Identification of Potential Brackish Groundwater Production Areas – Northern Trinity Aquifer

Technical Note 19-1

December 2019

Mark C. Robinson, P.G.
Texas Water Development Board

Neil E. Deeds, Ph.D., P.E.
Daniel M. Lupton, P.G.
INTERA Incorporated

Identification of Potential Brackish Groundwater Production Areas – Northern Trinity Aquifer

Technical Note 19-1

By
Mark C. Robinson, P.G.
Texas Water Development Board

Neil E. Deeds, Ph.D., P.E.
Daniel M. Lupton, P.G.
INTERA Incorporated

December 2019

Texas Water Development Board

Geoscientist and Engineering Seals

The contents of this report (including figures and tables) document the work of the following licensed Texas geoscientists and Engineer:

Mark C. Robinson, P.G. No. 5649

Mr. Robinson was responsible for salinity zone definition and preparing the report. The seal appearing on this document was authorized on October 15, 2019, by

Mark C. Robinson

Neil E. Deeds, P.E. No. 92741

Mr. Deeds was responsible for working on drawdown modeling. The seal appearing on this document was authorized on October 15, 2019, by

Neil E. Deeds

Daniel M. Lupton, P.G. No. 11354

Mr. Lupton was responsible for working on salinity calculations and preparing the report. The seal appearing on this document was authorized on October 15, 2019, by

Daniel M. Lupton

Cover photo courtesy of Jayme Lowry

“Buckeye Creek, Dinosaur Valley State Park, Upper Member of Glen Rose Formation Trinity Group”

Texas Water Development Board

To provide leadership, information, education, and support for planning, financial assistance, and outreach for the conservation and responsible development of water for Texas.

Published and distributed by the
Texas Water Development Board
P.O. Box 13231, Capitol Station
Austin, Texas 78711-3231

December 2019
(Printed on recycled paper)

This page is intentionally blank.

CONTENTS

List of Figures

List of Tables

1 Executive summary

To better formulate groundwater management strategies, planners and decision makers need reliable estimates of the available fresh and brackish groundwater in Texas. House Bill 30 passed in 2015 by the 84th Texas Legislative requires the Texas Water Development Board (TWDB) to identify and designate brackish groundwater production zones in the aquifers of Texas. Specifically, the legislation directed the TWDB to conduct studies on four aquifers and report the results of the studies to the legislature by December 1, 2016. Studies and reports on the remaining aquifers are to be completed by December 1, 2032. To meet this requirement, the Texas Legislature appropriated funding to the TWDB that was used to award seven contracts to conduct studies of brackish groundwater in eight Texas aquifers. The Trinity Aquifer was one of the aquifers selected for study.

This report utilizes the contracted work performed for the Trinity Aquifer and documents the brackish resources and potential production areas in the northern section of the Trinity Aquifer, hereafter referred to as the Northern Trinity Aquifer. The Northern Trinity Aquifer in Texas roughly corresponds to Groundwater Management Area (GMA) 8, although small portions of GMA 11 and GMA 12 are also encompassed by the project study area. All or portions of 53 counties lie within the study area covering a total area of 30,861 square miles.

The purpose of this study was to provide the information necessary for the TWDB to designate brackish groundwater production zones in the Northern Trinity Aquifer. To meet this objective, data was collected and analyzed to classify groundwater into four salinity classes for the five hydrostratigraphic units of the Northern Trinity Aquifer. Aquifer modeling was performed to provide guidance regarding the production of the aquifer in potential production areas and the nature of impacts to protected users and freshwater within the aquifer. This information was used to evaluate potential production areas and staff-recommended brackish groundwater production zones for the Board to consider for formal designation. On March 28, 2019, the Board designated 15 brackish groundwater production zones in the Northern Trinity Aquifer.

The Northern Trinity Aquifer was extensively studied during the development of the updated groundwater availability model (GAM) developed by Kelley and others (2014). The hydrostratigraphic framework developed for the GAM provided the geological structure that we used in this study for aquifer determination and for defining salinity zones. The GAM study utilized 1,302 geophysical well logs to define the vertical and lateral extents of the five hydrostratigraphic units that compose the Northern Trinity Aquifer. We used the GMA 8 Run 10 of the GAM model (Beach and others, 2016) for modeling the drawdown effects associated with pumping brackish groundwater at various rates in the identified potential production areas over 30-year and 50-year periods.

Northern Trinity Aquifer groundwater quality data for this study was sourced in part from water quality data from the TWDB Groundwater Database and the Texas Commission on Environmental Quality (TCEQ) Public Water Supply Database. We used petrophysical analysis techniques to analyze geophysical logs for water quality in the deeper down-dip portions of the aquifer since there are very few observed water quality data in those zones. The total dissolved solids calculations provided the additional data needed to better define the groundwater salinity zones within the deeper downdip portions of the Northern Trinity Aquifer.

We defined groundwater quality using the total dissolved solids concentration divided into four salinity classes corresponding to: (1) fresh groundwater with total dissolved solids concentration less than 999 milligrams per liter, (2) slightly saline groundwater with total dissolved solids concentration between 1,000 to 2,999 milligrams per liter, (3) moderately saline groundwater with total dissolved solids concentration between 3,000 and 9,999 milligrams per liter, and (4) very saline groundwater with total dissolved solids concentration between 10,000 to 35,000 milligrams per liter. Based upon our mapping of salinity, we calculated that the volume of groundwater in place for the Northern Trinity Aquifer is approximately 2,061 million acre-feet, of which 471 million acre-feet is fresh, 486 million acre-feet is slightly saline 703 million acre-feet is moderately saline, and 399 million acre-feet is very saline. Because of the geologic complexities and relatively low porosity and permeability of the Northern Trinity Aquifer a high percentage of the in-place groundwater volume calculated for the aquifer would be difficult to produce.

The final part of our analysis identifies potential production areas. In total, we evaluated 15 potential production areas. We used the Northern Trinity Aquifer GAM to estimate productivity of each potential production area and to evaluate potential impacts to freshwater resources and water use categories protected in House Bill 30. Based upon this analysis it is clear that the Hosston represents the best opportunity for high production rates of brackish groundwater. Other hydrostratigraphic units that have moderate potential are the Pearsall, Paluxy, and the Glen Rose. The Hensell was determined to have the lowest production rate potential. The results from this analysis was be used in recommending potential production areas to be designated as brackish groundwater production zones by the Board.

In addition to this study report the following digital information products are available: 1) Geographic Information System (GIS) map files, 2) data compiled and stored in the TWDB BRACS Database, 3) water well and geophysical well log files, and 4) computer code used to calculate volumes.

2 Introduction

Groundwater is a major source of water in Texas, providing about 50 percent of the water used in the state (TWDB, 2017). To better formulate water management strategies, planners and decision makers need reliable estimates of the available fresh and brackish groundwater. House Bill 30, passed by the 84th Texas Legislative Session in 2015, requires the TWDB to identify and designate brackish groundwater production zones in the aquifers within the state. Specifically, the legislation directed the TWDB to conduct studies on four aquifers and report results to the legislature by December 1, 2016. Studies and reports on the remaining aquifers are to be completed by December 1, 2032. To meet these requirements, the TWDB awarded contracts to conduct studies of brackish groundwater in Texas aquifers. The Trinity Aquifer was one of the aquifers selected. This report documents the study of brackish water resources in the Northern Trinity Aquifer (Figure 2-1).

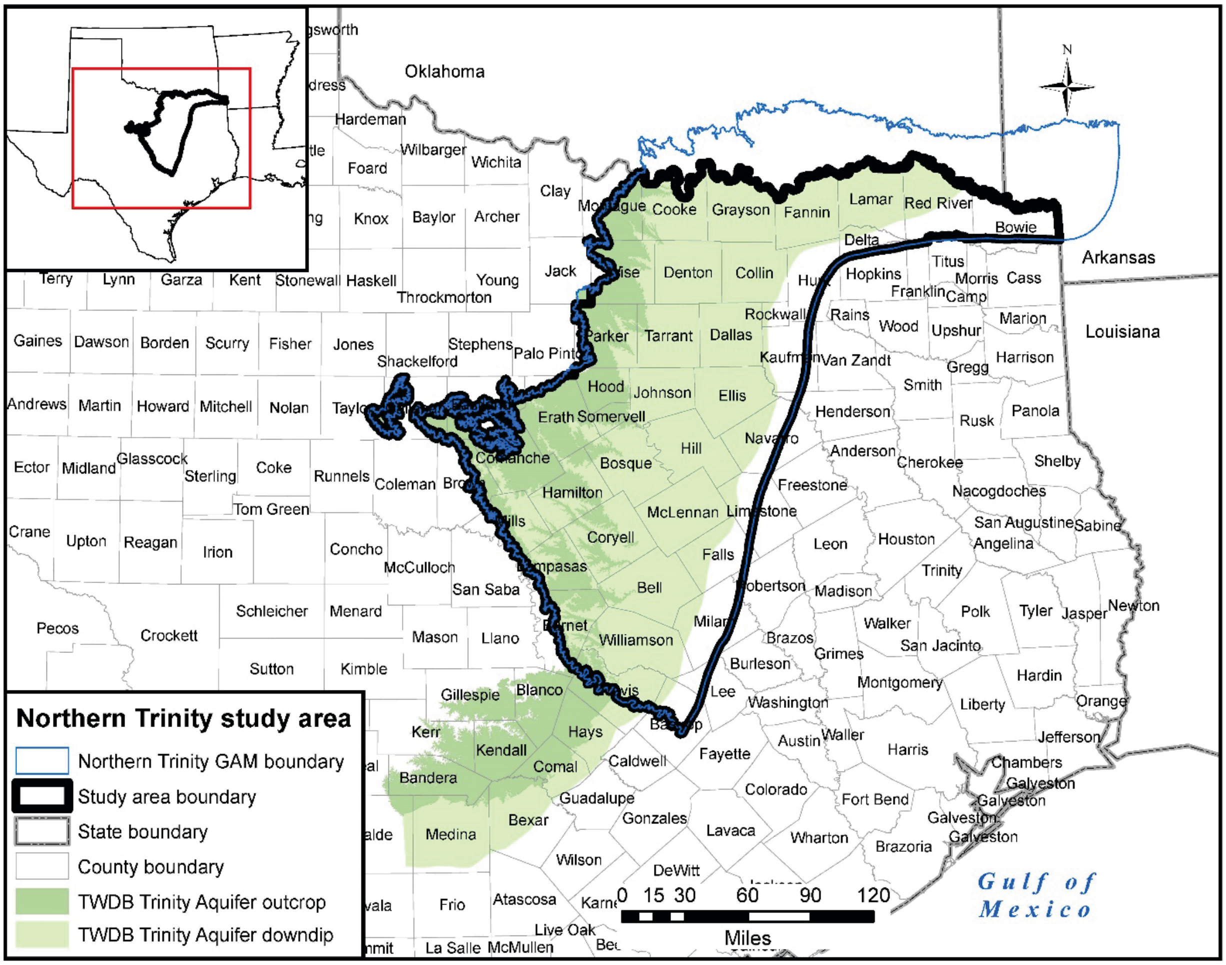


Figure 2-1 **Northern Trinity Aquifer study area.**

The Northern Trinity Aquifer underlies all or parts of 53 counties through Central Texas (Kelley and others, 2014). In Texas, it extends from the Oklahoma border to south-central Texas. Because of the large geographic extent of the Trinity Aquifer, it has been divided into southern and northern sections identified as the Hill Country Trinity Aquifer and the Northern Trinity Aquifer, respectively. This study will address the brackish groundwater resources of the Northern Trinity Aquifer and identify potential production areas.

The Northern Trinity Aquifer has provided north-central Texas with significant quantities of groundwater for more than 100 years. The most recent groundwater production estimate (Kelly and others, 2014) was approximately 185,000 acre-feet per year. Deep artesian wells flowed for many years in the study area and provided towns and cities with warm to hot, fresh to slightly saline water that was used for domestic, recreational, medicinal, agricultural, and livestock purposes.

The geology of the Northern Trinity Aquifer corresponds to the Trinity Group geological unit, which is composed of numerous named formations. Although referred to differently in different parts of the state, these formations include the Antlers, Cow Creek, Glen Rose, Hensell, Hosston, Paluxy, Pearsall, Sligo, Travis Peak, and Twin Mountains formations. The formations consist of interbedded limestones, sands, shales, gravels, and conglomerates. The combined saturated thickness of fresh groundwater in these formations is up to 1,900 feet in north-central Texas where the Trinity Group exists in both outcrop and subcrop.

Groundwater is typically classified into five salinity classes (Table 2-1): fresh, slightly saline, moderately saline, very saline, and brine (Winslow and Kister, 1956). In this study, groundwater salinity classification in the Northern Trinity Aquifer only required four classes because there was insufficient data to map the boundary between very saline and brine groundwater. Three-dimensional mapping of each salinity class was performed for this study to determine the volume of groundwater for each salinity class.

Table 2-1 Groundwater salinity classification used in the study (Winslow and Kister, 1956). Colors used in this table for each salinity classification are consistent throughout the report and GIS datasets.

Groundwater salinity classification	Total dissolved solids concentration (milligrams per liter)
Fresh	0 to 999
Slightly saline	1,000 to 2,999
Moderately saline	3,000 to 9,999
Very saline	10,000 to 34,999
Brine	Greater than 35,000

This study required the collection and review of a large quantity of geological and geophysical data. Much of this data was obtained from wells drilled for the extraction of water, but data from oil wells drilled through the Trinity Aquifer to deeper objectives was also used extensively.

All project information has been entered into the BRACS Database, which the TWDB developed to store and analyze the information. The BRACS Database is a Microsoft Access® database that is described in a detailed BRACS Database Data Dictionary (Meyer, 2017). Both are downloadable from the TWDB website (www.twdb.texas.gov/innovativewater/bracs/database.asp).

The project deliverables, both the report and data, are available to the public on the TWDB website. The data includes raw data in numerous digital formats and processed data in the form of GIS datasets. Digital geophysical well logs used for the studies are available upon request or downloadable from the TWDB Water Data Interactive website (www2.twdb.texas.gov/apps/waterdatainteractive/groundwaterdataviewer).

Information produced from this study is not intended to serve as a substitute for site-specific evaluations of local aquifer characteristics and groundwater conditions for desalination projects. During design and development of a well field, an entity will need to determine the productivity of the brackish aquifer using monitoring and production wells and groundwater modeling. It is important to note that existing TWDB GAMs are designed for regional assessment and are not applicable to well field analysis. These models are not constructed to analyze the effect of salinity on groundwater flow and in general should not be used for estimating withdrawal of saline water. Other significant factors an entity should evaluate before developing brackish groundwater are groundwater quantity, possible quality changes, and potential subsidence.

3 Study area characteristics

The study area overlies a diverse geographic section of Texas. It includes portions of the East Texas Piney Woods, the Dallas-Fort Worth Metroplex, the Central Texas Grand Prairie, and the Texas Hill Country.

3.1 Water-related organizations

Within the study area there are 984 public water systems currently serving almost 10 million people. The study area is located within six regional water planning groups (Table 3-1 and Figure 3-1) and three groundwater management areas (Table 3-2 and Figure 3-2). Contained in the project area are all or part of 14 groundwater conservation districts (Table 3-3 and Figure 3-3). The study area is located in six major river basins (Table 3-4 and Figure 3-4) and six river authorities (Table 3-4 and Figure 3-5).

Table 3-1 Regional water planning groups in the study area.

Group	Name
B	Region B
C	Region C
D	North East Texas
F	Region F
G	Brazos
K	Lower Colorado

Table 3-2 Groundwater Management Areas (GMA) in the study area.

GMA 8
GMA 11
GMA 12

Table 3-3 Groundwater conservation districts in the study area.

Brazos Valley GCD	Northern Trinity GCD
Central Texas GCD	Post Oak Savannah GCD
Clearwater UWCD	Prairielands GCD
Lost Pines GCD	Red River GCD
Middle Trinity GCD	Saratoga UWCD
Neches & Trinity Valleys GCD	Southern Trinity GCD
North Texas GCD	Upper Trinity GCD

Notes:
CD = Conservation District
GCD = Groundwater Conservation District
UWCD = Underground Water Conservation District

Table 3-4 River basins in the study area.

Brazos River Basin	Sabine River Basin
Colorado River Basin	Sulphur River Basin
Red River Basin	Trinity River Basin

Table 3-5 River authorities in the study area.

Brazos River Authority	Sabine River Authority
Lower Colorado River Authority	Sulphur River Authority
Red River Authority	Trinity River Authority

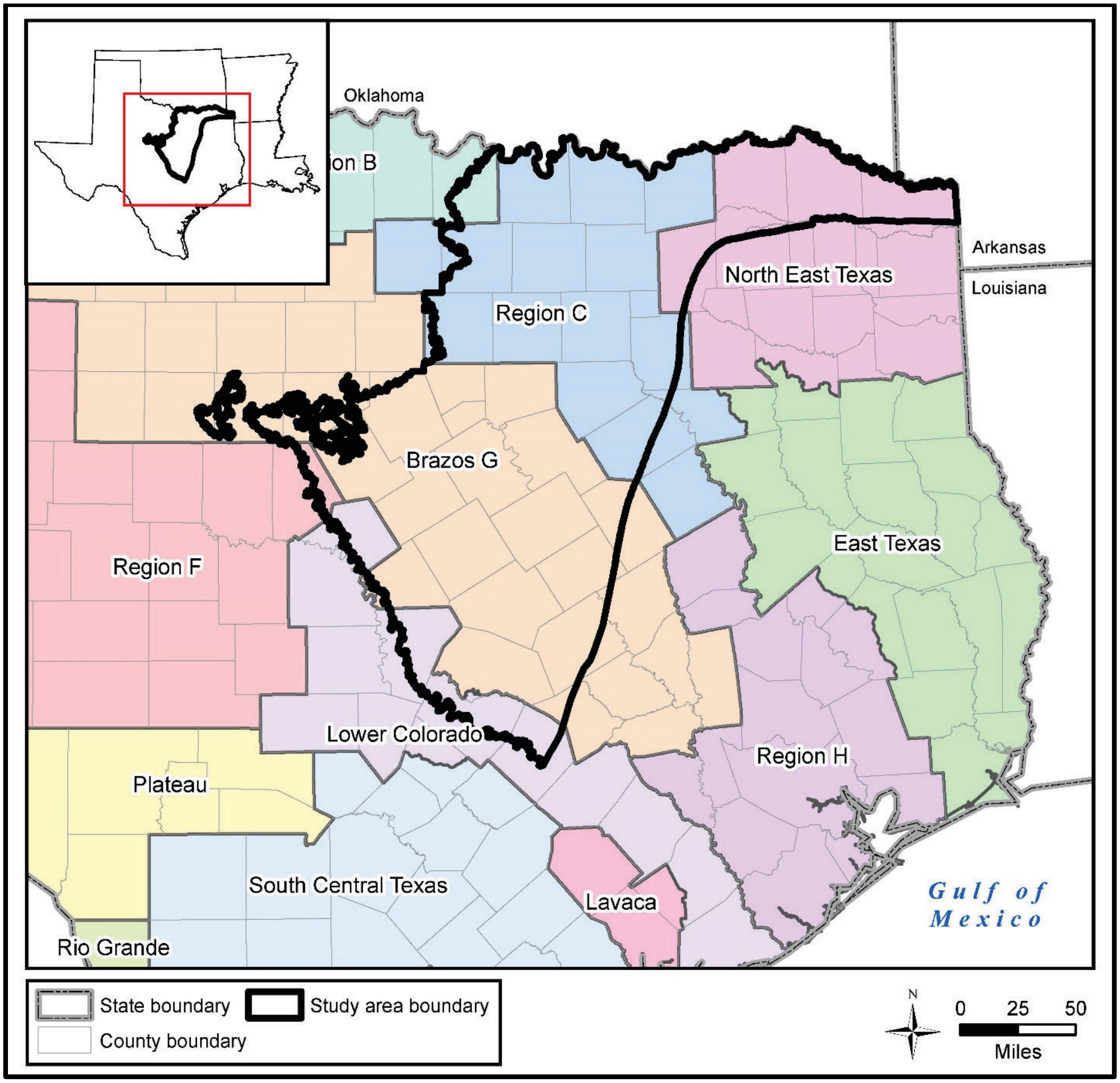


Figure 3-1 Regional water planning groups in the study area.

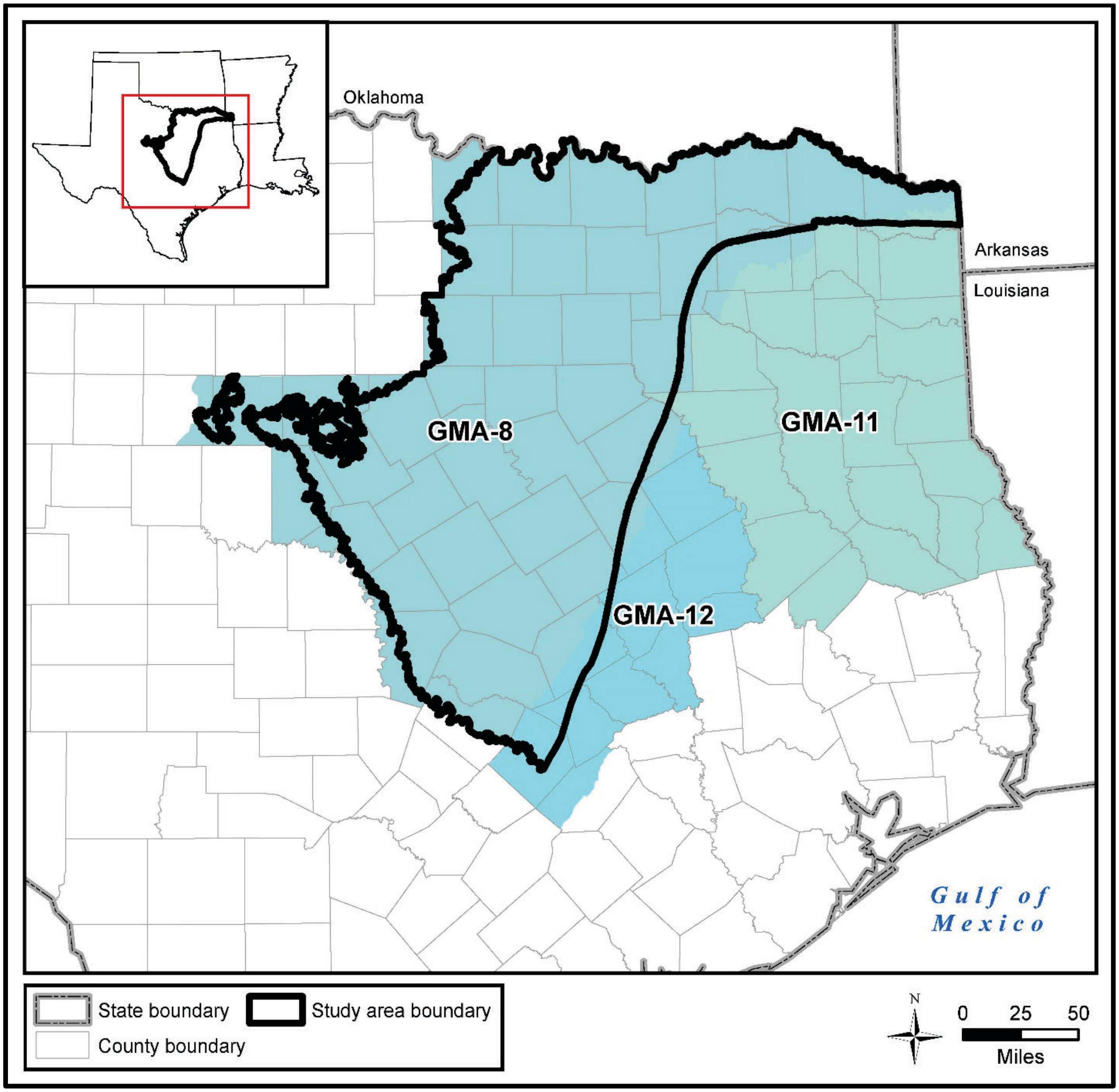


Figure 3-2 Groundwater Management Areas (GMA) in the study area.

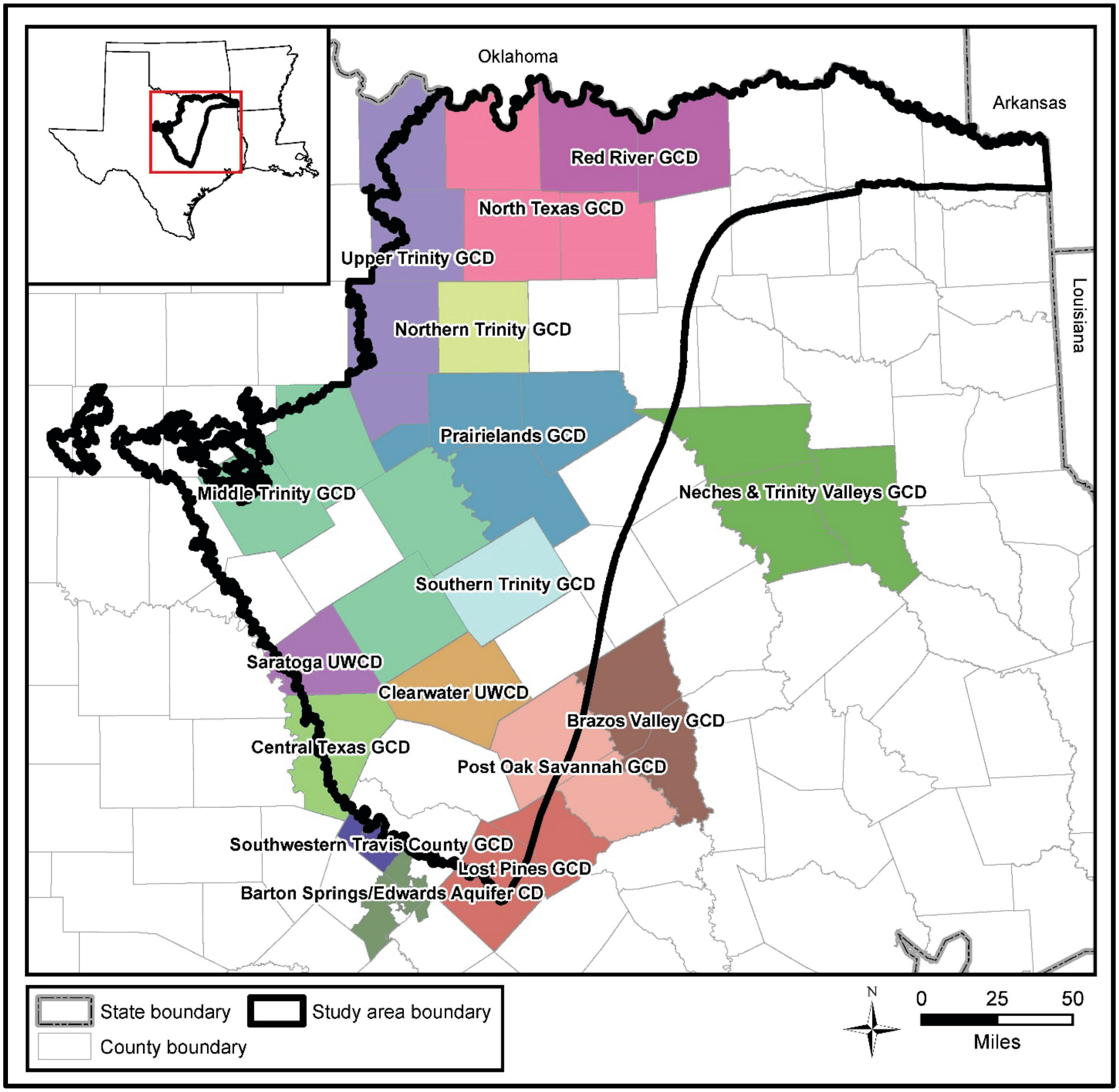


Figure 3-3 **Groundwater conservation districts in the study area. Note: CD = Conservation District; GCD = Groundwater Conservation District; UWCD = Underground Water Conservation District.**

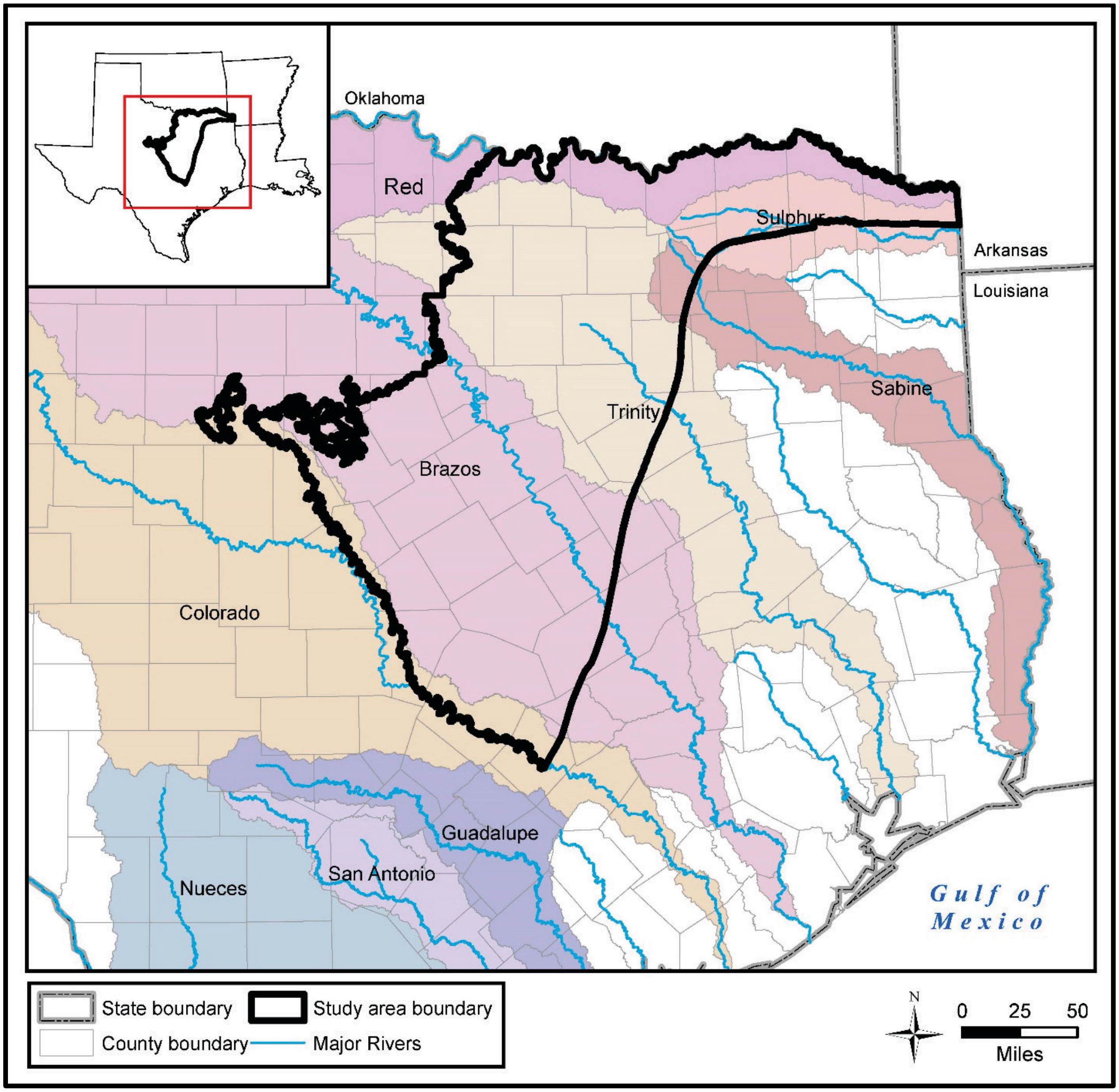


Figure 3-4 River basins in the study area.

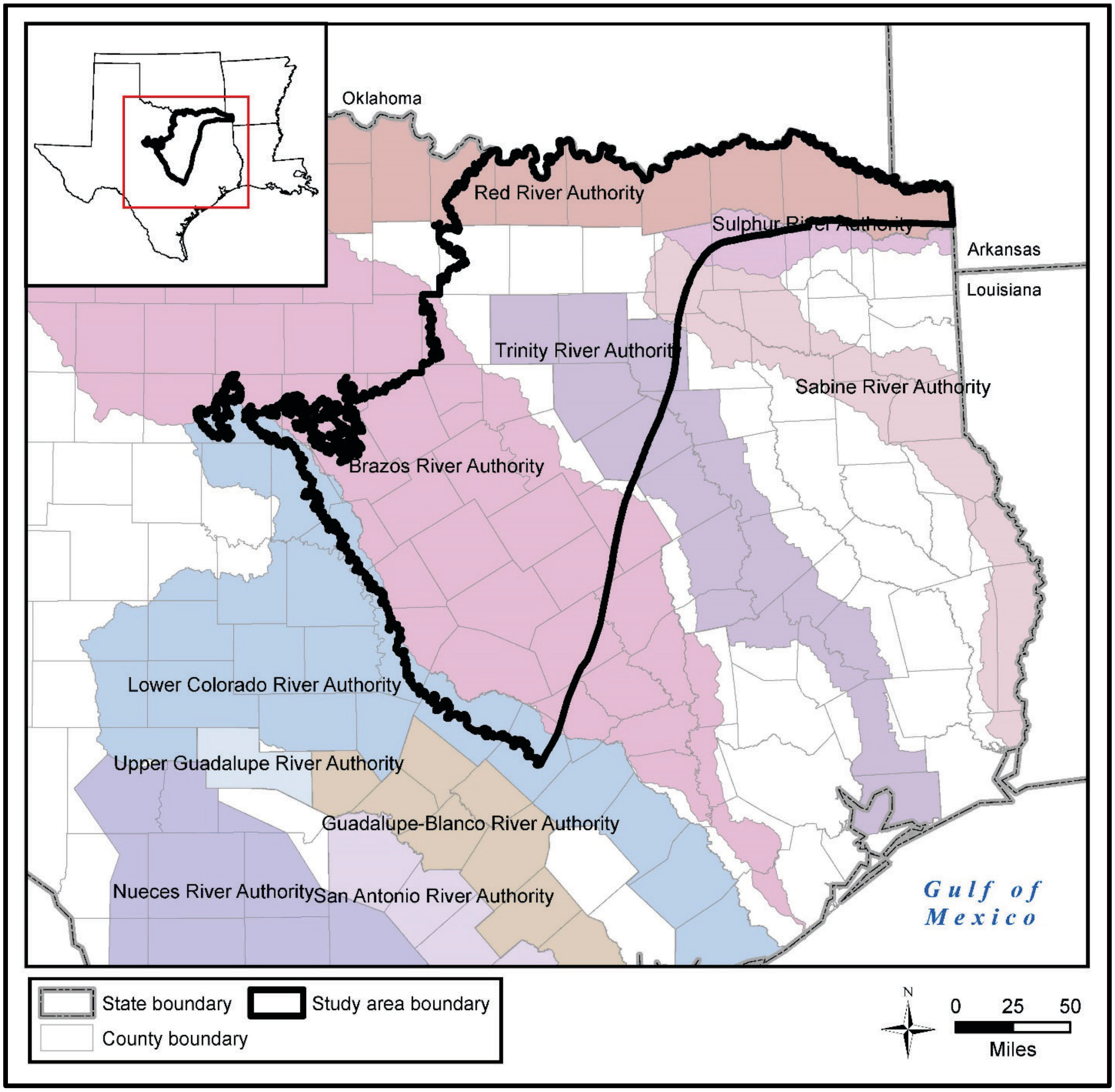


Figure 3-5 River authorities in the study area.

3.2 Northern Trinity Aquifer groundwater usage

The importance of Northern Trinity Aquifer groundwater is evidenced by the current extensive domestic, municipal, industrial, and agricultural use (Table 3-6). Consequently, drawdown of the static water level has been as much as 800 to 1,000 feet in portions of the aquifer (Bené and others, 2004), indicating that withdrawals have significantly exceeded recharge.

Table 3-6 Summary of pumping in acre-feet from the Northern Trinity Aquifer in Texas by water use category (Kelly and others, 2014).

Water use category	Pumping (acre-feet)						
	1980	1985	1990	1995	2000	2005	2010
Irrigation	31,904	45,033	45,089	50,399	39,839	37,579	29,106
Manufacturing	5,146	6,952	6,025	4,731	4,413	5,898	3,868
Mining	1,111	3,093	1,943	3,947	3,848	519	23,813
Municipal	104,437	111,832	104,734	91,139	109,601	99,612	103,255
Power	1,164	3,602	1,171	426	837	261	125
Rural Domestic	10,770	12,618	14,000	14,647	15,972	16,995	17,888
Livestock	9,784	8,960	10,582	13,654	12,949	6,638	6,527
Total	164,316	192,090	183,544	178,943	187,459	167,502	184,582
	Percentage of total						
Irrigation	19	23	25	28	21	22	16
Manufacturing	3	4	3	3	2	4	2
Mining	1	2	1	2	2	0	13
Municipal	64	58	57	51	58	59	56
Power	1	2	1	0	0	0	0
Rural Domestic	7	7	8	8	9	10	10
Livestock	6	5	6	8	7	4	4

4 Geologic setting

This study relied entirely on the Northern Trinity Aquifer GAM (Kelley and others, 2014) for the hydrostratigraphic framework, which used 1,302 geophysical logs to correlate stratigraphic boundaries and interpret lithologies. The well log stratigraphic correlations and the well data were carefully reviewed for accuracy and completeness. A small number of wells had incorrect well locations and in the up-dip portions of the Trinity Group it was often necessary to exercise best professional judgement when correlating geological surfaces. These issues did not significantly impact the overall correctness of the stratigraphic framework nor did they introduce significant errors into volume calculations and placement of brackish groundwater potential production areas.

4.1 Trinity Group stratigraphy

We utilized six of the correlated surfaces defined by Kelly and others (2014) to subdivide the Trinity Group into a consistent and continuous set of five hydrostratigraphic units (Figure 4-1). The six surfaces used, from oldest to youngest, were: 1) base of Cretaceous-aged sediments, 2) Hosston, 3) Pearsall, 4) Hensell, 5) Glen Rose, and 6) Paluxy. These surfaces were mapped in the subsurface using geophysical well logs and projected to the surface in outcrop areas. To some extent these surfaces adhere to the associated named stratigraphic units. However, the predominant use of geophysical well logs for correlation is an allostratigraphic approach (Bhattacharya and Walker, 1991) that tends to better reflect the depositional units rather than the named lithostratigraphic units. Examples of the well log correlations used to define these surfaces can be seen in Section 5.1.

Age m.y.	Period	Group	Formations: North and West	Formations: Central	Formations: South	Hydrostratigraphic Units
65	Upper Cretaceous	Eagle Ford	not present	undifferentiated	undifferentiated	
		Woodbine	not present	undifferentiated	undifferentiated	
		Washita	Grayson Mainstreet Pawpaw Weno Denton Fort Worth Duck Creek	Buda Del Rio Georgetown	Buda Del Rio Georgetown	
100	Lower Cretaceous	Fredericksburg	Kiamichi Goodland Walnut	Kiamichi Edwards Comanche Peak Walnut	Kiamichi Edwards Comanche Peak Walnut	
		Trinity	Antlers	Paluxy Glen Rose	Paluxy Glen Rose	Paluxy Glen Rose
				Twin Mountains: Hensell Pearsall Hosston	Travis Peak: Hensell Pearsall Cow Creek Hammett Sligo Hosston	Hensell Pearsall Hosston
127						
Pre-Cretaceous						

Figure 4-1 Stratigraphic column showing Cretaceous-age stratigraphy in various portions of the study area (modified from Fisher and Rodda, 1967). Note: m.y. = million years before present.

4.1.1 Pre-Cretaceous

Pre-Cretaceous formations that underlay the Trinity Group in the study area range from the much older Paleozoic formations in the western half to the Jurassic-aged formations along the down-dip eastern edge. The contact between Paleozoic rocks and the overlying Trinity Group is generally easy to observe in outcrop because of significant differences in lithologic and physical properties. The contact between the underlying Paleozoic rocks represents an erosional unconformity resulting in an age gap of more than 100 million years. In the eastern portion of the study area the Trinity Group unconformably overlies Jurassic aged sedimentary rocks of the Cotton Valley Group.

The Pre-Cretaceous rocks have the potential to be a source of very saline to brine groundwater when in contact with overlying Trinity Aquifer units. This was evidenced in a Grayson County well (State Well Number 18-19-306), which was drilled to a depth of 2,131 feet and penetrated over 200 feet of Paleozoic rocks. Water samples were taken at two intervals—1,952 to 1,981 feet and 1,989 to 2,072 fee—below ground surface with a measured total dissolved solids concentration of 28,145 milligrams per liter and 46,716 milligrams per liter, respectively. This well was subsequently plugged-back and completed in the Trinity Aquifer over an interval from 1,321 to 1,555 feet below ground surface producing water with a measured total dissolved solids concentration of 761 milligrams per liter.

4.1.2 Hosston

The Hosston hydrostratigraphic unit is defined as all sediments between the Hosston surface and the base of the Cretaceous aged sediments surface. This unit has a thickness of over 1,400 feet near the southeastern edge of the study area but quickly thins to 500 feet or less towards the north and west. The Hosston Formation is largely composed of interbedded sandstones, siltstones, and calcareous shales with less frequent conglomeritic units. The upper portions of the Hosston Formation transition into sandy dolomites and sandy limestones. This unit is a significant water bearing unit of the Northern Trinity Aquifer that has been used for municipal, industrial, domestic, and agricultural purposes. Wells producing from the Hosston hydrostratigraphic unit in the early 1900s were frequently artesian and often flowed at more than 100 gallons per minute (Hill, 1901). Recent municipal wells have been tested at rates of more than 1,000 gallons per minute and freshwater has been found to extend downdip to depths of more than 3,000 feet in this unit.

4.1.3 Pearsall

The Pearsall hydrostratigraphic unit is defined as all sediments between the Pearsall surface and the Hosston surface. This unit has thicknesses of 200 to 500 feet. The Pearsall hydrostratigraphic unit is composed of the limestone, siltstone, and shales of the Pearsall and Sligo Formations. Few wells are known to produce from this interval, which has generally low hydraulic conductivity (Kelly and others, 2014) and high salinity concentrations. However, some water wells have produced fresh water at rates over 100 gallons per minute (State Well Numbers: 19-47-102, 18-17-908, and 18-17-901) from this unit. In the southern portions of the study area, this unit includes the Cow Creek Limestone, which is capable of producing small quantities of generally fresh groundwater.

4.1.4 Hensell

The Hensell hydrostratigraphic unit is defined as all sediments between the Hensell surface and the Pearsall surface. This unit has a thickness generally less than 100 feet. The Hensell is composed of silty and shaly sandstone and limestone beds that grade into conglomerates towards its western outcrops (Hall, 1976). The Hensell is a significant source of water for municipal, domestic, industrial, and agricultural purposes in the central and western portions of the study area. The Hensell unit is capable of producing at rates from 10 to 200 gallons per minute of generally fresh groundwater.

4.1.5 Glen Rose

The Glen Rose hydrostratigraphic unit is defined as all sediments between the Glen Rose surface and the Hensell surface. This unit has a thickness of 400 feet to more than 1,000 feet. Limestones and shales are the major rock types of the Glen Rose hydrostratigraphic unit. In the western portions of the study area, the Glen Rose is a minor source of water used for domestic and livestock purposes with production rates between 10 and 100 gallons per minute of generally fresh groundwater. Evaporite beds are known to occur in this unit and can have deleterious effects on groundwater quality by introducing high concentrations of sulfate ions.

4.1.6 Paluxy

The Paluxy hydrostratigraphic surface is defined as all sediments between the Paluxy surface and the Glen Rose surface. This unit has a thickness of 400 feet in the northeastern portion of the study area that thins to less than 50 feet towards the south. Paluxy sandstones are a major source of water for the northern portions of the study area. Primary uses include municipal, domestic, irrigation, and livestock, and wells have production rates between 10 and 200 gallons per minute.

4.2 Structural setting

There are significant structural controls on the extents of the various hydrostratigraphic units in the Trinity Aquifer (Figure 4-2). The Mexia-Talco Fault Zone is a complex set of individual faults that have offsets of up to 700 feet and define the eastern down-dip extent of the Northern Trinity Aquifer. There are known oil and gas fields developed on the downdip (eastern) side of the Mexia-Talco Fault Zone, which provides some indication that these faults either act as seals to fluid migration or have juxtaposed impervious Trinity Formations and oil-bearing Woodbine strata. We considered these faults to be a major barrier to the movement of fluids.

The Balcones Fault Zone extends into the south-central portion of the study area. The Balcones Fault Zone is comprised of individual faults that have offsets generally less than 400 feet. South of the study area, the Balcones Fault Zone has been found to offset Trinity Group strata in such a way as to cause both isolation and communication between different hydrostratigraphic units (Klemt and others, 1975). In this study we did not address possible cross-aquifer flow potentially caused by these faults and assume that the Balcones Fault Zone does not significantly impede fluid movement within the Northern Trinity Aquifer (Collins and Hovorka, 1997).

The Preston Anticline extends southeast into northern Grayson County along with the corresponding Sherman Syncline (Bullard, 1931). There is no outcrop evidence of large-scale faulting of Cretaceous-aged formations related to these structural features even though the elevation difference from the crest of the anticline to the center of the syncline is almost 1,000 feet over a distance of only 12 miles. The impact of this structural feature on the occurrence and movement of groundwater in the Northern Trinity Aquifer is largely restricted to northern Grayson County and not studied in any detail for this report.

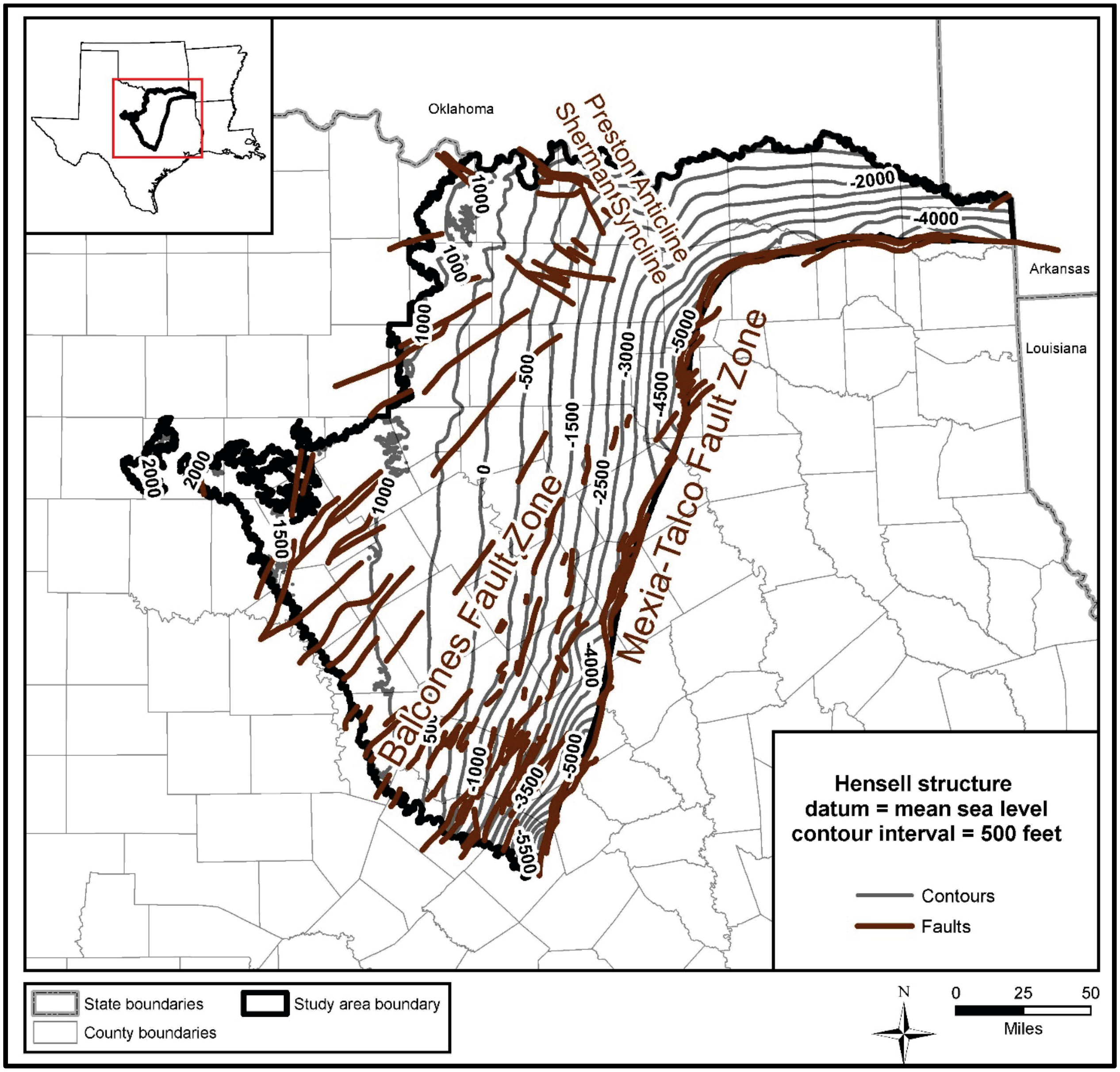


Figure 4-2 **Top of the Hensell hydrostratigraphic unit in feet above mean sea level and locations of faults that displace Cretaceous-age formations (from Ewing, 1990).**

4.3 Structure and isopach maps

A series of structure and isopach maps were created using the stratigraphic correlations from the Northern Trinity GAM (Kelley and others, 2014). The stratigraphic correlations were largely derived through interpretation of geophysical well logs. Outcrops mapped at the ground surface (Bureau of Economic Geology, 2012) were also used as control in the generation of the mapped surfaces. Structure maps represent the elevation of the surfaces in feet above mean sea level and use a contour interval of 400 feet. Isopach maps represent the vertical difference between two surfaces and use a contour interval of 100 feet. For all hydrostratigraphic units, the surfaces dip toward the south and east.

The base of Cretaceous surface represents an erosional unconformity throughout much of the study area (Figure 4-3). Cretaceous sediments were deposited upon much older Paleozoic rocks that were uplifted and eroded as a result of the Ouachita orogeny and subsequent tectonic events. The southeastern portions of the study area are underlain by Jurassic aged sediments. The Hosston unit onlaps the older rocks and forms a wedge of sediment that thickens towards the south and east with a maximum thickness of 1,800 feet (Figure 4-4 and Figure 4-5). The Pearsall unit onlaps the Hosston unit and forms a wedge of sediment that thickens towards the south and east with a maximum thickness of 600 feet (Figure 4-6 and Figure 4-7). The Hensell unit overlies the Pearsall unit and has a relatively uniform thickness of 100 to 200 feet throughout the study area (Figure 4-8 and Figure 4-9). The Glen Rose unit onlaps the Hensell unit and forms a wedge of sediment that thickens towards the south and east with a maximum thickness of 1,200 feet (Figure 4-10 and Figure 4-11).The Paluxy unit overlies the Glen Rose unit and has a maximum thickness of 600 feet in the northeastern portion of the study area (Figure 4-12 and Figure 4-13).

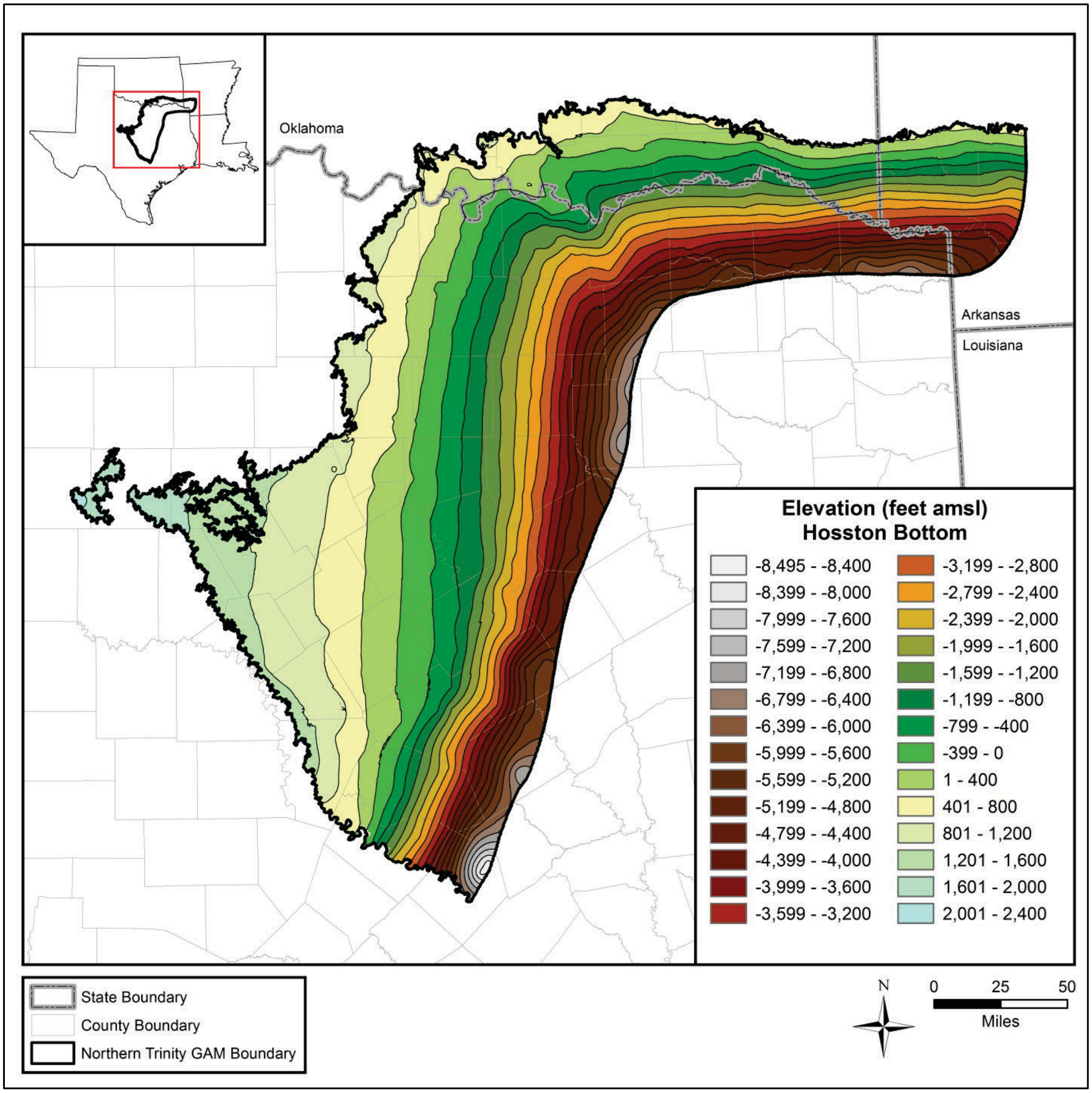


Figure 4-3 **Structure map of the elevation of the base of Cretaceous-aged Trinity Group . Note: amsl = above mean sea level.**

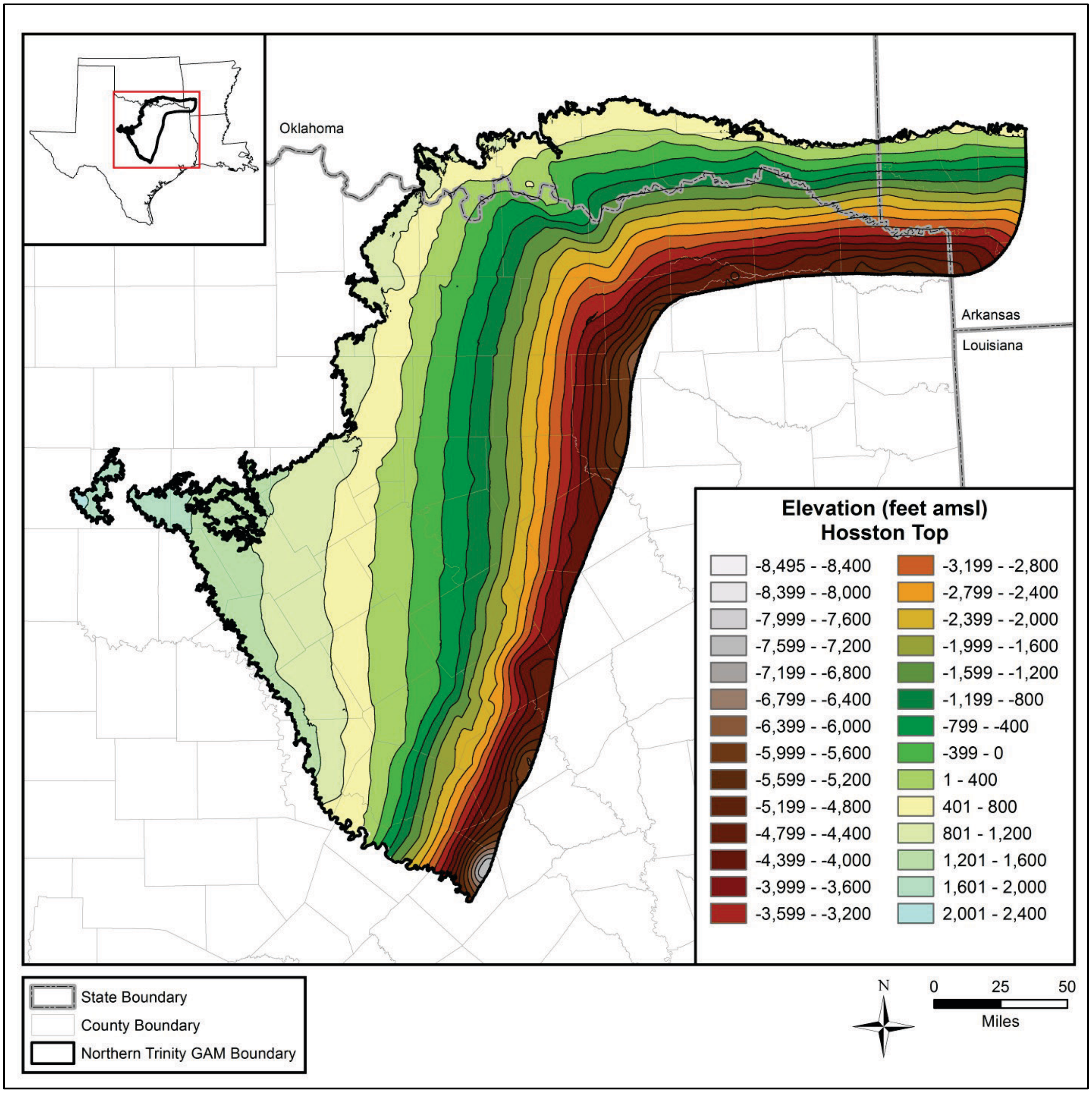


Figure 4-4 **Structure map showing the elevation of the top of the Hosston hydrostratigraphic unit. Note: amsl = above mean sea level.**

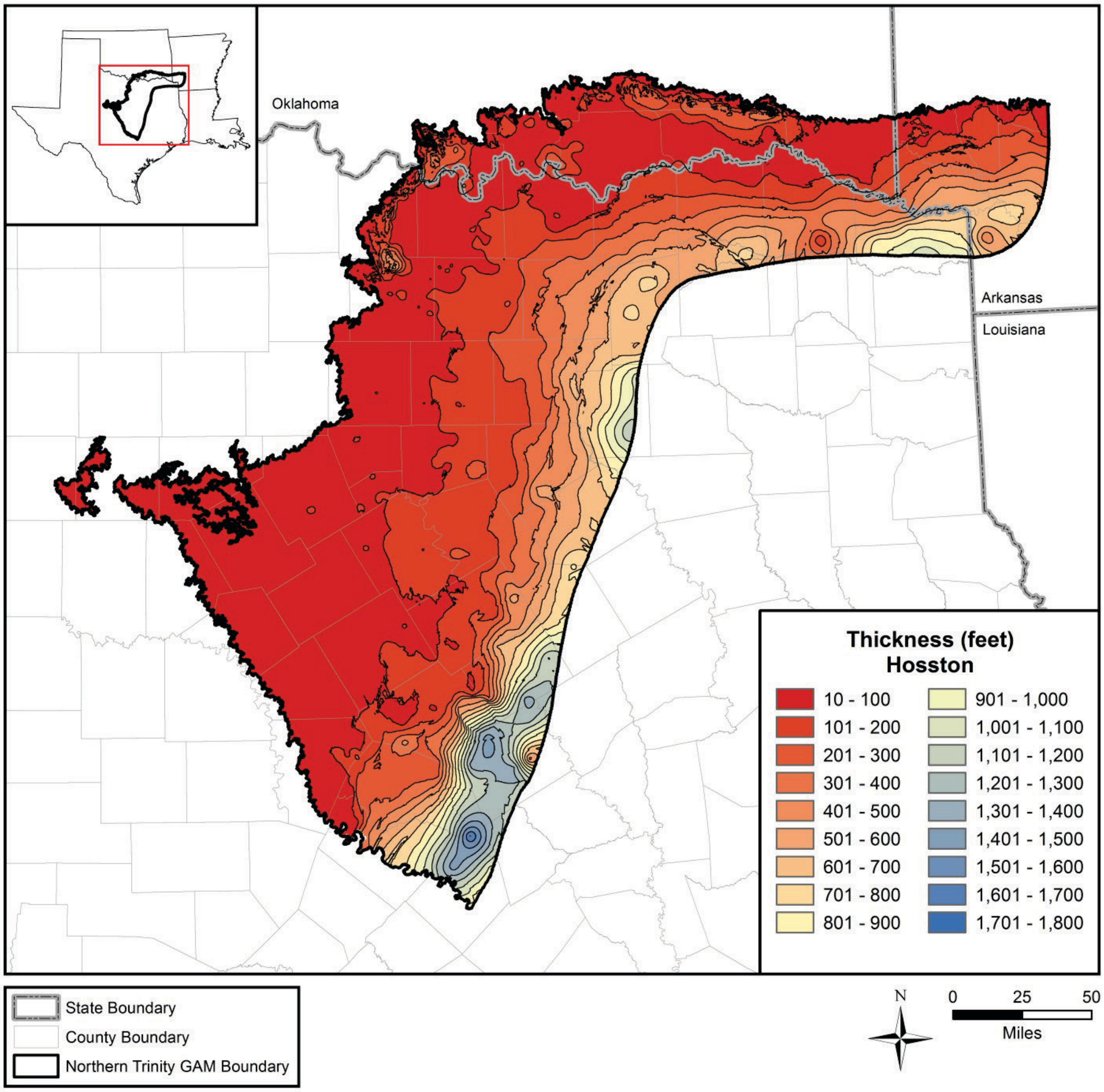


Figure 4-5 Isopach map of the Hosston hydrostratigraphic unit.

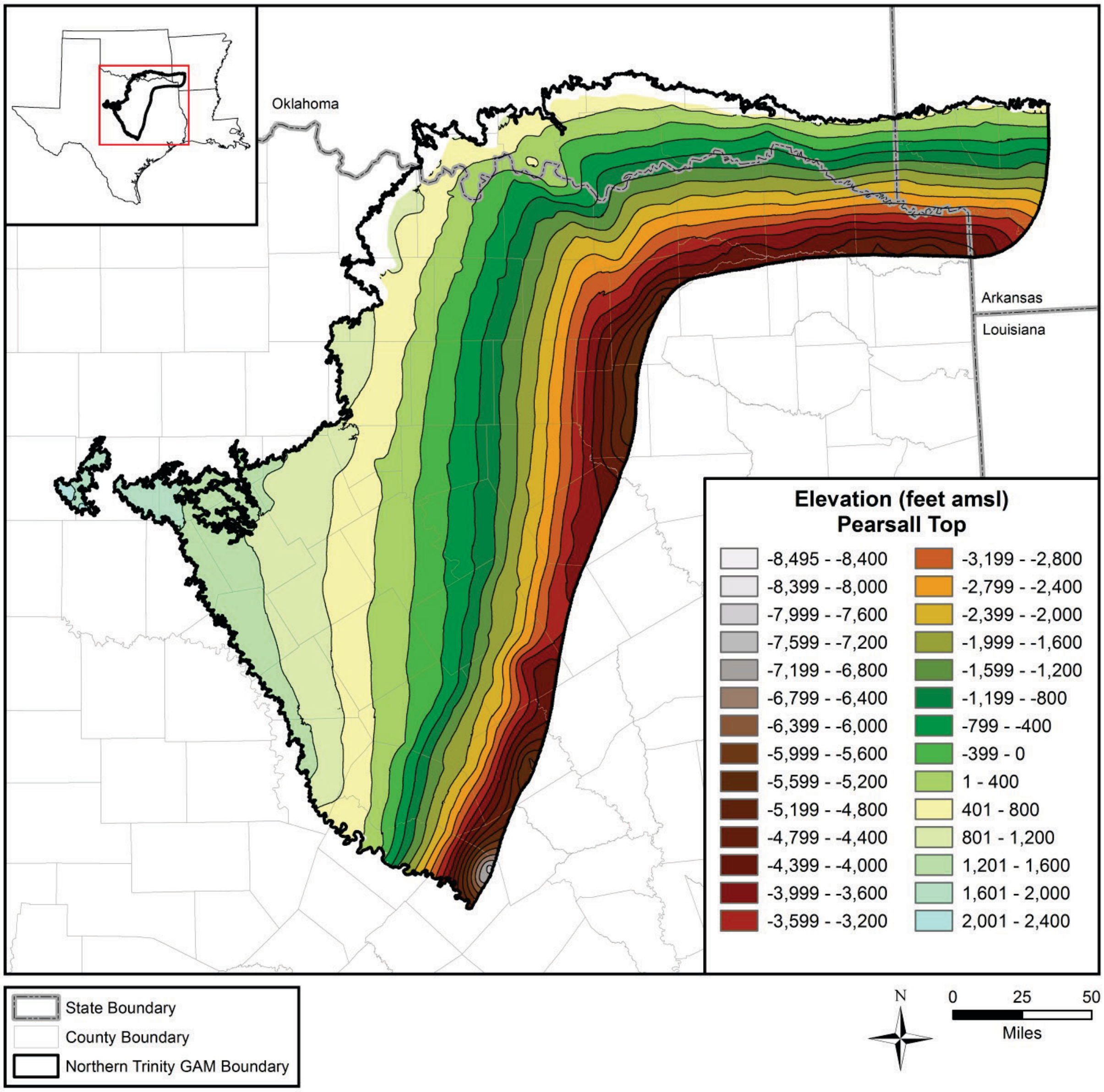


Figure 4-6 **Structure map showing the elevation of the top of the Pearsall hydrostratigraphic unit. Note: amsl = above mean sea level.**

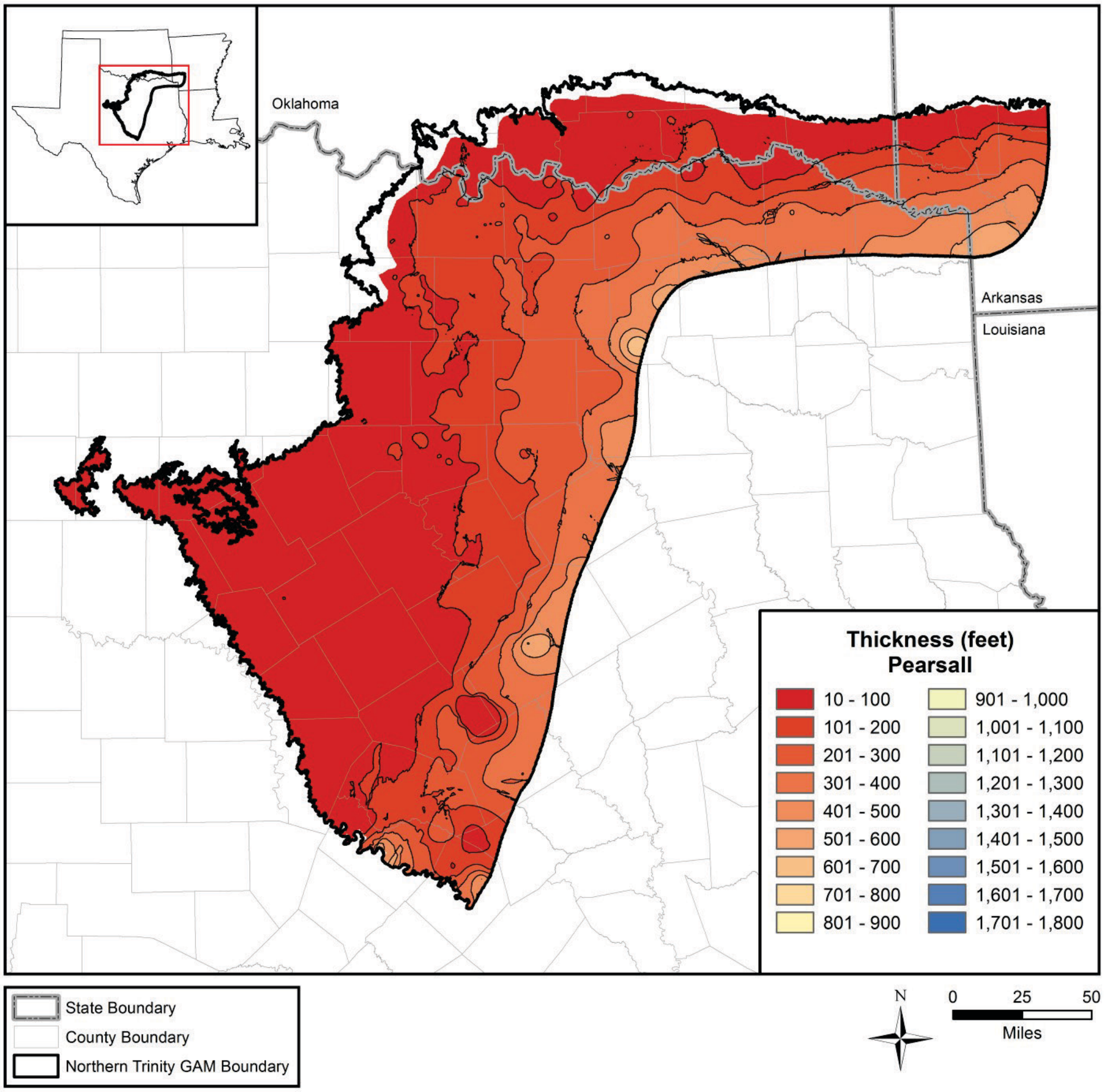


Figure 4-7 Isopach map of the Pearsall hydrostratigraphic unit.

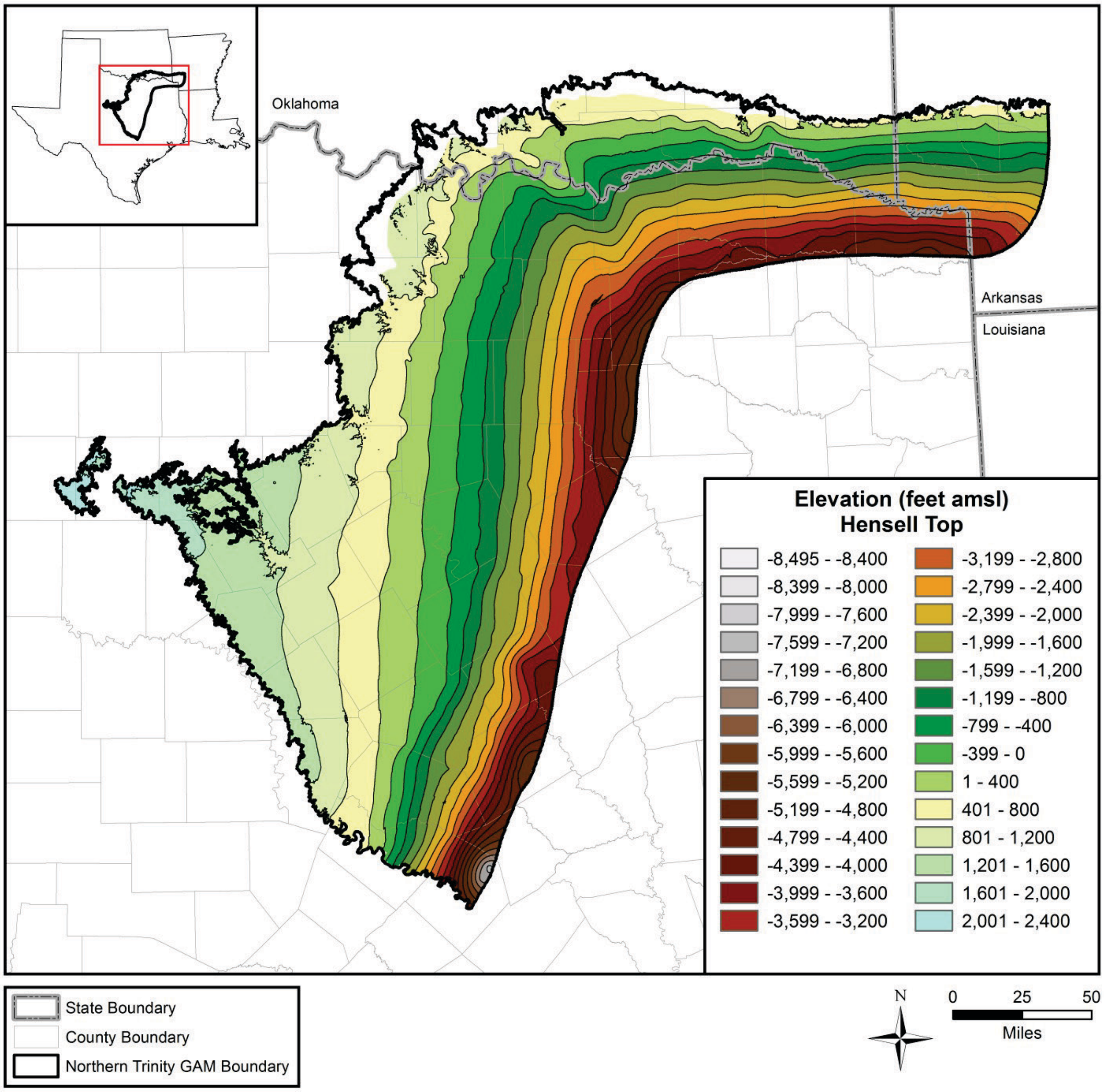


Figure 4-8 Structure map showing the elevation of the top of the Hensell hydrostratigraphic unit. Note: amsl = above mean sea level.

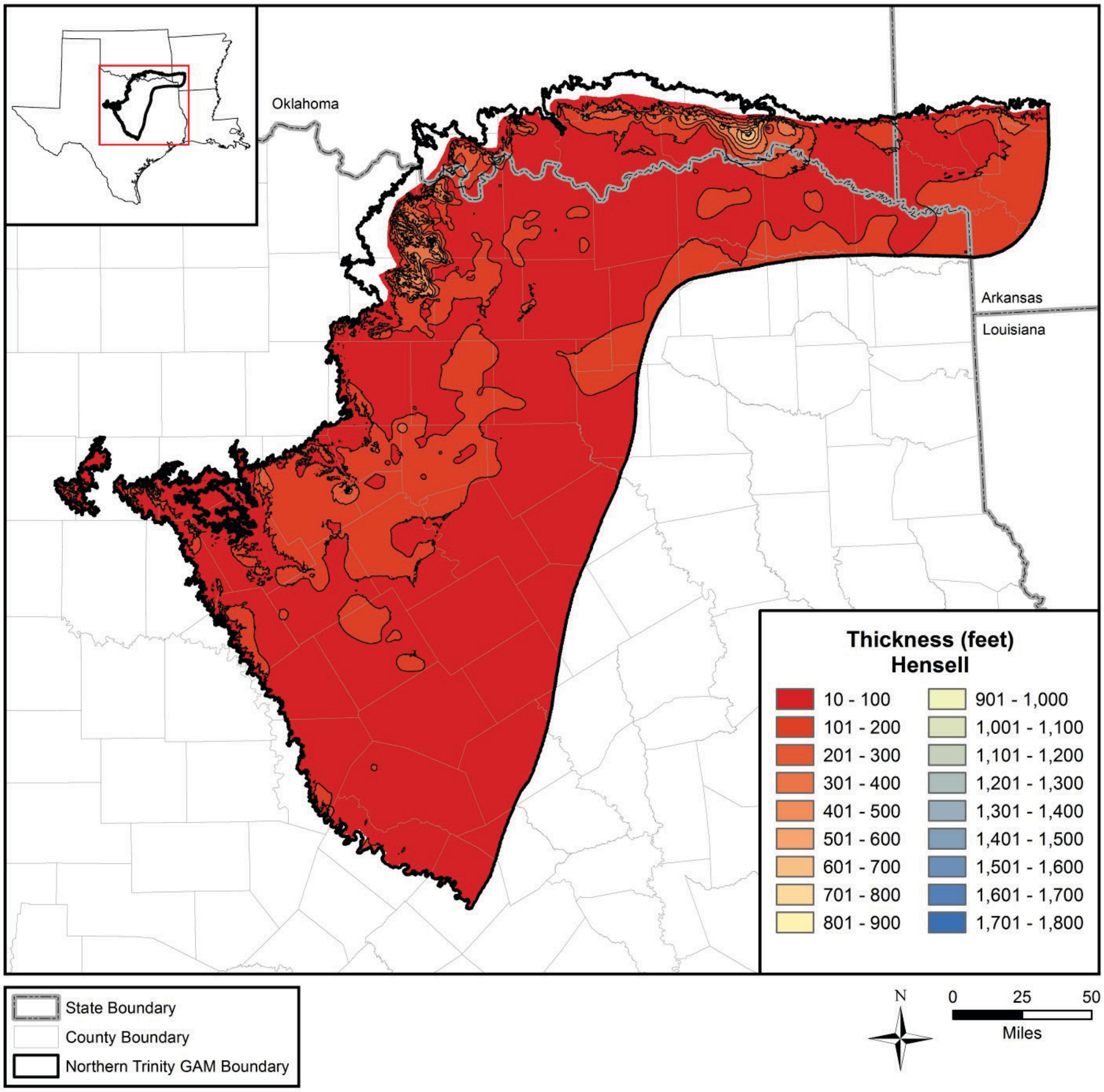


Figure 4-9 Isopach map of the Hensell hydrostratigraphic unit.

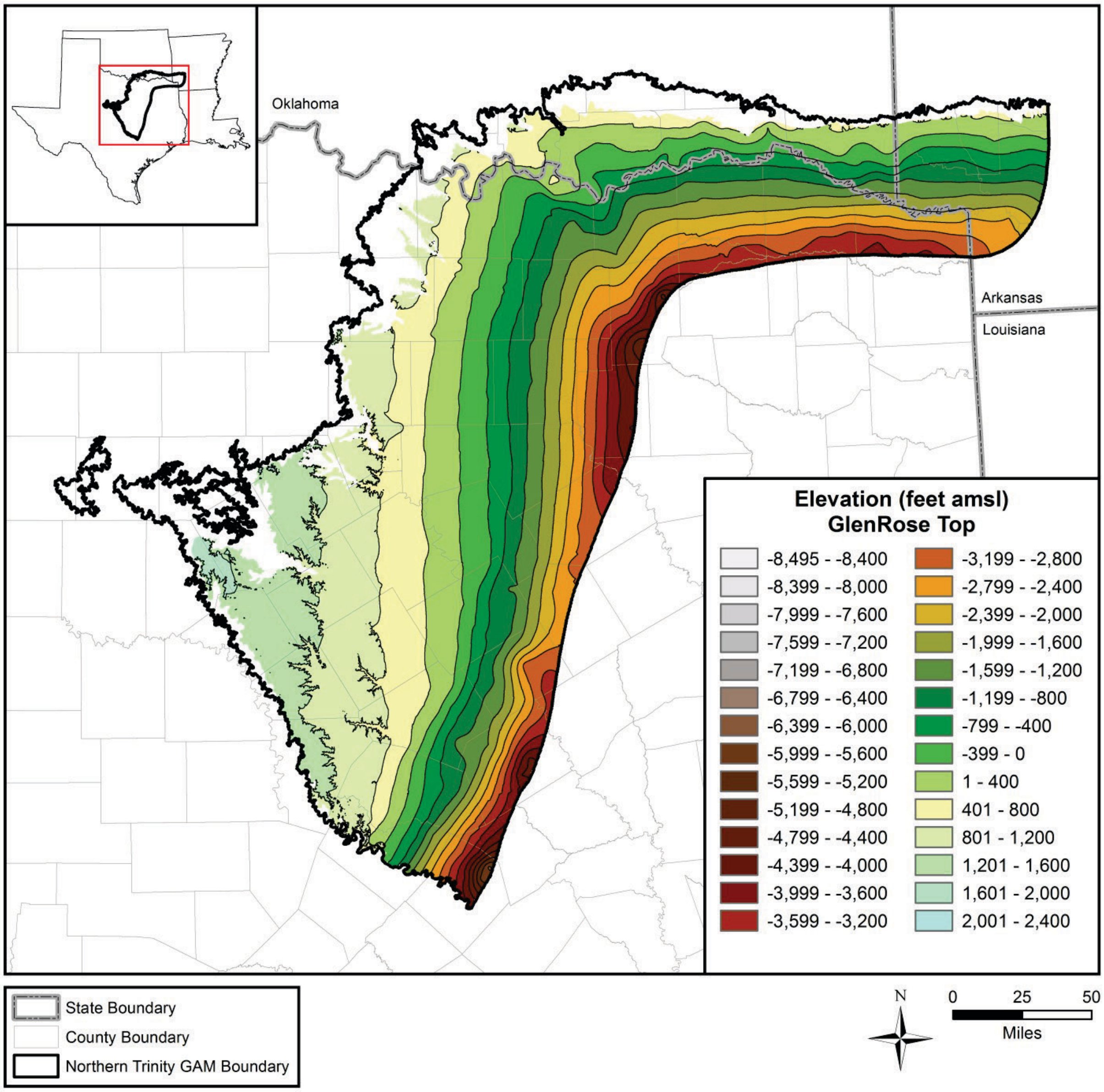


Figure 4-10 Structure map showing the elevation of the top of the Glen Rose hydrostratigraphic unit. Note: amsl = above mean sea level.

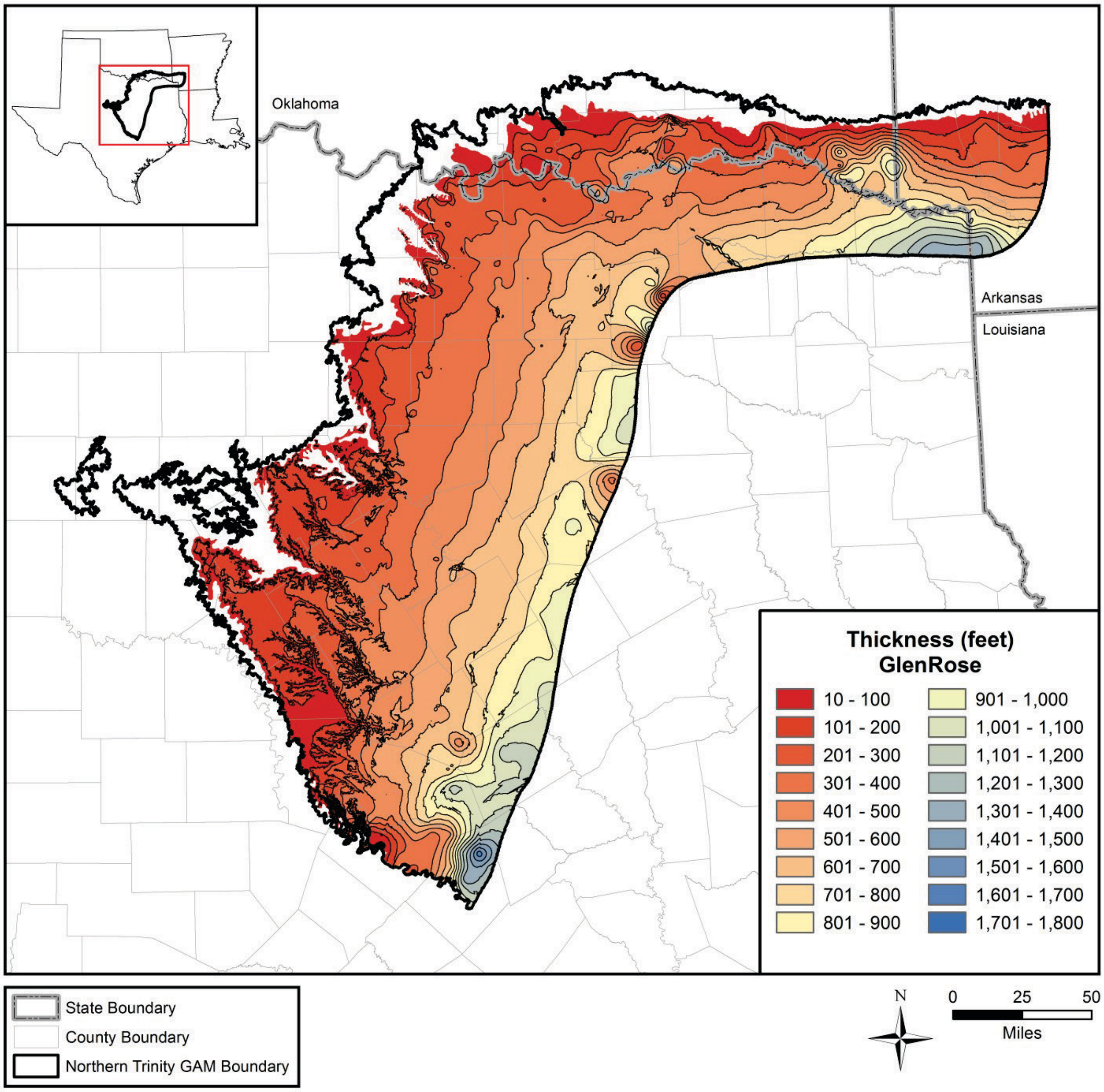


Figure 4-11 Isopach map of the Glen Rose hydrostratigraphic unit.

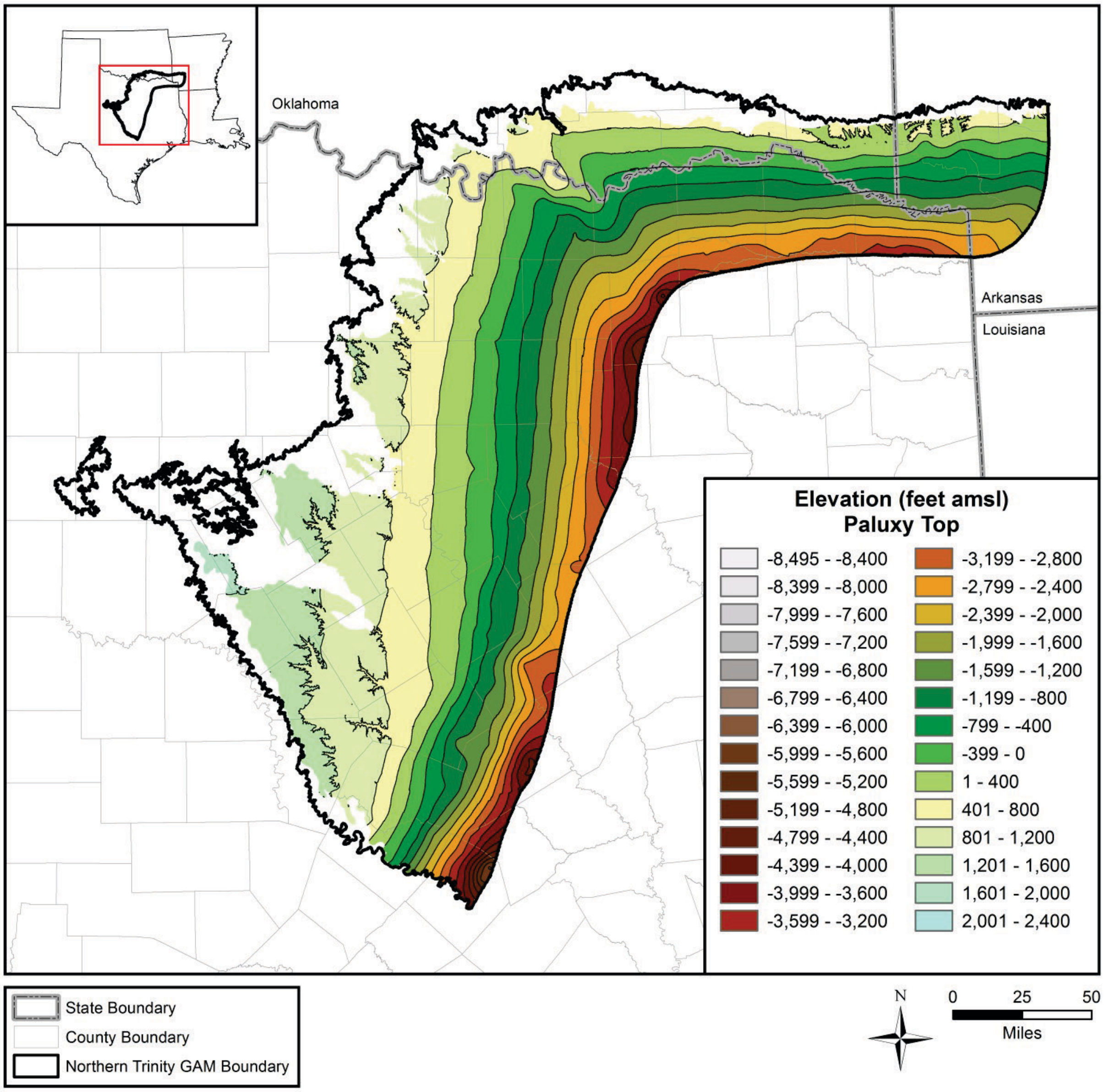


Figure 4-12 Structure map of the elevation of the top of the Paluxy hydrostratigraphic unit. Note: amsl = above mean sea level.

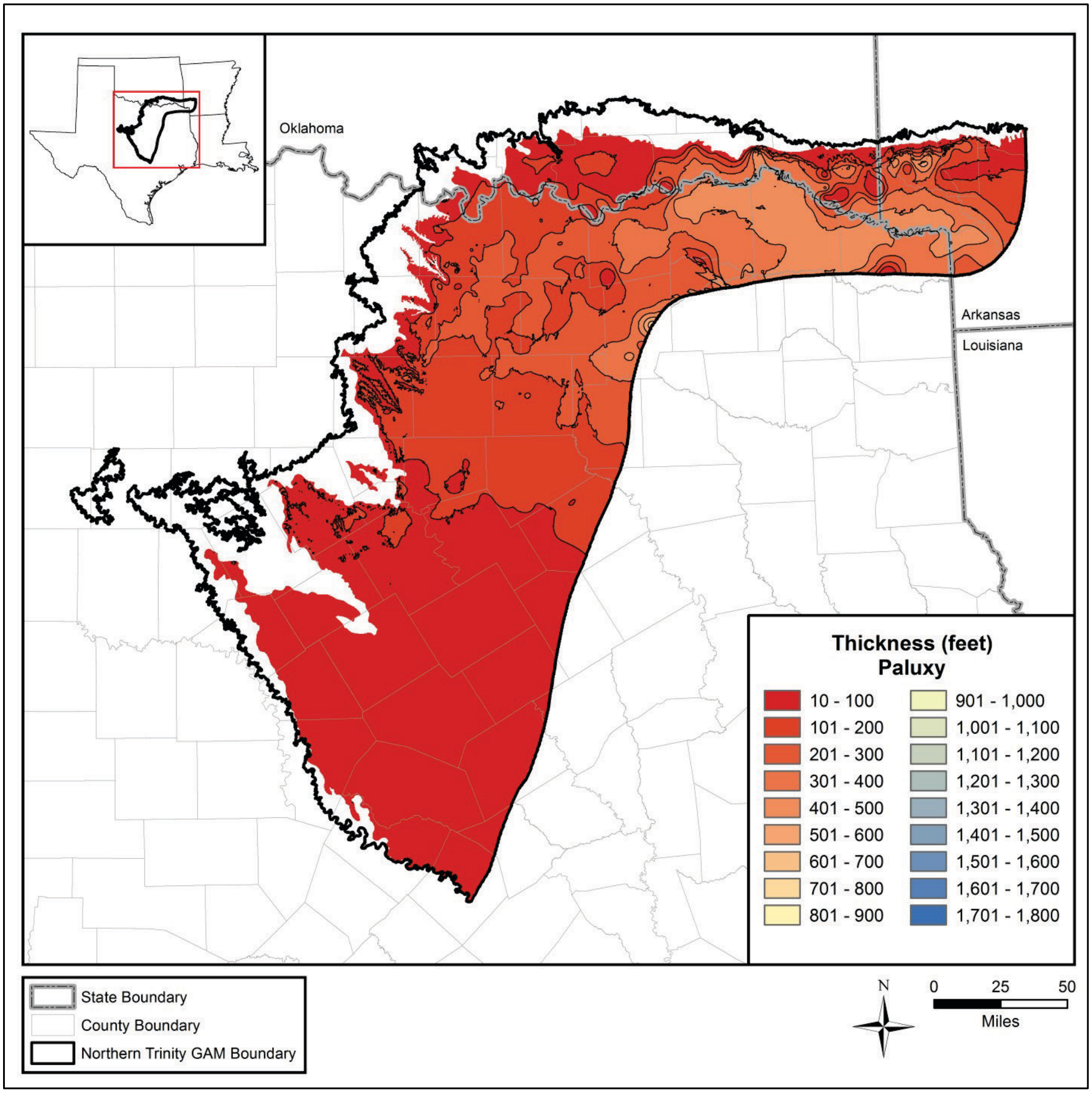


Figure 4-13 Isopach map of the Paluxy hydrostratigraphic unit.

5 Data sources

This study utilized digital data from wells and geological datasets. The main sources for well data to support the stratigraphic framework model include well information from the Northern Trinity Aquifer GAM study, TWDB BRACS Database, and IHS Markit Database. Groundwater chemistry data came from the TWDB Groundwater Database and the TCEQ Public Water Supply Database, providing over 2,900 measurements of total dissolved solids. Where wells have more than one historical measurement, the most recent measurement was used for purposes of this study. Digital elevation data was sourced from the United States Geological Survey (2016).

5.1 Northern Trinity Aquifer GAM well database

The stratigraphic framework for the Northern Trinity Aquifer GAM was created using stratigraphic pick interpretations from geophysical well logs. The final database includes 1,302 wells across the Northern Trinity Aquifer study area (Figure 5-1). This dataset includes well logs from 408 water wells and 894 oil and gas wells. Depth-registered image logs containing geophysical curve data (gamma ray, spontaneous potential, and resistivity) were used to correlate boundaries and interpret stratigraphic horizons and lithology. Of the 1,302 wells, stratigraphic and lithologic interpretations were conducted on 988 geophysical logs. For a complete summary of how the stratigraphic units were created from previous investigations, surface outcrops, and geophysical logs, see Kelley and others (2014).

Raster image logs are digital scans of paper copies of geophysical well logs. Historically, logging companies would provide paper copies of geophysical well logs to clients who maintained them in files. Some copies would also be made available to log libraries and archives, such as that maintained by the Texas Bureau of Economic Geology in Austin. Within the last 15 years, it has become common practice for geologists to utilize scanned well log images to facilitate the stratigraphic interpretation of large geographic areas.

The term "digital logs" refers to geophysical well logs that contain one or more of the recorded measurements in vector format. Historically, digital copies of geophysical well logs were generally not released to the public and no digital copies were made for older well logs. As a result, it is generally necessary to digitize the curves from scanned paper copies when this format is desired.

The digital log example (Figure 5-2) demonstrates how curve values can be used to identify lithologic intervals in the well. The left-most example in the figure demonstrates how lithology can be visually depicted based upon the relative values of the spontaneous potential (SP) and deep resistivity (Resistivity) curves. Also shown are examples of the correlations for the six surfaces used to delineate the hydrostratigraphic units of the Northern Trinity Aquifer.

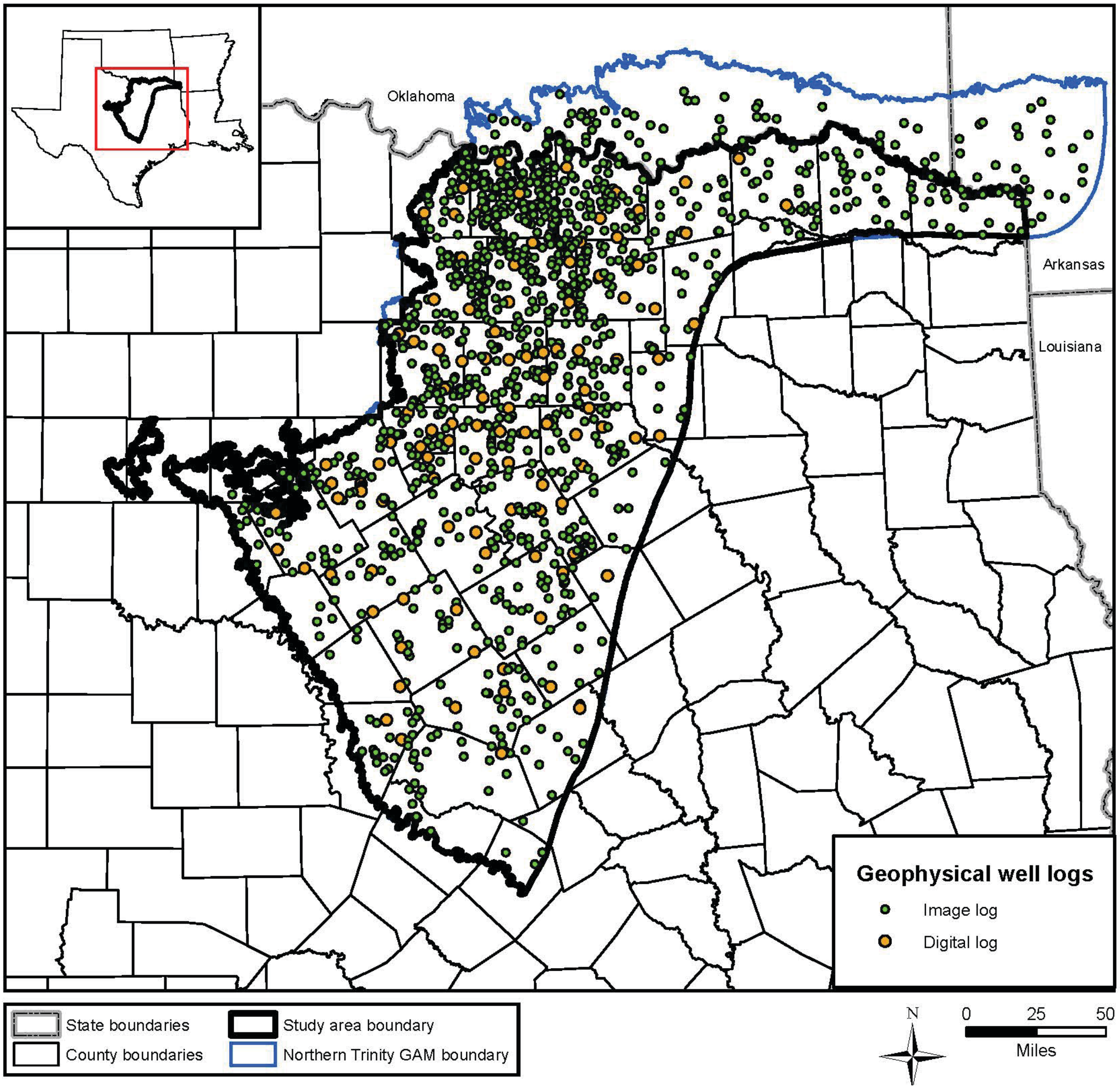
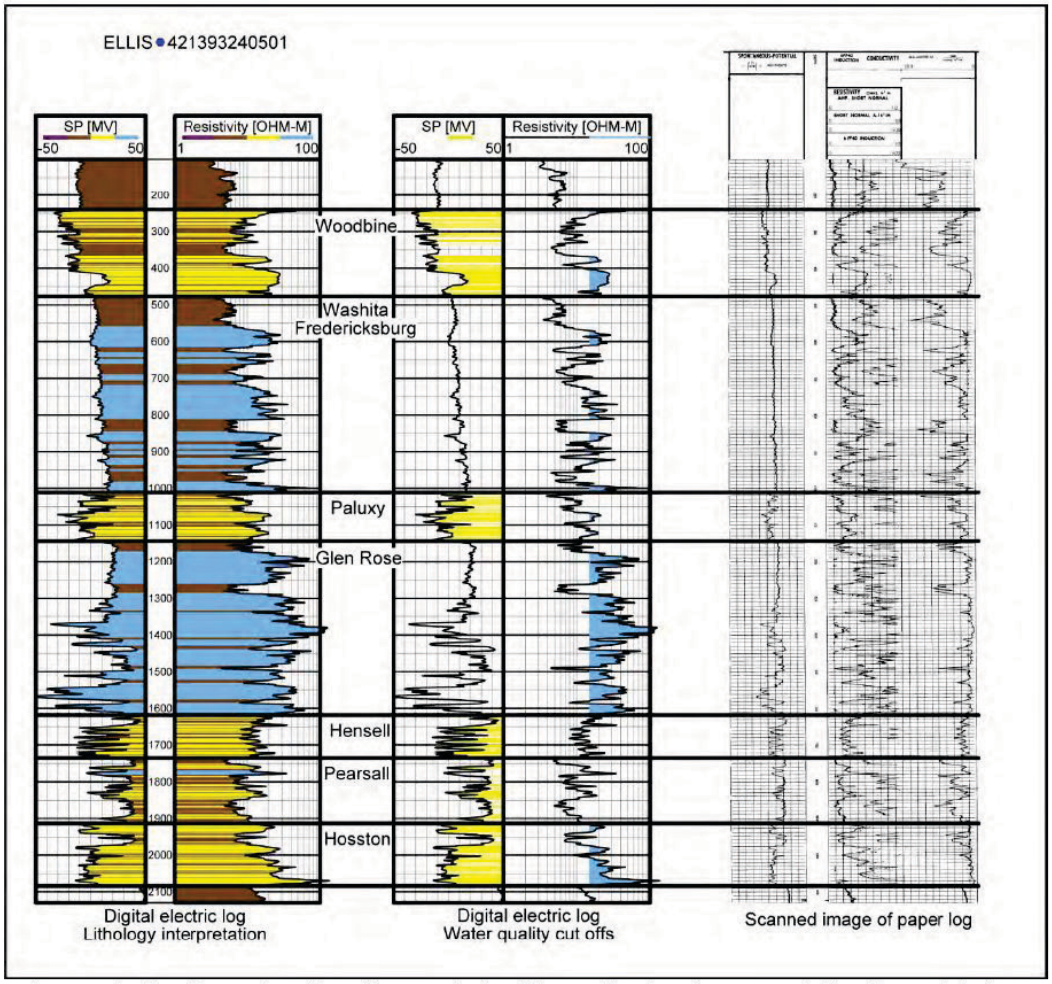


Figure 5-1 Location of geophysical well log data used for this study distinguishing between the 1,193 image logs and the 109 digital logs.



yellow = greater than 50 percent sandstone, blue = greater than 50 percent limestone, brown = greater than 50 percent shale

Figure 5-2 Example electric log from a well in Ellis County showing differences between digital (vector) logs and image (raster) logs from the same well.

6 Geophysical well log analysis and methodology

Analytical chemistry measurements from water well samples are the most accurate method of determining the salinity of groundwater. In general, the water well samples available for the Northern Trinity Aquifer have been obtained from water wells completed in generally fresh portions of the aquifer. Therefore, in order to map the distribution of brackish groundwater it was necessary to utilize geophysical well logs to calculate the total dissolved solids concentration where groundwater samples are not available. In this section, the calculation method chosen, and its limitations, are discussed in detail.

6.1 Salinity estimation methods

There are numerous methods for estimating the total dissolved solids concentration of groundwater using geophysical data from borehole logs (Estepp, 2010; Collier, 1993a; Collier, 1993b), that have been used with success for evaluations of brackish water resources in Texas.

Examples of these techniques are included in studies such as Alger (1966), Ayers and Lewis (1985), Fogg (1980), Fogg and Kreitler (1982), Fogg and Blanchard (1986), Hamlin (1988), Estepp (1998), Meyer (2012), and Young et al. (2016). Many of these applications were performed in the relatively unconsolidated sediments of the Gulf of Mexico Basin. Examples of techniques used specifically in the consolidated units of the Trinity Aquifer are sparse. Exceptions are Collier (1993a, 1993b) and Estepp (1998), both of which have specific examples of calculations performed in the Northern Trinity Aquifer system. Additionally, there also examples of resistivity and porosity-based methods applied to carbonate aquifers like the Glen Rose and Cow Creek limestones of the Trinity Aquifer (Schultz, 1994; Kwader, 1986; MacCary, 1980)

Most of these methods rely on three main assumptions: (1) the resistivity value of formation water can be determined from measurements and parameters recorded by the borehole electric log; (2) the calculated water resistivity can be corrected for variances in formation temperature and water chemistry; and (3) an appropriate relationship between corrected water resistivity and total dissolved solids can be determined.

6.2 Estimating salinity from borehole geophysical logs

Estimating the total dissolved solids concentration of groundwater in an area where few water quality samples are available requires the use of a proxy measurement for water quality (i.e., the resistivity of water (R_w) within a subsurface formation). The resistivity of groundwater is not typically measured directly. As a result, R_w is often calculated using parameters measured by borehole geophysical tools.

Under most conditions, R_w is inversely related to total dissolved solids concentration. That is, the higher the resistivity, the fresher the water. Conversely, the lower the resistivity is, the more brackish the water. Said another way, higher resistivity indicates that fewer ions are available to conduct electricity, and lower resistivity indicates that more ions are available to conduct electricity.

Borehole geophysical logging tools collect data for a number of parameters. The types of tools and specific parameters included in electric logging have varied significantly over time, but a few parameters relevant to calculating R_w are fairly common. These parameters include spontaneous potential (SP), deep resistivity (R_{deep}), flushed zone (or shallow) resistivity (R_{xo}), and porosity (ϕ). Ideally, the measured R_{deep} value is equivalent to the true formation resistivity (R_t) value. R_t represents the resistivity of the formation with no influence from invaded mud or other drilling fluids. Depending on the type of borehole geophysical tool used, some corrections to the R_{deep} value may be needed to make it more representative of R_t (Estepp, 2010). When a formation is fully saturated with water, as is the case for aquifers or brackish water production zones, the true formation resistivity (R_t) is equal to the water-saturated formation resistivity (R_o).

Archie (1942) developed a relationship between R_w and the resistivity of a water-saturated formation (R_o) expressed as:

$F = \frac{R_o}{R_w}$ Equation 6-1

Where F is the formation factor which is related to porosity by the equation:

$F = \frac{a}{\phi^m}$ Equation 6-2

In this equation, ϕ is the formation porosity, m is the cementation exponent, and a is the tortuosity factor, which is commonly assumed to equal 1 (Archie, 1942; Winsauer and others, 1952). Combining Equations 6-1 and 6-2 produces:

$R_w = R_o \times \phi^m$ Equation 6-3

Equation 6-3 provides the basis for development of several methods to calculate R_w from the measured borehole logging values. It is important to note that the relationships developed by Archie (1942) and the measurements of R_{deep} and R_{xo} are based on the presence of saline groundwater primarily composed of sodium chloride ions, which is common for deep groundwater associated with petroleum deposits. Fresh and brackish groundwaters have widely varying chemical compositions that are often very different from sodium chloride solutions. As a result, the calculated R_w in Equation 6-3 is more correctly called the resistivity of the water equivalent (R_{we}) because it represents an assumption of sodium chloride groundwater composition. Values of R_{we} must be corrected to account for the differences in chemical composition before a valid R_w can be determined.

6.3 Evaluation of salinity estimation methods

Given the paucity of data with which to determine porosity or the cementation exponent, two approaches were examined to characterize water quality in the Northern Trinity Aquifer study area. The first approach is the Mean R_o Method (Estepp, 1998, 2010). This method has been successfully implemented in unconsolidated sands of the Gulf Coast Basin (Ayers and Lewis, 1985; Fogg, 1980; Fogg and Kreitler, 1982; Fogg and Blanchard, 1986; Hamlin, 1988; Collier, 1993a; Collier, 1993b; Estepp, 1998; Meyer, 2012; Young et al., 2016), but has yet to be proven in consolidated rock formations such as the Trinity Aquifer system. Collier (1993a, 1993b) states that the Mean R_o Method is well suited for application in sandstones that have consistent lithology, are unconsolidated to semi-consolidated, and are Tertiary or younger in age.

The principal behind the Mean R_o Method involves the comparison of total dissolved solids sampled from a well against the corresponding observed resistivity (R_o) value for the same lithologic unit that supplied the water. The deep resistivity or induction curve is used to minimize the effects of mud filtrate invasion. The observed deep resistivity (R_o) is assumed to be approximately equal to true formation resistivity (R_t), where water saturation is 100 percent (no hydrocarbons) (Jones and Buford, 1951; Turcan, 1962; Alger, 1966). This is assumed to be the case in all analyses for the Northern Trinity Aquifer.

Sampled water quality and geophysical log data compiled by Kelley and others (2014) for the Northern Trinity Aquifer GAM provided a test dataset to evaluate the potential use of the Mean R_o Method. Within the dataset, there were 38 public water supply wells that had a water quality measurement, a geophysical log that included either deep resistivity and/or induction (equivalent to deep resistivity for the purposes of this analysis), and screen location information. Using stratigraphic picks made from the logs it was determined that most of these wells were screened exclusively in the Hosston hydrostratigraphic unit. Only one well was completed in both the Hosston and Pearsall units.

The sand units within the screened intervals for the wells were identified. The average and 80th percentile resistivity values for each of the sand units were derived from the digitized log. The 80th percentile value was used to see if using the higher amplitude portions of the resistivity kick would produce a better match to the sampled water quality. The resulting average and 80th percentile resistivity values were plotted against the sampled water quality value and a regression line was fit to the data (Table 6-1). As illustrated, there is no evident trend that could be used to correlate R_o and sampled total dissolved solids (Figures 6-1a and 6-1b). We then took the combined average resistivity for all of the sands in the screened interval of a well and plotted the value against the sampled total dissolved solids from the same well (Figures 6-2a and 6-2b). Averaging the results by well did not improve the correlation.

While multiple publications have shown successful use of the Mean R_o Method, the approach remains unproven in consolidated formations. For unconsolidated Gulf Coast Basin type sediments, the observed resistivity value is dominated by the electrical conductivity of the formation fluid as opposed to the interconnectivity of the formation. The cementation exponent reflects the tortuosity of current flow through the maze of rock pores (Dewan, 1983) and can be highly variable in a formation due to compaction, specific depositional environment, cementation, and many other post-depositional processes. This parameter is almost exclusively derived from rock core studies performed in the laboratory and that type of analysis is rarely publicly available.

Table 6-1 Average observed resistivity and total dissolved solids values for wells used in Mean Ro Analysis. All wells are screened in the Hosston hydrostratigraphic unit.

State well number	Depth (feet)		Mean R_o (ohm-m)		80th Percentile R_o (ohm-m)		TDS (mg/L)
	Top	Bottom	Sand interval	Average over screen interval	Sand interval	Average over screen interval	Average over screen interval
4055701	2,494	2,611	33	33	42	42	852
4061501	665	734	36	37	49	46	1183
	836	924	49		60		
	912	956	26		41		
	1,136	1,208	28		32		
	1,212	1,226	43		49		

State well number	Depth (feet)		Mean R_o (ohm-m)		80th Percentile R_o (ohm-m)		TDS (mg/L)
	Top	Bottom	Sand interval	Average over screen interval	Sand interval	Average over screen interval	Average over screen interval
	1,237	1,252	40		44		
4062801	2,209	2,307	33	36	35	38	1021
	2,326	2,358	39		41		
5805902	2,191	2,287	26	26	28	30	2288
	2,293	2,310	24		28		
	2,321	2,418	30		33		
5806102	2,024	2,173	30	30	34	34	1177
1850501	2,278	2,295	27	26	30	30	1541
	2,298	2,321	27		30		
	2,350	2,392	34		42		
	2,404	2,466	24		27		
	2,479	2,493	20		22		
4026102	565	612	36	36	40	40	920
3224306	1,880	1,996	31	38	40	56	851
	1,892	2,000	33		40		
	2,009	2,043	40		60		
	2,036	2,052	49		86		
3301301	2,016	2,066	23	22	27	28	1766
	2,068	2,076	17		20		
	2,088	2,172	24		33		
	2,186	2,268	26		33		
3309102	1,926	1,948	17	21	20	26	1079
	1,957	1,971	17		22		
	1,988	2,036	24		31		
	2,054	2,084	25		30		
	2,092	2,122	21		27		
3309403	1,924	1,943	25	27	30	31	979
	1,965	1,981	24		25		
	1,990	2,009	34		37		
	2,017	2,037	29		32		
	2,044	2,050	30		35		
	2,056	2,079	23		27		
3309503	2,115	2,178	35	30	39	34	1279
	2,189	2,215	25		29		

State well number	Depth (feet)		Mean R_o (ohm-m)		80th Percentile R_o (ohm-m)		TDS (mg/L)
	Top	Bottom	Sand interval	Average over screen interval	Sand interval	Average over screen interval	Average over screen interval
3320101	3,615	3,742	27	30	31	35	1549
	3,756	3,838	33		38		
3326301	2,956	2,982	31	33	31	38	1270
	2,999	3,028	28		33		
	3,054	3,104	29		35		
	3,116	3,139	25		27		
	3,153	3,162	49		61		
1857404	1,706	1,771	19	22	22	24	1015
	1,783	1,811	24		26		
	1,816	1,829	21		23		
	1,834	1,878	23		25		
1857602	2,231	2,396	23	23	25	25	1021
1962204	951	1,019	36	36	44	44	517
1964201	1,621	1,643	33	39	38	46	841
	1,650	1,664	40		56		
	1,675	1,683	52		57		
	1,686	1,693	31		35		
	1,697	1,706	39		43		
	1,710	1,727	42		48		
3333101	2,174	2,214	20	21	30	29	570
	2,228	2,354	23		27		
3342702	2,750	2,798	24	24	26	26	1215
3263802	1,441	1,480	11	11	14	14	627
	1,493	1,614	11		14		
3909902	3,066	3,095	14	17	17	19	800
	3,103	3,113	16		18		
	3,119	3,145	18		19		
	3,156	3,182	17		20		
	3,194	3,203	18		20		
	3,212	3,219	19		20		
3910201	3,490	3,557	22	22	26	26	1096
4007301	1,515	1,540	34	28	48	34	673

State well number	Depth (feet)		Mean R_o (ohm-m)		80th Percentile R_o (ohm-m)		TDS (mg/L)
	Top	Bottom	Sand interval	Average over screen interval	Sand interval	Average over screen interval	Average over screen interval
	1,571	1,585	33		39		
	1,604	1,631	27		36		
	1,642	1,670	26		31		
	1,678	1,690	28		38		
	1,697	1,712	27		30		
	1,719	1,738	30		34		
	1,741	1,747	20		20		
3238904	1,488	1,497	36	36	41	41	589
3925402	2,525	2,580	24	40	26	46	727
	2,619	2,644	31		34		
	2,649	2,678	30		34		
	2,700	2,730	21		25		
	2,758	2,795	21		26		
	2,822	2,854	30		31		
	2,868	2,919	80		104		
	2,928	2,946	79		87		
3925501	3,030	3,183	106	106	131	131	751
3933202	3,390	3,415	39	34	46	40	1024
	3,430	3,460	28		33		
4024301	2,644	2,805	34	34	46	46	1394
5807901	3,219	3,240	24	21	27	22	2366
	3,246	3,254	16		16		
	3,260	3,283	20		22		
	3,286	3,307	22		23		
	3,313	3,367	20		21		
	3,383	3,394	22		23		
	3,398	3,447	23		26		
3214110	876	891	15	14	18	17	939
	904	917	10		12		
	930	941	11		13		
	957	1,020	20		24		
3216203	1,588	1,604	21	32	25	37	985
	1,607	1,619	22		26		
	1,625	1,651	37		47		
	1,656	1,675	31		31		

State well number	Depth (feet)		Mean R_o (ohm-m)		80th Percentile R_o (ohm-m)		TDS (mg/L)
	Top	Bottom	Sand interval	Average over screen interval	Sand interval	Average over screen interval	Average over screen interval
	1,682	1,690	35		37		
	1,695	1,722	46		56		
3222602	1,052	1,075	24	20	35	26	625
	1,088	1,094	27		35		
	1,110	1,122	11		12		
	1,133	1,145	19		21		
3222903	1,068	1,081	19	21	20	25	730
	1,087	1,110	18		21		
	1,116	1,154	23		29		
	1,194	1,243	19		22		
	1,250	1,290	26		31		
3224101	1,573	1,596	8	16	11	20	1018
	1,601	1,605	5		6		
	1,608	1,644	15		18		
	1,646	1,668	23		24		
	1,670	1,758	30		39		
3231605	1,598	1,623	15	15	19	19	690
5813503	2,468	2,488	30	30	30	33	1201
	2,500	2,528	24		26		
	2,539	2,589	32		37		
	2,606	2,621	35		37		
5821204	2,337	2,391	19	19	21	22	1320
	2,414	2,580	20		23		

Note: TDS = total dissolved solids and mg/l = milligrams per liter.

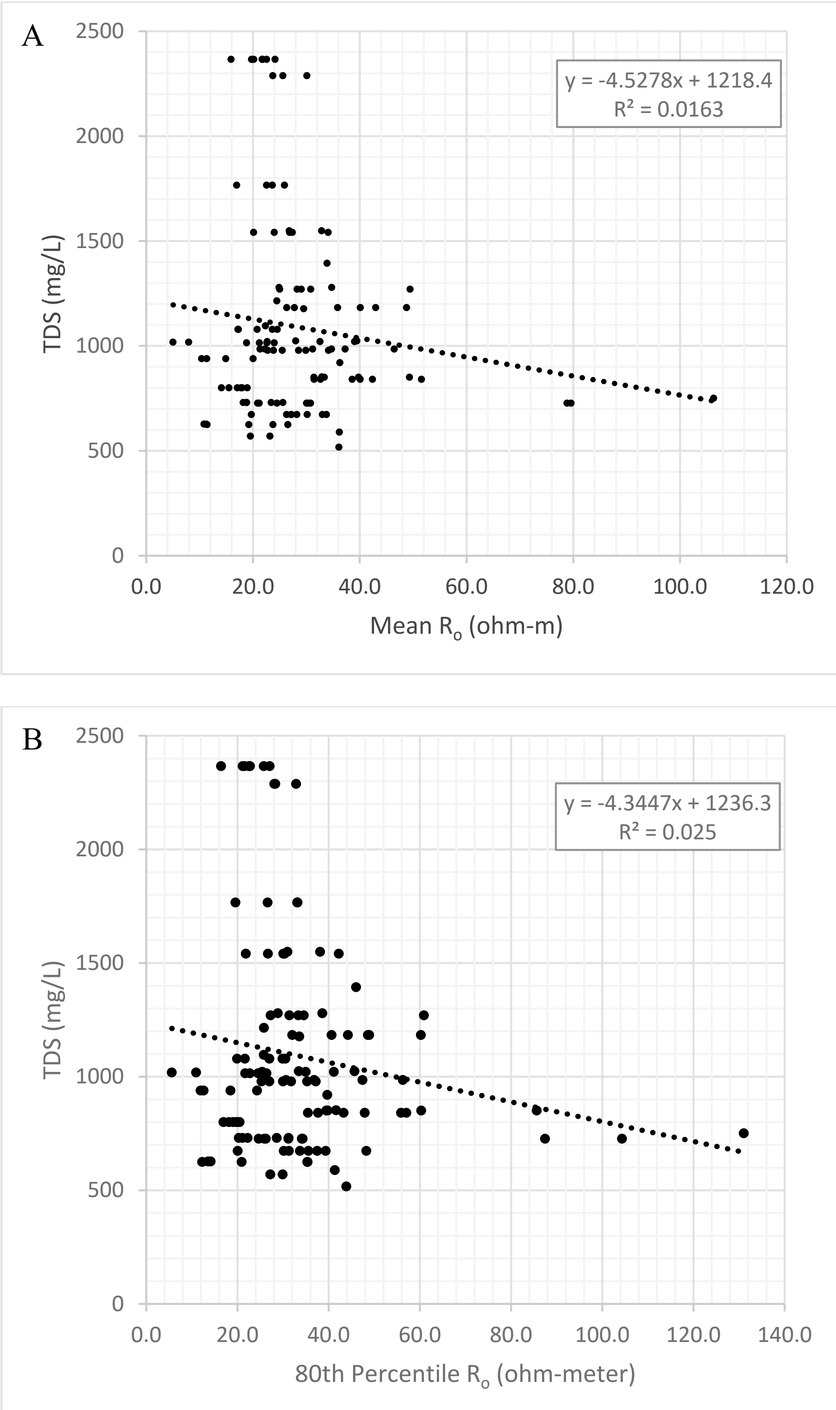
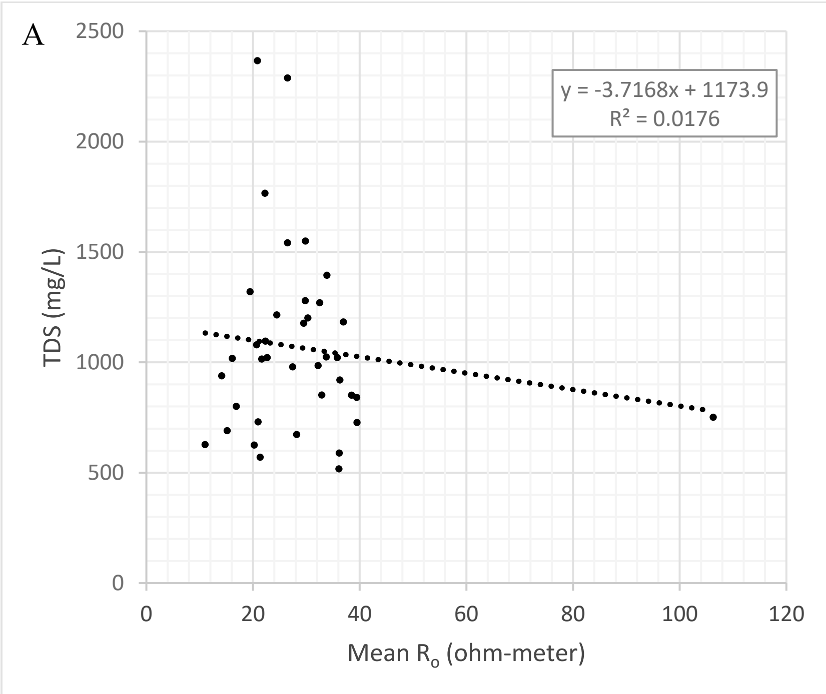


Figure 6-1 Hosston hydrostratigraphic unit data from Table 6-1. A) Sampled total dissolved solids plotted against average observed resistivity (R_o) for each sand identified in the screened portion of the water well. B) Sampled total dissolved solids plotted against the 80th percentile of the observed resistivity (R_o) for each sand identified in the screened portion of the water well. Note: mg/l = milligrams per liter and TDS = total dissolved solids.



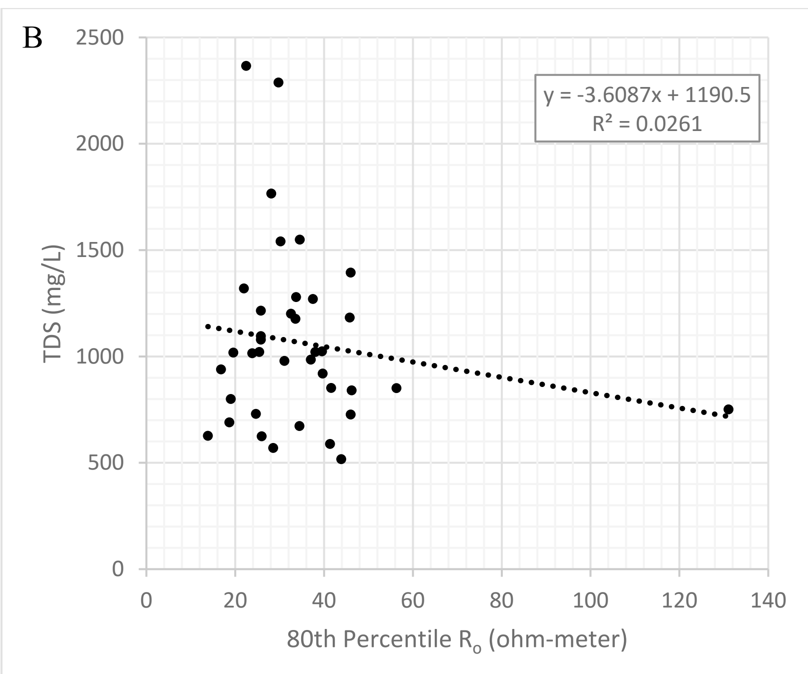


Figure 6-2 **Hosston hydrostratigraphic unit data from Table 6-1. A) Sampled total dissolved solids plotted against average observed resistivity (R_o) and averaged for combined sands identified in the screened portion of the water well and B) Sampled total dissolved solids plotted against 80th percentile of the observed resistivity (R_o) and averaged for combined sands identified in the screened portion of the water well. Note: mg/l = milligrams per liter and TDS = total dissolved solids.**

6.4 Application of the Resistivity Ratio Method

Given the variability of the formation factor and the difficulty in determining its value, a different approach was attempted to predict the formation water resistivity using Archie's (1942) resistivity relationships (Equations 6-1 to 6-3), the Resistivity Ratio, or modified Alger-Harrison Method (Estepp, 2010; Collier, 1993a, Collier 1993b; Alger and Harrison, 1989). Application of this technique only requires the resistivity measurements from geophysical well logs for the mud, mud filtrate, shallow curve, and deep curve.

In a typical borehole environment, like the one shown in Figure 6-3, the formation opposing the borehole can be separated into the flushed zone, transition zone, and uninvaded zone. Within the flushed zone, it is assumed that the native formation fluid has been replaced by the mud filtrate through the pressure created by the weight of the mud column and advection of the mud filtrate through the mud cake developed on permeable formations. In anticipation of this, the logging engineer will take a sample of the circulated mud to measure the temperature and resistivity of the mud (R_m). A filter press will be used to determine the resistivity of the mud filtrate (R_{mf}). These measurements, along with the bottom-hole temperature (BHT), are recorded on the header of the geophysical log along with other various parameters. For logs where R_m values or other mud characteristics (e.g., mud density and type) are available, but R_{mf} is not, R_{mf} can be calculated using the methods outlined in Collier (1993a, 1993b).

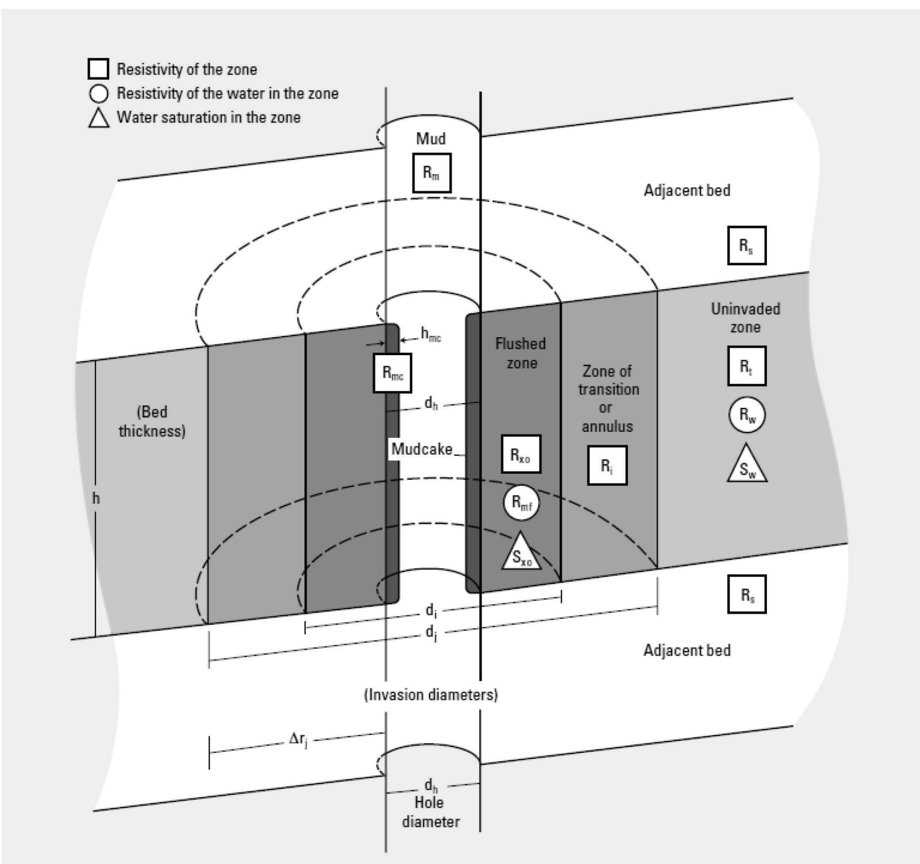


Figure 6-3 Wellbore shown traversing a zone of interest (Schlumberger, 2009).

For the flushed zone, the resistivity of the mud filtrate, R_{mf}, is defined as follows:

$$R_{mf} = \Phi^m \times R_{xo} \qquad \text{Equation 6-4}$$

where:

R_{mf}	=	resistivity of mud filtrate corrected to formation temperature
Φ	=	porosity
m	=	the cementation exponent
R_{xo}	=	the resistivity of a 100 percent mud filtrate-saturated formation
Φ^m	=	known as the formation factor (F)

The Resistivity Ratio Method allows calculation of an equivalent formation water resistivity (R_{we}) by substituting Equation 6-3 into Equation 6-4 to produce:

$$R_{we} = R_{mf} \times \frac{R_o}{R_{xo}} \qquad \text{Equation 6-5}$$

Advantages of the Resistivity Ratio Method include (1) specific formation factor parameters do not need to be measured or estimated, and (2) once R_{mf} is corrected for temperature to 25°C, formation temperatures are not needed. The R_{mf} temperature corrections were conducted using the Arps (1953) equations. Thus, after temperature correction (see Section 6.6), the final R_{we} calculation becomes:

$$R_{we25} = R_{mf25} \times \frac{R_o}{R_{xo}} \qquad \text{Equation 6-6}$$

Where R_{we25} and R_{mf25} are the equivalent formation water and mud-filtrate resistivities at 25°C.

Alternatively, resistivity values can be corrected to formation temperature in Equation 6-5 and then converted to equivalent resistivities at 25°C during the calculation of TDS_{NaCl} (see the following discussion for Equation 6-7 below). This approach was used by this study for the Northern Trinity Aquifer.

The calculated R_{we25} value is also impacted by variations in chemistry within the brackish and freshwater zones. Discussions of techniques for correcting R_{we25} (and R_{mf25}) for the effects of chemistry are found in Estepp (2010) and Collier (1993a, 1993b). In general, the presence of ions such as calcium, magnesium, bicarbonate, and sulfate can have a significant impact on measured resistance values. The variations in the groundwater chemical composition of the Trinity Aquifer require use of non-constant correction factors to convert R_{we25} to R_{w25}. With sufficient borehole geophysical data, correlations between the calculated R_{we25} and R_{w25} (as determined from water quality analyses) can be measured to guide the application of correction factors. Because the available geophysical data are limited, there is a high degree of uncertainty in this type of R_{we25} and R_{w25} correlations.

An alternative approach to correcting for chemistry is to calculate the sodium chloride (NaCl) equivalent of total dissolved solids (TDS_{NaCl}), which is the estimated total dissolved solids value if the groundwater was a simple sodium chloride solution. Then, compare it to water wells with measured water quality data. Water quality data from the Northern Trinity Aquifer region was used to calculate TDS_{NaCl} values using the ionic concentration of the groundwater and the conversion scheme provided in Schlumberger's GEN-4 Chart (Figure 6-4) (Desai and Moore, 1969; Collier, 1993a; Collier, 1993b; Schlumberger, 2013). The curves for each ion constituent in the GEN-4 chart are used with the calculated total dissolved solids for the water sample to produce a multiplier for each ion. This multiplier is then applied to the measured concentrations of each ion to give, when summed, an equivalent TDS_{NaCl}. To apply the GEN-4 Chart corrections, the correction curves for each ion were digitized and fit using various polynomial-rational equations. The parameters for the curve fits were then integrated into the water quality data sheets to calculate the appropriate multipliers.

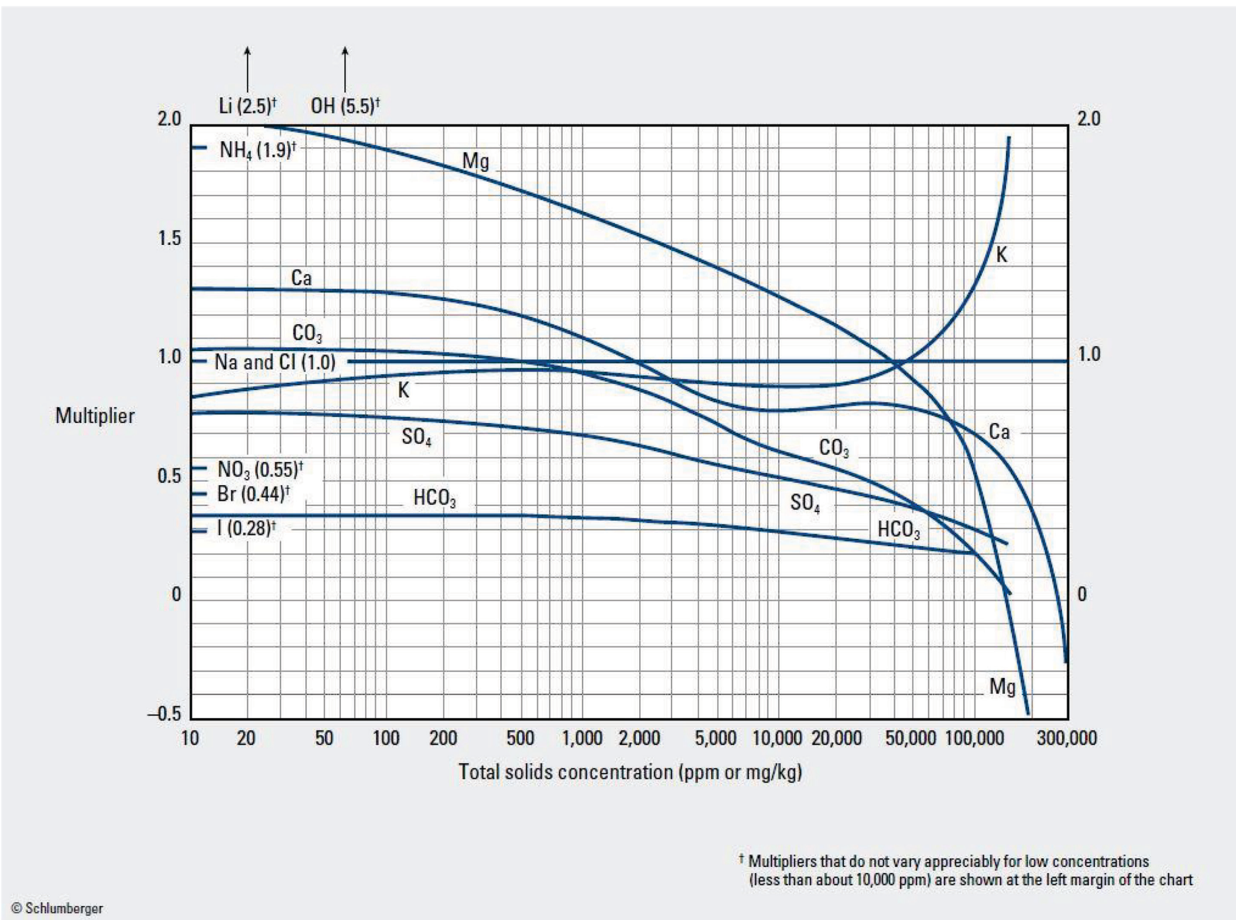


Figure 6-4 Schlumberger chart GEN-4 (Schlumberger, 2009) used to calculate equivalent sodium chloride total dissolved solids from a known water chemistry sample. Note: mg/kg = milligrams per kilogram and ppm stands for parts per million.

The correlation between total dissolved solids and TDS_{NaCl} for each hydrostratigraphic unit was determined by fitting the data using a linear regression approach. The resulting equations were used as a chemistry correction factor to convert the total dissolved solids values determined from borehole geophysics data to an estimate of total dissolved solids for the groundwater.

The R_{we25} calculated from the Resistivity Ratio Method (Equation 6-6) is converted into a TDS_{NaCl} value using the equation of Bateman and Konen (1977) and Bigelow (1992) (Equation 6-7):

$$TDS_{NaCl} = 10^{\left(\frac{3.562 - \log_{10}[R_{we25} - 0.0123]}{0.955}\right)} \qquad \text{Equation 6-7}$$

The TDS_{NaCl} is the equivalent sodium chloride total dissolved solids in milligram per liter and R_{we25} is the equivalent formation water resistivity in ohm-meter. This calculated TDS_{NaCl} value is then converted into an appropriate $TDS_{AquiferUnit}$ (estimated total dissolved solids of the hydrostratigraphic unit groundwater) value using the TDS-TDS_{NaCl} correlation equation for that particular hydrostratigraphic unit.

To test this approach, Northern Trinity Aquifer water wells screened to the Hosston Formation were examined. The selected wells all have a geophysical log with relevant header parameters, screen information, and water quality samples. In total, there were 32 wells that fit the criteria (Table 6-2). For the 32 wells, there were a total of 113 screened sand intervals. Average calculated total dissolved solids values from the Resistivity Ratio Method were plotted against sampled total dissolved solids values for all the wells (Figure 6-5A and B). The measured and estimated total dissolved solids values are somewhat poorly correlated because of the relatively small range over which the measured data is available. There are only four sample measurements that exceed 2,000 milligrams per liter, and most of total dissolved solids measurements cluster between 500 and 1,500 milligrams per liter. Because this technique has a sound theoretical basis, we would expect it to be broadly applicable over a wide range of water quality.

Table 6-2 Calculated total dissolved solids using the Resistivity Ratio Method for Hosston water wells that have a sampled water quality and geophysical log.

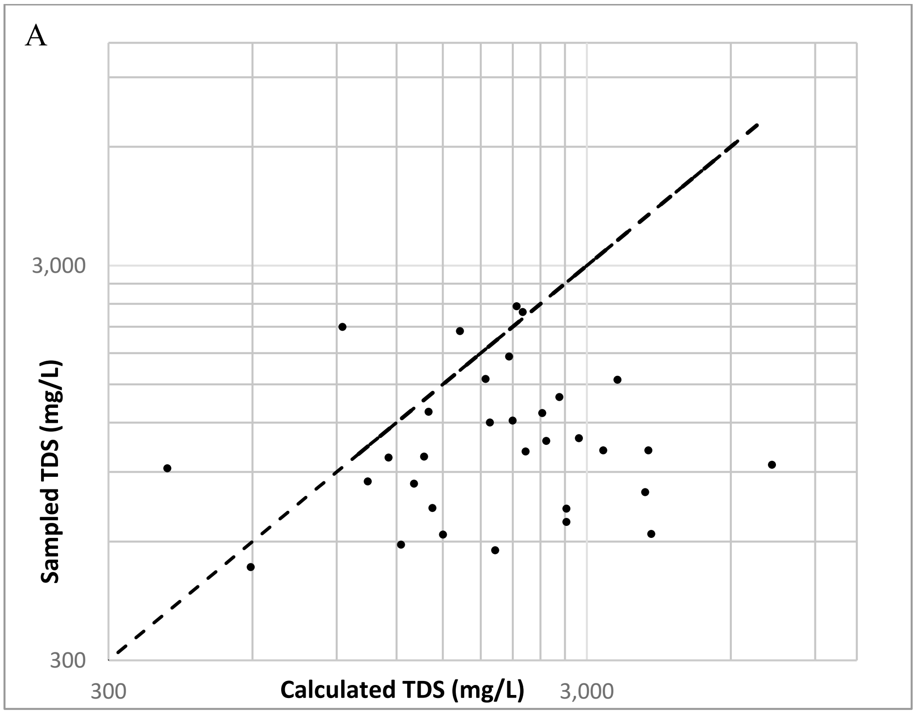
State well number	Depth (feet)		Resistivity (ohm-m)				TDS_{NaCl} (mg/l)	TDS_{NaCl} to TDS multiplier	Calculated TDS (mg/l)		Measured TDS (mg/l)
	Top	Base	R_o	R_s	R_{mfz}	R_w			Sand interval	Average over screen interval	
4055701	2,494	2,611	32.89	33.94	3.99	3.87	869	1.2	1,045	1,045	852
4061501	1,136	1,208	27.77	26.70	3.03	3.15	1,258	1.14	1,432	1,628	2,047
	1,212	1,226	42.99	52.08	2.99	2.47	1,604	1.14	1,826		
	1,237	1,252	40.11	43.50	2.97	2.74	1,428	1.14	1,626		
4062801	2,209	2,307	32.56	26.84	0.91	1.10	3,454	1.16	3,999	4,034	1,021
	2,326	2,358	39.04	32.70	0.90	1.07	3,513	1.16	4,068		
5805902	2,191	2,287	25.59	23.74	1.76	1.89	1,914	1.17	2,242	2,203	2,288
	2,293	2,310	23.71	22.55	1.74	1.83	1,964	1.17	2,301		
	2,321	2,418	30.09	25.83	1.72	2.01	1,764	1.17	2,066		
1850501	2,278	2,295	27.37	14.20	0.60	1.16	3,148	1.09	3,439	3,476	1,541

State well number	Depth (feet)		Resistivity (ohm-m)				TDS_{NaCl} (mg/l)	TDS_{NaCl} to TDS multiplier	Calculated TDS (mg/l)		Measured TDS (mg/l)
	Top	Base	R_o	R_s	R_{mfz}	R_w			Sand interval	Average over screen interval	
	2,298	2,321	26.85	13.66	0.60	1.18	3,084	1.09	3,370		
	2,350	2,392	34.09	16.89	0.60	1.21	2,999	1.09	3,276		
	2,404	2,466	23.98	12.51	0.60	1.14	3,166	1.09	3,459		
	2,479	2,493	20.12	11.56	0.59	1.03	3,509	1.09	3,834		
4026102	565	612	36.28	38.35	12.90	12.2 1	349	1.14	398	398	920
3224306	1,892	2,000	33.37	29.70	4.58	5.15	732	1.19	874	925	2,098
	2,009	2,043	39.78	39.34	4.52	4.57	818	1.19	977		
3301301	2,016	2,066	22.53	19.34	2.20	2.56	1,706	1.16	1,980	2,063	1,766
	2,068	2,076	16.93	15.62	2.19	2.37	1,840	1.16	2,136		
	2,088	2,172	23.61	19.99	2.16	2.55	1,681	1.16	1,951		
	2,186	2,268	25.89	24.39	2.11	2.24	1,882	1.16	2,184		
3309102	1,926	1,948	17.19	19.85	2.49	2.16	2,120	1.22	2,578	2,468	1,079
	1,957	1,971	17.28	18.65	2.49	2.31	1,975	1.22	2,401		
	1,988	2,036	23.61	24.44	2.48	2.40	1,890	1.22	2,298		
	2,054	2,084	24.56	27.58	2.47	2.20	2,059	1.22	2,504		
	2,092	2,122	20.79	23.81	2.47	2.15	2,103	1.22	2,557		
3309403	1,924	1,943	25.47	26.97	4.40	4.15	977	1.22	1,189	1,155	979
	1,965	1,981	23.82	24.19	4.36	4.30	936	1.22	1,138		
	1,990	2,009	34.14	35.13	4.34	4.22	948	1.22	1,154		
	2,017	2,037	28.54	30.76	4.32	4.01	996	1.22	1,212		
	2,044	2,050	29.89	28.86	4.30	4.46	887	1.22	1,079		
	2,056	2,079	22.74	23.47	4.29	4.15	951	1.22	1,157		
3309503	2,115	2,178	34.74	27.00	2.26	2.91	1,030	1.22	1,260	1,400	1,279
	2,189	2,215	24.87	23.40	2.24	2.38	1,259	1.22	1,540		
3320101	3,615	3,742	26.80	21.91	1.75	2.14	1,487	1.21	1,793	1,843	1,549
	3,756	3,838	32.86	28.27	1.73	2.01	1,569	1.21	1,893		
3326301	2,956	2,982	30.82	15.94	1.19	2.30	1,777	1.16	2,069	2,419	1,270
	2,999	3,028	28.28	17.46	1.18	1.91	2,141	1.16	2,493		
	3,054	3,104	29.06	18.90	1.17	1.80	2,262	1.16	2,634		
	3,116	3,139	25.00	17.20	1.16	1.69	2,400	1.16	2,795		
	3,153	3,162	49.43	26.00	1.16	2.20	1,809	1.16	2,106		
1857404	1,706	1,771	18.80	19.67	2.27	2.17	2,038	1.11	2,257	2,233	1,015
	1,783	1,811	23.97	24.39	2.26	2.23	1,979	1.11	2,192		
	1,816	1,829	21.19	22.22	2.26	2.16	2,043	1.11	2,262		
	1,834	1,878	22.61	23.31	2.26	2.19	2,007	1.11	2,222		
1857602	2,231	2,396	22.08	25.65	1.67	1.44	2,849	1.14	3,246	3,246	1,021

State well number	Depth (feet)		Resistivity (ohm-m)				TDS_{NaCl} (mg/l)	TDS_{NaCl} to TDS multiplier	Calculated TDS (mg/l)		Measured TDS (mg/l)
	Top	Base	R_o	R_s	R_{mfz}	R_w			Sand interval	Average over screen interval	
1962204	951	1,019	36.10	41.77	9.70	8.38	499	1.19	595	595	517
1964201	1,621	1,643	32.65	25.30	2.70	3.49	1,147	1.16	1,334	1,305	841
	1,650	1,664	40.07	30.89	2.70	3.50	1,141	1.16	1,327		
	1,675	1,683	51.55	35.70	2.69	3.89	1,019	1.16	1,186		
	1,686	1,693	31.46	25.23	2.69	3.35	1,189	1.16	1,383		
	1,697	1,706	38.57	29.02	2.69	3.57	1,112	1.16	1,294		
	1,710	1,727	42.40	32.25	2.68	3.53	1,125	1.16	1,308		
3333101	2,174	2,214	19.52	19.19	2.51	2.55	1,697	1.19	2,023	1,929	570
	2,228	2,354	23.18	20.76	2.48	2.77	1,539	1.19	1,835		
3342702	2,750	2,798	24.47	28.24	2.05	1.78	1,859	1.13	2,099	2,099	1,215
3263802	1,441	1,480	11.22	20.07	2.33	1.30	3,488	1.21	4,233	4,089	627
	1,493	1,614	10.83	18.13	2.32	1.38	3,251	1.21	3,946		
3909902	3,066	3,095	14.08	16.88	1.21	1.01	3,520	1.19	4,187	3,972	800
	3,103	3,113	15.51	16.67	1.21	1.13	3,134	1.19	3,728		
	3,119	3,145	17.76	19.68	1.21	1.09	3,238	1.19	3,851		
	3,156	3,182	17.07	20.41	1.20	1.00	3,510	1.19	4,175		
	3,194	3,203	17.95	20.77	1.20	1.04	3,390	1.19	4,032		
	3,212	3,219	18.92	21.01	1.20	1.08	3,246	1.19	3,861		
3910201	3,490	3,557	22.33	20.14	1.15	1.27	2,427	1.19	2,886	2,886	1,096
4007301	1,515	1,540	33.74	40.35	2.24	1.87	2,290	1.21	2,769	2,718	673
	1,571	1,585	33.01	38.19	2.23	1.93	2,211	1.21	2,673		
	1,604	1,631	27.18	31.60	2.23	1.91	2,223	1.21	2,687		
	1,642	1,670	26.29	29.43	2.22	1.98	2,136	1.21	2,583		
	1,678	1,690	28.21	31.97	2.21	1.95	2,164	1.21	2,616		
	1,697	1,712	27.13	29.24	2.21	2.05	2,052	1.21	2,481		
	1,719	1,738	30.17	32.65	2.21	2.04	2,061	1.21	2,492		
	1,741	1,747	19.70	28.97	2.20	1.50	2,848	1.21	3,444		
3238904	1,488	1,497	36.18	28.97	3.18	3.98	1,019	1.2	1,227	1,227	589
3925402	2,525	2,580	24.48	19.84	1.36	1.68	2,180	1.25	2,731	2,718	727
	2,619	2,644	30.79	22.05	1.34	1.88	1,913	1.25	2,396		
	2,649	2,678	30.37	21.72	1.34	1.87	1,910	1.25	2,393		
	2,700	2,730	20.87	18.55	1.33	1.49	2,403	1.25	3,010		
	2,758	2,795	21.16	19.87	1.32	1.40	2,548	1.25	3,192		
	2,822	2,854	30.05	24.87	1.30	1.58	2,229	1.25	2,792		
	2,868	2,919	79.58	57.46	1.29	1.79	1,930	1.25	2,418		
	2,928	2,946	78.85	65.72	1.29	1.54	2,246	1.25	2,814		
4024301	2,644	2,805	33.87	30.07	1.44	1.62	2,419	1.09	2,628	2,628	1,394

State well number	Depth (feet)		Resistivity (ohm-m)				TDS_{NaCl} (mg/l)	TDS_{NaCl} to TDS multiplier	Calculated TDS (mg/l)		Measured TDS (mg/l)
	Top	Base	R_o	R_s	R_{mfz}	R_w			Sand interval	Average over screen interval	
5807901	3,219	3,240	24.14	36.42	3.08	2.04	1,858	1.23	2,288	2,140	2,366
	3,246	3,254	15.88	20.31	3.08	2.40	1,561	1.23	1,923		
	3,260	3,283	19.72	30.16	3.07	2.01	1,885	1.23	2,321		
	3,286	3,307	21.71	28.98	3.07	2.30	1,633	1.23	2,011		
	3,313	3,367	20.16	26.77	3.07	2.31	1,624	1.23	2,000		
	3,383	3,394	21.80	33.49	3.06	1.99	1,894	1.23	2,332		
	3,398	3,447	22.53	31.39	3.06	2.20	1,708	1.23	2,104		
3214110	876	891	14.91	17.08	0.83	0.72	6,396	1.23	7,893	7,310	939
	904	917	10.36	11.58	0.82	0.74	6,232	1.23	7,691		
	930	941	11.32	11.15	0.82	0.83	5,448	1.23	6,724		
	957	1,020	20.03	20.30	0.81	0.80	5,616	1.23	6,932		
3216203	1,588	1,604	21.33	25.89	3.57	2.94	1,468	1.21	1,772	1,370	985
	1,607	1,619	22.24	22.48	3.56	3.53	1,211	1.21	1,462		
	1,625	1,651	37.25	28.54	3.55	4.64	905	1.21	1,093		
	1,656	1,675	31.19	34.25	3.54	3.22	1,321	1.21	1,595		
	1,682	1,690	34.72	30.04	3.53	4.08	1,028	1.21	1,242		
	1,695	1,722	46.45	34.53	3.52	4.74	877	1.21	1,059		
3222602	1,052	1,075	23.75	32.39	3.71	2.72	1,510	1.24	1,865	1,501	625
	1,088	1,094	26.52	20.06	3.69	4.88	813	1.24	1,004		
	1,110	1,122	11.39	17.69	3.67	2.36	1,732	1.24	2,140		
	1,133	1,145	19.23	14.44	3.65	4.86	806	1.24	996		
3222903	1,068	1,081	18.81	20.44	3.20	2.94	1,202	1.21	1,456	1,426	730
	1,087	1,110	18.18	18.72	3.18	3.09	1,136	1.21	1,376		
	1,116	1,154	23.42	21.77	3.16	3.40	1,020	1.21	1,236		
	1,194	1,243	18.81	22.84	3.11	2.56	1,350	1.21	1,637		
	1,250	1,290	25.60	27.25	3.08	2.89	1,176	1.21	1,425		
5813503	2,468	2,488	29.61	30.76	2.32	2.23	1,636	1.14	1,864	1,882	1,201
	2,500	2,528	24.24	24.46	2.31	2.29	1,586	1.14	1,808		
	2,539	2,589	32.27	32.09	2.29	2.31	1,562	1.14	1,780		
	2,606	2,621	35.09	40.32	2.28	1.98	1,819	1.14	2,074		

Note: TDS = total dissolved solids and mg/l = milligrams per liter.



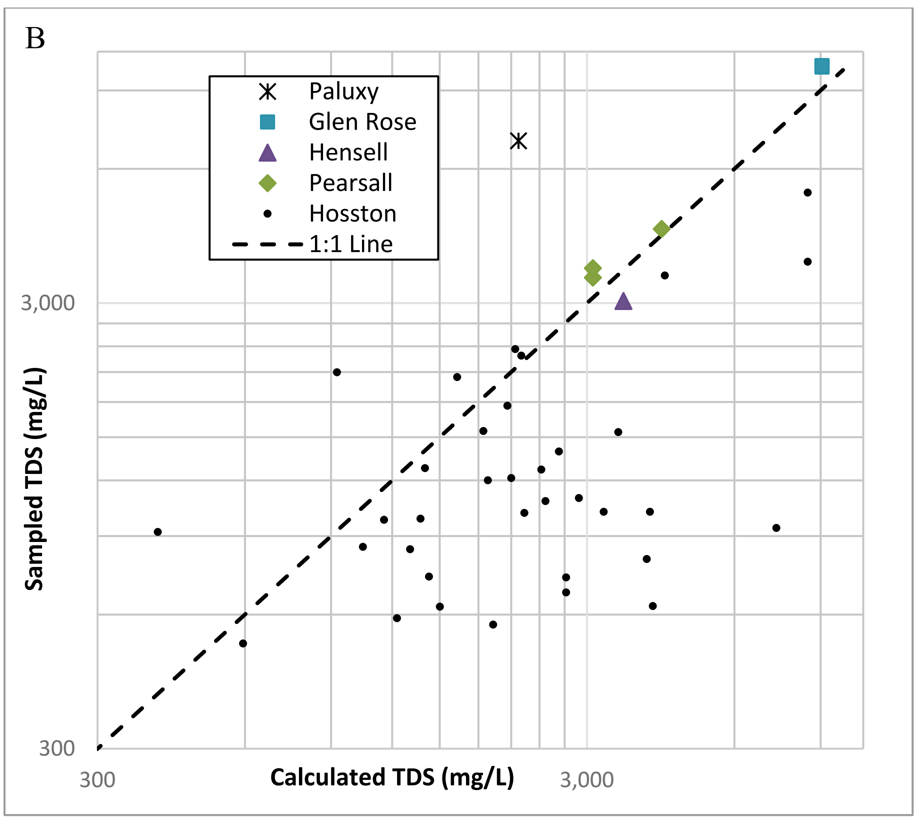


Figure 6-5 **Plot of sampled versus calculated total dissolved solids concentrations. A) Hosston hydrostratigraphic unit only and B) previous data with higher sampled concentration well pair results added. Note: mg/l = milligrams per liter and TDS = total dissolved solids.**

To assess the performance of the technique over wider ranges of total dissolved solids, the few water quality samples that exceed 3,000 milligrams per liter total dissolved solids were plotted versus the calculated value from the nearest resistivity log along strike. There were only 10 pairs of data that met this criterion, these were added to the existing Hosston dataset. While still showing scatter around the 1:1, the correlation line improves significantly (R^2=0.32 versus R^2=0.01) with the addition of the data from 3,000 to 10,000 milligrams per liter of total dissolved solids (Figure 6-5B). Because the 1,000 milligrams per liter total dissolved solids line can largely be determined based on sampled water quality, the improvement in the Resistivity Ratio Method at higher total dissolved solids ranges allows for a complementary approach. In other words, the Resistivity Ratio Method allows for better estimates of the total dissolved solids transition lines from 3,000 to 10,000 milligrams per liter. While sampled water quality is a better data source for estimating the location of the total dissolved solids transition line from 1,000 to 3,000 milligrams per liter.

When the Resistivity Ratio Method was applied more broadly to other formations in the Northern Trinity Aquifer, a discernable trend of increasing calculated total dissolved solids with depth was observed. This trend generally matched the conceptual model of the extent of fresh water delineated by Kelley and others (2014). For these reasons, we consider this method to be the best available for application on a regional basis in the Northern Trinity Aquifer.

Broad application of this method involved acquiring log header parameters and digitized shallow and deep resistivity/induction curves for a geographically and stratigraphically distributed log dataset. Lithologic determinations were made in the five hydrostratigraphic units through the analysis of geophysical well logs. This allowed for the average short and deep resistivity values to be calculated from digitized curves over just the sand/limestone intervals, thereby avoiding clay/shale portions of the units. For the Northern Trinity Aquifer study area, the lithologic determinations were made on a sub 5-foot basis as part of the Northern Trinity Aquifer GAM study. These lithologic intervals were then used to average the shallow and deep resistivity values that were ultimately used in Equations 6-6 and 6-7.

6.5 TDS–TDS_{NaCl} equations and fits for Northern Trinity Aquifer

The total dissolved solids concentration (TDS) measured from water sample data was plotted versus a calculated sodium-chloride total dissolved solids concentration (TDS_{NaCl}) for each hydrostratigraphic unit. The plotted data and the calculated regressions are shown in Figures 6-6 to 6-10. This provided us with the TDS–TDS_{NaCl} equations for the five hydrostratigraphic units modeled for the Northern Trinity Aquifer that are listed in Equations 6-8 to 6-12 below.

$$TDS_{Paluxy} = 1.0559(TDS_{NaCl\ Paluxy}) + 67.946$$ Equation 6-8

$$TDS_{Glen\ Rose} = 1.2238(TDS_{NaCl\ Glen\ Rose}) - 21.92$$ Equation 6-9

$$TDS_{Hensell} = 1.0272(TDS_{NaCl\ Hensell}) + 67.404$$ Equation 6-10

$$TDS_{Pearsall} = 1.0879(TDS_{NaCl\ Pearsall}) + 36.409 \qquad \text{Equation 6-11}$$

$$TDS_{Hosston} = 1.1597(TDS_{NaCl\ Hosston}) - 3.5185 \qquad \text{Equation 6-12}$$

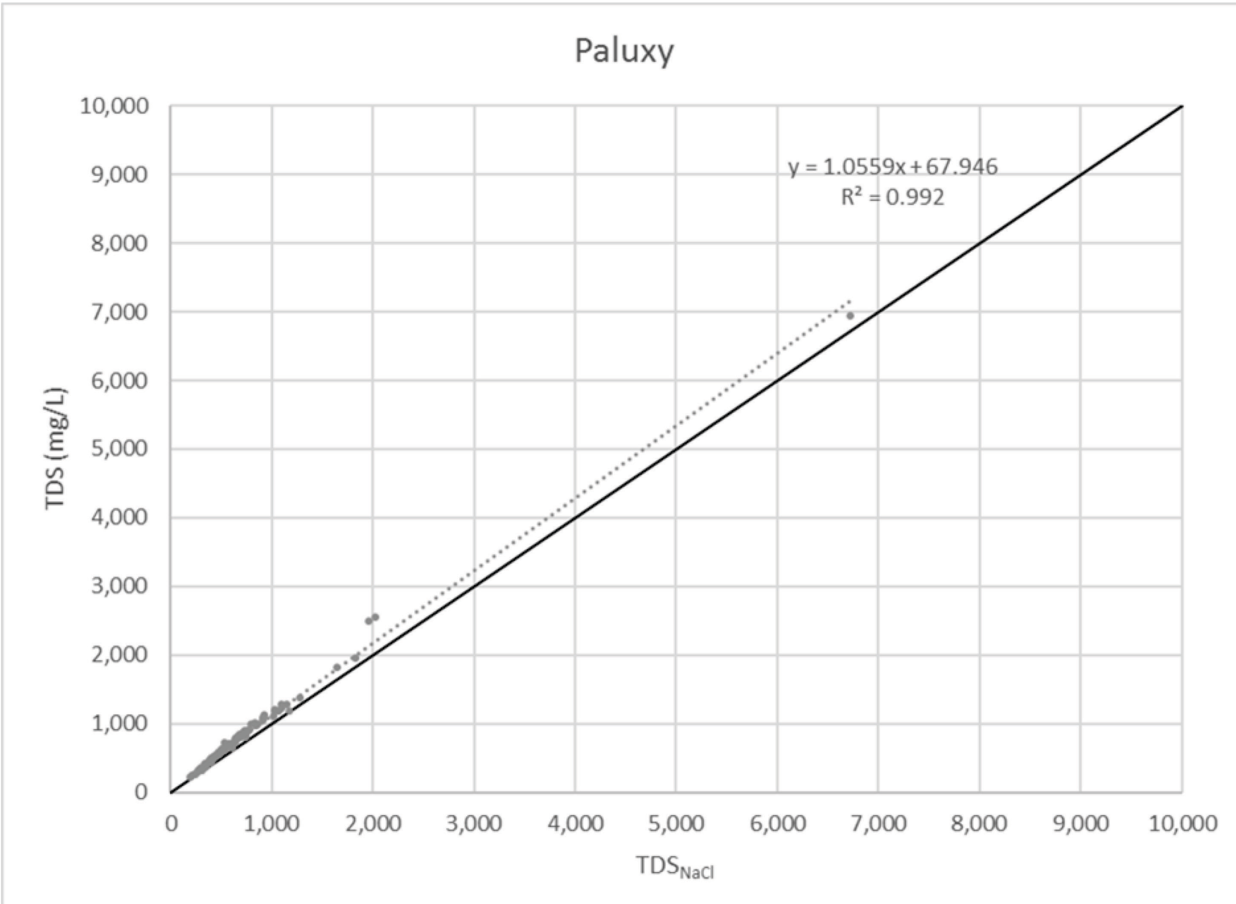


Figure 6-6 **Sampled TDS versus sodium chloride equivalent TDS for the Paluxy hydrostratigraphic unit. Solid line indicating 1:1 relationship is shown for comparison. Note: TDS = total dissolved solids and mg/l = milligrams per liter.**

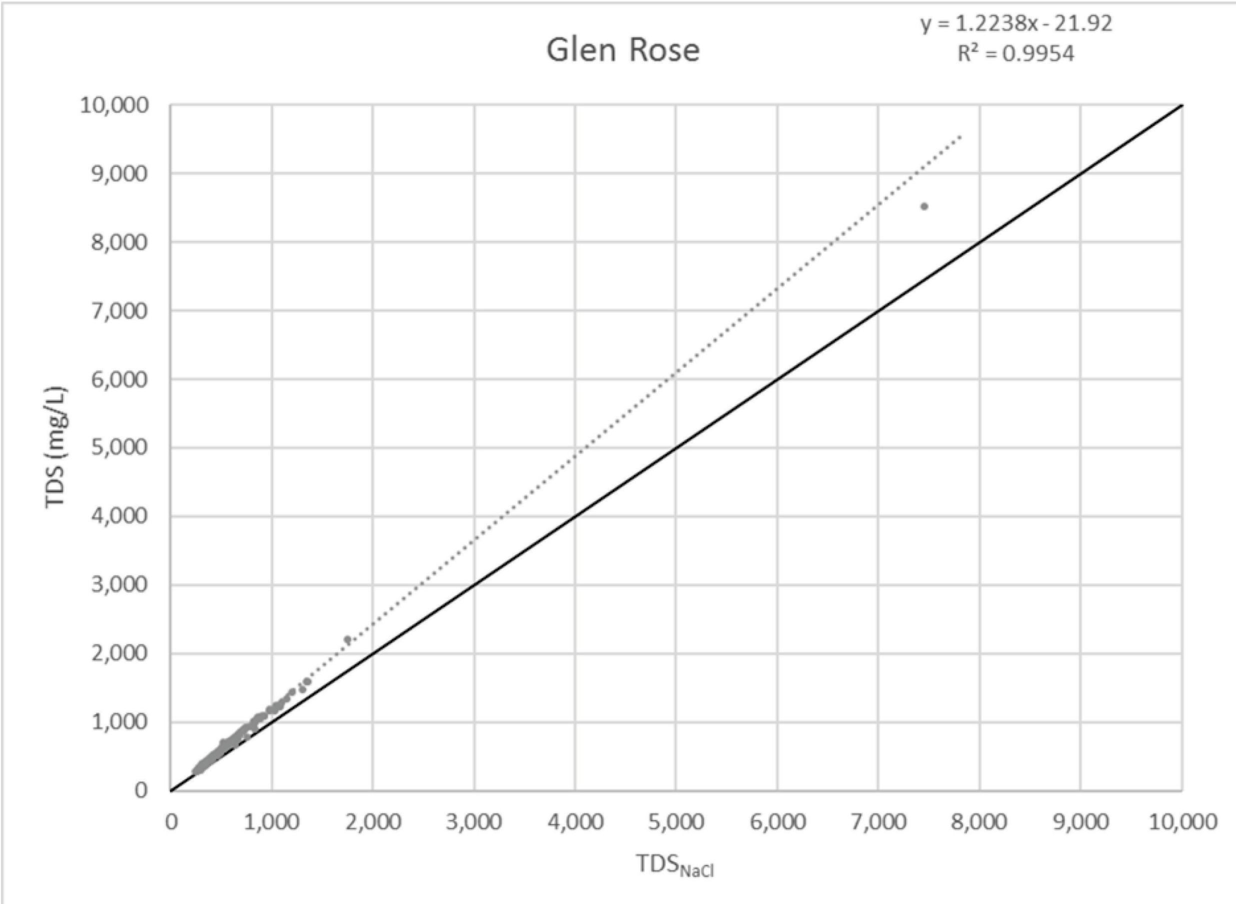


Figure 6-7 **Sampled TDS versus sodium chloride equivalent TDS for the Glen Rose hydrostratigraphic unit. Solid line indicating 1:1 relationship is shown for comparison. Note: TDS = total dissolved solids and mg/l = milligrams per liter.**

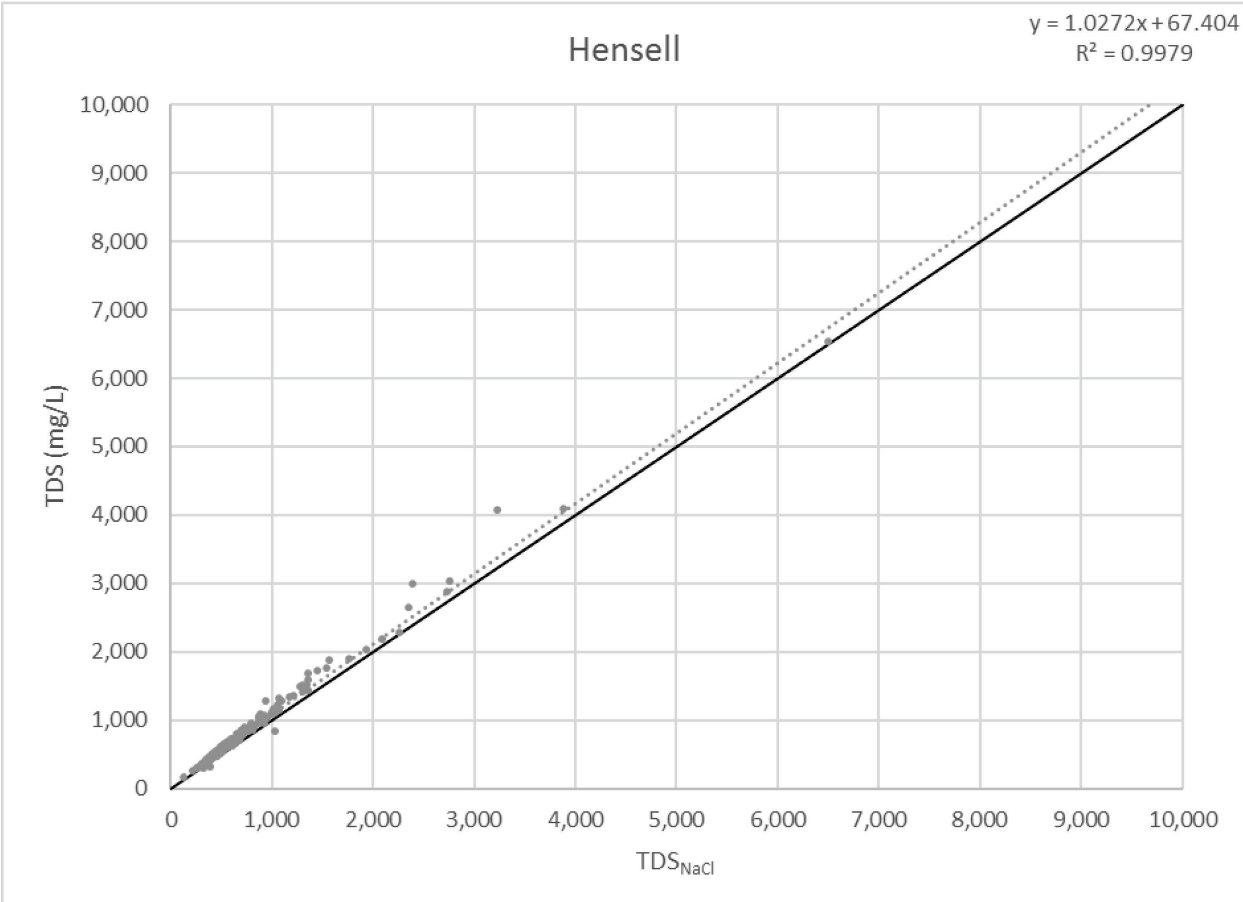


Figure 6-8 **Sampled TDS versus sodium chloride equivalent TDS for the Hensell hydrostratigraphic unit. Solid line indicating 1:1 relationship is shown for comparison. Note: TDS = total dissolved solids and mg/l = milligrams per liter.**

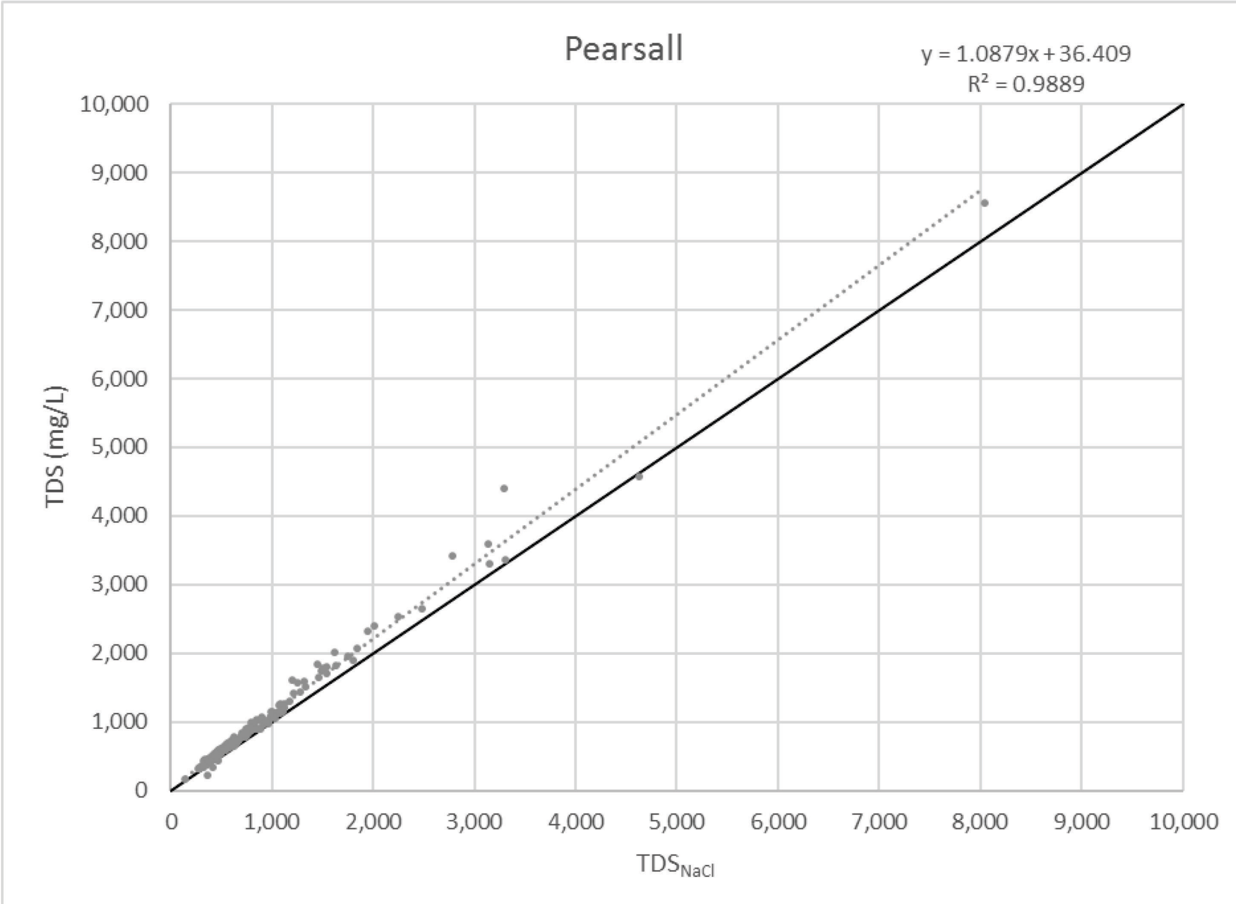


Figure 6-9 **Sampled TDS versus sodium chloride equivalent TDS for the Pearsall hydrostratigraphic unit. Solid line indicating 1:1 relationship is shown for comparison. Note: TDS = total dissolved solids and mg/l = milligrams per liter.**

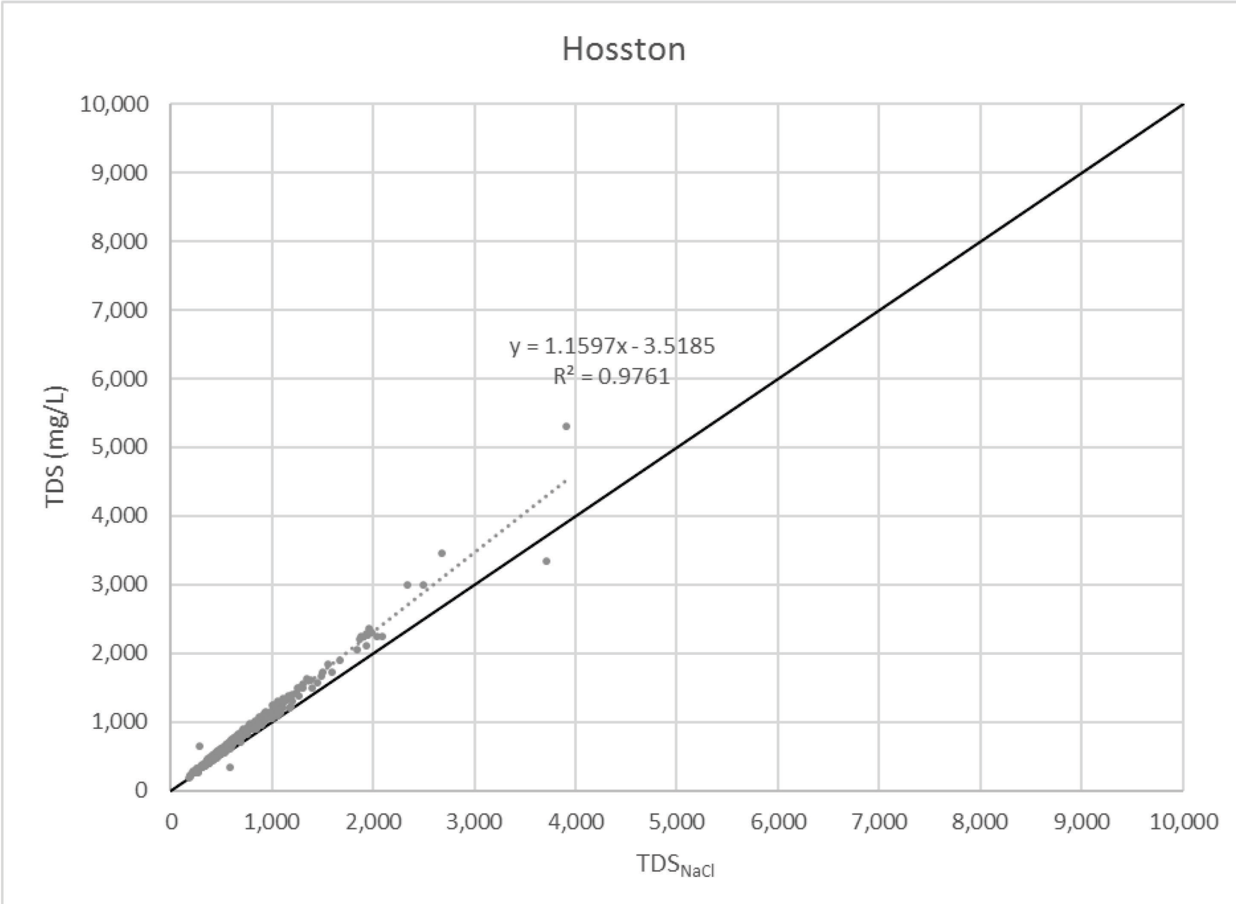


Figure 6-10 Sampled TDS versus sodium chloride equivalent TDS for the Hosston hydrostratigraphic unit. Solid line indicating 1:1 relationship is shown for comparison. Note: TDS = total dissolved solids and mg/l = milligrams per liter.

6.6 Temperature Calculation Sensitivity Analyses

Before water-resistivity values were calculated, an analysis was performed to better understand the different datasets that are available for calculating the mud temperature (Equation 6-13) and the formation temperature (Equation 6-14). The calculated $T_m(z)$ value is used in the correction of R_{mf} in Equation 6-6.

The method for determining $T_m(z)$ utilizes only the data available in the geophysical well log header. The mud temperatures (Equation 6-13) used to convert the resistivity of mud filtrate at surface temperature to the resistivity of mud filtrate at depth were determined from the surface temperature and bottom hole temperature recorded on the log header. There remains considerable question as to whether this dataset is optimal for calculating the mud temperature gradient. The return of the borehole temperature to ambient conditions is sensitive to the contrast between the thermal properties of the drilling fluid and of the surrounding rock as well as the disturbance time (Luheshi, 1982). Equilibrating the temperature in the borehole to the natural geothermal gradient can take up to a few months in some cases (Luheshi, 1982) and it is uncommon in the oil and gas industry to wait until the temperature returns to ambient conditions. Therefore, in calculating the mud temperature gradient, it is assumed that the borehole was continually circulated up to the point that the logging engineer arrived to take the mud temperature/resistivity measurements and subsequently log the borehole.

This leads to the following calculation of mud temperature at formation depth:

$$T_m(z) = T(z_1) + \frac{T(z_2)-T(z_1)}{z_2-z_1}(z - z_1) \qquad \text{Equation 6-13}$$

where:

$T_m(z)$ = temperature (degrees Fahrenheit) of mud at depth of interest (z)

$T(z_1)$ = temperature (degrees Fahrenheit) at depth one, which corresponds to the temperature of the mud filtrate recorded by the logging engineer on the log header

$T(z_2)$ = temperature (degrees Fahrenheit) at depth two, which corresponds to the bottom hole temperature recorded by the logging engineer on the log header

z = depth at which $T(z)$ is being calculated

z_1 = depth at which $T(z_1)$ was taken, which usually corresponds to ground surface

z_2 = depth at which $T(z_2)$ was taken, which usually corresponds to the total depth of the log run

For the formation temperature (Equation 6-14), three different calculation scenarios were tested to determine the impact on the resulting calculated water quality:

1) Both surface and bottom temperature determined from the geophysical log header
2) Surface temperature determined using the Parameter-elevation Relationships on Independent Slopes Model Climate Group (2016) raster dataset (PRISM), average annual surface-temperature dataset and bottom hole temperature determined from the geophysical log header
3) Surface temperature determined using the PRISM average annual surface-temperature dataset and temperature at 3.5km of depth determined from Southern Methodist University's geothermal dataset (Blackwell and others, 2011)

The second method for determining $T_m(z)$ involves calculation of formation temperature at depth (T_z) using values from the PRISM Climate Group's (2016) 30-year Normal Mean Annual Temperature Map (1981–2010) and bottom hole temperatures was preferred:

$$T(z) = T(z_1) + \frac{T(z_2)-T(z_1)}{z_2-z_1}(z - z_1) \qquad \text{Equation 6-14}$$

where:

$T(z)$ = temperature (degrees Fahrenheit) at depth of interest (z)

$T(z_1)$ = temperature (degrees Fahrenheit) at depth one, which corresponds to the PRISM average annual surface temperature

$T(z_2)$ = temperature (degrees Fahrenheit) at depth two, which corresponds to the bottom hole temperature (BHT) as recorded on the log header

z = depth at which $T(z)$ is being calculated

z_1 = depth at which $T(z_1)$ was taken, which corresponds to ground surface

z_2 = depth at which $T(z_2)$ was taken, which is the depth at which the bottom-hole temperature was measured

Two datasets are available for the surface temperature (T_Z1) in the gradient calculation, which includes the temperature of mud filtrate (taken directly from the geophysical log header) and the average annual surface temperature (taken from a raster map of PRISM temperature data). For each well location, mean annual surface temperature between 1981 and 2010 were obtained from the Parameter-elevation Relationships on Independent Slopes Model (PRISM) Climate Group (2016) raster dataset. This raster dataset uses the PRISM interpolation method (Daly and others, 2008). PRISM uses current state of knowledge of spatial climate patterns in the United States to develop precipitation–elevation regressions for the conterminous United States. Two datasets are available for the temperature at bottom depth (T_Z2) in the gradient calculation: bottom hole temperature (taken directly from the geophysical log header) and a dataset of temperature at 3.5 km of depth produced by Southern Methodist University's Geothermal Laboratory (Blackwell and others, 2011).

Calculated TDS_{NaCl} results by formation were plotted for the three-separate temperature calculation method scenarios (Table 6-3 and Figure 6-11). As can be seen from the table and plot, the difference among the three scenarios is small, especially compared to the standard deviation. This comparison does not account for individual scenarios where the spread in the calculated bottom-hole temperature values is larger due to a substantial difference in the surface temperature (log derived as opposed to PRISM) or bottom-hole temperature (log derived vs Southern Methodist University's geothermal dataset). Based on discussions with TWDB staff and the results of this analysis, it was decided to use Scenario #2 to calculate the formation temperature in Equation 6-14. This decision is primarily based on two things: (1) average annual surface temperature from the PRISM data is much more stable than the log-derived temperature of the mud and (2) the bottom-hole temperature is a relatively stable temperature measurement (Torres-Verdin, 2016) and the depth at which the measurement is taken is closer to the base of the Trinity Aquifer than the Southern Methodist University 3.5 km data. It is likely that there are additional variations in the geothermal gradient between the average bottom-hole temperature depth (3,803 feet below ground surface) and 3.5 km of depth (11,480 feet below ground surface).

Table 6-3 Average sodium chloride equivalent total dissolved solids calculated using the Resistivity Ratio Method for the three geothermal gradient scenarios.

Formation	Scenario 1 (mg/l)	Scenario 2 (mg/l)	Scenario 3 (mg/l)	Standard deviation
Paluxy	4,364	4,645	4,596	150
Glen Rose	5,090	5,344	5,367	154
Hensell	3,858	3,998	4,007	84
Pearsall	4,347	4,493	4,530	97
Hosston	5,572	5,715	5,681	75

Note: mg/l = milligrams per liter.

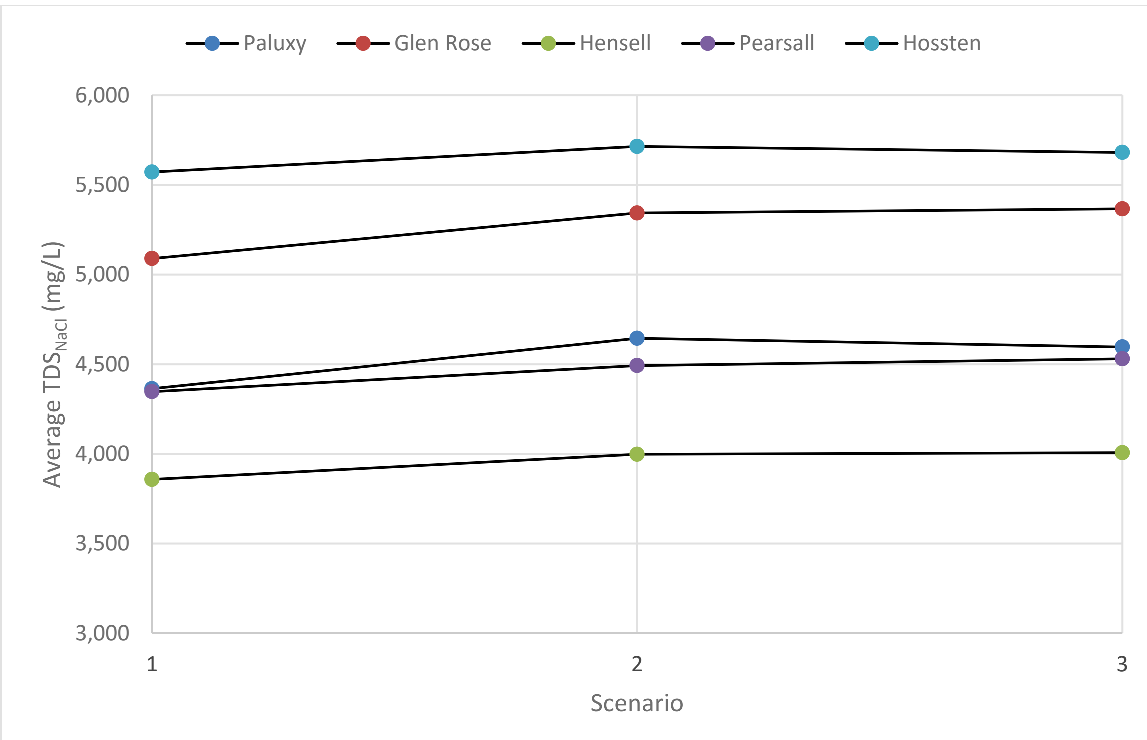


Figure 6-11 Average sampled TDS versus calculated geothermal gradient scenario. Note: TDS = total dissolved solids and mg/l = milligrams per liter.

The total dissolved solids concentration for every sand and limestone unit was calculated using this methodology for the Paluxy, Glen Rose, Hensell, Pearsall, and Hosston hydrostratigraphic units in the Northern Trinity Aquifer. These calculated salinity values were averaged by hydrostratigraphic unit and subsequently plotted on maps of the study area along with sampled water quality by hydrostratigraphic unit. The data were used to classify groundwater of each hydrostratigraphic unit within the Northern Trinity Aquifer into fresh (0-999 milligrams per liter), slightly saline (1,000-2,999 milligrams per liter), moderately saline (3,000-9,999 milligrams per liter), and very saline (>10,000 milligrams per liter).

7 Groundwater salinity classification

The groundwater salinity was delineated based upon sampled water quality and water quality values from the interpretation of geophysical logs. It was necessary to employ water quality results interpreted from geophysical well logs in the deeper portions of the Trinity Aquifer because of the limited availability of sampled water quality data. Salinity was classified using the criteria developed by the United States Geological Survey (Winslow and Kister, 1956), as illustrated in Table 2-1. Salinity boundaries for 1,000, 3,000, and 10,000 milligrams per liter of total dissolved solids were delineated.

7.1 Aquifer determination

A critical process performed prior to utilizing measured groundwater samples is to determine from which hydrostratigraphic zone the groundwater was sampled. We compiled a table of all available wells from the TWDB Groundwater Database, Submitted Drillers Report Database, and BRACS Database. The compiled table of wells contained locations, total depths, surface elevations, and completed intervals (where available). Using GIS tools, we captured the intersection of each well with the six hydrostratigraphic surfaces that defined the Trinity Aquifer. Using this information, a computer program was used to assign an aquifer code to each well based upon the depths of the completed well intervals and their relative position with respect to the surface depths. Wells that did not have a screened interval available were assigned an aquifer code that corresponded to all hydrostratigraphic intervals between the ground surface and the total depth of the well.

7.2 Delineation of salinity

Water quality data from Kelley and others (2014) was supplemented with additional sample data from the TCEQ Public Water Supply Database and TWDB Groundwater Database. Then the groundwater sample data and the average calculated water quality values from the geophysical log analyses (see Section 6), were plotted in GIS and total dissolved solids lines were contoured by hand. Contours were created for 1,000, 3,000, and 10,000 milligrams per liter total dissolved solids.

The total dissolved solids line for 1,000 milligrams per liter varies significantly from the one in Kelley and others (2014). The variations are a result of using additional sample data and only plotting those samples that were clearly obtained from a single hydrostratigraphic interval. Variations are also a result of incorporating the calculated total dissolved solids estimates from geophysical well logs.

The poorest agreement between the sampled and calculated values in the fresh water area occurred in the Hosston hydrostratigraphic unit. This poor agreement may be because most of these geophysical logs are from water wells and the drilling fluids were probably not circulated for as long as in deeper oil and gas wells. It is assumed that the longer the well is circulated, more opportunity exists for the mud filtrate to replace the formation water in the near borehole zone. Additionally, higher density muds are used when drilling the deeper oil and gas wells, which would increase the pressure on the borehole wall. This increased pressure could be responsible for a more complete replacement of the formation fluid with the mud filtrate. If the mud filtrate replacement is incomplete, then the resulting calculated water quality will be different from the sampled water quality because the equation assumes there is complete mud filtrate replacement.

In areas where both sampled and calculated (resistivity-derived) estimates of water quality were available, the sampled water quality estimates were considered to have the higher confidence than the calculated estimates. In some areas, local variability in the calculated water quality data required best professional judgement to determine which values to use for salinity contours. Calculated estimates of water quality marked with an “X” were not considered when contouring. We also assumed that there exists a general trend of increasing total dissolved solids with depth and that there is a degradation of water quality near the Mexia-Talco Fault Zone.

7.3 Discussion of salinity contours

In all cases, the total dissolved solids concentrations generally increase from the updip (western) to the downdip (eastern) areas (Figures 7-1 to 7-5). In the Paluxy hydrostratigraphic unit (Figure 7-1), the 10,000 milligrams per liter total dissolved solids contour runs approximately parallel to the Mexia-Talco Fault Zone, with a larger very saline zone occurring to the south, and generally thinning to the north. The moderately saline zone is about a county wide in the south, with the 3,000 milligrams per liter total dissolved solids contour running parallel to the 10,000 milligrams per liter total dissolved solids contour. The exception is in the region around Collin and Grayson counties, where the 3,000 milligrams per liter total dissolved solids contour moves updip based on estimates from the geophysical log data. The 1,000 milligrams per liter total dissolved solids contour is generally parallel to strike, other than a movement downdip in the region around Dallas County, based on water quality measurements.

In the Glen Rose hydrostratigraphic unit (Figure 7-2), the 10,000 milligrams per liter total dissolved solids contour is nearly coincident with the Mexia-Talco Fault Zone except to the north in Collin, Hunt, and Bowie counties. The 3,000 milligrams per liter total dissolved solids contour moves significantly updip into Bosque, Johnson, Dallas, and Fannin counties. The 1,000 milligrams per liter total dissolved solids contour extends downdip into Williamson, McLennan, and Ellis counties. There was no fresh water calculated or observed for the Glen Rose hydrostratigraphic unit in Fannin, Lamar, and Red River counties.

In the Hensell hydrostratigraphic unit (Figure 7-3), the 10,000 milligrams per liter total dissolved solids contour is almost coincident with the Mexia-Talco Fault Zone. The 3,000 milligrams per liter total dissolved solids contour mostly follows the same trend along strike. Moderately saline water shows a pattern similar to that seen with the Glen Rose unit without the updip trends in Bosque and Johnson counties. The 1,000 milligrams per liter total dissolved solids contour shows almost no fresh water in Coryell County but otherwise also approximates that seen in the overlying Glen Rose unit.

In the Pearsall hydrostratigraphic unit (Figure 7-4), the 10,000 milligrams per liter total dissolved solids contour approximately corresponds to the Mexia-Talco Fault Zone. The 3,000 milligrams per liter total dissolved solids contour is similar to that seen for the Hensell and Glen Rose units except for an updip extension into Tarrant County. The 1,000 milligrams per liter total dissolved solids contour shows very little fresh water in Tarrant and Johnson counties but does show the presence of fresh water far downdip in Ellis, McLennan, and Williamson counties.

In the Hosston hydrostratigraphic unit (Figure 7-5), the 10,000 milligrams per liter total dissolved solids contour lies roughly 10 miles updip from the Mexia-Talco Fault Zone. The 3,000 milligrams per liter total dissolved solids contour denotes a very thin zone of moderately saline water, especially in the southern portion of the study area. The 1,000 milligrams per liter total dissolved solids contour is largely based upon samples from water wells and shows that although fresh water extents far downdip in Falls, McLennan, Hill, and Ellis counties there are significant updip occurrences of slightly saline water in Lampasas, Coryell, Tarrant, Parker and Wise counties.

No clear geologic explanation was found for the complexities denoted by the 1,000 milligrams per liter total dissolved contours associated with each of the hydrostratigraphic units. The number of measured water samples is greatest in the fresh and slightly saline zones, which may contribute to our ability to map the complexity of this boundary in greater detail. It is entirely possible that if more water quality samples were available for the moderately and highly saline zones, their boundaries would also show increased complexity.

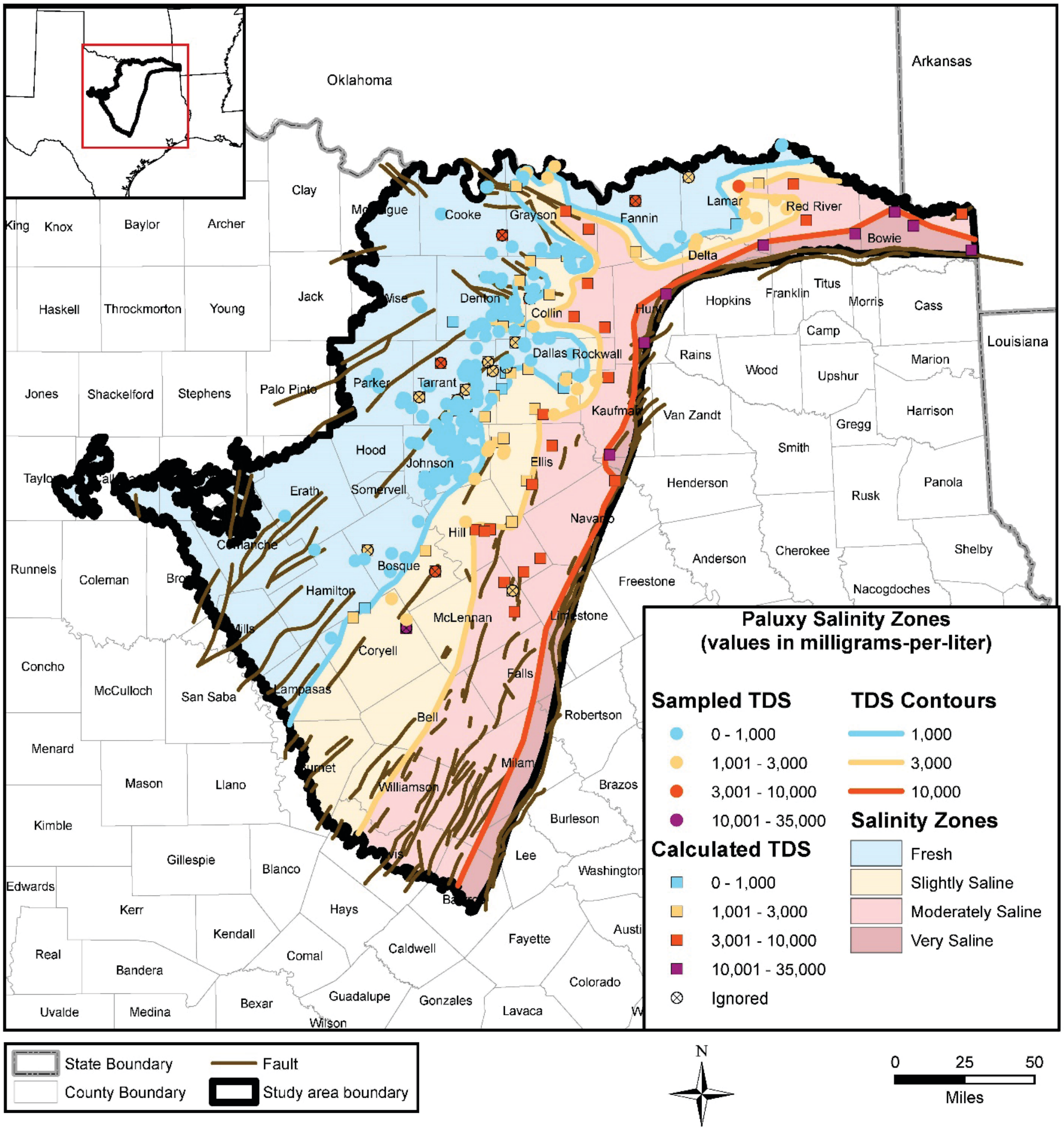


Figure 7-1 **Salinity map for the Paluxy hydrostratigraphic unit showing sampled and calculated water quality locations. Note: TDS = total dissolved solids.**

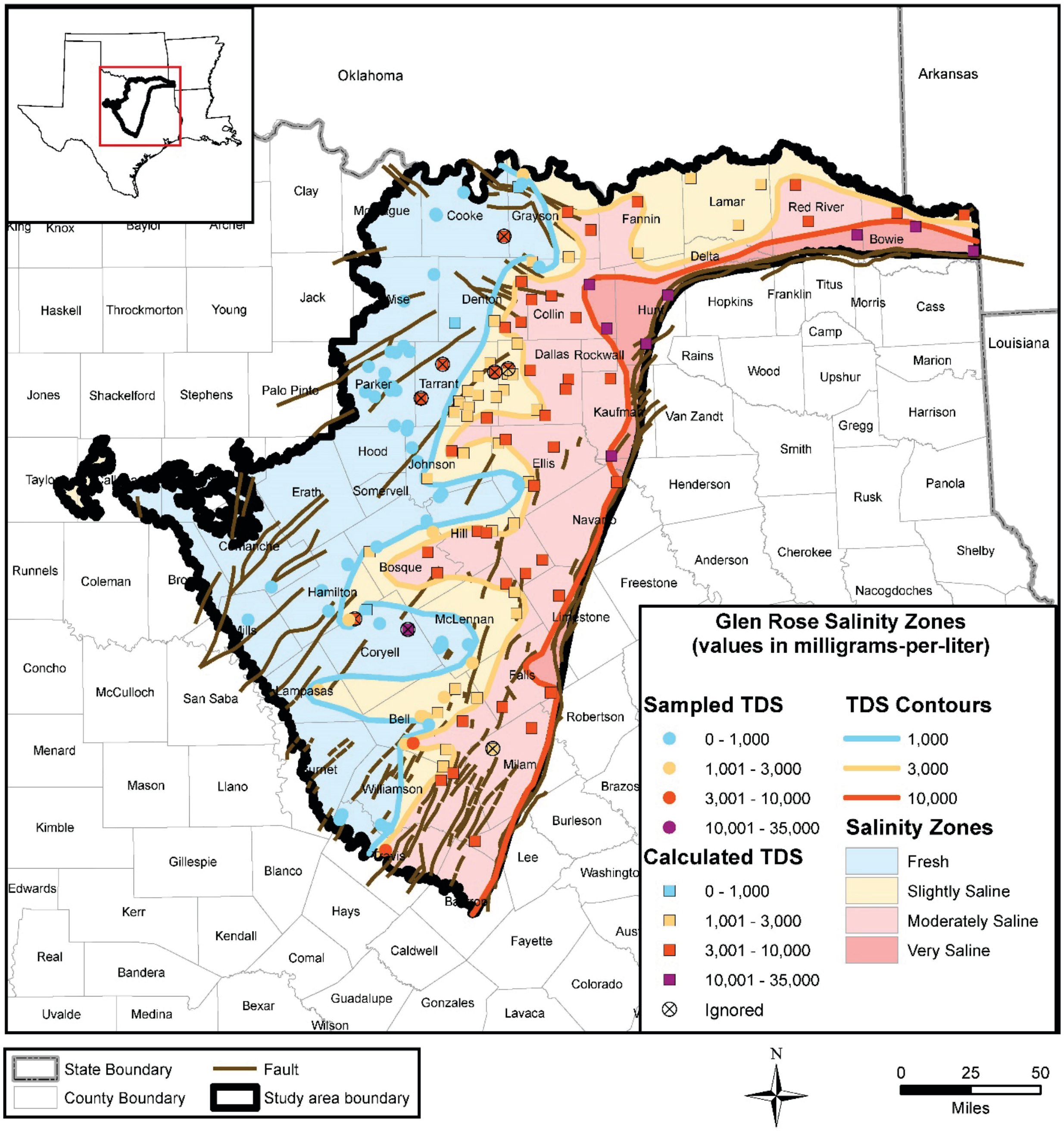


Figure 7-2 **Salinity map for the Glen Rose hydrostratigraphic unit showing sampled and calculated water quality locations. Note: TDS = total dissolved solids.**

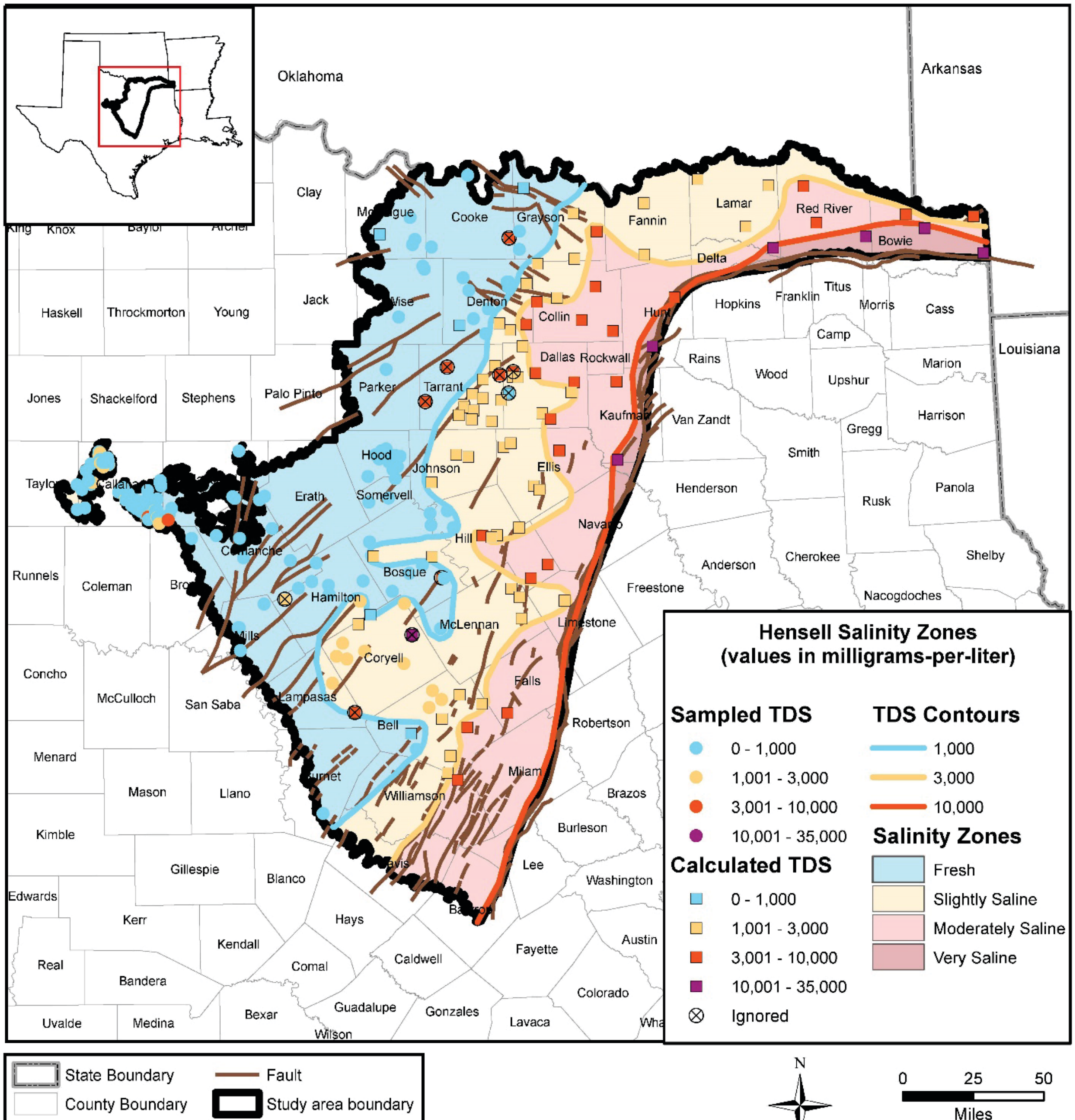


Figure 7-3 **Salinity map for the Hensell hydrostratigraphic unit showing sampled and calculated water quality locations. Note: TDS = total dissolved solids.**

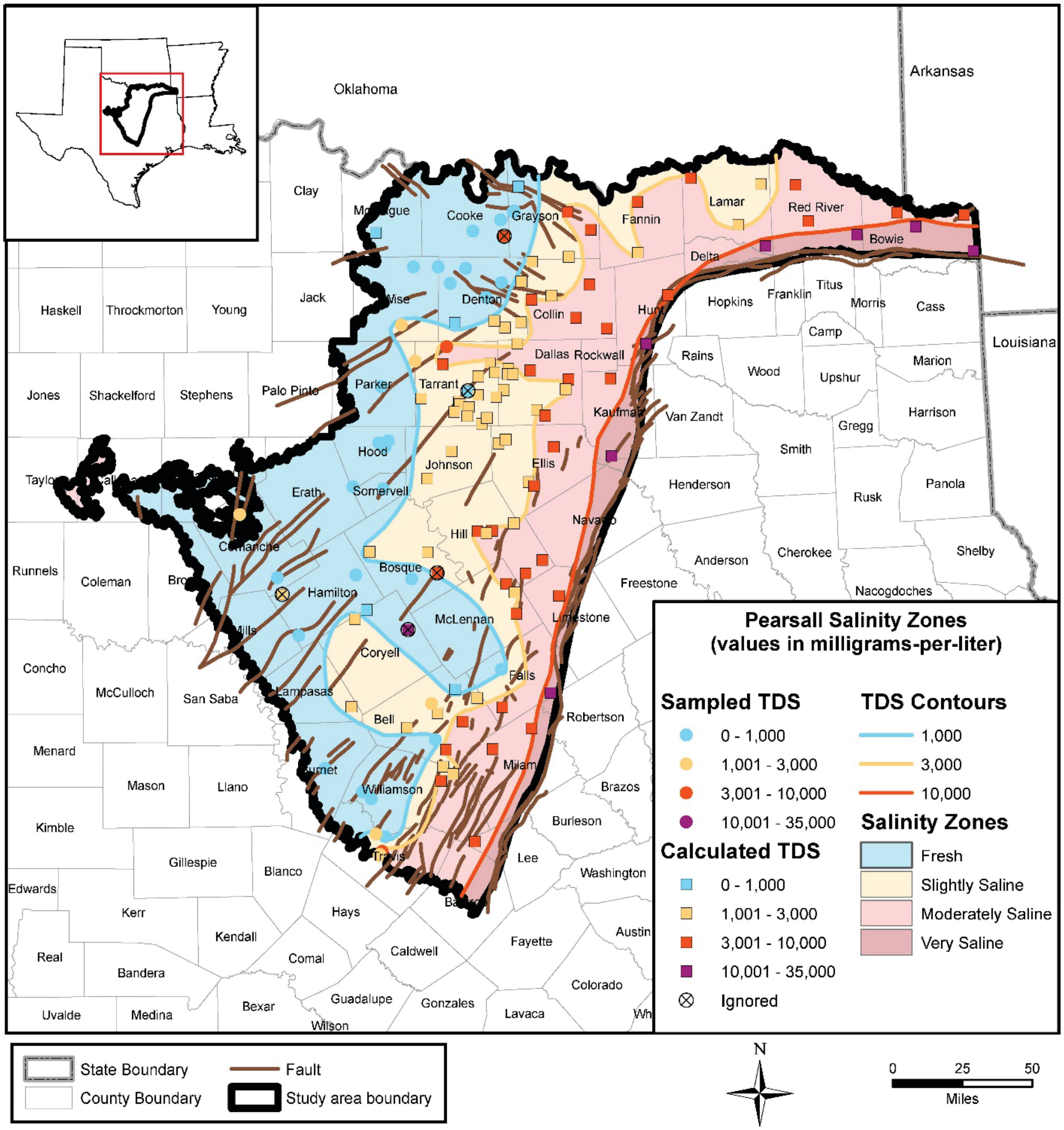


Figure 7-4 **Salinity map for the Pearsall hydrostratigraphic unit showing sampled and calculated water quality locations. Note: TDS = total dissolved solids.**

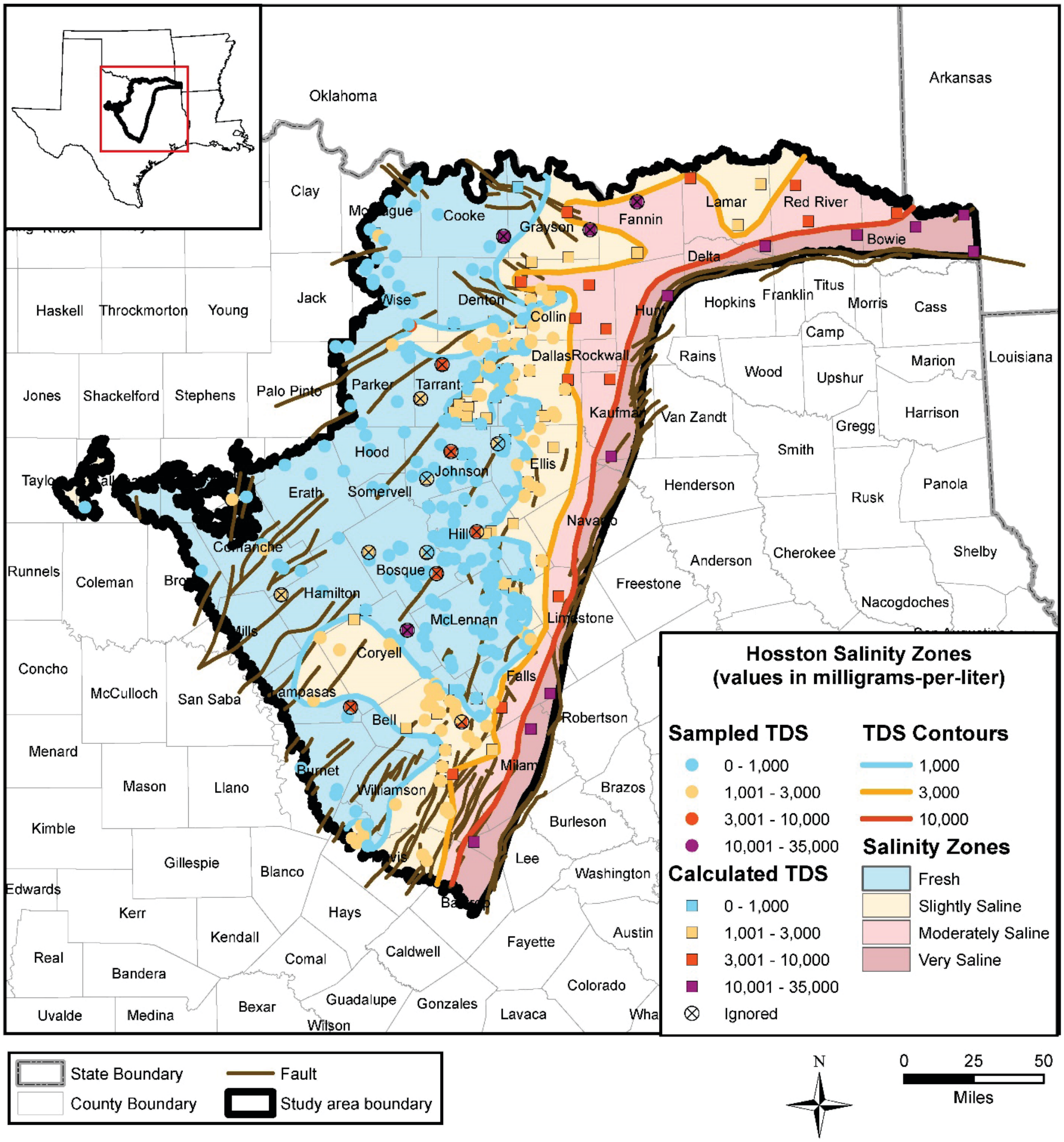


Figure 7-5 **Salinity map for the Hosston hydrostratigraphic unit showing sampled and calculated water quality locations. Note: TDS = total dissolved solids.**

8 Aquifer hydraulic properties

Aquifer hydraulic properties refer to the physical characteristics that govern flow of groundwater through an aquifer. Groundwater volume calculations for the Northern Trinity Aquifer require input values for aquifer properties such as aquifer thickness, water level, and specific yield. These values are described below.

For the five hydrostratigraphic units of the Northern Trinity Aquifer, the unit thickness and the elevations of unit tops and bottoms are based upon the structure in the updated Northern Trinity Aquifer and Woodbine Aquifer GAM (Kelley and others, 2014), where:

- Model Layer 3 represents the Paluxy hydrostratigraphic unit
- Model Layer 4 represents the Glen Rose hydrostratigraphic unit
- Model Layer 5 represents the Hensell hydrostratigraphic unit
- Model Layer 6 represents the Pearsall hydrostratigraphic unit
- Model Layer 7 represents the Hosston hydrostratigraphic unit

The static water levels are based upon the last year of calibration (beginning of 2010) from the updated Northern Trinity Aquifer and Woodbine Aquifer GAM (Kelley and others, 2014). Storativity values used in the volume calculations are also from GAM model (Kelly and others, 2014). The specific yield values for each of the five hydrostratigraphic units of the Northern Trinity Aquifer were assigned based on the Northern Trinity Aquifer and Woodbine Aquifer GAM (Bené and others, 2004), where:

- Paluxy specific yield = 0.15
- Glen Rose specific yield = 0.05
- Hensell specific yield = 0.15
- Pearsall specific yield = 0.05
- Hosston specific yield = 0.15

9 Groundwater volume methodology

In this section, we discuss how estimates of the volumes of groundwater were generated for the different classes of salinity in the Northern Trinity Aquifer. These volumes are based upon the groundwater salinity defined in Section 7 and were developed using water quality data from samples and through the analysis of geophysical logs as presented in Section 6. The five water producing intervals defined for the Northern Trinity Aquifer are the Paluxy, Glen Rose, Hensell, Pearsall, and Hosston hydrostratigraphic units. The method used to calculate groundwater volume is dependent on whether the aquifer is confined or unconfined. The following section based on Shi and others (2014) provides a general discussion about confined and unconfined aquifers and how storage is calculated differently in each type of aquifer.

9.1 Confined and unconfined aquifers

In general, the Northern Trinity Aquifer is a dipping aquifer that is unconfined updip and confined downdip (Figure 9-1). The term "unconfined" refers to the portion of the aquifer where the water level occurs below the top of the aquifer. This generally coincides with the outcrop area and area immediately downdip of the outcrop. In the Northern Trinity Aquifer, the formations generally dip southeast. Therefore, the unconfined portions of the Northern Trinity Aquifer hydrostratigraphic units fall along their western edge in the outcrop area. The term "confined" refers to the portion of the aquifer where the water level occurs above the top of the aquifer. The Trinity Aquifer hydrostratigraphic units become confined east of their outcrops, as the units dip deeper and are overlain by younger units.

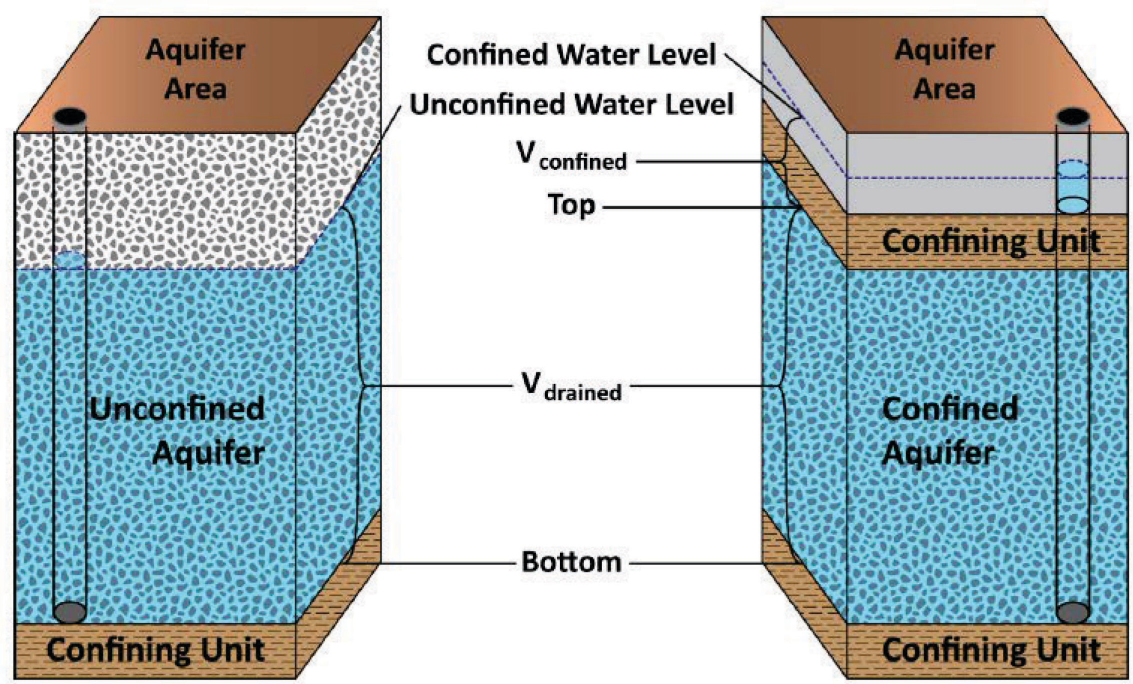


Figure 9-1 Schematic graph showing the difference between unconfined and confined aquifers (from Shi and others, 2014).

Storage is conceptualized differently in confined and unconfined aquifers. For an unconfined aquifer, the total storage is equal to the volume of groundwater removed by pumping that makes the water level fall to the aquifer bottom. For a confined aquifer, the total storage is the sum of two parts. The first part is groundwater released from the aquifer when the water level falls from above the top of the aquifer to the top of the aquifer. The reduction of hydraulic head in the aquifer, which can be thought of as pressure, due to pumping causes expansion of groundwater and deformation of the aquifer matrix. The aquifer is still fully saturated to this point and referred to as the confined aquifer storage.

The second part of groundwater storage is from actual dewatering of the aquifer as the water level in the aquifer falls below the top of the aquifer and ultimately to the bottom of the aquifer. This portion of aquifer storage is referred to as the unconfined aquifer storage. Given the same aquifer area and water level decline, the amount of water released from unconfined storage is much greater (orders of magnitude) than that released from confined storage. The difference is because of the physical nature of storage reduction occurring under confined versus unconfined conditions. In confined storage reduction, water is being supplied through groundwater expansion and aquifer volume reduction. In unconfined storage reduction, water is being supplied through dewatering of pore space. The parameters that quantify these physical differences are storativity of a confined aquifer and specific yield of an unconfined aquifer. Aquifer storativity typically ranges from 10^{-5} to 10^{-3} for most confined aquifers. While specific yield values typically range from 0.01 to 0.3 for most unconfined aquifers. The TWDB makes a distinction between the total volume of groundwater in unconfined aquifer storage versus the portion that is considered drainable. The equations for calculating the total groundwater volume are presented below:

For unconfined aquifers

$$\text{Total Volume} = V_{drained} = \text{Area} * Sy * (\text{Water level} - \text{Bottom}) \qquad \text{Equation 9-1a}$$

For confined aquifers

$$\text{Total Volume} = V_{confined} + V_{drained} \qquad \text{Equation 9-1b}$$

Volume for confined part

$$V_{confined} = \text{Area} * [S * (\text{Water level} - \text{Top})] \qquad \text{Equation 9-2a}$$

or

$$V_{confined} = \text{Area} * [Ss * (\text{Thickness}) * (\text{Water level} - \text{Top})] \qquad \text{Equation 9-2b}$$

Volume for unconfined part

$$V_{drained} = \text{Area} * [Sy * (\text{Thickness})] \qquad \text{Equation 9-3}$$

where (variables illustrated in Figure 9-1)

$V_{drained}$ = storage volume due to water draining from the formation (acre-feet)

$V_{confined}$ = storage volume due to elastic properties of the aquifer and water (acre-feet)

Area = area of aquifer (acre)

Water level = groundwater elevation (feet above mean sea level)

Top = elevation of aquifer top (feet above mean sea level)

Bottom = elevation of aquifer bottom (feet above mean sea level)

Thickness = thickness of aquifer (feet)

Sy = specific yield (no units)

Ss = specific storage (feet-1)

S = storativity or storage coefficient (no units)

9.2 Process for calculating in-place groundwater volumes based on water quality

The in-place groundwater volume calculations for groundwater storage are implemented on a quarter-mile grid scale coincident with the GAM grid (Kelley and others, 2014). Where present, both confined storage and unconfined drained storage were calculated for each of the five hydrostratigraphic units of the Northern Trinity Aquifer: the Paluxy, the Glen Rose, the Hensell, the Pearsall, and the Hosston. We calculated the unconfined drained groundwater storage for each unit using equation 9-1a. We calculated the confined groundwater storage for each unit using Equation 9-2b. The variable "Top" is the top elevation of the hydrostratigraphic unit in question, while the variable "Bottom" is the bottom elevation of that unit. The variable "Thickness" is calculated specifically for each hydrostratigraphic unit based on the difference between the variables "Top" and "Bottom." The calculations were developed using a Python code. The complete detailed algorithm and equations implemented are described in detail in the Appendix section of this report (Section 15).

The total estimated recoverable storage (TERS) is defined as the estimated amount of groundwater within an aquifer that accounts for recovery scenarios that range between 25 percent and 75 percent of the porosity-adjusted aquifer volume (Texas Administrative Code § 356.10). In other words, the TWDB assumes that between 25 and 75 percent of groundwater held within an aquifer can be removed by pumping. TERS does not account for a variety of important conditions and aquifer characteristics that limit groundwater production such as well withdrawal rate, well density, hydraulic conductivity, withdrawal costs, aquifer petrology, permeability, and potential water quality degradation, etc. The TERS calculation represents the approximate percentage of total storage volume in the water-producing zones of an aquifer; however, not all the water in those zones are "practicably recoverable." The in-place volumes calculated in this study represent the groundwater within an aquifer or the total aquifer storage volume (Texas Administrative Code § 36.001(24)) and are provided for the sole purpose of evaluating brackish groundwater production opportunities.

Shi and others (2014) use the TERS approach to calculate in-place volume of groundwater stored in the different aquifers in Groundwater Management Area 8. They use the combined thickness of the five hydrostratigraphic units to report the storage of the Northern Trinity Aquifer. We use a similar calculation method in this report to calculate a separate groundwater storage value for each of the hydrostratigraphic units of the Northern Trinity Aquifer. The groundwater volumes we calculated largely agree with those listed in Shi and others (2014) except for downdip counties that are outside the established boundaries of the Trinity Aquifer and counties that extend outside GMA 8.

9.3 Calculated in-place groundwater volumes

The calculated in-place volumes of groundwater in the Northern Trinity Aquifer study area are rounded to the nearest 1,000 acre-feet per year (Table 9-1). The in-place volumes of groundwater are summarized by salinity classification in the five hydrostratigraphic units: the Paluxy, the Glen Rose, the Hensell, the Pearsall, and the Hosston. The total in-place volume of groundwater in the Northern Trinity Aquifer study area is 2,061,350,000 acre-feet. The total in-place volume of groundwater in the Paluxy, the Glen Rose, the Hensell, the Pearsall, and the Hosston is 339,847,000 acre-feet, 438,130,000 acre-feet, 212,588,000 acre-feet, 167,270,000 acre-feet, and 903,514,000 acre-feet, respectively.

The Pearsall has the smallest in-place volume of the hydrostratigraphic units, which is expected given that it is generally the least productive. Approximately half of the groundwater in the Northern Trinity Aquifer study area can be classified as either fresh or slightly saline with the remaining groundwater in the moderately to very saline classifications. The percentages of groundwater per salinity classifications are approximately 23 percent fresh, 24 percent slightly saline, 34 percent moderately saline, and 19 percent very saline.

Table 9-1 The in-place groundwater volumes of fresh, slightly saline, moderately saline, and very saline in the Northern Trinity Aquifer study area.

Hydrostratigraphic unit	Total in-place volume (acre-feet)				
	Fresh	Slightly saline	Moderately saline	Very saline	Total
Paluxy	120,076,000	68,236,000	105,908,000	45,627,000	339,847,000
Glen Rose	75,808,000	97,625,000	207,415,000	57,281,000	438,130,000
Hensell	80,659,000	74,447,000	45,208,000	12,273,000	212,588,000
Pearsall	26,276,000	34,774,000	76,128,000	30,093,000	167,270,000
Hosston	169,157,000	211,584,000	268,826,000	253,947,000	903,514,000

Notes:

Fresh = 0 to 999 milligrams per liter total dissolved solids
Slightly saline = 1,000 to 2,999 milligrams per liter total dissolved solids
Moderately saline = 3,000 to 9,999 milligrams per liter total dissolved solids
Very saline = 10,000 to 35,000 milligrams per liter total dissolved solids

Table 9-2 provides the in-place volume of groundwater by hydrostratigraphic unit and by salinity class for all the counties that intersect the boundaries of the Northern Trinity Aquifer within the study area. Table 9-3 provides the in-place volume of groundwater by hydrostratigraphic unit and by salinity class for all the Groundwater Conservation Districts that intersect the boundaries of the Northern Trinity Aquifer within the study area. Slightly more than half (51 percent) of the total calculated groundwater is not within the boundaries of a groundwater conservation district. Table 9-4 provides the in-place volume of groundwater by hydrostratigraphic unit and by salinity class for Groundwater Management Areas 8, 11, and 12 in the Northern Trinity Aquifer within the study area.

Table 9-2 The in-place groundwater volumes of fresh, slightly saline, moderately saline, and very saline in the Northern Trinity Aquifer within the study area by county and hydrostratigraphic unit.

County and hydrostratigraphic unit	Total in-place volume (acre-feet)				
	Fresh	Slightly saline	Moderately saline	Very saline	Total
Bastrop County					
Paluxy	0	0	437,000	525,000	962,000
Glen Rose	0	0	9,167,000	384,000	9,551,000
Hensell	0	0	901,000	60,000	961,000
Pearsall	0	0	1,418,000	1,494,000	2,912,000
Hosston	0	695,000	10,794,000	19,985,000	31,474,000
Bell County					
Paluxy	0	993,000	1,611,000	0	2,604,000
Glen Rose	2,115,000	10,884,000	6,722,000	0	19,721,000
Hensell	1,130,000	3,311,000	813,000	0	5,254,000
Pearsall	623,000	2,016,000	1,804,000	0	4,443,000
Hosston	7,670,000	20,605,000	1,039,000	0	29,314,000
Bosque County					
Paluxy	2,522,000	1,406,000	0	0	3,928,000
Glen Rose	3,428,000	4,543,000	3,684,000	0	11,655,000
Hensell	7,091,000	2,844,000	0	0	9,935,000
Pearsall	845,000	942,000	0	0	1,787,000
Hosston	10,737,000	0	0	0	10,737,000
Bowie County					
Paluxy	0	0	10,961,000	16,537,000	27,498,000
Glen Rose	0	3,540,000	5,721,000	14,386,000	23,647,000
Hensell	0	1,176,000	1,892,000	3,952,000	7,020,000
Pearsall	0	0	3,022,000	6,341,000	9,363,000
Hosston	0	0	5,520,000	43,095,000	48,615,000
Brown County					
Paluxy	0	0	0	0	0
Glen Rose	2,000	0	0	0	2,000
Hensell	153,000	0	0	0	153,000
Pearsall	112,000	0	0	0	112,000
Hosston	1,772,000	27,000	0	0	1,799,000
Burnet County					
Paluxy	0	0	0	0	0
Glen Rose	1,796,000	0	0	0	1,796,000

County and hydrostratigraphic unit	Total in-place volume (acre-feet)				
	Fresh	Slightly saline	Moderately saline	Very saline	Total
Hensell	2,547,000	0	0	0	2,547,000
Pearsall	813,000	3,000	0	0	816,000
Hosston	4,792,000	0	0	0	4,792,000
Callahan County					
Paluxy	0	0	0	0	0
Glen Rose	0	0	0	0	0
Hensell	13,000	0	0	0	13,000
Pearsall	9,000	0	0	0	9,000
Hosston	1,146,000	961,000	0	0	2,107,000
Collin County					
Paluxy	2,770,000	7,580,000	8,140,000	0	18,490,000
Glen Rose	369,000	1,553,000	10,479,000	3,949,000	16,350,000
Hensell	0	2,087,000	4,843,000	0	6,930,000
Pearsall	0	1,850,000	5,646,000	0	7,496,000
Hosston	1,051,000	11,402,000	20,377,000	0	32,830,000
Comanche County					
Paluxy	0	0	0	0	0
Glen Rose	91,000	0	0	0	91,000
Hensell	2,603,000	0	0	0	2,603,000
Pearsall	642,000	0	0	0	642,000
Hosston	5,376,000	0	0	0	5,376,000
Cooke County					
Paluxy	11,553,000	0	0	0	11,553,000
Glen Rose	6,388,000	40,000	0	0	6,428,000
Hensell	7,492,000	0	0	0	7,492,000
Pearsall	3,837,000	0	0	0	3,837,000
Hosston	6,394,000	90,000	0	0	6,484,000
Coryell County					
Paluxy	3,000	1,374,000	0	0	1,377,000
Glen Rose	9,026,000	2,457,000	0	0	11,483,000
Hensell	150,000	8,867,000	0	0	9,017,000
Pearsall	432,000	1,181,000	0	0	1,613,000
Hosston	2,902,000	5,331,000	0	0	8,233,000
Dallas County					
Paluxy	8,140,000	7,883,000	932,000	0	16,955,000
Glen Rose	0	4,683,000	11,541,000	0	16,224,000
Hensell	0	3,984,000	3,492,000	0	7,476,000
Pearsall	0	2,692,000	4,025,000	0	6,717,000

County and hydrostratigraphic unit	Total in-place volume (acre-feet)				
	Fresh	Slightly saline	Moderately saline	Very saline	Total
Hosston	3,380,000	18,482,000	4,929,000	0	26,791,000
Delta County					
Paluxy	140,000	1,775,000	3,226,000	1,934,000	7,075,000
Glen Rose	0	1,830,000	1,821,000	1,861,000	5,512,000
Hensell	0	901,000	1,561,000	344,000	2,806,000
Pearsall	0	0	2,078,000	1,503,000	3,581,000
Hosston	0	0	7,524,000	7,687,000	15,211,000
Denton County					
Paluxy	16,345,000	1,578,000	0	0	17,923,000
Glen Rose	6,073,000	2,574,000	1,936,000	0	10,583,000
Hensell	6,459,000	1,825,000	521,000	0	8,805,000
Pearsall	2,917,000	1,862,000	13,000	0	4,792,000
Hosston	7,396,000	4,725,000	358,000	0	12,479,000
Eastland County					
Paluxy	0	0	0	0	0
Glen Rose	0	0	0	0	0
Hensell	267,000	0	0	0	267,000
Pearsall	66,000	0	0	0	66,000
Hosston	2,266,000	97,000	0	0	2,363,000
Ellis County					
Paluxy	0	5,490,000	6,857,000	0	12,347,000
Glen Rose	1,500,000	3,413,000	14,911,000	0	19,824,000
Hensell	0	4,035,000	1,953,000	0	5,988,000
Pearsall	0	2,618,000	4,160,000	108,000	6,886,000
Hosston	4,783,000	20,684,000	4,881,000	650,000	30,998,000
Erath County					
Paluxy	620,000	0	0	0	620,000
Glen Rose	1,370,000	0	0	0	1,370,000
Hensell	9,711,000	0	0	0	9,711,000
Pearsall	1,049,000	0	0	0	1,049,000
Hosston	5,577,000	0	0	0	5,577,000
Falls County					
Paluxy	0	0	1,952,000	705,000	2,657,000
Glen Rose	0	2,123,000	13,523,000	4,576,000	20,222,000
Hensell	0	128,000	1,954,000	94,000	2,176,000
Pearsall	698,000	1,840,000	4,394,000	1,108,000	8,040,000
Hosston	7,304,000	6,089,000	26,094,000	15,454,000	54,941,000
Fannin County					

County and hydrostratigraphic unit	Total in-place volume (acre-feet)				
	Fresh	Slightly saline	Moderately saline	Very saline	Total
Paluxy	19,124,000	2,822,000	3,813,000	0	25,759,000
Glen Rose	0	8,013,000	4,231,000	0	12,244,000
Hensell	0	6,275,000	762,000	0	7,037,000
Pearsall	0	2,130,000	5,176,000	0	7,306,000
Hosston	0	7,101,000	16,221,000	0	23,322,000
Franklin County					
Paluxy	0	0	0	872,000	872,000
Glen Rose	0	0	0	555,000	555,000
Hensell	0	0	0	233,000	233,000
Pearsall	0	0	0	279,000	279,000
Hosston	0	0	0	1,106,000	1,106,000
Grayson County					
Paluxy	9,426,000	6,013,000	2,632,000	0	18,071,000
Glen Rose	4,361,000	3,882,000	2,248,000	0	10,491,000
Hensell	4,356,000	3,117,000	644,000	0	8,117,000
Pearsall	1,390,000	2,275,000	1,031,000	0	4,696,000
Hosston	2,645,000	8,728,000	697,000	0	12,070,000
Hamilton County					
Paluxy	411,000	5,000	0	0	416,000
Glen Rose	3,412,000	1,475,000	0	0	4,887,000
Hensell	6,301,000	1,123,000	0	0	7,424,000
Pearsall	1,483,000	23,000	0	0	1,506,000
Hosston	5,205,000	155,000	0	0	5,360,000
Henderson County					
Paluxy	0	0	116,000	604,000	720,000
Glen Rose	0	0	241,000	761,000	1,002,000
Hensell	0	0	29,000	162,000	191,000
Pearsall	0	0	0	535,000	535,000
Hosston	0	0	0	3,291,000	3,291,000
Hill County					
Paluxy	330,000	3,953,000	2,519,000	0	6,802,000
Glen Rose	4,351,000	2,688,000	10,890,000	0	17,929,000
Hensell	854,000	4,220,000	2,152,000	0	7,226,000
Pearsall	0	2,058,000	2,002,000	0	4,060,000
Hosston	13,381,000	6,556,000	363,000	0	20,300,000
Hood County					
Paluxy	234,000	0	0	0	234,000
Glen Rose	1,382,000	0	0	0	1,382,000

County and hydrostratigraphic unit	Total in-place volume (acre-feet)				
	Fresh	Slightly saline	Moderately saline	Very saline	Total
Hensell	3,664,000	0	0	0	3,664,000
Pearsall	584,000	0	0	0	584,000
Hosston	2,719,000	0	0	0	2,719,000
Hopkins County					
Paluxy	0	0	0	2,107,000	2,107,000
Glen Rose	0	0	0	1,362,000	1,362,000
Hensell	0	0	61,000	577,000	638,000
Pearsall	0	0	0	860,000	860,000
Hosston	0	0	0	3,757,000	3,757,000
Hunt County					
Paluxy	29,000	1,028,000	11,364,000	6,433,000	18,854,000
Glen Rose	0	1,012,000	2,411,000	10,622,000	14,045,000
Hensell	0	192,000	4,534,000	2,038,000	6,764,000
Pearsall	0	0	7,516,000	1,888,000	9,404,000
Hosston	0	0	23,044,000	18,454,000	41,498,000
Johnson County					
Paluxy	6,540,000	902,000	0	0	7,442,000
Glen Rose	3,596,000	4,252,000	1,259,000	0	9,107,000
Hensell	2,150,000	6,004,000	0	0	8,154,000
Pearsall	177,000	2,092,000	0	0	2,269,000
Hosston	7,779,000	0	0	0	7,779,000
Kaufman County					
Paluxy	125,000	1,234,000	8,571,000	3,135,000	13,065,000
Glen Rose	0	0	11,675,000	6,369,000	18,044,000
Hensell	0	0	3,379,000	1,394,000	4,773,000
Pearsall	0	0	2,855,000	4,105,000	6,960,000
Hosston	0	0	18,941,000	31,683,000	50,624,000
Lamar County					
Paluxy	18,162,000	11,033,000	2,739,000	770,000	32,704,000
Glen Rose	0	12,451,000	836,000	471,000	13,758,000
Hensell	0	7,305,000	598,000	205,000	8,108,000
Pearsall	0	3,017,000	3,145,000	431,000	6,593,000
Hosston	0	10,153,000	12,822,000	1,876,000	24,851,000
Lampasas County					
Paluxy	0	0	0	0	0
Glen Rose	337,000	287,000	0	0	624,000
Hensell	1,787,000	1,086,000	0	0	2,873,000
Pearsall	603,000	224,000	0	0	827,000

County and hydrostratigraphic unit	Total in-place volume (acre-feet)				
	Fresh	Slightly saline	Moderately saline	Very saline	Total
Hosston	2,103,000	1,375,000	0	0	3,478,000
Lee County					
Paluxy	0	0	70,000	332,000	402,000
Glen Rose	0	0	4,194,000	280,000	4,474,000
Hensell	0	0	338,000	65,000	403,000
Pearsall	0	0	209,000	549,000	758,000
Hosston	0	0	140,000	15,101,000	15,241,000
Limestone County					
Paluxy	0	0	1,415,000	996,000	2,411,000
Glen Rose	0	0	7,571,000	3,357,000	10,928,000
Hensell	0	667,000	888,000	202,000	1,757,000
Pearsall	0	0	2,923,000	1,945,000	4,868,000
Hosston	0	4,345,000	12,642,000	8,726,000	25,713,000
McLennan County					
Paluxy	0	1,696,000	2,844,000	0	4,540,000
Glen Rose	5,025,000	12,116,000	4,225,000	0	21,366,000
Hensell	572,000	4,904,000	446,000	0	5,922,000
Pearsall	1,790,000	1,654,000	1,128,000	0	4,572,000
Hosston	18,926,000	3,237,000	0	0	22,163,000
Milam County					
Paluxy	0	0	1,322,000	1,007,000	2,329,000
Glen Rose	0	0	25,223,000	459,000	25,682,000
Hensell	0	0	2,195,000	120,000	2,315,000
Pearsall	0	0	5,464,000	2,370,000	7,834,000
Hosston	0	8,693,000	37,853,000	44,444,000	90,990,000
Mills County					
Paluxy	188,000	0	0	0	188,000
Glen Rose	1,022,000	0	0	0	1,022,000
Hensell	3,324,000	0	0	0	3,324,000
Pearsall	825,000	0	0	0	825,000
Hosston	2,779,000	0	0	0	2,779,000
Montague County					
Paluxy	212,000	0	0	0	212,000
Glen Rose	829,000	0	0	0	829,000
Hensell	2,443,000	0	0	0	2,443,000
Pearsall	793,000	0	0	0	793,000
Hosston	2,514,000	4,000	0	0	2,518,000
Navarro County					

County and hydrostratigraphic unit	Total in-place volume (acre-feet)				
	Fresh	Slightly saline	Moderately saline	Very saline	Total
Paluxy	0	0	6,244,000	1,130,000	7,374,000
Glen Rose	0	0	16,549,000	1,650,000	18,199,000
Hensell	0	159,000	2,251,000	481,000	2,891,000
Pearsall	0	0	4,166,000	3,430,000	7,596,000
Hosston	0	6,786,000	13,915,000	21,084,000	41,785,000
Parker County					
Paluxy	3,068,000	0	0	0	3,068,000
Glen Rose	3,271,000	0	0	0	3,271,000
Hensell	3,863,000	0	0	0	3,863,000
Pearsall	1,103,000	105,000	0	0	1,208,000
Hosston	3,962,000	52,000	0	0	4,014,000
Red River County					
Paluxy	2,996,000	9,062,000	22,818,000	8,388,000	43,264,000
Glen Rose	0	3,521,000	10,059,000	5,900,000	19,480,000
Hensell	0	2,245,000	5,084,000	2,290,000	9,619,000
Pearsall	0	129,000	5,857,000	2,793,000	8,779,000
Hosston	0	1,203,000	17,033,000	10,452,000	28,688,000
Robertson County					
Paluxy	0	0	0	102,000	102,000
Glen Rose	0	0	857,000	140,000	997,000
Hensell	0	0	46,000	42,000	88,000
Pearsall	0	0	0	328,000	328,000
Hosston	0	0	0	3,596,000	3,596,000
Rockwall County					
Paluxy	418,000	1,565,000	1,804,000	0	3,787,000
Glen Rose	0	0	3,208,000	145,000	3,353,000
Hensell	0	0	1,633,000	0	1,633,000
Pearsall	0	0	1,437,000	0	1,437,000
Hosston	0	0	8,521,000	0	8,521,000
Somervell County					
Paluxy	330,000	0	0	0	330,000
Glen Rose	1,152,000	0	0	0	1,152,000
Hensell	2,149,000	0	0	0	2,149,000
Pearsall	352,000	0	0	0	352,000
Hosston	1,623,000	0	0	0	1,623,000
Tarrant County					
Paluxy	13,225,000	538,000	0	0	13,763,000
Glen Rose	4,770,000	4,600,000	609,000	0	9,979,000

County and hydrostratigraphic unit	Total in-place volume (acre-feet)				
	Fresh	Slightly saline	Moderately saline	Very saline	Total
Hensell	4,387,000	4,204,000	0	0	8,591,000
Pearsall	28,000	2,768,000	474,000	0	3,270,000
Hosston	5,463,000	3,983,000	0	0	9,446,000
Taylor County					
Paluxy	0	0	0	0	0
Glen Rose	0	0	0	0	0
Hensell	0	0	0	0	0
Pearsall	0	0	2,000	0	2,000
Hosston	0	420,000	0	0	420,000
Titus County					
Paluxy	0	0	0	0	0
Glen Rose	0	0	0	0	0
Hensell	0	0	0	1,000	1,000
Pearsall	0	0	0	0	0
Hosston	0	0	0	0	0
Travis County					
Paluxy	0	20,000	1,116,000	0	1,136,000
Glen Rose	783,000	101,000	8,104,000	0	8,988,000
Hensell	70,000	1,708,000	1,060,000	0	2,838,000
Pearsall	407,000	1,359,000	3,094,000	0	4,860,000
Hosston	7,422,000	38,257,000	1,483,000	0	47,162,000
Williamson County					
Paluxy	0	287,000	2,393,000	4,000	2,684,000
Glen Rose	6,698,000	5,586,000	13,506,000	0	25,790,000
Hensell	1,403,000	2,070,000	1,177,000	0	4,650,000
Pearsall	3,149,000	1,663,000	3,089,000	0	7,901,000
Hosston	15,658,000	20,873,000	23,635,000	3,374,000	63,540,000
Wise County					
Paluxy	3,167,000	0	0	0	3,167,000
Glen Rose	2,663,000	0	0	0	2,663,000
Hensell	5,717,000	0	0	0	5,717,000
Pearsall	1,549,000	274,000	0	0	1,823,000
Hosston	4,433,000	475,000	0	0	4,908,000

Notes:

Fresh = 0 to 999 milligrams per liter total dissolved solids
Slightly saline = 1,000 to 2,999 milligrams per liter total dissolved solids
Moderately saline = 3,000 to 9,999 milligrams per liter total dissolved solids
Very saline = 10,000 to 35,000 milligrams per liter total dissolved solids

Table 9-3 The in-place groundwater volumes of fresh, slightly saline, moderately saline, and very saline in the Northern Trinity Aquifer study area by conservation district.

Conservation district and hydrostratigraphic unit	Total in-place volume (acre-feet)				
	Fresh	Slightly saline	Moderately saline	Very saline	Total
Brazos Valley GCD					
Paluxy	0	0	0	102,000	102,000
Glen Rose	0	0	857,000	140,000	997,000
Hensell	0	0	46,000	42,000	88,000
Pearsall	0	0	0	328,000	328,000
Hosston	0	0	0	3,596,000	3,596,000
Central Texas GCD					
Paluxy	0	0	0	0	0
Glen Rose	1,796,000	0	0	0	1,796,000
Hensell	2,547,000	0	0	0	2,547,000
Pearsall	813,000	3,000	0	0	816,000
Hosston	4,792,000	0	0	0	4,792,000
Clearwater UWCD					
Paluxy	0	993,000	1,611,000	0	2,604,000
Glen Rose	2,115,000	10,884,000	6,722,000	0	19,721,000
Hensell	1,130,000	3,311,000	813,000	0	5,254,000
Pearsall	623,000	2,016,000	1,804,000	0	4,443,000
Hosston	7,670,000	20,605,000	1,039,000	0	29,314,000
Lost Pines GCD					
Paluxy	0	0	508,000	857,000	1,365,000
Glen Rose	0	0	13,361,000	664,000	14,025,000
Hensell	0	0	1,238,000	125,000	1,363,000
Pearsall	0	0	1,627,000	2,042,000	3,669,000
Hosston	0	695,000	10,934,000	35,087,000	46,716,000
Middle Trinity GCD					
Paluxy	3,145,000	2,780,000	0	0	5,925,000
Glen Rose	13,914,000	7,001,000	3,684,000	0	24,599,000
Hensell	19,555,000	11,711,000	0	0	31,266,000
Pearsall	2,967,000	2,123,000	0	0	5,090,000
Hosston	24,591,000	5,331,000	0	0	29,922,000
Neches & Trinity Valleys GCD					
Paluxy	0	0	116,000	604,000	720,000
Glen Rose	0	0	241,000	761,000	1,002,000
Hensell	0	0	29,000	162,000	191,000
Pearsall	0	0	0	535,000	535,000
Hosston	0	0	0	3,291,000	3,291,000

Conservation district and hydrostratigraphic unit	Total in-place volume (acre-feet)				
	Fresh	Slightly saline	Moderately saline	Very saline	Total
North Texas GCD					
Paluxy	30,669,000	9,158,000	8,140,000	0	47,967,000
Glen Rose	12,830,000	4,167,000	12,415,000	3,949,000	33,361,000
Hensell	13,951,000	3,913,000	5,364,000	0	23,228,000
Pearsall	6,754,000	3,712,000	5,659,000	0	16,125,000
Hosston	14,841,000	16,216,000	20,734,000	0	51,791,000
Northern Trinity GCD					
Paluxy	13,225,000	538,000	0	0	13,763,000
Glen Rose	4,770,000	4,600,000	609,000	0	9,979,000
Hensell	4,387,000	4,204,000	0	0	8,591,000
Pearsall	28,000	2,768,000	474,000	0	3,270,000
Hosston	5,463,000	3,983,000	0	0	9,446,000
Post Oak Savannah GCD					
Paluxy	0	0	1,322,000	1,007,000	2,329,000
Glen Rose	0	0	25,223,000	459,000	25,682,000
Hensell	0	0	2,195,000	120,000	2,315,000
Pearsall	0	0	5,464,000	2,370,000	7,834,000
Hosston	0	8,693,000	37,853,000	44,444,000	90,990,000
Prairielands GCD					
Paluxy	7,200,000	10,344,000	9,377,000	0	26,921,000
Glen Rose	10,600,000	10,352,000	27,060,000	0	48,012,000
Hensell	5,153,000	14,260,000	4,104,000	0	23,517,000
Pearsall	529,000	6,768,000	6,162,000	108,000	13,567,000
Hosston	27,567,000	27,240,000	5,244,000	650,000	60,701,000
Red River GCD					
Paluxy	28,549,000	8,835,000	6,445,000	0	43,829,000
Glen Rose	4,361,000	11,896,000	6,479,000	0	22,736,000
Hensell	4,356,000	9,393,000	1,405,000	0	15,154,000
Pearsall	1,390,000	4,405,000	6,206,000	0	12,001,000
Hosston	2,645,000	15,828,000	16,918,000	0	35,391,000
Saratoga UWCD					
Paluxy	0	0	0	0	0
Glen Rose	337,000	287,000	0	0	624,000
Hensell	1,787,000	1,086,000	0	0	2,873,000
Pearsall	603,000	224,000	0	0	827,000
Hosston	2,103,000	1,375,000	0	0	3,478,000
Southern Trinity GCD					
Paluxy	0	1,696,000	2,844,000	0	4,540,000

Conservation district and hydrostratigraphic unit	Total in-place volume (acre-feet)				
	Fresh	Slightly saline	Moderately saline	Very saline	Total
Glen Rose	5,025,000	12,116,000	4,225,000	0	21,366,000
Hensell	572,000	4,904,000	446,000	0	5,922,000
Pearsall	1,790,000	1,654,000	1,128,000	0	4,572,000
Hosston	18,926,000	3,237,000	0	0	22,163,000
Upper Trinity GCD					
Paluxy	6,681,000	0	0	0	6,681,000
Glen Rose	8,146,000	0	0	0	8,146,000
Hensell	15,688,000	0	0	0	15,688,000
Pearsall	4,029,000	379,000	0	0	4,408,000
Hosston	13,628,000	532,000	0	0	14,160,000

Notes: GCD = Groundwater Conservation District and UWCD = Underground Water Conservation District

Fresh = 0 to 999 milligrams per liter total dissolved solids

Slightly saline = 1,000 to 2,999 milligrams per liter total dissolved solids

Moderately saline = 3,000 to 9,999 milligrams per liter total dissolved solids

Very saline = 10,000 to 35,000 milligrams per liter total dissolved solids

Table 9-4 The in-place groundwater volumes of fresh, slightly saline, moderately saline and, very saline in the Northern Trinity Aquifer within the study area by Groundwater Management Area (GMA).

GMA and hydrostratigraphic unit	In-place volume (acre-feet)				
	Fresh	Slightly Saline	Moderately Saline	Very Saline	Total
Groundwater Management Area 8					
Paluxy	120,076,000	68,236,000	104,603,000	37,802,000	330,717,000
Glen Rose	75,808,000	97,625,000	179,731,000	48,746,000	401,910,000
Hensell	107,740,000	49,017,000	33,911,000	17,434,000	208,102,000
Pearsall	26,276,000	34,774,000	72,801,000	22,312,000	156,163,000
Hosston	89,139,000	201,308,000	421,179,000	79,998,000	791,624,000
Groundwater Management Area 11					
Paluxy	0	0	554,000	5,880,000	6,434,000
Glen Rose	0	0	721,000	6,917,000	7,638,000
Hensell	0	0	0	1,874,000	1,874,000
Pearsall	0	0	0	3,042,000	3,042,000
Hosston	0	0	1,316,000	16,646,000	17,962,000
Groundwater Management Area 12					
Paluxy	0	0	738,000	1,900,000	2,638,000
Glen Rose	0	0	26,941,000	1,562,000	28,503,000
Hensell	0	16,000	330,000	2,251,000	2,597,000
Pearsall	0	0	3,322,000	4,711,000	8,033,000
Hosston	0	0	82,891,000	10,749,000	93,640,000

Notes:

Fresh = 0 to 999 milligrams per liter total dissolved solids

Slightly saline = 1,000 to 2,999 milligrams per liter total dissolved solids

Moderately saline = 3,000 to 9,999 milligrams per liter total dissolved solids
Very saline = 10,000 to 35,000 milligrams per liter total dissolved solids

10 Potential production area analysis and groundwater modeling methodology

House Bill 30 of the 84th Texas Legislature (2015) directs the TWDB to identify and designate local or regional brackish groundwater production zones in areas of the state with moderate to high availability and productivity of brackish groundwater that can be used to reduce the use of fresh groundwater. Table 10-1 defines the criteria set forth in House Bill 30 to be used for designation of brackish groundwater production zones. On March 28, 2019, the Board officially designated 15 brackish groundwater production zones for the Northern Trinity Aquifer based upon the potential production areas (PPAs) evaluated in this report.

Table 10-1 House Bill 30 criteria for designation of brackish groundwater production zones.

Criteria type	Criteria for designation of a brackish groundwater production zone
Water quality	Has an average total dissolved solids level of more than 1,000 milligrams per liter.
Hydraulic isolation	Separated by hydrogeologic barriers sufficient to prevent significant impacts to water availability or water quality in the area of the same or other aquifers, subdivisions of aquifers, or geologic strata that have an average total dissolved solids level of 1,000 milligrams per liter or less at the time of designation of the zone.
Aquifer use	Is not serving as a significant source of water supply for municipal, domestic, or agricultural purposes at the time of designation of the zone.
Aquifer use	Is not in an area or geologic stratum that is designated or used for wastewater injection through the use of injection wells or disposal wells permitted under Chapter 27.
Regulatory jurisdiction	Is not located in: an area of the Edwards Aquifer subject to the jurisdiction of the Edwards Aquifer Authority; the boundaries of the: (a) Barton Springs-Edwards Aquifer Conservation District, (b) Harris-Galveston Subsidence District, or (c) Fort Bend Subsidence District.

10.1 Barriers to flow

The potential barriers to flow in the Northern Trinity Aquifer occur both horizontally and vertically. The potential horizontal barriers are primarily faults that occur, mostly along strike, in the downdip portions of the aquifer. The Mexia-Talco Fault Zone is a complex structural feature that significantly offsets hydrostratigraphic units of the Northern Trinity Aquifer. Additional detailed studies would be required to fully understand the effects of these faults on groundwater flow. For purposes of this study, it is assumed that the Mexia-Talco Fault Zone is a significant barrier to horizontal flow and defines the downdip extent of the study area.

Faults related to the Balcones Fault Zone, updip of the Mexia-Talco Fault Zone, occur in the study area. However, it cannot be demonstrated that these faults pose regionally significant horizontal resistance to flow because the thickness of the units is typically larger than the fault throw, and the faults are not laterally extensive on a regional scale (Kelley and others, 2014).

Primary vertical barriers to flow are laterally extensive clays or shales that occur in the Trinity Group formations. The Hosston hydrostratigraphic unit overlies Paleozoic-aged sedimentary rocks that have very low permeability and generally prevent significant cross-formational flow. The Pearsall hydrostratigraphic unit is separated from the underlying Hosston unit by the Hammett Shale, which ranges between 50 and 100 feet thick throughout the downdip portions of the study area. The Pearsall Shale separates the Hensell hydrostratigraphic unit from the underlying Pearsall hydrostratigraphic unit. Although there is no regionally significant shale layer separating the Glen Rose unit from the Hensell unit, the lower Glen Rose Formation has several massive carbonate beds that could help isolate the Hensell unit. The Paluxy hydrostratigraphic unit is composed of relatively porous sandstones that overlie the low porosity shaly carbonate beds of the upper Glen Rose Formation that lie directly beneath and tend to isolate the Paluxy unit. The Paluxy unit is overlain by lower porosity limestone and shale formations of the Lower Fredericksburg Group.

10.2 Aquifer productivity

Producing water wells exist in all hydrostratigraphic units that make up the Northern Trinity Aquifer. Most of the wells are completed in or near the fresh water portions of the units. Well density generally decreases downdip in a given formation as a result of water quality, well productivity, and well construction costs.

House Bill 30 requires that brackish groundwater production zones be moderately to highly productive; therefore, a hydraulic conductivity limit was set at 0.10 feet per day. Whether an aquifer is productive is dependent on the needs of the user. A well with a 500-foot open interval in an aquifer with hydraulic conductivity of 0.10 feet per day could produce about 50 gallons per minute with 200 feet of drawdown. This is a relatively small amount of water for the amount of drawdown, so we consider a 0.10-foot-per-day hydraulic conductivity cutoff a conservative lower productivity limit.

Kelley and others (2014) conceptualized aquifer hydraulic conductivity as decreasing with depth, so generally decreasing downdip. The calibrated horizontal hydraulic conductivity from the Northern Trinity Aquifer and Woodbine Aquifer GAM (Kelley and others, 2014) was used to define areas of hydrostratigraphic units that were less than 0.10 feet per day.

10.3 Selection of potential production areas

A buffer distance was selected that would minimize significant impacts to fresh groundwater and to existing municipal, domestic, and agricultural water wells. The modeled drawdown results discussed in Section 11 were used to calculate the minimum distance that a well field needs to be placed away from existing water wells and fresh groundwater. Each hydrostratigraphic unit had a slightly different buffer distance based upon the hydrologic properties of the unit as shown in Table 10-2. Also shown in the table are the maximum pumping rates, hydraulic heads, and percentage of potential impact that a 100-foot drawdown would represent after 50 years of production.

Table 10-2 Calculated buffer distances based on 50-year production rate.

Well field	Buffer distance (miles)	Max rate (acre-feet per year)	Max rate (million gallons per day)	Minimum hydraulic head (feet)	100-foot drawdown (percentage)
Pa141	5	1,000	0.89	980	10
Pa241	5	380	0.34	913	11
GR151	7	725	0.65	1,218	8
GR251	7	315	0.28	1,000	10
GR351	7	600	0.54	716	14
GR451	7	780	0.70	995	10
He161	6	375	0.33	1,627	6
He261	6	350	0.31	1,112	9
He361	6	77	0.07	837	12
He362	6	40	0.04	837	12
Pe171	3	1,400	1.25	1,324	8
Pe271	3	1,600	1.43	640	16
Ho181	4	975	0.87	1,623	6
Ho281	4	1,700	1.52	1,067	9
Ho282	4	2,250	2.01	1,067	9
Ho381	4	1,400	1.25	1,448	7
Ho382	4	2,150	1.92	1,448	7
Ho481	4	650	0.58	1,636	6
Ho482	4	515	0.46	1,636	6

Buffers were applied around all water wells listed as municipal, domestic, or agricultural that penetrated the hydrostratigraphic unit. It was not necessary for the well to be screened in a penetrated unit for purposes of it being used. The fresh water salinity zone as defined by the 1,000-milligram-per-liter salinity contour and the state boundary line were also buffered. The resulting area with a salinity of less than 10,000 milligrams per liter of total dissolved solids was determined to be acceptable for the production of brackish groundwater.

Only one hydrostratigraphic unit was found to be designated or used for injection within the study area. A Class II injection well located in eastern Bowie County and identified as the Tiller SWD-1 well (API#4203730259) injects into the Paluxy hydrostratigraphic unit at a depth of 3,396 feet, where the water salinity is greater than 10,000 milligrams per liter of total dissolved solids. The well is more than 15 miles from either potential production area in the Paluxy hydrostratigraphic unit and therefore presented low risk of any negative impacts. All other identified Class I and

Class II injection wells either in the study area or in proximity to the study area were determined to be injecting into formations either significantly below or above the Northern Trinity Aquifer.

10.4 Potential production areas

A total of 15 potential production areas are identified for the Northern Trinity Aquifer in the Paluxy (Figure 10-1), Glen Rose (Figure 10-2), Hensell (Figure 10-3), Pearsall (Figure 10-4), and Hosston (Figure 10-5) hydrostratigraphic units. The PPAs are labeled using a two-letter prefix that represents the hydrostratigraphic unit and then numbered sequentially for each hydrostratigraphic unit starting in the northeast and moving along strike to the southwest. Table 10-3 summarizes the volume of brackish groundwater calculated in place within each potential production area.

The volume of brackish groundwater calculated in place for the Hosston potential production areas is more than the sum of the other potential production areas. The total volume of brackish groundwater calculated in place for the Glen Rose potential production areas is about half of that calculated for the Hosston. Combined, the volume calculated in place for the Glen Rose and the Hosston hydrostratigraphic units is 517,262,000 acre-feet, which represents 75 percent of the total brackish groundwater in place within the potential production areas. We determined the minimum, maximum, and average depths expected to the top and thickness of the hydrostratigraphic unit associated with each potential production area (Table 10-4).

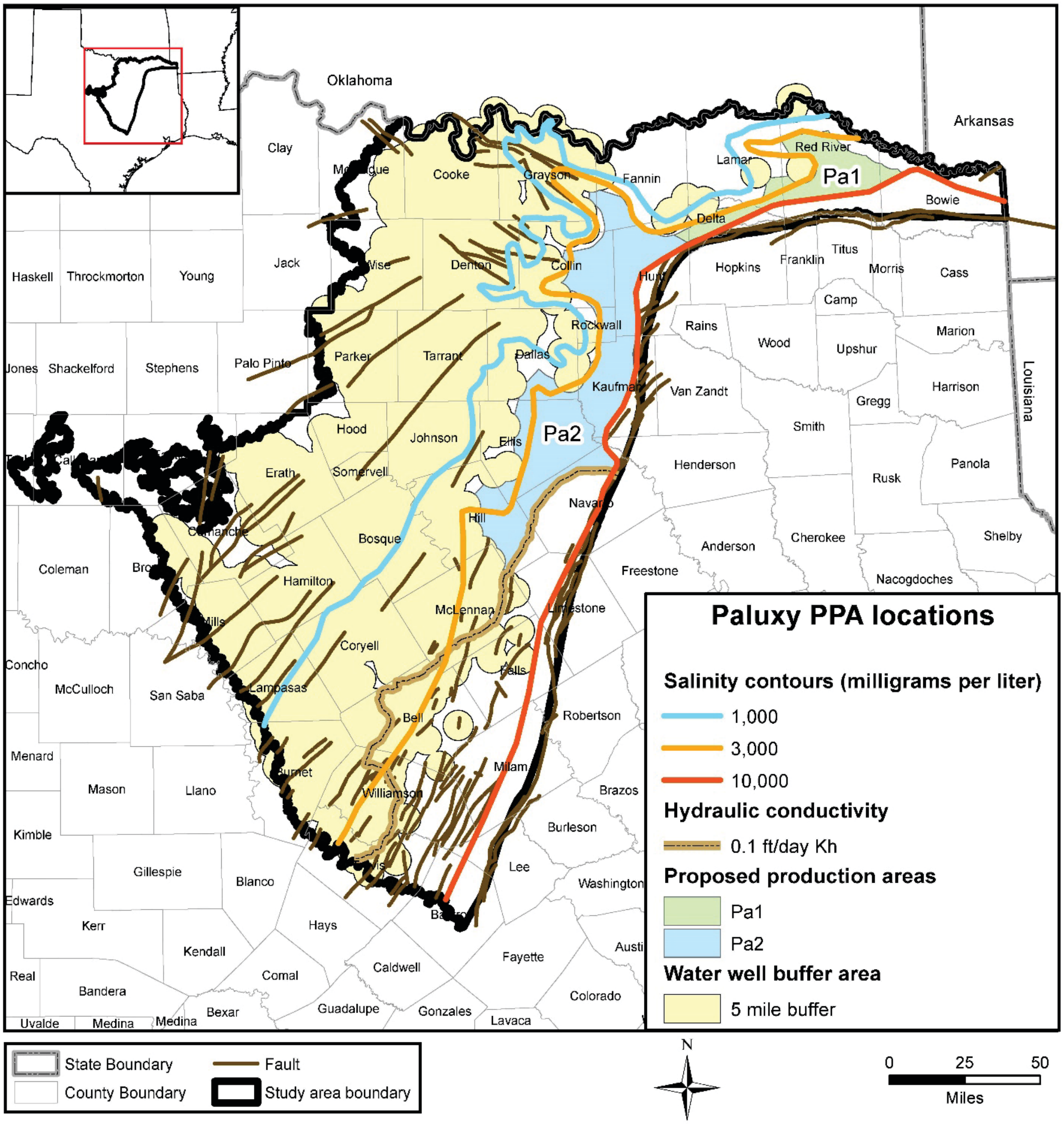


Figure 10-1 **Northern Trinity Aquifer potential production areas in the Paluxy hydrostratigraphic unit.**

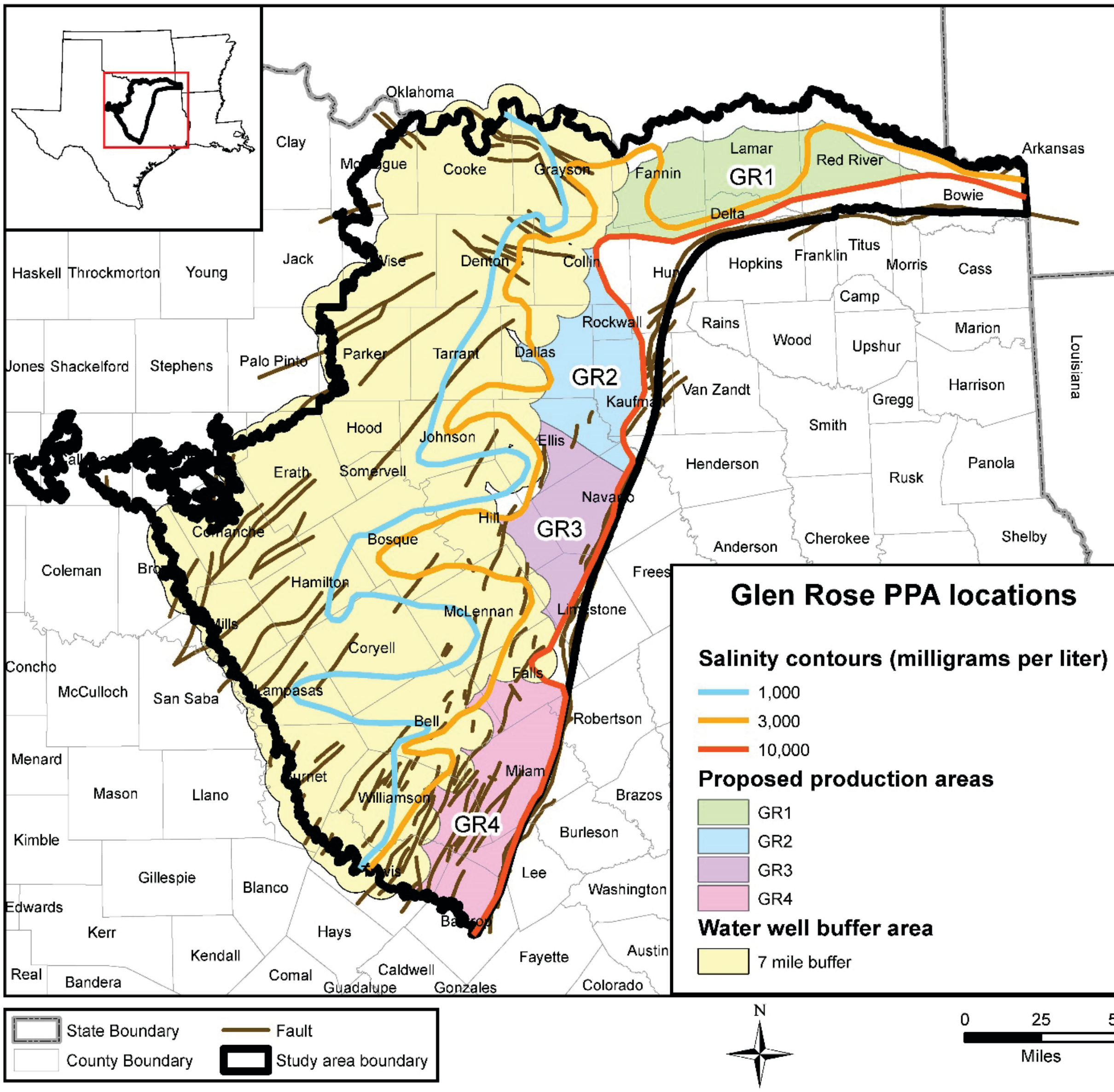


Figure 10-2 **Northern Trinity Aquifer potential production areas in the Glen Rose hydrostratigraphic unit.**

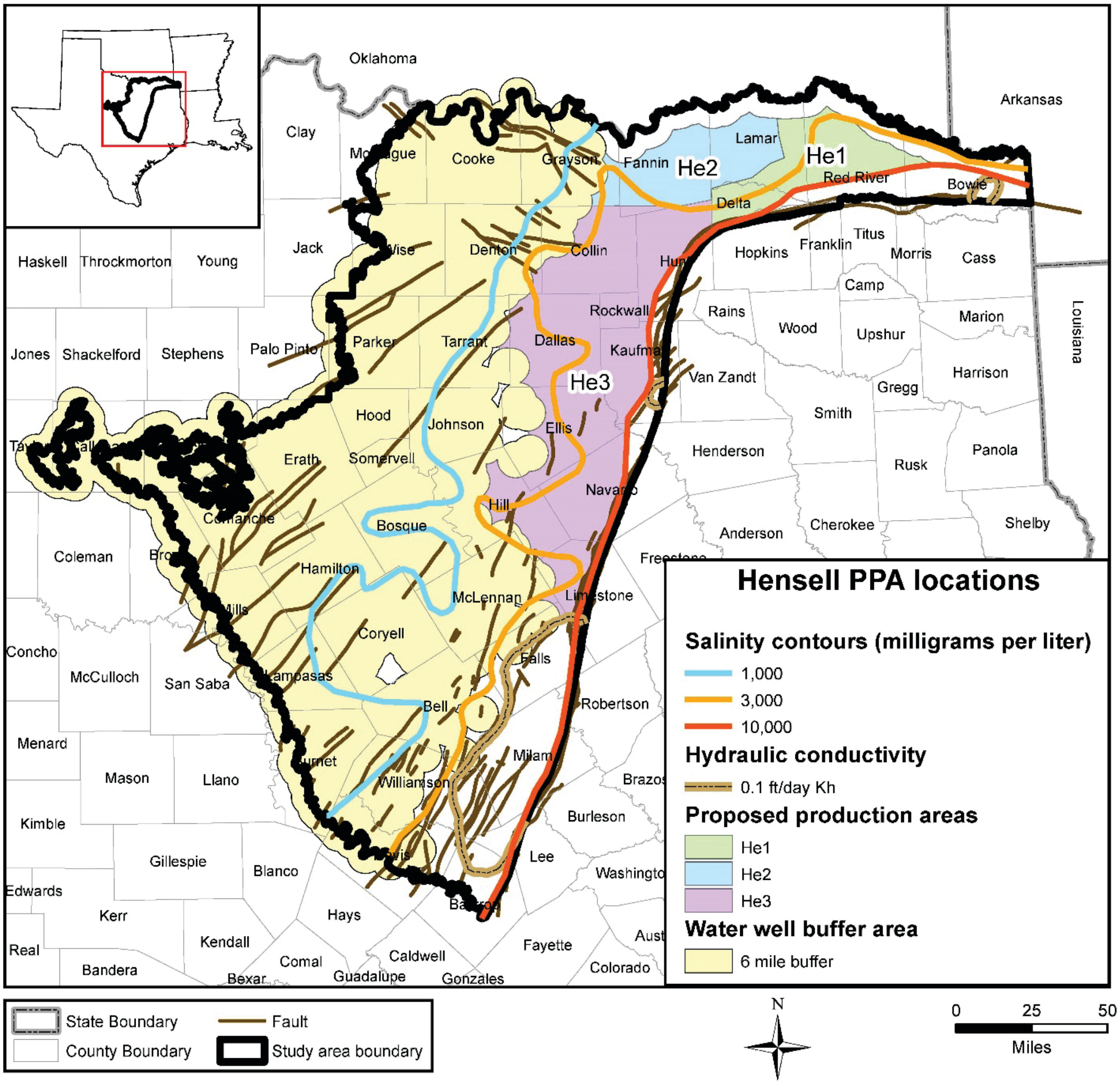


Figure 10-3 Northern Trinity Aquifer potential production areas in the Hensell hydrostratigraphic unit.

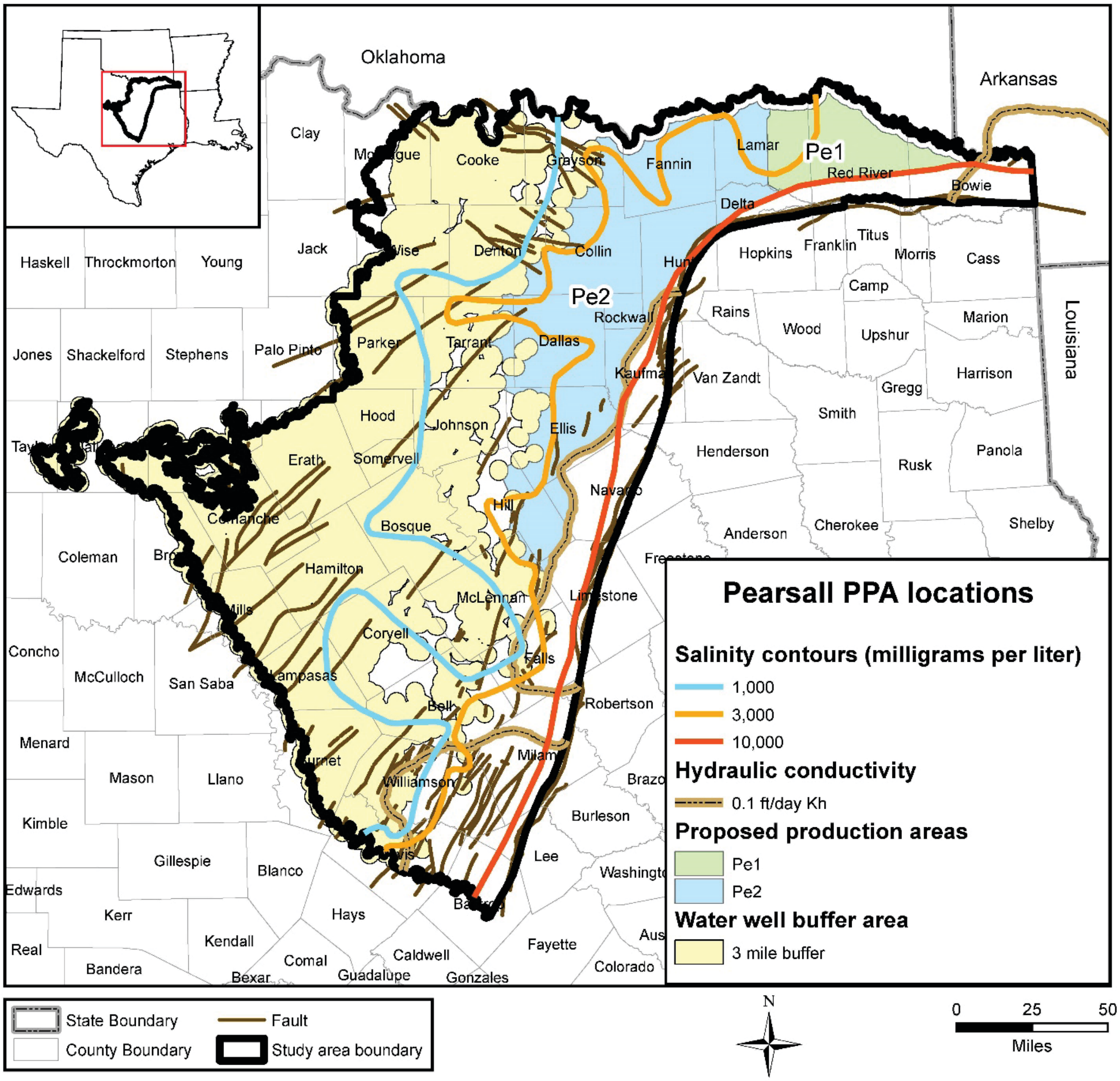


Figure 10-4 **Northern Trinity Aquifer potential production areas in the Pearsall hydrostratigraphic unit.**

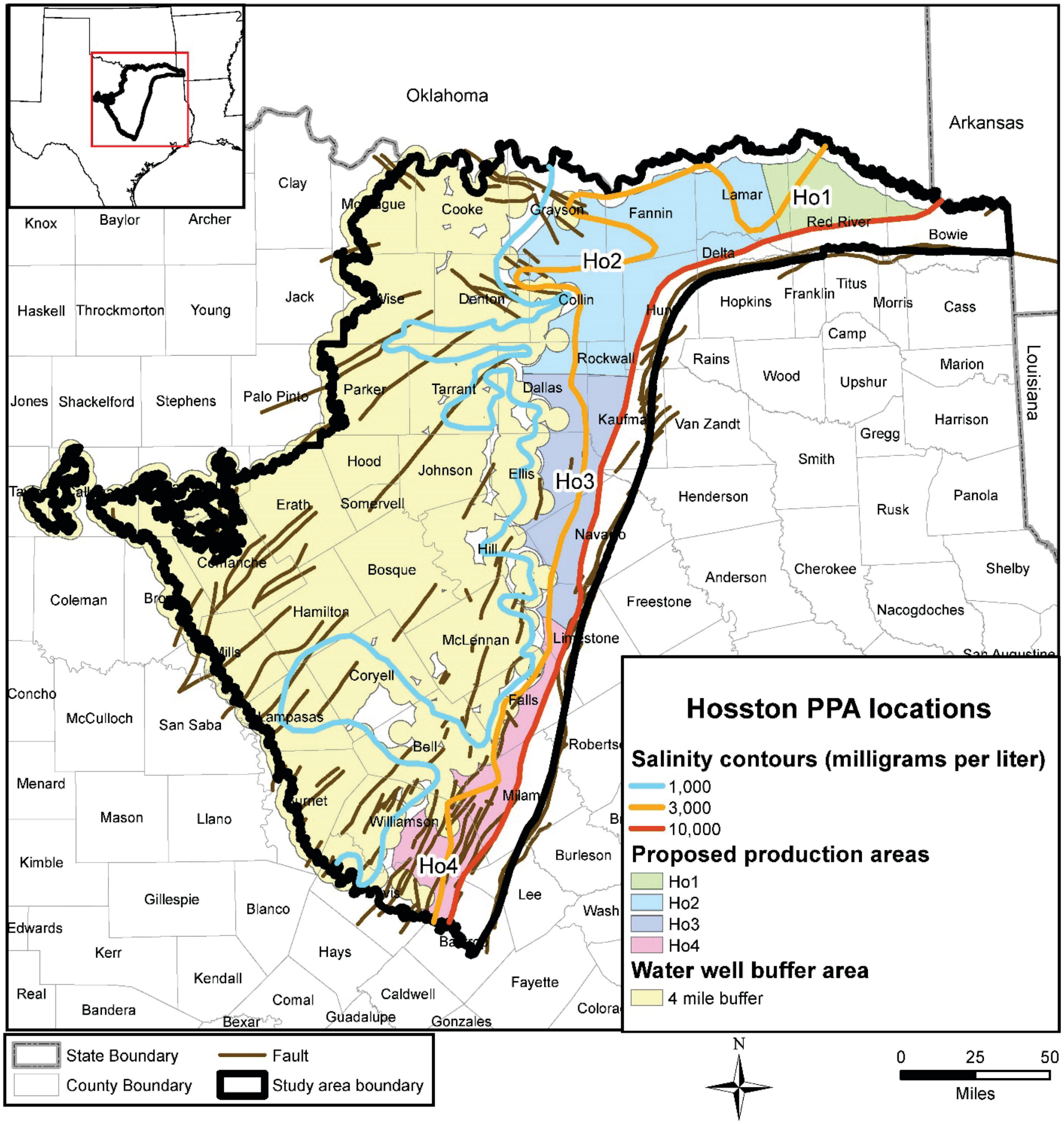


Figure 10-5 Northern Trinity Aquifer potential production areas in the Hosston hydrostratigraphic unit.

Table 10-3 In-place volume of brackish groundwater calculated in place for potential production areas.

Potential production areas	Slightly saline (acre-feet)	Moderately saline (acre-feet)	Total (acre-feet)
Pa1	1,989,674	24,453,134	26,442,808
Pa2	3,975,110	41,218,465	45,193,575
Paluxy total	**5,964,784**	**65,671,599**	**71,636,383**
GR1	19,714,836	17,663,970	37,378,806
GR2	651,587	33,211,559	33,863,146
GR3	158,163	31,029,135	31,187,298
GR4	766,402	58,533,118	59,299,520
Glen Rose total	**21,290,988**	**140,437,782**	**161,728,770**
He1	3,071,782	7,011,846	10,083,628
He2	8,782,686	1,063,593	9,846,279
He3	7,194,508	24,450,798	31,645,306
Hensell total	**19,048,976**	**32,526,237**	**51,575,213**
Pe1	1,556,441	7,383,684	8,940,125
Pe2	8,999,762	36,080,278	45,080,040
Pearsall total	**10,556,203**	**43,463,962**	**54,020,165**
Ho1	2,687,969	20,091,600	22,779,569
Ho2	28,785,239	88,132,220	116,917,459
Ho3	29,489,991	48,503,810	77,993,801
Ho4	40,401,730	97,440,988	137,842,718
Hosston total	**101,364,929**	**254,168,618**	**355,533,547**

Notes:
Slightly saline = 1,000 to 2,999 milligrams per liter total dissolved solids
Moderately saline = 3,000 to 9,999 milligrams per liter total dissolved solids

Table 10-4 Depths and thicknesses determined for potential production areas (PPA).

PPA	Minimum head (feet)	100-Foot drawdown (percentage)	Minimum surface depth (feet)	Maximum surface depth (feet)	Average surface depth (feet)	Minimum unit thickness (feet)	Maximum unit thickness (feet)	Average unit thickness (feet)
Pa1	980	10.2	998	3,992	2,476	109	465	393
Pa2	913	11.0	1,411	4,901	2,934	97	405	207
GR1	1,218	8.2	1,420	4,063	2,654	248	869	538
GR2	1,000	10.0	1,214	4,687	3,001	363	1,010	716
GR3	716	14.0	1,120	3,996	2,505	539	946	783
GR4	995	10.1	1,032	6,614	3,056	411	1,269	934
He1	1,627	6.1	1,676	4,729	3,387	57	133	96
He2	1,112	9.0	1,496	4,071	2,795	66	113	89
He3	837	11.9	1,132	5,577	3,326	30	169	72
Pe1	1,324	7.6	1,316	4,541	3,046	57	494	250
Pe2	640	15.6	1,155	5,669	3,070	81	610	260
Ho1	1,623	6.2	1,655	5,946	4,092	61	1,089	453
Ho2	1,067	9.4	1,398	6,645	3,721	56	913	415
Ho3	1,448	6.9	2,114	6,404	4,189	194	1,170	605
Ho4	1,636	6.1	1,707	8,116	4,289	205	1,670	1,050

11 Potential production area modeling methodology

The primary objective of the modeling task is to determine the amount of brackish groundwater that a potential production area can produce over 30-year and 50-year periods without causing significant impacts to fresh water availability and existing municipal, domestic, and agricultural use. The modeling approach is based upon four primary features: (1) modeling tool used, (2) wellfield assumptions, (3) metrics used to assess drawdown, and (4) metrics used to assess change in water quality.

11.1 Modeling tool used

The Northern Trinity Aquifer and Woodbine Aquifer GAM (Kelly and others, 2014) is the primary state-accepted tool for assessing groundwater availability in the Northern Trinity Aquifer. This model covers the entirety of the Northern Trinity Aquifer study area and is well-calibrated throughout the study area. While fewer calibration targets were available in the far downdip sections at the locations of some of the potential production areas, the conceptualization of hydraulic conductivity provided an accurate calibration in areas where current brackish groundwater production is occurring (e.g., in the Hosston Aquifer to the south). Because a consistent conceptualization was used, this provides confidence that the estimates of hydraulic conductivity are reasonable in those areas where fewer calibration targets were available, and that this existing model provides the best available tool for estimating brackish groundwater availability.

An existing predictive simulation was available (Beach and others, 2016) that had been created to support the adoption of desired future conditions in GMA 8 for the 2016 Regional Water Plans. This predictive simulation was called “Run 10” and contained estimates of future pumping supplied by groundwater conservation districts in GMA 8. We consider this predictive simulation to be an appropriate baseline predictive scenario for estimating impacts of brackish water production in the potential production areas and will use this as the “base case” for modeling wellfield production.

11.2 Wellfield assumptions

One or more wellfields were located in each potential production area, with the number of wellfields depending on the size of the potential production area. The wellfield locations were chosen by inspection, since the shape of the potential production areas were not regular enough to allow for a distance or area-based location strategy. In general, wellfields were approximately centered with respect to the updip and downdip boundaries of a potential production area.

Three wellfield configurations were tested, containing one, three, and five wells. For a given wellfield, wells were spaced approximately a half mile apart. The model grid has cell dimensions of one quarter mile, and there was one grid cell between the locations of the cells containing the wells. Adding additional wells did increase the overall production for a given amount of local drawdown; however, diminishing returns occurred with respect to per-well productivity due to increasing interference effects (Figure 11-1). Given the potential costs of very deep brackish wells, the decrease in productivity per well would not be favorable to potential producers and the single well configuration was selected to perform the final modeling.

Because potential production areas were defined for each hydrostratigraphic unit, wellfields were isolated to a single hydrostratigraphic unit, which would coincide with one of the layers in the model grid. A simulation was performed for each wellfield, i.e., only one wellfield was active in any simulation.

Production rates were varied based on the relative productivity of the hydrostratigraphic unit at each wellfield location. These rates were estimated by placing drains utilizing the MODFLOW DRN package, (Harbaugh, 2005) at the potential well locations and setting the drain elevation at 500 feet below the initial head in the hydrostratigraphic unit at that location. The drains conductance values were set to 10,000 feet squared per day. After running the simulation with the drains, the average flow from the drains was extracted and used to set flow rates in a following simulation using the MODFLOW WEL package (Harbaugh, 2005). In this way, the pumping rates for wellfields in areas with higher conductivity were comparatively higher.

The production rates estimated from the drain simulations resulted in average wellfield drawdowns ranging from about 200 to 400 feet, depending on the conductivity of the hydrostratigraphic unit, and interference from “existing” pumping (the pumping that was in the baseline Run 10 simulation). Two additional simulations with 25 percent and 50 percent of these rates were also performed. The 25 percent simulation is called the “low” case, the 50 percent simulation the “medium” case, and the 100 percent simulation the “high” case.

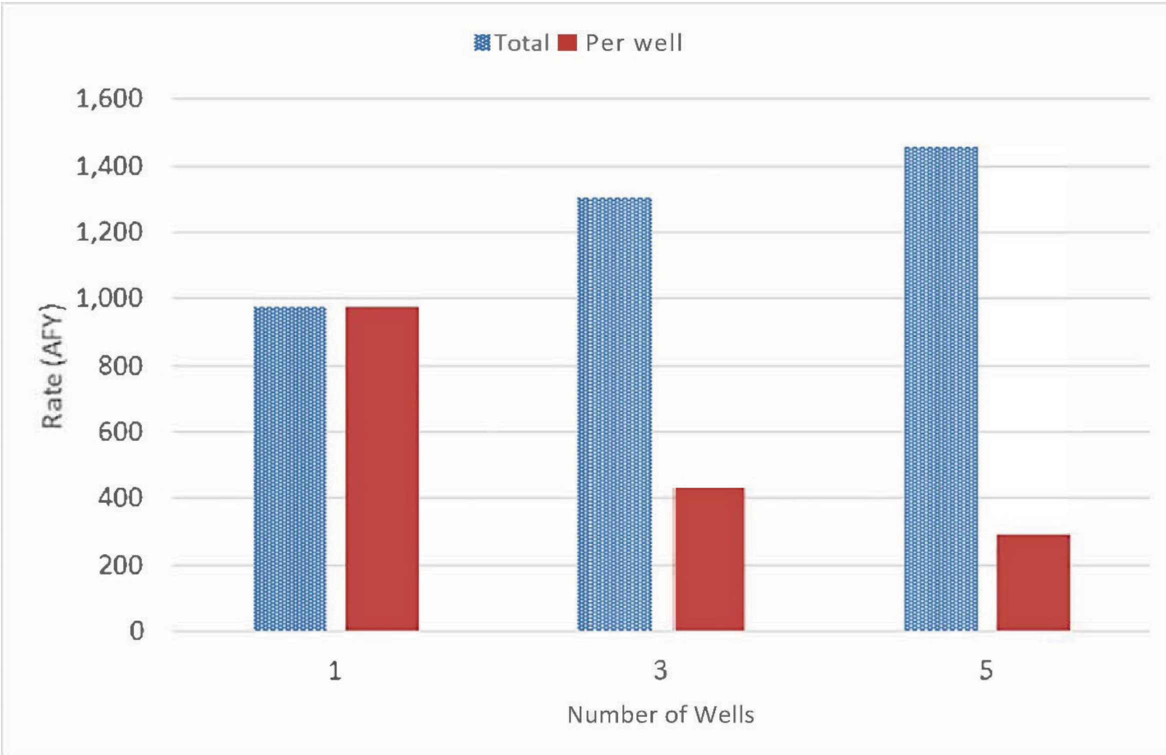


Figure 11-1 **Average wellfield and per well productivity for one-, three-, and five-well versions . Note: AFY = acre-feet per year.**

11.3 Drawdown metrics

The drawdown was modeled for various simulations for each wellfield after 30 and 50 years of production (Table 11-1 and Table 11-2). Maximum drawdowns are reported for any existing well at the fresh water/brackish water transition and in the unit overall (occurring at the production well). Simulated maximum drawdown at the production well is an average value over the quarter-mile square grid cell, so actual drawdown at a well would be higher than the simulated value. The simulated drawdown at each wellfield after 50 years of maximum modeled production rate was compared to the base case (Figure 11-2 to Figure 11-20).

Maximum drawdown and production rate vary by wellfield, depending on the productivity of the hydrostratigraphic unit and interference from existing wells in the simulation. Maximum drawdown at 50 years (for the “high” production case) in any unit ranges from 168 feet for wellfield He361 to 409 feet for wellfield GR151 (see Table 11-1 for wellfield nomenclature). Total production rate (for the “high” production case) varies from 39 acre-feet per year for wellfield He362 to 2,796 acre-feet per year for wellfield Ho382.

Analysis of the relationship between drawdown and production rate at a given wellfield indicates that the relationship is linear. That is, for a given wellfield, the ratio between drawdown and production rate is constant for the low, medium, and high production cases. This is an expected result for confined aquifers. This linearity allows us to predict the drawdown for any production rate without having to complete additional simulations. The predicted drawdown impacts for each wellfield at a production rate of 1,000 acre-feet per year were predicted (Table 11-3). The predicted drawdown for wellfield He362 exceeds the depth to the unit top, and so would not be physically possible to achieve.

11.4 Change in water quality

For each wellfield simulation, the distance between the starting and ending point for each particle was compared to the base case (Table 11-4). In some cases, the “with project” distance was greater than the base case, and in some cases it was less. The maximum and minimum differences in distance, where positive numbers indicate that the “with project” simulated particle distance, were greater than the base case distance.

Whether the particle moves a lesser or greater distance when the brackish wellfield is pumping is dependent on whether the particle was moving toward or away from the wellfield location in the base case. Although under natural conditions the flow is generally downdip toward the Mexia-Talco Fault Zone, under the simulated future pumping conditions, the large drawdowns updip resulted in reversal of gradients. The head contours in the Hosston hydrostratigraphic unit at the end of the base case simulation illustrate this effect (Figure 11-21).

In general, the particle tracking results indicate that very little movement of the particles occurs over the 50-year simulation (typically less than one mile). The difference between the base case and “with project” case also results in small movement (Figure 11-22). Note that for this example, pumping caused the particle to move a shorter distance, since the particle was moving updip under base case conditions, while during brackish production, movement is downdip.

Table 11-1 Simulation of drawdown in the Northern Trinity Aquifer after 30 years of production.

					Total pumping rate (afy)			Max. drawdown at existing well (ft)			Max drawdown at fresh water line (ft)			Max drawdown in unit (ft)		
Unit	**PPA#**	**Wellfield**	**Wellfield label**	**Depth to unit top (ft)**	**Low**	**Medium**	**High**	**Low**	**Medium**	**High**	**Low**	**Medium**	**High**	**Low**	**Medium**	**High**
Paluxy	1	1	Pa141	1,279	205	411	822	15	29	59	4	8	15	95	191	382
Paluxy	2	1	Pa241	3,873	77	155	309	9	18	36	10	19	38	73	147	294
Glen Rose	1	1	GR151	2,808	164	328	657	4	8	16	0	1	1	102	205	409
Glen Rose	2	1	GR251	4,527	65	129	258	6	12	23	7	13	27	65	130	259
Glen Rose	3	1	GR351	2,754	121	242	483	11	22	43	1	3	5	76	152	305
Glen Rose	4	1	GR451	3,024	145	290	581	7	14	29	3	7	14	75	151	301
Hensell	1	1	He161	3,387	92	184	368	4	8	16	0	0	0	100	201	401
Hensell	2	1	He261	2,180	83	166	332	16	31	62	1	2	4	84	168	335
Hensell	3	1	He361	4,497	18	36	73	2	4	7	1	2	4	42	84	168
Hensell	3	2	He362	4,165	10	19	39	3	6	13	0	0	1	77	154	308
Pearsall	1	1	Pe171	4,010	445	890	1,780	5	10	19	0	1	1	101	203	406
Pearsall	2	1	Pe271	3,634	376	752	1,504	7	13	27	9	17	34	63	126	252
Hosston	1	1	Ho181	3,913	317	633	1,267	16	32	63	1	1	2	102	203	407
Hosston	2	1	Ho281	5,099	553	1,105	2,211	19	37	74	4	8	17	85	171	341
Hosston	2	2	Ho282	4,408	465	931	1,861	9	19	37	11	21	42	53	106	213
Hosston	3	1	Ho381	4,752	479	957	1,915	21	42	83	13	26	51	71	141	282
Hosston	3	2	Ho382	4,506	699	1,398	2,796	17	34	67	13	25	51	73	146	292
Hosston	4	1	Ho481	3,098	163	327	653	18	36	72	17	34	69	46	93	186
Hosston	4	2	Ho482	3,615	154	308	616	23	46	91	10	21	42	68	135	270

Note: afy = acre-feet per year, ft = feet

Table 11-2 Simulation of drawdown in the Northern Trinity Aquifer after 50 years of production.

					Total pumping rate (afy)			Max. drawdown at existing well (ft)			Max drawdown at fresh water line (ft)			Max drawdown in unit (ft)		
Unit	**PPA#**	**Wellfield**	**Wellfield label**	**Depth to unit top (ft)**	**Low**	**Medium**	**High**	**Low**	**Medium**	**High**	**Low**	**Medium**	**High**	**Low**	**Medium**	**High**
Paluxy	1	1	Pa141	1,279	205	411	822	15	30	60	4	8	17	96	191	383
Paluxy	2	1	Pa241	3,873	77	155	309	9	19	38	10	20	40	74	148	295
Glen	1	1	GR151	2,808	164	328	657	4	9	17	1	1	2	103	205	411
Glen	2	1	GR251	4,527	65	129	258	6	12	24	7	14	28	65	130	260
Glen	3	1	GR351	2,754	121	242	483	11	22	44	1	3	6	76	153	306
Glen	4	1	GR451	3,024	145	290	581	8	15	30	4	7	15	76	152	304
Hensell	1	1	He161	3,387	92	184	368	4	8	16	0	0	1	100	201	402
Hensell	2	1	He261	2,180	83	166	332	16	31	63	1	2	5	84	168	336
Hensell	3	1	He361	4,497	18	36	73	2	4	7	1	2	4	42	84	168
Hensell	3	2	He362	4,165	10	19	39	3	7	13	0	0	1	77	154	308
Pearsall	1	1	Pe171	4,010	445	890	1,780	5	10	21	1	1	2	102	204	407
Pearsall	2	1	Pe271	3,634	376	752	1,504	7	15	29	9	18	36	64	127	254
Hosston	1	1	Ho181	3,913	317	633	1,267	17	34	68	1	2	4	103	206	411
Hosston	2	1	Ho281	5,099	553	1,105	2,211	20	39	78	5	10	20	86	173	346
Hosston	2	2	Ho282	4,408	465	931	1,861	10	20	41	12	23	46	54	109	217
Hosston	3	1	Ho381	4,752	479	957	1,915	23	46	92	15	29	59	73	146	291
Hosston	3	2	Ho382	4,506	699	1,398	2,796	18	37	73	14	28	56	75	149	299
Hosston	4	1	Ho481	3,098	163	327	653	19	39	77	19	37	74	48	96	191
Hosston	4	2	Ho482	3,615	154	308	616	27	54	107	13	26	52	71	143	286

Note: afy = acre-feet per year, ft = feet

Table 11-3 Estimated drawdown for a 1,000 acre-feet per year wellfield after 50 years of production.

Unit	PPA#	Wellfield	Wellfield label	Depth to unit top (ft)	Total pumping rate (afy)	Maximum drawdown at existing well (ft)	Maximum drawdown at fresh water line (ft)	Maximum drawdown in unit (ft)
Paluxy	1	1	Pa141	1,279	1,000	73	20	466
Paluxy	2	1	Pa241	3,873	1,000	123	128	954
Glen Rose	1	1	GR151	2,808	1,000	26	3	625
Glen Rose	2	1	GR251	4,527	1,000	94	107	1,007
Glen Rose	3	1	GR351	2,754	1,000	91	12	633
Glen Rose	4	1	GR451	3,024	1,000	52	25	523
Hensell	1	1	He161	3,387	1,000	44	1	1,093
Hensell	2	1	He261	2,180	1,000	188	14	1,010
Hensell	3	1	He361	4,497	1,000	102	57	2,315
Hensell	3	2	He362	4,165	1,000	341	25	*7,993
Pearsall	1	1	Pe171	4,010	1,000	12	1	229
Pearsall	2	1	Pe271	3,634	1,000	19	24	169
Hosston	1	1	Ho181	3,913	1,000	53	3	325
Hosston	2	1	Ho281	5,099	1,000	35	9	156
Hosston	2	2	Ho282	4,408	1,000	22	25	117
Hosston	3	1	Ho381	4,752	1,000	48	31	152
Hosston	3	2	Ho382	4,506	1,000	26	20	107
Hosston	4	1	Ho481	3,098	1,000	118	114	293
Hosston	4	2	Ho482	3,615	1,000	174	84	463

Note: afy = acre-feet per year, ft = feet

*exceeds available drawdown

Table 11-4 Minimum and maximum change in simulated travel distances at 50 years.

				Maximum difference in distance				Minimum difference in distance			
Unit	**PPA#**	**Wellfield**	**Wellfield label**	**Particle ID**	**Base distance (ft)**	**Project distance (ft)**	**Difference (ft)**	**Particle ID**	**Base distance (ft)**	**Project distance (ft)**	**Difference (ft)**
Paluxy	1	1	Pa141	6733	56	78	22	7060	52	41	-11
Paluxy	2	1	Pa241	6109	59	101	42	5944	35	4	-31
Glen Rose	1	1	GR151	13598	43	44	1	13640	44	42	-2
Glen Rose	2	1	GR251	13925	10	17	7	10753	102	99	-3
Glen Rose	3	1	GR351	8514	355	361	5	13755	3,117	3,111	-5
Glen Rose	4	1	GR451	16171	127	140	13	13755	3,117	2,541	-576
Hensell	1	1	He161	17106	1,814	1,815	1	19546	1,225	1,224	-1
Hensell	2	1	He261	17106	1,814	1,820	6	19950	1,373	1,363	-10
Hensell	3	1	He361	17594	1,079	1,089	10	17172	1,514	1,495	-19
Hensell	3	2	He362	20376	1,779	1,787	8	19827	567	562	-5
Pearsall	1	1	Pe171	32457	1,627	1,631	4	34056	1,413	1,409	-4
Pearsall	2	1	Pe271	32394	1,587	1,617	30	33721	575	553	-23
Hosston	1	1	Ho181	32796	1,636	1,716	80	33096	5,978	5,904	-74
Hosston	2	1	Ho281	36045	368	429	61	34935	814	725	-89
Hosston	2	2	Ho282	36046	143	226	82	35770	201	104	-97
Hosston	3	1	Ho381	35671	3,057	3,137	80	37614	1,441	1,297	-144
Hosston	3	2	Ho382	36712	2,316	2,494	177	36748	1,970	1,816	-153
Hosston	4	1	Ho481	23677	889	892	2	27515	280	278	-2
Hosston	4	2	Ho482	27467	280	307	27	26908	380	347	-33

Note: ft = feet

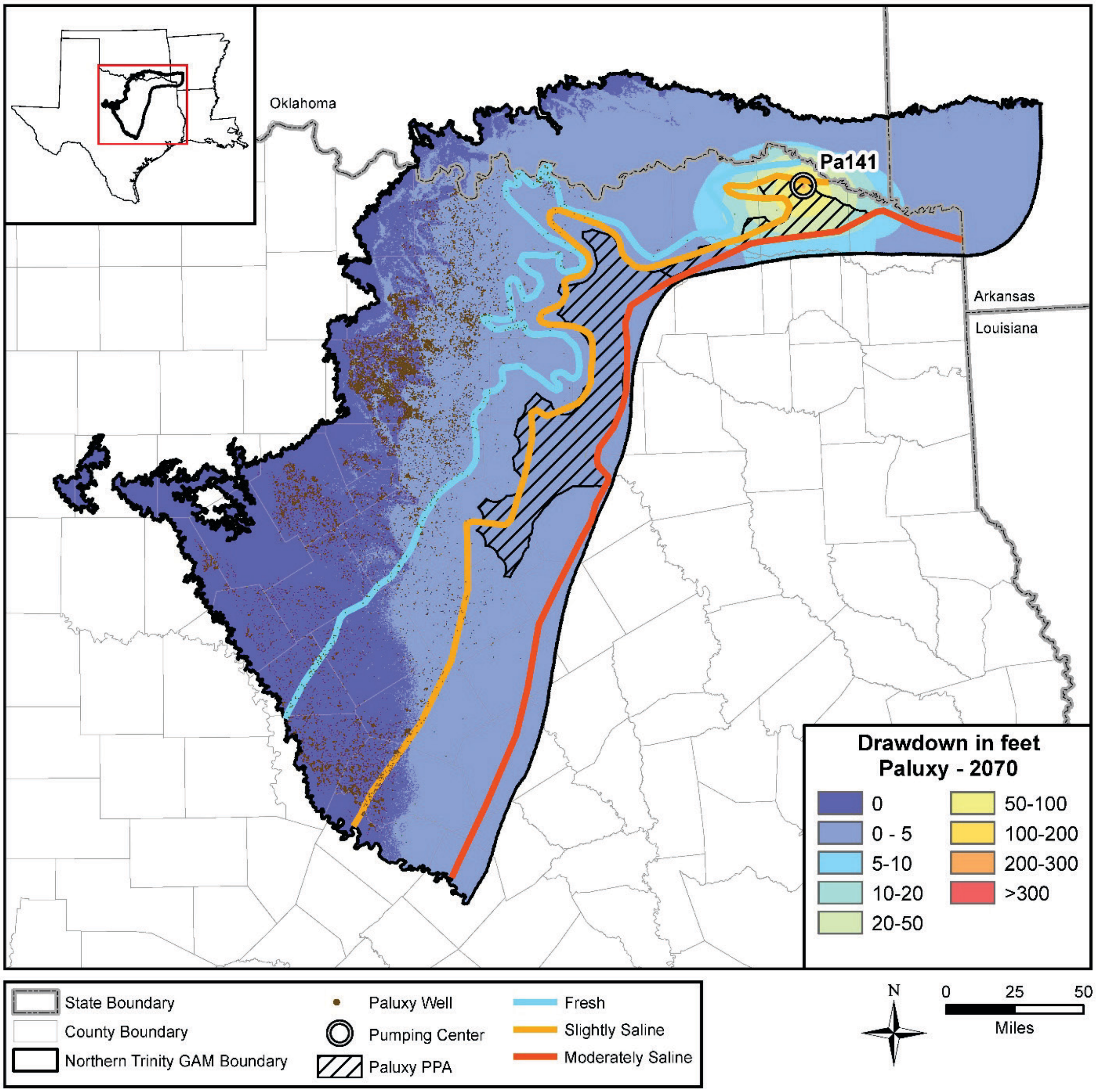


Figure 11-2 Estimated drawdown from wellfield Pa141 in the Paluxy hydrostratigraphic unit of the Northern Trinity Aquifer after 50 years of production at a rate of 822 acre-feet per year.

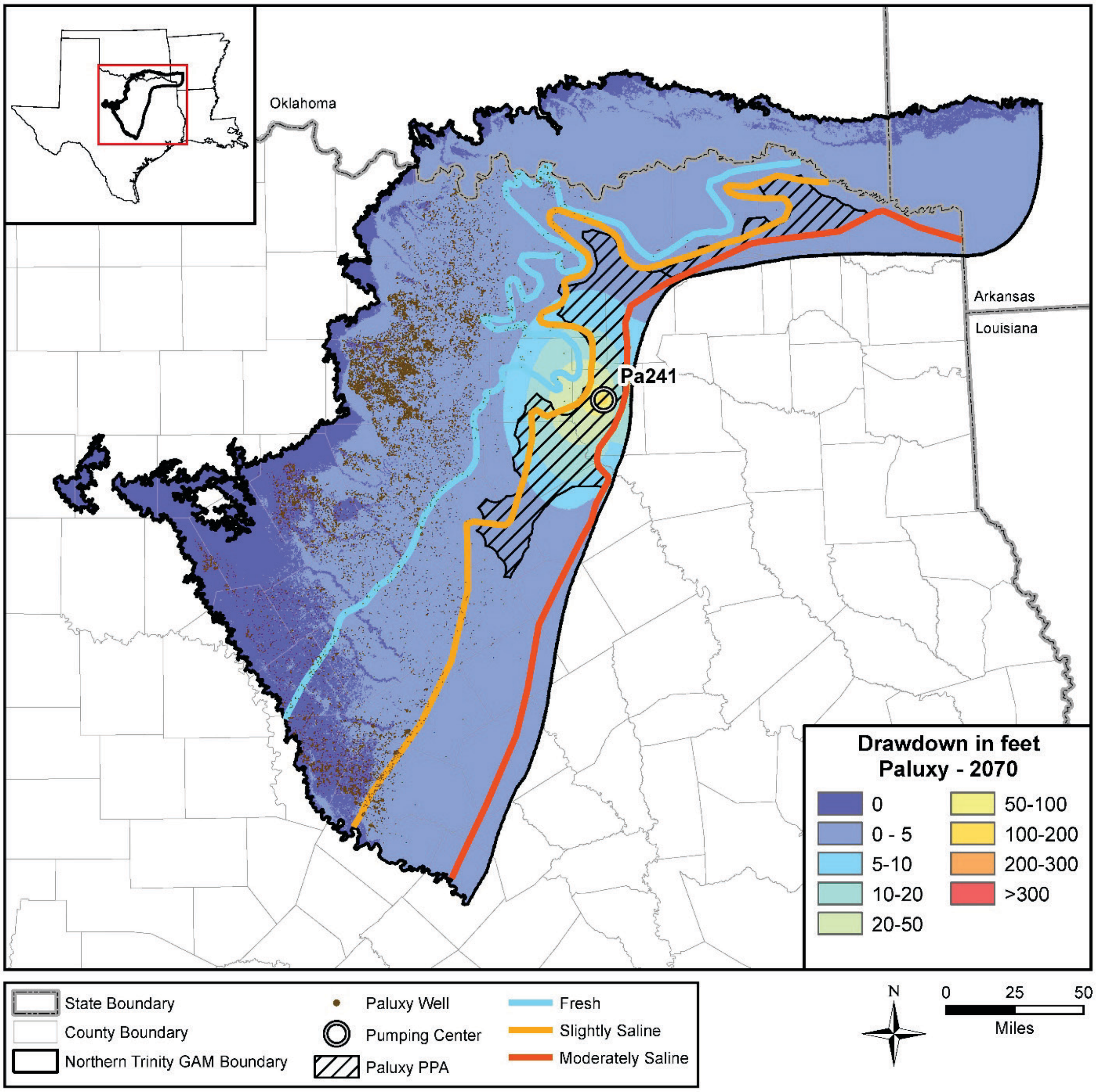


Figure 11-3 **Estimated drawdown from wellfield Pa241 in the Paluxy hydrostratigraphic unit of the Northern Trinity Aquifer after 50 years of production at a rate of 309 acre-feet per year.**

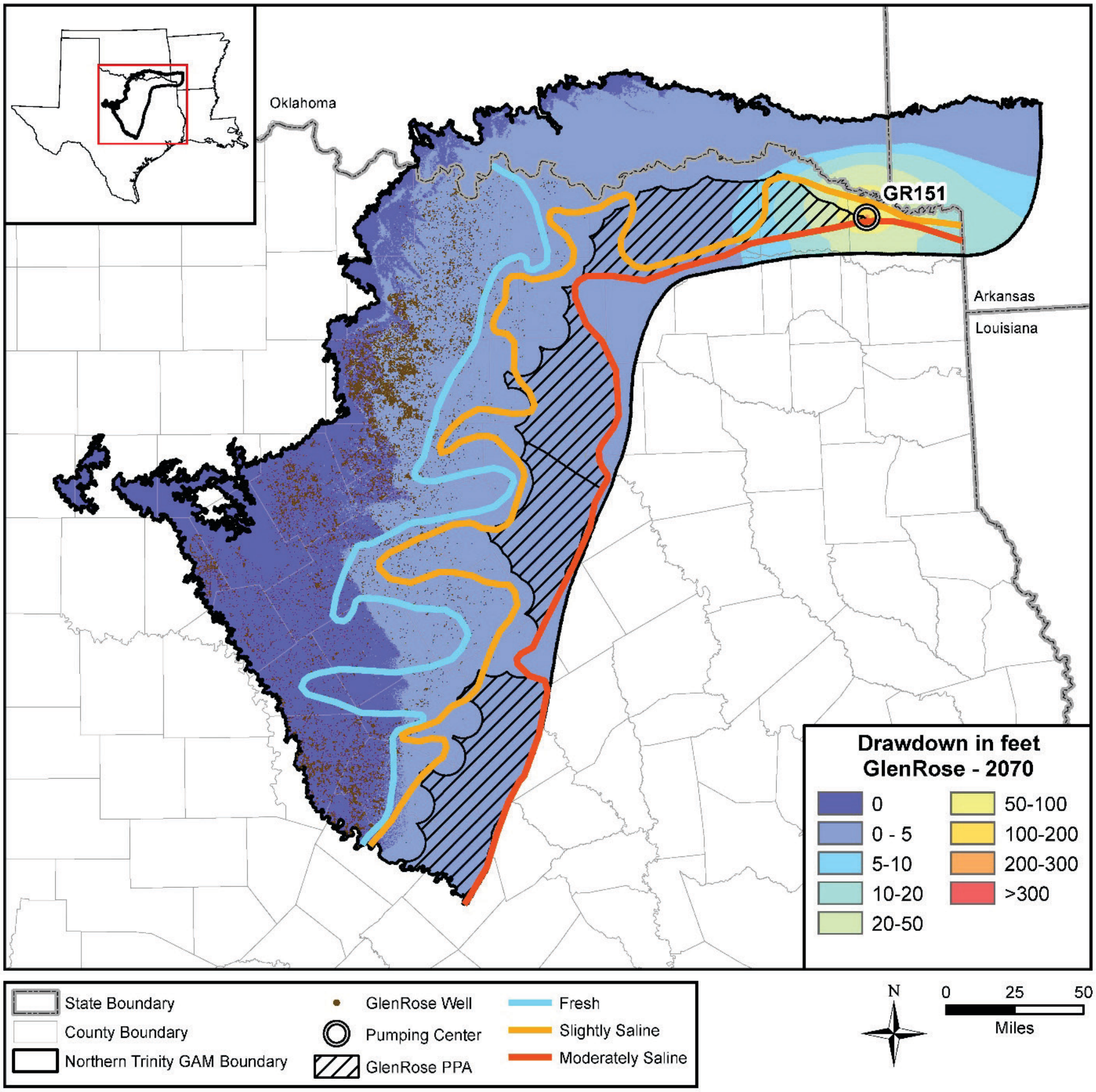


Figure 11-4 Estimated drawdown from wellfield GR151 in the Glen Rose hydrostratigraphic unit of the Northern Trinity Aquifer after 50 years of production at a rate of 657 acre-feet per year.

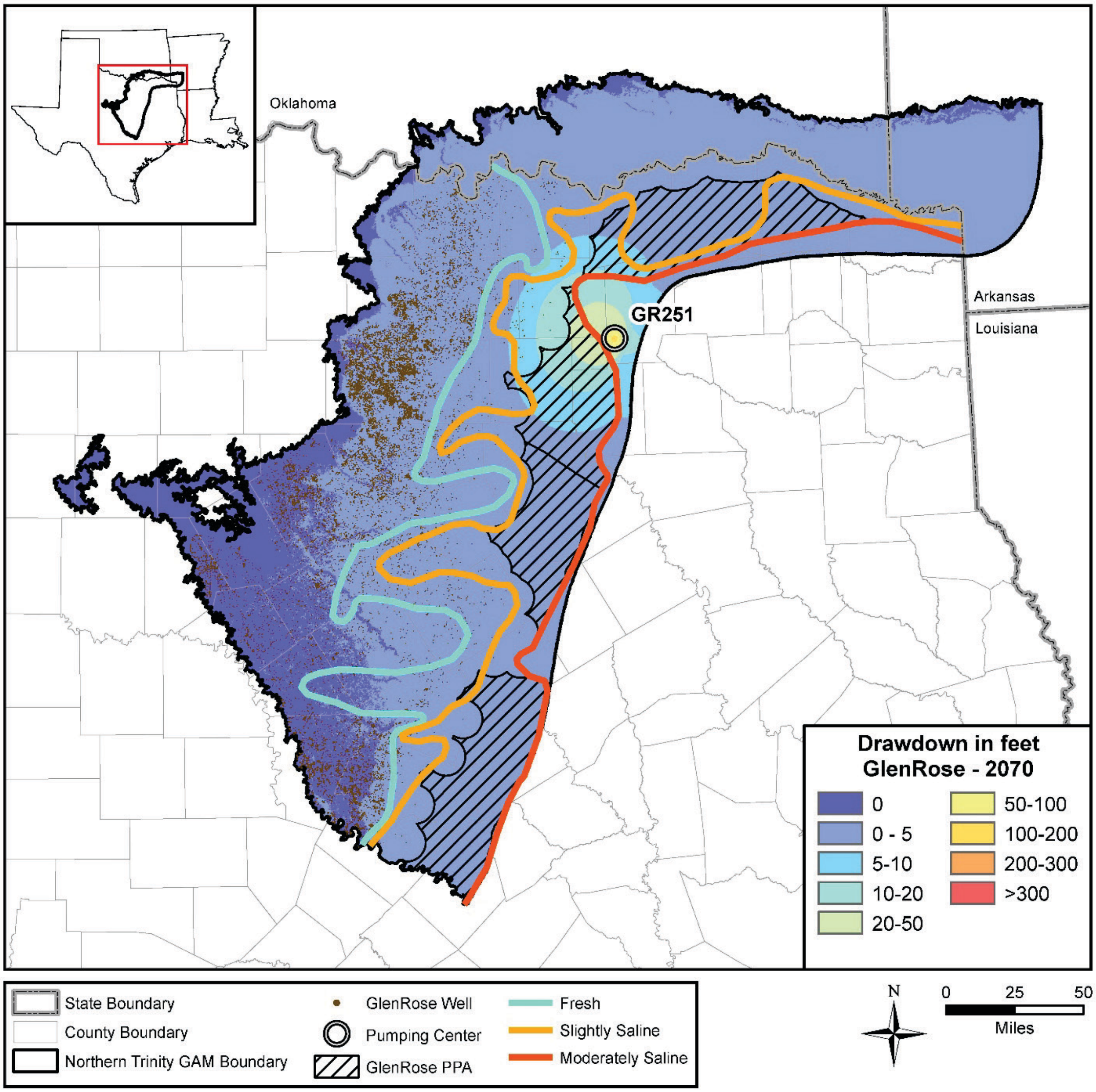


Figure 11-5 Estimated drawdown from wellfield GR251 in the Glen Rose hydrostratigraphic unit of the Northern Trinity Aquifer after 50 years of production at a rate of 258 acre-feet per year.

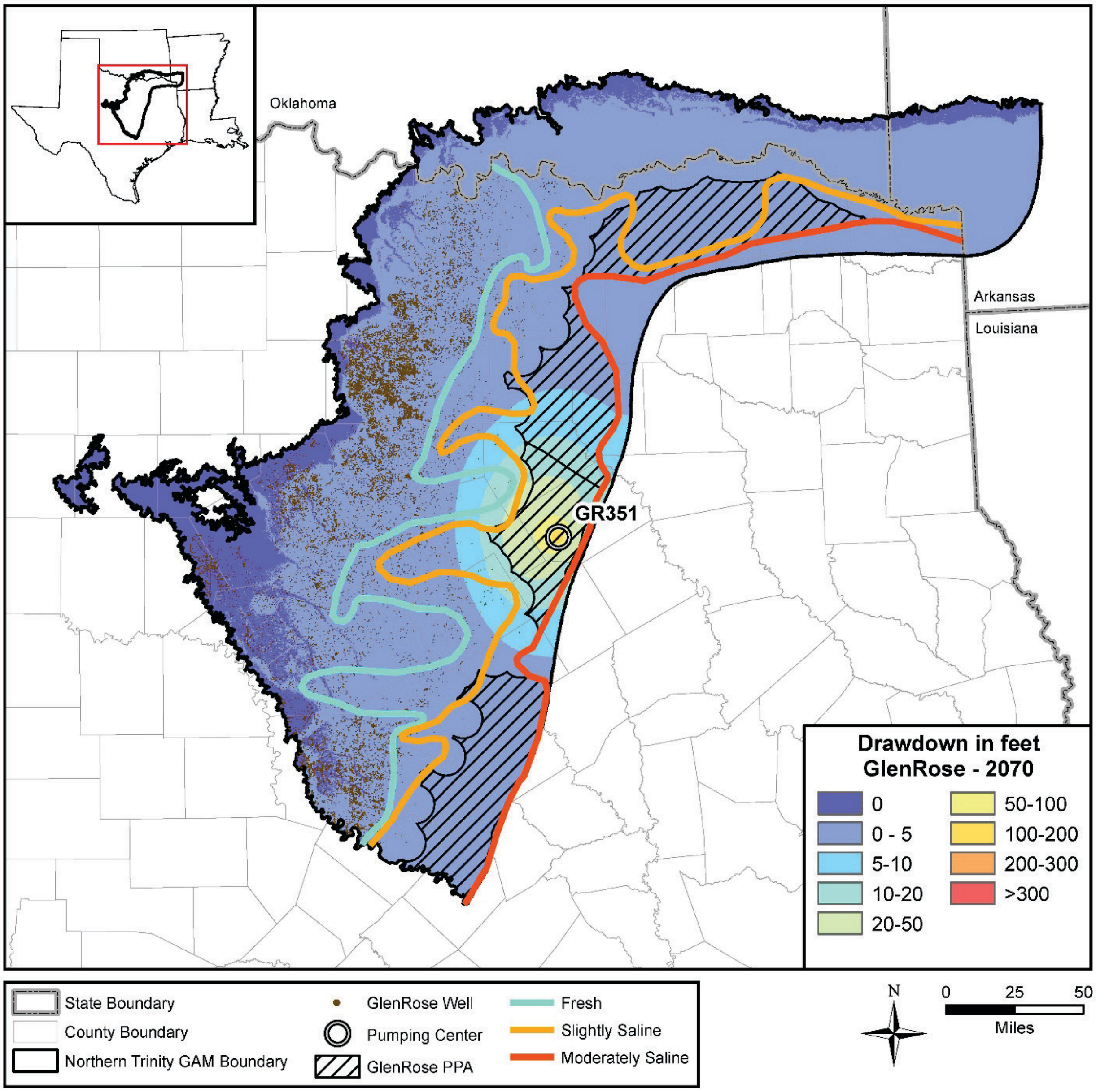


Figure 11-6 **Estimated drawdown from wellfield GR351 in the Glen Rose hydrostratigraphic unit of the Northern Trinity Aquifer after 50 years of production at a rate of 483 acre-feet per.**

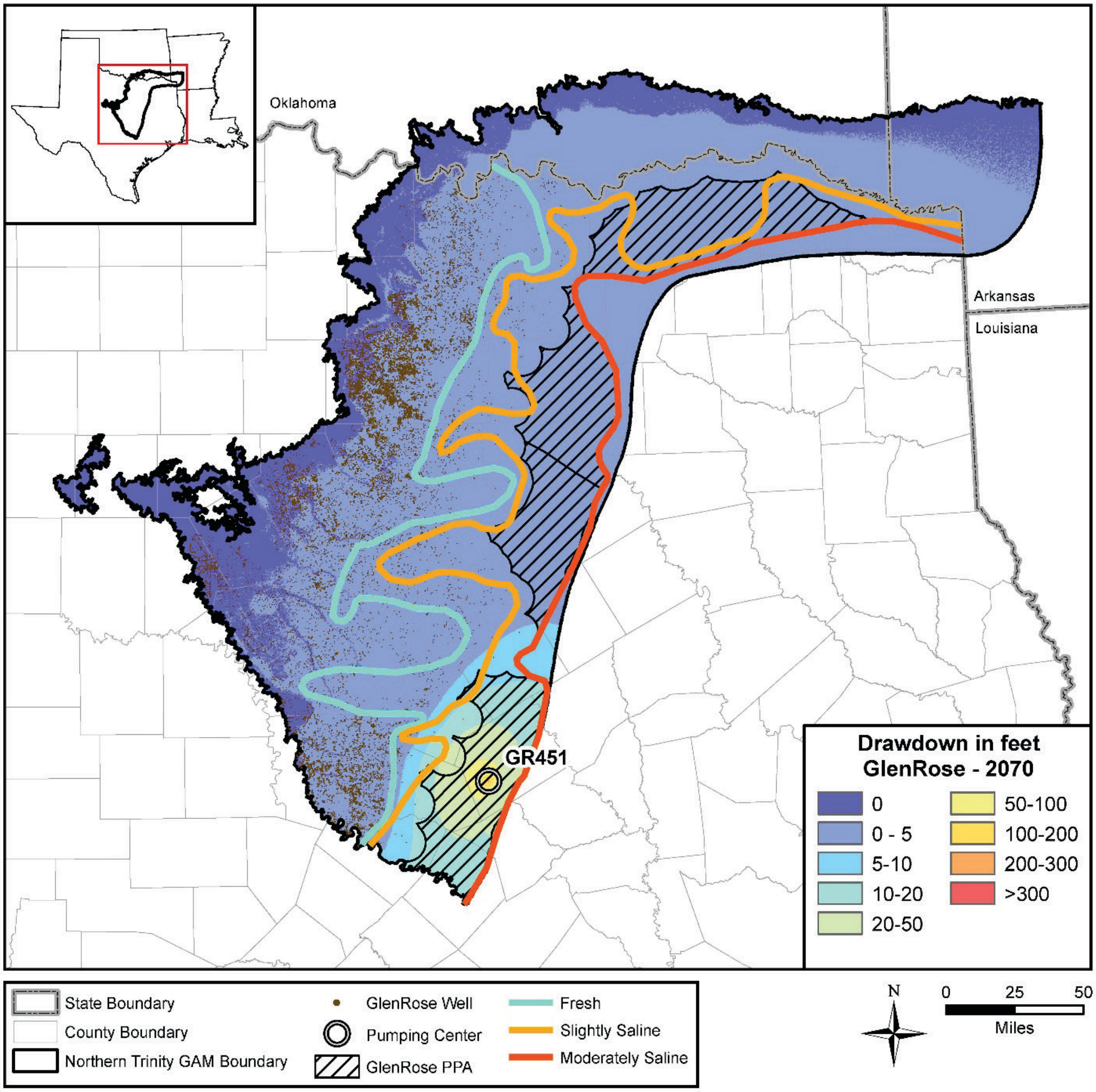


Figure 11-7 **Estimated drawdown from wellfield GR451 in the Glen Rose hydrostratigraphic unit of the Northern Trinity Aquifer after 50 years of production at a rate of 581 acre-feet per year.**

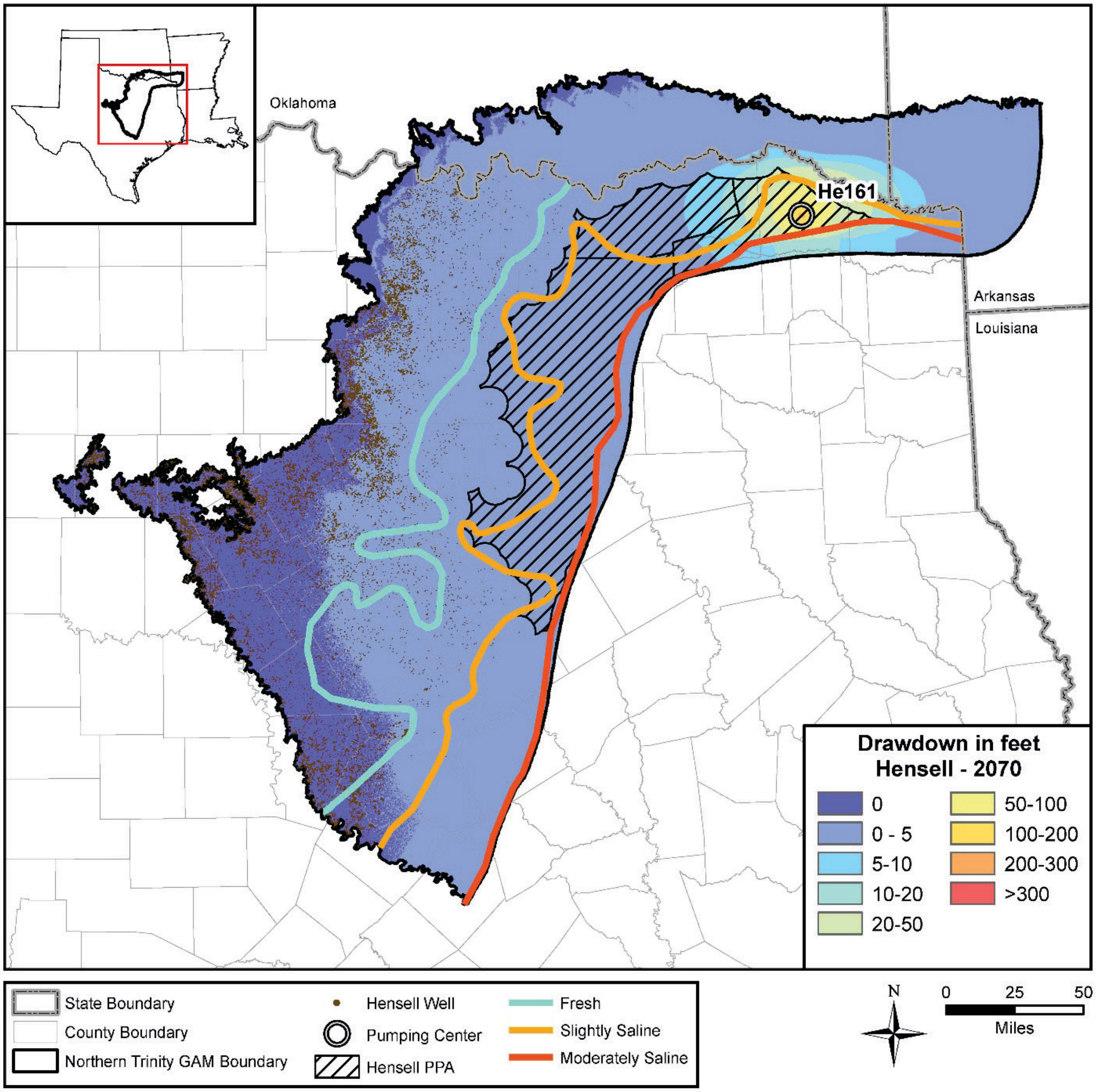


Figure 11-8 **Estimated drawdown from wellfield He161 in the Hensell hydrostratigraphic unit of the Northern Trinity Aquifer after 50 years of production at a rate of 368 acre-feet per year.**

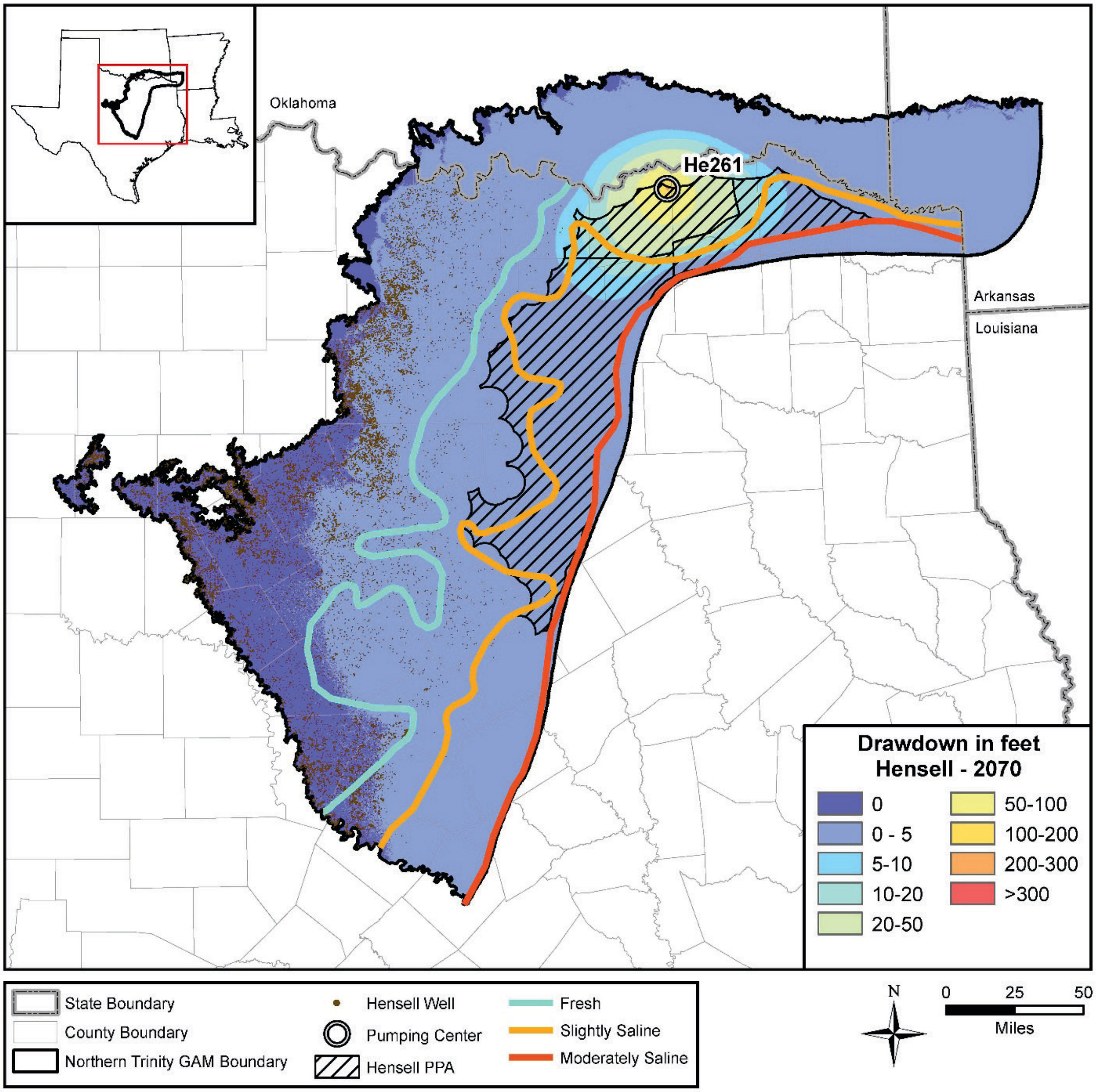


Figure 11-9 **Estimated drawdown from wellfield He261 in the Hensell hydrostratigraphic unit of the Northern Trinity Aquifer after 50 years of production at a rate of 332 acre-feet per year.**

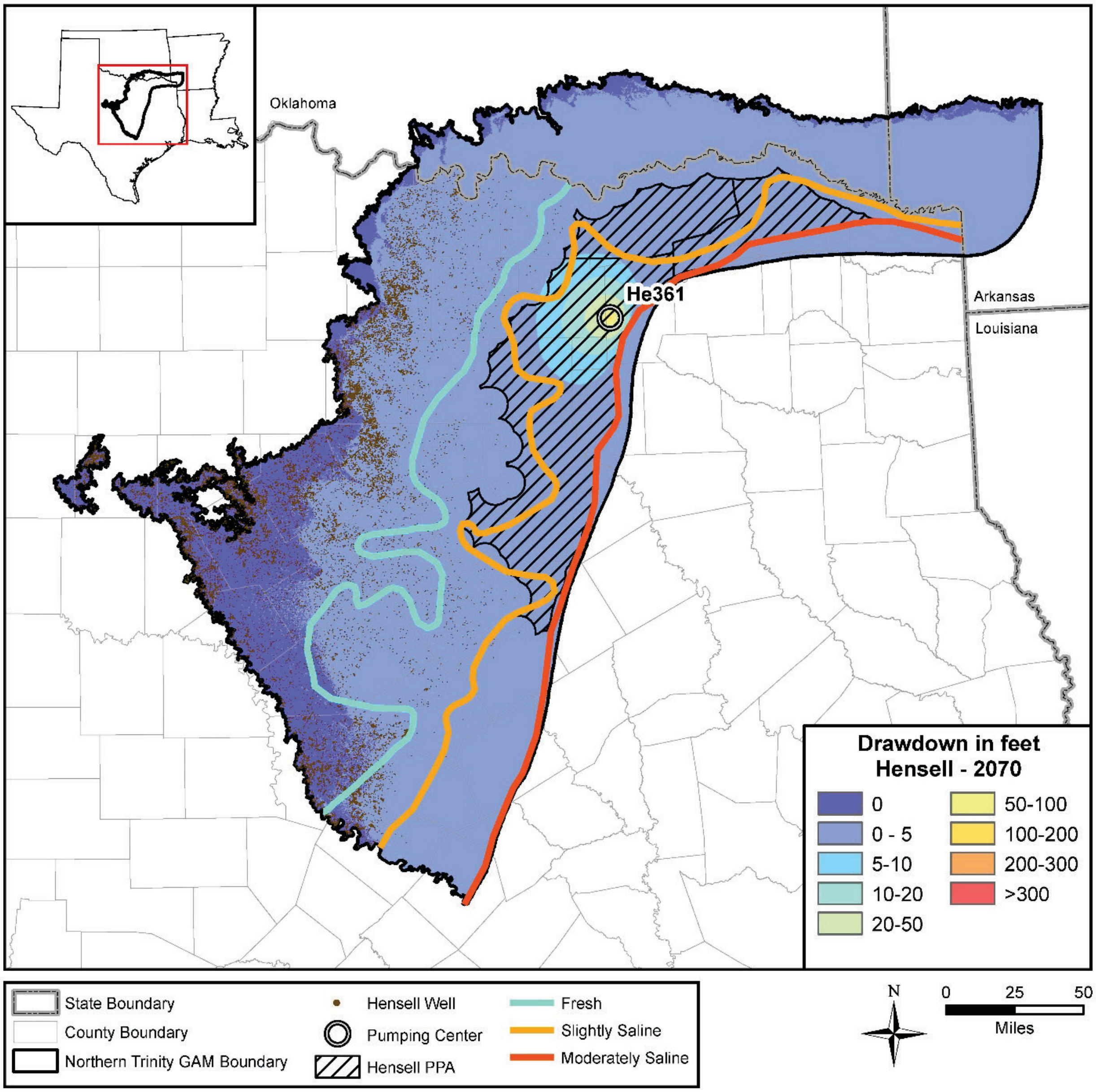


Figure 11-10 Estimated drawdown from wellfield He361 in the Hensell hydrostratigraphic unit of the Northern Trinity Aquifer after 50 years of production at a rate of 73 acre-feet per year.

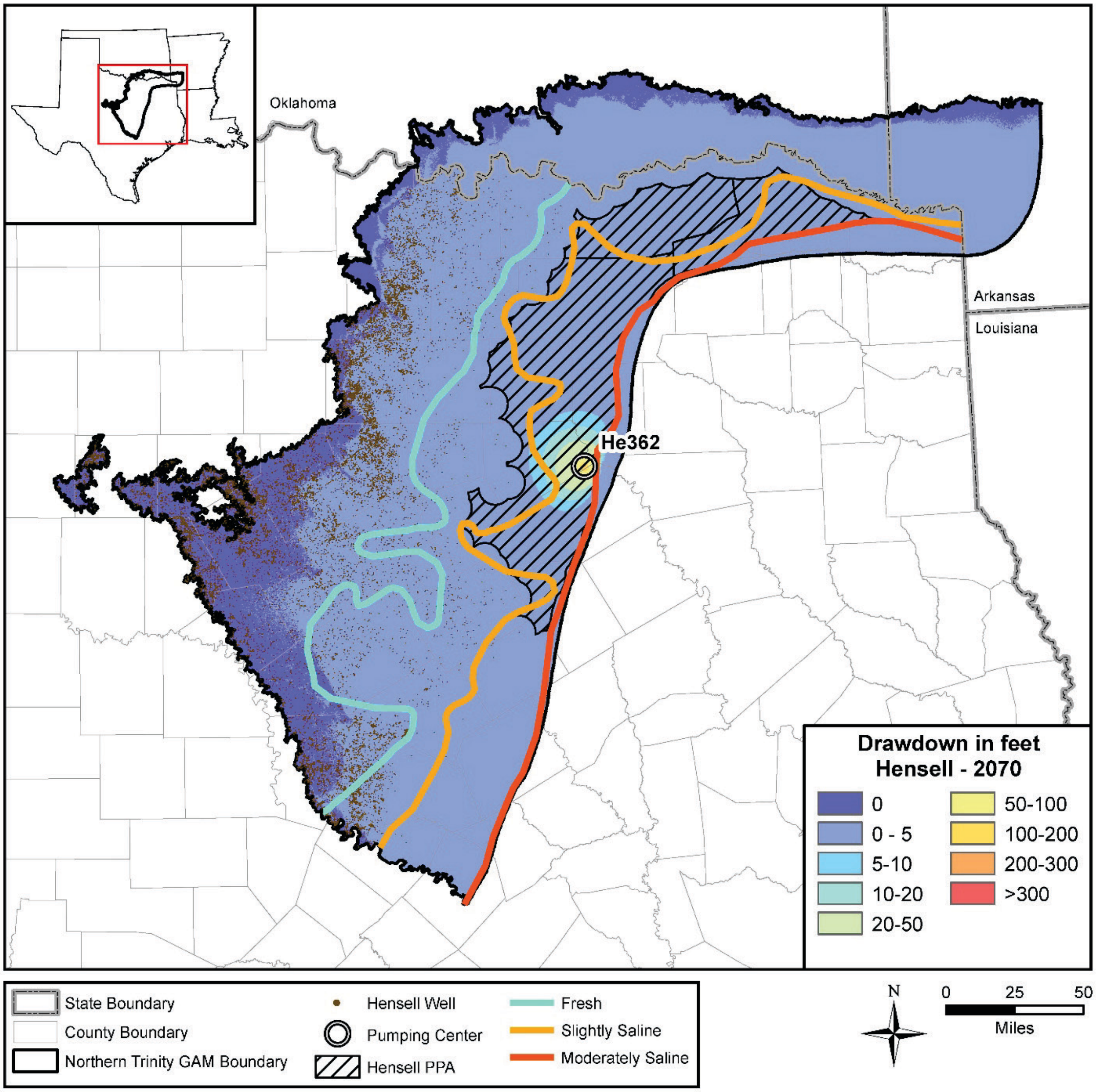


Figure 11-11 Estimated drawdown from wellfield He362 in the Hensell hydrostratigraphic unit of the Northern Trinity Aquifer after 50 years of production at a rate of 39 acre-feet per year.

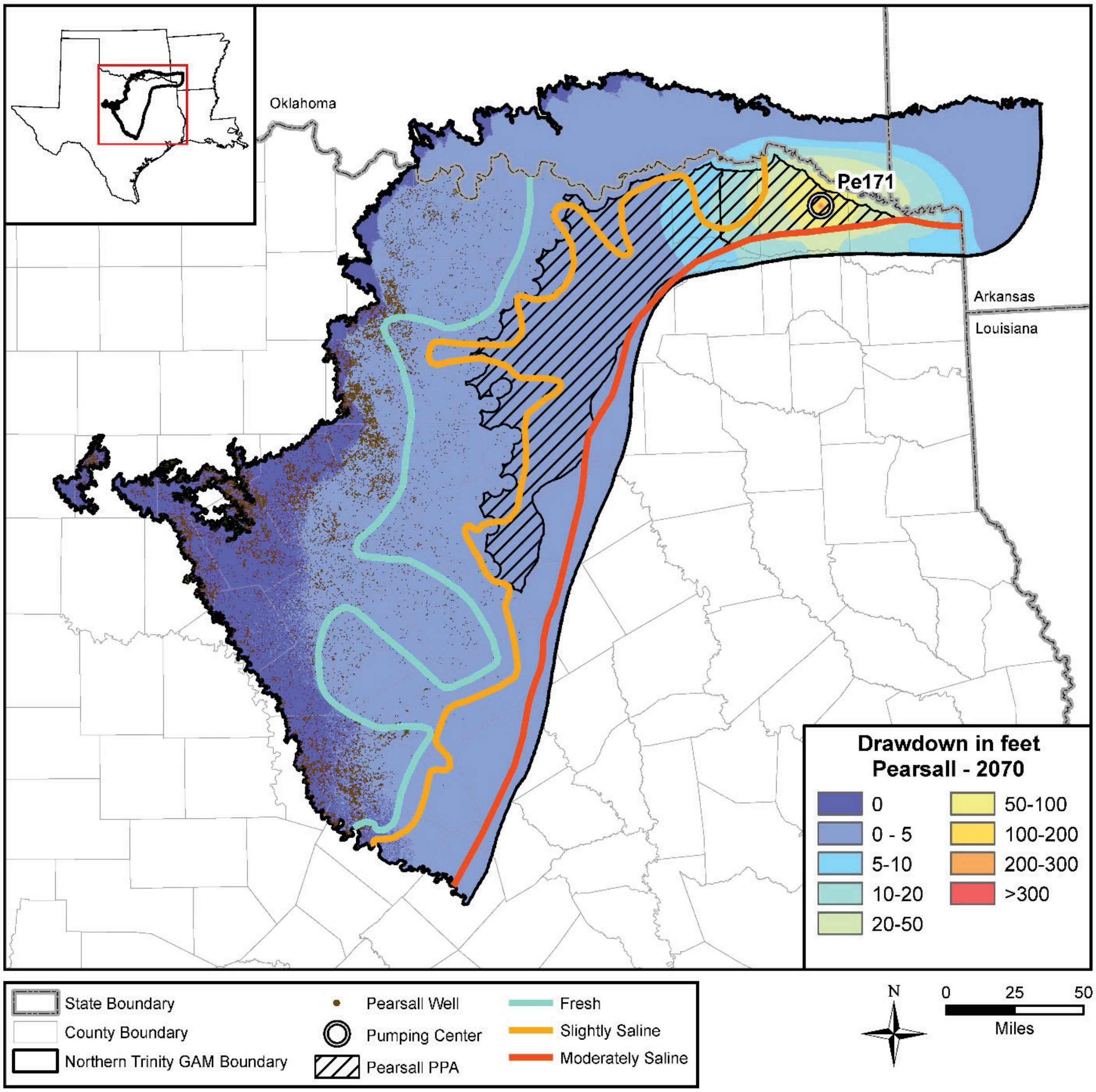


Figure 11-12 **Estimated drawdown from wellfield Pe171 in the Pearsall hydrostratigraphic unit of the Northern Trinity Aquifer after 50 years of production at a rate of 1,780 acre-feet per year.**

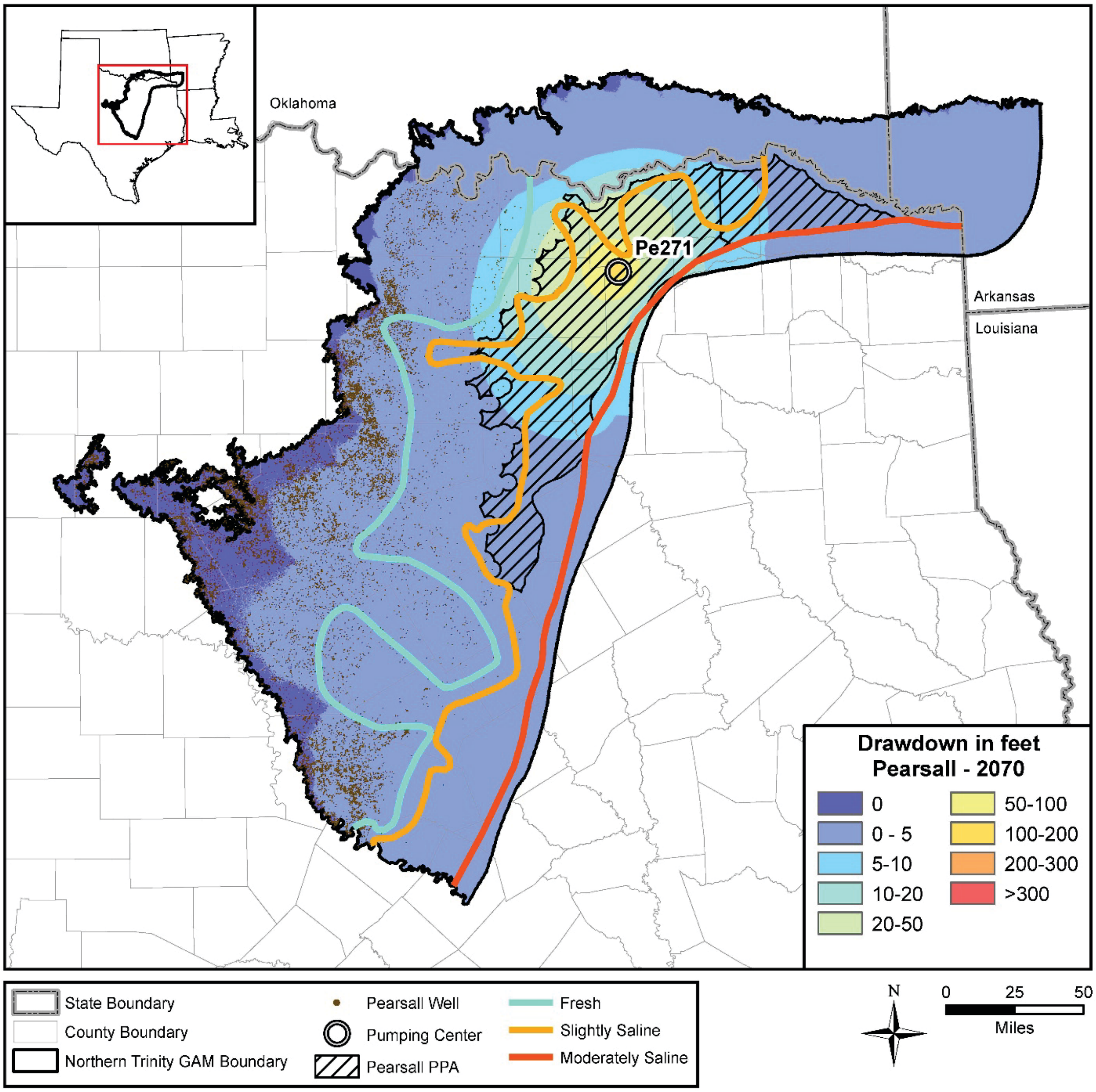


Figure 11-13 Estimated drawdown from wellfield Pe271 in the Pearsall hydrostratigraphic unit of the Northern Trinity Aquifer after 50 years of production at a rate of 1,504 acre-feet per year.

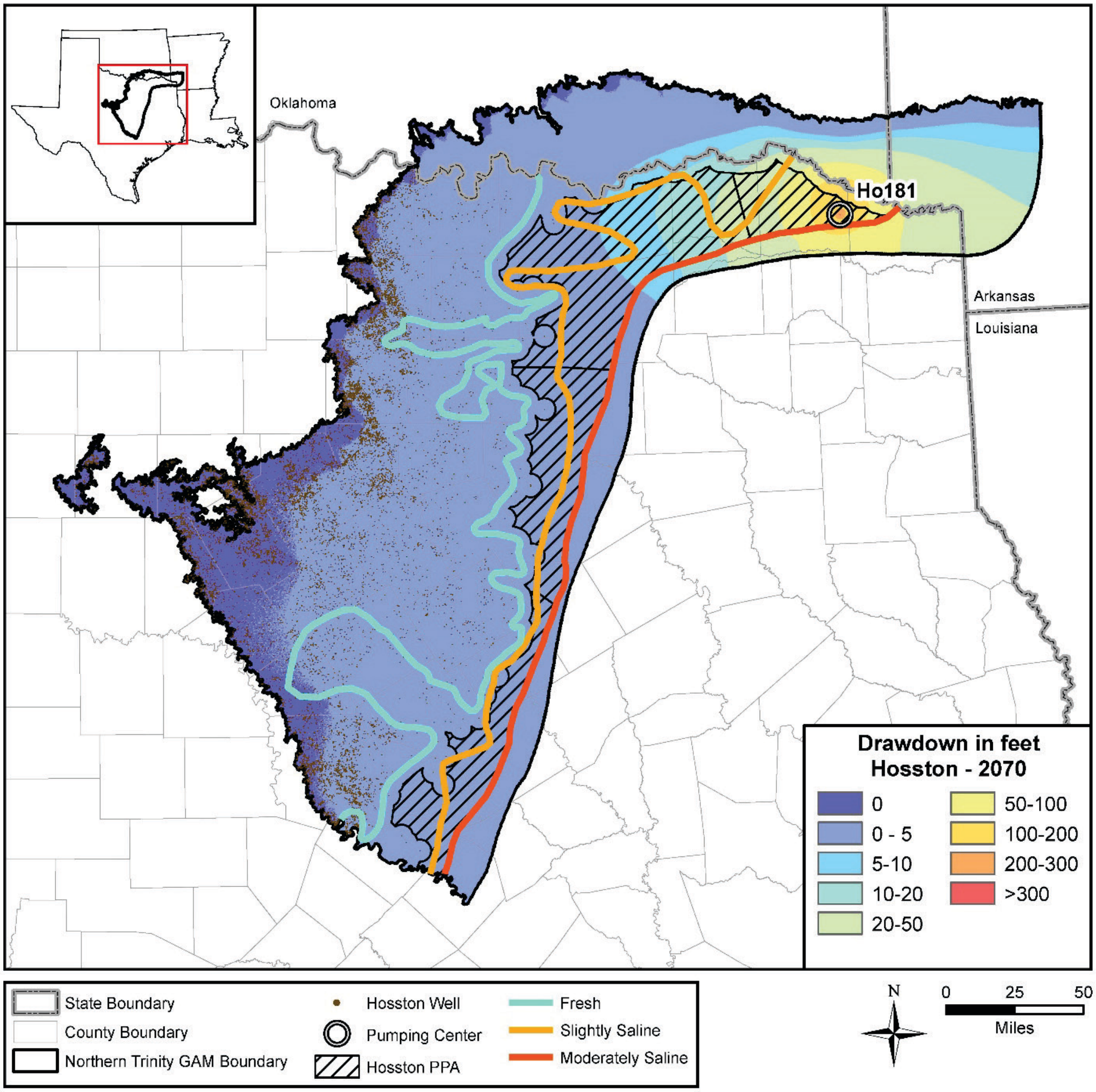


Figure 11-14 Estimated drawdown from wellfield Ho181 in the Hosston hydrostratigraphic unit of the Northern Trinity Aquifer after 50 years of production at a rate of 1,267 acre-feet per year.

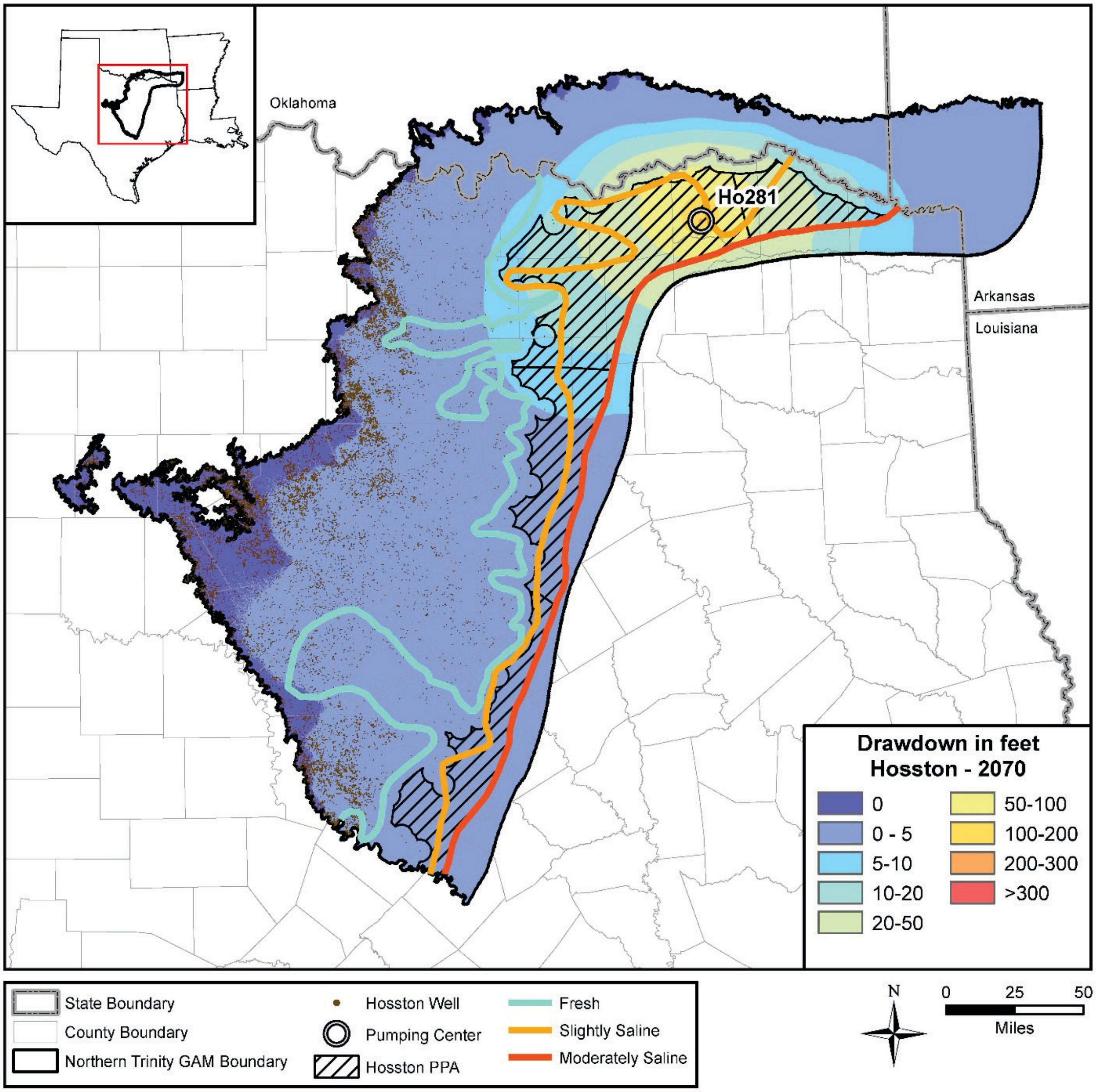


Figure 11-15 Estimated drawdown from wellfield Ho281 in the Hosston hydrostratigraphic unit of the Northern Trinity Aquifer after 50 years of production at a rate of 2,211 acre-feet per year.

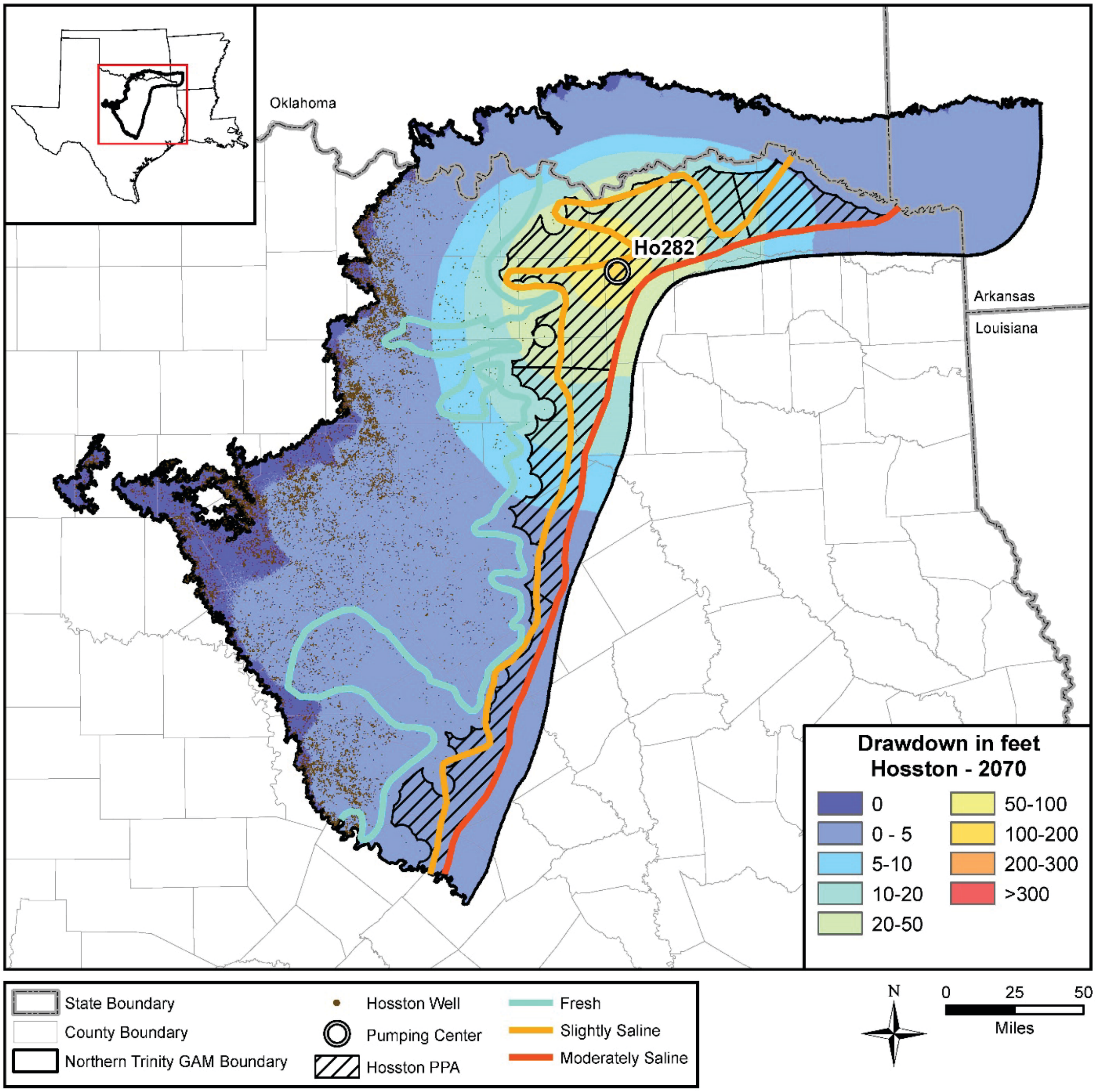


Figure 11-16 Estimated drawdown from wellfield Ho282 in the Hosston hydrostratigraphic unit of the Northern Trinity Aquifer after 50 years of production at a rate of 1,861 acre-feet per year.

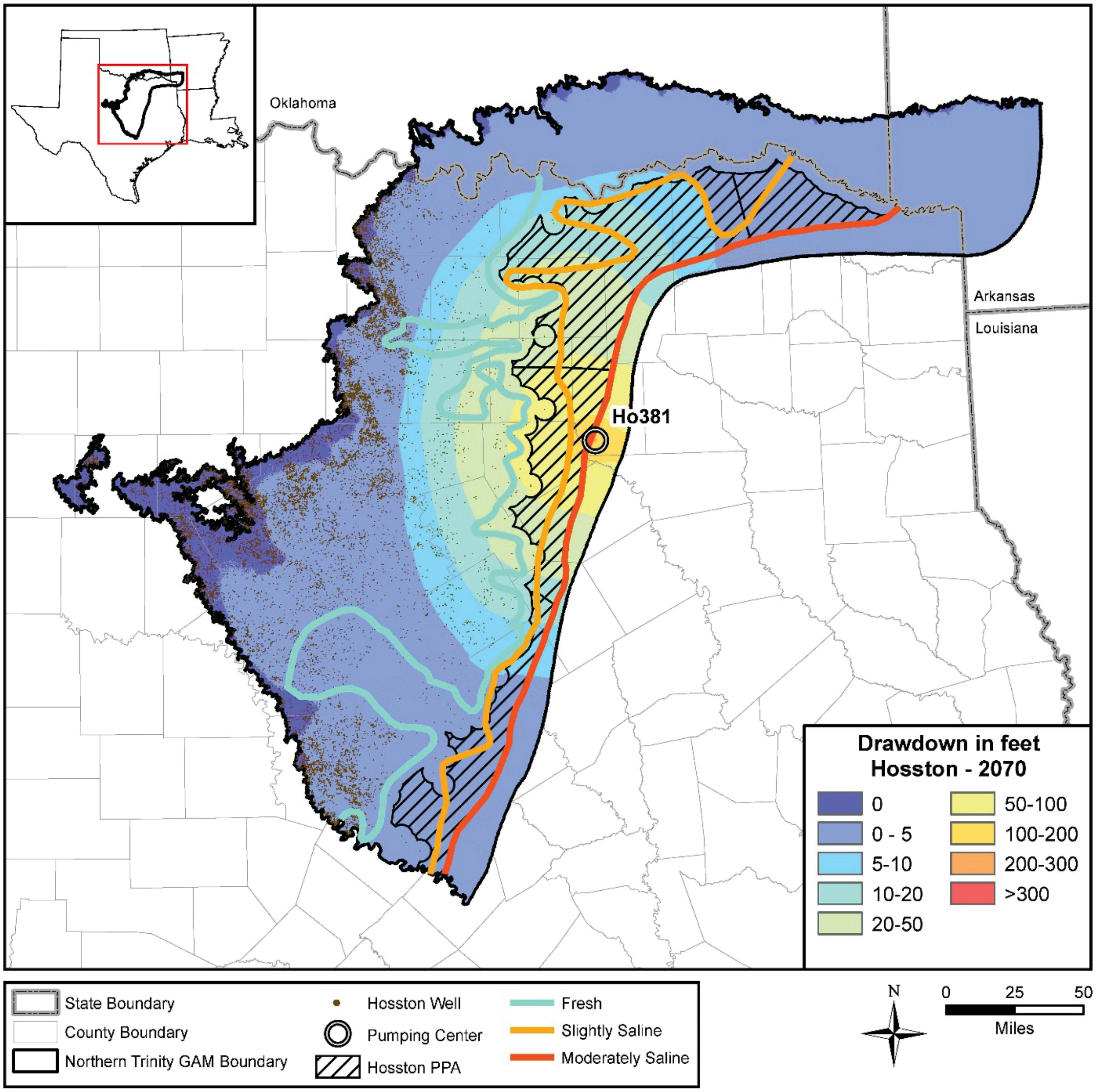


Figure 11-17 Estimated drawdown from wellfield Ho381 in the Hosston hydrostratigraphic unit of the Northern Trinity Aquifer after 50 years of production at a rate of 1,915 acre-feet per year.

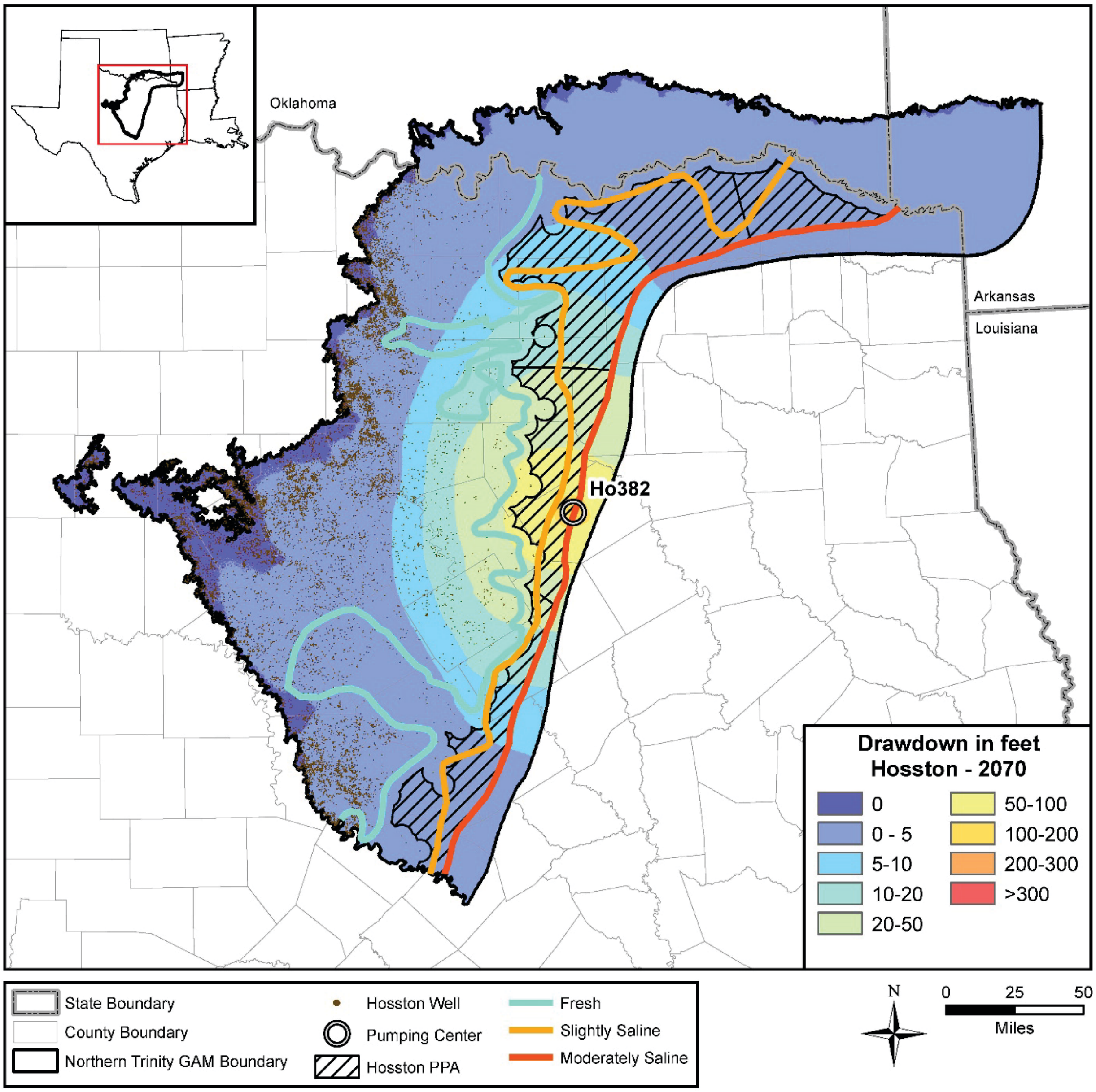


Figure 11-18 Estimated drawdown from wellfield Ho382 in the Hosston hydrostratigraphic unit of the Northern Trinity Aquifer after 50 years of production at a rate of 2,796 acre-feet per year.

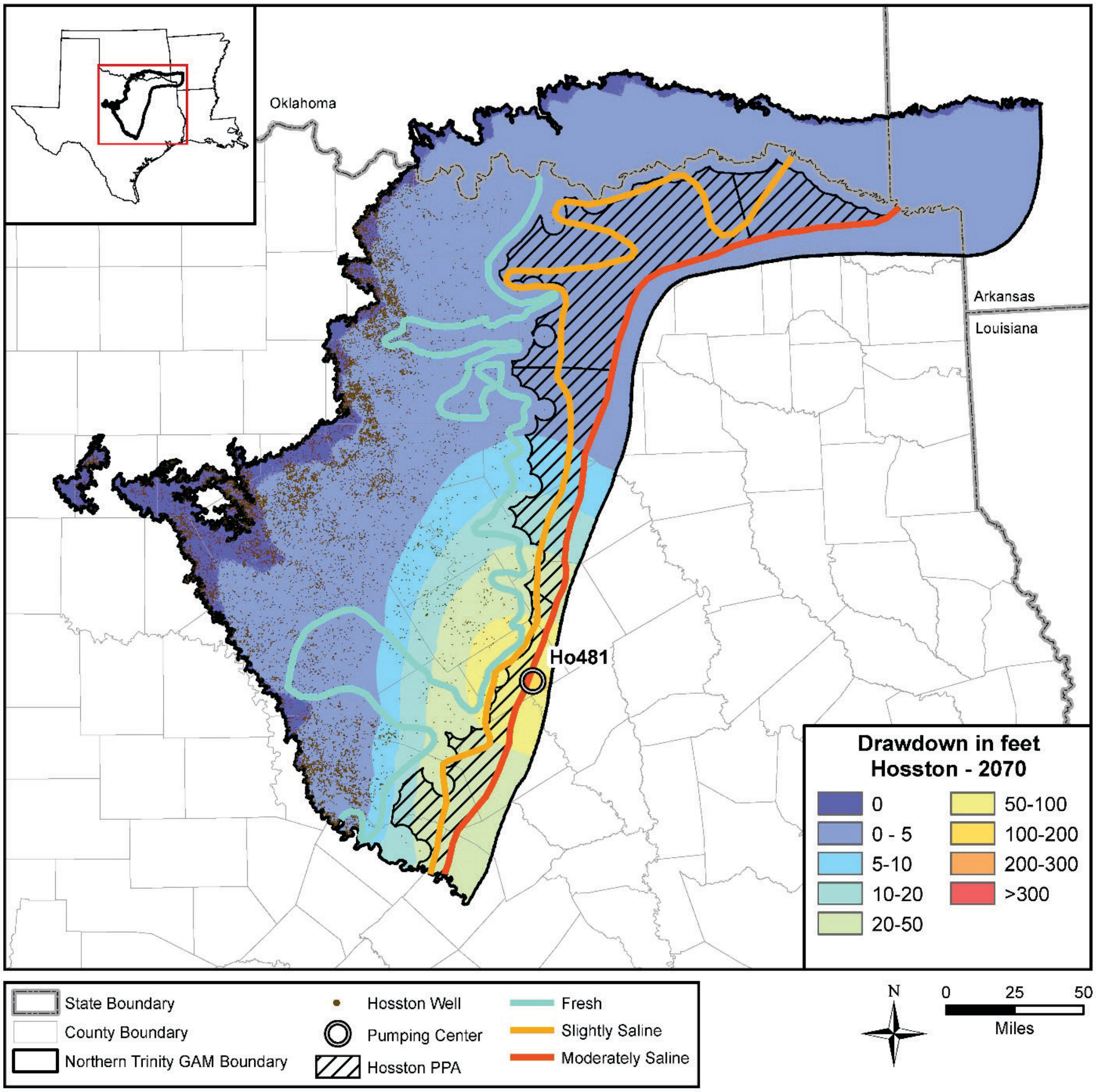


Figure 11-19 Estimated drawdown from wellfield Ho481 in the Hosston hydrostratigraphic unit of the Northern Trinity Aquifer after 50 years of production at a rate of 653 acre-feet per year.

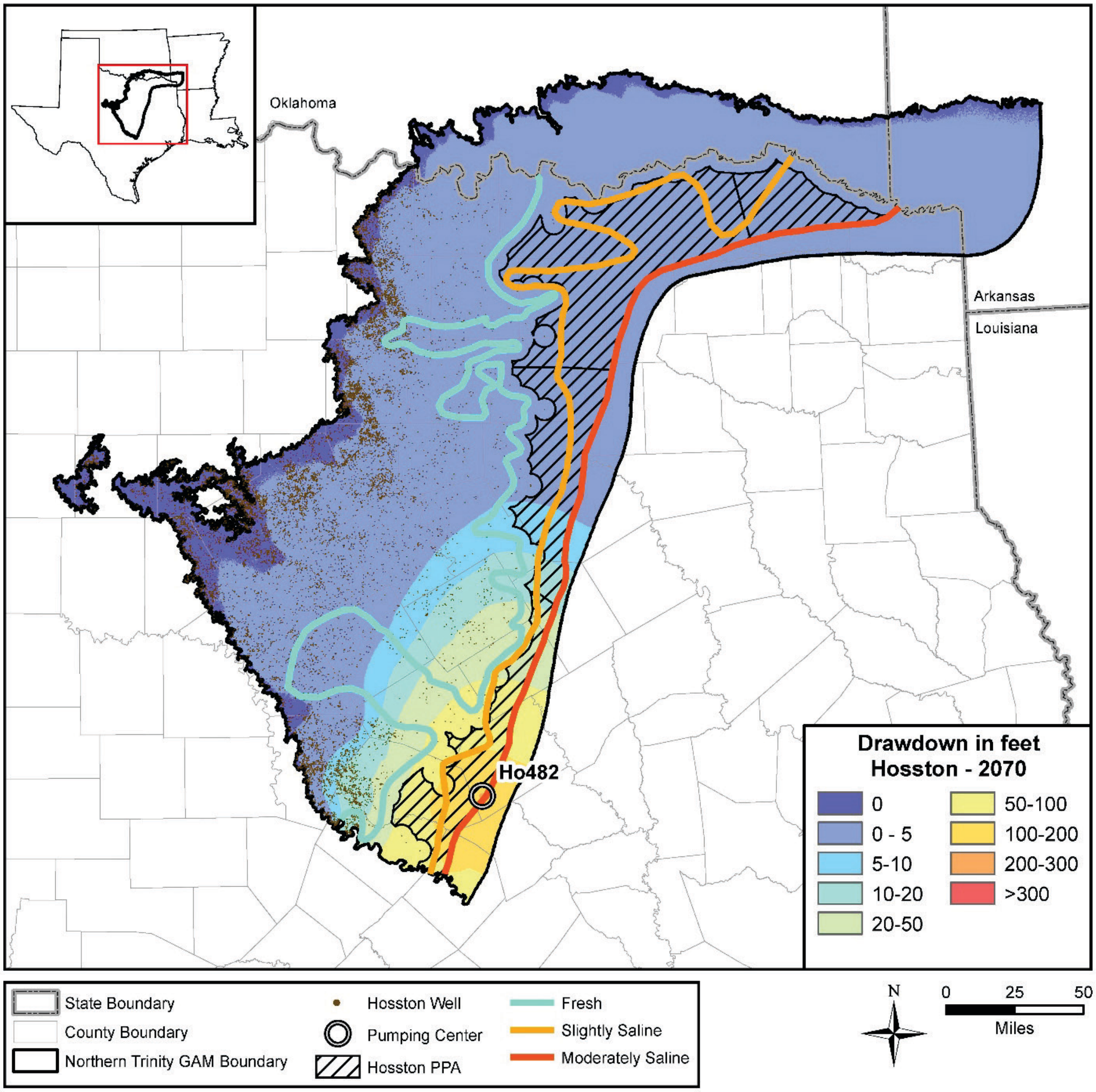


Figure 11-20 Estimated drawdown from wellfield Ho482 in the Hosston hydrostratigraphic unit of the Northern Trinity Aquifer after 50 years of production at a rate of 616 acre-feet per year.

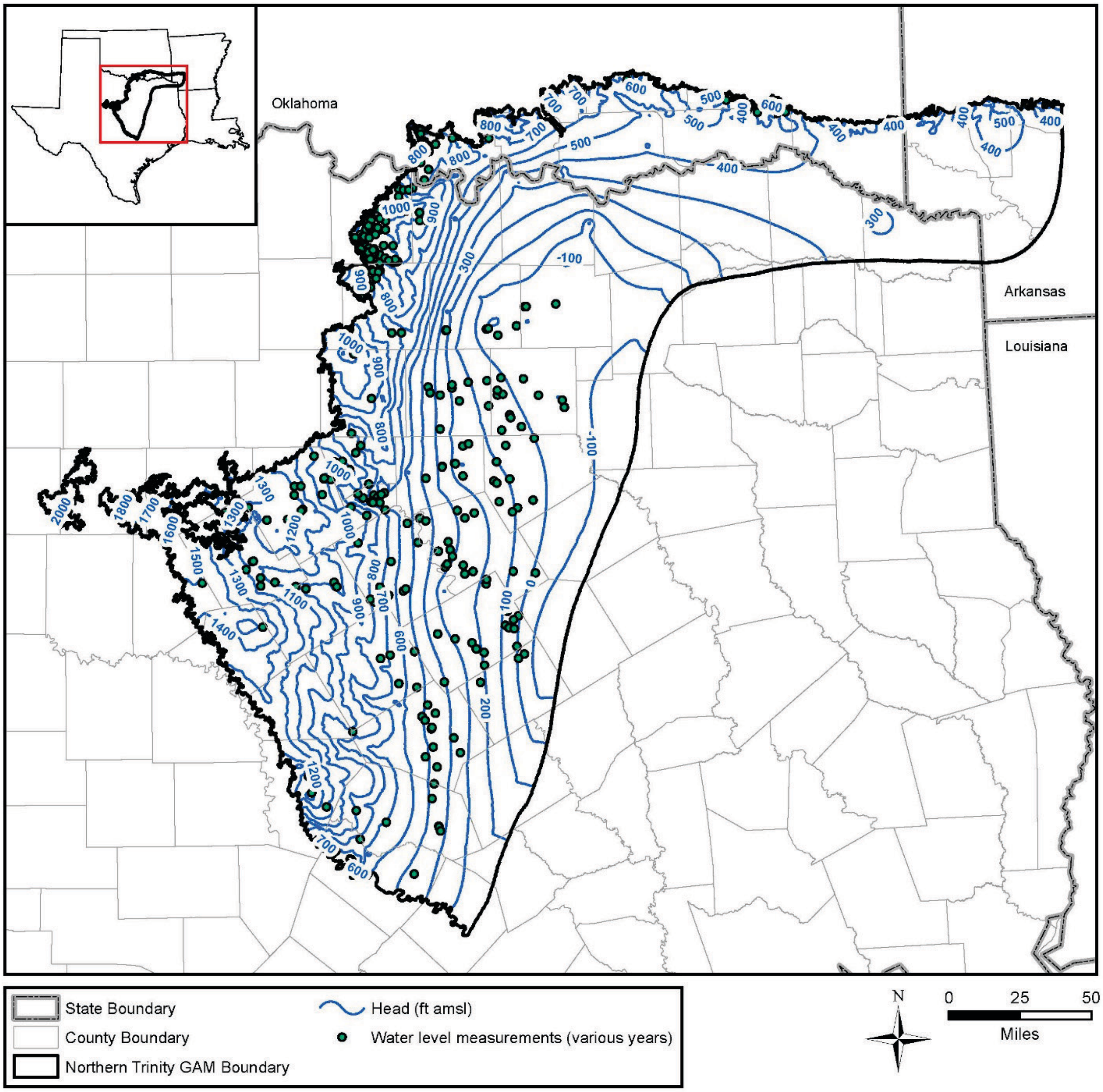


Figure 11-21 Head contours in the Hosston hydrostratigraphic unit at the end of the base case simulation. Note: ft amsl = feet above mean sea level.

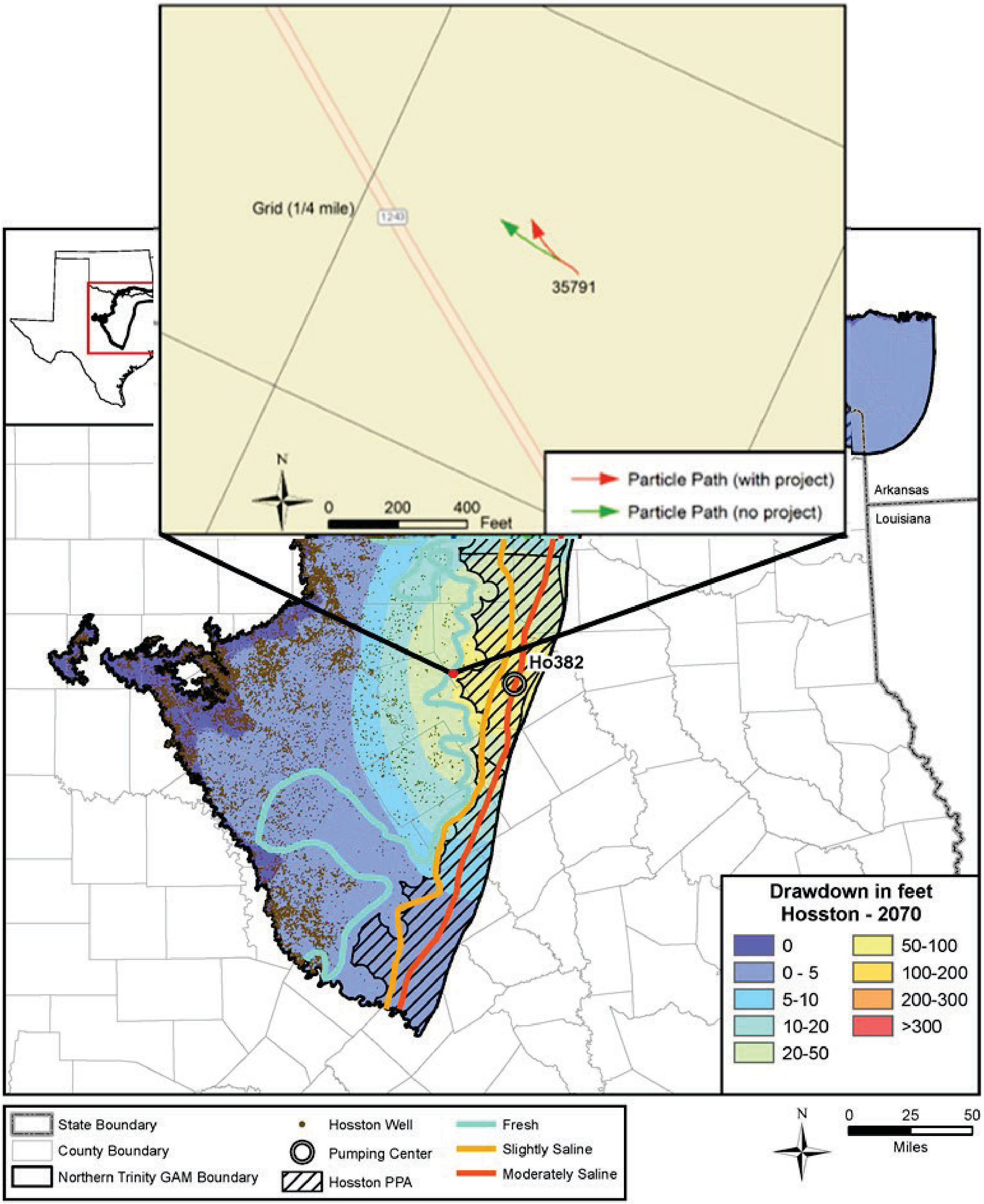


Figure 11-22 Example of particle tracks after 50 years for simulation of wellfield Ho382.

12 Conclusions

The Northern Trinity Aquifer is the northern portion of the Trinity Aquifer, which is designated by the TWDB as a major aquifer in the state of Texas. It underlies all or parts of 53 counties in central and northern Texas. The aquifer provides significant quantities of groundwater to municipal, domestic, industrial, and agricultural users throughout a large area of the state. The Northern Trinity Aquifer is composed of five water-bearing hydrostratigraphic units: (1) Paluxy, (2) Glen Rose, (3) Hensell, (4) Pearsall, and (5) Hosston.

Much of the material presented in this study was developed under contract with the TWDB to support work authorized under House Bill 30, passed by the 84th Texas Legislature (2015). This bill requires the TWDB to identify and designate brackish groundwater production zones in Texas aquifers. The Trinity Aquifer was selected for a contracted study by TWDB staff because of its complexity. The objective of this study is to characterize the quantity and quality of groundwater within the Northern Trinity Aquifer and to evaluate potential production areas that can be used by TWDB staff to make recommendations to the Executive Administrator and the Board on designation of brackish groundwater production zones. On March 28, 2019, the Board designated 15 brackish groundwater production zones in the Northern Trinity Aquifer based upon the potential production areas identified in this report.

In order to estimate water quality from geophysical logs, this study used the Modified Alger-Harrison Method (Alger and Harrison, 1989), also known as the Resistivity Ratio Method. This method requires resistivity values of the drilling fluid (R_m) and mud filtrate (R_{mf}) from the log header and deep (R_t) and shallow resistivities (R_{xo}) from the geophysical well log curves. The primary advantage of this method is that it does not require determination of the porosity and cementation factor. Disadvantages of this method are that it often requires adjustments of resistivity values due to tool differences and that values must be adjusted for the influence of variable water chemistry. With this study we have documented that the calculation of water quality from geophysical logs in the Northern Trinity Aquifer is very complex and requires advanced petrophysical techniques to accurately derive salinity (total dissolved solids) estimates. We hope that this study provides a foundation for these techniques.

The absence of groundwater chemistry sample data is significant and especially limiting in the downdip area of the Northern Trinity Aquifer. As a result, total dissolved solids concentrations were estimated from 123 geophysical well logs. These calculated values along with measured total dissolved solids concentrations from 2,917 water wells were used to define the salinity boundaries across the study area. These boundaries allowed us to delineate the geometry of four groundwater salinity classes in each hydrostratigraphic unit: fresh, slightly saline, moderately saline, and very saline.

We used the total dissolved solids boundaries, the geometry of the salinity zones, hydrogeologic analysis, and criteria set by House Bill 30 to identify 15 potential brackish production areas in the Northern Trinity Aquifer.

Out of the 2,061 million acre-feet of in-place groundwater that we calculated for the Northern Trinity Aquifer within the study area, 472 million acre-feet are fresh groundwater, 487 million acre-feet are slightly saline groundwater, 703 million acre-feet are moderately saline groundwater, and 399 million acre-feet are very saline groundwater. These in-place groundwater volumes are tabulated by groundwater management areas, groundwater conservation districts, and counties for each hydrostratigraphic unit in tables found in Section 9 of this report.

13 Acknowledgements

This report involved the cooperative efforts of the staff and management from both the Texas Water Development Board and INTERA, Inc. Special thanks to John Meyers, Andrea Croskrey, and Erika Mancha from the Texas Water Development Board for providing valuable technical advice and editorial input.

14 References

Alger, R.P. and Harrison, C.W., 1989, Improved fresh water assessment in sand aquifers utilizing geophysical well logs: The Log Analyst, Jan.-Feb., 1989, p. 31-44.

Alger, R.P., 1966, Interpretation of electric logs in fresh water wells in unconsolidated sediments, in Society of Professional Well Log Analysts, Tulsa, Oklahoma, 7th Annual Logging Symposium Transactions, 25 p.

Archie, G.E., 1942, The electrical resistivity log as an aid in determining some reservoir characteristics: Petroleum Transactions of AIME, vol. 146, p. 54-62.

Arps, J.J., 1953, The effect of temperature on the density and electrical resistivity of sodium chloride solutions: Petroleum Transactions, AIME, vol. 198, p. 327-330.

Ayers, W.B., Jr., and Lewis, A.H., 1985, The Wilcox Group and Carrizo Sand (Paleogene) in East-Central Texas: depositional systems and deep-basin lignite: Bureau of Economic Geology, The University of Texas at Austin, Geologic Folio No. 1, 19 p. with 30 plates.

Bateman, R.M. and Konen, C.E., 1977, Wellsite log analysis and the programmable pocket calculator: Society Professional Well Log Analysts Annual Logging Symposium, 18th, Houston, Texas, p. B1-B35.

Beach, J., Keester, M., and Konetchy, B., 2016, LBG-Guyton Associates Technical Memorandum: Results of Predictive Simulation in Support of GMA 8 Joint Planning – NTGCD GMA 8 Run 10 (January 14, 2016).

Bené, J., Harden, B., O'Rourke, D., Donnelly, A., and Yelderman, J., 2004, Northern Trinity/Woodbine groundwater availability model: Prepared for the TWDB by R.W. Harden & Associates, Inc., with Freese and Nichols, Inc, HDR Engineering, Inc., LBG Guyton Associates, USGS, and Dr. Joe Yelderman, Jr., www.twdb.texas.gov/groundwater/models/gam/trnt_n/TRNT_N_Model_Report.pdf.

Bhattacharya, J. and Walker, R.G, 1991, Allostratigraphic subdivision of the Upper Cretaceous Dunvegan, Shaftesbury, and Kaskapau formations in the subsurface of northwestern Alberta: Bulletin of Canadian Petroleum Geology, v. 39., p. 145-164.

Bigelow, E.L., 1992, Introduction to wireline log analysis: Western Atlas International, Inc., Houston, Texas, 312 p.

Blackwell, D., Richards, M., Frone, Z., Batir, J., Ruzo, A., Dingwall, R., and Williams, M., 2011, Temperature-at-depth maps for the conterminous US and Geothermal Resource Estimate: Geothermal Resources Council Transactions, v. 35, Document ID 1029452.

Bullard, F.M., 1931, The geology of Grayson County, Texas: Bureau of Economic Geology, The University of Texas at Austin, Bulletin 3125, Austin, TX.

Bureau of Economic Geology, 2012, Digital 15-minute GAT (Geologic Atlas of Texas) Quads for the State of Texas. store.beg.utexas.edu/geologic-atlas-of-texas/299-dqall4.html.

Collier, H.A., 1993a, Borehole geophysical techniques for determining the water quality and reservoir parameters of fresh and saline water aquifers in Texas, Volume I: Texas Water Development Board, Report 343, 414 p., 1 Appendix, 5 plates.

Collier, H.A., 1993b, Borehole geophysical techniques for determining the water quality and reservoir parameters of fresh and saline water aquifers in Texas, Volume II: Texas Water Development Board, Report 343, 216 p.

Collins, E.W., and Hovorka, S.D., 1997, Structure map of the San Antonio segment of the Edwards Aquifer and Balcones fault zone, south-central Texas: Structural framework of a major limestone aquifer: Kinney, Uvalde, Medina, Bexar, Comal, and Hays Counties: The University of Texas at Austin, Bureau of Economic Geology, Miscellaneous Map No. 38, scale 1:250,000, 2 sheets.

Daly, C., Halbleib, M., Smith, J., Gibson, W., Doggett, M., Taylor, G., Curtis, J., and Pasteris, P., 2008, Physiographically sensitive mapping of climatological temperature and precipitation across the conterminous United States: International Journal of Climatology, v. 28, no.15, p. 2031-2064.

Dewan, J.T., 1983, Essentials of modern open-hole log interpretation: PennWell Books.

Desai, K.P. and Moore, E.J., 1969, Equivalent NaCl determination from ionic concentrations: The Log Analyst, May-June 1969, p. 12-21.

Estepp, J.D., 1998, Evaluation of ground-water quality using geophysical logs: Texas Natural Resource Conservation Commission, unpublished report, 516 p.

Estepp, J.D., 2010, Determining groundwater quality using geophysical logs: Texas Commission on Environmental Quality, unpublished report, 85 p.

Ewing, T.E., 1990, Tectonic map of Texas scale 1:750,000, 4 sheets: Bureau of Economic Geology, The University of Texas at Austin, Austin, TX.

Fisher, W.L. and Rodda, P.U., 1967, Lower Cretaceous sands of Texas; stratigraphy and resources: The University of Texas at Austin, Bureau of Economic Geology, Report of Investigations no. 59, 116 p.

Fogg, G.E., 1980, Geochemistry of ground water in the Wilcox aquifer, in Kreitler, C.W., Agagu, O.K., Basciano, J.M., Collins, E.W., Dix, O., Dutton, S.P., Fogg, G.E., Giles, A.B., Guevara, E.H., Harris, D.W., Hobday, D.K., McGowen, M.K., Pass, D., and Wood, D.H., 1979, Geology and geohydrology of the East Texas Basin; A report on the progress of nuclear waste isolation feasibility studies: Bureau of Economic Geology (1979), The University of Texas at Austin, Geologic Circular No. 80-12, p. 73-78.

Fogg, G.E., and Blanchard, P.E., 1986, Empirical relations between Wilcox groundwater quality and electric log resistivity, Sabine Uplift area, in Kaiser, W.R. ed., Geology and Groundwater hydrology of deep-basin lignite in the Wilcox Group of East Texas: The University of Texas at Austin, Bureau of Economic Geology, Special Report No. 10, p. 115-118.

Fogg, G.E., and Kreitler, C.W., 1982, Groundwater hydraulics and hydrochemical facies in Eocene aquifers of the East Texas Basin: The University of Texas at Austin, Bureau of Economic Geology, Report of Investigation No. 127, 75 p.

Hall, W.D., 1976, Hydrogeologic significance of facies in lower Cretaceous sandstones: The University of Texas at Austin, Bureau of Economic Geology, circ. 76-1, 29 p.

Hamlin, H.S., 1988, Depositional and ground-water flow systems of the Carrizo–Upper Wilcox, South Texas: The University of Texas at Austin, Bureau of Economic Geology, Report of Investigations No. 175, 61 p.

Harbaugh, A.W., 2005, MODFLOW-2005, the U.S. Geological Survey modular ground-water model – the Ground-Water Flow Process: U.S. Geological Survey Techniques and Methods 6-A16.

Hill, R.T., 1901, Geography and geology of the Black and Grand Prairies, Texas: U. S. Geological Survey, Twenty-first Annual Report, part VII-Texas, 667 p.

Jones, P.H., and Buford, T.B., 1951, Electric logging applied to ground water exploration: Geophysics, vol. 16, p. 115-139.

Kelley, V.A., Ewing, J., Jones, T.L., Young, S.C., Deeds, N., and Hamlin, S., 2014, Updated Groundwater Availability Model of the Northern Trinity Aquifer and Woodbine Aquifer: Prepared for the Texas Water Development Board, 942 p.

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: Texas Water Development Board Report 195, v. 1, 63 p.

Kwader, T., 1986, The use of geophysical logs for determining formation water quality: Ground Water, v. 24, no. 1, p. 11-15.

Luheshi, M.N., 1982, Estimation of formation temperature from borehole measurements: Journal of Geophysical Research, v. 74, p. 747-776.

MacCary, L.M., 1980, Use of geophysical logs to estimate water quality trends in carbonate aquifers: US Geological Survey, Water Resources Investigations 80-57, 29 p.

Meyer, J.E., 2012, Geologic characterization of and data collection in the Corpus Christi Aquifer Storage and Recovery Conservation District and surrounding counties: Texas Water Development Board, Open File Report 12-01.

Meyer, J.E., 2017, Brackish resources aquifer characterization system database data dictionary: Texas Water Development Board Open File Report 12-02, Third Edition, 170 p.

PRISM Climate Group, 2016, Prism temperature data raster map: Oregon State University. prism.oregonstate.edu.

Schlumberger, 2009, Log interpretation charts: Schlumberger, Houston, Texas.

Schlumberger, 2013, Log interpretation charts: Schlumberger, Houston, Texas.

Schultz, A.L. 1994, Review and update of the position of the Edwards aquifer freshwater/salinewater interface from Uvalde to Kyle, Texas: Edwards Underground Water District Report 94-05, 31 p.

Shi, J., Bradley, R.G., Wade, S., Jones, I., Anaya, R., and Seiter-Weatherford, C., 2014, GAM TASK 13-031: Total estimated recoverable storage for aquifers in Groundwater Management Area 8: Texas Water Development Board GAM Task Report, 41 p. www.twdb.texas.gov/groundwater/docs/GAMruns/Task13-031.pdf.

Turcan, A.N., Jr., 1962, Estimating water quality from electrical logs: U.S. Geological Survey Professional Paper 450-C, p. 135-136.

TWDB (Texas Water Development Board), 2017, Water for Texas: Texas Water Development Board State Water Plan. www.twdb.texas.gov/waterplanning/swp/2017/index.asp.

United States Geological Survey, 2016, National Elevation Dataset, nationalmap.gov/elevation.html.

Winsauer, W.O., Shearin Jr., H.M., Masson, P.H., and Williams, M., 1952, Resistivity of brine saturated sands in relation to pore geometry, AAPG Bulletin, v. 36, p. 253-277.

Winslow, A.G., and Kister, L. R., 1956, Saline-water resources of Texas: United States Geological Survey, Water Supply Paper 1363.

Young, S.C., Jigmond, M., Deeds, N., Blainey, J., Ewing, T.E., Banerj, D., Piemonti, D., Jones, T., Griffith, C., Lupton, D., Martínez, G., Hudson, C., Hamlin, S., and Sutherland, J., 2016, Identification of potential brackish groundwater production areas – Gulf Coast Aquifer System: Prepared for the Texas Water Development Board, 664 p., www.twdb.texas.gov/publications/reports/contracted_reports/doc/1600011947_InteraGulf_Coast_Brackish.pdf.

15 Appendix

15.1 Groundwater volume GIS tool documentation

As part of the study, INTERA developed a series of Python scripts to calculate in-place volumes for each aquifer unit and groundwater salinity class considered in the analysis, as well as to output this data in report format. This appendix discusses the groundwater volume calculation, the data inputs required by the scripts and the output tables generated by the scripts.

Groundwater Volume Calculation

The volume calculations are performed for each aquifer unit as explained below. Volume estimates are calculated for each cell and then tabulated in different ways by spatial units (County, GMA, GCD, PPA), water quality classes (fresh, slightly saline, moderately saline, and very saline), and hydrostratigraphic units (Paluxy, Glen Rose, Hensell, Pearsall, Hosston).

The total volume for each hydrostratigraphic unit is estimated as follows.

If Aquifer is Outcrop

$$\text{Volume(unconfined)}_{aq} = (\text{WL}_{aq} - \text{Bottom}_{aq}) \text{ x } \text{Area}_{cell} \text{ x } \text{Sy}_{aq}$$

$$\text{Volume(confined)}_{aq} = 0$$

$$\text{Volume(total)}_{aq} = \text{Volume(unconfined)}_{aq} + \text{Volume(confined)}_{aq}$$

else if Aquifer is Subcrop

$$\text{Volume(confined)}_{aq} = (\text{WL}_{aq} - \text{Top}_{aq}) \text{ x } \text{Area}_{cell} \text{ x Ss x } \text{Thickness}_{aq}$$

$$\text{Volume(unconfined)}_{aq} = \text{Thickness}_{aq} \text{ x } \text{Area}_{cell} \text{ x } \text{Sy}_{aq}$$

$$\text{Volume(total)}_{aq} = \text{Volume(unconfined)}_{aq} + \text{Volume(confined)}_{aq}$$

Else

$$\text{Volume(unconfined)}_{aq} = 0$$

$$\text{Volume(confined)}_{aq} = 0$$

$$\text{Volume(total)}_{aq} = \text{Volume(unconfined)}_{aq} + \text{Volume(confined)}_{aq}$$

where:

$Area_{cell}$ = area of a single grid cell (0.0625 square miles)

aq = aquifer abbreviation:

PX = Paluxy

GR = Glen Rose

HN = Hensell

PR = Pearsall

HS = Hosston

Ss = specific storage (1/feet)

Surface = Elevation of stratigraphic unit surface (feet)

Sy_{aq} = specific yield (unitless)

Thickness_{aq}= thickness of aquifer unit (feet)

Top_{aq}= elevation of top of aquifer unit (feet above mean sea level)

WL = water level elevation (feet above mean sea level) modeled for the last year of calibration (beginning of 2010) in the Northern Trinity GAM (Kelley and others, 2014).

Python Scripts

The Electronic Deliverable contains the following five scripts that must be run in order:

1_TrinityHydroGeoTool.py

2_TrinityHydroGeoTables.py

3_CombiningAquiferFiles.py

4_Trinity_MakeReportTables_byAQ.py

5_Trinity_MakeReportTables.py

1_TrinityHydroGeoTool

Purpose:

- adds PPA and WQ zone designations to each grid cell
- calculates layer thicknesses for Paluxy, Glen Rose, Hensell, Pearsall, Hosston layers
- calculates groundwater volumes in each layer in each cell
- outputs this information as a grid feature class and table

Inputs:

- a polygon shapefile of the model grid containing the following information for each grid cell: surface elevations, water levels, and storage properties for each layer. (*Electronic_deliverable\GIS\shp\trnt_n_grid_poly082615_wElevsWLsProp.shp*)
- polygon shapefiles of Potential Production Areas for each layer (*Electronic_deliverable\GIS\shp\PPA_*<Aquifer Name>*_ALL_Final3.shp)*
- polygon shapefiles of Water Quality zones for each layer (*Electronic_deliverable\GIS\shp\WQ_Polygon_*<Aquifer Name>4.*shp*)

Outputs:

- a feature class of the model grid containing PPA and WQ zone designations, layer thicknesses, and groundwater volumes in each layer for each cell (*Electronic_deliverable\Volume_Calculator\Results\Trinity2.gdb\AOI*)
- a table containing PPA and WQ zone designations, layer thicknesses, and groundwater volumes in each layer for each cell in the model grid (*Electronic_deliverable\Volume_Calculator\Results\Trinity2.gdb\OutputGrid2*)

***2*_TrinityHydroGeoTables**

Purpose:

- tabulates groundwater volumes by categories, including water quality type, PPA, and spatial unit (County, GCD, or GMA)

Inputs:

- the output files from the script 1_TrinityHydroGeoTool.py (*Electronic_deliverable\Volume_Calculator\\Results\Trinity2.gdb*)

Outputs:

- "Table_1" .csv files for each aquifer (layer) that provides groundwater volumes tabulated by water quality zone, spatial unit (County, GCD, GMA), and PPA (*Electronic_deliverable\Volume_Calculator\Results\Table_1_by_*<Aquifer Acronym>*_PPA.csv*)

- "Table_2" .csv files for each aquifer (layer) that provides groundwater volumes tabulated by spatial unit (County, GCD, GMA) (*Electronic_deliverable\Volume_Calculator\Results\Table_2_by_*<Aquifer Acronym>*_Aquifer.csv*)
- "Table_3" .csv files for each aquifer (layer) that provides groundwater volumes tabulated by water quality zone and spatial unit (County, GCD, GMA) (*Electronic_deliverable\Volume_Calculator\Results\Table_3_by_*<Aquifer Acronym>*_WQ.csv*)
- "Table_4" .csv files for each aquifer (layer) that provides groundwater volumes tabulated by water quality zone (*Electronic_deliverable\Volume_Calculator\Results\Table_4_by_*<Aquifer Acronym>*_AquiferTotal.csv*)

3_CombiningAquiferFiles.py

Purpose:

- Combines individual groundwater volume tables by aquifer into one table for all aquifers.

Inputs:

- output "Table_2" .csv files from script 2_TrinityHydroGeoTables.py (*Electronic_deliverable\Volume_Calculator\Results\Table_2_by_*<Aquifer Acronym>*_Aquifer.csv*)
- output "Table_3" .csv files from script 2_TrinityHydroGeoTables.py (*Electronic_deliverable\Volume_Calculator\Results\Table_3_by_*<Aquifer Acronym>*_WQ.csv*)
- output "Table_4" .csv files from script 2_TrinityHydroGeoTables.py (*Electronic_deliverable\Volume_Calculator\Results\Table_4_by_*<Aquifer Acronym>*_AquiferTotal.csv*)

Outputs:

- "Table_2" combination .csv file for all aquifers (*Electronic_deliverable\Volume_Calculator\Results\Table_2_by_Aquifer_ALL.csv*)
- "Table_3" combination .csv file for all aquifers (*Electronic_deliverable\Volume_Calculator\Results\Table_3_by_WQ_ALL.csv*)
- "Table_4" combination .csv file for all aquifers (*Electronic_deliverable\Volume_Calculator\Results\Table_4_by_Aquifer_ALL.csv*)

4_Trinity_MakeReportTables_byAQ

Purpose:

- Formats output files from 3_CombiningAquiferFiles.py into report format

- outputs a .csv that corresponds to Table 9-1 in the report (table of volumes per aquifer tabulated by water quality zone)

Inputs:

- "Table_3" combination .csv file for all aquifers from 3_CombiningAquiferFiles.py (*Electronic_deliverable\Volume_Calculator\Results\Table_3_by_WQ_ALL.csv*)

Outputs:

- a .csv file that corresponds to Table 9-1 in the report (*Electronic_deliverable\Volume_Calculator\Results\Aq_forReport_gmaCheck.csv*)

5_Trinity_MakeReportTables

Purpose:

- Formats output files from 3_CombiningAquiferFiles.py into report format - outputs .csv files that corresponds to Tables 9-2, 9-3, and 9-4 in the report

Inputs:

- "Table_3" combination .csv file for all aquifers from 3_CombiningAquiferFiles.py (*Electronic_deliverable\Volume_Calculator\Results\Table_3_by_WQ_ALL.csv*)

Outputs:

- a .csv file that corresponds to Table 9-2 (table of volumes per aquifer tabulated by water quality zone and county) (*Electronic_deliverable\Volume_Calculator\Results\CountyName_forReport.csv*)
- a .csv file that corresponds to Table 9-3 (table of volumes per aquifer tabulated by water quality zone and GCD) (*Electronic_deliverable\Volume_Calculator\Results\GCD_Name_forReport.csv* and *nonGCD_forReport.csv*)
- a .csv file that corresponds to Table 9-4 (table of volumes per aquifer tabulated by water quality zone and GMA) (*Electronic_deliverable\Volume_Calculator\Results\GMA_forReport.csv*)