1995, Major and Minor Aquifers of Texas, Texas Water Development Board, Report 345, p. 18-19.

Avakian, A.J., and Wermund, E.G., 1994, Physical Environment of Fort Wolters military reservation, Parker and Palo Pinto Counties, Texas: The University of Texas at Austin, Bureau of Economic Geology, report prepared for the Texas Army National Guard, 90 p.

Baker, B., Flores, R., and Lynch, T., 1990, Evaluation of Water Resources in Part of North-Central Texas, Texas Water Development Board Report 318.

Bené, J., Griffin, S.W., Harden, B., and Nicot J., 2007, Assessment of Groundwater Use in the Northern Trinity Aquifer Due To Urban Growth and Barnett Shale Development, prepared for TWDB, November 2007.

Bradley, R.G., 1999, Updated evaluation of water resources within the Trinity Aquifer area, Central Texas, Texas Water Development Board, Report 99-03.

Bureau of Economic Geology, 1972, University of Texas at Austin, Geological Atlas of Texas, Abilene Sheet.

Bureau of Economic Geology, 1987, University of Texas at Austin, Geological Atlas of Texas, Wichita Falls-Lawton Sheet.

Bureau of Economic Geology, 1972, University of Texas at Austin, Geological Atlas of Texas, Dallas Sheet.

Crandall, C.A., and Berndt, M.P., 1996, Water Quality of Surficial Aquifers in the Georgia–Florida Coastal Plain, U.S. Geological Survey Water-Resources Investigations Report 95-4269.

Cronin, J.G., and Wilson, C.A., 1967, Groundwater in the flood-plain alluvium of the Brazos River, Whitney Dam to vicinity of Richmond, Texas: TWDB Rept. 41, 206 p.

Duffin, G.L., and Beynon, B.E., 1992, Evaluation of Water Resources in Parts of the Rolling Prairies Region of North-Central Texas, TWDB Report 337.

Fisher R.S., Mace R. E., and Boghici E., 1996, Groundwater and Surface Water Hydrology of Fort Wolters, Parker and Palo Pinto Counties, Texas.

Gas Technology Institute, 2007, Gas Technology Report – Barnett Shale Water Resources, from http://www.gastechnology.org.

Galusky, L.P., Jr., 2009, An Update and Prognosis on the Use of Fresh Water Resources in the Development of Fort Worth Basin Barnett Shale Natural Gas. Report prepared for the Barnett Shale Education Council and The Barnett Shale Water Conservation and Management Committee.

Hart, D.L., Jr., 1974, Reconnaissance of the water resources of the Ardmore and Sherman quadrangles, Southern Oklahoma: Oklahoma Geological Survey Hydrologic Atlas No. 3, 4 sheets.

Hentz, T.F., 1988, Report of Investigations No. 170. Lithostratigraphy and paleoenvironments of upper Paleozoic continental red beds, north-central Texas: Bowie (new) and Wichita (revised) Groups. Austin, Bureau of Economic Geology: 55.

Hentz, T. F. and Brown, L. F., Jr., 1987, Geologic Atlas of Texas, Wichita Falls-Lawton Sheet. Alfred Sherwood Romer Memorial Edition, The University of Texas at Austin, Bureau of Economic Geology.

Hsu, S.C., and Nelson, P.P., 2002, Characterization of Eagle Ford Shale, Engineering Geology, Volume 67, Issues 1-2, Pages 169-183.

Ketter, A.A., Heinze J.R., Daniels J.L., and Waters G., 2008, A Field Study in Optimizing Completion Strategies for Fracture Initiation in Barnett Shale Horizontal Wells, SPE Production & Operations, Volume 23, Number 3.

Kier, R.S., Brown, L.F. Jr., and McBride, E.F., 1979, The Mississippian and Pennsylvanian (Carboniferous) Systems in the United States - Texas. Geological Survey Professional Paper 1110-S. Prepared in cooperation with the Bureau of Economic Geology, The University of Texas at Austin. Washington, U.S. Geological Survey.

Klemt, W.B., Perkins, R.D., and Alvarez, H.J., 1975, Ground-water resources of part of Central Texas, with emphasis on the Antlers and Travis Peak formations: TWDB Rept. 195, 2 vols.

Langley, L., 1999, Updated Evaluation of Water Resources in Part of North-Central Texas, 1990-1999, Texas Water Development Board Report 349.

LBG-Guyton Associates, 2004, An Evaluation of Brackish and Saline Water Resources in Region F, Region F Regional Water Planning Group.

Mace, R.E., Smyth, R.C., Xu, L., and Liang, J., 1999, Transmissivity, Hydraulic Conductivity, and Storativity of the Carrizo-Wilcox Aquifer in Texas: TWDB Contract No. 99-483-279, Part 1.

Mace, R.E. , Chowdhury, A.H., Amaya, R., and Way, T., 2000, Groundwater Availability of the Trinity Aquifer, Hill Country Area, Texas- Numerical Simulations through 2050, Texas Water Development Board Report 353.

Marcher, M.V., and Bergman, D.L., 1983, Reconnaissance of the water resources of the McAlester and Texarkana quadrangles, Southeastern Oklahoma: Oklahoma Geological Survey Hydrologic Atlas 9, 4 sheets.

Mills, K., Byrd, L., 2007, North-Central and Central Texas Update PGMA Studies for the Trinity Aquifer, TCEQ Water Supply Division.

Montgomery S.L., Jarvie D.M., Bowker K.A. and Pollastro R. M., 2005, Mississippian Barnett Shale, Fort Worth basin, north-central Texas: Gas-shale play with multi–trillion cubic foot potential, AAPG Bulletin; v. 89; no. 2; p. 155-175.

Moore, R.C., and Plummer, F.B., 1922, Pennsylvanian Stratigraphy of North Central Texas, The Journal of Geology, Vol. 30, No. 1, pp. 18-42.

Nicot, J.P., Gross, B., Walden, S., and Baier, R., 2009, Self-Sealing Evaporation Ponds for Desalination Facilities in Texas, Prepared for Texas Water Development Board.

Nicot, J.P., 2009, Assessment of Industry Water-Use in the Barnett Shale Gas Play (Fort Worth Basin), Prepared for Texas Water Development Board.

Nicot,J.P., Huang, Y., Wolaver, B.D., Costlley, R.A., Breton, C., Hentz, T.F., McGlynn, E., Hingst, M., and Mercier, J., 2011, 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, Bureau of Economic Geology.

Nicot,J.P., Huang, Y., Wolaver, B.D., Costlley, R.A., Breton, C., Hentz, T.F., McGlynn, E., Hingst, M., and Mercier, J., 2011, Groundwater Flow Model of the Low Permeability Palezoic Aquifers in North-Central Texas, Bureau of Economic Geology.

Nicot,J.P., Huang, Y., Wolaver, B.D., Costlley, R.A., Breton, C., Howard, T., Walden, S., Baier, R., Strassberg, G., McGlynn, E., Hingst, M., Mercier, J., and Lam, C., 2012, Feasibility of Using Alternative Water Sources for Shale Gas Well Completions, Bureau of Economic Geology.

Nordstrom, P.L., 1982, Occurrence, availability, and chemical quality of groundwater in the Cretaceous aquifers of North- Central Texas: TDWR Rept. 269, 2 vols.

Nordstrom, P.L., 1988, Occurrence and quality of groundwater in Jack County, Texas, TWDB Rpt 308.

Plummer, F.B., and Sargent, E.C., 1931, Underground waters and subsurface temperatures of the Woodbine Sand in Northeast Texas: Univ. of Texas, Bureau of Economic Geology Bull. 3138, 175 p.

Powell, Jr. M.E., 2009, Recent Developments in the Barnett Shale, Powell Barnett Shale Newsletter from http://www.barnettshalenews.com.

Stramel, G.J., 1951, Ground water Resources of Parker County, Texas, Bulletin 5103.

Texas Commission on Environmental Quality, 2009, "Water Utility Database (WUD)."

Texas Commission on Environmental Quality, 2011, "Water Well Report Viewer." from http://www.tceq.state.tx.us/gis/waterwellview.html.

Texas Water Development Board, 2007, Water for Texas 2007 Volume II, Document No. GP-8-1, p. 214.

Texas Water Development Board, 2011, "Groundwater Database." from http://www.twdb.state.tx.us/publications/reports/GroundWaterReports/GWDatabaseReports/GWdatabaserpt.asp.

Texas Water Development Board, 2011, "Submitted Driller's Report Database." from http://www.twdb.state.tx.us/publications/reports/GroundWaterReports/GWDatabaseReports/Drillers_Report_Database/Disclaimer.asp.

Texas Water Development Board, 2011, "TWDB Numbered Reports." from http://www.twdb.state.tx.us/publications/reports/numbered_reports/index.asp.

Theis, C.V., 1935. The relation between the lowering of the piezometric surface and the rate and duration of discharge of a well using groundwater storage, Am. Geophys. Union Trans., vol. 16.

Veni, G., 1994, Geomorphology, hydrology, geochemistry, and evolution of karstic Lower Glen Rose aquifer, south-central Texas: Pennsylvania State University, Ph.D. Dissertation, 712 p.