Draft Final Report for the Study of Brackish Aquifers in Texas – Project No. 4 – Trinity Aquifer

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1 Executive Summary

To better formulate groundwater management strategies, planners and decision makers need reliable estimates of the available fresh, brackish, and saline groundwater in Texas. House Bill 30 passed by the 84th Texas Legislative Session, 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 results to the legislature. This report documents the study of brackish water resources in the Trinity Aquifer, one of the aquifers selected for study in House Bill 30.

The purpose of this study is to provide the information necessary for the TWDB to designate brackish groundwater production zones for the Trinity Aquifer, a major aquifer that underlies all or parts of 52 counties. To meet this goal, the Southwest Research Institute® led team collected and analyzed data to define geologic structure, sand intervals, salinity zones, and potential brackish production areas.

The project developed and implemented a methodology for estimating the vertical profile of total dissolved solids concentrations using information extracted from geophysical logs. Our methodology involved using both empirically-derived and theoretically-based approaches for calculating the total dissolved solids concentrations in groundwater from the formation resistivity of sands. In order to have a consistent and reliable set of formation resistivity values from which to quantify and map estimated total dissolved solids concentrations across the Trinity Aquifer, we characterized the thickness and formation resistivities. After combining our total dissolved solid concentrations estimated from geophysical logs with measured total dissolved solids concentrations from water wells, we delineated the salinity zones in Table 1-1.

Table 1-1 Total dissolved solids concentrations for fresh, slightly saline, moderately saline, very saline, and brine zones

Salinity Zone	Total Dissolved Solids Concentrations
Fresh	Less than 1,000 mg/L
Slightly Saline	1,000 to 3,000 mg/L
Moderately Saline	3,000 to 10,000 mg/L
Very Saline	10,000 to 35,000 mg/L
Brine	>35,000 mg/L

Note: mg/L=milligrams per liter

We evaluated the salinity zones using selection criteria set forth by House Bill 30 to evaluate potential brackish production areas. Each of the potential production areas is a large area that encompasses several geological formations, spans multiple counties, and contains brackish groundwater. To evaluate the capacity of the potential production areas to produce groundwater, we developed five regional groundwater models and used them to simulate pumping from the candidate well fields located in the potential brackish production areas. Each well field was pumped at 3,000, 10,000, and 20,000 acre-feet per year for 50 years. Drawdown values at the well field and at monitoring locations were recorded after 30 years and after 50 years of pumping.

The groundwater models were based on the regional groundwater models developed by TWDB to support the joint planning in Groundwater Management Areas 8, 9, and 10. As part of our model development process, we incorporated approaches for accounting for how temperature and porosity differences with depth affect aquifer properties. Because aquifer hydraulic properties were based on limited field data in the deeper portions of the Trinity Aquifer, a sensitivity analysis of aquifer properties was performed. Sixteen different sensitivity simulations for each well field provide a range of drawdown results based on the specified variation in the aquifer hydraulic properties.

Formation structure and thickness discerned from geophysical logs were used in concert with water levels to calculate groundwater volumes by formation. The calculated groundwater volumes are listed by groundwater management area, groundwater conservation district, and county.

For our study area, we estimate that the Trinity Aquifer contains approximately 2 billion acre-feet of groundwater. This groundwater is contained in the void spaces of both the sands and clays, and the majority of the groundwater would not be recoverable or economical to produce. Out of the 2 billion acre-feet of groundwater, 552 million acre- feet is fresh water, 582 million acre-feet is slightly saline groundwater, 501 million acre-feet is moderately saline groundwater, and 470 million acre-feet is very saline groundwater.. These groundwater volumes are tabulated by groundwater management areas, groundwater conservation districts, and counties per geological formation.

2 Introduction

Groundwater is a major source of water in Texas, providing about 60 percent of the water used in the state. To better formulate water management strategies, planners and decision makers need reliable estimates of the available fresh, brackish, saline, and brine groundwater. House Bill 30, passed by the 84th Texas Legislative Session, requires the Texas Water Development Board (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, 2022. To meet these requirements, the TWDB released contracts to conduct studies of brackish groundwater in Texas aquifers. The Trinity Aquifer was one of the aquifers selected for study in House Bill 30. This report documents the study of brackish water resources in the Trinity Aquifer.

The Trinity Aquifer is a TWDB-designated major aquifer in the state of Texas and underlies all or parts of 52 counties through central Texas (Jones et al., 2011; Fratesi et al., 2014; Kelley et al., 2014) (Figure 2-1). It extends from the Oklahoma border to south-central Texas. The Trinity Aquifer is defined to include the Trinity (Hill Country) Aquifer and the Northern Trinity and Woodbine Aquifer. The Northern Trinity and Woodbine Aquifer is hereafter referred to as the Northern Trinity Aquifer. The Trinity Aquifer is designated as a major aquifer because it provides large quantities of water in large areas of the state. The Trinity Aquifer is composed of several small aquifers contained within the Trinity Group. Although referred to differently in different parts of the state, they include the Antlers, Glen Rose, Paluxy, Twin Mountains, Travis Peak, Hensell, and Hosston aquifers. These aquifers consist of limestones, sands, clays, gravels, and conglomerates. Their combined freshwater saturate thickness averages about 600 ft in south Texas and about 1,900 ft in central Texas (Figure 2-2). The Trinity Aquifer exists in outcrop and subcrop.

One objective of this study is to characterize the quantity and quality of groundwater within potential brackish groundwater production areas such that the TWDB staff will be able to make recommendation to the Executive Administrator and the Board on designation of brackish groundwater production zones. House Bill 30 provides direction to 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 utilized to reduce the use of fresh groundwater. Table 2-1 defines the criteria set forth in House Bill 30 to be used for designation of brackish groundwater production zones.

The stratigraphy of the Trinity Group is complicated (Figure 2-2), in part because of the large area that it covers. The downdip extent of the Trinity Aquifer is defined by the TWDB where the total dissolved solids (TDS) concentration in the aquifer transitions to 10,000 mg/L TDS. Groundwater flow is generally from the outcrop of the aquifer units in the north and northwest to the east or southeast, in a down-dip direction (Figure 2-1). Because the Trinity Aquifer is comprised of several individual smaller layered aquifers, the location of slightly (1,000 to 2,999 mg/L TDS)-to-moderately (3,000 to 9,999 mg/L TDS) saline groundwater within the aquifer is quite variable. Water of poor quality may be found at one location above and/or beneath another layer of good quality water. In many cases, areas may contain wells that produce slightly-to-moderately saline water adjacent to wells that produce fresh water from another zone in the Trinity Aquifer. This, along with greater distance from recharge zones, results in increasing salinities in the down-dip direction. In general, because of the poorer water quality, lower production, and increasing well depths, almost no water wells are constructed in the Trinity Aquifer down-dip, brackish water areas. There are few water-quality samples available to indicate where water quality transitions from fresh-to-brackish-to-saline. At locations where direct measurement of water quality is not available due to the lack of water wells in zones with slightly-to-moderately saline water, water quality needs to be inferred from geophysical logs for oil and gas wells which do penetrate these zones.

To evaluate the capacity of the brackish potential areas to produce groundwater, we simulated pumping from well fields located in the production areas. The study area for the Trinity Aquifer Brackish Water project incorporates two Groundwater Availability Model (GAM) regions, the Hill Country portion of the Trinity Aquifer GAM and the Northern Trinity Aquifer GAM. The impact of production of brackish water resources is modeled using different methods for the two areas. The Northern Trinity Aquifer GAM has had a recent revision which incorporated the brackish zones of the Northern Trinity Aquifer (INTERA, 2014) (Figure 7-1). For the purposes of modeling the impact of pumping in potential productions areas, the existing Northern Trinity Aquifer GAM is an appropriate tool.

For the purpose of predicting impact from pumping in potential brackish water production zones in the Hill Country portion of the Trinity Aquifer, the existing Hill Country Trinity Aquifer GAM is not adequate. The existing Hill Country Trinity Aquifer GAM does not cover the portion of the Trinity Aquifer beyond the estimated 1,000 mg/L TDS line, nor does the domain of the existing GAM extend sufficiently west (Figure 7-1). Thus, a simplified groundwater flow model of the Hill Country portion of the Trinity Aquifer was developed to evaluate the impact of production of brackish water resources. In order to perform these simulations, a MODFLOW model was developed using vertical sections to assess the impact of pumping in the Hill Country Trinity Aquifer portion of the study area. The four sides of the vertical section represent the up-dip, down-dip, top, and bottom of the brackish water zone. The vertical sections will be constructed using the geologic framework model developed during this project. Each potential production zone will be created and discretized into a two-dimensional vertical MODFLOW grid. The grid will then be extruded on both sides by adding duplicate grids with the cell width increasing with each grid slice progressing from the center or original vertical grid. Data from the existing Hill Country Trinity Aquifer GAM were used as appropriate.

The objective of the modeling is to provide the TWDB and potential users with estimates of the amount of brackish water that can be produced from potential production areas over 30-year and 50-year periods without impacting the quantity and quality of fresh-water sources. To meet these objectives, well fields in 15 potential production areas from the Northern Trinity and well fields in 5 potential production areas in the Hill Country portions of the Trinity Aquifer are simulated. A range of wellfield production rates, (e.g. 3,000, 5,000, and 10,000 afy) are simulated for a 30-year period and a 50-year period. The modeling of pumping at each well field included simulated pumping over a 50-year period using three different pumping rates and a sensitivity analysis. The sensitivity analysis included changing the modeled aquifer properties used as input to the groundwater model and documenting the resulting change in the simulated drawdowns.

To help characterize the groundwater resources in the Trinity Aquifer, groundwater volumes were estimated for different classifications of groundwater quality, including slightly and moderately saline. Formation structure and thickness discerned from geophysical logs were used in concert with water levels to calculate groundwater volumes by formation. The groundwater volumes are tabulated for groundwater management areas, groundwater conservation districts, and counties per geological formation.

Table 2-1 House Bill 30 criteria for designation of Brackish Production Zones.

Criterion Type	**Criterion 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 of Texas Water Code.
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

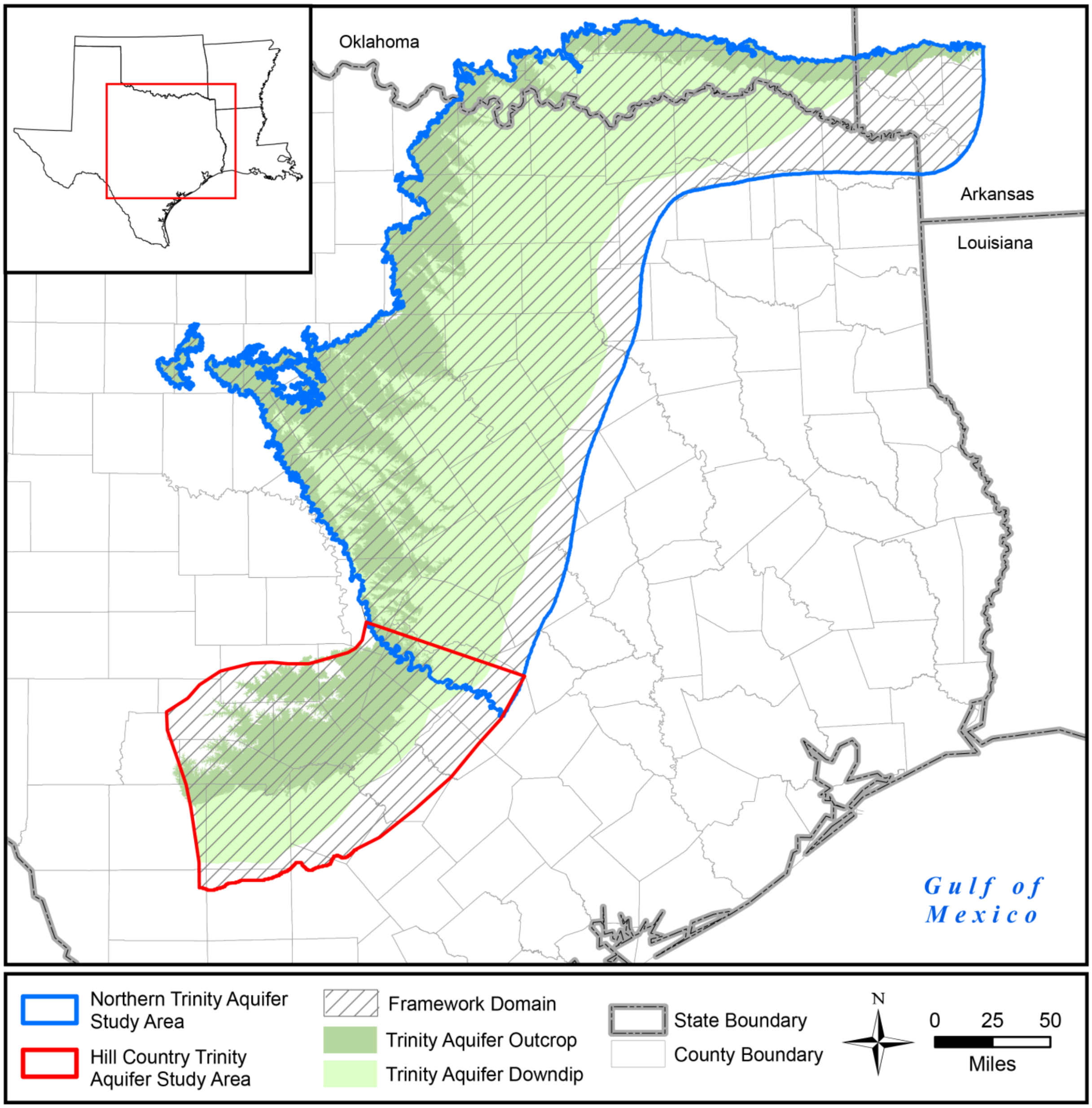


Figure 2-1 **Figure showing location and extent of the Northern Trinity Aquifer and Hill Country Trinity Aquifer study areas, the Trinity Aquifer outcrop boundary, and Trinity Aquifer downdip/subcrop boundary.**

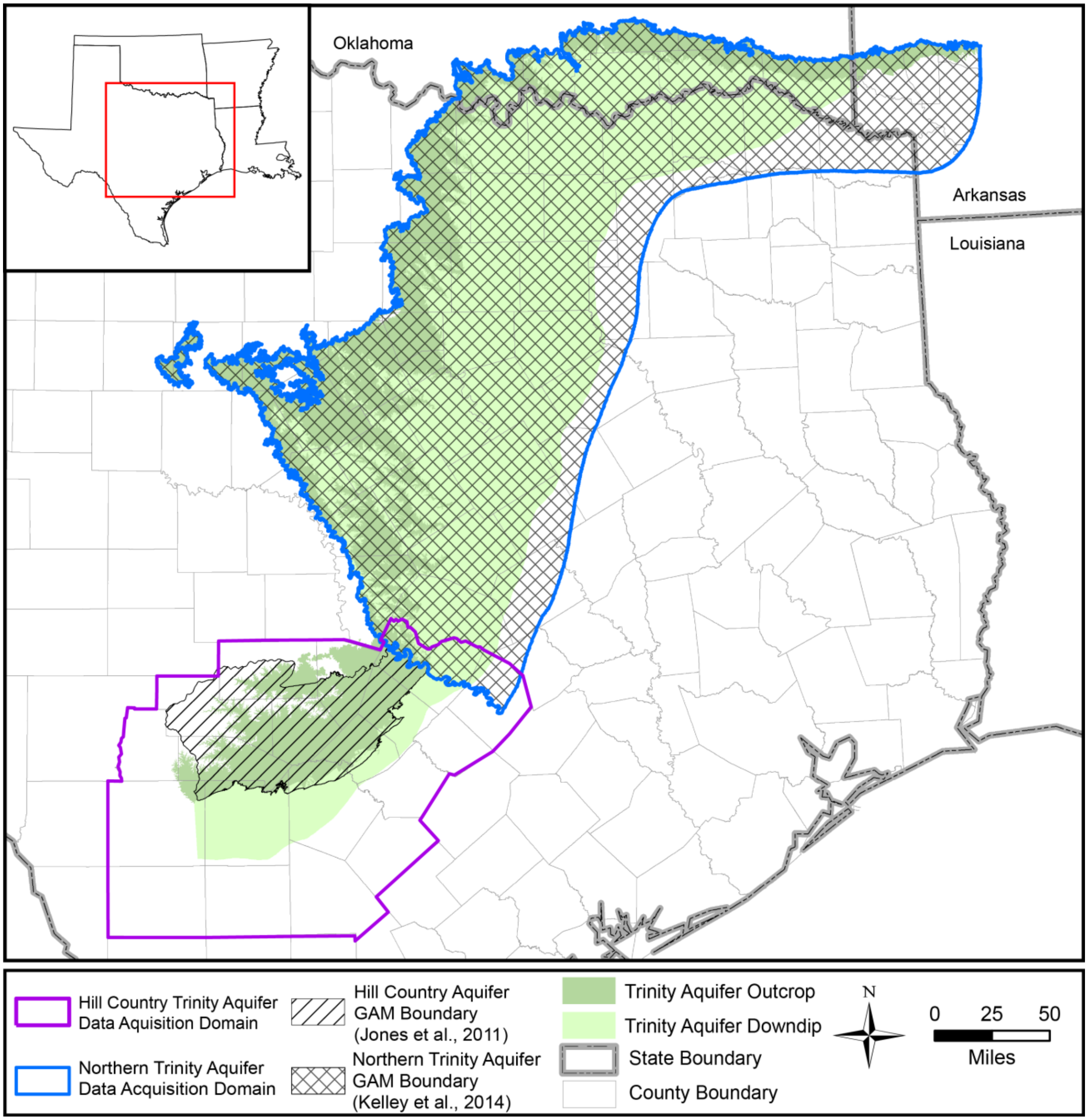


Figure 2-2 **Figure showing location and extent of the Northern Trinity , Trinity Aquifer outcrop boundary, and Trinity Aquifer downdip/subcrop boundary.**

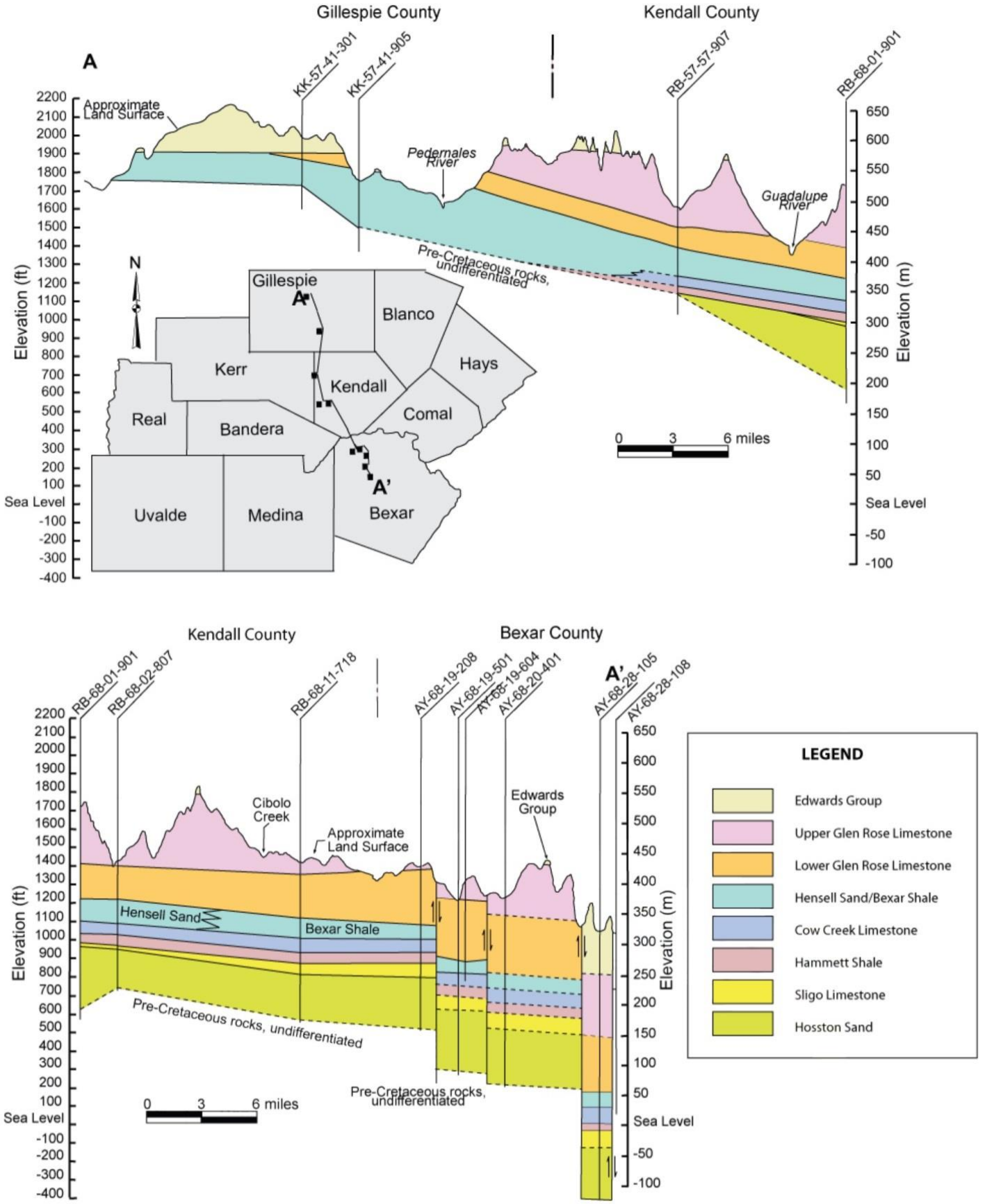


Figure 2-3 **Geologic cross section through the study area from Jones and others 2009 (modified from Ashworth, 1983; Mace and others, 2000). Inset map shows cross-section line AA′**

3 Project Deliverables

Project deliverables for this study include this report and associated ArcGIS files, as well as geophysical logs, data, and study results for inclusion in the Brackish Resources Aquifer Characterization System (BRACS) database. Information contained in this report includes a discussion of the project study area (Section 4), hydrogeologic setting (Section 5), groundwater salinity zones (Section 6), previous investigations (Section 7), data collection and analysis (Section 8), hydraulic properties (Section 9), and water quality data investigated and analyzed for this study (Section 10). In addition, the report includes discussions of the methodologies employed for net sand analysis (Section 11), calculating groundwater volumes (Section 12), analyzing geophysical logs (Section 13), evaluating potential brackish groundwater production areas, and modeling the impact of pumping from well fields located in the potential brackish production areas (Section 14). Based on the study results, our suggestions for future improvements are discussed (Section 15). The report ends with conclusions (Section 16). ArcGIS files (shapefiles and rasters) developed for this study are provided, along with metadata, in an ArcGIS file database. The information provided to the BRACS group for inclusion in the BRACS database is summarized in Table 3-1, and the contents of the geodatabases are provided in Section 19, Appendices.

Table 3-1 Information for inclusion in the Brackish Resources Aquifers Characterization System Database.

Information	**Information Type**
Digital Images of Geophysical Logs	Obtained Data
Locations of Logged Wells and Water Wells	Obtained Data
Total Dissolved Solids from Water Wells	Obtained Data
Well Identification Information	Obtained Data
Well Construction Information	Obtained Data
Calculated Total Dissolved Solids from Geophysical Log Analysis	Study Results
Stratigraphy Picks from Geophysical Log Analysis	Study Results
Hydrochemical Zone Picks from Geophysical Log Analysis	Study Results
Identification of Potential Brackish Production Areas in the Trinity Aquifer	Study Results
Development and Application of Groundwater Models to Predict Drawdown	Study Results

4 Project Area

The project area is located within seven regional water planning groups (Table 4-1, Figure 4-1) and Groundwater Management Areas 8, 9, and 10 (Figure 4-2). Contained in the project area are all or part of 32 groundwater conservation districts (Table 4-1, Figure 4-2). The study area is located in 9 major river basins and 9 river authorities (Table 4-2, Figures 4-3 and 4-4, respectively).

Table 4-1 Regional Water Planning Groups in the study area.

Group	Name
B	Region B
C	Region C
D	North East Texas
G	Brazos
J	Plateau
K	Lower Colorado
L	South Central Texas

Table 4-2 Groundwater Conservation Districts in the study area.

Bandera County River Authority & Ground Water District	Lost Pines GCD
Barton Springs/Edwards Aquifer CD	Medina County GCD
Blanco-Pedernales GCD	Middle Trinity GCD
Brazos Valley GCD	Neches & Trinity Valleys GCD
Central Texas GCD	North Texas GCD
Clearwater UWCD	Northern Trinity GCD
Comal Trinity GCD	Plum Creek CD
Cow Creek GCD	Post Oak Savannah GCD
Edwards Aquifer Authority	Prairielands GCD
Evergreen UWCD	Real-Edwards C and R District
Gonzales County UWCD	Red River GCD
Guadalupe County GCD	Saratoga UWCD
Hays Trinity GCD	Southern Trinity GCD
Headwaters UWCD	Upper Trinity GCD
Hill Country UWCD	Uvalde County UWCD
Kimble County GCD	Wintergarden GCD

Table 4-3 River basins in the study area.

Brazos River Basin	Red River Basin
Guadalupe River Basin	San Antonio River Basin
Sabine River Basin	Trinity River Basin
Sulphur River Basin	Nueces River Basin
Colorado River Basin	

Table 4-4 River Authorities in the study area.

Brazos River Authority	Central Colorado River Authority
Guadalupe-Blanco River Authority	Lower Colorado River Authority
Nueces River Authority	Red River Authority
Sabine River Authority	San Antonio River Authority
Trinity River Authority	

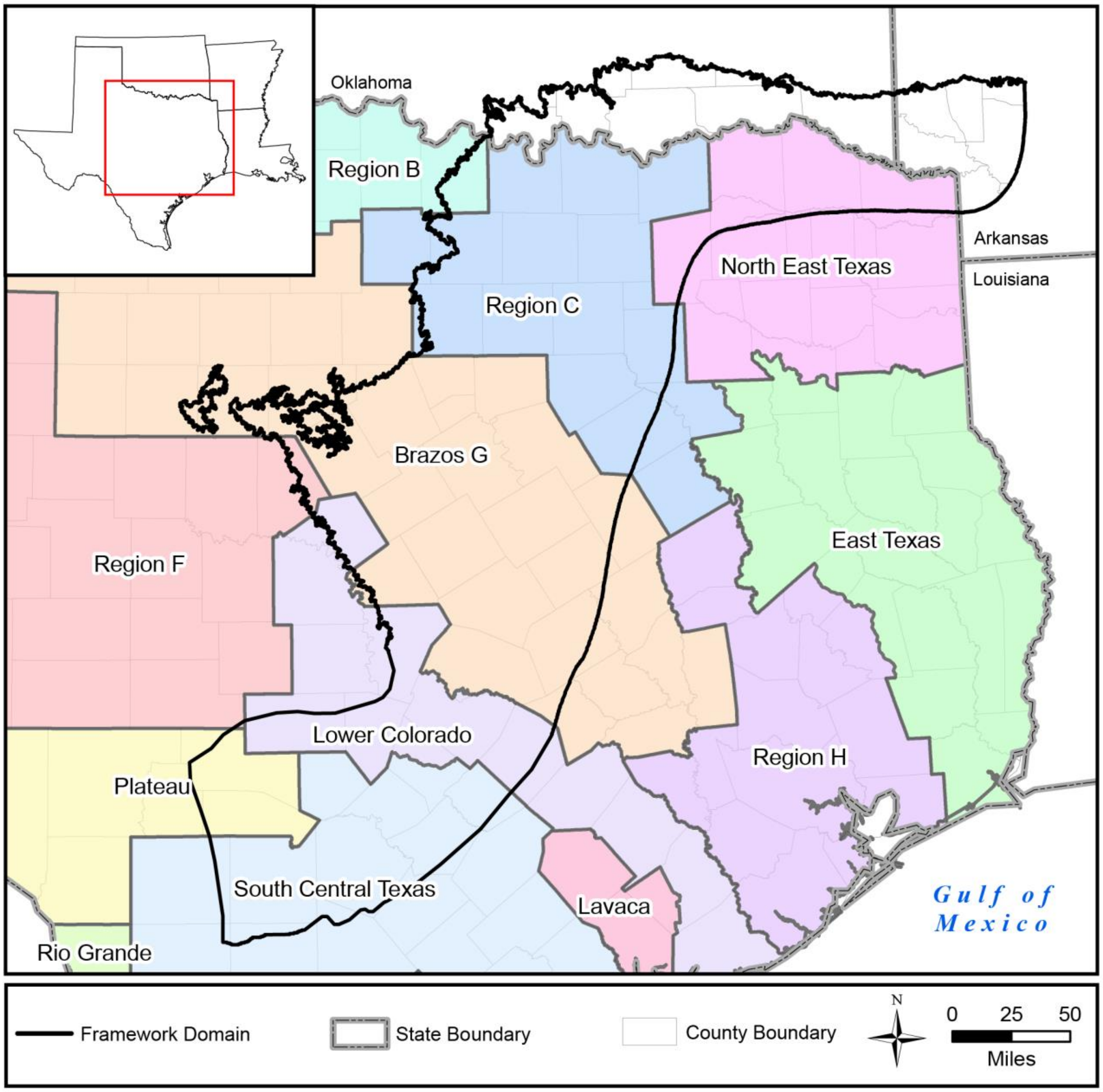


Figure 4-1 **Regional water planning groups in the study area.**

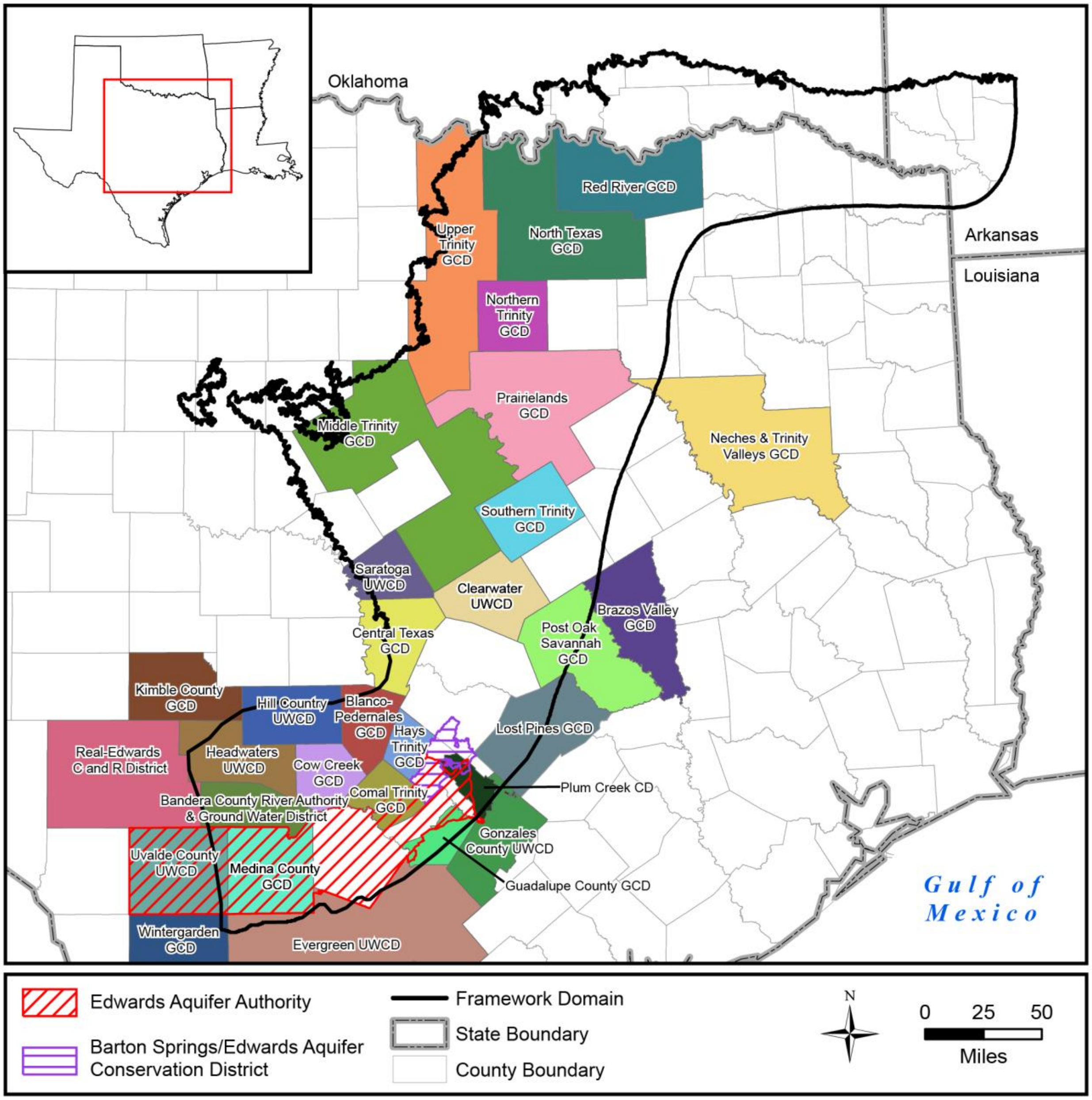


Figure 4-2 **Groundwater management areas, subsidence districts, aquifer storage and recovery district, and groundwater conservation districts in the study area. *Note*: GCD = Groundwater Conservation District; UWCD = Underground Water Conservation District**

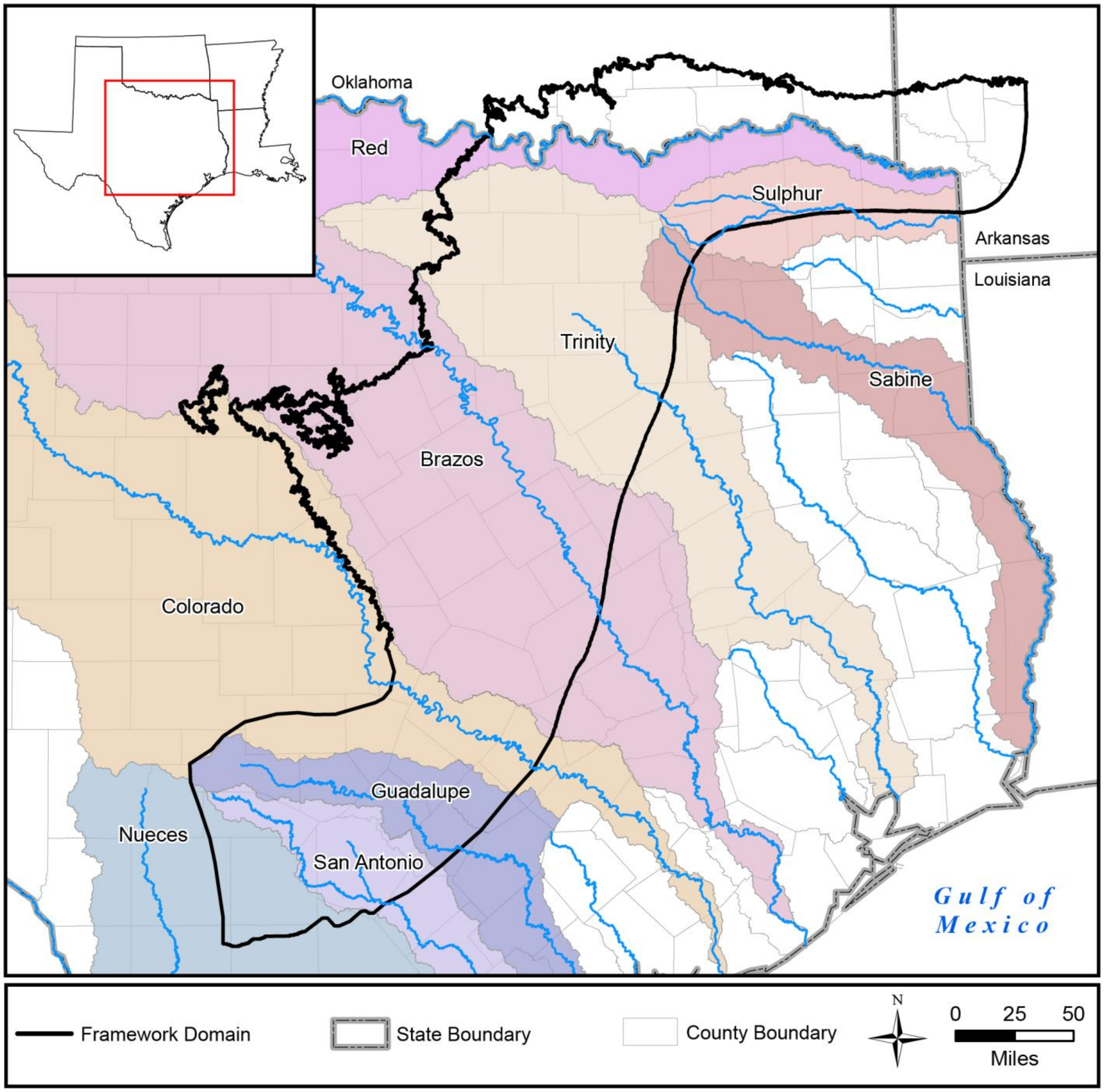


Figure 4-3 **River basins in the study area.**

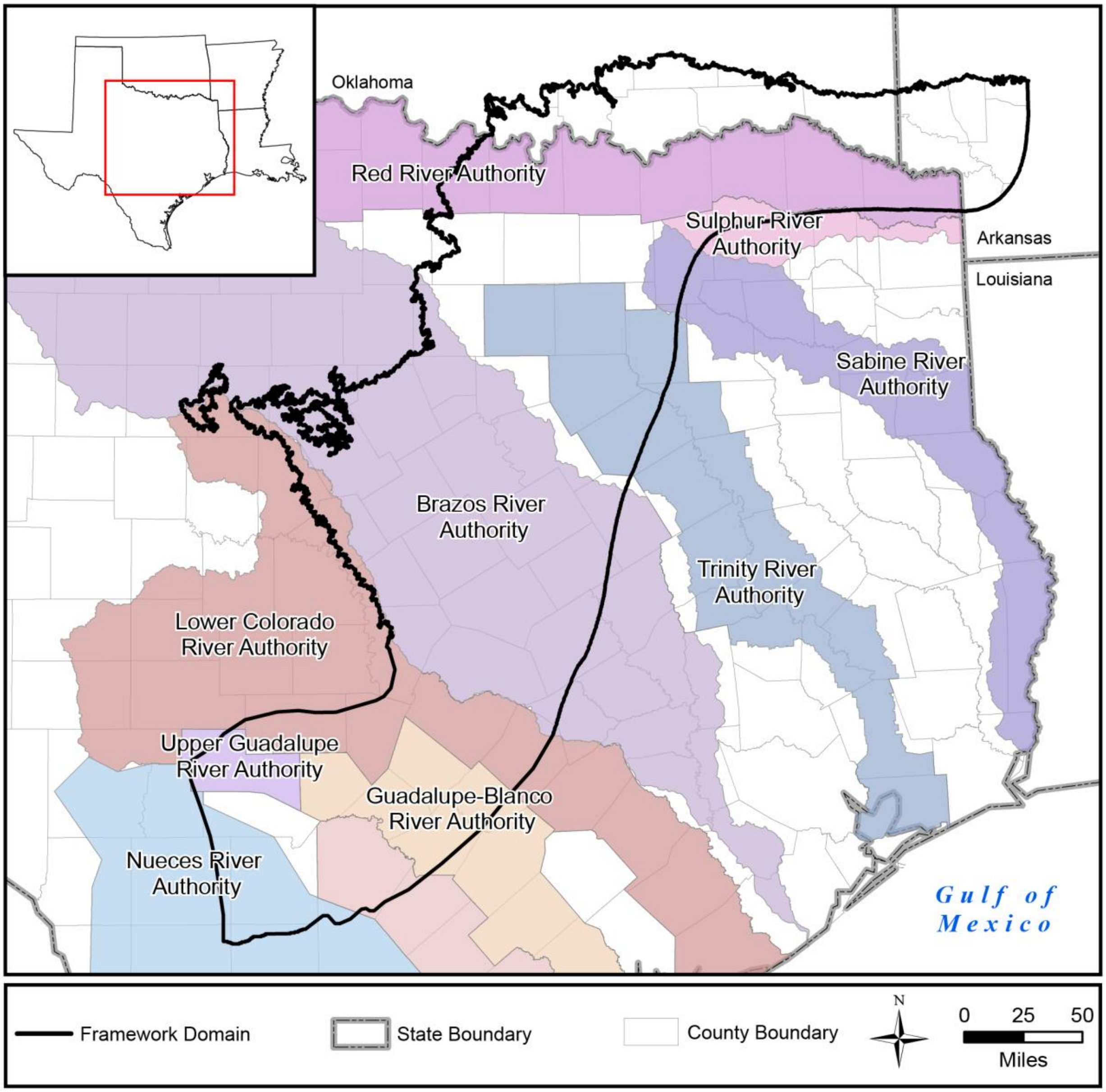


Figure 4-4 **River authorities in the study area.**

5 Geologic Setting

5.1 Trinity Aquifer Domain

The domain for this project includes the Northern Trinity and the Hill Country Trinity portions of the Trinity Aquifer. The Northern Trinity Aquifer GAM (Kelley et al., 2014) boundary extends downdip to include moderately-saline groundwater with total dissolved solids (TDS) of up to 10,000 mg/L. Because of this coverage, the project team was able to use the Northern Trinity Aquifer GAM to determine the extent of slightly saline (1,000 to 2,999 mg/L TDS) and moderately saline (3,000 to 9,999 mg/L TDS) groundwater in this region. The Northern Trinity Aquifer GAM was developed recently (i.e., 2014), therefore, there has not been significant additional information available to update the stratigraphic framework model of the Northern Trinity Aquifer. Nonetheless, additional geophysical logs that are available and relevant have been incorporated into the Northern Trinity Aquifer stratigraphic framework model as appropriate. The resulting ArcGIS database for the Northern Trinity Aquifer GAM is therefore appropriate for mapping water quality zones and calculating aquifer volumes.

The Hill Country Trinity Aquifer GAM (Jones et al., 2011) was considered in this study for use in developing the stratigraphic framework model of the Hill Country Trinity Aquifer, but due to its limited spatial extent, it was not sufficient for the needs of this project (Figure 2-2). The current Hill Country Trinity Aquifer GAM does not include in its domain the moderately saline groundwater with total dissolved solids of up to 9,999 mg/L. In addition, there is a substantial gap between the Northern Trinity Aquifer GAM domain and the Hill Country Trinity Aquifer GAM domain. Development of the stratigraphic framework for the Hill County Trinity Aquifer domain was a major task of this study. The Hill Country Trinity Aquifer domain now extends sufficiently west and downdip to include the areas with total dissolved solids of up to 10,000 mg/L, and sufficiently east and northeast to create a continuous domain between the Northern Trinity and the Hill Country Trinity Aquifers. The main sources of data for this task are well log data from the TWDB BRACS database and the Information Handling Services Markit (IHS Markit) database (refer to Section 8 for data acquisition discussion).

5.2 Geologic Units

The Trinity Aquifer, as defined in George et al. (2011), includes several smaller aquifers within the Trinity Group. These aquifers include the Antlers, Glen Rose, Paluxy, Twin Mountains, Travis Peak, Hensell, Cow Creek, and Hosston. The rocks that make up the Trinity Aquifer include lithologies such as limestone, sand, clay, gravel, and conglomerate. The Trinity Aquifer underlies more than 50 counties and consists of dozens of different named stratigraphic units. Due to the large domain and complexity of the different stratigraphic units and lithologies across the domain, this study uses different stratigraphic nomenclature for each particular region within the Trinity Aquifer domain (Figure 5-1 – Figure 5-4). The existing Northern Trinity Aquifer GAM database is used as the basis for the Northern Trinity Aquifer portion of the project domain. The Hill Country Trinity Aquifer GAM database was not particularly useful for the stratigraphic framework model because of its limited domain. Additional geological and water chemistry data are required to extend the Hill Country Trinity Aquifer portion of the model to include zones where water quality measurements exceed 1,000 TDS, as well as to fill in the model gap between the Hill Country Trinity Aquifer and the Northern Trinity Aquifer. Formation picks from geophysical logs were used to develop the stratigraphic framework model for the Hill Country portion of the Trinity Aquifer domain.

Period	Age	Age M.Y.	Group	North Formation	Central Formation		South Formation		Hill Country Formation
Cretaceous	Cenomanian		Washita	Grayson Marl	Buda		Buda		Buda
					Del Rio		Del Rio		Del Rio
				Mainstreet	Georgetown		Georgetown		Georgetown
				Pawpaw					
				Weno					
				Denton					
				Duck Creek					
				Fort Worth					
	Albian	97.0	Fredericksburg	Kiamichi	Kiamichi		Kiamichi		Edwards
				Goodland	Edwards		Edwards		
					Comanche Peak		Comanche Peak		
				Walnut Clay	Walnut Clay		Walnut Clay		
			Trinity	Antlers	Paluxy		Paluxy		Paluxy
					Glen Rose		Glen Rose		Upper Glen Rose
									Lower Glen Rose
	Aptian	112.0			Twin Mountains	Hensell	Travis Peak	Hensell	Hensell
						Pearsall		Pearsall	Cow Creek
								Cow Creek	Hammett
								Hammett	Sligo
						Hosston		Sligo	
	Pre-Aptian	124.5						Hosston	Hosston
Pre-Cretaceous	Tithonian	145.0	Pre-Cretaceous Undifferentiated	Pre-Cretaceous Undifferentiated	Pre-Cretaceous Undifferentiated		Pre-Cretaceous Undifferentiated		Pre-Cretaceous Undifferentiated

Figure 5-1 **Stratigraphic column for regional depositional domains of the Trinity Aquifer.**

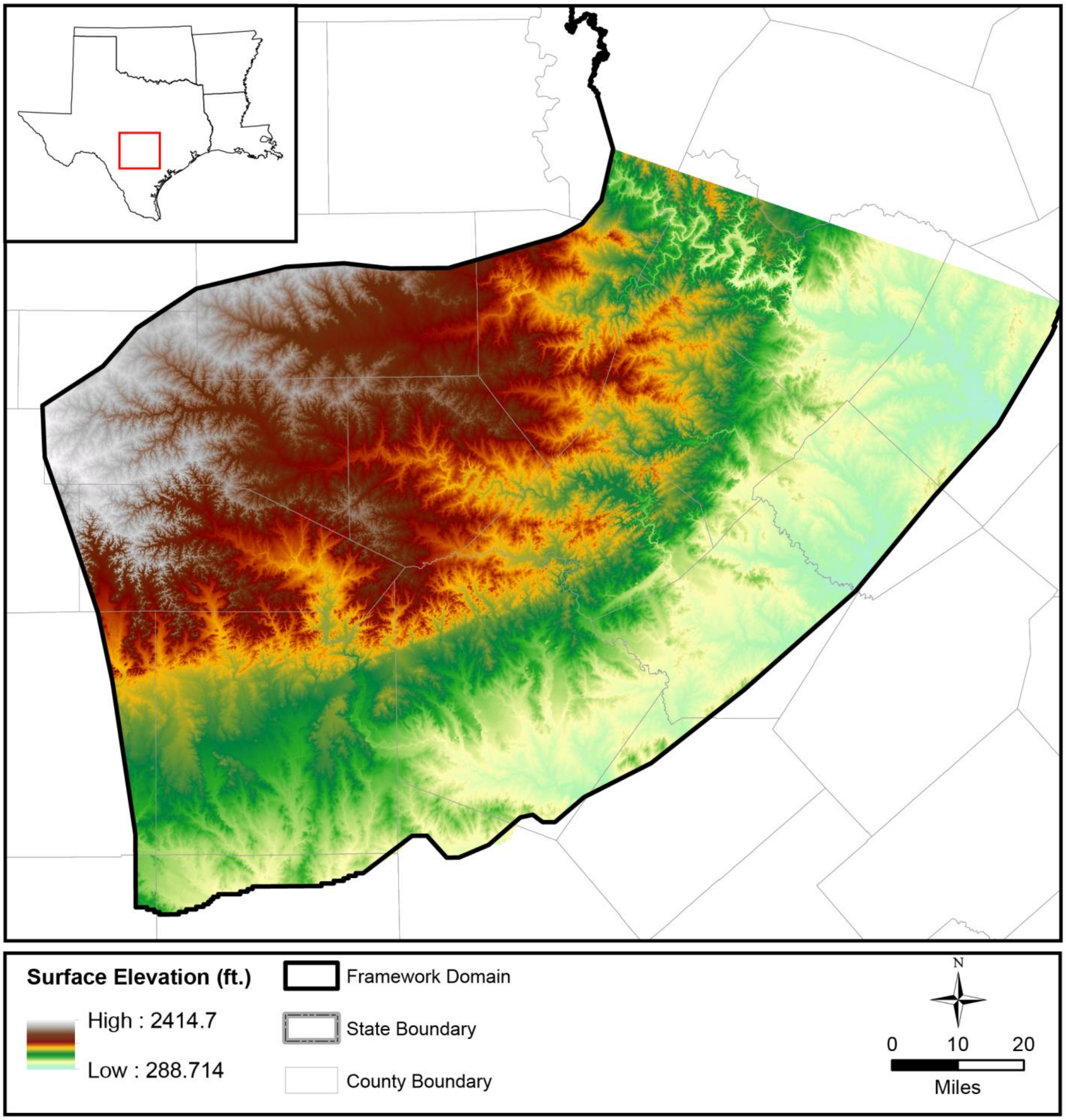


Figure 5-2 Topographic map of the study area showing land surface elevation in feet above mean sea level.

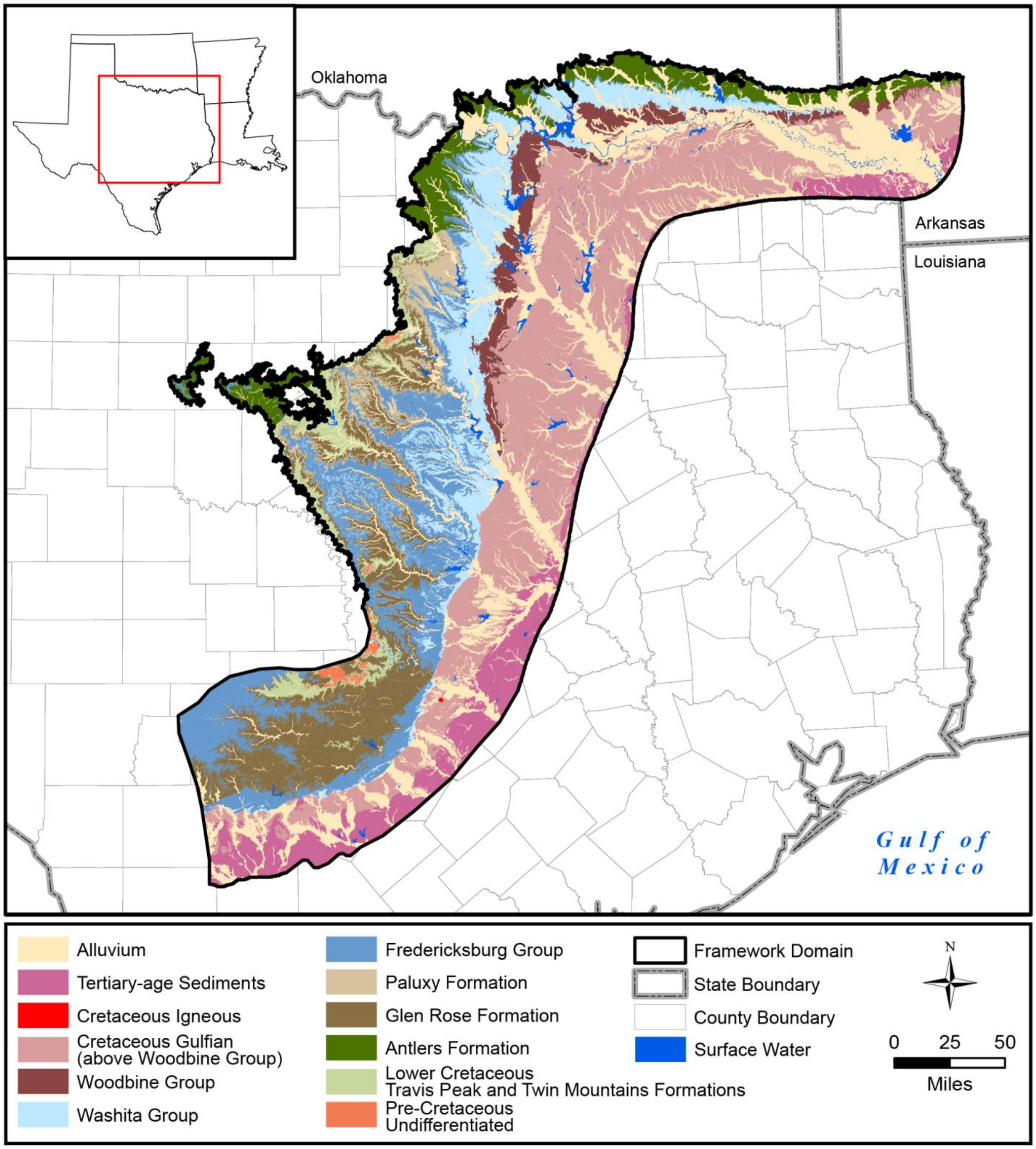


Figure 5-3 Generalized surface geology for the Trinity Aquifer study area (Bureau of Economic Geology, 2012).

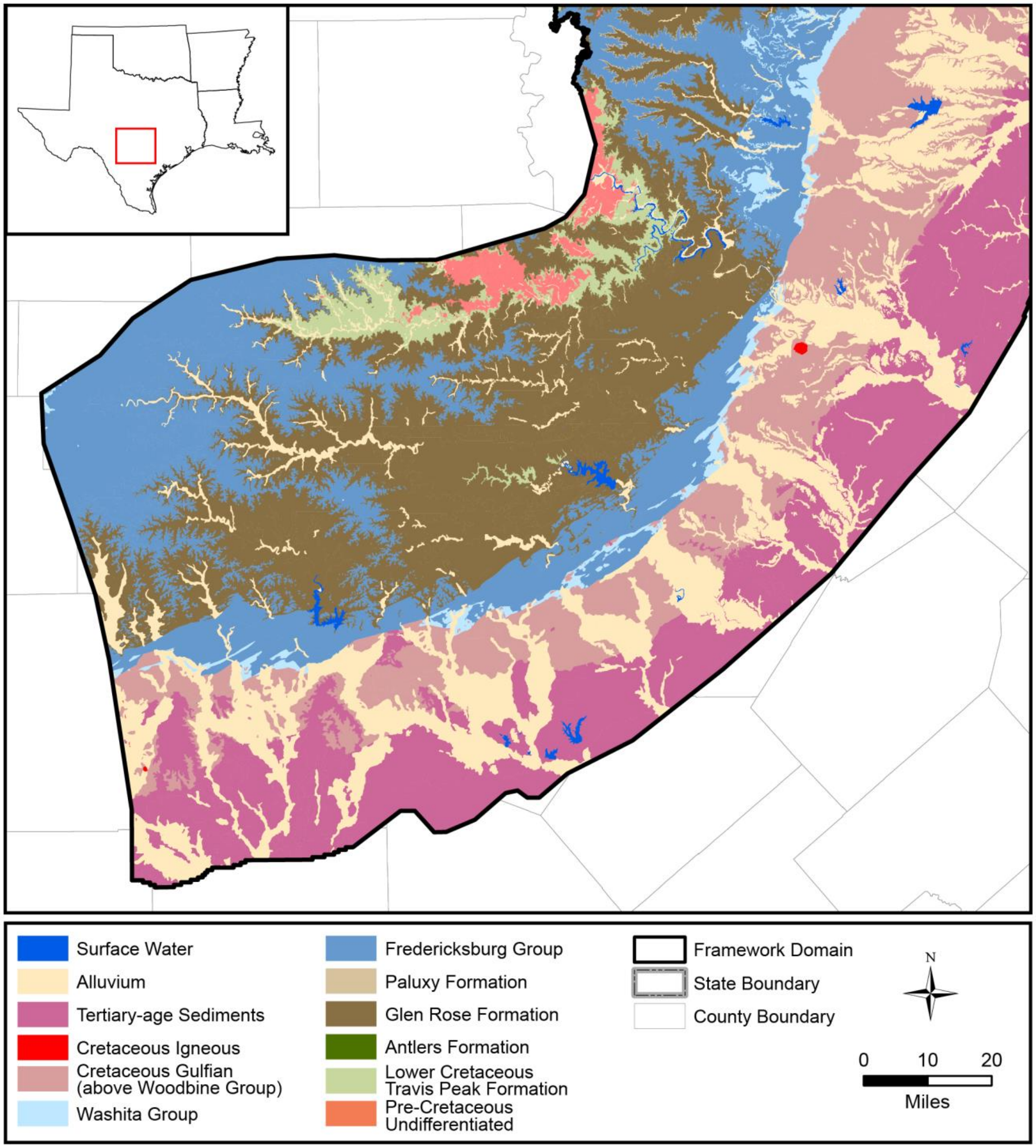


Figure 5-4 **Generalized surface geology for the Hill Country portion of the Trinity Aquifer study area (Bureau of Economic Geology, 2012).**

5.2.1 Lithologic and stratigraphic characterization

The two main lithologies that characterize the water bearing units within the Trinity Aquifer domain are Cretaceous-age limestone and sand/sandstone. The Northern Trinity Aquifer is dominated by sand while the Hill Country Aquifer is dominated by limestone. The non-water bearing units (confining units) for both areas are dominated by clay and shale. The difference in lithologies between these two systems is a crucial component to understanding brackish water availability. In addition, it is one of the biggest challenges and areas of uncertainty when considering a domain as large as the Trinity Aquifer. The main challenge is to correctly characterize the stratigraphic unit variations where they transition from sand (aquifer) or limestone (aquifer) to shale (confining unit), or from sand (aquifer) to limestone (aquifer). For this study, we relied entirely on the Northern Trinity Aquifer GAM (Kelley et al., 2014) for lithologic facies and stratigraphic surfaces. The surfaces were developed from 1,302 geophysical logs to correlate stratigraphic boundaries and interpret lithologies. For the Hill Country Trinity Aquifer portion, we collected 1,678 stratigraphic formation picks for eleven units (Figure 5-1) from geophysical log curve data from 261 wells (Figure 5-5 and Figure 5-6) using modern well log correlation techniques. We developed tops and bottoms for the Georgetown Formation, Edwards Group, Hensell Formation, Cow Creek Formation, Hammett Formation, Sligo Formation, Hosston Formation, and Pre-Cretaceous undifferentiated (top only). In addition, we interpreted lithology (sand, limestone, shale) at a 5-foot-scale through the Trinity Aquifer units from 26 wells using natural gamma, spontaneous potential (SP), and resistivity log data (Figure 5-32 – 5-35).

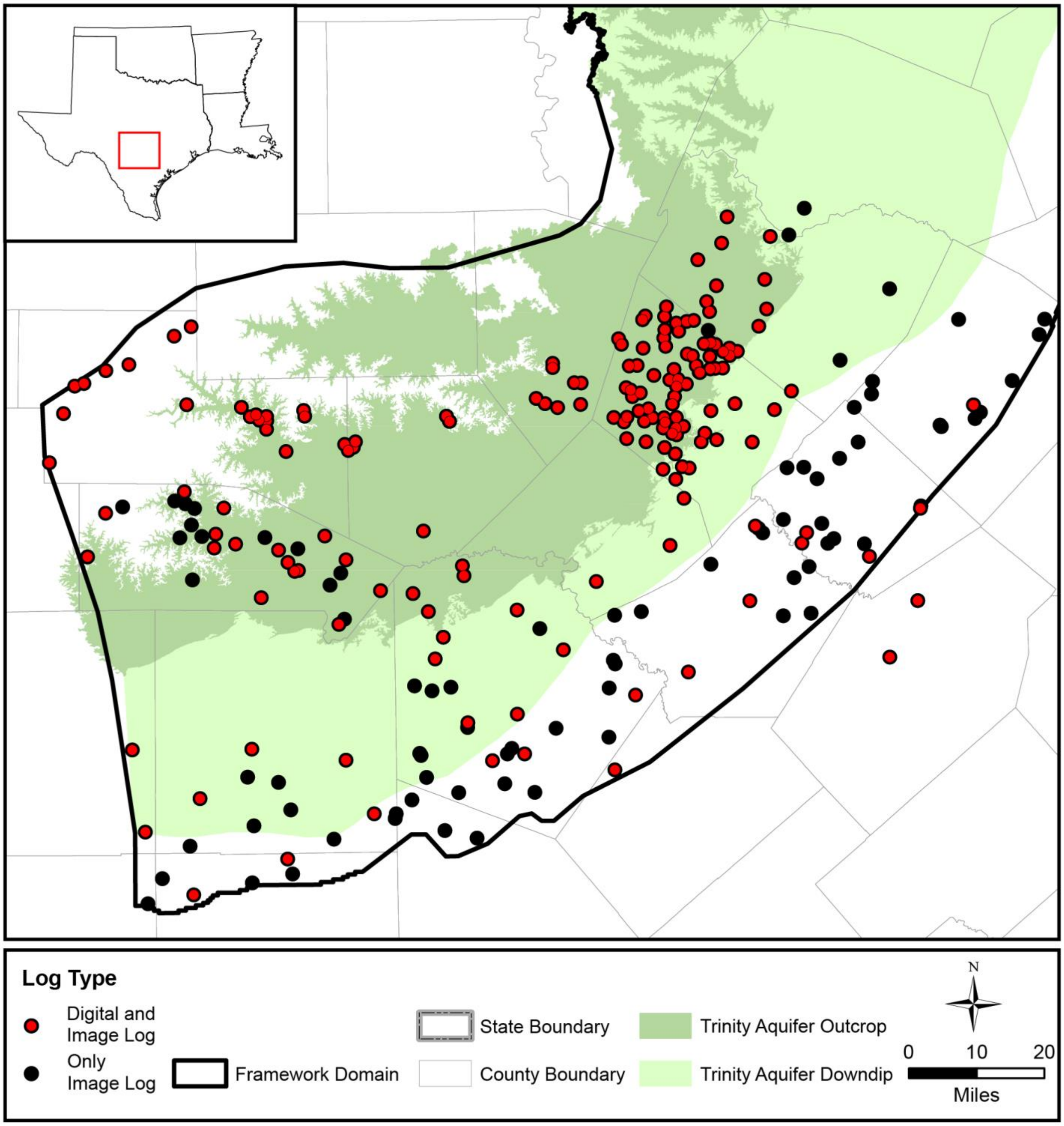


Figure 5-5 **Location of geophysical well log data used for this study distinguishing between digitized and image-only logs.**

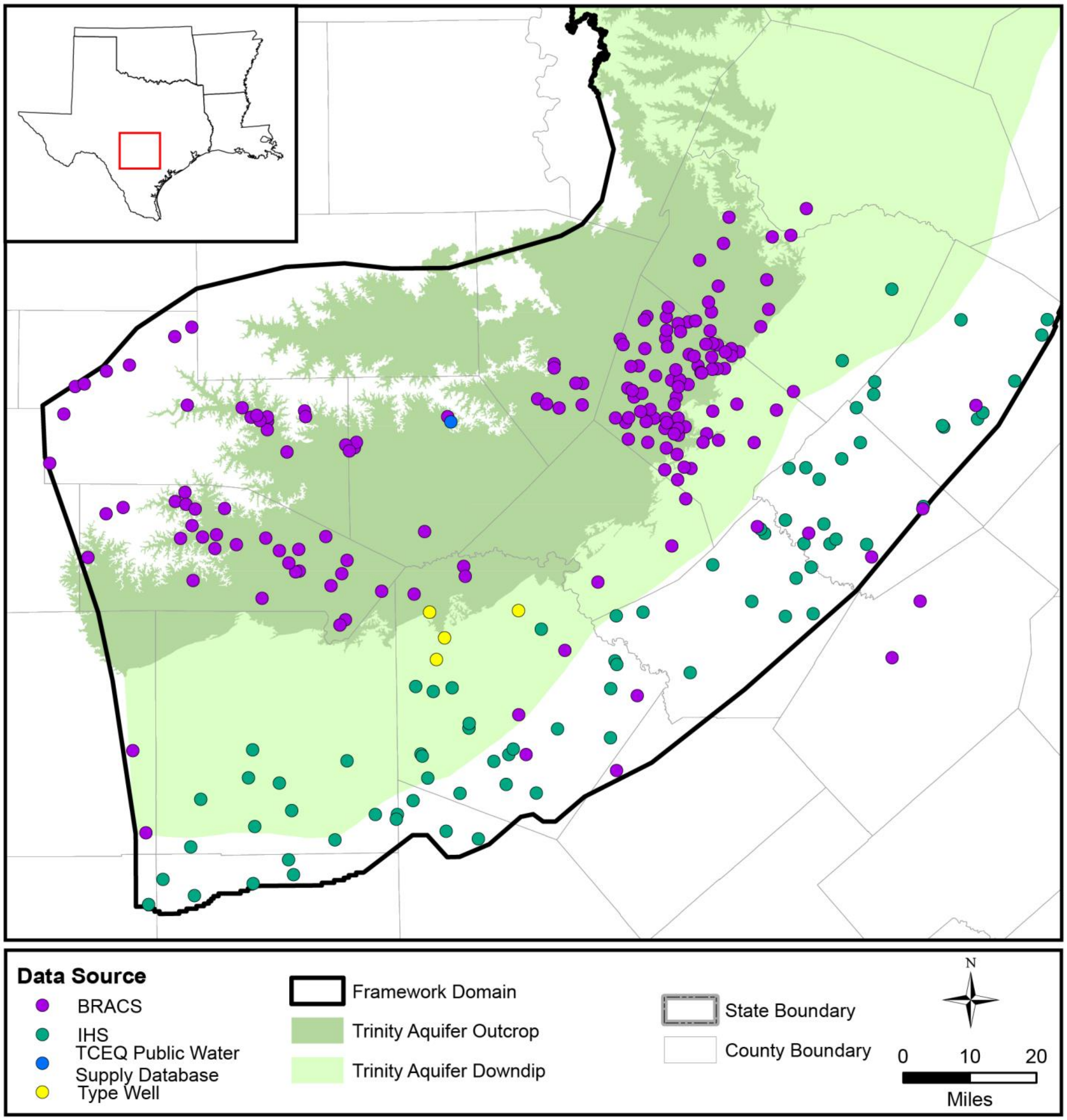


Figure 5-6 **Location of geophysical well log data used for this study distinguishing between data sources.**

5.2.2 Lithology and Stratigraphy of the Trinity Group

Throughout the entire Trinity Aquifer, the Trinity Group formations are overlain by the Washita and Fredericksburg groups and underlain by Pre-Cretaceous rocks (Figure 5-3 and 5-4). The Washita and Fredericksburg groups are comprised of limestone, dolomite, marl, and shale, and lie conformably on the Trinity Group. The Pre-Cretaceous rocks vary from Permian strata in the Northern Trinity portion of the aquifer to Jurassic-age strata in the Hill Country Trinity portion of the aquifer. The Trinity Group stratigraphy varies considerably across the Trinity Aquifer and will be discussed separately in the following sections.

5.2.3 Northern Trinity Lithostratigraphy

In the northern portion of the Northern Trinity Aquifer, the entire Trinity Group consists of the undifferentiated sand, clay, silt, gravel, and conglomerates of the Antlers Formation. In the central portion of the Northern Trinity Aquifer area, the top of the Trinity Group is comprised of the Paluxy Formation, which consists of poorly consolidated sands. In the southern and western portions of the Northern Trinity Aquifer area, the Paluxy thins dramatically. Beneath the Paluxy and Glen Rose are the Lower Cretaceous units. In the central portion of the Northern Trinity Aquifer, these units are called the Twin Mountain Group, which consists of the Hensell Formation (sand), the Pearsall Formation (sand and clay), and the Hosston Formation (sand). In the southern portion of Northern Trinity Aquifer, the lower Cretaceous units are called the Travis Peak Group, which consists of the Hensell Formation (sand), the Pearsall Formation (sand and clay), the Cow Creek Formation (limestone), the Hammett Formation (shale), the Sligo Formation (limestone), and the Hosston Formation (sand). See Kelly et al. (2014) for a detailed description of the Northern Trinity Aquifer lithostratigraphy.

5.2.4 Hill Country Lithostratigraphy

The stratigraphy of the Trinity Groups in the Hill Country Aquifer is revealed through creek bed exposures, hillsides, roadcuts, and quarries, as well as scattered waterwell cuttings and cores. Few large-scale contiguous, non-weathered exposures exist, which makes it difficult to trace out the stratal geometries (Ward and Ward, 2007). Therefore, much of what is known about these formations has been pieced together by correlating marker beds across large areas of the Edwards Plateau (Stricklin et al., 1971) in outcrop and in core.

In the Hill Country Trinity Aquifer region, the Pre-Cretaceous rocks that underlie the Trinity Group include Precambrian metamorphic and igneous rocks and Paleozoic sedimentary rocks. The Llano uplift was a topographic high during the deposition of the Trinity Group. The Llano uplift shed debris into the Trinity depositional basin. The topographic high and the variable erosion of the Llano uplift contributed to uneven terrain at the time of Trinity Group deposition. The lateral and vertical distributions of the Trinity Group were greatly influenced by the Llano uplift (Stricklin et al., 1971). In the vicinity of the Llano uplift (updip) the Trinity Group thins to less than 150 feet. Beneath the Balcones Fault Zone (downdip) it thickens to greater than 1,000 feet thick and further downdip it thickens to more than 2,000 feet thick (Barker and Ardis, 1996 and this report).

The base of the Hill Country Trinity Aquifer is the Hosston Formation, which overlies the Pre-Cretaceous rocks. The Hosston is a siliclastic siltstone and sandstone in the updip region and dolomitic mudstone and grainstone in the downdip region (Barker and Ardis, 1996). This unit varies greatly in thickness from less than 200 feet updip to greater than 1,000 feet downdip. Further updip along the southern flanks of the Llano uplift, the Hosston grades into the Sycamore Sand (Amsbury, 1974). The Sligo Formation overlies the Hosston and is composed of evaporates, limestone and dolostone. Downdip, the Sligo is shallow-marine carbonate that is up to 500 feet thick and updip it thins to less than 250 feet where it grades into terrigenous clastics.

Above the Sligo is the Hammett Formation, which is also referred to as the Pine Island Shale Member (Murray, 1961). This unit is a mixture of clay, silt, mud, dolomite, and carbonate (Amsbury, 1974). The unit thins to near zero updip and thickens to greater than 100 feet downdip. The Hammett Formation has a transitional boundary with the overlying Cow Creek Formation. The Hammett-Cow Creek contact is arbitrarily determined to be the first well-developed limestone as you transition from shale (Lozo and Stricklin, 1956). The Cow Creek Formation is a fine- to coarse-grained calcarenitic limestone at the bottom that transitions into silty carbonate grains throughout the middle and consists of cross-bedded beach coquina at the top (Barker and Ardis, 1996). The Cow Creek Formation thins to near zero updip and thickens to greater than 300 feet downdip (Imlay, 1945). Overlying the Cow Creek Formation is the Hensell Formation. For much of the Hill Country Trinity Aquifer region the Hensell Formation is comprised of weakly cemented clay, quartz, and calcareous sand (Inden, 1974). In some parts of the Hill Country Trinity Aquifer region, especially the furthest downdip portions and southern Bexar County, the Hensell Formation (referred to Bexar Shale in these locations) is comprised of a mixture of dark mudstone, clay, and shale (Barker and Ardis, 1996). According to Loucks (1977), the shales in the Hensell Formation are the fine-grained, marine equivalent of the near-shore (updip), terrigenous sands. The Hensell Formation varies in thickness from less than 50 feet in the updip to greater than 200 feet thick in the downdip (Imlay, 1945).

Above the Hensell Formation lies the Glen Rose Formation, consisting of the Lower Glen Rose Formation, which sits on top of the Hensell Formation, and the Upper Glen Rose Formation, which represents the top of the Trinity Group for much of the Trinity Aquifer domain. Lozo and Stricklin (1956) and Stricklin et al. (1971) established these informal lithostratigraphic subdivisions of the Glen Rose Formation that Scott and Filkorn (2007) formalized. These subdivisions are now used throughout the updip and downdip regions of the Hill Country Trinity Aquifer region. The boundary between the two members was put at the top of a widespread, meter-thick unit rich in the small bivalve “Corbula” (Eoursivivas harveyi). Both the Lower and Upper Glen Rose formations are comprised of cyclic depositional units on several scales. Lithologic units include shallow-water wackestone, packstone, and grainstone, as well as finely crystalline dolostone beds and a terrigenous claystone (Ferrill et al., 2011). Where the Glen Rose Formation crops out in the Hill Country, the Lower Glen Rose Formation is about 260 ft thick (Abbott, 1966), and the upper Glen Rose Formation is about 480 ft thick (estimated from Abbott, 1966; Stricklin et al., 1971; and Farlow et al., 2006). The Glen Rose Formation in the subsurface and downdip is much thicker, in excess of 1,500 ft thick (Welder and Reeves, 1964).

In the Northern Trinity Aquifer and at the transition between the Northern Trinity Aquifer and the Hill Country Aquifer, the Glen Rose Formation is overlain by the Paluxy Formation. Throughout the Hill Country, however, the Paluxy Formation is quite thin and diminishes to zero across much of the region. Where it is absent, the upper Glen Rose Formation is considered the top of the Trinity Group in this region. For most of the Hill Country, the top of the Trinity Group is overlain by the Walnut Formation, which, in turn, is overlain by the Kainer Formation of the Edwards Group. The Edwards Group consists of massive, porous, highly fractured lower Cretaceous limestone with thicknesses that range from less than 500 feet thick in the updip and greater than 1,000 feet in the downdip (Rose, 1972). Above the Edwards Group is the Georgetown Formation. The Georgetown Formation is comprised of discontinuous beds of alternating thin, fine-grained limestone or marly limestone. It ranges in thickness from less than 60 feet in the updip and greater than 100 feet to absent in other parts of the Hill Country region (Rose, 1972).

5.2.5 Hydrostratigraphy

As mentioned earlier in this section, the Northern Trinity Aquifer spans a very large area (Figure 5-3). This large area crosses several different depositional domains (Figure 5-1) as well as structural domains (Figure 5-7). Crossing these domains makes it difficult to correlate hydrostratigraphic units across the entire region. For this reason, we break the domain into two hydrostratigraphic regions, the Northern Trinity Aquifer and the Hill Country Trinity Aquifer. The Northern Trinity Aquifer hydrostratigraphy is consistent with the Northern Trinity Aquifer GAM (Kelley et al., 2014). These units, in hydrostratigraphic order, are the Hosston, the Pearsall, the Hensell, the Glen Rose, and the Paluxy (Appendix ?). The Hill Country Aquifer hydrostratigraphy is consistent with the stratigraphy shown in Figure 5-1. These units, in hydrostratigraphic order, are the Pre-Cretaceous Undifferentiated, Hosston, Sligo, Hammett, Cow Creek, Hensell, Lower Glen Rose, Upper Glen Rose, Paluxy, Edwards, and Georgetown. The hydrostratigraphic units in the Hill Country Aquifer require a higher level of resolution because the lithologic and hydrologic properties change vertically and laterally across this domain. In order to capture that variability, it is important to not coarsen the hydrostratigraphy by lumping the units. In addition, a higher level of unit resolution allows a modeler the flexibility when applying hydrologic properties to a given unit.

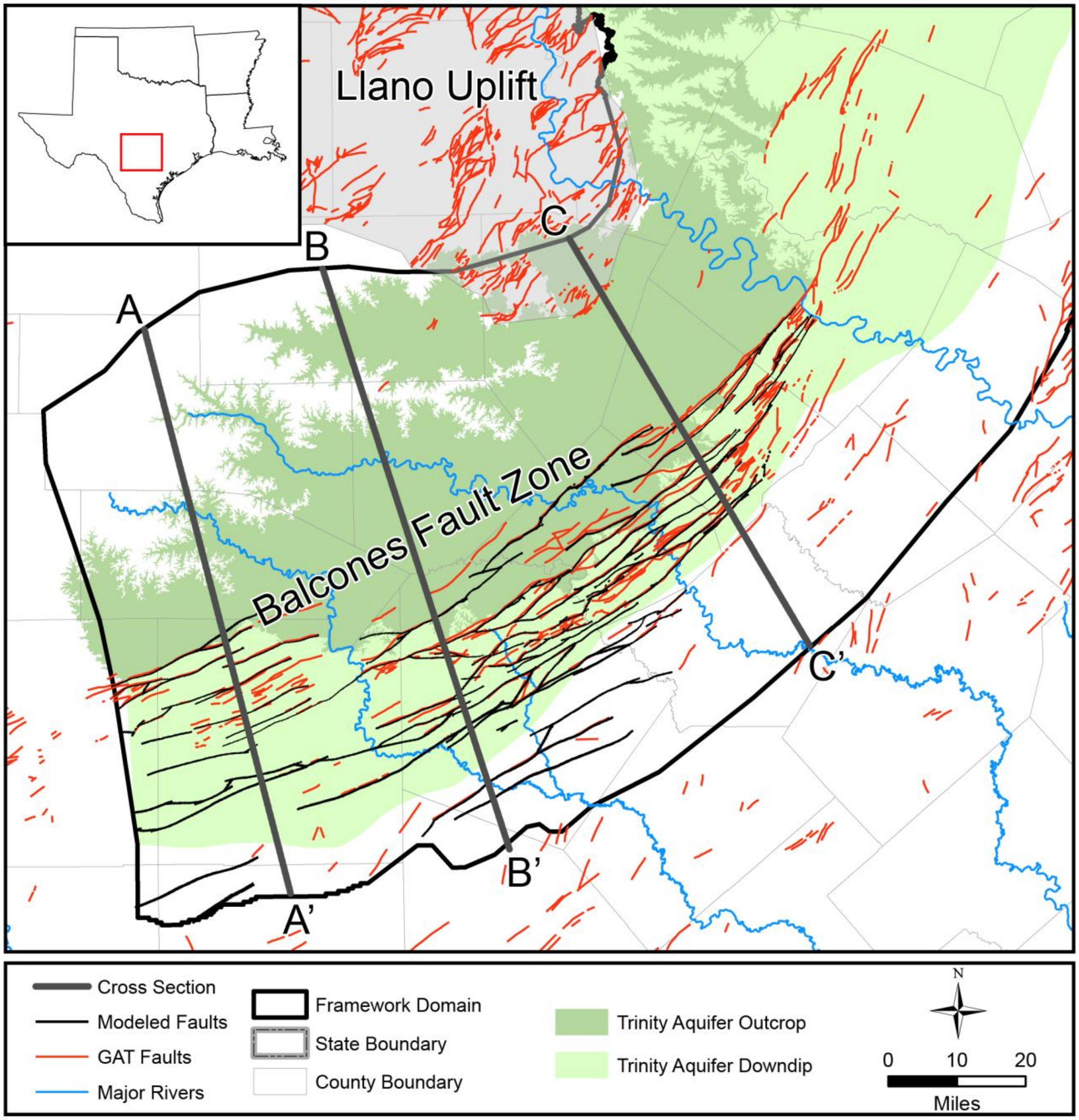


Figure 5-7 **The main structural features in the Hill Country study area and the location of cross sections A-A', B-B' and C-C'. modeled faults are from Fratesi and others (2015) and GAT faults are from Pearson and others (2006)**

5.3 Balcones Fault Zone

Rocks of both the Edwards and Trinity aquifers crop out in the Edwards Plateau region of Texas, and their southern and eastern outcrop boundary are within the Balcones Fault Zone (Figure 5-7). The Balcones Fault Zone changes trend from nearly east-west between Del Rio and San Antonio to nearly north-south between Austin and Dallas. In the Hill Country region, the Balcones Fault Zone changes trend by 30° from 080° west of San Antonio to 050° northeast of San Antonio. This fault zone is a 25- to 30-km-wide en echelon system of mostly south-dipping normal faults that formed during the middle to late Tertiary (Foley, 1926; Murray, 1961; Young, 1972; Maclay and Small, 1983, 1984; Stein and Ozuna, 1996; Clark, 2000; Collins, 2000). The zone defines the transition from structurally stable flat-lying rocks of the Texas Craton to gently coastward-dipping sediments of the subsiding Gulf of Mexico with a maximum total displacement across its extent of about 1500 ft (Weeks, 1945). The larger normal faults in the Balcones fault system have displacements of 100–1,000 ft) or more (Hill, 1889, 1890; Sellards, 1919; Hovorka et al., 1998; Collins, 2000). Although the overall geometry of the Balcones Fault Zone parallels the strike of the Mesozoic–Paleozoic unconformity (top of Ouachita orogen rocks) and is indirectly controlled by the relict Ouachita structure, faults in the systems have orientations that accommodated Tertiary regional extension. Individual fault and fracture strikes are relatively consistent throughout the region, with an average strike of between 055° and 065° (Ferrill and Morris, 2008; Ferrill et al., 2011; Morris et al., 2014; McGinnis et al., 2015). Faults are generally considered to be steep (60-70°) to nearly vertical based on local measurements and nearly linear fault traces in areas of significant topographic relief (Hill, 1889; Sellards, 1919; Holt, 1956; McGinnis et al., 2015). Offset of Cretaceous platform carbonate strata (Rose, 1972) across the Balcones Fault Zone, including the Edwards and Trinity aquifers, resulted in a broad, weathered escarpment of vegetated limestone hills rising from the predominantly clastic coastal plains to the uplands of the Texas Craton. Within the fault system, the dip of bedding varies from gentle coastward to nearly horizontal, with occasional localized dip of hanging wall beds northward into some faults. Faulting has been interpreted as being rooted in the deeply buried foreland-basin sediments of the Ouachita orogeny (Murray, 1956).

Faults of the Balcones Fault Zone exert important first order controls on fluid flow within the Trinity and the overlying Edwards aquifers and are major areas of uncertainty when modeling hydrologic properties in this region. The faults that make up the Balcones Fault Zone juxtapose both permeable and relatively impermeable hydrogeologic units, they cause substantial structural thinning of the lower Cretaceous strata, and they provide potential pathways for infiltration of surface water into the groundwater systems and for lateral and vertical movement of groundwater (Ferrill and Morris, 2008; Ferrill et al., 2008, 2011; McGinnis et al., 2015). Extensional deformation in the Balcones Fault Zone has produced a network of faults likely to influence intra-aquifer permeability due to fault zone processes producing permeability anisotropy with maximum transmissivity parallel to fault strike (Ferrill et al., 2009). Displacement on these faults has thinned the aquifer along each fault, further restricting aquifer connectivity perpendicular to fault strike. Displacement on the large faults can thin the Trinity units by 50–100 percent of their total stratal thickness, and juxtapose Pre-Cretaceous rocks against Trinity strata or Trinity strata against Edwards strata. The impact of this scale of offset is that potential water bearing units can be absent in places or there is the opportunity for interaquifer communication. Understanding the fault network in the Balcones Fault Zone is a daunting task, however, it is a necessary effort in order to reduce uncertainty in hydrologic models for this area.

Fratesi et al. (2015) developed a fault model that was used to model flow in the Edwards and Trinity aquifers. We utilized and improved on that fault model for this project. The Balcones Fault Zone model for this project contains 126 faults that have an average dip of 70° and fault displacement that are near zero at the fault tips and maximum displacements of up to 1,000 feet (Figure 5-7 – Figure 5-10).

5.4 Stratigraphic Framework Model

The stratigraphic framework model was developed to set the boundaries, define distribution of layer thicknesses, and to provide a sufficient-resolution, data- and observation-constrained stratigraphic framework to support the brackish water volume estimation for the Hill Country Trinity Aquifer domain. The stratigraphic framework model refines major areas of uncertainty in the existing Trinity Aquifer domain, such as the zones where water quality data exceed 1,000 mg/L TDS within the Hill Country portion, and the gap between the Northern Trinity Aquifer GAM and the Hill Country Trinity Aquifer GAM. To reduce these uncertainties and develop an improved estimate on volume (i.e., with fewer inaccuracies and less uncertainty), it is important to have a data-constrained stratigraphic framework model.

The stratigraphic model was created using currently available data, including published geologic and topographic maps (Figure 5-2 – Figure 5-4), stratigraphic-horizon picks from wells (Figure 5-5 and Figure 5-6), and stratigraphic interpretations. The stratigraphic model was structured into eleven stratigraphic layers (Figure 5-1, Figure 5-7 – Figure 5-31), these include the Fredericksburg/Washita Group (Georgetown and Edwards Formations), the upper Trinity (Upper Glen Rose), the middle Trinity (Lower Glen Rose, Hensell, Cow Creek, Hammett), the lower Trinity (Sligo and Hosston), and the Pre-Cretaceous. By developing a detailed stratigraphic model, additional layers can be incorporated into the numerical model without having to redevelop a new stratigraphic model. As new data become available, this model can be efficiently modified in an iterative fashion to keep the stratigraphic framework up-to-date for use as the basis for increasingly refined groundwater flow and availability modeling.

5.4.1 Stratigraphic Framework Model Software

Three primary software programs were used to develop the stratigraphic framework model: (i) Microsoft Excel 2010, (ii) ESRI ArcGIS 10.4, and (iii) Schlumberger Petrel 2015.1. These programs were used to organize tabulated data, assemble and analyze geographically distributed data and interpretations, and conduct three-dimensional stratigraphic framework modeling, respectively.

Microsoft Excel 2010 was used to compile well data including locations, well head elevation (datum), stratigraphic picks, and thickness information. A spreadsheet of formation thicknesses across the model domain and a quality controlled database of well picks was compiled using this information.

ESRI ArcGIS 10.4 was used to assemble topography, geologic maps, structural data, and other geographically distributed data. These data were used as the basis for defining the model domain and constructing the stratigraphic framework model. Digital data used to create the model were georeferenced. Well picks were evaluated using published maps and point shapefiles.

Petrel is a Windows PC software package that is used primarily by the oil and gas industry and was used to construct the stratigraphic framework model. This software package allows surface and subsurface data to be assimilated from multiple sources. Stratigraphic and structural geologic interpretation can then be performed using the database. This integrated software package was selected for this application because of its flexibility in handling data, interpretation, and model development and manipulation, which eliminates the need for multiple highly specialized tools, which would otherwise be required. Petrel has a wide range of export options that facilitate preparing data for input into models and into other software packages.

The stratigraphic framework model was developed in the custom GAM coordinate system. This system uses an Albers projection and the North American 1983 geographic coordinate system and vertical datum. Vertical positions are in feet with respect to mean sea level.

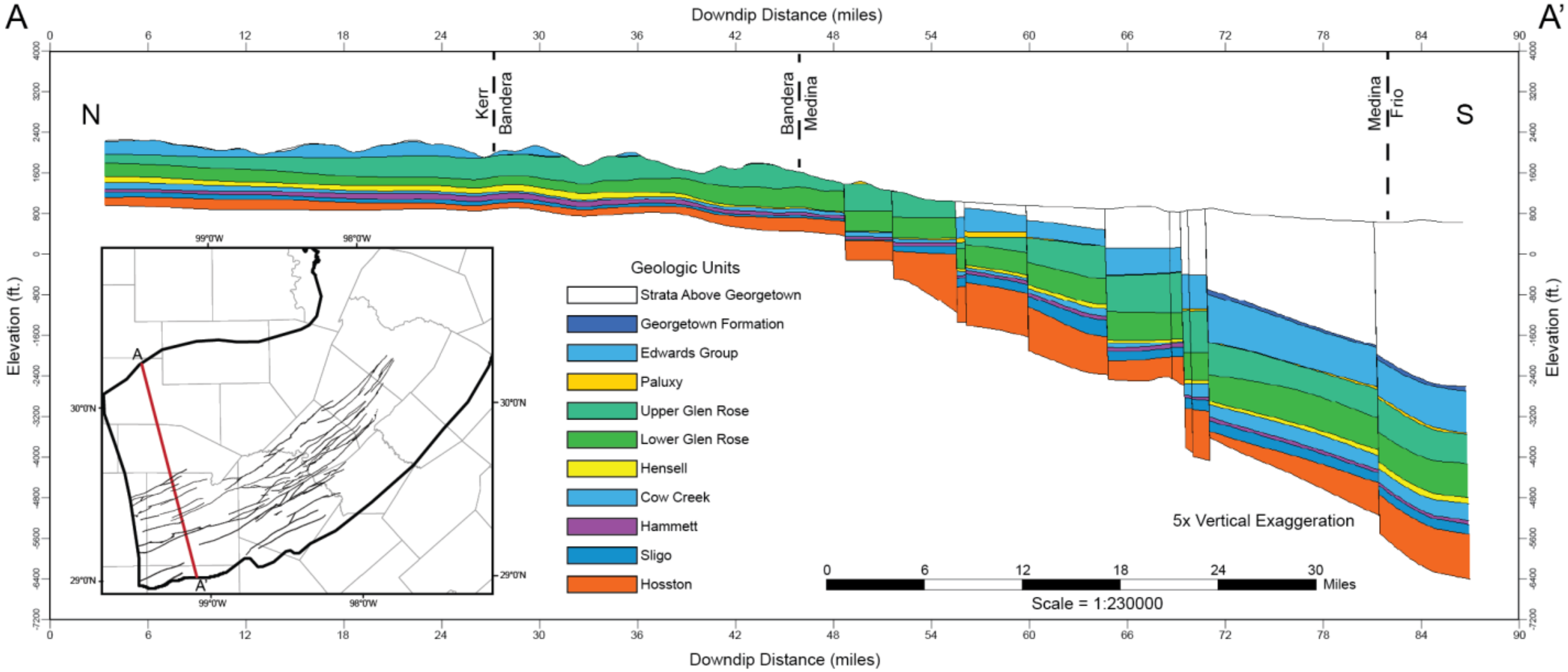


Figure 5-8 **Stratigraphic cross section A-A'**

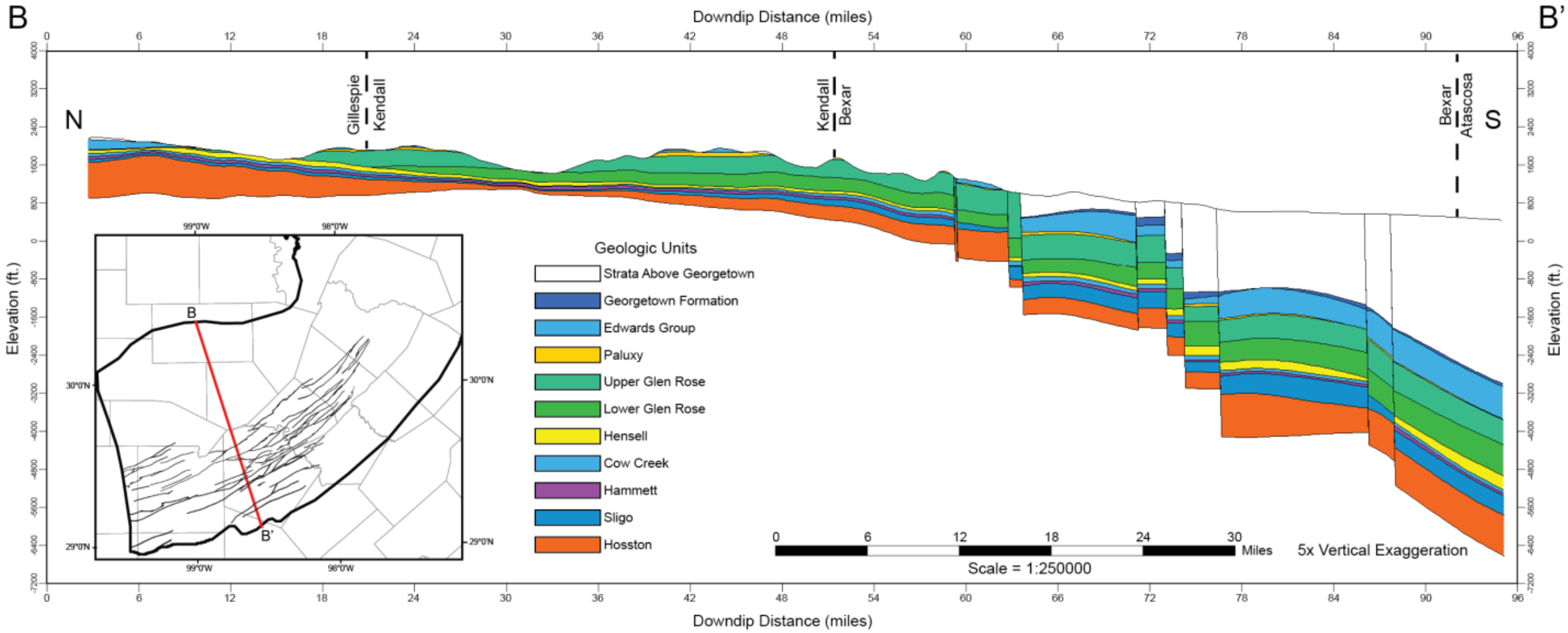


Figure 5-9 **Stratigraphic cross section B-B'**

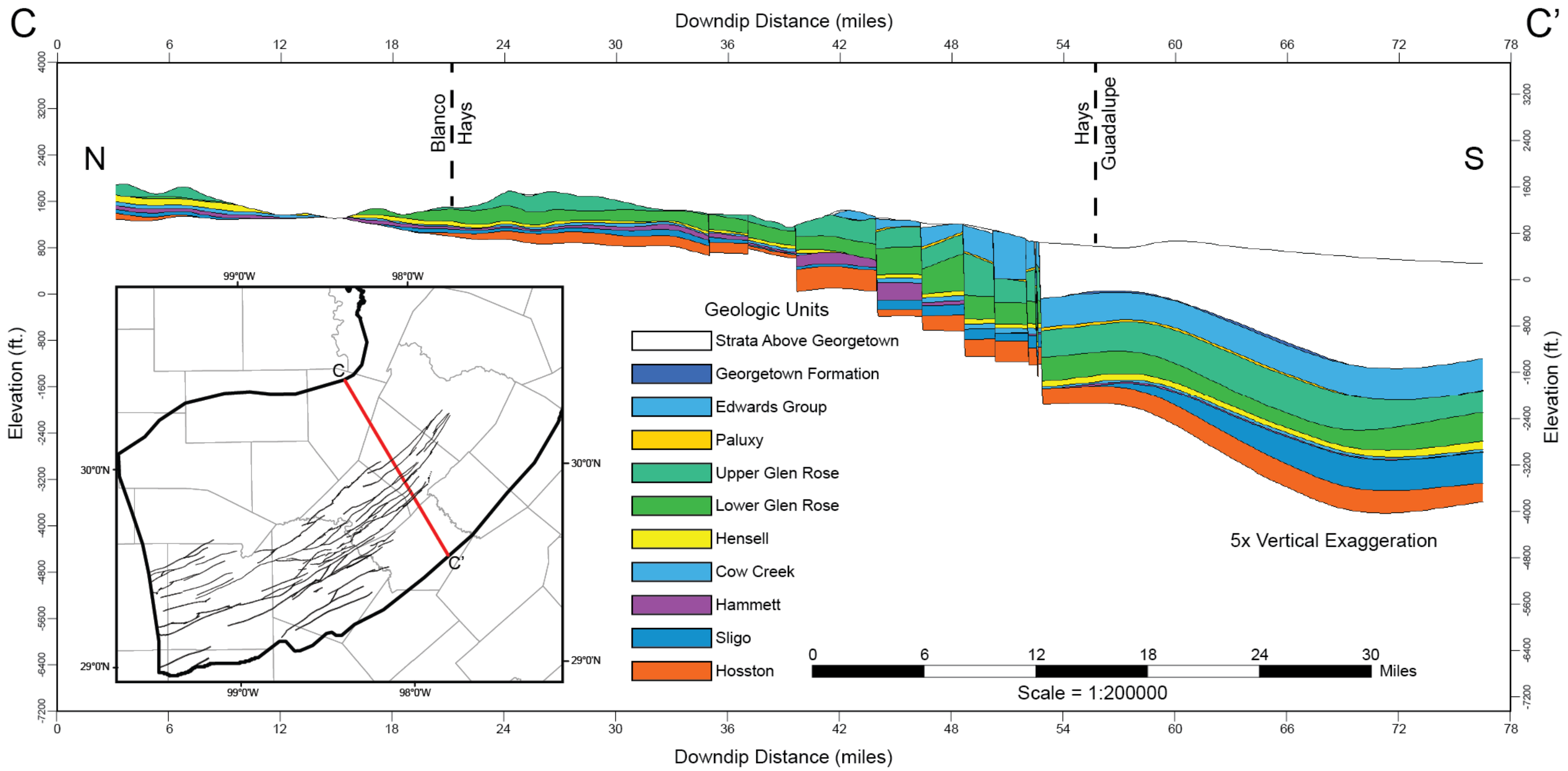


Figure 5-10 **Stratigraphic cross section C-C’**

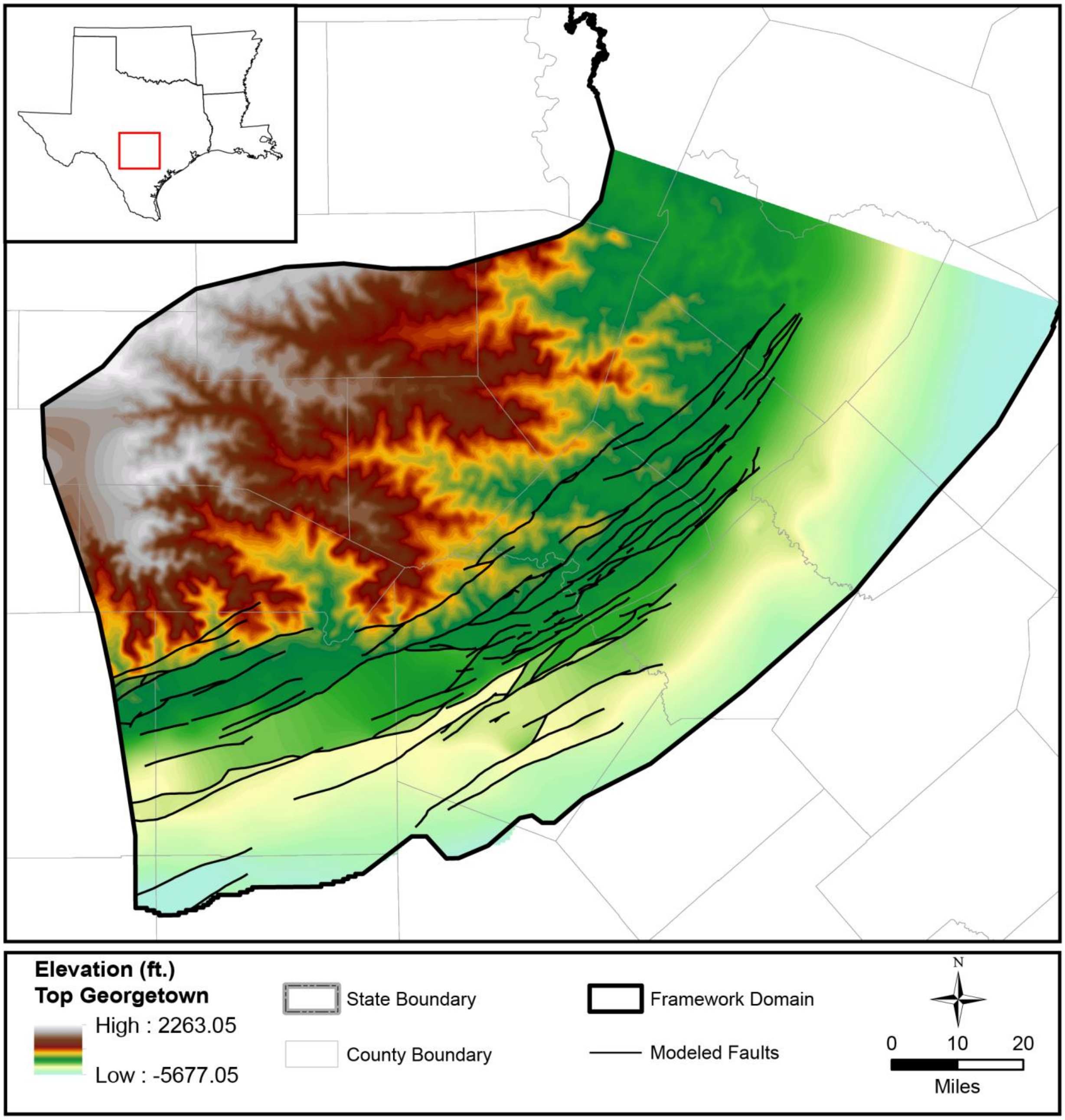


Figure 5-11 Top of the Georgetown Formation (in feet above mean sea level) and locations of faults that displace Cretaceous-age strata (from Fratesi and others 2015).

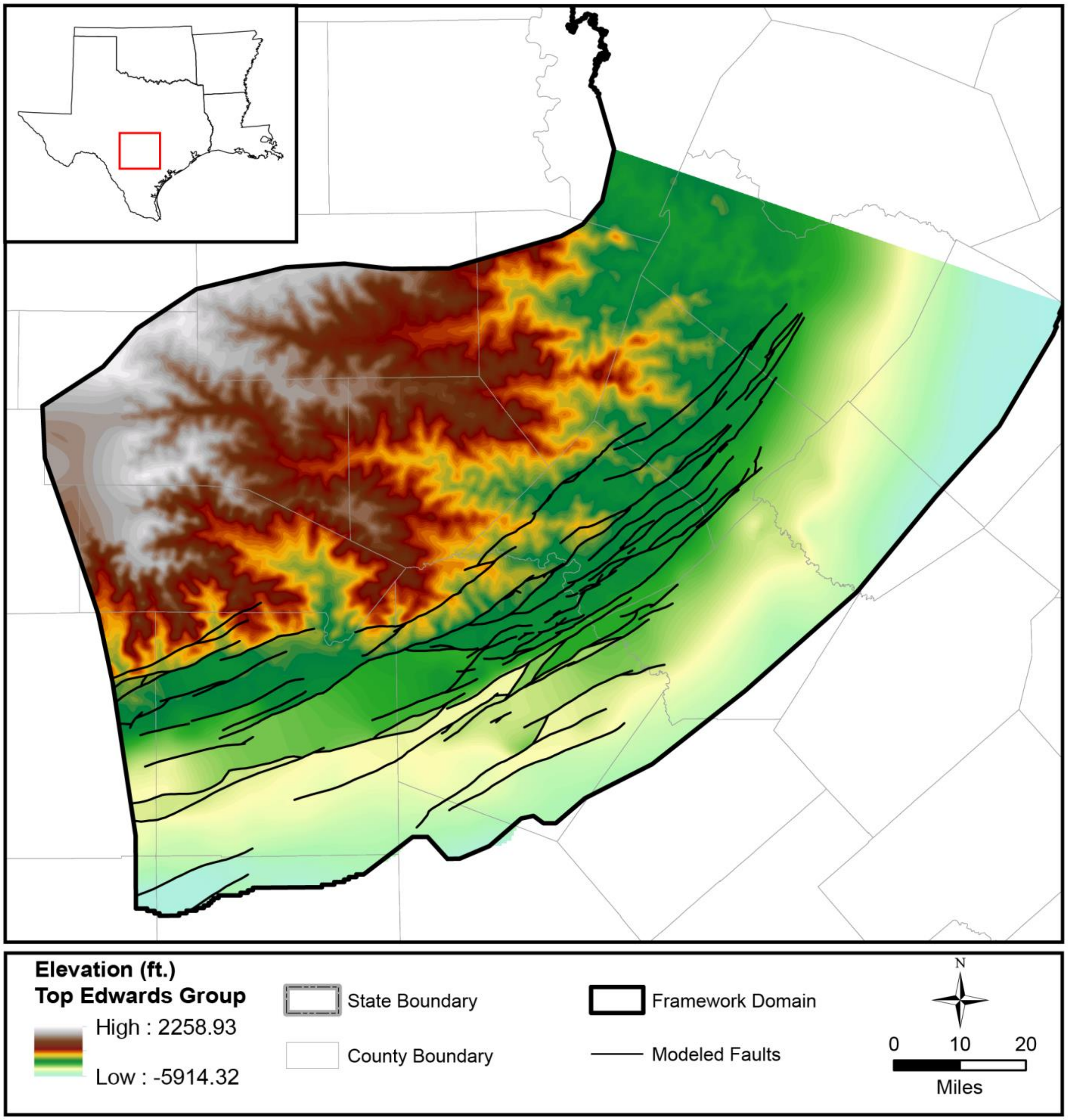


Figure 5-12 Top of the Edwards Group (in feet above mean sea level) and locations of faults that displace Cretaceous-age strata (from Fratesi and others 2015).

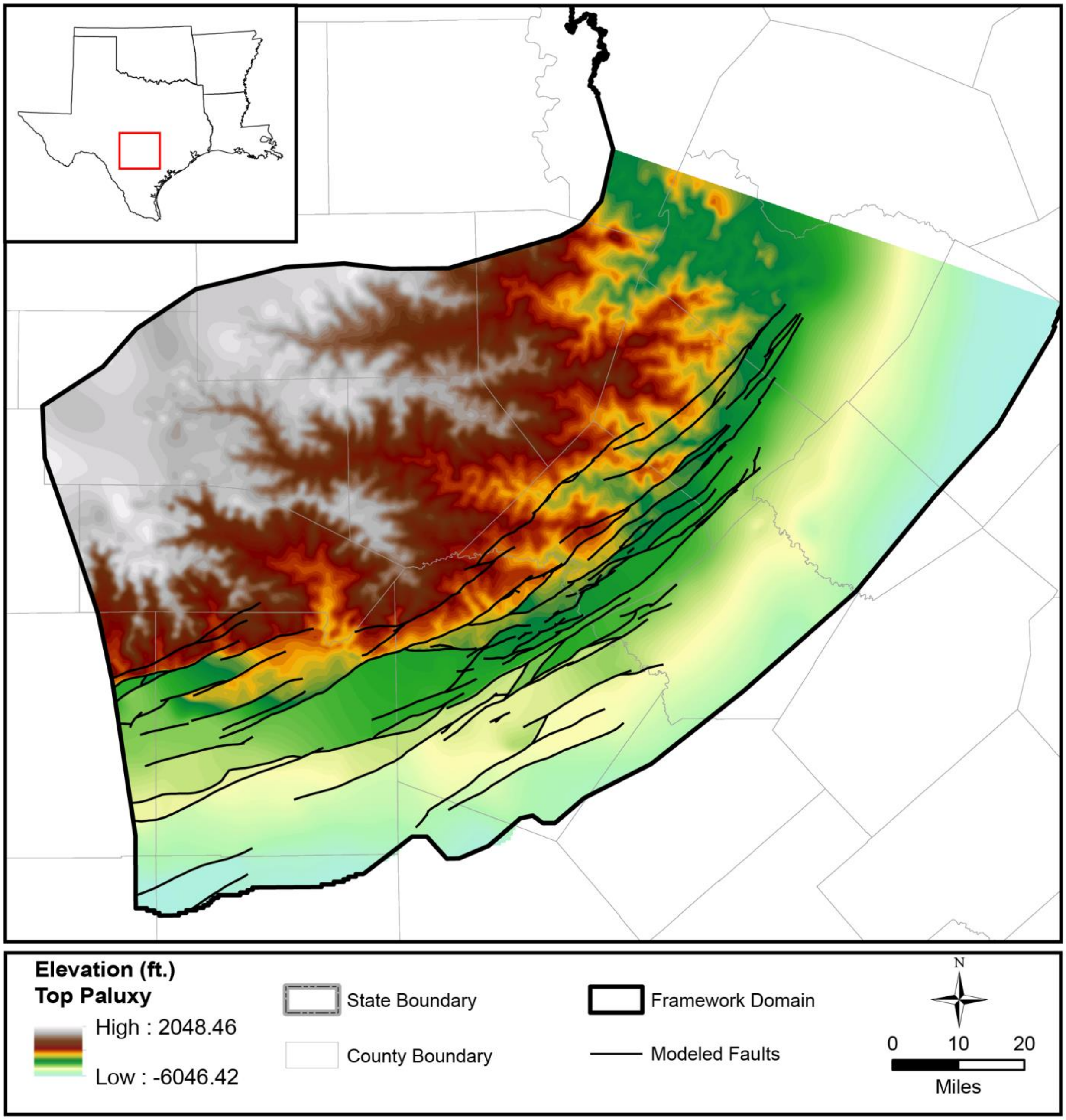


Figure 5-13 Top of the Paluxy Formation (in feet above mean sea level) and locations of faults that displace Cretaceous-age strata (from Fratesi and others 2015).

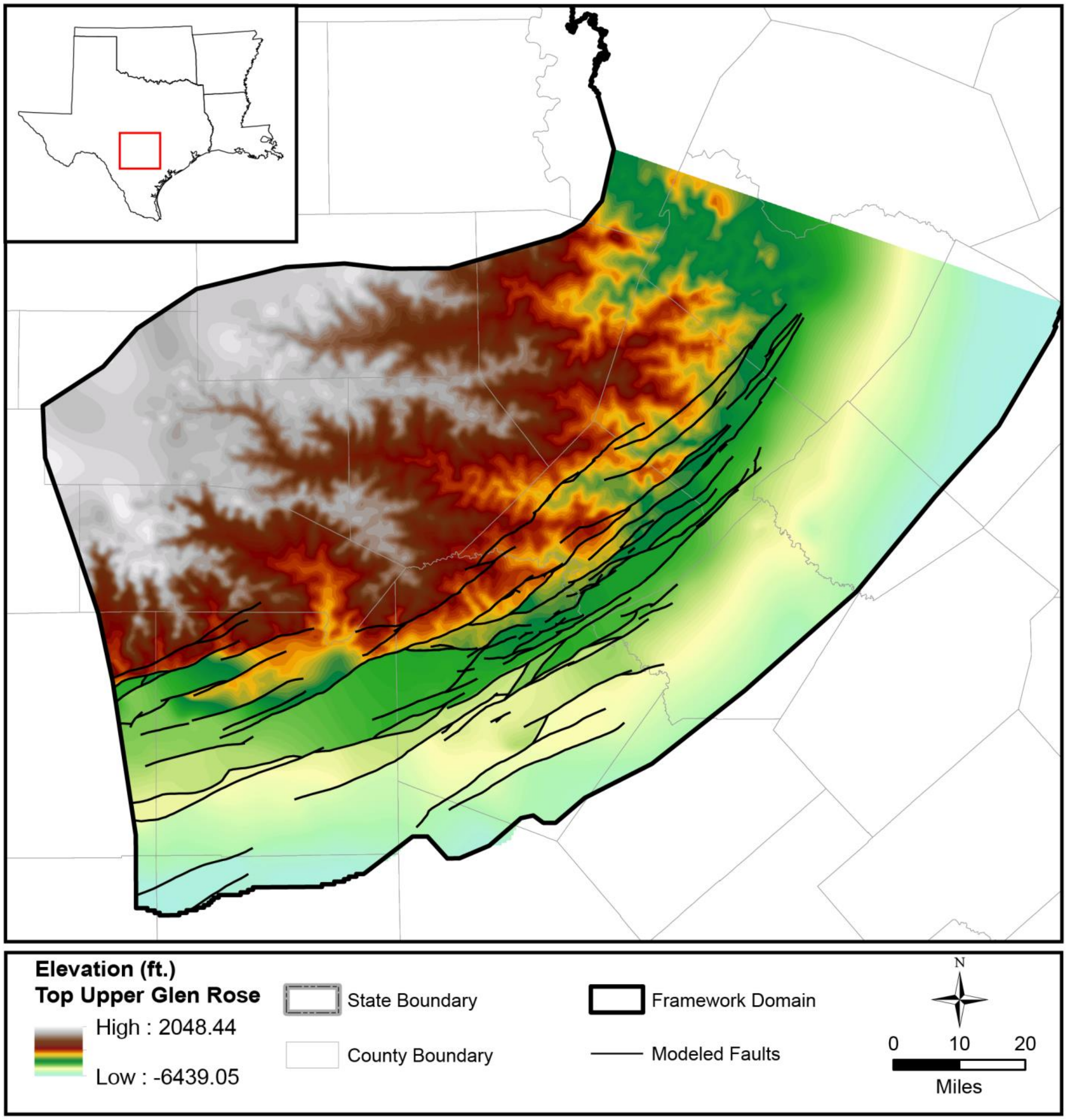


Figure 5-14 Top of the Upper Glen Rose Formation (in feet above mean sea level) and locations of faults that displace Cretaceous-age strata (from Fratesi and others 2015).

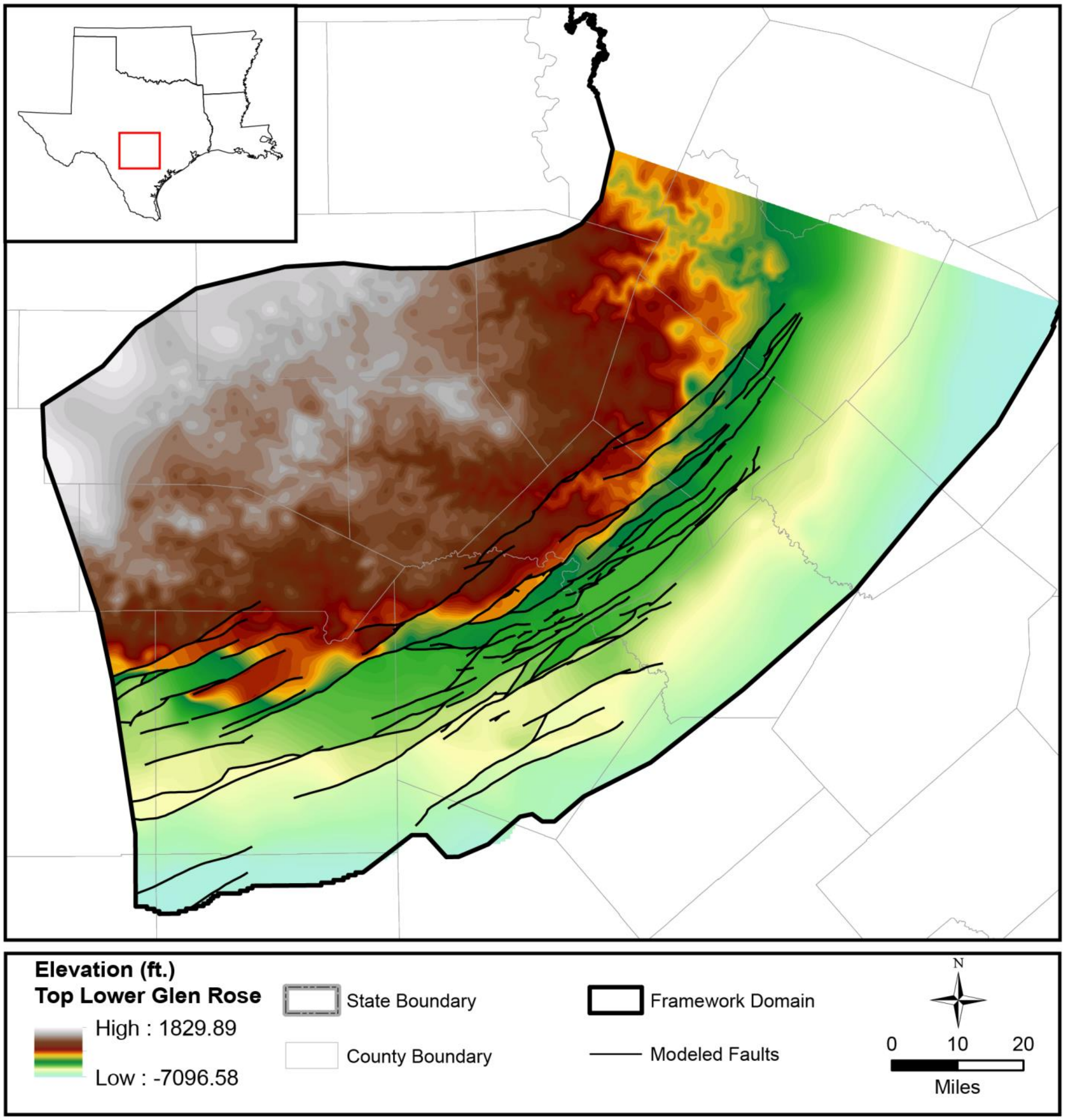


Figure 5-15 Top of the Lower Glen Rose Formation (in feet above mean sea level) and locations of faults that displace Cretaceous-age strata (from Fratesi and others 2015).

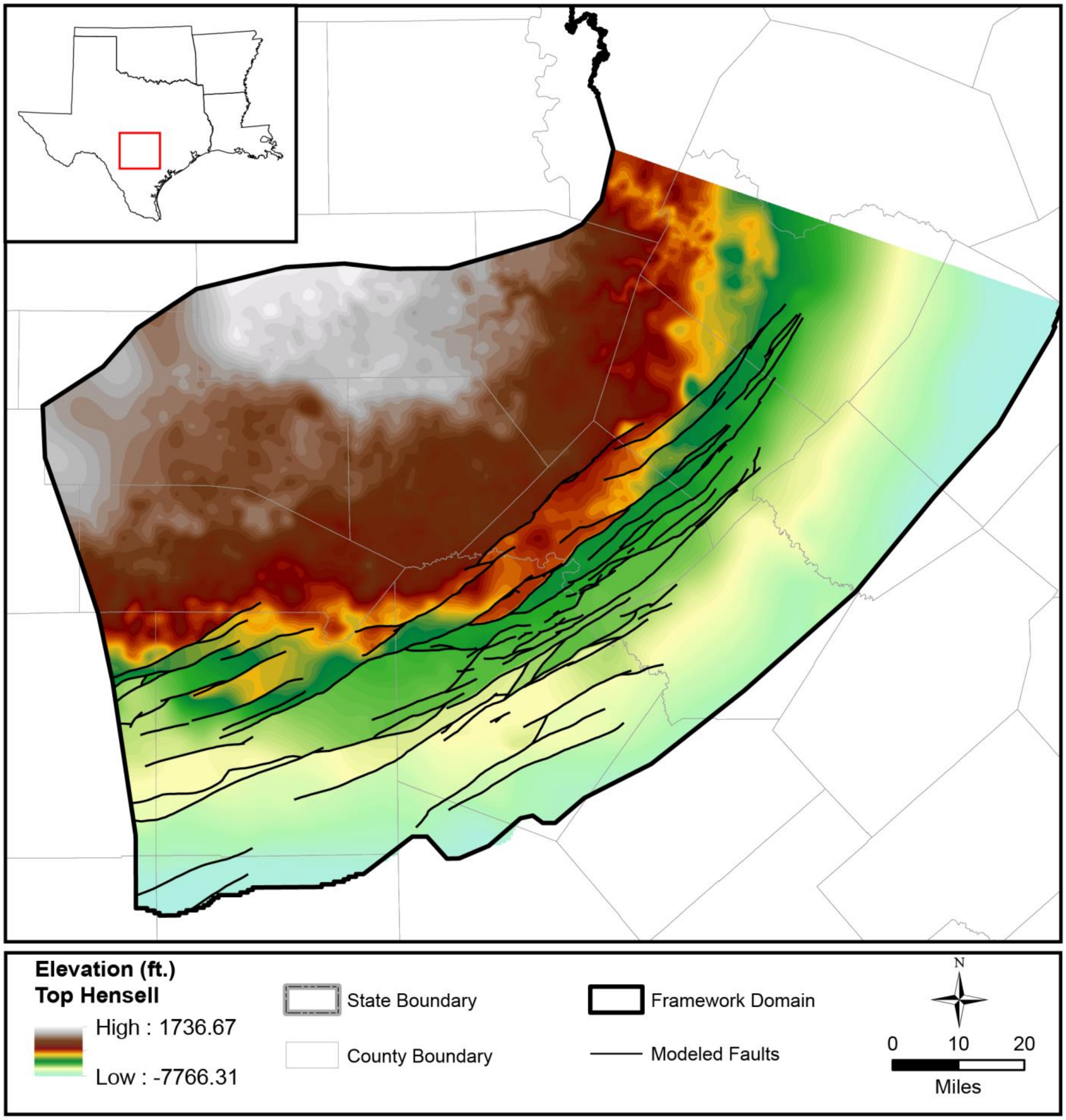


Figure 5-16 Top of the Hensell Formation (in feet above mean sea level) and locations of faults that displace Cretaceous-age strata (from Fratesi and others 2015).

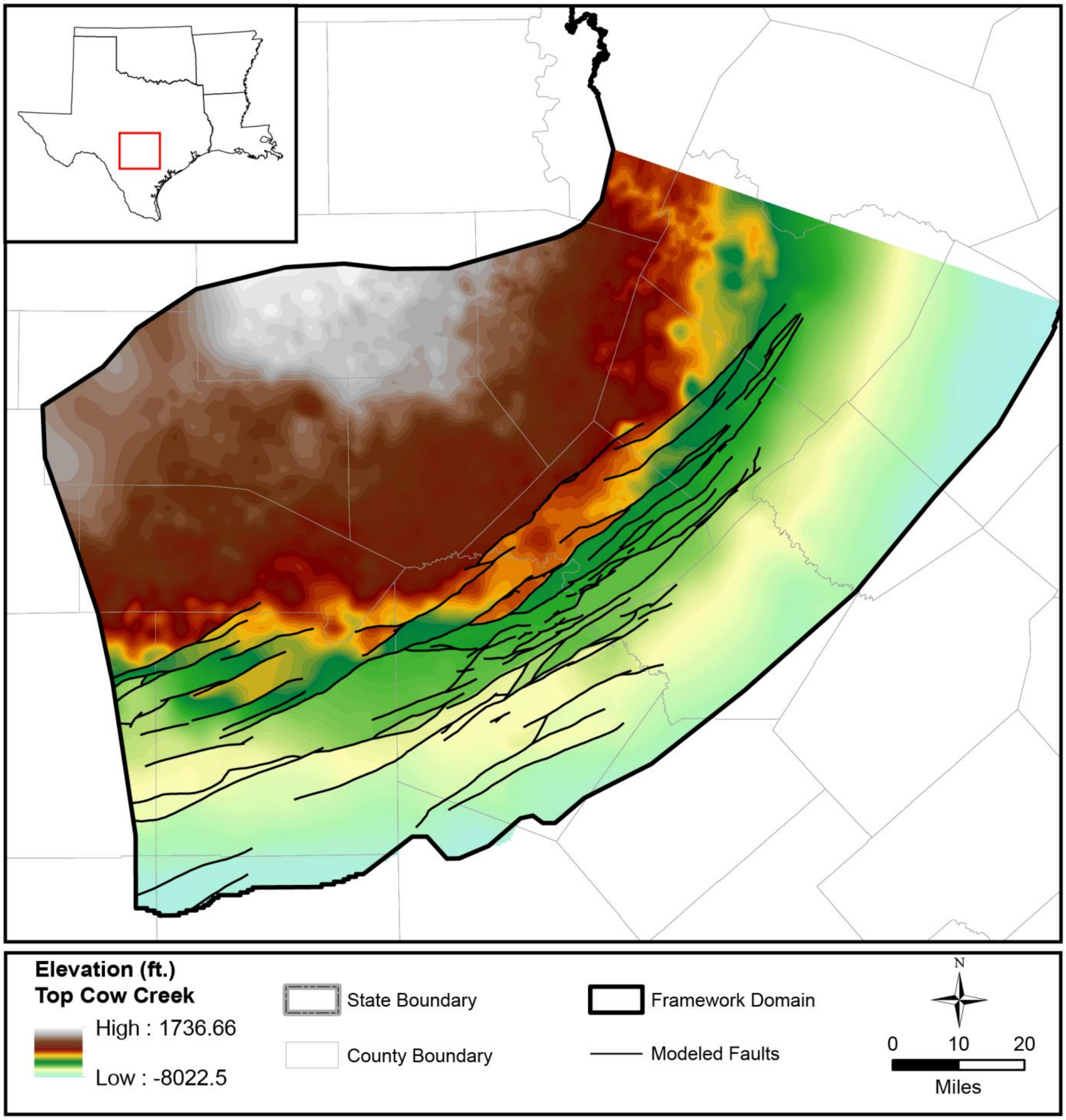


Figure 5-17 Top of the Cow Creek Formation (in feet above mean sea level) and locations of faults that displace Cretaceous-age strata (from Fratesi and others 2015).

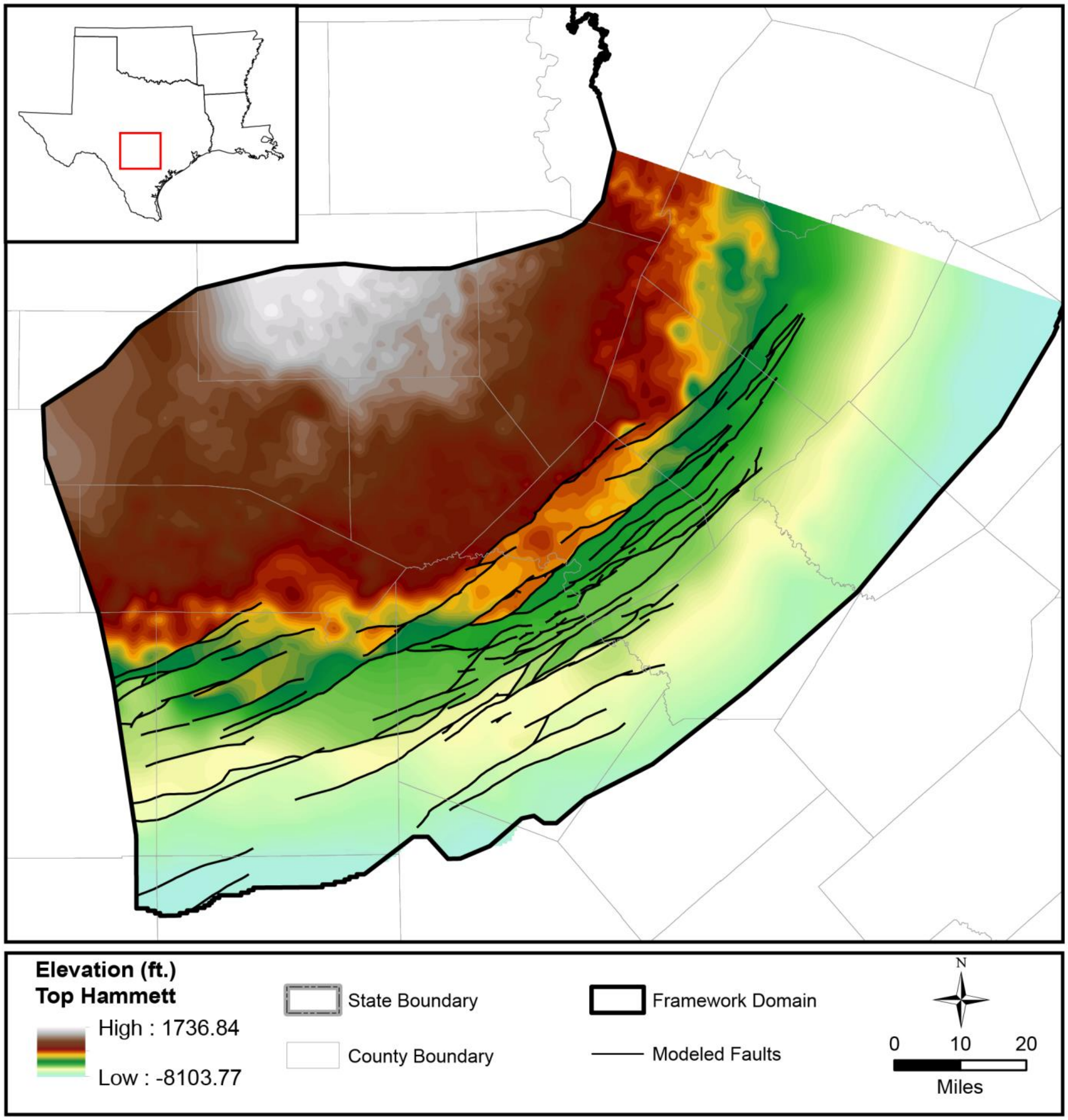


Figure 5-18 **Top of the Hammett Formation (in feet above mean sea level) and locations of faults that displace Cretaceous-age strata (from Fratesi and others 2015).**

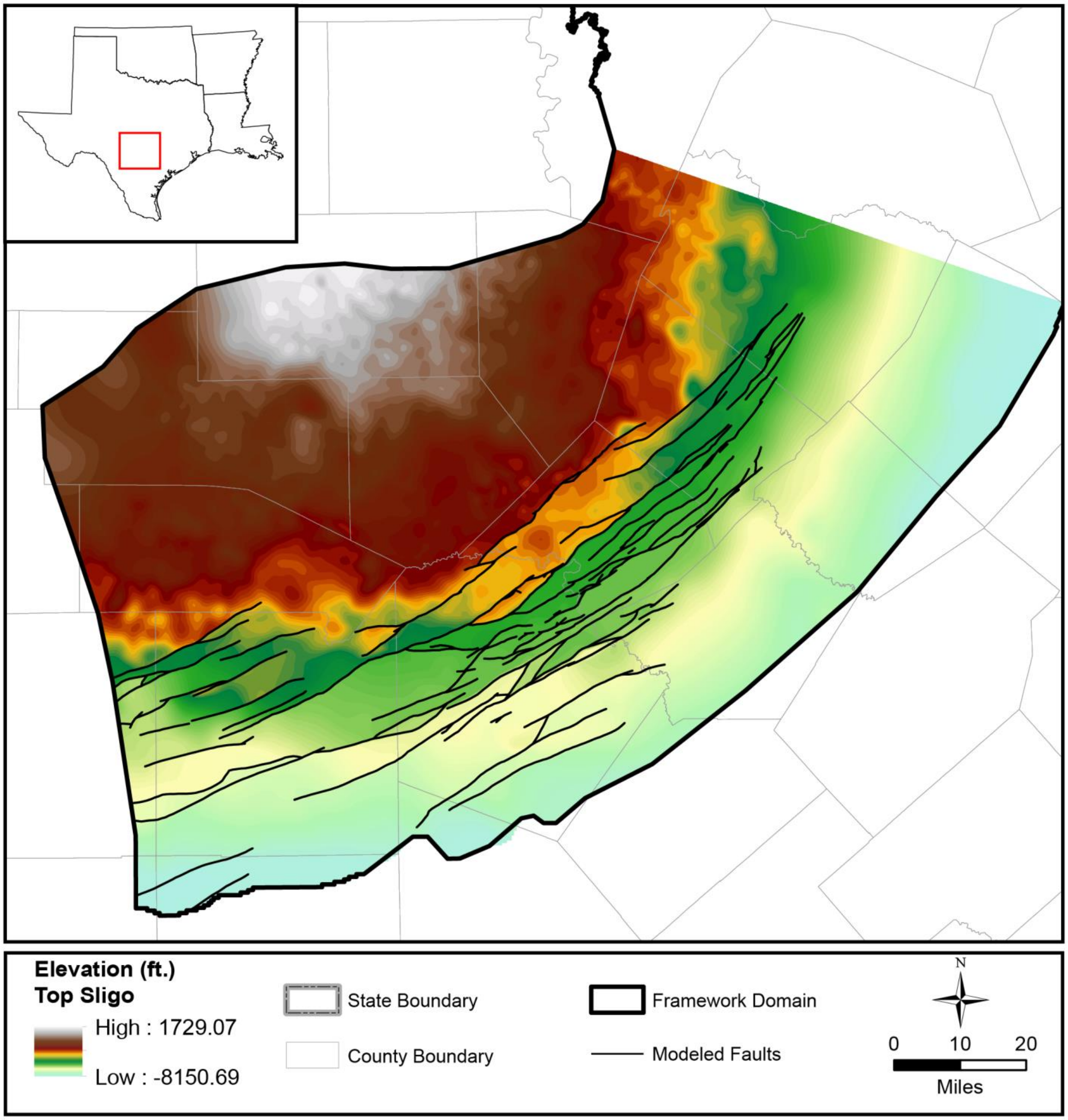


Figure 5-19 **Top of the Sligo Formation (in feet above mean sea level) and locations of faults that displace Cretaceous-age strata (from Fratesi and others 2015).**

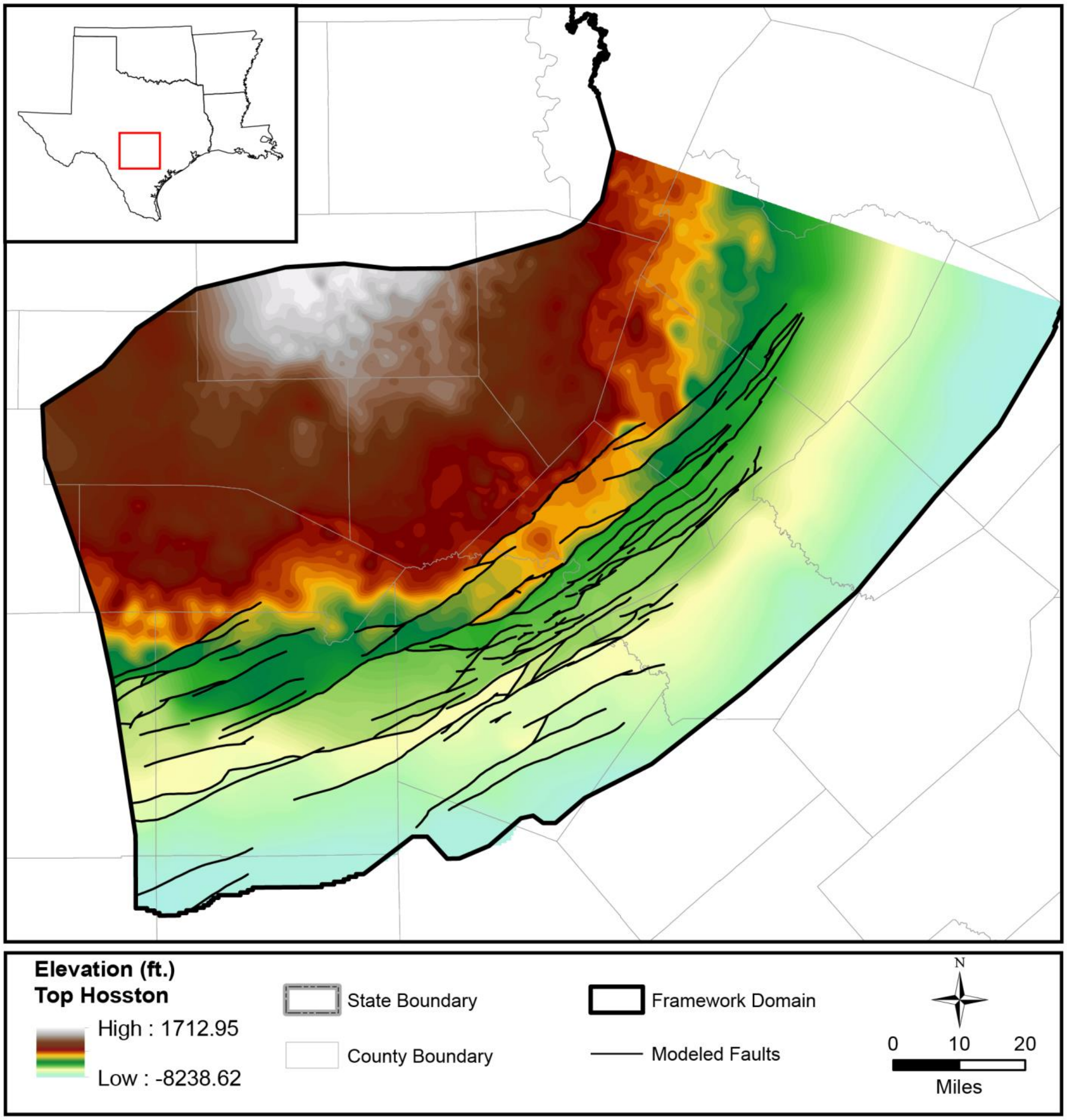


Figure 5-20 Top of the Hosston Formation (in feet above mean sea level) and locations of faults that displace Cretaceous-age strata (from Fratesi and others 2015).

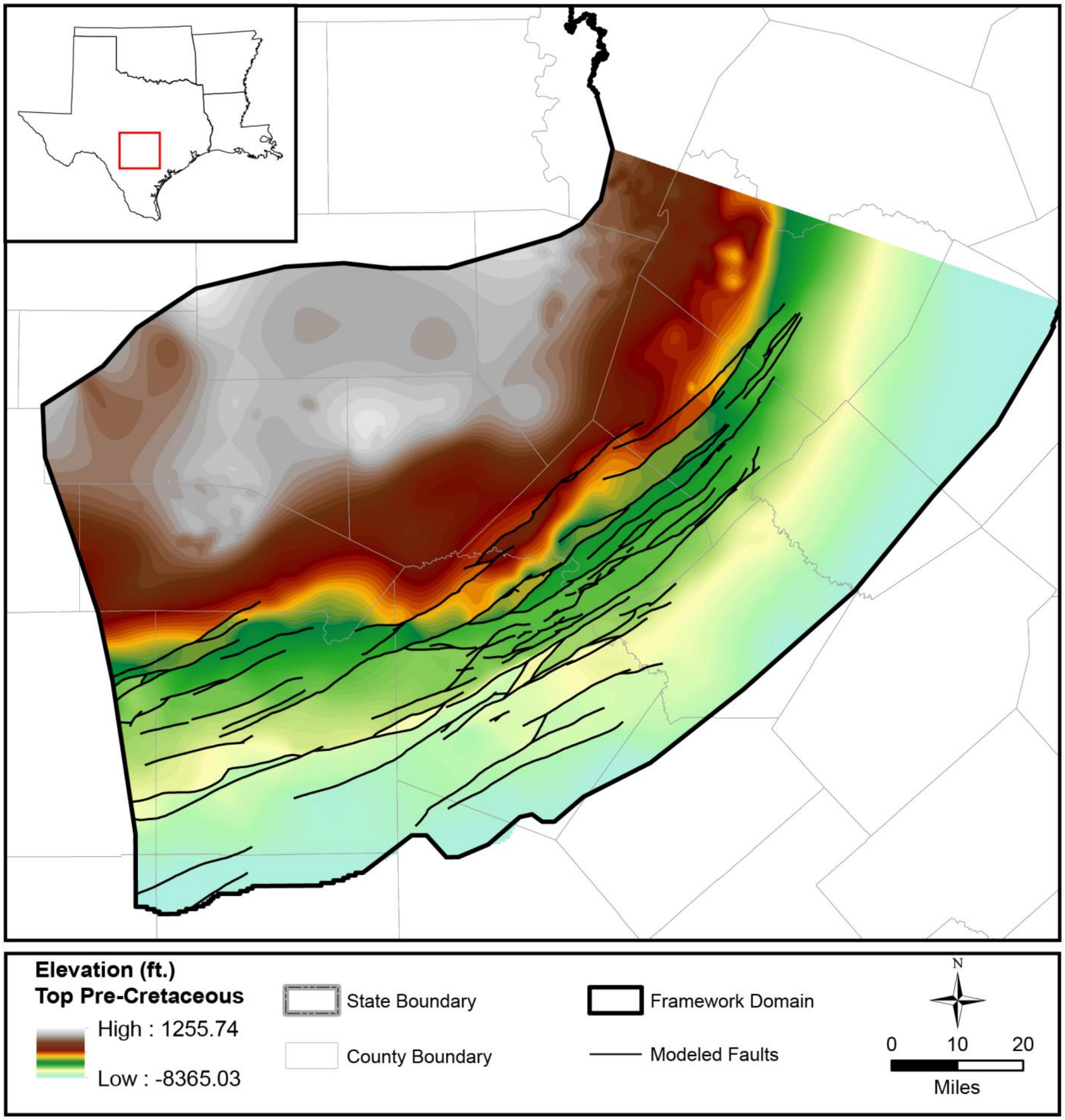


Figure 5-21 Top of Pre-Cretaceous strata (in feet above mean sea level) and locations of faults that displace Cretaceous-age strata (from Fratesi and others 2015).

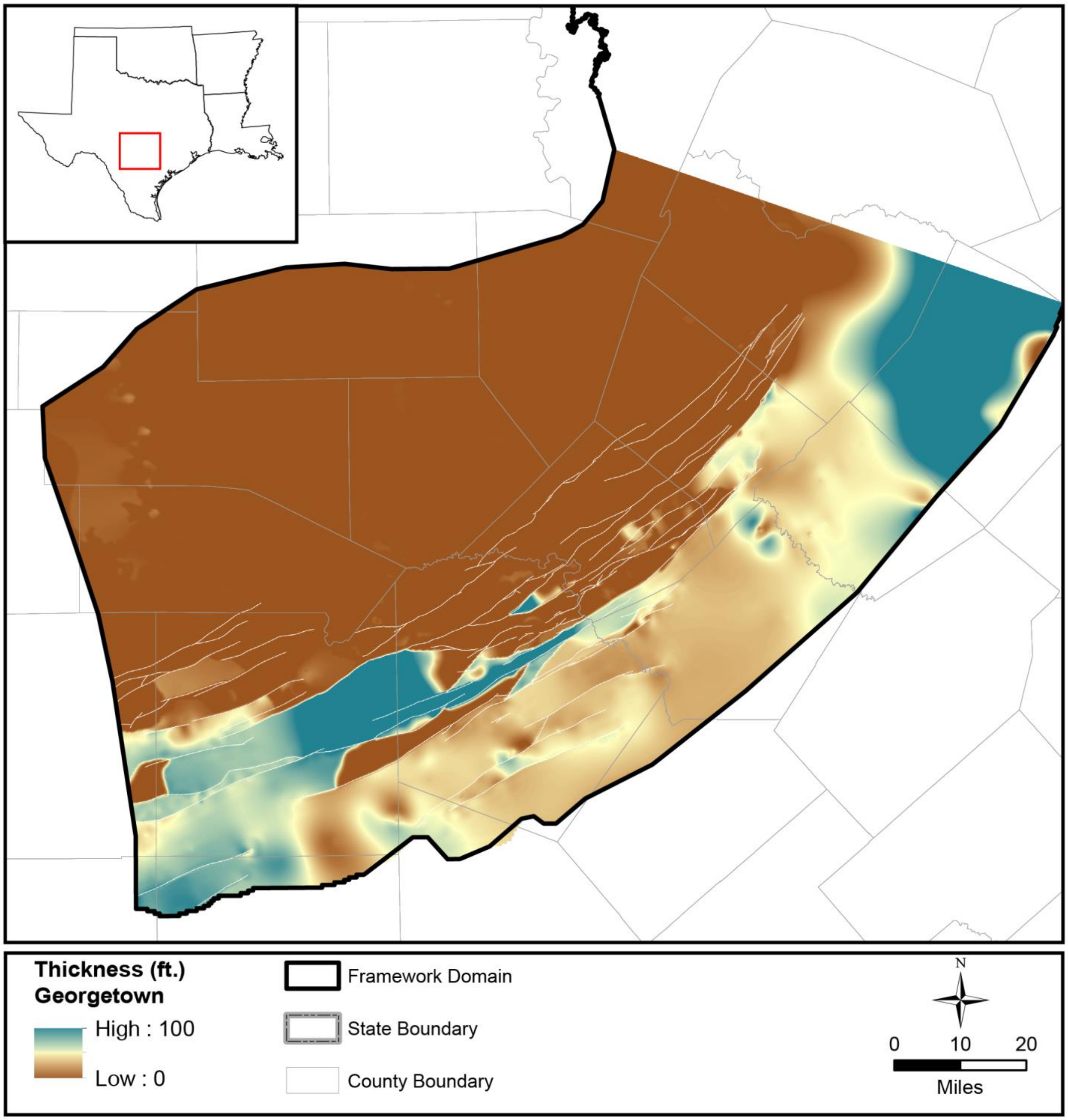


Figure 5-22 Isopach (thickness) map of the Georgetown Formation (in feet) for the Hill Country study area.

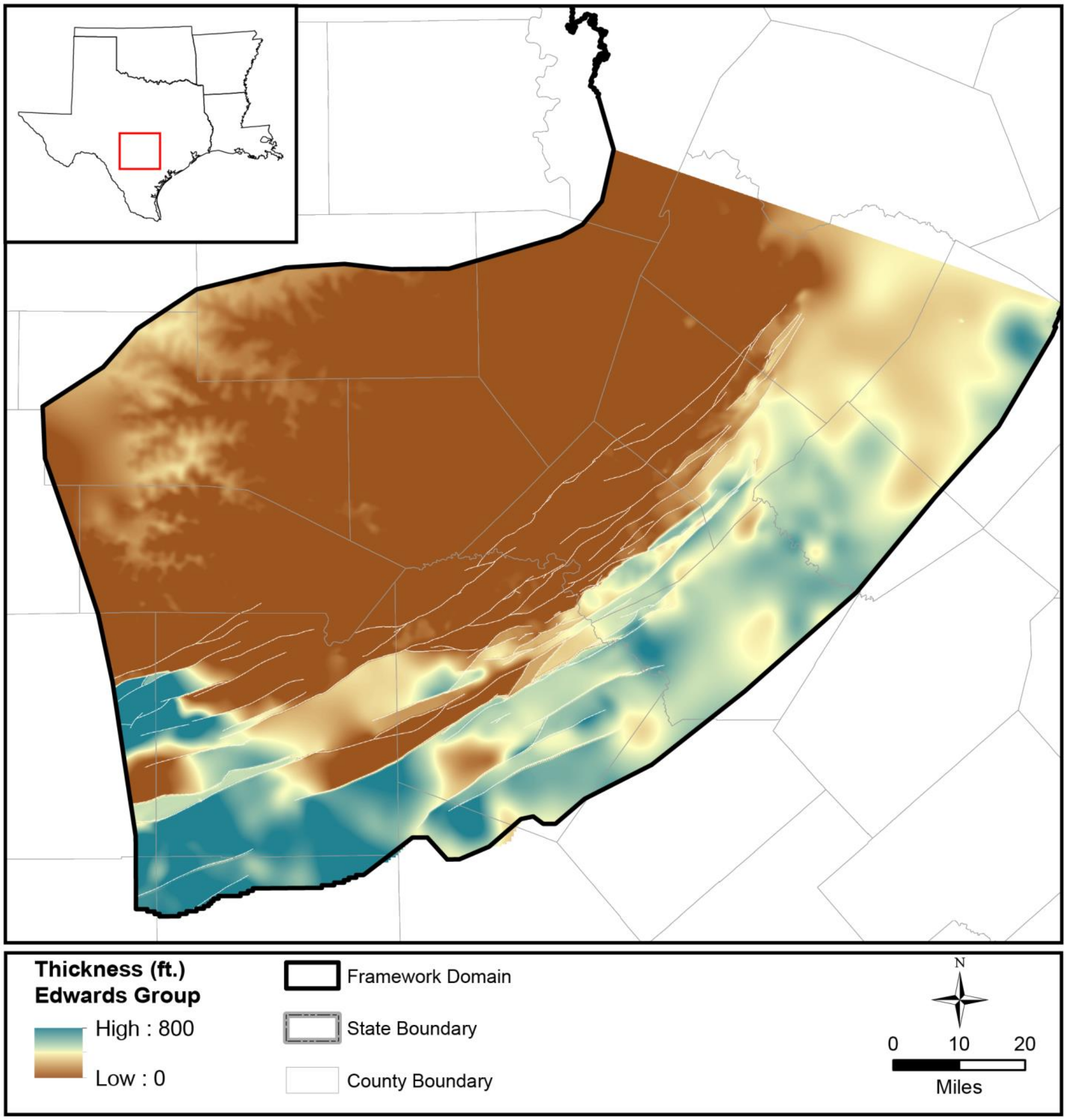


Figure 5-23 Isopach (thickness) map of the Edwards Group (in feet) for the Hill Country study area.

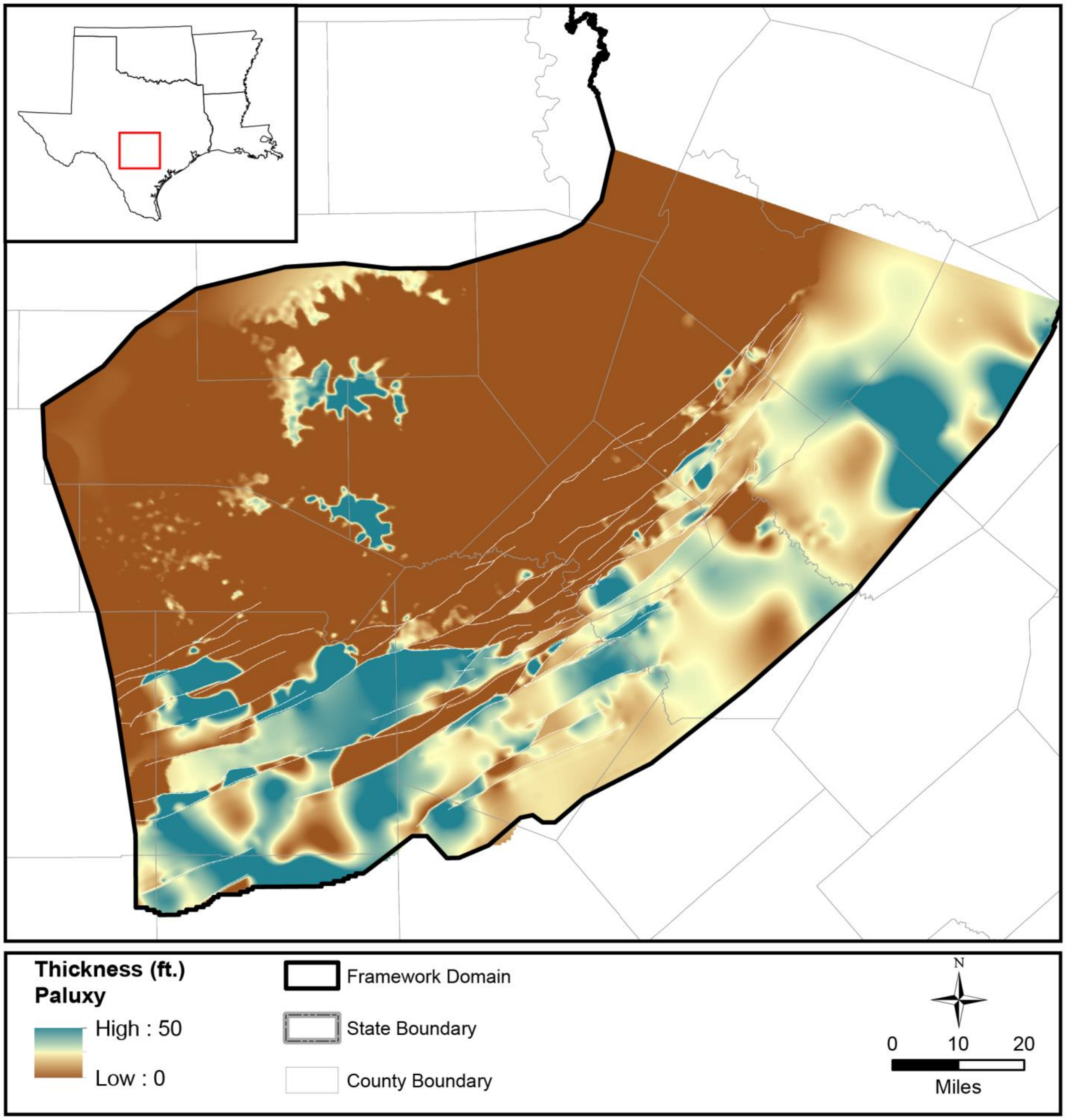


Figure 5-24 Isopach (thickness) map of the Paluxy Formation (in feet) for the Hill Country study area.

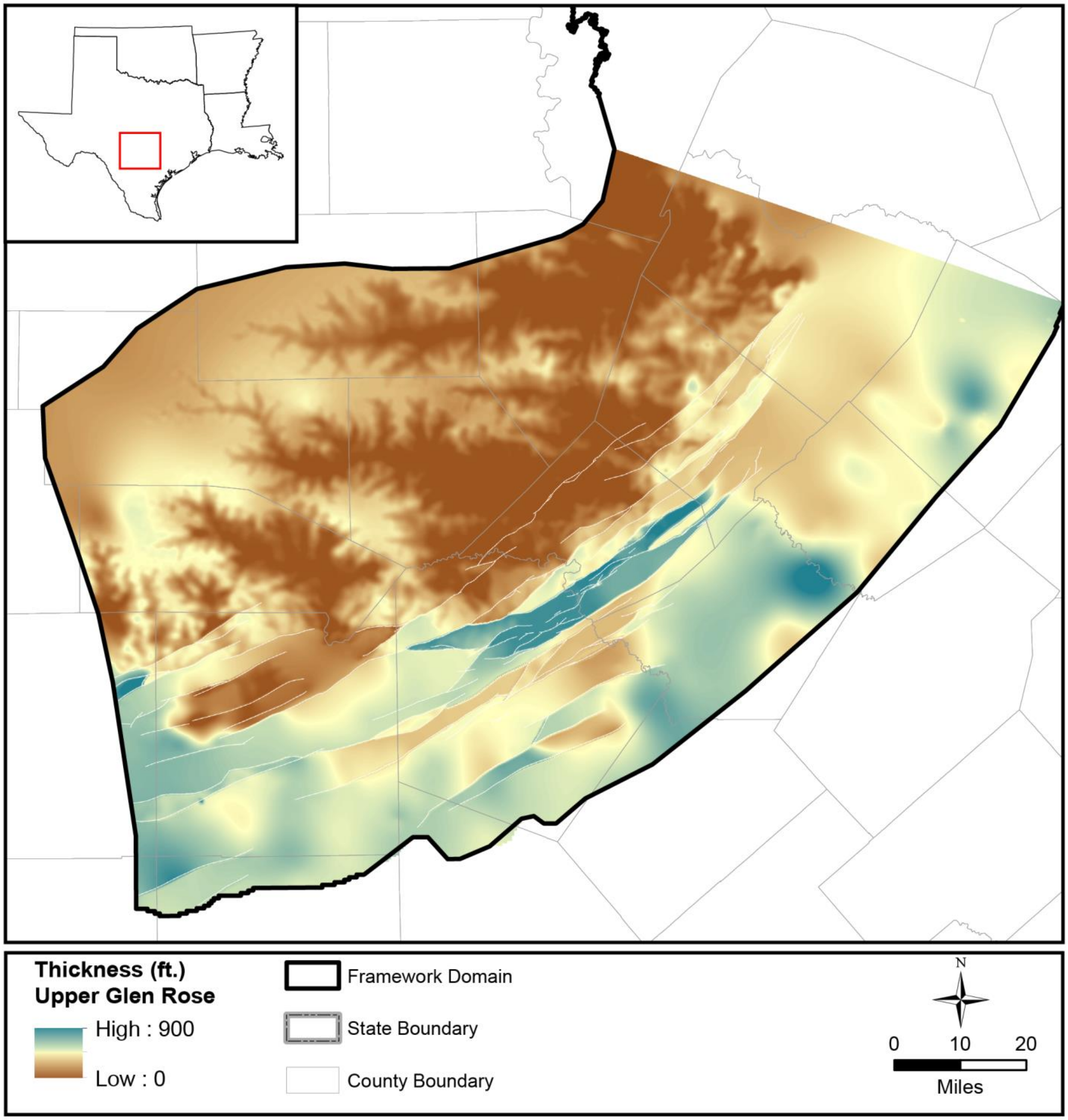


Figure 5-25 **Isopach (thickness) map of the Upper Glen Rose Formation (in feet) for the Hill Country study area.**

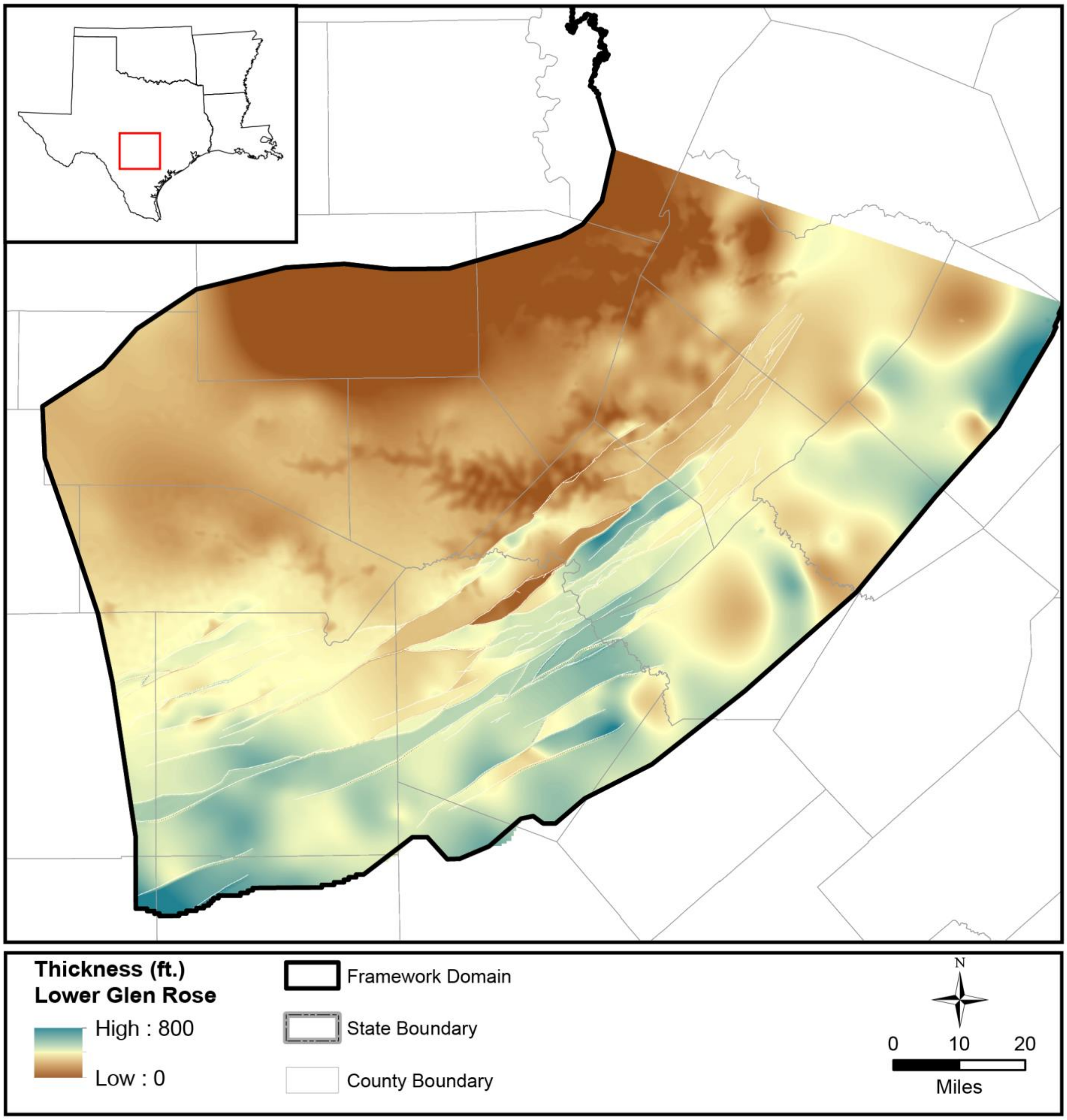


Figure 5-26 Isopach (thickness) map of the Lower Glen Rose Formation (in feet) for the Hill Country study area.

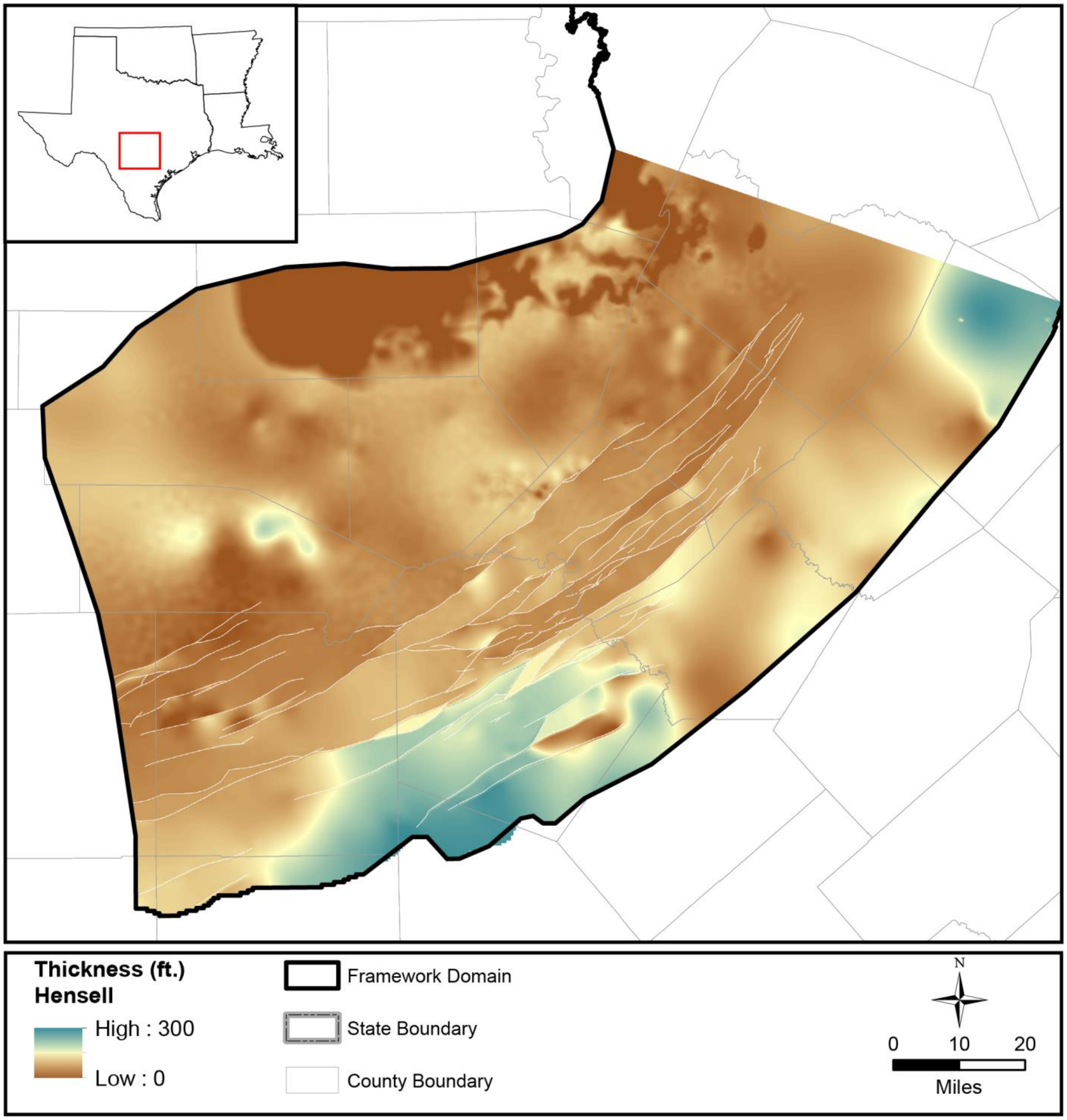


Figure 5-27 **Isopach (thickness) map of the Hensell Formation (in feet) for the Hill Country study area.**

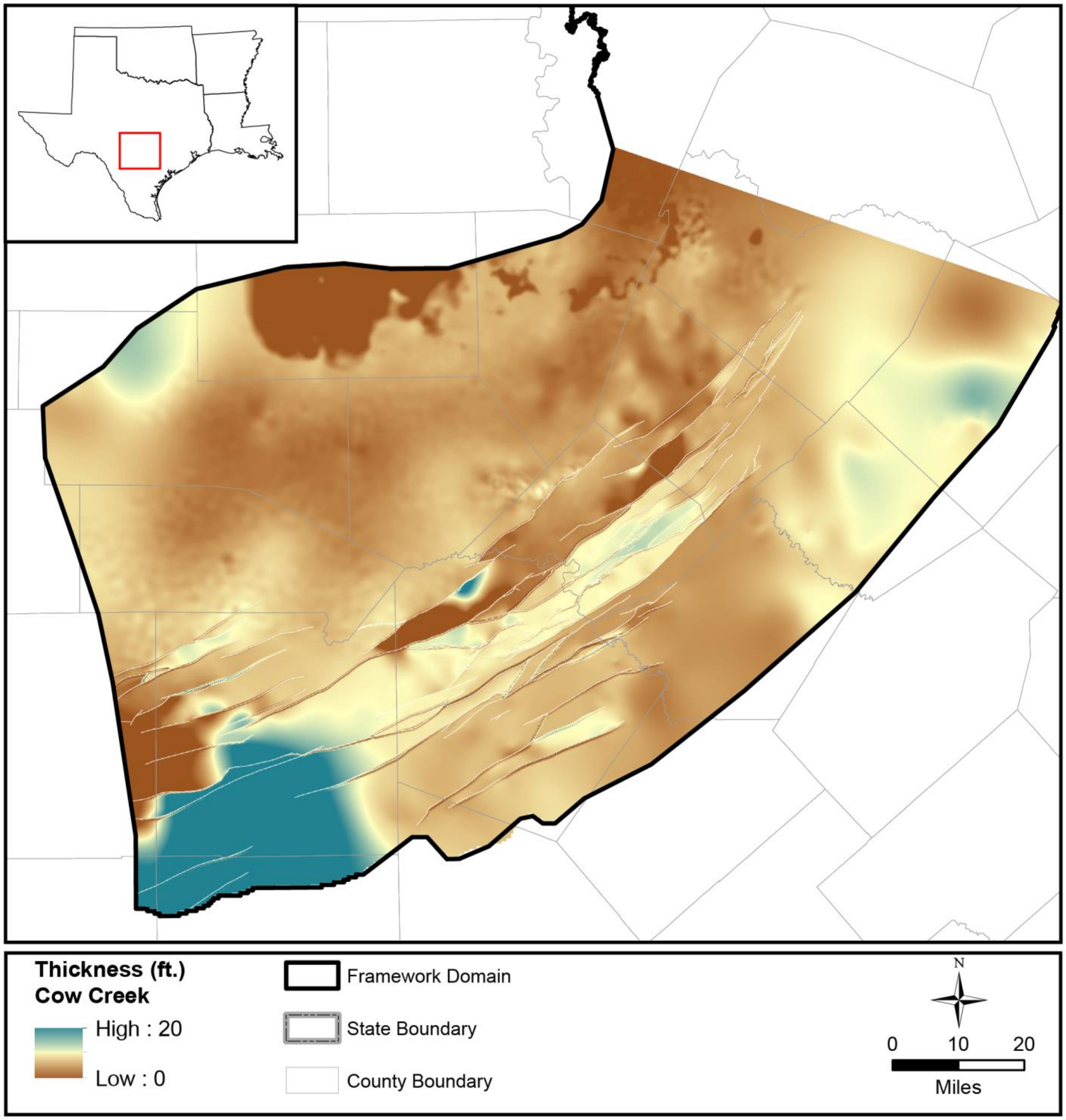


Figure 5-28 **Isopach (thickness) map of the Cow Creek Formation (in feet) for the Hill Country study area.**

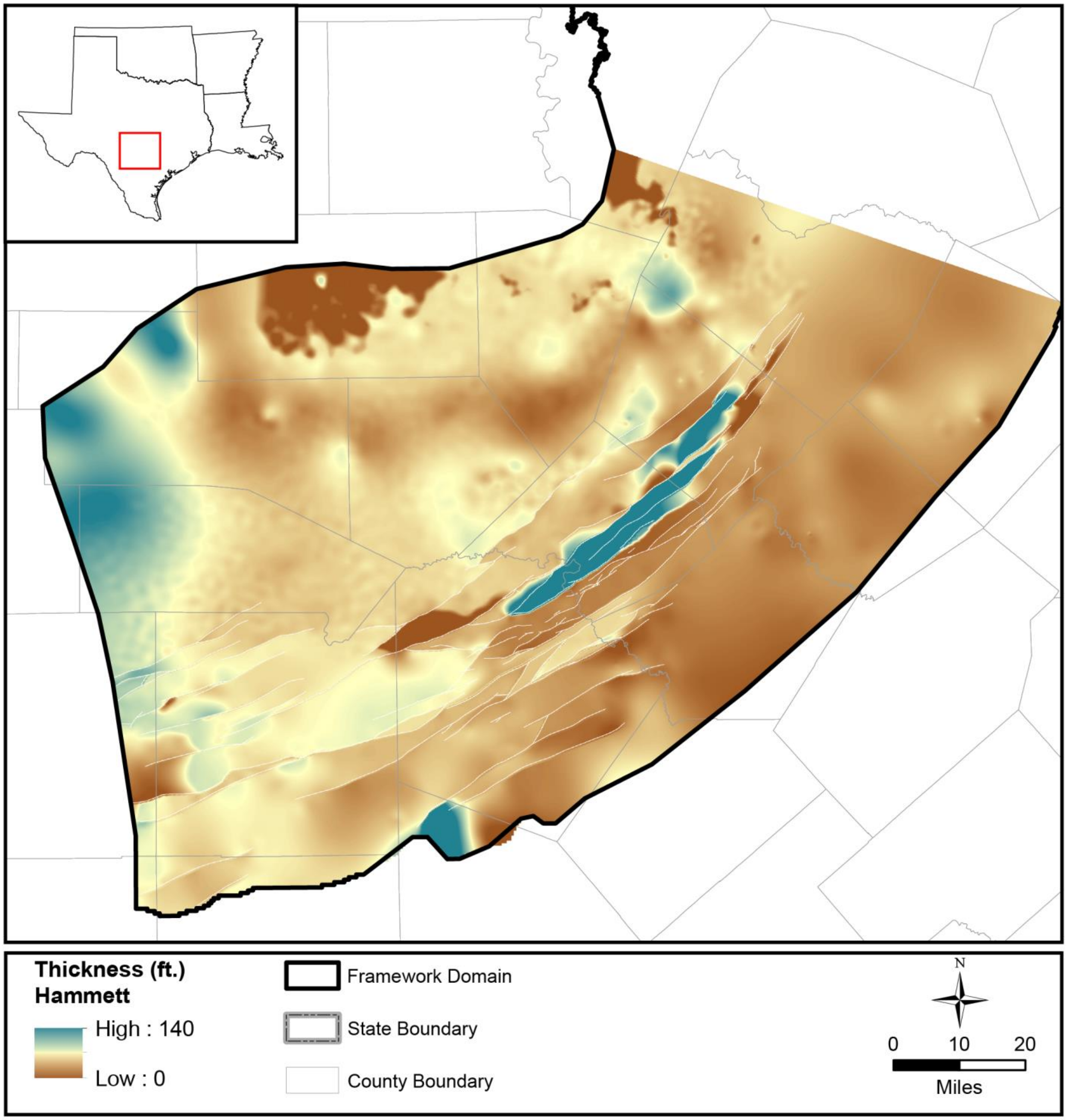


Figure 5-29 Isopach (thickness) map of the Hammett Formation (in feet) for the Hill Country study area.

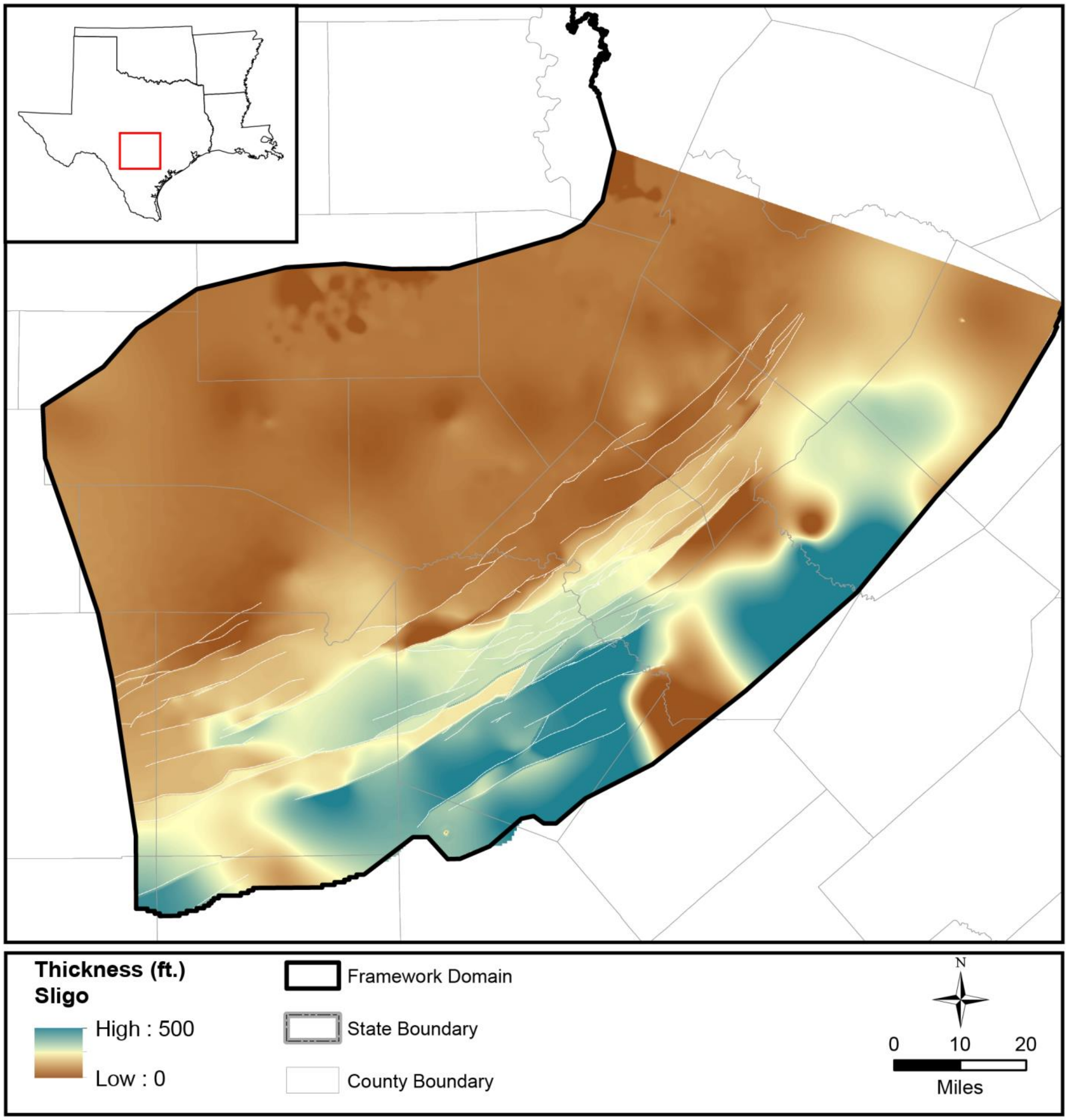


Figure 5-30 **Isopach (thickness) map of the Sligo Formation (in feet) for the Hill Country study area.**

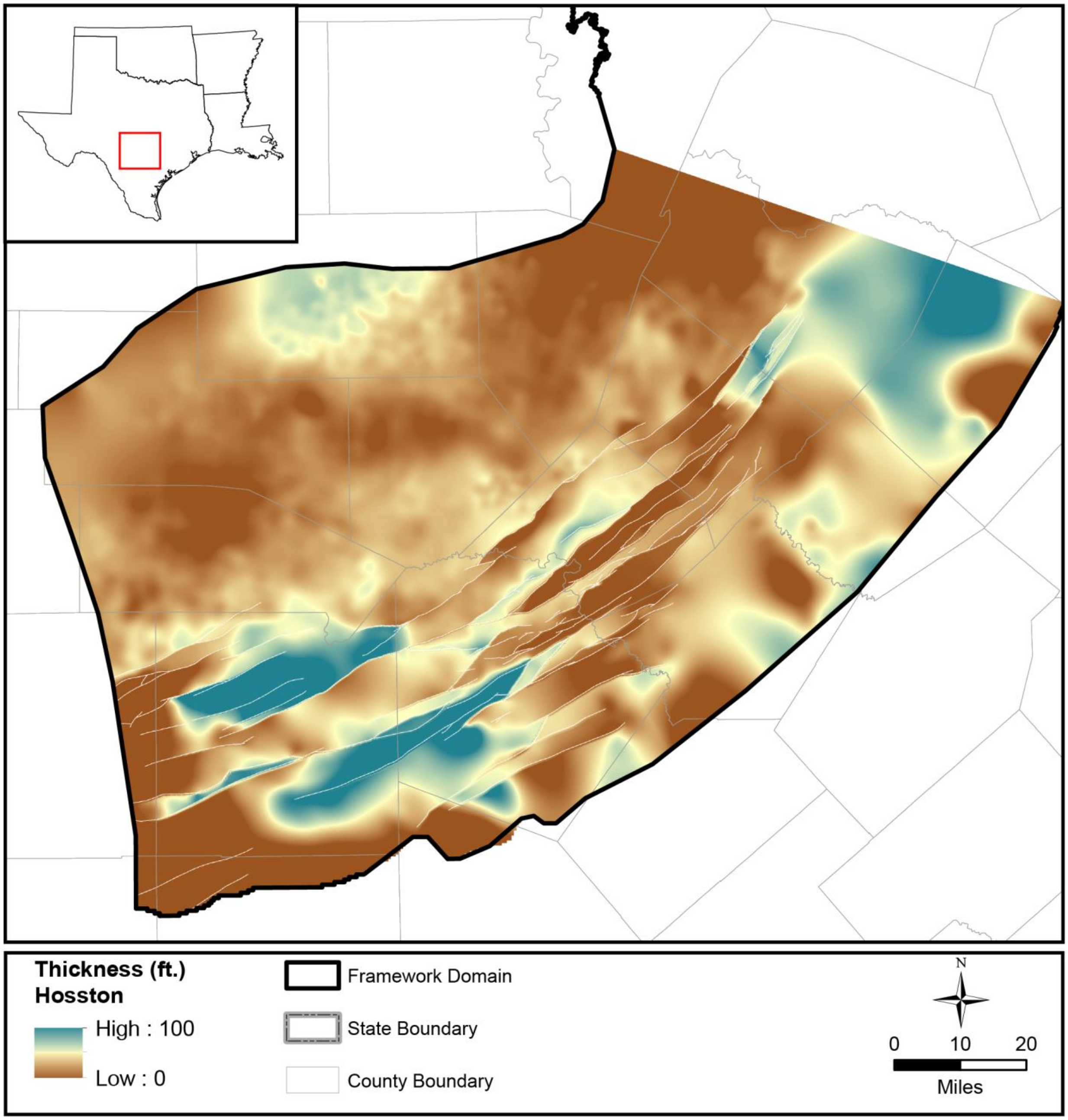


Figure 5-31 **Isopach (thickness) map of the Hosston Formation (in feet) for the Hill Country study area.**

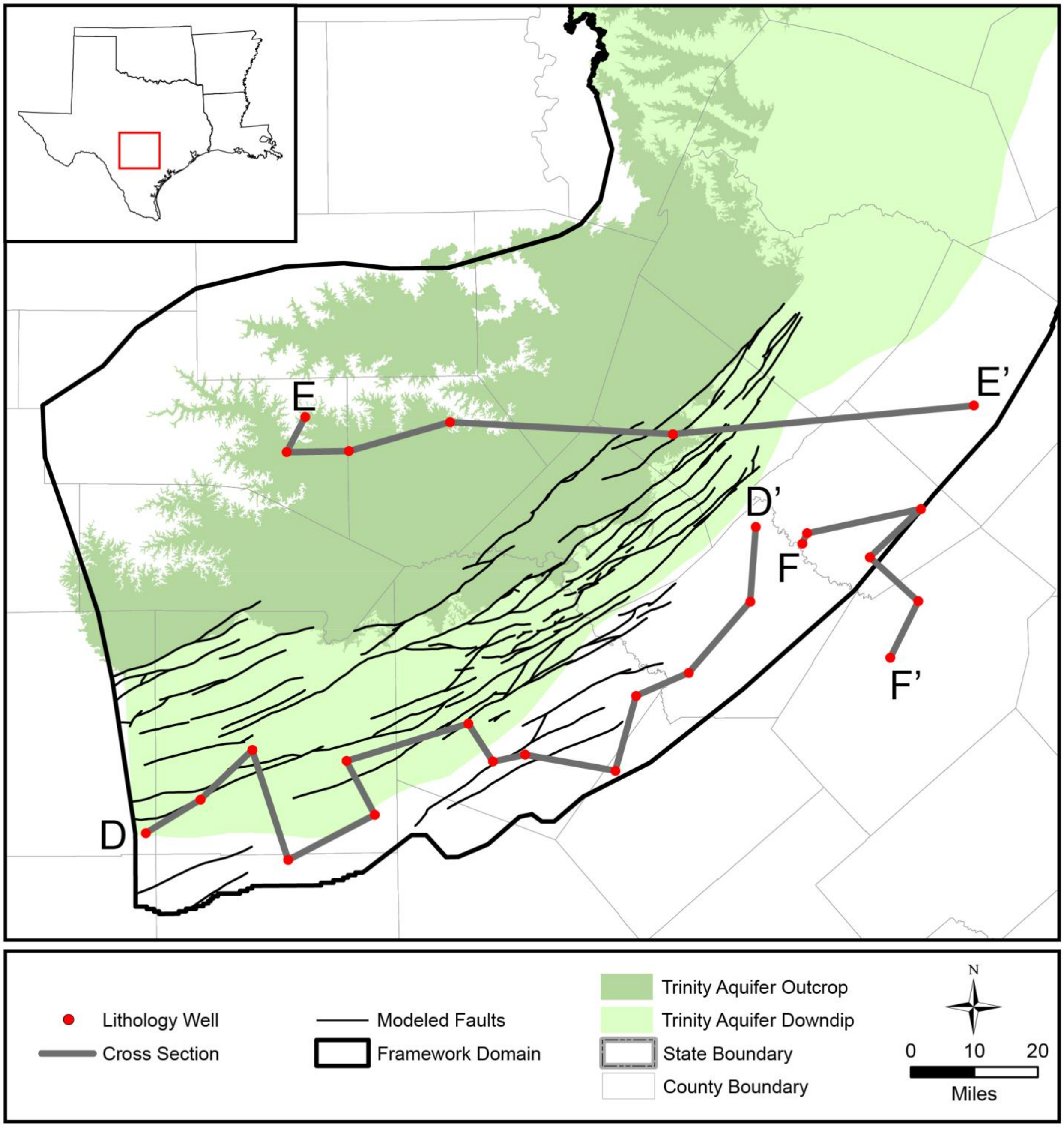


Figure 5-32 Map showing the location of faults (from Fratesi and others 2015) displacing Cretaceous strata in relation to lithologic fence diagrams D-D', E-E', and F-F'.

6 Groundwater Salinity Zones

The groundwater salinity zones delineated in this study were developed via interpretation of geophysical logs used to estimate the concentration of total dissolved solids (TDS) across the study area, as well as available sampled water quality data. It was necessary to employ interpretation of geophysical well logs in the downdip region due to the limited availability of sampled water quality data. A detailed description of sampled water quality data is provided in Section 10.

Salinity zones were classified using the criteria developed by the United States Geological Survey (Winslow and Kister, 1956), illustrated below in Table 6-1. In this study, salinity zones were developed by interpolation of total dissolved solids concentrations picked at sand beds and porous zones using the modified Alger-Harrison method (Alger and Harrison, 1989; Collier, 1993; Estepp, 2010) and explicit correction for variances in the ionic composition of the groundwater. Salinity zones 1,000, 3,000, and 10,000 mg/L were identified. The development and methodology associated with these methods is provided in Section 13.

Table 6-1 Groundwater classification based on the criteria established by Winslow and Kister (1956).

Water Classification Description	TDS Range
Fresh Water	Less than 1,000 mg/L
Slightly Saline	1,000 to 3,000 mg/L
Moderately Saline	3,000 to 10,000 mg/L
Very Saline	10,000 to 35,000 mg/L
Brine	>35,000 mg/L

Note: TDS=total dissolved solids; mg/L=milligrams per liter

6.1 Delineation of Salinity Zones

The following subsections describe the process of delineating the salinity zones for the Hill Country and Northern Trinity aquifers from the sampled water quality data and geophysical log interpretations of water quality.

6.1.1 Hill Country Trinity Aquifer

Water quality calculations were made for lithologic picks from 19 geophysical well logs in the Hill Country Trinity Aquifer. These data were plotted on maps along with sampled water quality data. All wells that had a screened interval measurement and sampled water quality from either the TWDB database or a Groundwater Conservation District were included in the dataset.

The TDS values calculated for this study according to the method described in Section 13 were plotted along with those previously measured on a series of maps (Figures 6-1 – 6-4). These values were contoured by hand to produce TDS > 1,000 mg/L, TDS > 3,000 mg/L, and TDS > 10,000 mg/L contour lines. The 1,000 mg/L TDS lines were generally similar to those from the 2011 Hill Country Trinity Aquifer GAM (Jones et al., 2011), and were modified where additional water quality data or estimates from geophysical logs were available.

6.1.2 Northern Trinity Aquifer

The Kelley et al. (2014) sampled water quality dataset, including formation designations, was used without modification. These data were plotted on a series of maps along with the average calculated water quality value from the geophysical log analyses. These posted values were contoured by hand to produce 1,000, 3,000, and 10,000 mg/L TDS contour lines. The 1,000 mg/L TDS lines were generally similar to those from Kelley et al. (2014), and were modified where additional estimates from geophysical logs were available. The poorest agreement between the sampled and calculated values in the fresh water area occurred in the Hosston Formation. This poor agreement may be because the majority of these wells are water wells and were likely not circulated as long as deeper oil and gas wells. It is assumed that the longer the well is circulated, the more opportunity that 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.

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 expert judgement to determine which values to use when determining the contours. On Figures 6-5 through 6-9, calculated estimates of water quality that were generally not considered when contouring are marked with an “X” through the posted location of the well. On the whole, this approach produces moderate agreement with the sampled water quality data and good agreement with the assumed trend of increasing TDS with depth, and the degradation of water quality near the Mexia Talco fault zone.

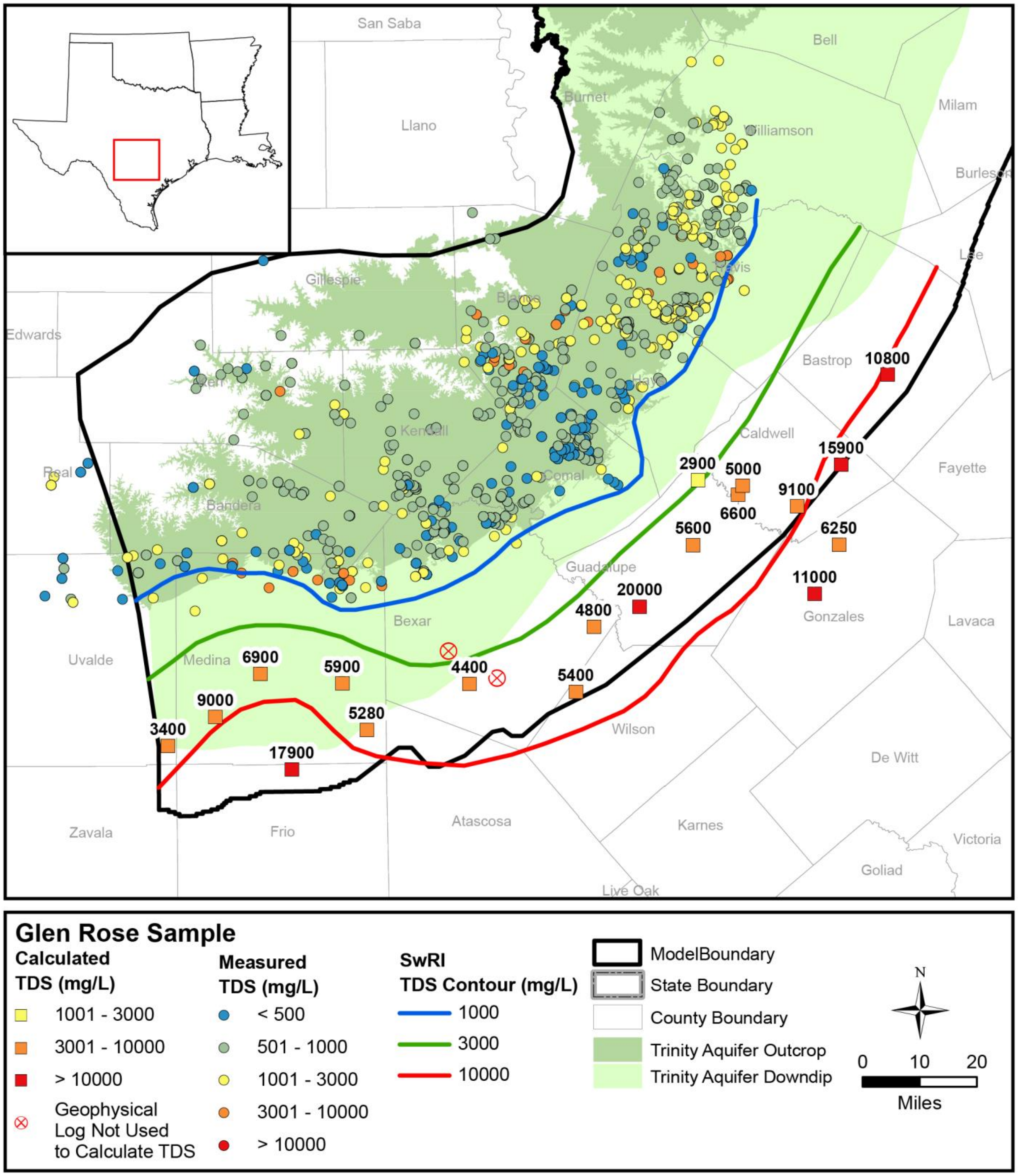


Figure 6-1 Sampled and calculated water quality for the Glen Rose Formation (Hill Country Trinity Aquifer Study Area).

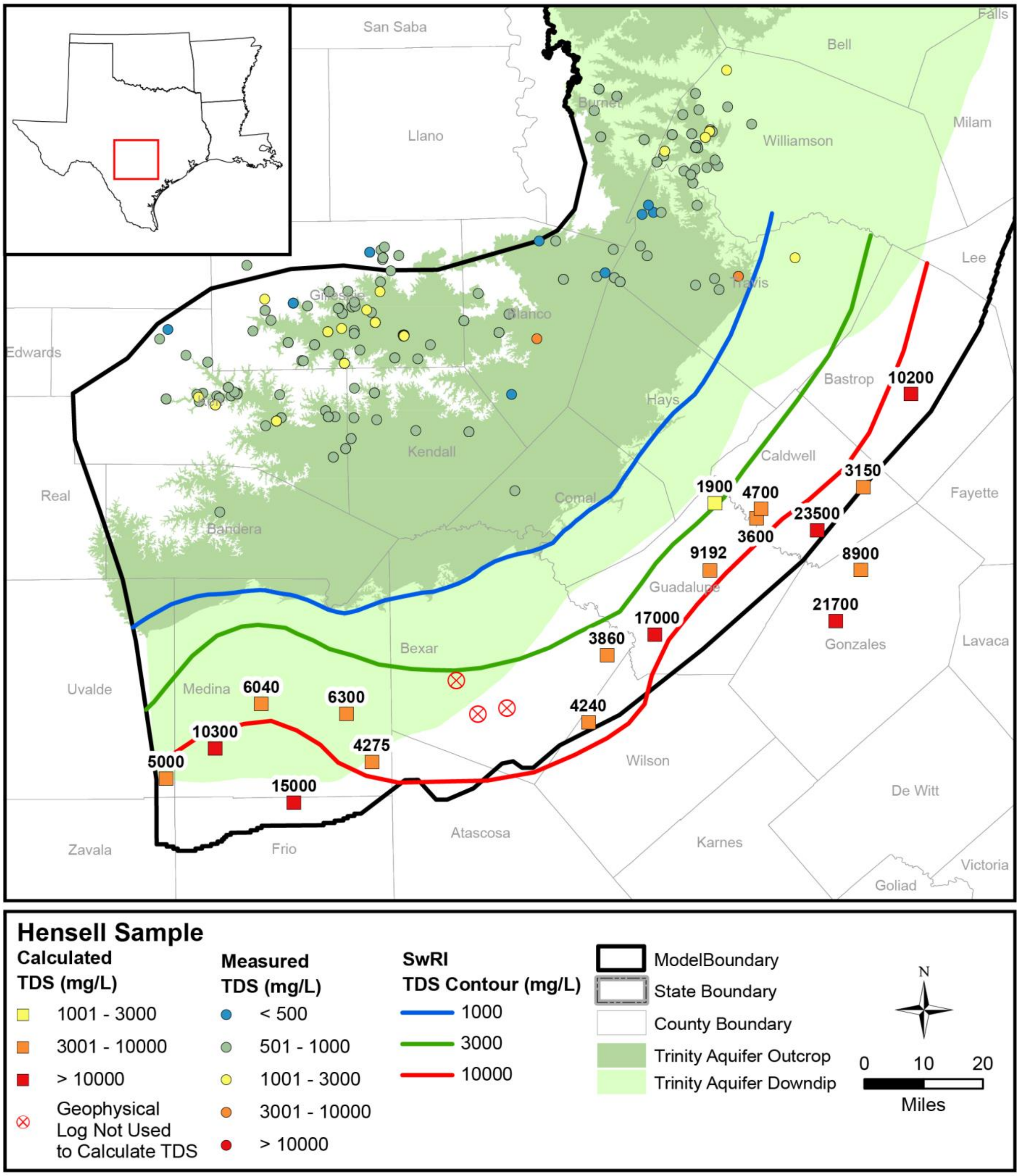


Figure 6-2 Sampled and calculated water quality for the Hensell Formation (Hill Country Trinity Aquifer Study Area).

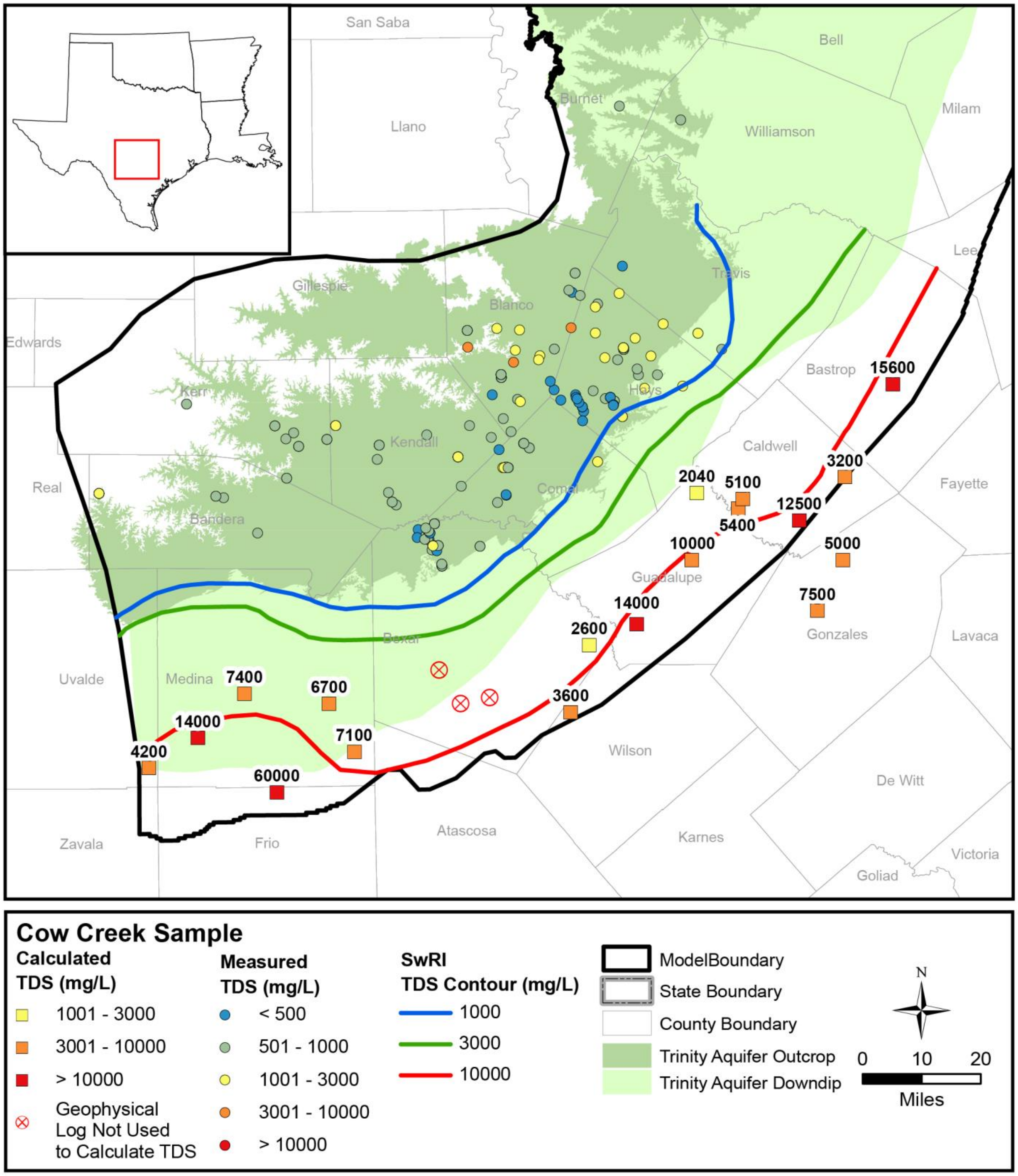


Figure 6-3 Sampled and calculated water quality for the Cow Creek Formation (Hill Country Trinity Aquifer Study Area).

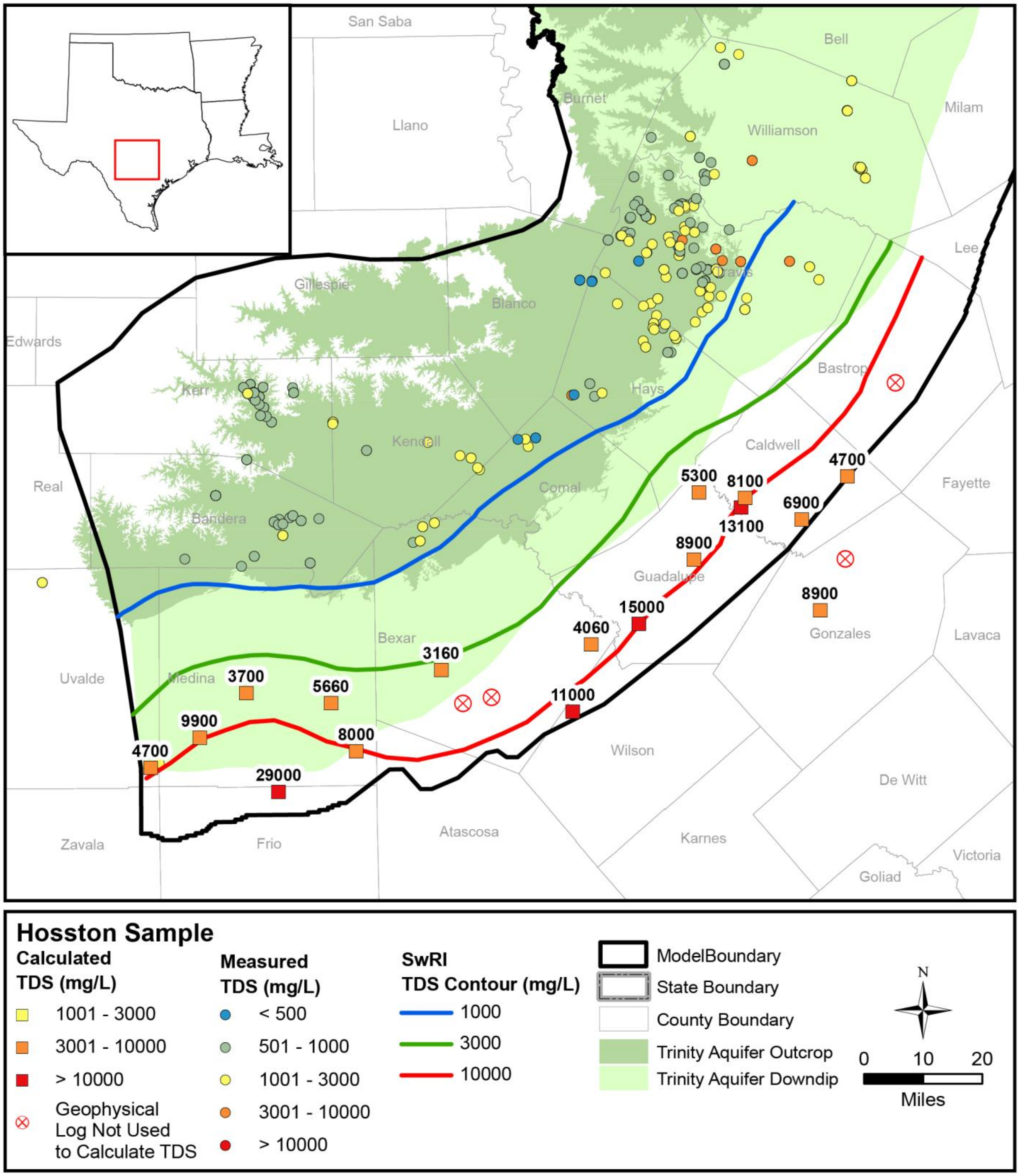


Figure 6-4 Sampled and calculated water quality for the Hosston Formation (Hill Country Trinity Aquifer Study Area).

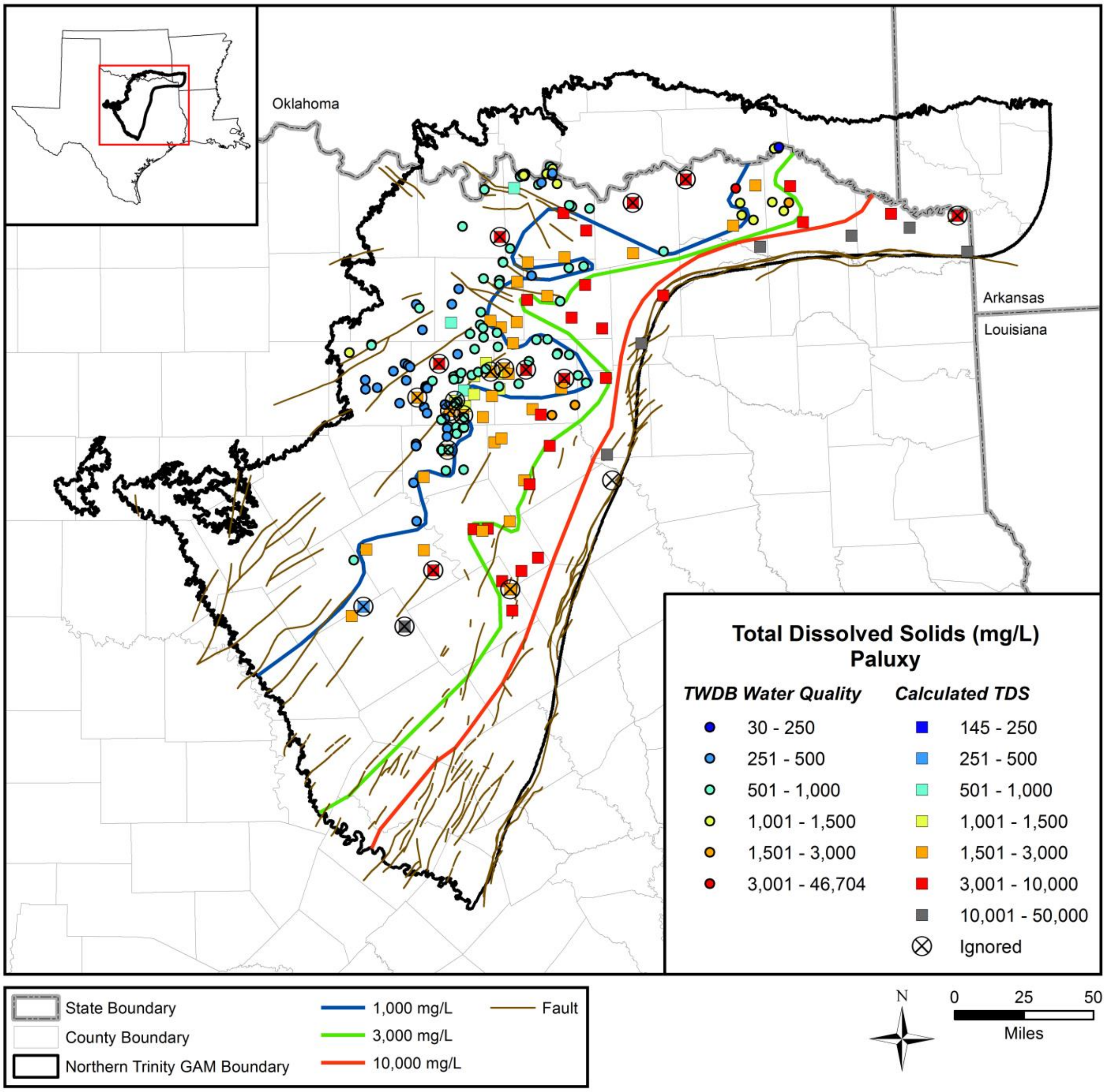


Figure 6-5 Sampled and calculated water quality for the Paluxy Formation (Northern Trinity Aquifer Study Area).

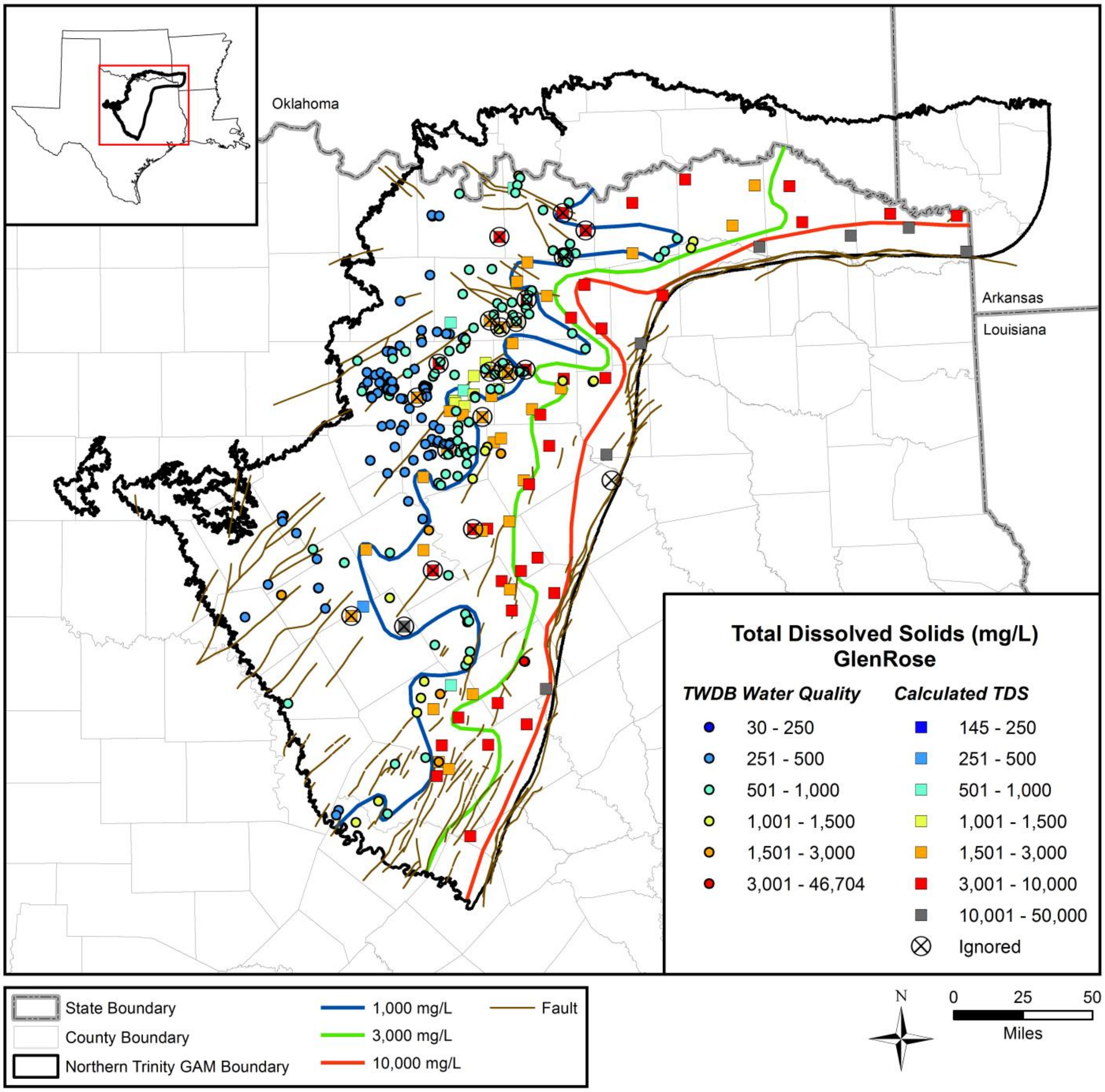


Figure 6-6 **Sampled and calculated water quality for the Glen Rose Formation (Northern Trinity Aquifer Study Area).**

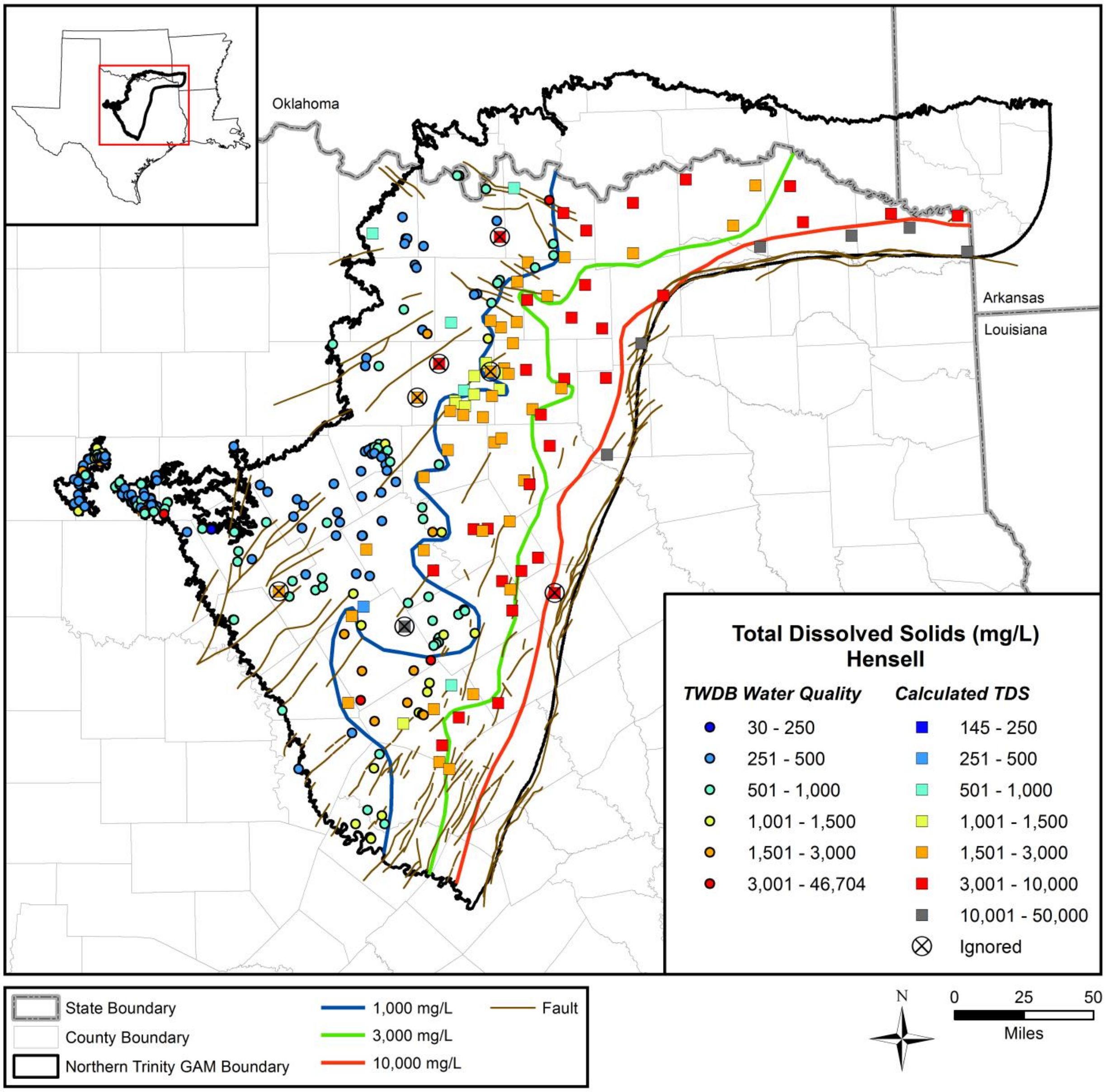


Figure 6-7 **Sampled and calculated water quality for the Hensell Formation (Northern Trinity Aquifer Study Area).**

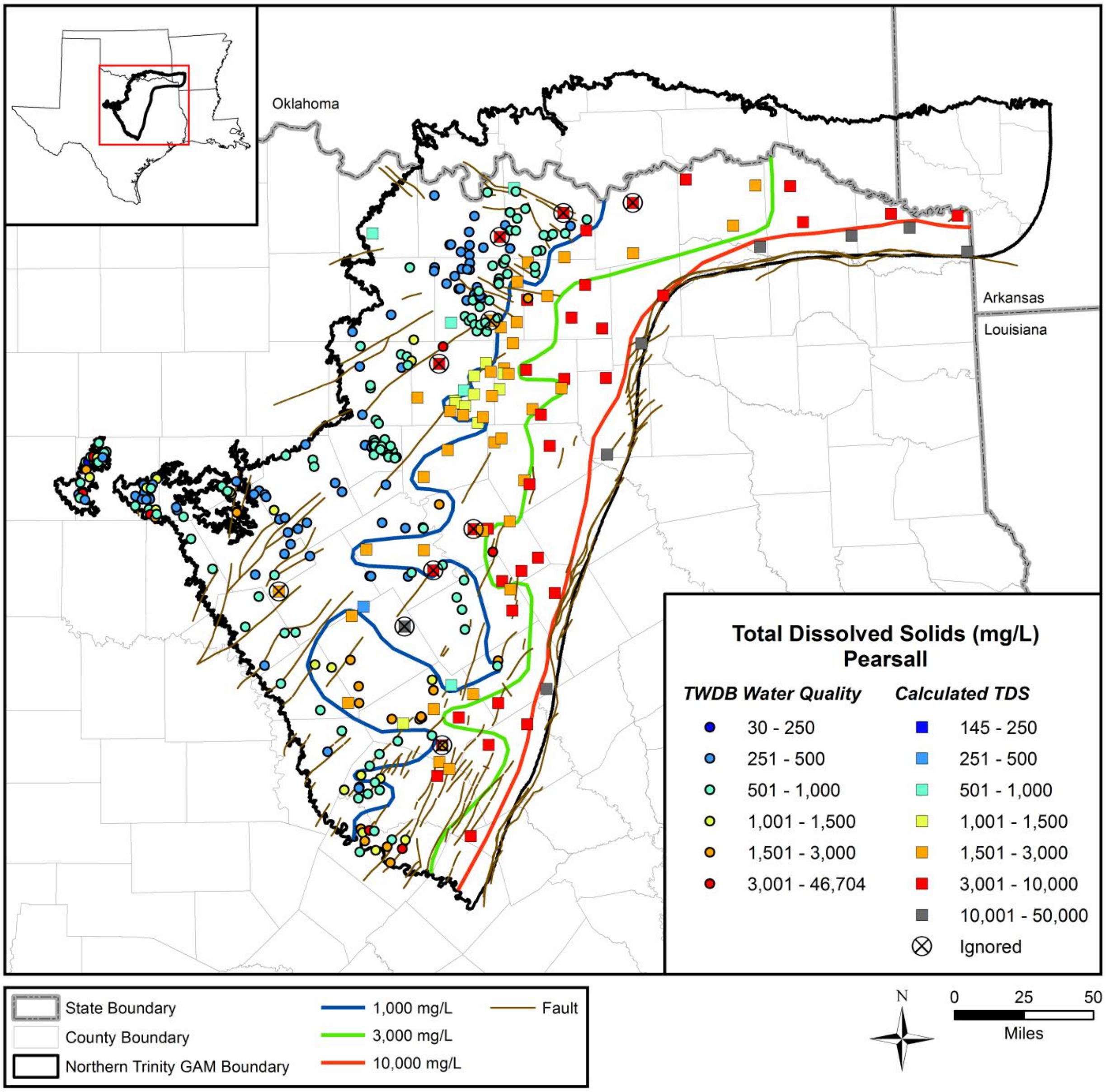


Figure 6-8 Sampled and calculated water quality for the Pearsall Formation (Northern Trinity Aquifer Study Area).

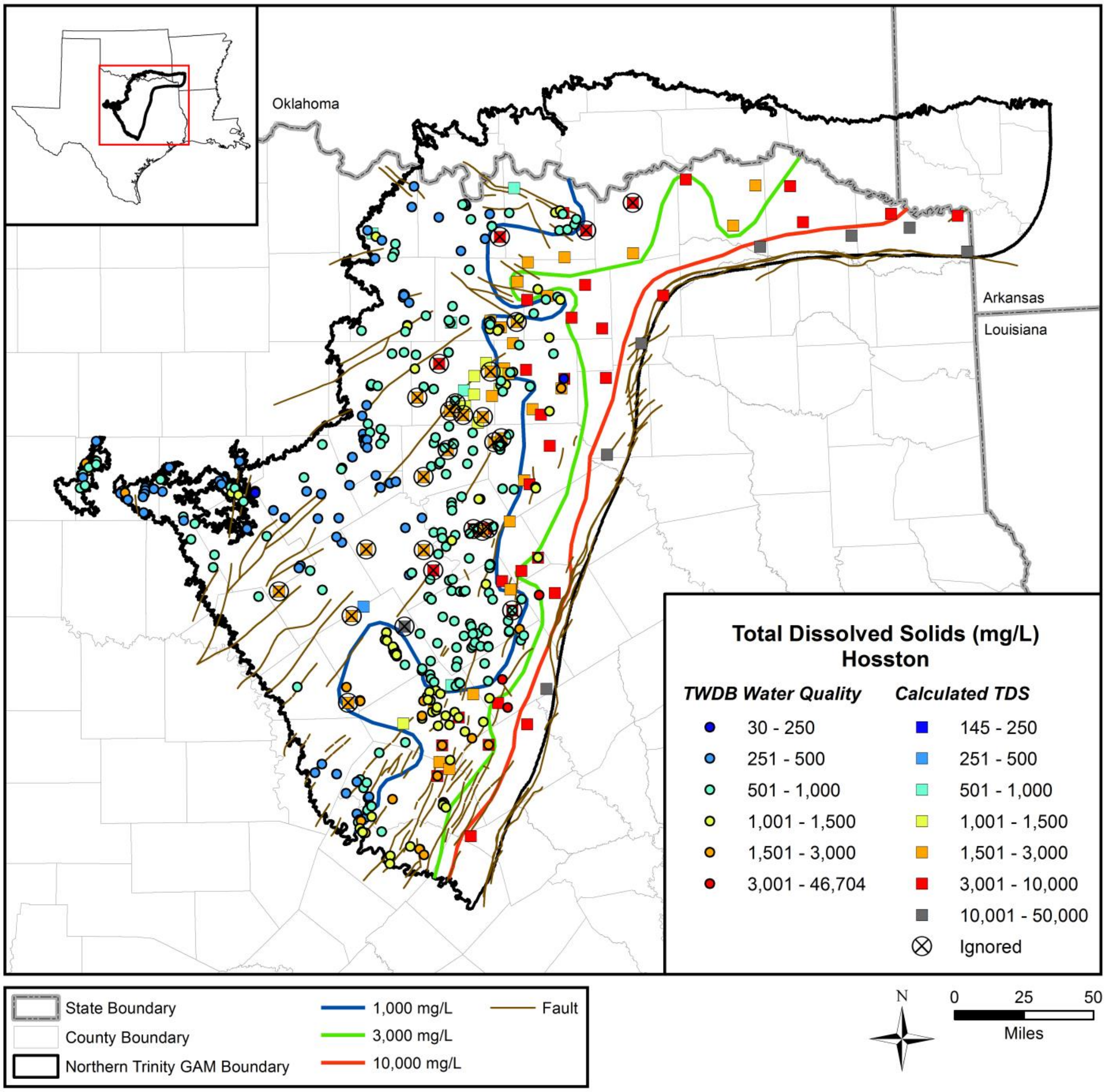


Figure 6-9 Sampled and calculated water quality for the Hosston Formation (Northern Trinity Aquifer Study Area).

6.2 Discussion of Salinity Zones

The following section provides a brief discussion of the salinity zones estimated for the Hill Country and Northern Trinity aquifers.

6.2.1 Hill Country Trinity Aquifer

As illustrated in Figure 6-1, the boundary between fresh water and slightly saline water (the 1,000 mg/L line) for the Glen Rose Formation follows the Trinity Aquifer outcrop line rather closely. The boundary between the slightly saline and moderately saline water (3,000 mg/L contour line) in the Glen Rose Formation mirrors the 1,000 mg/L contour line except for where the 1,000 mg/L contour line moves southeast in Comal County and then northwest in Hays County. This line roughly follows the Trinity Aquifer subcrop boundary but diverges to reflect measurements of higher-TDS data points in Medina County, as well as a shift to the west and back in Bell County. The boundary between moderately saline and very saline water (>10,000 mg/L TDS) mirrors the 3,000 mg/L line. The TDS measurements of the four wells in Medina County, as well as the one well in Frio County, all influence the shape of the salinity zone boundaries around Medina County, causing the boundaries to shift to the north in Medina County.

The Hensell Formation salinity zone boundaries (Figure 6-2) follow trends similar to those of the Cow Creek Formation. The boundary between fresh water and slightly saline water (the 1,000 mg/L contour line) follows the Trinity Aquifer outcrop line, just as the Glen Rose Formation and Cow Creek Formation boundaries do. The boundary between the slightly saline and moderately saline water (3,000 mg/L contour line) in the Hensell Formation mirrors the 1,000 mg/L contour line as the Glen Rose Formation and Cow Creek Formation contour lines do, but bows down into Bexar County. The boundary between moderately saline and very saline water (>10,000 mg/L) mirrors the 1,000 mg/L and 3,000 mg/L contour lines, but dips down to the south more than the others around Bexar County. As in the Cow Creek Formation, the total dissolved solids measurements of the four wells in Medina and Frio counties influence the shape of the salinity zone boundaries in mid-to-western Medina County.

The Cow Creek Formation salinity zone boundaries are illustrated in Figure 6-3. Similarly to the Glen Rose Formation boundary between fresh water and slightly saline water (the 1,000 mg/L contour line), the Cow Creek Formation 1,000 mg/L contour line follows the Trinity Aquifer outcrop line rather closely. The boundary between the slightly saline and moderately saline water (3,000 mg/L contour line) in the Cow Creek Formation mirrors the 1,000 mg/L contour line similar to the Glen Rose Formation contour line, but more closely. A notable exception is where the 1,000 mg/L and 3,000 mg/L contour lines diverge as the 1,000 mg/L contour line curves west into Williamson County, then hooks back east in Bell County before moving back west into Lampasas County . The boundary between moderately saline and very saline water (>10,000 mg/L TDS) mirrors the 1,000 mg/L contour line more closely than the 3,000 mg/L contour line, but continues in a NE-NNE direction out of and past Caldwell County. The total dissolved solids measurements of the four wells in Medina County, as well as the one in Frio County, all influence the shape of the salinity zone boundaries around Medina County as they did in the Glen Rose Formation. In the Cow Creek Formation, this shift to the north occurs farther west in Medina County.

The Hosston Formation salinity zone boundaries (Figure 6-4) follow trends similar to those formations previously mentioned. The boundary between fresh water and slightly saline water (the 1,000 mg/L contour line) follows the Trinity Aquifer outcrop line, but lies a bit farther north toward the southwest. The boundary between the slightly saline and moderately saline water (3,000 mg/L contour line) in the Hosston Formation mirrors the 1,000 mg/L contour line as the others do, with a slight movement north in Hays County, and bows down into Bexar County as the Hensell Formation contour line does. The boundary between moderately saline and very saline water (>10,000 mg/L TDS) mirrors the 1,000 mg/L and 3,000 mg/L contour lines most closely in this formation. As in the previously discussed formations, the TDS measurements of the four wells in Medina and Frio counties influence the shape of the salinity zone boundaries in mid-to-western Medina County with a movement northward and back south toward the west.

6.2.2 Northern Trinity Aquifer

Figures 6-5 through 6-9 show the salinity zone boundaries for the Northern Trinity Aquifer. In all cases, the total dissolved solids concentrations increase from the updip area to the downdip area. In the Paluxy Formation (Figure 6-5), the 10,000 mg/L contour runs approximately parallel to the Mexia-Talco fault zone, with a larger zone of >10,000 mg/L occurring to the south, and generally thinning to the north. The zone between 3,000 mg/L and 10,000 mg/L is about half a county wide in the south, with the 3,000 mg/L contour running parallel to the 10,000 mg/L contour. The exception is in the region around Collin County, where the 3,000 mg/L contour moves updip based on estimates from the geophysical log data. The 1,000 mg/L 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 Formation (Figure 6-6), the 10,000 mg/L contour is nearly coincident with the Mexia-Talco fault zone. Similarly, the 3,000 mg/L contour line is closer to the downdip boundary than in the Paluxy, especially in the southern portion of the area of interest. The 1,000 mg/L contour extends downdip near McLennen County, as well as in southern Collin and Fannin counties.

The 10,000 mg/L contour in the Hensell Formation (Figure 6-7) is set back by about 15 miles from the downdip boundary, and gets nearer to the boundary to the north near the counties bordering Oklahoma. The 3,000 mg/L line mostly follows the same trend along strike, with the exception of an updip bow in Collin County, which is a similar feature as was evident in the Paluxy Formation. The 1,000 mg/L line shows a similar downdip bulge in McLennen County as was seen in the overlying Glen Rose Formation.

In the Pearsall Formation (Figure 6-8), the salinity zone boundaries are similar to those in the Hensell Formation, with the exception of a more pronounced deviation of the fresh water line, updip in Coryell County trending to downdip in McLennen and Falls counties.

In the southern part of the region, the 1,000 mg/L contour in the Hosston Formation (Figure 6-9) is farther downdip than in the overlying formations, especially in the central portion of the study area, where fresh water is present downdip into Dallas and Ellis counties. The brackish zones are correspondingly more compressed towards the downdip boundary at the Mexia-Talco fault zone. The moderately saline zone in particular is narrow in the southern portion of the study area, with less than 10 miles between the 3,000 mg/L and 10,000 mg/L contours in counties such as Falls County.

7 Previous Investigations

Results from previous investigations were used as the foundation to evaluate brackish water in the Trinity Aquifer and other aquifers in Texas (Winslow and Kister, 1956; Flores, 1969; Duffin, 1974, LBG-Guyton Associates and NRS Consulting Engineers, 2003; R.W. Harden and Associates, 2004, 2007; Lambert et al., 2010; Meyer et al., 2012, 2014; Lupton et al., 2016; Young et al., 2016). Given the expanse of the study domain, the scope of investigations is not uniform over the aquifer. For example, the GAM studies for the Northern Trinity Aquifer (Kelley et al., 2014; Kelley and Ewing, 2014) are more comprehensive than similar studies for the Hill Country portion of the Trinity Aquifer (Mace et al., 2000a,b; Jones et al., 2011). This section provides a summary of the previous investigations that were used to develop the stratigraphic; hydrogeological, geochemical, geothermal gradient, and geophysical frameworks of the study domain.

7.1 Stratigraphic Framework Studies

Stratigraphic and structural data over the extent of the domain were collected and evaluated. Sources for data compiled for this project include: (i) Brackish Resources Aquifer Characterization System (BRACS)/TWDB databases, (ii) groundwater conservation districts, (iii) oil and gas databases including IHS Markit, (iv) water-supply wells, (v) Texas Commission on Environmental Quality (TCEQ) Public Supply, (vi) United Stated Geological Survey (USGS) Produced Water databases, and (vii) literature.

Fundamental to development of the stratigraphic framework are geologic maps prepared by the Bureau of Economic Geology (Brown et al., 1974; Barnes, 1979, 1981a,b, 1983; Pittman, 1989; Collins et al., 1991; Collins and Hovorka, 1997; Collins, 2002). Structural stratigraphic maps and study results are available for sub-domains within the greater study domain (Flawn et al., 1961; Tucker (1962a,b); Rogers, 1967; Rose, 1967; Stricklin et al., 1971; Maclay and Small, 1986; Collins, 1995; Small et al., 1996; Small and Lambert, 1997; Clark, 2004; Clark et al., 2009; Clark and Morris, 2015). Of particular interest are results of studies from the lower and middle Trinity rocks (Amsbury, 1974, 1988, 1996; Amsbury and Jones, 1999) the lower units in the Cretaceous Formation (Imlay, 1945) including the Antlers Formation (Morton, 1992), Hosston Formation (Bebout et al., 1981; McGowen and Harris, 1984) and the basal Trinity sands (Fisher and Rodda, 1967; Boone, 1968) because of their potential as a source of brackish water.

7.1.1 Well Log Studies

Significant efforts have been devoted to the interpretation of geophysical logs when discerning geology and water chemistry. Much of this effort has been driven by the petrochemical industry. A host of analytical tools were assessed for use in this study (Bateman and Konen, 1977; Dewan, 1983).

Geophysical logs acquired from BRACS/TWDB databases, the IHS Markit database, and other sources (listed above) were compiled for use in this project. The main geophysical logs used on this project include gamma, resistivity (shallow and deep), and spontaneous potential (SP). Other logs considered include sonic, mud filtrate, and density. Wells from the BRACS database were selected using a structure-contour surface of the (i) upper Glen Rose and (ii) lower Glen Rose designated by the GAM for the Northern Trinity Aquifer and by Fratesi et al. (2015) for the Hill Country Trinity Aquifer. Elevations from these surfaces are consistent with the elevations of the Upper Trinity Aquifer structure contour surface from the Hill Country Trinity Aquifer and Northern Trinity Aquifer GAMs. Total depth for each well was used to constrain logs that fell within the horizon defined by these two Glen Rose surfaces.

Published geologic maps were used to extract elevations for mapped geologic contacts that define hydrologic boundaries to provide control on boundaries in areas of limited or no well data. Geologic maps used in this fashion included maps published by the Bureau of Economic Geology (Barnes, 1977, 1983; Fisher, 1983; Collins and Hovorka, 1997; Collins, 2000) and the U.S. Geological Survey (Blome et al., 2005a,b).

Given the vast extent of the Trinity Aquifer in Texas, there are changes in facies of the formations that comprise the aquifer. Evaluations of the facies include Stricklin and Smith (1973); Inden (1974), Stricklin and Amsbury (1974); Hall (1976); Inden and Moore (1983), Maclay, (1995), Clark (2003), Scott (2007),

Fault interpretations produced by the United States Geological Survey (Blome et al., 2005a,b) and the Bureau of Economic Geology (Barnes, 1977, 1983; Fisher, 1983; Collins and Hovorka, 1997; Collins, 2000) were evaluated and compared as part of the data assimilation process.

The Trinity Aquifer consists of the following formations: (i) the upper portion of the aquifer consists of the upper member of the Glen Rose Formation, (ii) the middle portion consists of the lower member of the Glen Rose Formation and the Cow Creek Limestone, which are separated by the Hensell Sand or Bexar Shale, and (iii) the lower portion consists of the Hosston Formation and overlying Sligo Formation, and is separated from the Cow Creek Limestone by the intervening Hammett Shale (Mace et al., 2000). The lower Glen Rose unit includes the entire stratigraphic section from the upper/lower Glen Rose boundary, marked by the “Corbula bed” (Lozo and Stricklin, 1956; Stricklin, et al., 1971), to the top of Precambrian basement – this unit effectively represents the lower confining unit for the Edwards aquifer. The upper Glen Rose unit includes the upper Glen Rose Formation. This unit is separated from the lower Glen Rose unit because the upper Glen Rose unit is recognized as hydraulically more similar to the Edwards Aquifer than it is to the lower Glen Rose Formation (Smith and Hunt, 2009, 2010, 2011). Thus, the rest of the Trinity Aquifer and the upper Glen Rose Unit are designated as separate layers in the model. The stratigraphic column is illustrated in Figure 2-1 (Hovorka et al., 1996).

7.2 Hydrogeological Studies

The water resources of subdomains in the Trinity Aquifer have been evaluated to varying degrees. While more recent studies tend to build on earlier work, many seminal evaluations date to several decades ago. These seminal and recent documents were perused in evaluation of the hydrogeology of the study domain. Expressed in terms of formation and geographical location, sub-domains include: aquifers of Texas (Guyton and Rose, 1945); George et al., 2011); Trinity Aquifer (Lang, 1953; Weirman et al., 2010); Cretaceous aquifers (Nordstrom, 1982); Glen Rose Formation (Hammond, 1984); Antlers and Travis Peak formations (Nordstrom, 1987); central Texas (Klemt et a., 1975; Baker et al., 1990a); north-central Texas (Baker et al.,1990b; Landley, 1999); the contributing zone of the San Antonio segment of the Edwards Aquifer (Fratesi et al., 2014); Bandera and Kerr counties (Ashworth et al., 2001); Bell, Burnet, and Travis County (Brune and Duffin, 1983; Duffin and Musick, 1991); Blanco County (Follett, 1972); Caldwell County (Follett, 1966); Comal County (George et al., 1952); Edwards County (1962, 1963); Hays County (DeCook, 1963; Muller and McCoy, 1987; Broun et al., 2007); Hill County (Ashworth, 1983; Bluntzer, 1992); Kendall County (Reeves, 1967); Kerr County (Reeves, 1969); Real County (Lang, 1958); Travis County (George et al., 1941); Cypress Creek/Jacob's Well (Broun et al., 2008a,b); Dripping Springs (Muller, 1990); Seco Creek (Brown, 1999).

Although the Trinity Aquifer is the focus of this study, this evaluation cannot be fully engaged without recognizing the hydraulic relationship with the Edwards Aquifer (Small, 1986; Ridgeway and Petrini, 1991; LBG-Guyton and Associates and NRS Consulting Engineers, 1995; Smith and Hunt, 2009; Fratesi et al., 2014).

The western boundary of the study domain was the focus of a U.S. Geological Survey Regional Aquifer-System Analysis (RASA) (Kuniansky, 1989; Kuniansky and Hooligan, 1994; Barker et al., 1994; Barker and Ardis, 1996). Although the focus of this RASA was the Edwards-Trinity Aquifer, information gained during these studies was useful in developing the hydrogeological framework of the western boundary of this study domain.

Hydraulic testing using nested wells conducted by the Barton Springs Edwards Aquifer Conservation District provide insight on the hydraulic properties and the hydraulic relationship among the sub-units of the Edwards and Trinity aquifers (Hunt et al., 2010, 2015; 2016).

7.3 Geochemical and Salinity Studies

Winslow and Kister (1956) and Core Laboratories (1972) are two studies which provided early comprehensive investigations for characterizing brackish and saline groundwater in Texas. Subsequent methods have been developed to estimate the TDS of groundwater using geophysical data from borehole logs (e.g., Collier, 1993; Estepp, 2010), and many have been used with success for evaluations of brackish water resources in Texas. Examples of these techniques include Alger (1966), Ayers and Lewis (1985), Fogg (1980), Fogg and Kreitler (1982), Fogg and Blanchard (1986), Hamlin (1988), Estepp (1998), Meyer (2012), and Young and others (2016). Many of these applications were performed in the unconsolidated sediments of the Gulf of Mexico Basin. Techniques used specifically in the consolidated units of the Trinity Aquifer are sparse to non-existent. Exceptions are Collier (1993a,b) and Estepp (1998) who both have specific examples of calculations performed in the Northern Trinity Aquifer system. Additionally, there have been examples of resistivity-based methods applied to carbonate aquifers like the Trinity Aquifer (e.g., Schultz, 1994; Kwader, 1986; MacCary, 1980).

Given the availability of mud and mud filtrate borehole resistivity data, the resistivity ratio, or Alger-Harrison method (Estepp, 2010; Collier, 1993; Alger and Harrison, 1989), is most useful for calculative TDS for the Hill Country region of the Trinity Aquifer. Other approaches successfully implemented in unconsolidated sands have been demonstrated by Ayers and Lewis, (1985), Fogg (1980), Fogg and Kreitler (1982), Fogg and Blanchard (1986), Hamlin (1988), Collier (1993), Estepp (1998), Meyer (2012), Young et al., (2016). Sampled water quality and geophysical log data compiled by Kelley et al. (2014) for the Northern Trinity Aquifer GAM provided a test dataset to determine TDS.

7.4 Geothermal Gradient Studies

For this study, the geothermal gradient studies of interest are those that help define the spatial variability in the geothermal gradient across the study area. Formation temperature affects a wide range of well log measurements, including resistivity, induction, density, and neutron. Temperature is also important because it affects the electrical conductivity of groundwater. Therefore, there is a need to account for temperature as part of data analysis and interpretation of geophysical log data.

The relationship of temperature to fluid density and electrical resistivity has been recognized for some time (Archie, 1942; Arps, 1953; Luheshi, 1982) although challenges remain in establishing the full nature of the relationship. Regional studies of geothermal gradients were evaluated for their usefulness in the study area (Daly et al., 2008; Blackwell et al., 2011; PRISM Climate Group, 2016).

8 Data Collection and Analysis

The domain for data acquisition for this project is illustrated in Figure 2-2. This domain was selected to be inclusive of the entire Trinity Aquifer in Texas and provide a reference for where data were to be collected and evaluated. Stratigraphic, structural, and geochemical data over the extent of the domain were collected and evaluated. Sources for data compiled for this project include: (i) Brackish Resources Aquifer Characterization System (BRACS)/TWDB databases, (ii) groundwater conservation districts, (iii) oil and gas databases including IHS Markit, (iv) water-supply wells, (v) Texas Commission on Environmental Quality (TCEQ) Public Supply, (vi) United Stated Geological Survey (USGS) Produced Water databases, and (vii) literature.

There were three primary types of data required for this study, including water quality measurements, geophysical logs, and well locations.

The primary source of water quality measurements was the TWDB groundwater database. The groundwater database was used to locate groundwater wells with measured concentrations of total dissolved solids, major cations and anions, radionuclides, and well construction information. A primary objective of the data collection was to identify geophysical logs within one mile of water wells with both total dissolved solids and well screen information.

The pairing of water wells with geophysical logs was performed in order to investigate and develop approaches for estimating total dissolved solids concentrations using formation resistivity of geophysical logs. The geophysical logs used for the study were identified and obtained from the Brackish Resources Aquifers Characterization System (BRACS) database, the Bureau of Economic Geology Geophysical Log Library, the Texas Railroad Commision, the Subsurface Library, DrillingInfo, and IHS Inc. A prerequisite for using a geophysical log as part of the study was that it could be made available to the public. To meet this requirement, we obtained permission from the commercial firms to release their logs to the State of Texas for this project. All of the geophysical logs, along with their metadata, are provided as a deliverable for this project. In addition, the metadata have been chronicled in a format consistent with entry into the Brackish Resources Aquifers Characterization System database.

All logs that were obtained from outside sources were received as Tagged Image Format (TIF) files. Tagged Imaged Format (or TIF) is an efficient file format for storage of high quality raster graphics. TIF files are bitmap-based images comprised of pixels in a grid. TIF files have a fixed resolution and cannot be resized without losing image quality. Figure 8-1 is an example of a TIF image of a geophysical log.

The primary analysis performed on the geophysical logs was to identify sand beds and record their thickness and formation resistivity. The identification of the sand beds was performed manually on the TIF images. The determination of the formation resistivity of the sand was performed using a computer program written to analyze digitized curves of the deep resistivity curve. The standard file-format common in the oil-and-gas and water well industries to store digital well log information is the Log ASCII Standard (LAS). A LAS file is a structured ASCII file containing log curve data and header information. ASCII is abbreviated from American Standard Code for Information Interchange, and is a character encoding standard that is used for most text files. Figure 8-2 shows the header and several sections from an LAS file. In order to facilitate the calculation of formation resistivity, we digitized over 1,000 TIF files to LAS files.

All of these logs had their deep resistivity curve digitized. Approximately 292 of the logs also had their spontaneous potential curve digitized.

To help define the exclusion zones for our study, we obtained well information from the following sources:

- Bureau of Economic Geology Geophysical Log Facility
- Texas Commission on Environmental Quality water well image files and public drinking water files
- Texas Department of Licensing and Regulation Submitted Driller's Report Database
- Texas Water Development Board Groundwater Database, Brackish Resources Aquifers Characterization System Database, and Submitted Driller Reports database
- Groundwater conservation districts located in the Texas Gulf Coast Aquifer System

Besides well construction information, we also obtained well yields and estimates of specific capacity from the TWDB Submitted Drillers Report Database. The details regarding data sources and means of collection and analysis are described in the relevant sections of the report.

8.1 Literature

In order to construct a stratigraphic framework for the Hill Country portion of the Trinity Aquifer, relevant literature was assessed for useful stratigraphic and structural information (e.g., cross sections, fence diagrams, structure-contour maps, well-header information, stratigraphic horizon picks from wells, and fault maps). A table with the minimum, maximum, and average thickness for the major geological units encountered at each county (where available) was created (Appendix 19.2).

8.2 Geophysical Well Logs and Key Wells

Geophysical well logs were acquired from BRACS/TWDB databases, the IHS Markit database, and other sources. The main geophysical logs used for this project include gamma, resistivity (shallow and deep), and spontaneous potential (SP). Wells from the BRACS database were selected using a structure-contour surface of the (i) upper Glen Rose and (ii) lower Glen Rose designated by the GAM for the Northern Trinity Aquifer and by Fratesi et al. (2015) for the Hill Country Trinity Aquifer. Elevations from these surfaces are consistent with the elevations of the Upper Trinity Aquifer structure contour surface from the Hill Country Trinity Aquifer and Northern Trinity Aquifer GAMs. Total depth for each well was used to constrain logs that fell within the horizon defined by these two Glen Rose surfaces.

A well-log matrix was created to categorize well logs based on digital quality and information useful for this analysis (Appendix X). The matrix was used to fully evaluate each well and any subsequent data that were acquired during the project. A database was developed with spatial attributes of all available logs [e.g. BRACS, IHS Markit, the Bureau of Economic Geology (BEG)], with care to adhere to the BRACS format.

For this study, we relied on the stratigraphic framework produced for the Northern Trinity GAM, so no updates or revisions to the Northern Trinity Aquifer framework were made for this project.

The Hill Country Trinity Aquifer stratigraphic framework was not used for this study because of its limited domain and lack of well information. Therefore, substantial work went into evaluating data to support the construction of a new Hill Country framework model. Well logs from the BRACS well database were evaluated for existing stratigraphic horizon picks (e.g., hand-drawn stratigraphic picks) and lithologic information. After the picks were tabulated they were loaded into Petrel and a well comparison was performed. The well comparison consisted of (i) checking the datum of each well for accuracy against ground-surface elevations (e.g., 30-ft NED) and adjusting the well datum if the difference with the ground-surface elevation exceeded 30 ft, (ii) checking surface geology at the well location to ensure that the stratigraphic picks in the well are geologically reasonable (e.g., based on the aforementioned thickness table, that the picks in the well are in proper sequence), (iii) compare picks against the digitized gamma curves to ensure that the picks are valid or justified, (iv) and compare picks to nearby evaluated well picks or key wells. Well picks that met the evaluation criteria were used. Those that did not were re-interpreted. Four key wells were used to help with interpreting the gamma curves across the Hill Country Trinity Aquifer domain.

A key well is a well that is clearly identified, has unambiguous position information and well geometry, pick information with clearly measured depth, wireline-log data that are tied to interval picks with known depth, and the formation of interest with known water chemistry. Ideally, a key well for each depositional domain and structural position within the study area would be available. This would allow calibration of each well-log interpretation against a geologically reasonable dataset including depositional environment and structural domain changes across the study area. Below is a list of desired information for each key well (if available):

- Identification – To be able to consistently track key wells across multiple databases. The following fields for each key well are desirable: well name, well ID, unique well identifier (UWI), American Petroleum Institute (API) number, and well type.
- Position – To properly place key wells in space and to confidently determine the datum from which all measurements were taken; reliable XY location and land-surface datum for each well are needed.
- Well geometry – To construct the correct well trajectory in three dimensions, total vertical depth of each well and the deviation survey for each well are required.
- Pick information – To be able to utilize the key well for regional log interpretation, stratigraphic-horizon tops, fault tops, and any layer-dip information are required.
- Log data – To be able to interpret key data, existing log data (i.e., gamma ray, SP, resistivity, sonic, and density logs) relative to formation boundaries are desirable.
- Water chemistry – A key well for water chemistry would have the following characteristics:
    - A record of the depth of the screened or open-hole interval so that the source of water in the well can be linked to a particular formation.
    - Results of analyses of at least one water-chemistry sample. The results must include measured specific conductivity, TDS, all major ions, pH, or all of these. The most useful data will be from analyses conducted after 1970.

Table 8-1 Well Logs used for the Hill Country portion of this study.

Source	**Number of Wells**			
	Raster Log	**Digitized Log**	**Stratigraphic Characterization**[3]	**Lithologic Characterization**[3]
Brackish Water Database	172	156	172	15
IHS Markit Gulf Coast Database[1]	84	11	84	10
Type Wells[2]	4	4	4	-
TCEQ	1	1	1	1
Total	261	161	261	26

[1] IHS Markit Gulf Coast Database is a membership that is paid for by SwRI.
[2] Type Wells are hand interpreted logs that were provided to SwRI by Alvin Schultz from a separate project.
[3] Stratigraphic and lithologic picks were made based on the well log curve data.

Four wells that met the criteria to be a key well were identified for use in re-interpreting existing well picks and interpreting new well picks. The geophysical logs for each key well were acquired and digitized. The search for additional key wells that relate to other aspects of this project continued for the duration of the project. There were 172 wells from the BRACS database considered for the stratigraphic framework (Table 8-1). Of these wells, 156 were selected to have curve data digitized (gamma, SP, and resistivity). Figure 8-1 shows a comparison of the digital logs and scanned logs for two wells, and demonstrates that there is good agreement between them.

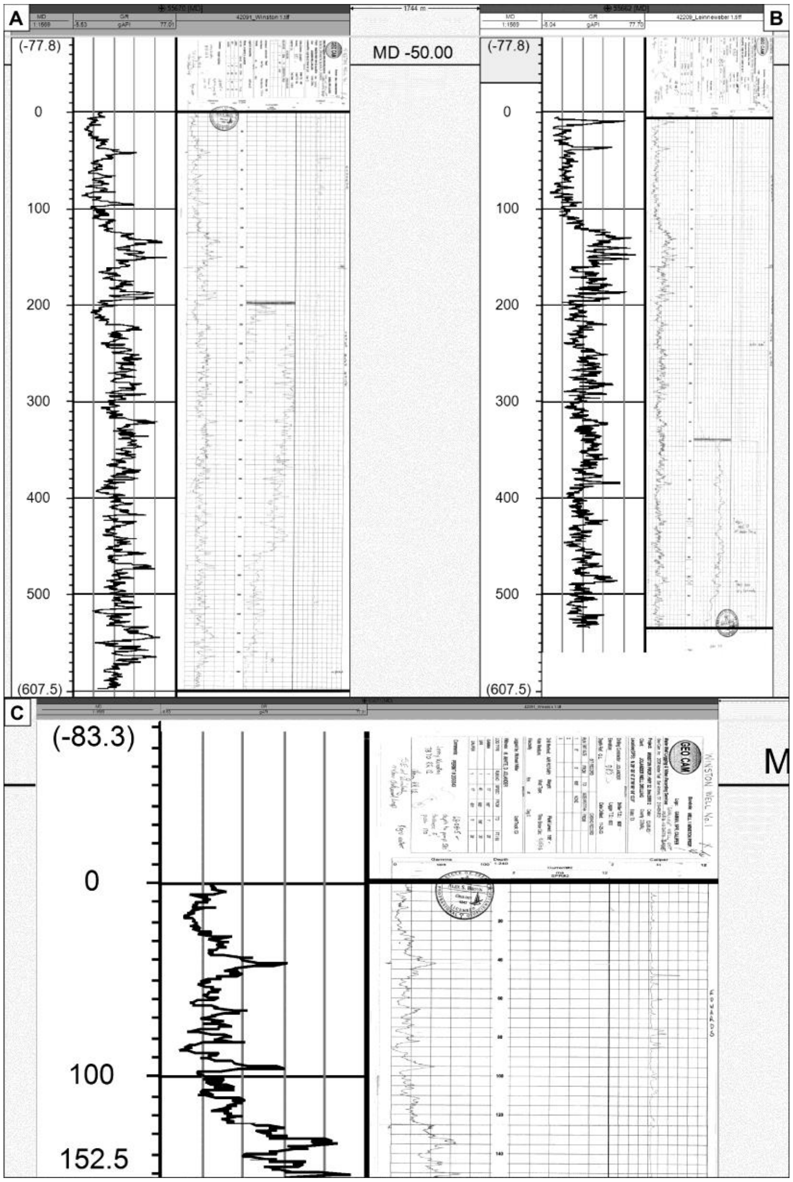


Figure 8-1 **Comparison of the digitized gamma curves and raster gamma curves for wells #55670 (A) and #55662 (B) from the BRACS database. (C) Enlargement of upper portion of logs for well #55670.**

In addition to the BRACS database, a license for the Gulf Coast IHS Markit database was acquired (purchased using SwRI internal funds). Staff were trained to use the database, and a large number of wells were evaluated to identify those which are potentially useful for this task. For selected wells, the depth-referenced logs were retrieved from the IHS Markit database for use on this project. Each well used from this database was evaluated based on the same criteria as described above for the BRACS database. There were 84 wells from the IHS database considered for the stratigraphic framework (Table 8-1). Of these wells, 11 were selected to have curve data digitized (gamma, SP, and resistivity).

The quality of the well logs available for this study was evaluated; electric logs from the 1950's to the present are satisfactory for salinity interpretation, and porosity logs from the 1970's to the present yield acceptable porosity estimations. Only logs from wells completed within these time periods with clearly visible SP and resistivity curves were selected for use. Outliers were determined by comparison with neighboring logs. Empirical and computational approaches were compared when geophysical well logs and groundwater-quality data were available for the same wells.

A total of 122 gamma-ray log curves, 116 resistivity log curves, and 56 spontaneous potential log curves were digitized from 261 unique wells. Additional logs, utilized to calculate TDS and formation porosity, were identified and sent to Well Green Tech for digitization.

8.3 Well Databases

The main sources for well data to support the stratigraphic framework task include well information from the Northern Trinity Aquifer GAM, the BRACS/TWDB database, and the IHS Markit database. Additional well data have been sourced from water supply wells, groundwater conservation districts, TCEQ Public Supply, USGS Produced Water databases, and the literature.

8.3.1 Northern Trinity Aquifer GAM Well Database

The stratigraphic framework for the Northern Trinity Aquifer GAM was created using wells and stratigraphic pick interpretations from geophysical logs. The final database included 1,498 well logs across the Northern Trinity Aquifer domain. The well database includes 408 water wells and 894 oil and gas wells. Depth-registered raster logs containing geophysical curve data (gamma ray, SP, and resistivity) were used to correlate boundaries and interpret stratigraphic horizons and lithology. Of the 1,498 wells, stratigraphic and lithologic interpretation was 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 Kelly et al. (2014).

8.3.2 Brackish Resources Aquifer Characterization System (BRACS)/TWDB Database

The BRACS well database consists of well data that support groundwater resources in Texas. The well information is updated on a daily basis, but at the time of download for this project there were 58,638 wells in the database. Of those wells, a subset was selected based on the Hill Country Trinity Aquifer brackish data acquisition domain (Figure 1-1). A total of 1,591 wells within the domain of the Hill Country Trinity Aquifer were evaluated for depth. To determine the depth and thickness of the Trinity Aquifer, stratigraphic horizons from the stratigraphic framework model in Fratesi et al. (2015) and the framework in the existing Hill Country Trinity Aquifer GAM were extrapolated to the boundaries of the Hill Country Trinity Aquifer domain. In addition, buffers of 100 ft above the top Trinity surface and 100 ft below the bottom of the base Trinity surface were added. This produced 204 wells that met the depth criteria for the Hill Country portion of the Trinity Aquifer domain. Stratigraphic and lithologic interpretation was conducted on the geophysical logs for a subset of these wells (Table 8-1)

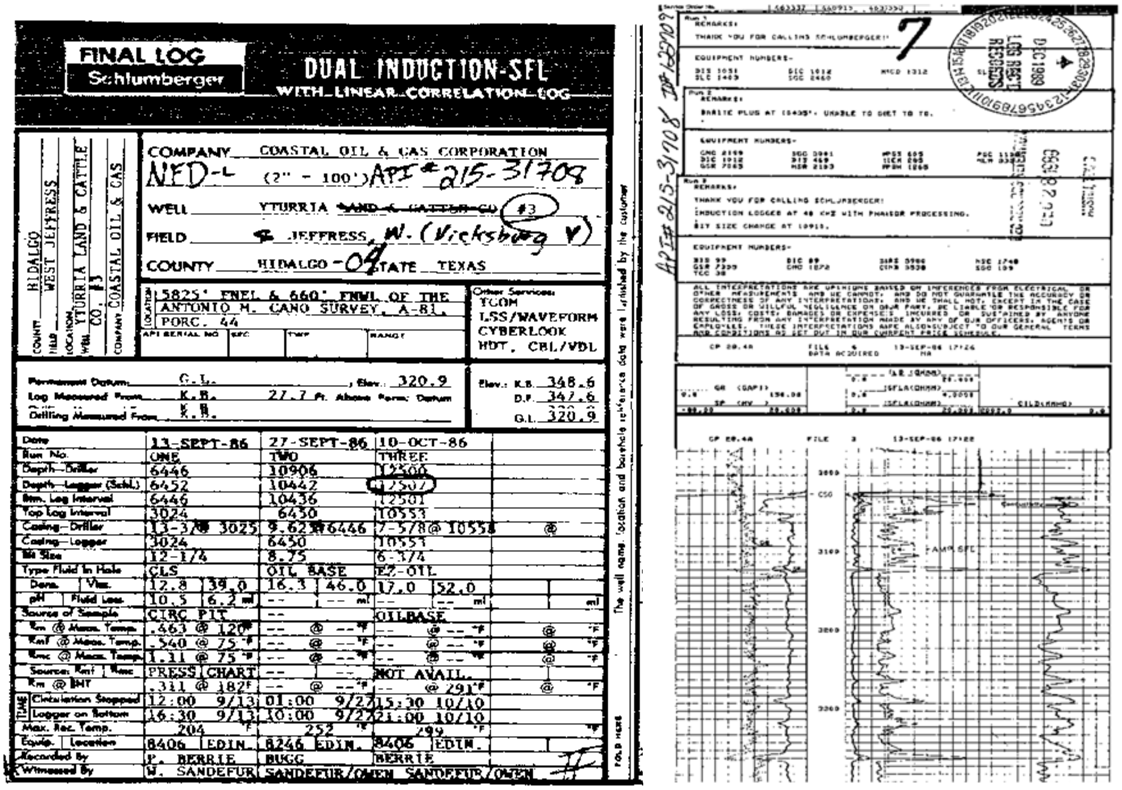
8.3.3 Information Handling Services Markit (IHS Markit) Database

The IHS Markit Well Database is the largest, most comprehensive U.S. well database. The U.S. database includes almost 1,000 data elements for more than 4.5 million well records, which comprise nearly every well drilled and completed since 1859. The U.S. well data are sourced from regulatory agencies and sometimes directly from operators prior to state filings. The database allows access through memberships based on regions throughout the U.S. The project team has access to the Gulf Coast region of this database. Access provides subscribing members with well records, formation-pick information, and depth registered geophysical logs. After an exhaustive search through the database, 458 wells were identified to (i) have existing formation-pick information (either supplied by operator or interpreted by IHS staff) and (ii) penetrate the Trinity Aquifer within or near the Hill Country portion of the domain. After further evaluation to determine the most strategic positions for well information within the domain, we settled on 84 IHS wells that were used for stratigraphic and lithologic interpretation.

8.3.4 Physical Geology Database

Data sources include USGS topographic data (digital elevation models), published geologic maps, stratigraphic measured sections, stratigraphic fence diagrams, cross sections, stratigraphic thicknesses, and well data. Surface-elevation data were downloaded from the USGS National Map Viewer. The data have vertical accuracy of 8 ft, and horizontal data spacing of 1/3 arc-second or 31.4 ft.

Published geologic maps were used to extract elevations for mapped geologic contacts that define hydrologic boundaries in areas of limited or no well data. Geologic maps used in this fashion include maps published by the Bureau of Economic Geology (BEG) (Bureau of Economic Geology, 1979, 1981a, 1981b, 1983) and the USGS. Stratigraphic data were collected from a wide range of sources to construct a formation-thickness database. This database was compared with measured sections described in the literature.



FINAL LOG
Schlumberger

DUAL INDUCTION-SFL
WITH LINEAR CORRELATION LOG

COUNTY HIDALGO
FIELD WEST JEFFRESS
LOCATION YTURRIA LAND & CATTLE
WELL CO. #3
COMPANY COASTAL OIL & GAS

COMPANY COASTAL OIL & GAS CORPORATION
NED-L (2" - 100') API # 215-31708
WELL YTURRIA ~~LAND & CATTLE CO~~ #3
FIELD JEFFRESS, W. (Vicksburg V)
COUNTY HIDALGO -04 STATE TEXAS

LOCATION 5825' FNEL & 660' FNWL OF THE ANTONIO M. CANO SURVEY, A-81, PORC. 44
API SERIAL NO SEC TWP RANGE

Other Services:
TCOM
LSS/WAVEFORM
CYBERLOOK
HDT, CBL/VDL

Permanent Datum: G.L., Elev.: 320.9
Log Measured From K.B. 27.7 Ft. Above Perm. Datum
Drilling Measured From K.B.

Elev.: K.B. 348.6
D.F. 347.6
G.L. 320.9

Date	13-SEPT-86	27-SEPT-86	10-OCT-86	
Run No.	ONE	TWO	THREE	
Depth—Driller	6446	10906	12500	
Depth—Logger (Schl.)	6452	10442	12507	
Btm. Log Interval	6446	10436	12501	
Top Log Interval	3024	6450	10553	
Casing—Driller	13-3/8 @ 3025	9.625 @ 6446	7-5/8 @ 10558	@
Casing—Logger	3024	6450	10553	
Bit Size	12-1/4	8.75	6-3/4	
Type Fluid in Hole	CLS	OIL BASE	EZ-OIL	
Dens. | Visc.	12.8 | 39.0	16.3 | 46.0	17.0 | 52.0	
pH | Fluid Loss	10.5 | 6.2 ml	-- | -- ml	-- | -- ml	ml
Source of Sample	CIRC PIT	--	OILBASE	
Rm @ Meas. Temp.	.463 @ 120°F	-- @ -- °F	-- @ -- °F	@ °F
Rmf @ Meas. Temp.	.540 @ 75 °F	-- @ -- °F	-- @ -- °F	@ °F
Rmc @ Meas. Temp.	1.11 @ 75 °F	-- @ -- °F	-- @ -- °F	@ °F
Source: Rmf | Rmc	PRESS | CHART	-- | --	NOT AVAIL.	
Rm @ BHT	.311 @ 182°F	-- @ -- °F	-- @ 291°F	@ °F
TIME Circulation Stopped	12:00 9/13	01:00 9/27	15:30 10/10	
TIME Logger on Bottom	16:30 9/13	10:00 9/27	21:00 10/10	
Max. Rec. Temp.	204 °F	252 °F	299 °F	°F
Equip. | Location	8406 | EDIN.	8246 | EDIN.	8406 | EDIN.	
Recorded By	P. BERRIE	BUGG	BERRIE	
Witnessed By	W. SANDEFUR	SANDEFUR/OWEN	SANDEFUR/OWEN	

The well name, location and borehole reference data were furnished by the customer

FOLD HERE

API# 215-31708

7

DEC 1989

Run 1
REMARKS:
THANK YOU FOR CALLING SCHLUMBERGER!
EQUIPMENT NUMBERS-

Run 2
REMARKS:
EQUIPMENT NUMBERS-

Run 3
REMARKS:
THANK YOU FOR CALLING SCHLUMBERGER!
INDUCTION LOGGED AT 40 KHZ WITH PHASOR PROCESSING.
BIT SIZE CHANGE AT 10915.
EQUIPMENT NUMBERS-

CP 28.4A FILE 4 13-SEP-86 17:26
DATA ACQUIRED

GR (GAPI)
SP (MV)
ILD (OHMM)
SFLA (OHMM)
CILD (MMHO)

CP 28.4A FILE 3 13-SEP-86 17:22

Figure 8-2 Example of a raster image of a geophysical well log that uses the American Petroleum Institute format.

```
#   VellGreen Tech Inc.   Digitizing Services
#   www.wellgreentech.com
#   email: sales@wellgreentech.com
#
~Version Information Block
 VERS.                 2.00:    CWLS LOG ASCII STANDARD - VERSION 2.000000
 WRAP.                   NO:    One Line Per Depth Step
#
~Well Information Block
#MNEM.UNIT                    Data                             Information
#----------   ------------------------------------------   ----------------
 STRT.FT                                         40.0000:     START DEPTH
 STOP.FT                                       2010.0000:     STOP DEPTH
 STEP.FT                                          0.5000:     STEP
 NULL.                                         -999.2500:     NULL VALUE
 COMP.                      SUN EXPLORATION & PROD. CO.:        COMPANY
 WELL.                              SANTOS MONTOYA #1:     WELL
 FLD .                                           OILTON:     FIELD
 LOC .                                                 :     LOCATION
 CNTY.                                             WEBB:     COUNTY
 STAT.                                            TEXAS:     STATE
 CTRY.                                              USA:     COUNTRY
 SRVC.                                     SCHLUMBERGER:     SERVICE COMPANY
 DATE.                                       01/24/1984:     DATE
 API .                                   42479338120000:     API NUMBER
 UWI .                                   42479338120000:     UWI NUMBER
 TVD .                                               NO:     TVD flag
 WSTA.                                              LOC:     Well status
#
~Curve Information Block
#MNEM.UNIT       API CODE       Curve Description
#----------   -------------   --------------------
 DEPT.FT                   :   Depth in Feet
 SP   .MV     01 010 01 01:   Spontaneous Potential
 RES_SHAL.OHMM 10 220 01 01:   Spherically Focused Laterolog
 RES_DEEP.OHMM 05 120 46 01:   Deep Induction
#
~Parameter Information Block
#MNEM.UNIT            Value                Description
#----------   --------------------   -------------------
 RUN .                            ONE:    Run Number
 PDAT.                            UNK:    Permanent Datum
 EPD .FT                       0.0000:    Elevation Of Perm. Datum
 WSTA.                            LOC:
 E   .FT                       0.0000:    E (Stretch Coefficient Of The Cable)
 TD  .FT                    2000.0000:    Total Depth
 LMF .                   KELLY BUSHING:    Logging measured from Kelly Bushing
 EKB .FT                                  870.0:     Elevation Kelly Bushing
 GL .FT                                     859.0:     Ground Level
 DF .FT                                     869.0:     Drill Floor
 CSGL   .FT                               53.0:     Casing Bottom Logger
 CSGD   .FT                              53.0:     Casing Bottom Driller
 MUD    .                                 GEL-DRISPAC:     Mud Type
 MUDD   .LB/USG                    9.7:     Mud Weight/Density
 MUDV   .CP                              41.0:     Mud Viscosity
 PH     .                                         9.5:     Mud ph
 FL     .ml/30min                         7.0:     Mud Fluid Loss Rate
 MUDS   .                                       TANK:     Mud Source
 Rm     .OHMM                           2.98:     Mud Resistivity
 RmT    .DEGF                            70.0:     Mud Temperature
 Rmf   .OHMM                            2.59:     Mud Filtrate Resistivity
 RmfT   . DEGF                           74.0:     Mud Filtrate Temperature
 Rmc .OHMM                             4.2:     Mud Cake Resistivity
 RmcT .DEGF                              75.0:     Mud Cake Temperature
 RMB    .OHMM                           2.1:     Mud Resistivity Bottom Hole
 BHT   .DEGF                            102.0:     Bottom Hole Temperature
#
~Other Information Block
<DescLogPlotStart>   NEURALOG PLOT DEFINITION
PLOTDEFVERSION: 3
LASFILE: E:\nds\projects\Intera - Feb 23\las\42479338120000.las
DEPTHSCALE: 240.000000
RESOLUTION: 400
DEPTHLABELFREQ: 100.000000
HEAVYGRIDFREQ: 100.000000
MEDIUMGRIDFREQ: 50.000000
LIGHTGRIDFREQ: 10.000000
#
#   TRACK 1
#
STARTTRACK:
 LEFTX: 0.500000 inch
 RIGHTX: 3.000000 inch
 SCALETYPE: Linear
 NUMCHARTDIVISIONS: 10
CURVE: SP    -80.000000 20.000000  (0,0,255)      Solid             2     N
ENDTRACK:
#
#   TRACK 2
#
STARTTRACK:
 LEFTX: 3.500000 inch
 RIGHTX: 8.500000 inch
 SCALETYPE: Log
 NUMCYCLES: 4
 STARTCYCLE: 2
CURVE: RES_SHAL 0.200000   2000.000000 (0,131,131)    Solid             2     N
CURVE: RES_DEEP 0.200000   2000.000000 (255,0,255)    Dot               2     N
ENDTRACK:
<DescLogPlotEnd>
~A DEPTH     SP                RES_SHAL             RES_DEEP
      40.000 -999.250          0.324            -999.250
      40.500 -999.250          0.322            -999.250
      41.000 -999.250          0.321            -999.250
      41.500 -999.250          0.318            -999.250
      42.000 -999.250          0.315            -999.250
      42.500 -999.250          0.316            -999.250
      43.000 -999.250          0.317            -999.250
      43.500 -999.250          0.318            1888.541
      44.000 -999.250          0.318            1074.619
      44.500 -999.250          0.319            606.204
      45.000 -999.250          0.322            604.297
      45.500 -999.250          0.322            1640.593
      46.000 -999.250          0.320            1963.692
```

Figure 8-3 **Example of a .LAS file that was produced from a .tif file.**

9 Aquifer Hydraulic Properties

Aquifer hydraulic properties refer to the physical characteristics that govern flow of groundwater through an aquifer. This section introduces several of the important terms and concepts associated with characterization of aquifer hydraulic properties, such as horizontal and vertical hydraulic conductivity, transmissivity, and specific storage, as well as aquifer structure, aquifer lithology, depositional environment, and the presence of fractures and faults.

9.1 Hydraulic and physical properties for the Northern Trinity Aquifer

The groundwater volume calculations described above require input values for aquifer properties such as aquifer structure, thickness, water level and specific yield. These are described below.

Structure and Thickness – For volume calculations in the five transmissive members of the Trinity Aquifer, the member unit thickness and the elevations of unit tops and bottoms are based upon the structure in the updated Groundwater Availability Model of the Northern Trinity and Woodbine Aquifers (Kelley and others, 2014), where:

- Model Layer 4 represents the Paluxy Aquifer
- Model Layer 5 represents the Glen Rose Formation
- Model Layer 6 represents the Hensell Aquifer
- Model Layer 7 represents the Pearsall Formation
- Model Layer 8 represents the Hosston Aquifer

Northern Trinity Aquifer Water Level – The water levels used to calculate the aquifer volumes are based upon the last year of calibration (beginning of 2010) from the updated Groundwater Availability Model of the Northern Trinity and Woodbine Aquifers (Kelley and others, 2014).

Specific Yield – Specific yield values for each of the five transmissive members of the Trinity Aquifer were assigned based on the Northern Trinity / Woodbine Aquifer Groundwater Availability Model (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

9.2 Hydraulic and physical properties for the Hill Country Trinity Aquifer

The groundwater volume calculations described above require input values for aquifer properties such as aquifer structure, thickness, water level and specific yield. These are described below.

Structure and Thickness – For volume calculations in the four transmissive members of the Hill Country portion of the Trinity Aquifer, the member unit thickness and the elevations of unit tops and bottoms are based upon the structure developed in Section 5 of this report (Geologic setting and framework development).

Hill Country Trinity Aquifer Water Level – The water levels used to calculate the aquifer volumes are based upon the water levels obtained from the TWDB groundwater database. Water levels for the Hill Country Trinity portion were limited to water levels measured after January 1, 2000. Water levels were interpolated for the unconfined portion of the Trinity aquifer as a whole. Hydrostatic gradients are assumed throughout the Trinity aquifer in the absence of a GAM that is inclusive of the entire aquifer.

Specific Yield – Specific yield values for each of the four transmissive members of the Hill Country Trinity Aquifer were assigned based on the Groundwater Availability Model: Hill Country Portion of the Trinity Aquifer (Jones and others, 2011), where:

- Glen Rose Specific yield = 0.0008
- Hensell Specific yield = 0.0008
- Cow Creek Specific yield = 0.0008
- Hosston Specific yield = 0.0008

10 Water Quality

Water quality data were assembled from the Texas Water Development Board Groundwater Database (TWDB-GWDB) (TWDB, 2016) for both the Northern Trinity Aquifer and Hill Country Trinity Aquifer regions. In general, these data were sufficient to identify the spatial and statistical trends needed to develop the conductivity and total dissolved solids relationships used in the brackish zone analyses. Additional sources of information, such as published reports, groundwater district data files, and the U.S. Geological Survey (USGS) Produced Water database (Blondes et al., 2016) were reviewed to assess the need to incorporate additional data. In most cases, additional data from those sources were not incorporated into the analyses because they did not impact the results derived from the data assembled in the TWDB database for the purposes of this study. An exception is the inclusion of some measured water chemistry values from the USGS Produced Water database, which added information for some units in downdip areas.

Detailed descriptions of Trinity Aquifer water quality are found in numerous reports [e.g., Jones et al., 1997, 2011; Kelley et al., 2014 (and references therein), Holland, 2011, Fahlquist and Ardis, 2004; Rapp, 1988]. Major conclusions from these studies include:

- In both the Northern and Hill Country sections of the Trinity Aquifer, water chemistry is controlled by water interaction with the predominant rock types. Precipitation and dilute waters along recharge zones interact with limestones to produce calcium bicarbonate waters. Water chemistry evolves as water moves downdip within the aquifer as dissolution, precipitation, and ion-exchange reactions occur. Farther downdip, some mixing with sodium chloride brines occurs.

- The principal water types (or hydrochemical facies) in the Hill Country Trinity Aquifer are calcium magnesium bicarbonate and calcium magnesium sulfate. Interactions with dolomitic limestones and dissolution of evaporate minerals, such as gypsum, help to promote increases in magnesium and sulfate concentrations. In deeper layers toward the eastern convergence with the Balcones Fault Zone, some mixing of sodium chloride waters occurs, but ion exchange of calcium in the groundwater for sodium in clays is also important.

- In the Northern Trinity Aquifer, some dissolution of dolomitic limestone occurs but to a much lesser extent than in the Hill Country region. In some areas, especially southward to Bell and Williamson counties, sulfate concentrations increase due to evaporate dissolution, however, the primary compositional evolution of Northern Trinity Aquifer waters downdip is toward a sodium bicarbonate water type. In the confined fresh water region of the Northern Trinity, higher sodium chloride waters are thought to be evidence of upwelling brines from deeper layers.

- Multivariate statistical analyses clearly identify the differences in compositional change between the Northern and Hill Country Trinity aquifers (Holland, 2011). For both the

> Hill Country Trinity and Northern Trinity regions, the similarity of groundwater compositions spatially and between layers is interpreted as evidence of cross-formational flow. Some studies (Rapp, 1988) have suggested that the sulfate in units such as the Cow Creek, Hensell and Hosston are derived from the Glen Rose.

For this study, a detailed description of water quality is limited to the characteristics used to estimate water quality from borehole geophysics data and to guide the estimation of Trinity Aquifer water quality trends in downdip areas where measurements of water quality are lacking. These characteristics include the relationships between specific conductance, total dissolved solids, and various chemical constituents for the hydrostratigraphic units assessed for brackish water production. They also include the spatial variation of chemical constituents that have the most influence on measured specific conductance.

TWDB-GWDB water quality data were extracted for the region to be included in the brackish water assessment. This region extended beyond the boundaries of the current Hill Country Trinity Aquifer and Northern Trinity Aquifer GAMs. Following extraction, the data were processed to exclude samples with analyses that were identified as having a calculated charge balance error greater than ±5% (code “U” in the TWDB-GWDB). Water quality samples collected prior to 1960 were also excluded due to significant differences in measurement and analytical techniques. However, some quality-verified samples from the 1950s and 1960s were reinstated because of the limited number of samples with total dissolved solids values above 2,000 mg/L. The water quality data were subsequently modeled using the geochemical software WATEQ4F (Ball and Nordstrom, 1991; USGS, 2012) as part of the data assessment. Samples with modeled charge balance errors greater than ±10% were also removed from the water quality dataset[1]. The final balanced dataset was then partitioned to bin the data according to the hydrostratigraphic units assessed in the brackish water analysis.

In general for the Hill Country Trinity segment of the aquifer, water quality data from the TWDB-GWDB were initially assigned to each hydrostratigraphic unit using information provided in the “aquifer code” and “aquifer code description” fields for each well in the database. Thorough spot checks (approximately 25% of wells) of wells’ screened intervals or open borehole intervals using the TWDB Groundwater Data Viewer confirmed the aquifer code designations were reasonably accurate. With some specific exceptions, data were excluded for those wells and associated water quality samples where the aquifer codes indicated contributions of water from multiple hydrostratigraphic zones or were ambiguous or non-specific (e.g., “other” and “Trinity Group”). An extensive water quality data scoping analysis identified several sample characteristics common to some hydrostratigraphic units and aquifer codes. These characteristics, especially the relationship between specific conductivity and total dissolved solids, indicated likely primary sources of water for many wells and were used to incorporate

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[1] The charge balance error calculation method used in standard water quality sample analyses (e.g., as found in the TWDB-GWDB) differs from the method used by WATEQ4F, which is more restrictive (the WATEQ4F percentage value is approximately double the TWDB-GWDB value but is a much smaller absolute value because of differences in calculation method). Furthermore, WATEQ4F explicitly considers additional constituents; thus, some samples exceed the modeled charge balance error threshold even though they meet the analytical charge balance error threshold.

samples from some dual coded wells into the water quality analyses. Specific exceptions of multi-coded values used in the water quality analyses included 218HSCC (Hensell and Cow Creek) and 218PRSL (Pearsall Formation) wells in the Blanco County area, which were added to the Cow Creek and Hensell hydrostratigraphic units, respectively. Similarly, wells coded 218GRCCU (Lower Glen Rose and Cow Creek Limestones) in Bexar County were grouped with the Glen Rose hydrostratigraphic unit, while 218TSEB [Trinity (Hensell Sand) and Ellenberger Group] wells in Gillespie County were grouped with the Hensell unit. Figure 10-1 clearly demonstrates how binning of these multi-coded values was consistent with the water quality characteristics of the primary (e.g., Cow Creek and Hensell) hydrostratigraphic units.

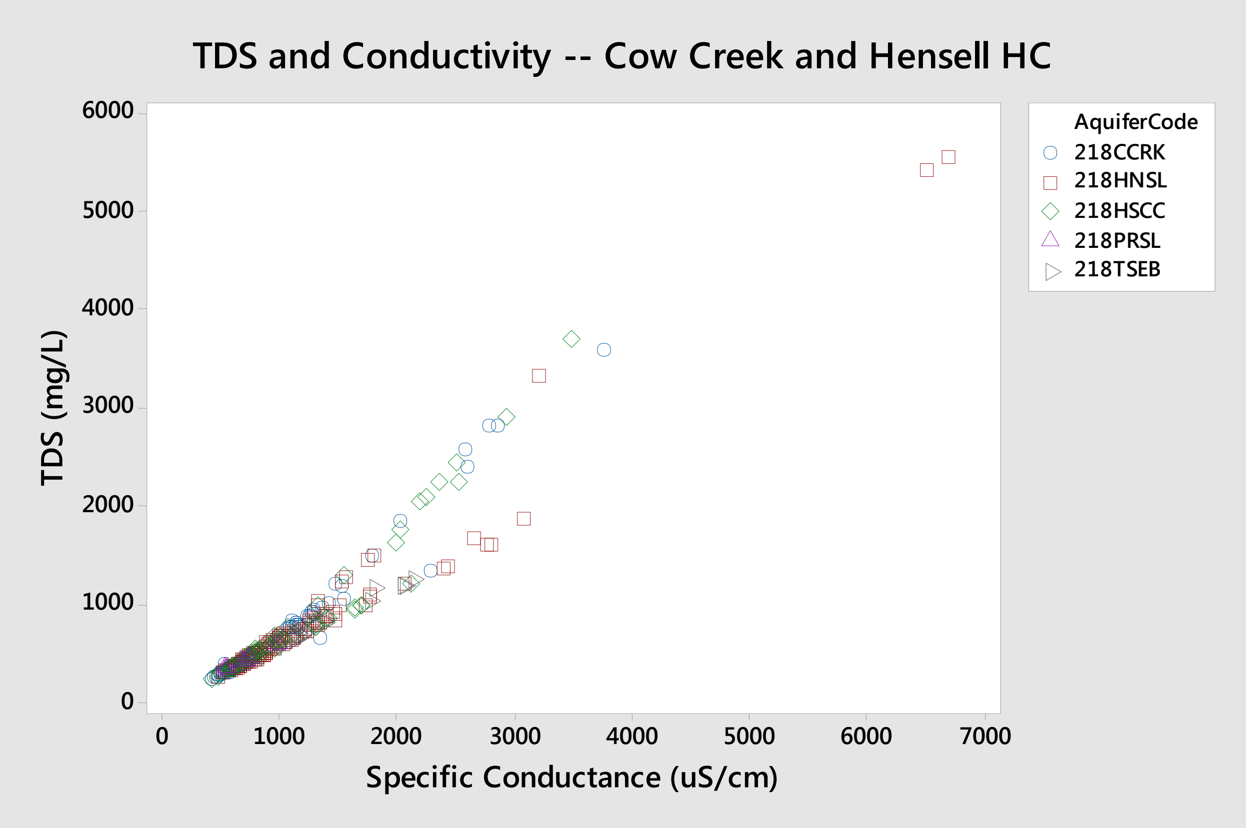

Figure 10-1 **Plot of TDS (mg/L) and specific conductance (µS/cm) for Hill Country Trinity Aquifer samples with the Cow Creek (218CCRK), Hensell (218HNSL), Hensell-Cow Creek (218HSCC), Pearsall (218PRSL), and Trinity (Hensell)-Ellenberger (218TSEB) aquifer codes. 218CCRK and 218HSCC samples group along the same trend while 218HNSL, 218PRSL, and 218TSEB group along a different trend. Groupings such as these were used to bin some water samples into appropriate hydrostratigraphic units.**

TWDB-GWDB water quality data for the Northern Trinity segment were initially assigned using the total depth of the well to estimate the appropriate hydrostratigraphic horizon. This method was consistent with the process used to bin water quality data during the development of the Northern Trinity GAM (Kelly et al., 2014) and results in groupings that combine several different aquifer code combinations with each hydrostratigraphic unit.

For wells with multiple samples, total dissolved solids and other constituent data were averaged (arithmetic mean) for use in maps and in comparisons to estimated total dissolved solids from borehole geophysics data. For scoping analyses, development of specific conductance and total dissolved solids relationships, and geochemical modeling, data were not averaged and all samples are included.

Trilinear or Piper plots (Piper, 1953) are diagrams commonly used to represent water quality data characteristics and trends. A typical Piper plot provides information about common major cation and anion components of groundwater. The common major cations are plotted on a triangular graph (ternary plot) with the apexes representing concentrations of calcium (Ca), magnesium (Mg), and sodium plus potassium (Na+K) in percent molar equivalents, which normalizes the data for molecular weight, charge, and the sum of cations in solution. Similarly, the common major anions chloride (Cl), sulfate (SO_4), and bicarbonate (HCO_3) are represented as apexes of a second triangular graph. All major ion composition values are combined in a central diamond graph that can provide information about water type (often referred to as groundwater or hydrochemical facies) and possible mixing.

Figures 10-2 through 10-7 present summaries of water quality data grouped by aquifer segments and hydrostratigraphic units. The water quality compositions represented are the Northern Trinity Aquifer Paluxy (Figure 10-2), the Northern Trinity Aquifer and Hill Country Trinity Aquifer Glen Rose (Figure 10-3), the Northern Trinity Aquifer and Hill Country Trinity Aquifer Hensell (Figure 10-4), the Northern Trinity Aquifer Pearsall unit and Hill Country Trinity Aquifer Cow Creek unit (Figure 10-5), the Northern Trinity Aquifer and Hill Country Trinity Aquifer Hosston unit (Figure 10-6), and a summary of all samples from the Northern Trinity and Hill Country Trinity aquifers (Figure 10-7).

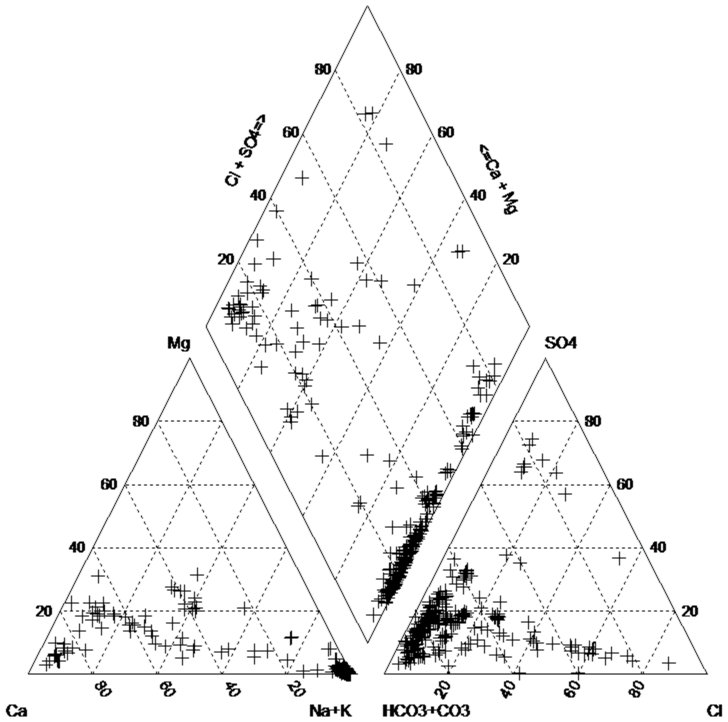

Figure 10-2 Piper plot of water quality data from the Northern Trinity Paluxy unit.

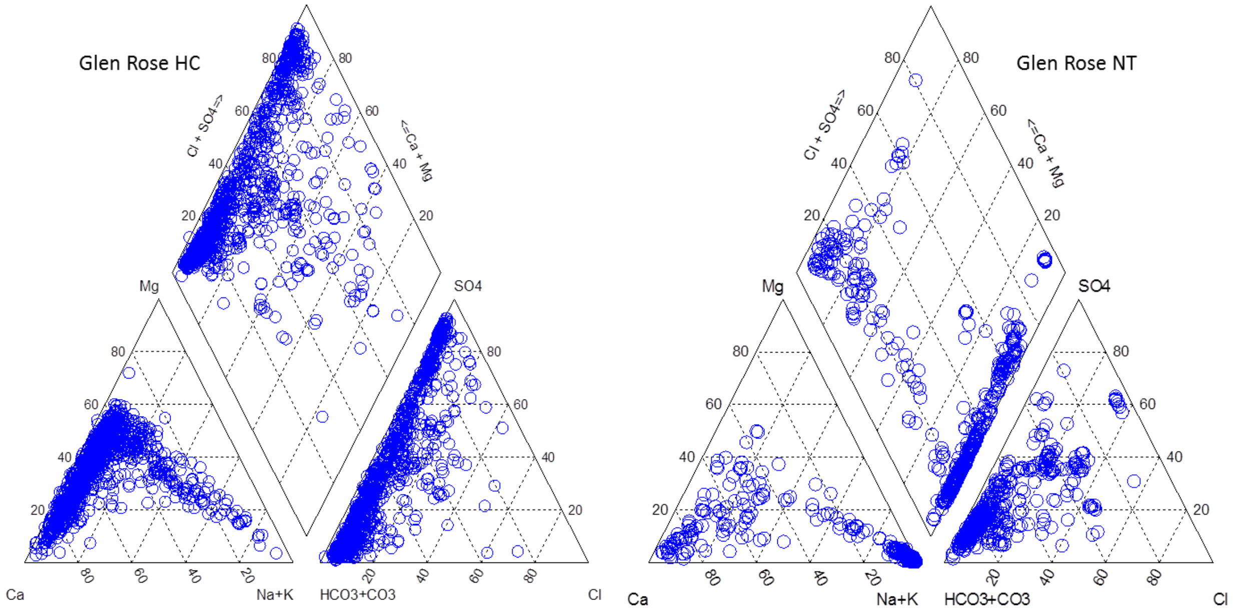

Figure 10-3 Piper plots of water quality for the Hill Country Trinity region (left) and Northern Trinity region (right) Glen Rose unit.

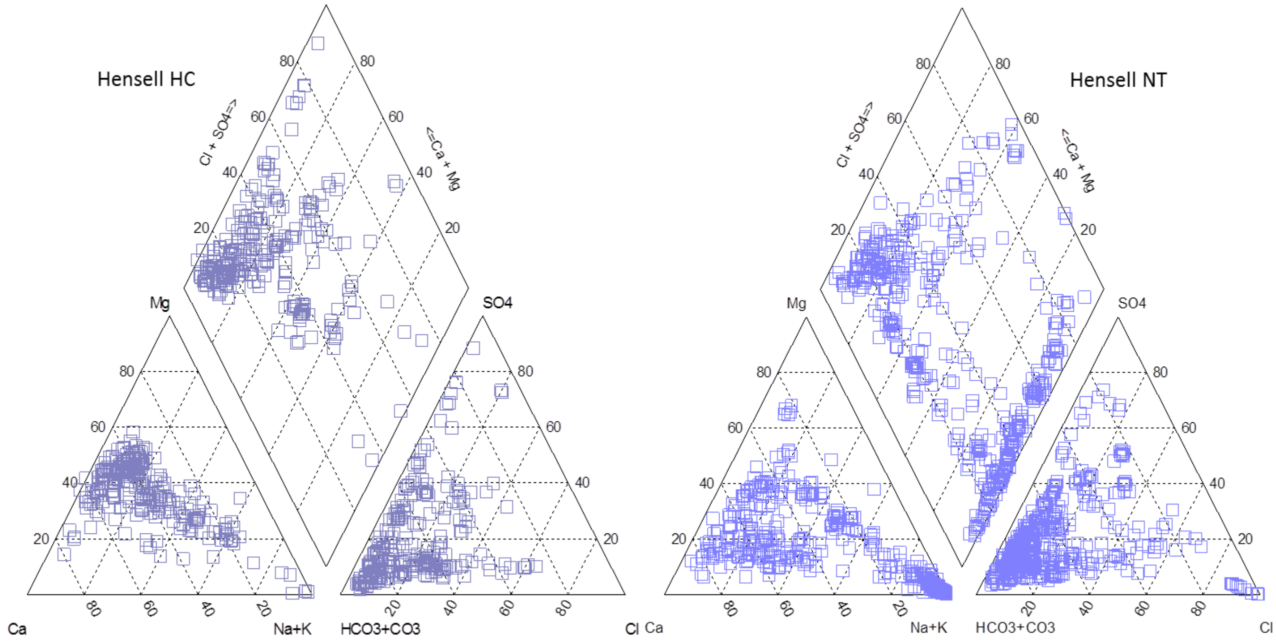

Figure 10-4 Piper plots of water quality for the Hill Country Trinity region (left) and Northern Trinity region (right) Hensell unit.

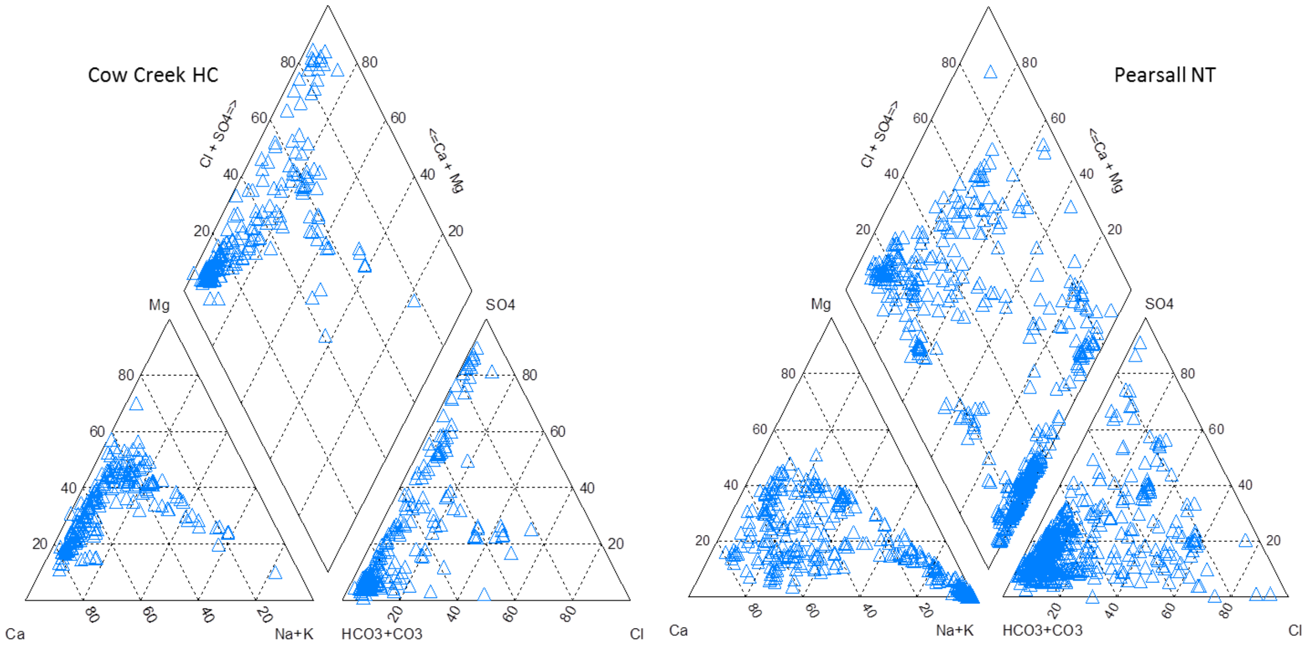

Figure 10-5 Piper plots of water quality for the Hill Country Trinity region Cow Creek unit (left) and Northern Trinity region (right) Pearsall unit.

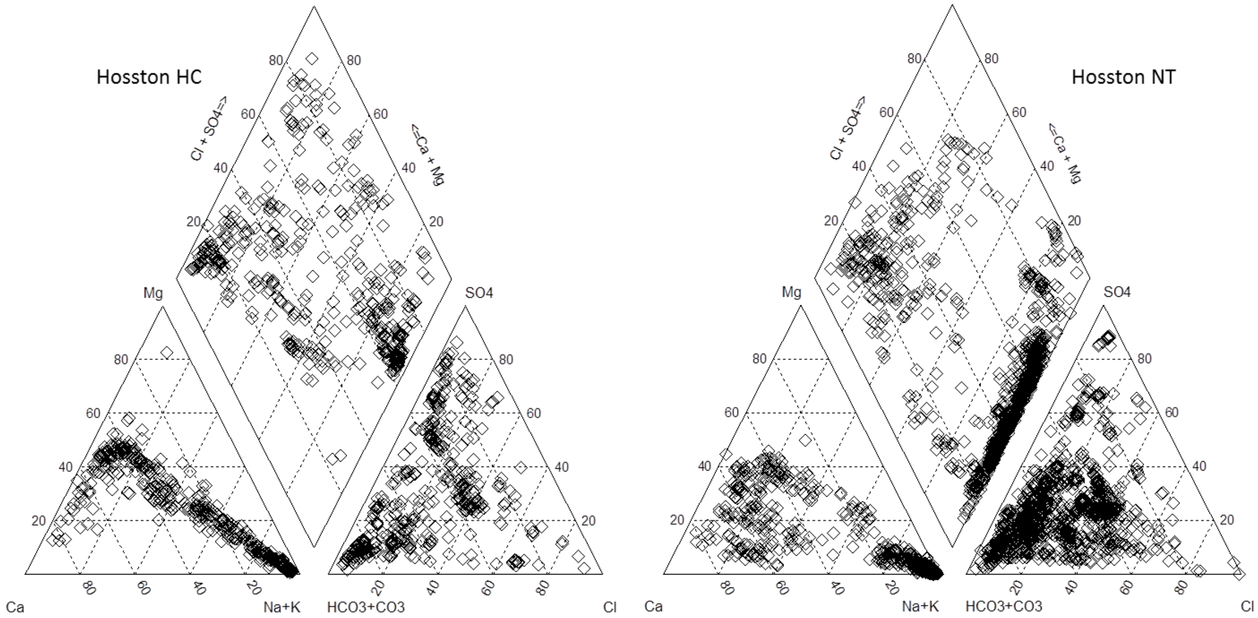

Figure 10-6 Piper plots of water quality for the Hill Country Trinity region (left) and Northern Trinity region (right) Hosston unit.

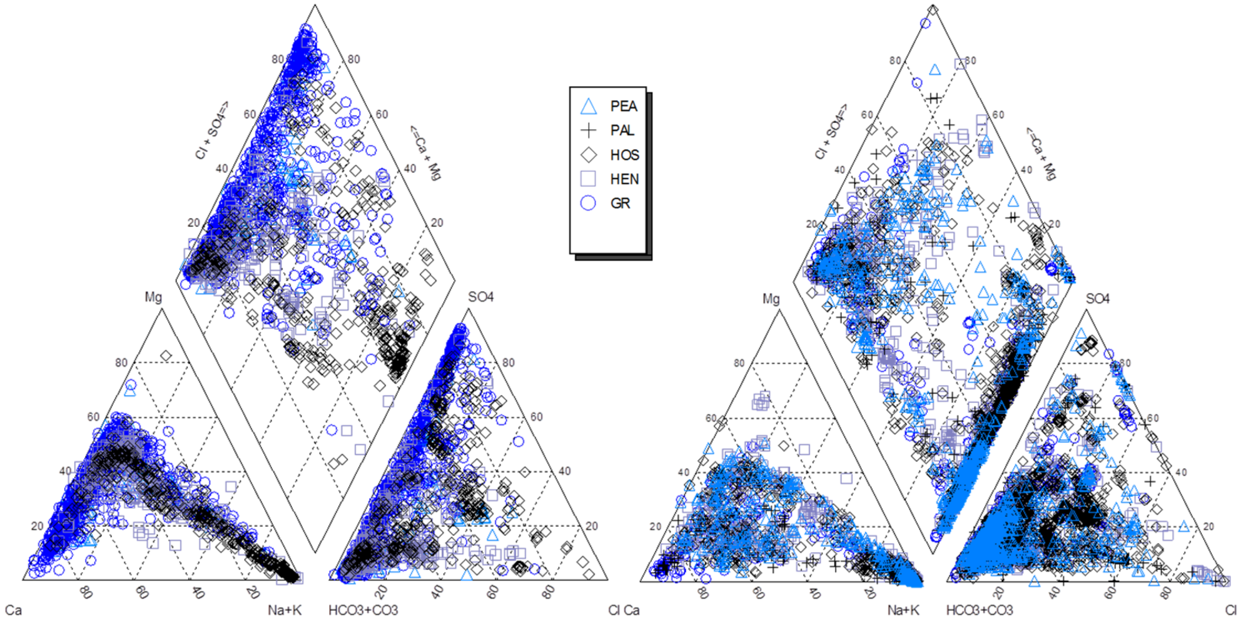

Figure 10-7 **Piper plots of water quality for all units of the Hill Country Trinity region (left) and Northern Trinity region (right).**

The features observed in the various Piper plots are quite consistent with the general descriptions of Northern Trinity Aquifer and Hill Country Trinity Aquifer water quality found in previous studies. Inspection of the diagrams reveals significant differences between and similarities within the Northern and Hill Country Trinity aquifers. For example, with exception of the Hensell unit, Hill Country Trinity Aquifer units have more sulfate and less sodium and potassium than the Northern Trinity Aquifer units (Figures 10-2 – 10-7). The Hill Country Trinity Aquifer units generally have higher magnesium concentrations (e.g., Figures 10-3 and 10-6). Notably, the compositions of the Hill Country Trinity Cow Creek and Glen Rose units are quite similar (Figures 10-3 and 10-5). The Hosston unit of the Hill Country Trinity Aquifer has the most sodium and chloride relative to other Hill Country Aquifer units (Figure 10-6). As noted by previous studies, the compositions of the Northern Trinity Aquifer units are similar, and the similarities have been used as evidence of cross-formational flow (Figures 10-2 – 10-7).

Despite the strength of enabling inspection of an aquifer's water quality characteristics on the whole, a weakness of Piper plots is a lack of spatial information. Figures 10-8 through 10-16 present water quality trends for the Hill Country Aquifer and Northern Trinity Aquifer units in map form. In each map figure, the total dissolved solids concentration for all samples assigned to each modeled brackish water unit are shown along with the calculated 1,000, 3,000, and 10,000 mg/L TDS downdip limit contours developed in this study. In the Northern Trinity region TDS concentrations for all units generally increase downdip to the east and southeast (Figures 10-8 – 10-12). TDS values increase rapidly near the Mexia-Talco Fault Zone (Kelley et al., 2014). These trends are consistent with conceptual models of flow and residence times within the Northern Trinity Aquifer (Kelley et al., 2014). As water moves downdip it has more time to interact with the various geological materials of the aquifer matrix, and dissolved constituent concentrations increase. In the southern part of the Northern Trinity Aquifer region, near and within Bell County, there is a significant updip trend of higher TDS waters for all units (Figures 10-8 – 10-12). The specific causes of the increased TDS concentrations in this area are unclear but may due to a greater occurrence of evaporite minerals, isolation of the aquifer from updip recharge areas, increased cross-formational flow from higher TDS units, or a combination of these.

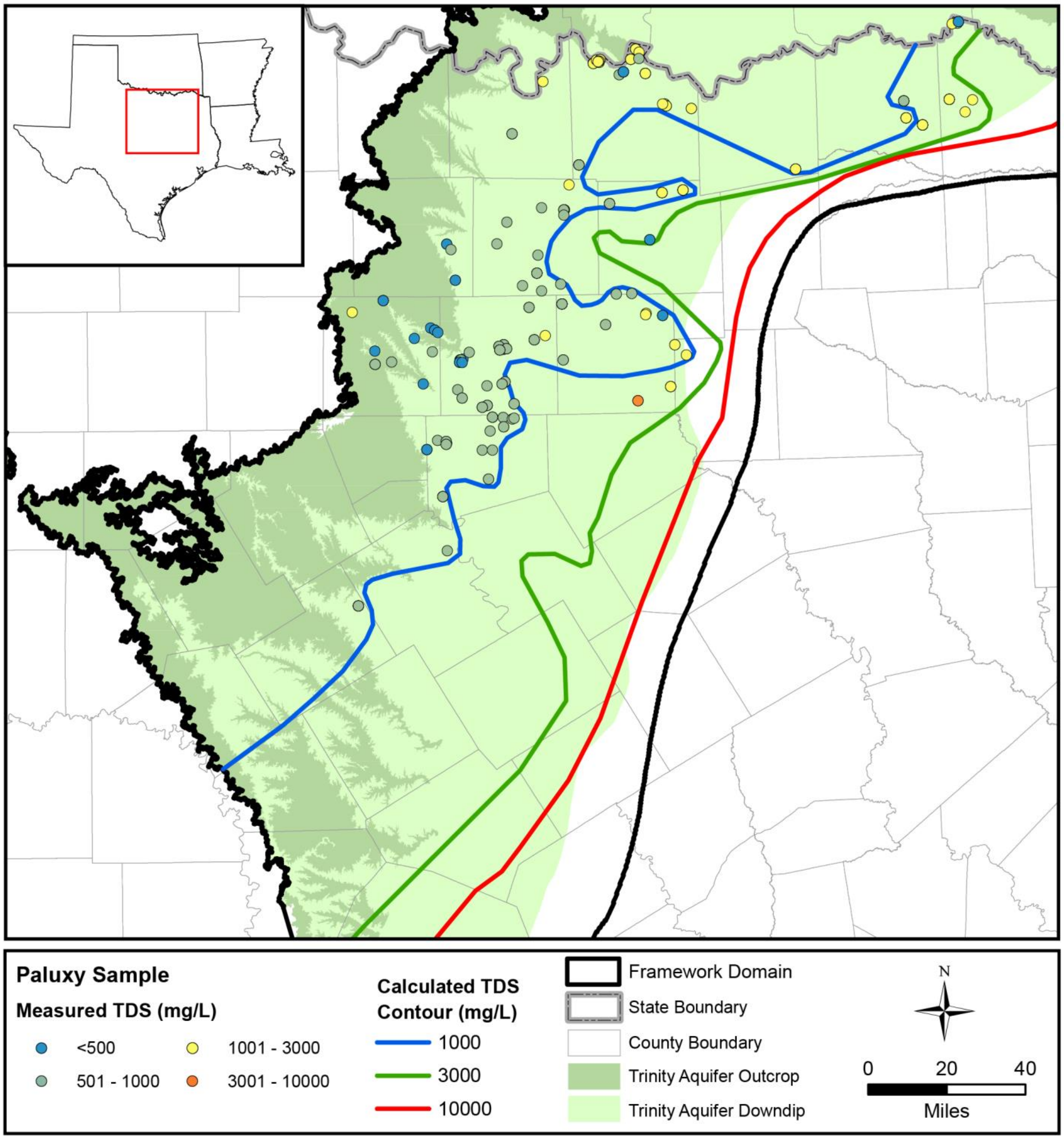

Figure 10-8 **Map of TDS (mg/L) data for the Northern Trinity Paluxy unit. Contour lines estimating extent of 1000, 3000, and 10000 mg/L TDS are also shown.**

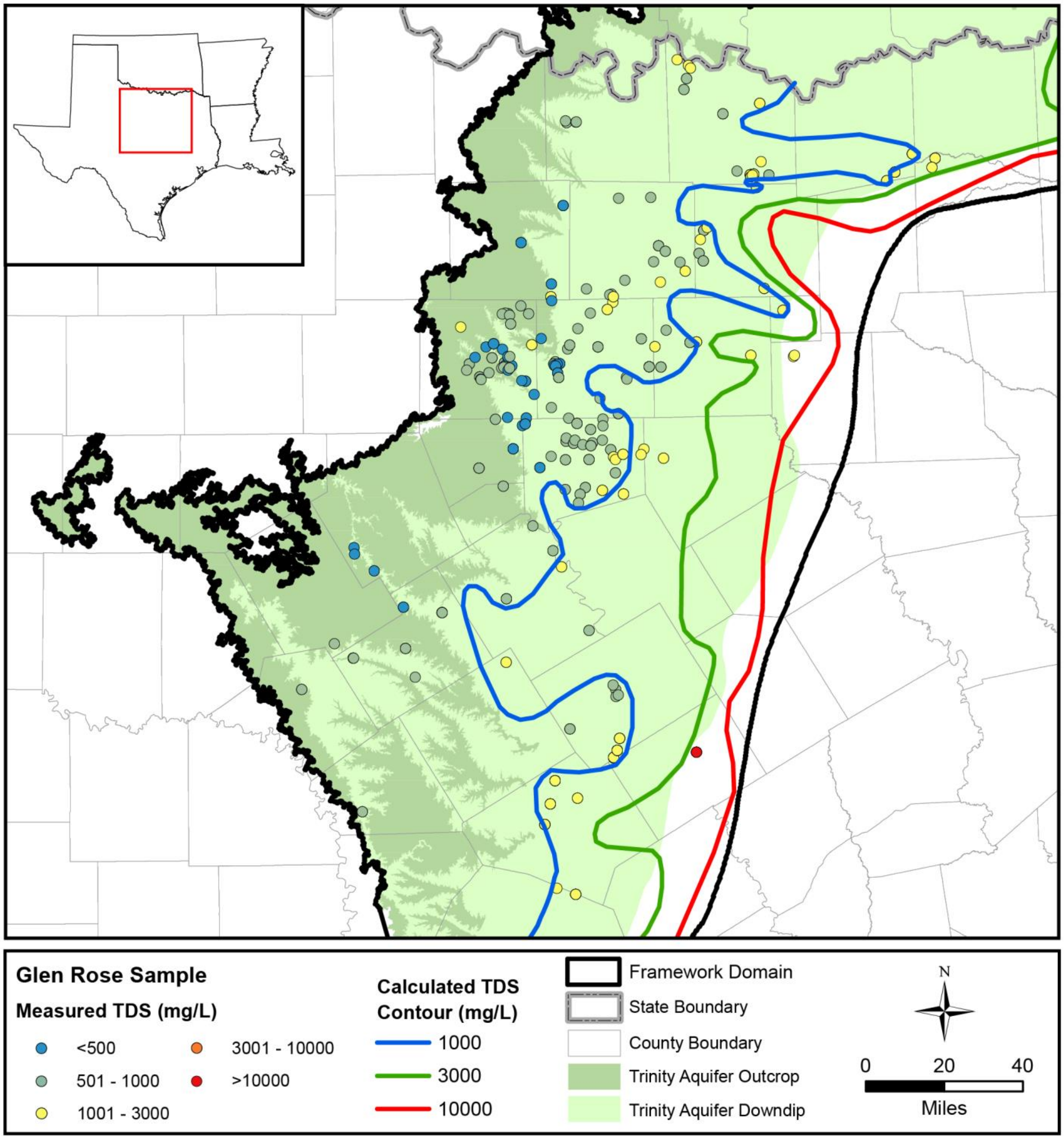

Figure 10-9 Map of TDS (mg/L) data for the Northern Trinity Glen Rose unit. Contour lines estimating extent of 1000, 3000, and 10000 mg/L TDS are also shown.

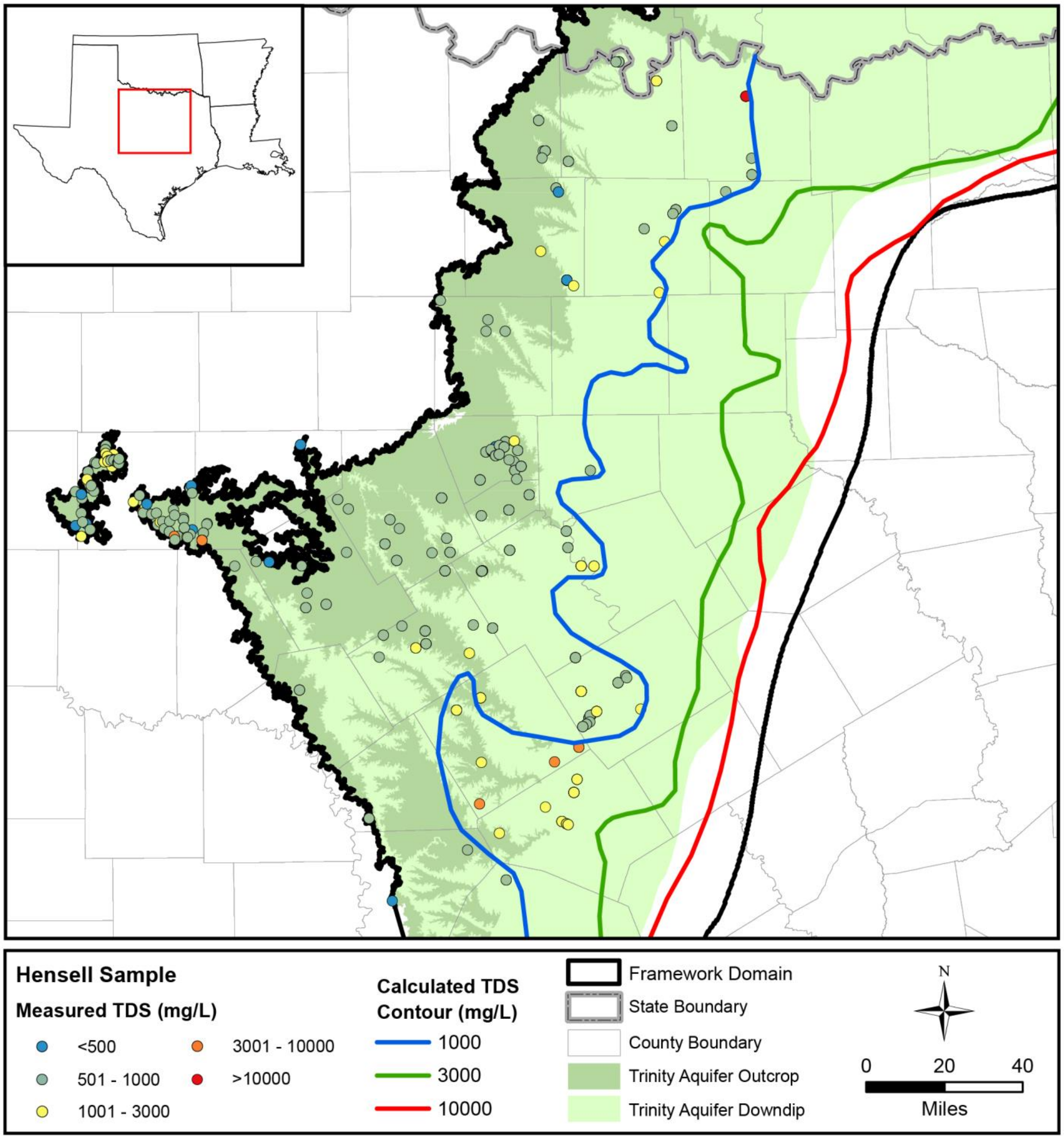

Figure 10-10 Map of TDS (mg/L) data for the Northern Trinity Hensell unit. Contour lines estimating extent of 1000, 3000, and 10000 mg/L TDS are also shown.

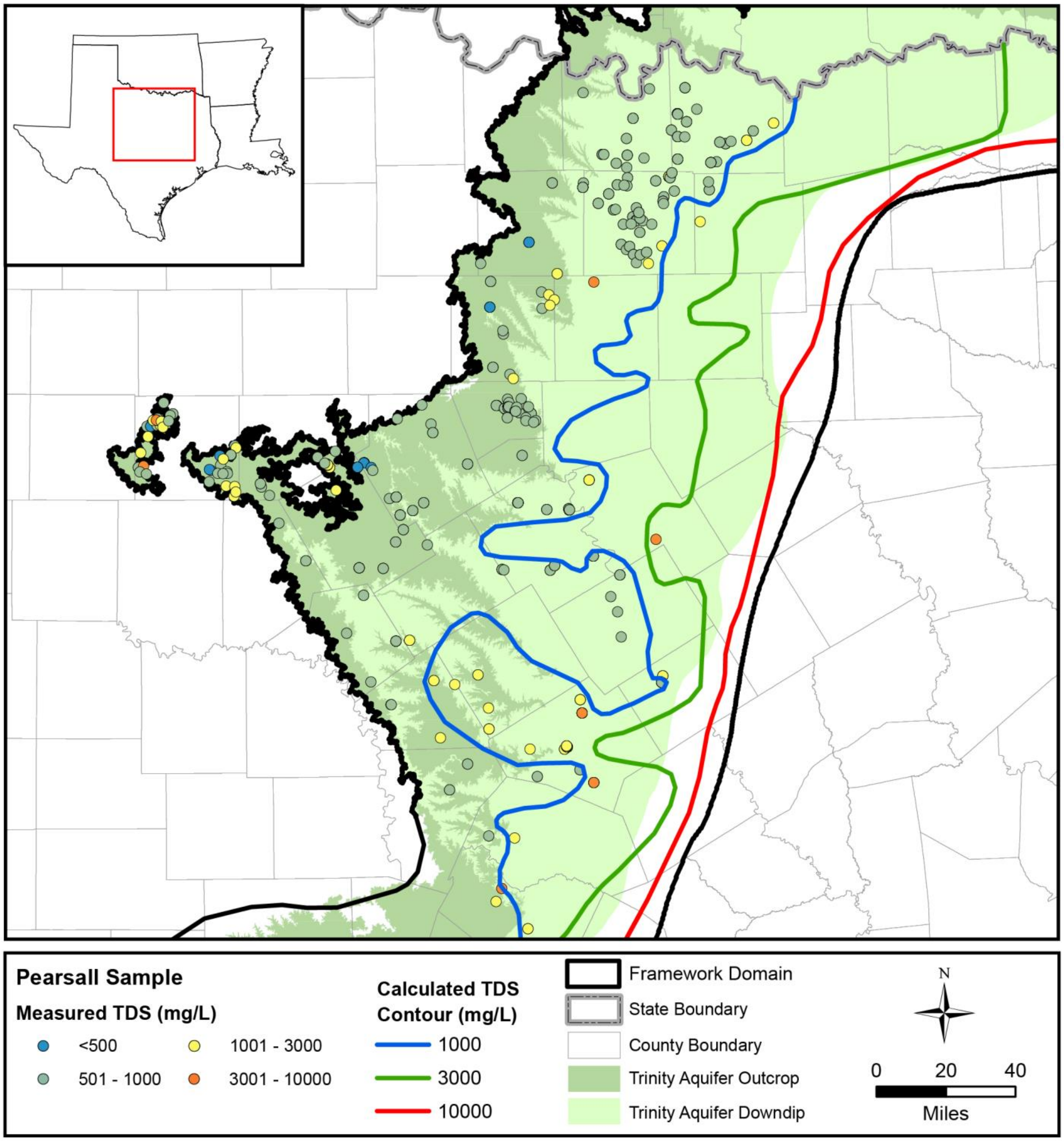

Figure 10-11 Map of TDS (mg/L) data for the Northern Trinity Pearsall unit. Contour lines estimating extent of 1000, 3000, and 10000 mg/L TDS are also shown.

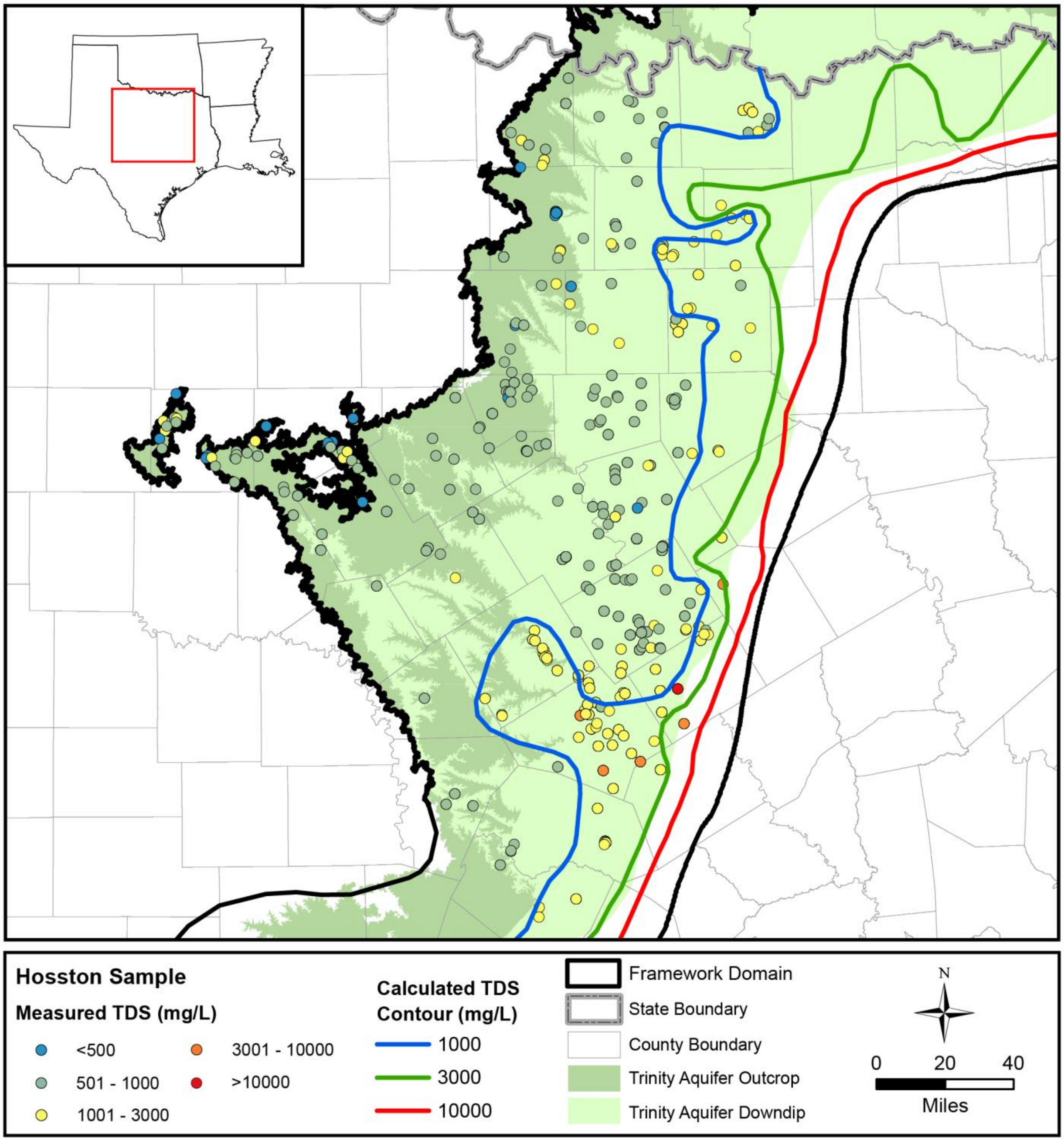

Figure 10-12 Map of TDS (mg/L) data for the Northern Trinity Hosston unit. Contour lines estimating extent of 1000, 3000, and 10000 mg/L TDS are also shown.

As noted by Jones et al. (2011), there is no real trend of TDS concentrations in the Hill Country Trinity units (Figures 10-13 – 10-16). Higher TDS concentrations generally occur near the southern and eastern extent of the outcrop of Trinity Aquifer rocks, but low and high TDS waters are spatially variable even along that boundary (Figures 10-13 – 10-16). These is a zone of elevated TDS in southwestern Travis County extending into Blanco County (Figure 10-13), but even within that zone there are several wells with low TDS water. The increased TDS concentrations are primarily the result of increase in sulfate concentrations for the Hill Country Trinity Aquifer wells. If cross-formational flow was extensive in this area, mixing of waters impacted by dissolution of evaporite minerals could be a cause of the high TDS zone.

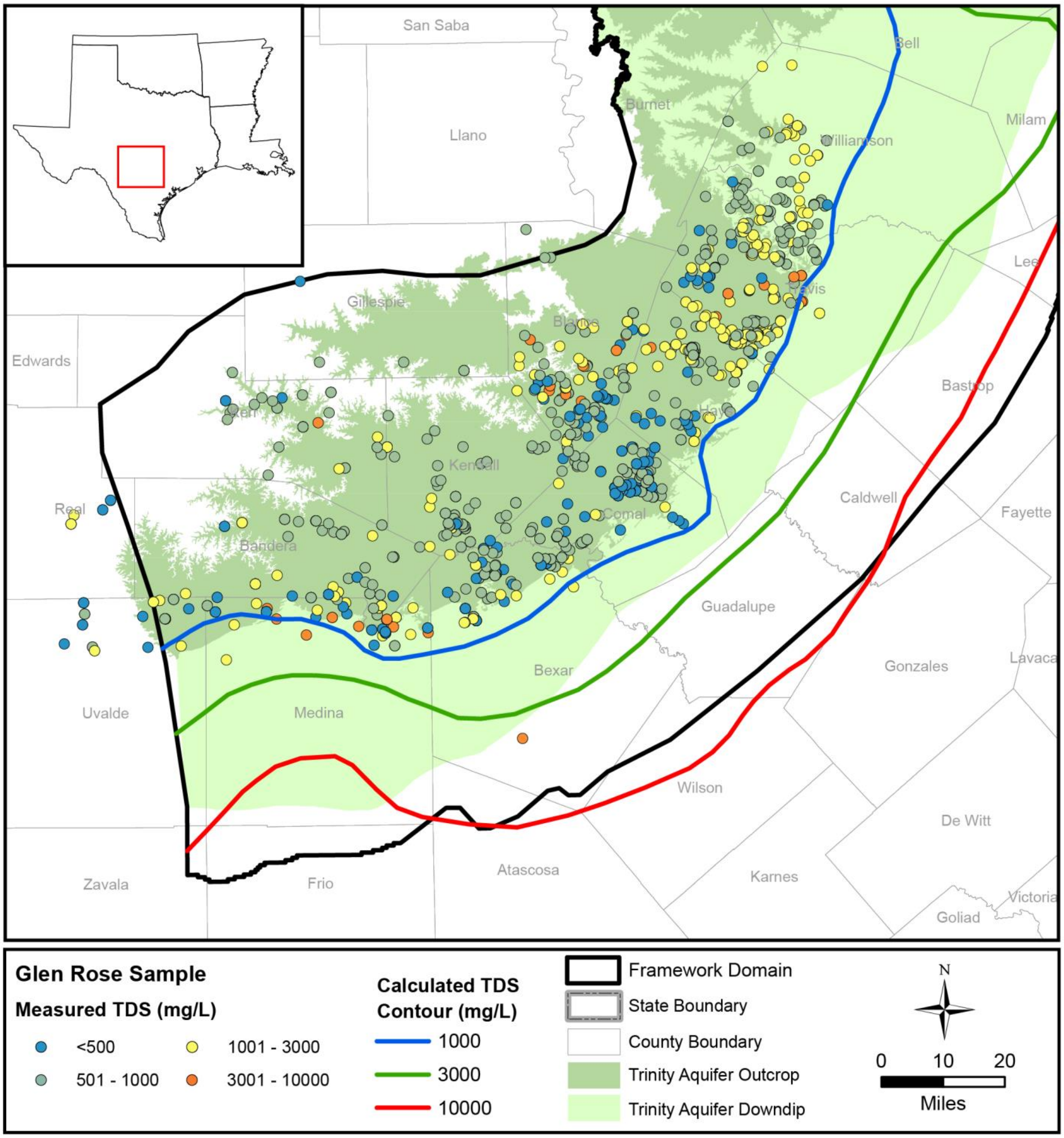

Figure 10-13 Map of TDS (mg/L) data for the Hill Country Trinity Glen Rose unit. Contour lines estimating extent of 1000 and 3000 mg/L TDS are also shown.

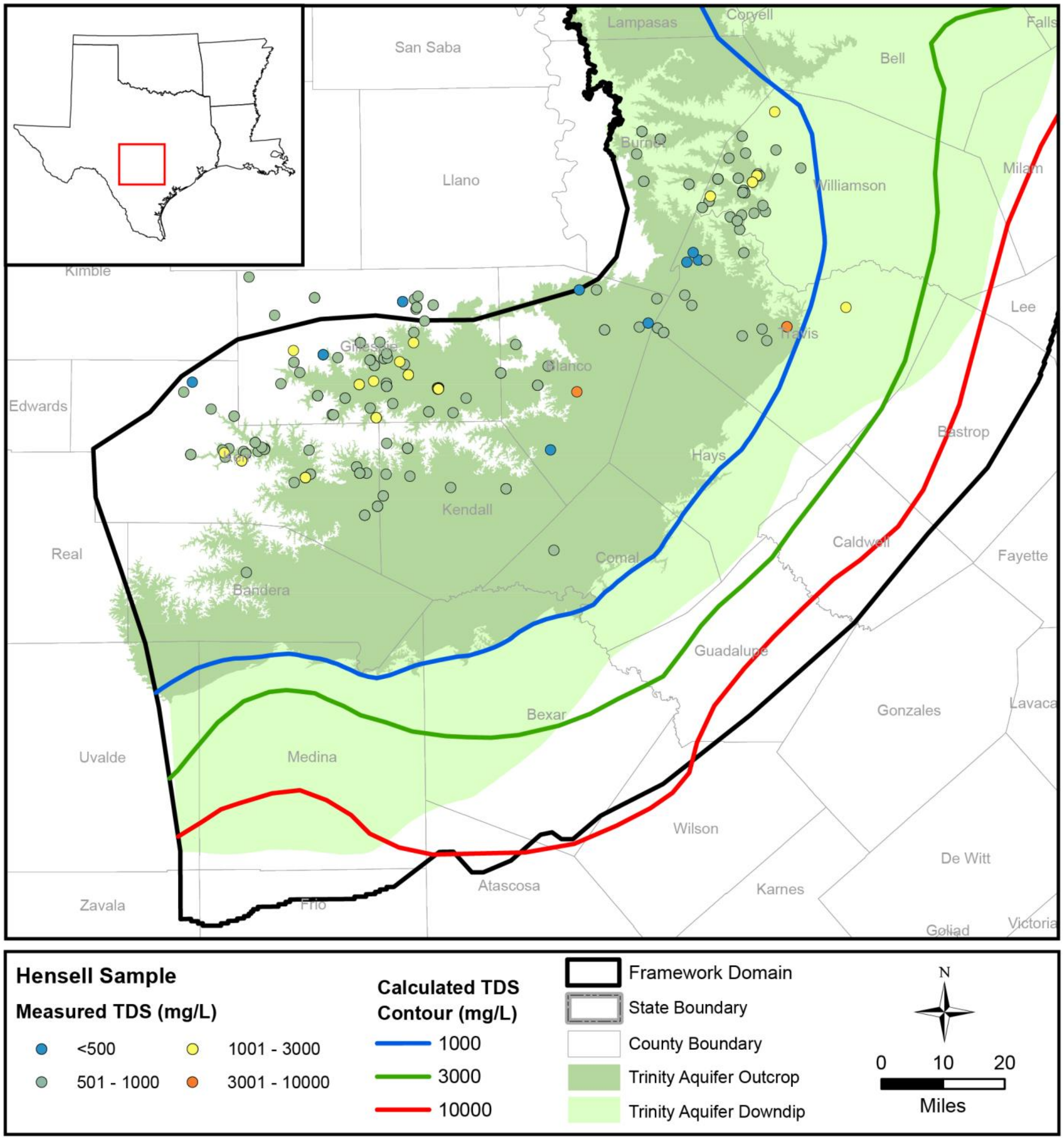

Figure 10-14 Map of TDS (mg/L) data for the Hill Country Trinity Hensell unit. Contour lines estimating extent of 1000 and 3000 mg/L TDS are also shown.

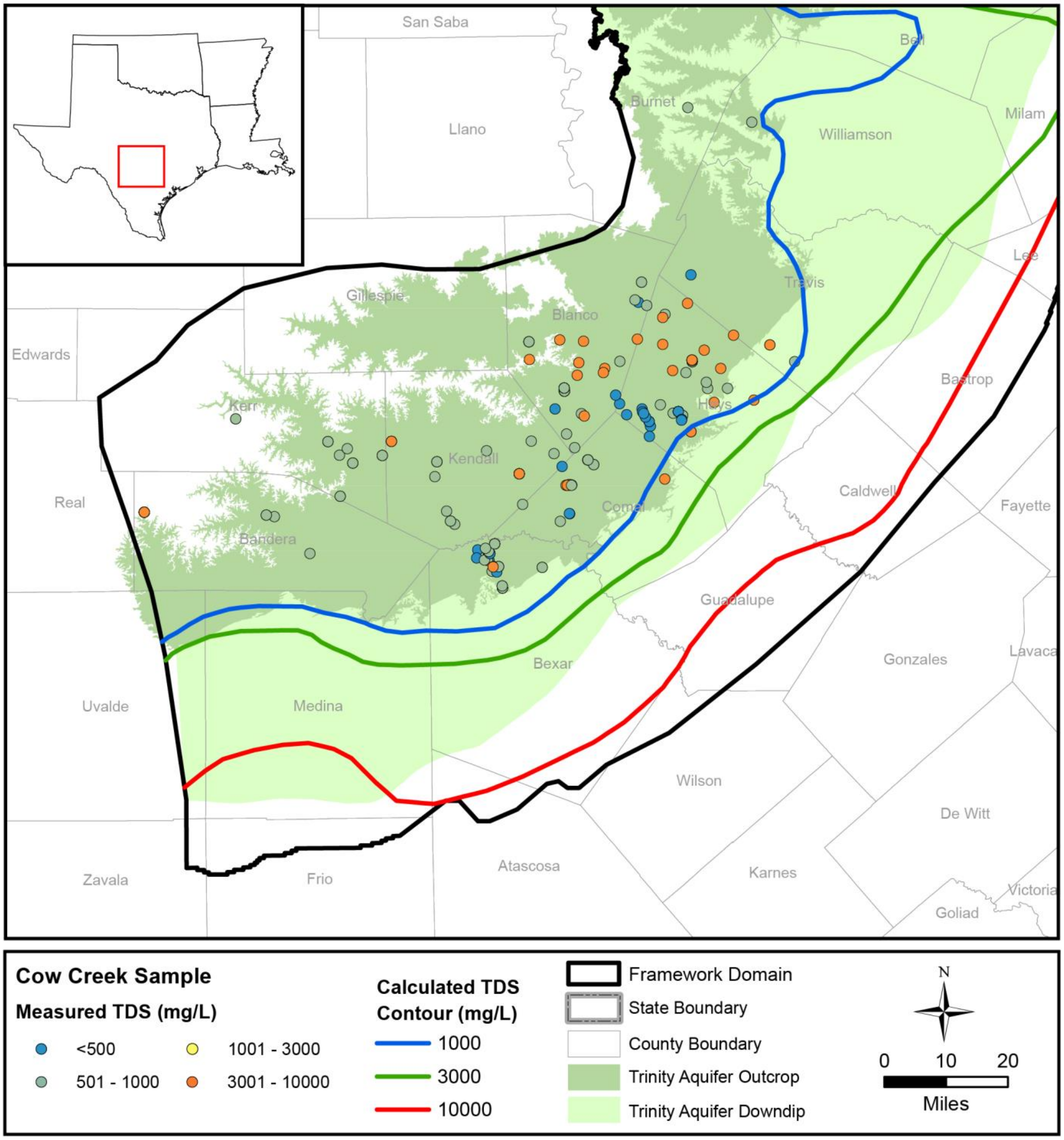

Figure 10-15 Map of TDS (mg/L) data for the Hill Country Trinity Cow Creek unit. Contour lines estimating extent of 1000 and 3000 mg/L TDS are also shown.

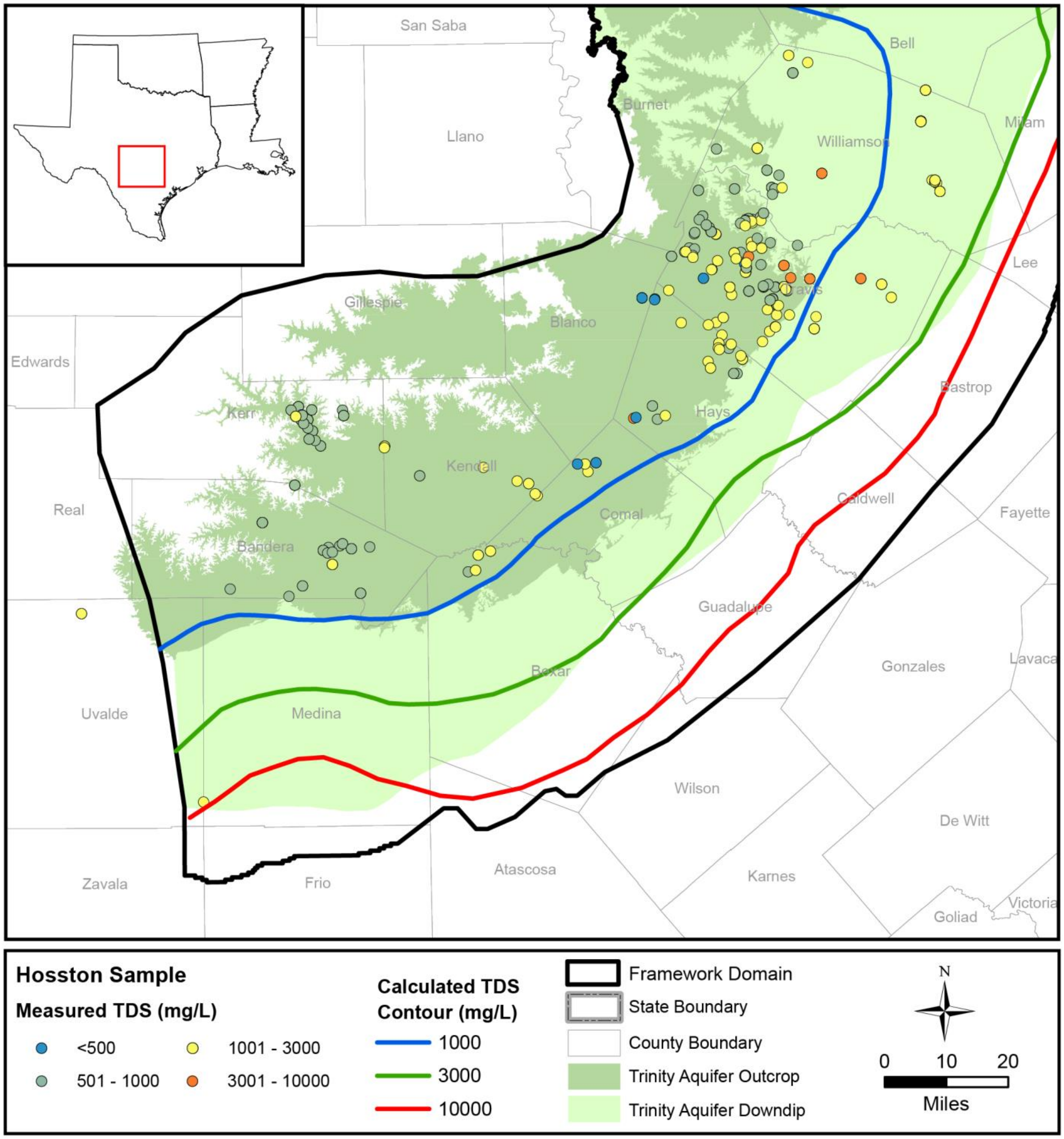

Figure 10-16 **Map of TDS (mg/L) data for the Hill Country Trinity Hosston unit. Contour lines estimating extent of 1000 and 3000 mg/L TDS are also shown.**

Experiences from studies of aquifers with deep productive zones (e.g., Carrizo-Wilcox Aquifer) and data from petroleum exploration activities indicate groundwater chemistries evolve toward high TDS sodium bicarbonate or sodium chloride type waters (e.g., Hamlin, 1988; Blondes et al., 2016). Thus, studies of brackish water resources often incorporate assumptions of similar chemical evolution with depth and downdip distance. However, as the Hill Country Trinity Aquifer region data and some of the Northern Trinity Aquifer region data indicate, Trinity Aquifer groundwaters and TDS are heavily influenced by increases in sulfate. Figure 10-17 shows the strong correlation between TDS and sulfate for Hill Country Trinity Glen Rose unit samples. The downdip depth and spatial extent to which the sulfate and TDS correlation applies is uncertain, and it is likely that as Trinity Aquifer groundwater exceeds 10,000 mg/L, the concentration and influence of sodium chloride will predominate. Nonetheless, the concentrations calcium, bicarbonate, and sulfate in the Trinity Aquifer are important for brackish water concentrations between 1,000 and 10,000 mg/L. Moreover, because dissolved calcium, bicarbonate, and sulfate are known to significantly influence the measured conductivity (and thus, resistivity) of water, methods estimating water quality from borehole geophysical data must take these constituents and their distributions into account. The methods used to address this issue are discussed in detail in Section 13.

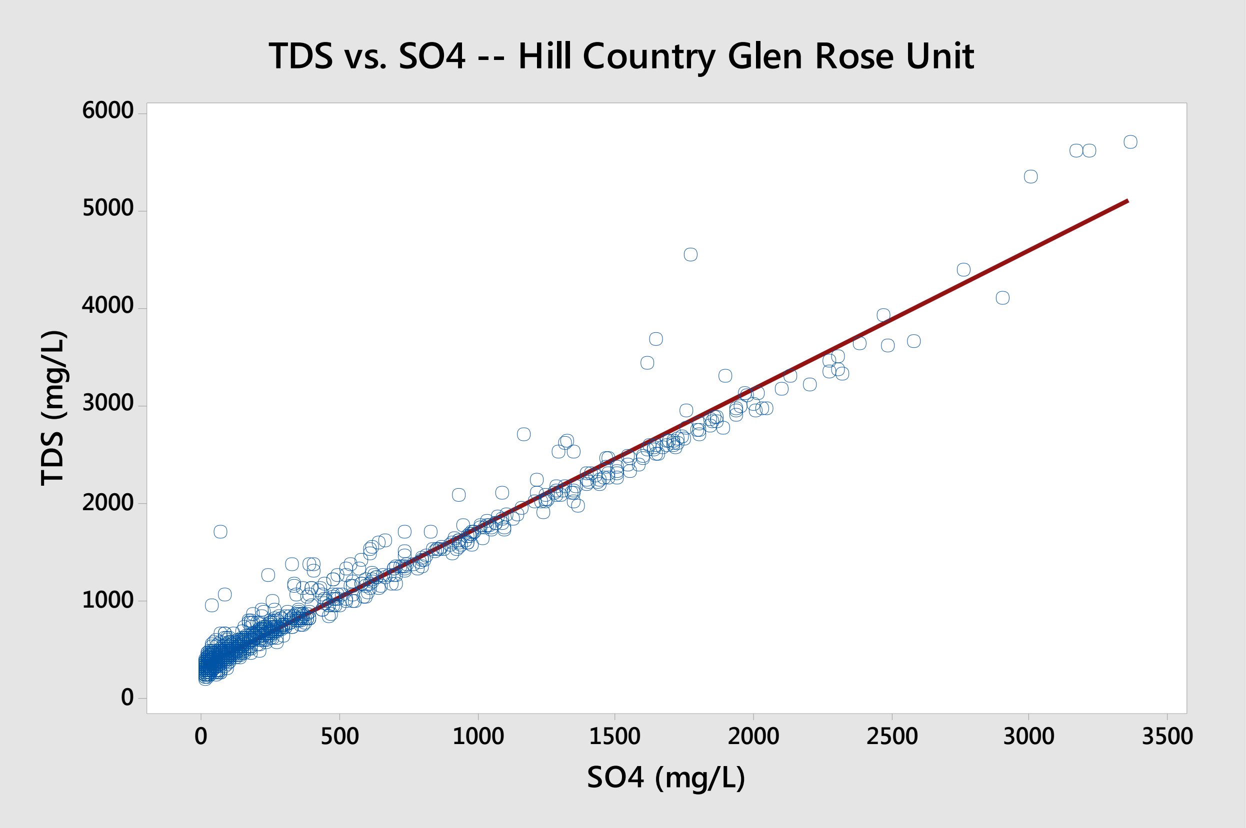

Figure 10-17 **Plot of TDS (mg/L) versus sulfate (SO_4) (mg/L) data for the Hill Country Trinity Glen Rose unit. The two parameters are highly correlated with a degree of freedom adjusted R^2=0.97.**

11 Net Sand Analysis

The Trinity Aquifer is comprised of a complex assemblage of lithologies including limestone, sand, clay, gravel, and conglomerate. As discussed in Section 5 of this report, the transmissive water-bearing formations of the Trinity Aquifer are the Antlers, the Glen Rose, the Paluxy, the Twin Mountains, the Travis Peak, the Hensell, the Cow Creek, and the Hosston. Therefore, no net sand analyses have been performed for this study. Lithologic descriptions and isopach maps of the dolomite and limestone units are discussed in Section 5 and relevant appendices.

12 Groundwater Volume Methodology

In this section, estimates of groundwater volumes are generated for different classifications of groundwater quality for the Trinity Aquifer based on the water salinity zones defined in Section 6. The salinity zones in the Trinity Aquifer have been developed based upon observed water quality data and analysis of geophysical logs presented (see Section 13). As has been discussed previously in this report, the five transmissive water-producing units of the Northern Trinity Aquifer are the Paluxy Formation, the Glen Rose Formation, the Hensell Formation, the Pearsall Formation, and the Hosston Formation. The water producing zones of the Hill Country Trinity are the Glen Rose Formation, the Hensell Formation, the Cow Creek Formation, and the Hosston Formation. Separate groundwater salinity zones and potential production areas for each of these transmissive these units have been defined within the Trinity Aquifer, and discussion is separated below by the Northern Trinity Aquifer and the Hill Country Trinity Aquifer.

12.1 Mechanics of calculating groundwater volumes in the Trinity Aquifer

Shi and others (2014) provide a good overview of the calculation of the volume of groundwater stored in an aquifer as part their calculation of Total Estimated Recoverable Storage for different aquifers in Groundwater Management Area 8. The approach used to calculate aquifer groundwater volumes is essentially the same as the process used by the TWDB to estimate Total Estimated Recoverable Storage. Shi and others (2014) use the combined thickness of the five transmissive units to calculate storage of the Trinity Aquifer. However, in this report, separate calculated groundwater storage values are provided for each of the transmissive members of the Trinity Aquifer.

The water quality classifications used in this report are based upon water quality classifications developed by the United States Geological Survey (Winslow and Kister, 1956) and presented in Table 12-1.

The method used to calculate groundwater volume in both Shi and others (2014) and in this report is dependent on whether or not the aquifer is confined or unconfined. The following section provides a general discussion about confined and unconfined aquifers and how storage is calculated differently in each type of aquifer.

12.1.1 Confined and unconfined aquifer

In general, the Trinity Aquifer is a dipping aquifer that is unconfined updip and confined downdip. Figure 12-1 shows a schematic of idealized groundwater conditions in this kind of aquifer. 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 Trinity Aquifer, the formations generally dip southeast. Therefore, the unconfined portions of the Trinity Aquifer transmissive 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 transmissive units become confined east of their outcrops, as the units dip deeper and are overlain by younger units. As shown in the schematic provided in Figure 12-1, 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 (which can be couched as pressure) in the aquifer by pumping causes expansion of groundwater and deformation of aquifer solids. The aquifer is still fully saturated to this point. This portion of aquifer storage is referred to as the confined aquifer storage.

The second part of groundwater storage is sourced 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 that portion that is considered drainable. The equations for calculating the total groundwater volume are presented below:

For unconfined aquifers:

$$\text{Total Volume} = V_{\text{drained}} = \text{Area} * S_y * (\text{Water Level} - \text{Bottom}) \qquad \text{(Equation 12-1a)}$$

For confined aquifers:

$$\text{Total Volume} = V_{\text{confined}} + V_{\text{drained}} \qquad \text{(Equation 12-1b)}$$

Volume for confined part

$$V_{\text{confined}} = \text{Area} * [S *(\text{Water level-Top})] \qquad \text{(Equation 12-2)}$$

or

$$V_{\text{confined}} = \text{Area} * [S_s *(\text{Thickness})*(\text{Water level-Top})] \qquad \text{(Equation 12-3)}$$

Volume for unconfined part

$$V_{\text{drained}} = \text{Area} * [S_y *(\text{Thickness})] \qquad \text{(Equation 12-4)}$$

Where:

$V_{drained}$ = 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)
S_s = specific yield (no units)
S_y = specific storage (feet^{-1})

S = storativity or storage coefficient (no units)

12.1.2 Hydraulic and physical properties for the Northern Trinity Aquifer

The groundwater volume calculations described above require input values for aquifer properties such as aquifer structure, thickness, water level and specific yield. These are described below.

Structure and Thickness – For volume calculations in the five transmissive members of the Trinity Aquifer, the member unit thickness and the elevations of unit tops and bottoms are based upon the structure in the updated Groundwater Availability Model of the Northern Trinity and Woodbine Aquifers (Kelley and others, 2014), where:

- Model Layer 4 represents the Paluxy Aquifer
- Model Layer 5 represents the Glen Rose Formation
- Model Layer 6 represents the Hensell Aquifer
- Model Layer 7 represents the Pearsall Formation
- Model Layer 8 represents the Hosston Aquifer

Northern Trinity Aquifer Water Level – The water levels used to calculate the aquifer volumes are based upon the last year of calibration (beginning of 2010) from the updated Groundwater Availability Model of the Northern Trinity and Woodbine Aquifers (Kelley and others, 2014).

Specific Yield – Specific yield values for each of the five transmissive members of the Trinity Aquifer were assigned based on the Northern Trinity / Woodbine Aquifer Groundwater Availability Model (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

12.1.3 Hydraulic and physical properties for the Hill Country Trinity Aquifer

The groundwater volume calculations described above require input values for aquifer properties such as aquifer structure, thickness, water level and specific yield. These are described below.

Structure and Thickness – For volume calculations in the four transmissive members of the Hill Country portion of the Trinity Aquifer, the member unit thickness and the elevations of unit tops and bottoms are based upon the structure developed in Section 5 of this report (Geologic setting and framework development).

Hill Country Trinity Aquifer Water Level – The water levels used to calculate the aquifer volumes are based upon the water levels obtained from the TWDB groundwater database. Water levels for the Hill Country Trinity portion were limited to water levels measured after January 1, 2000. Water levels were interpolated for the unconfined portion of the Trinity aquifer as a whole. Hydrostatic gradients are assumed throughout the Trinity aquifer in the absence of a GAM that is inclusive of the entire aquifer.

Specific Yield – Specific yield values for each of the four transmissive members of the Hill Country Trinity Aquifer were assigned based on the Groundwater Availability Model: Hill Country Portion of the Trinity Aquifer (Jones and others, 2011), where:

- Glen Rose Specific yield = 0.0008
- Hensell Specific yield = 0.0008
- Cow Creek Specific yield = 0.0008
- Hosston Specific yield = 0.0008

12.1.4 Process for calculating groundwater volumes based on water quality for the Northern Trinity Aquifer

The groundwater volume calculations for groundwater storage are implemented on a quarter-mile grid scale coincident with the Groundwater Availability Model Grid (Kelley and others, 2014). Where present, both confined storage and unconfined drained storage were calculated for each of the five transmissive members of the 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 12-1a. We calculated the confined groundwater storage for each unit using Equation 12-3. The variable “Top” is the top elevation of the transmissive member in question while the variable “Bottom” is the bottom elevation of that unit. The variable “Thickness” is calculated specifically for each transmissive member based on the difference between the variable “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 19).

12.1.5 Process for calculating groundwater volumes based on water quality for the Hill Country Trinity Aquifer

The groundwater volume calculations for groundwater storage are implemented 200m by 200m raster cell size. Unconfined drained storage was calculated for each of the four transmissive members of the Hill Country Trinity Aquifer: the Glen Rose, the Hensell, the Cow Creek and the Hosston. The unconfined drained groundwater storage for each unit was calculated using equation 12-1a. The confined groundwater storage for each unit was calculated using Equation 12-4. Equation 12-3 is not included in the calculation because the S_s values that were estimated in the GAM (Jones and others, 2011) were so low that the contribution to storage from compressible release of water was negligible. The variable “Top” is the top elevation of the transmissive member in question while the variable “Bottom” is the bottom elevation of that unit. The variable “Thickness” is calculated specifically for each transmissive member based on the difference between the variable “Top” and “Bottom.”

The calculations were developed using spatial analysis in ARCGIS 10.4. The complete detailed algorithm and equations implemented are described in detail in Appendix section of this report (Section 19).

12.2 Calculated groundwater volumes: Northern Trinity Aquifer

Table 12-2 provides the total calculated volume of groundwater in the Northern Trinity Aquifer. The calculations are rounded to the nearest 1,000-acre foot per year. Table 12-2 summarizes the volumes of groundwater, by salinity classification, in the five transmissive members of the Trinity Aquifer: the Paluxy, the Glen Rose, the Hensell, the Pearsall, and the Hosston. The total volume of groundwater calculated is 2,075,217,820 acre-feet of groundwater. Total groundwater in the Paluxy, the Glen Rose, the Hensell, the Pearsall, and the Hosston is 343,626,000 acre-feet, 440,588,000 acre-feet, 213,749,000 acre-feet, 168,347,000 acre-feet, and 908,909,000 acre-feet, respectively. The Pearsall has the smallest volume of the hydrologic units which is expected given that it is generally the least productive of the mapped transmissive units. The groundwater in the Northern Trinity Aquifer is split nearly evenly between the water quality classifications with approximately 25% of the groundwater classified as fresh, approximately 28% as slightly saline, approximately 24% as moderately saline and approximately 23% as very saline.
Table 12-3 provides the volume of groundwater by aquifer unit and by salinity class for all the counties which intersect the boundaries of the Trinity Aquifer. Table 12-4 provides the volume of groundwater by aquifer unit and by salinity class for all the Groundwater Conservation or Underground Water Districts that intersect the boundaries of the Trinity Aquifer. Table 12-4 includes groundwater in Texas but not within the boundaries of a groundwater conservation district which accounts for slightly more than half (51%) of the total aquifer groundwater. Table 12-5 provides the volume of groundwater by aquifer unit and by salinity class for all the Groundwater Management Areas that intersect the Trinity Aquifer.

12.3 Calculated groundwater volumes: Hill Country Trinity Aquifer

Table 12-6 provides the total calculated volume of groundwater in the Hill Country portion of the Trinity Aquifer. The calculations are rounded to the nearest 1,000-acre foot per year. Table 12-6 summarizes the volumes of groundwater, by salinity classification, in the four transmissive members of the Hill Country portion of the Trinity Aquifer: the Glen Rose, the Hensell, the Cow Creek, and the Hosston. The total volume of groundwater calculated is 6,544,000 acre-feet of groundwater. Total groundwater in the Cow Creek, the Glen Rose, the Hensell, and the Hosston is 441,000 acre-feet, acre-feet, 3,217,000 acre-feet, 617,000 acre-feet, and 2,269,000 acre-feet, respectively. The groundwater in the Hill Country Trinity Aquifer tends toward fresher water, with approximately 31% of the groundwater classified as fresh, approximately 26% as slightly saline, approximately 30% as moderately saline and approximately 13% as very saline.

Table 12-7 provides the volume of groundwater by aquifer unit and by salinity class for all the counties which intersect the boundaries of the Trinity Aquifer. Table 12-8 provides the volume of groundwater by aquifer unit and by salinity class for all the Groundwater Conservation Districts and Underground Water Districts which intersect the boundaries of the Trinity Aquifer. Table 12-9 provides the volume of groundwater by aquifer unit and by salinity class for all the Groundwater Management Areas that intersect the Trinity Aquifer.

Table 12-1 Groundwater classification based on the Criteria Establish by Winslow and Kister (1956).

Water Classification Description	TDS Range (milligrams per liter)
Fresh	Less than 1,000
Slightly Saline	1,000 to 3,000
Moderately Saline	3,000 to 10,000
Very Saline	10,000 to 35,000

Table 12-2 The volumes of fresh, moderately saline, slightly saline, very saline, and total groundwater volumes in the Northern Trinity Aquifer.

Aquifer Unit	Total Volume (Acre-feet)				
	Fresh	Slightly saline	Moderately saline	Very saline	Total
Paluxy	114,748,000	80,676,000	64,503,000	81,312,000	341,239,000
Glen Rose	107,622,000	137,657,000	114,292,000	79,875,000	439,446,000
Hensell	94,766,000	63,080,000	34,648,000	20,647,000	213,141,000
Pearsall	31,834,000	52,494,000	52,433,000	31,124,000	167,885,000
Hosston	171,110,000	246,770,000	232,964,000	256,357,000	907,201,000

Table 12-3 **The volumes of fresh, moderately saline, slightly saline, very saline, and total groundwater volumes in the Northern Trinity Aquifer by county.**

County and Aquifer Unit	Total Volume (Acre-feet)				
	Fresh	Slightly saline	Moderately saline	Very saline	Total
Bastrop County					
Paluxy	0	0	0	967,000	967,000
Glen Rose	0	0	6,491,000	3,130,000	9,621,000
Hensell	0	0	390,000	577,000	967,000
Pearsall	0	0	1,422,000	1,512,000	2,934,000
Hosston	0	703,000	10,813,000	20,146,000	31,662,000
Bell County					
Paluxy	0	1,046,000	1,218,000	340,000	2,604,000
Glen Rose	6,071,000	10,694,000	2,955,000	0	19,720,000
Hensell	0	4,384,000	869,000	0	5,253,000
Pearsall	635,000	2,760,000	1,048,000	0	4,443,000
Hosston	4,487,000	23,991,000	837,000	0	29,315,000
Bosque County					
Paluxy	1,128,000	2,800,000	0	0	3,928,000
Glen Rose	4,509,000	7,147,000	0	0	11,656,000
Hensell	8,507,000	1,428,000	0	0	9,935,000
Pearsall	1,222,000	565,000	0	0	1,787,000
Hosston	10,737,000	0	0	0	10,737,000
Bowie County					
Paluxy	0	0	1,182,000	26,374,000	27,556,000
Glen Rose	0	0	6,999,000	16,709,000	23,708,000
Hensell	0	0	2,278,000	4,762,000	7,040,000
Pearsall	0	0	3,022,000	6,364,000	9,386,000
Hosston	0	0	5,520,000	43,237,000	48,757,000
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	1,799,000	0	0	0	1,799,000
Burnet County					
Paluxy	0	0	0	0	0
Glen Rose	1,796,000	0	0	0	1,796,000
Hensell	2,445,000	103,000	0	0	2,548,000
Pearsall	813,000	3,000	0	0	816,000
Hosston	4,792,000	0	0	0	4,792,000

County and Aquifer Unit	Total Volume (Acre-feet)				
	Fresh	Slightly saline	Moderately saline	Very saline	Total
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	2,107,000	0	0	0	2,107,000
Collin County					
Paluxy	2,285,000	6,265,000	9,940,000	0	18,490,000
Glen Rose	3,346,000	5,321,000	3,787,000	3,896,000	16,350,000
Hensell	316,000	2,613,000	4,002,000	0	6,931,000
Pearsall	408,000	3,156,000	3,932,000	0	7,496,000
Hosston	2,776,000	10,592,000	19,461,000	0	32,829,000
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	6,428,000	0	0	0	6,428,000
Hensell	7,493,000	0	0	0	7,493,000
Pearsall	3,837,000	0	0	0	3,837,000
Hosston	5,596,000	888,000	0	0	6,484,000
Coryell County					
Paluxy	0	1,377,000	0	0	1,377,000
Glen Rose	9,165,000	2,318,000	0	0	11,483,000
Hensell	4,068,000	4,948,000	0	0	9,016,000
Pearsall	421,000	1,192,000	0	0	1,613,000
Hosston	3,415,000	4,818,000	0	0	8,233,000
Dallas County					
Paluxy	10,744,000	6,201,000	10,000	0	16,955,000
Glen Rose	2,682,000	8,514,000	5,028,000	0	16,224,000
Hensell	160,000	4,967,000	2,349,000	0	7,476,000
Pearsall	28,000	3,541,000	3,147,000	0	6,716,000
Hosston	3,370,000	23,378,000	45,000	0	26,793,000
Delta County					
Paluxy	452,000	922,000	689,000	5,012,000	7,075,000
Glen Rose	0	1,209,000	2,536,000	1,767,000	5,512,000

County and Aquifer Unit	Total Volume (Acre-feet)				
	Fresh	Slightly saline	Moderately saline	Very saline	Total
Hensell	0	276,000	1,564,000	966,000	2,806,000
Pearsall	0	595,000	1,483,000	1,503,000	3,581,000
Hosston	0	0	7,524,000	7,687,000	15,211,000
Denton County					
Paluxy	13,551,000	4,317,000	56,000	0	17,924,000
Glen Rose	10,022,000	561,000	0	0	10,583,000
Hensell	6,928,000	1,828,000	49,000	0	8,805,000
Pearsall	3,792,000	1,001,000	0	0	4,793,000
Hosston	7,320,000	4,536,000	622,000	0	12,478,000
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	2,363,000	0	0	0	2,363,000
Ellis County					
Paluxy	0	6,727,000	5,513,000	107,000	12,347,000
Glen Rose	0	7,958,000	10,720,000	1,146,000	19,824,000
Hensell	0	3,772,000	2,142,000	74,000	5,988,000
Pearsall	0	2,606,000	4,172,000	108,000	6,886,000
Hosston	5,880,000	20,631,000	3,837,000	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	42,000	770,000	1,848,000	2,660,000
Glen Rose	130,000	6,193,000	12,266,000	1,655,000	20,244,000
Hensell	0	505,000	1,108,000	565,000	2,178,000
Pearsall	535,000	2,774,000	3,623,000	1,116,000	8,048,000
Hosston	5,590,000	13,958,000	19,939,000	15,531,000	55,018,000
Fannin County					
Paluxy	20,136,000	5,623,000	0	0	25,759,000
Glen Rose	4,506,000	7,738,000	0	0	12,244,000
Hensell	0	6,858,000	179,000	0	7,037,000
Pearsall	121,000	7,184,000	0	0	7,305,000
Hosston	0	16,149,000	7,172,000	0	23,321,000

County and Aquifer Unit	Total Volume (Acre-feet)				
	Fresh	Slightly saline	Moderately saline	Very saline	Total
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	9,671,000	8,399,000	0	0	18,070,000
Glen Rose	9,289,000	1,202,000	0	0	10,491,000
Hensell	4,748,000	3,369,000	0	0	8,117,000
Pearsall	3,807,000	889,000	0	0	4,696,000
Hosston	4,700,000	7,370,000	0	0	12,070,000
Hamilton County					
Paluxy	283,000	133,000	0	0	416,000
Glen Rose	4,609,000	278,000	0	0	4,887,000
Hensell	7,330,000	95,000	0	0	7,425,000
Pearsall	1,462,000	43,000	0	0	1,505,000
Hosston	5,360,000	0	0	0	5,360,000
Henderson County					
Paluxy	0	0	13,000	710,000	723,000
Glen Rose	0	0	0	1,007,000	1,007,000
Hensell	0	0	0	192,000	192,000
Pearsall	0	0	0	538,000	538,000
Hosston	0	0	0	3,308,000	3,308,000
Hill County					
Paluxy	9,000	4,421,000	2,371,000	0	6,801,000
Glen Rose	128,000	13,628,000	4,174,000	0	17,930,000
Hensell	786,000	5,720,000	720,000	0	7,226,000
Pearsall	370,000	1,886,000	1,805,000	0	4,061,000
Hosston	11,362,000	6,463,000	2,475,000	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
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

County and Aquifer Unit	Total Volume (Acre-feet)				
	Fresh	Slightly saline	Moderately saline	Very saline	Total
Hensell	0	0	0	638,000	638,000
Pearsall	0	0	0	860,000	860,000
Hosston	0	0	0	3,757,000	3,757,000
Hunt County					
Paluxy	0	925,000	8,810,000	9,120,000	18,855,000
Glen Rose	26,000	1,291,000	4,353,000	8,376,000	14,046,000
Hensell	0	53,000	4,107,000	2,603,000	6,763,000
Pearsall	0	370,000	6,632,000	2,402,000	9,404,000
Hosston	0	9,000	23,035,000	18,454,000	41,498,000
Jack County					
Paluxy	0	0	0	0	0
Glen Rose	0	0	0	0	0
Hensell	8,000	0	0	0	8,000
Pearsall	12,000	0	0	0	12,000
Hosston	411,000	0	0	0	411,000
Johnson County					
Paluxy	4,164,000	3,278,000	0	0	7,442,000
Glen Rose	6,842,000	2,264,000	0	0	9,106,000
Hensell	3,363,000	4,792,000	0	0	8,155,000
Pearsall	937,000	1,333,000	0	0	2,270,000
Hosston	7,779,000	0	0	0	7,779,000
Kaufman County					
Paluxy	510,000	2,376,000	3,902,000	6,277,000	13,065,000
Glen Rose	0	0	7,185,000	10,859,000	18,044,000
Hensell	0	0	2,883,000	1,890,000	4,773,000
Pearsall	0	0	2,848,000	4,112,000	6,960,000
Hosston	0	3,022,000	15,919,000	31,683,000	50,624,000
Lamar County					
Paluxy	20,685,000	9,721,000	634,000	1,664,000	32,704,000
Glen Rose	31,000	12,295,000	774,000	658,000	13,758,000
Hensell	0	7,136,000	656,000	315,000	8,107,000
Pearsall	0	5,685,000	476,000	431,000	6,592,000
Hosston	0	10,153,000	12,822,000	1,876,000	24,851,000
Lampasas County					
Paluxy	0	0	0	0	0
Glen Rose	624,000	0	0	0	624,000
Hensell	2,445,000	428,000	0	0	2,873,000
Pearsall	495,000	332,000	0	0	827,000
Hosston	3,251,000	226,000	0	0	3,477,000

County and Aquifer Unit	**Total Volume (Acre-feet)**				
	Fresh	**Slightly saline**	**Moderately saline**	**Very saline**	**Total**
Lee County					
Paluxy	0	0	0	403,000	403,000
Glen Rose	0	0	2,084,000	2,401,000	4,485,000
Hensell	0	0	24,000	380,000	404,000
Pearsall	0	0	209,000	551,000	760,000
Hosston	0	0	140,000	15,134,000	15,274,000
Limestone County					
Paluxy	0	0	539,000	1,872,000	2,411,000
Glen Rose	0	933,000	6,019,000	3,976,000	10,928,000
Hensell	0	0	824,000	933,000	1,757,000
Pearsall	0	155,000	2,768,000	1,945,000	4,868,000
Hosston	20,000	3,123,000	13,844,000	8,726,000	25,713,000
McLennan County					
Paluxy	0	3,172,000	1,340,000	29,000	4,541,000
Glen Rose	6,656,000	14,530,000	179,000	0	21,365,000
Hensell	2,281,000	3,169,000	472,000	0	5,922,000
Pearsall	1,948,000	2,179,000	446,000	0	4,573,000
Hosston	18,271,000	3,892,000	0	0	22,163,000
Milam County					
Paluxy	0	0	0	2,343,000	2,343,000
Glen Rose	0	6,781,000	14,102,000	4,958,000	25,841,000
Hensell	0	0	803,000	1,528,000	2,331,000
Pearsall	0	2,213,000	3,251,000	2,425,000	7,889,000
Hosston	0	16,160,000	30,386,000	44,837,000	91,383,000
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	2,518,000	0	0	0	2,518,000
Navarro County					
Paluxy	0	0	2,712,000	4,662,000	7,374,000
Glen Rose	0	0	9,174,000	9,026,000	18,200,000

County and Aquifer Unit	Total Volume (Acre-feet)				
	Fresh	Slightly saline	Moderately saline	Very saline	Total
Hensell	0	140,000	838,000	1,913,000	2,891,000
Pearsall	0	0	4,166,000	3,430,000	7,596,000
Hosston	0	6,168,000	14,533,000	21,084,000	41,785,000
Palo Pinto County					
Paluxy	0	0	0	0	0
Glen Rose	0	0	0	0	0
Hensell	0	0	0	0	0
Pearsall	0	0	0	0	0
Hosston	131,000	0	0	0	131,000
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	1,208,000	0	0	0	1,208,000
Hosston	4,014,000	0	0	0	4,014,000
Red River County					
Paluxy	0	9,665,000	21,084,000	12,514,000	43,263,000
Glen Rose	0	1,939,000	10,718,000	6,823,000	19,480,000
Hensell	0	1,095,000	5,952,000	2,573,000	9,620,000
Pearsall	0	292,000	5,695,000	2,793,000	8,780,000
Hosston	0	1,203,000	17,033,000	10,452,000	28,688,000
Robertson County					
Paluxy	0	0	0	120,000	120,000
Glen Rose	0	0	473,000	692,000	1,165,000
Hensell	0	0	0	103,000	103,000
Pearsall	0	0	0	385,000	385,000
Hosston	0	0	0	4,180,000	4,180,000
Rockwall County					
Paluxy	199,000	1,005,000	2,583,000	0	3,787,000
Glen Rose	417,000	2,011,000	899,000	26,000	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	585,000	7,937,000	0	8,522,000
Shackelford County					
Paluxy	0	0	0	0	0
Glen Rose	0	0	0	0	0
Hensell	0	0	0	0	0
Pearsall	0	0	0	0	0
Hosston	0	0	0	0	0

County and Aquifer Unit	Total Volume (Acre-feet)				
	Fresh	Slightly saline	Moderately saline	Very saline	Total
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	11,559,000	2,203,000	0	0	13,762,000
Glen Rose	7,893,000	2,086,000	0	0	9,979,000
Hensell	5,886,000	2,705,000	0	0	8,591,000
Pearsall	2,079,000	1,190,000	0	0	3,269,000
Hosston	9,386,000	60,000	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	2,000	0	0	0	2,000
Hosston	420,000	0	0	0	420,000
Titus County					
Paluxy	0	0	0	1,344,000	1,344,000
Glen Rose	0	0	0	855,000	855,000
Hensell	0	0	0	327,000	327,000
Pearsall	0	0	0	372,000	372,000
Hosston	0	0	0	1,135,000	1,135,000
Travis County					
Paluxy	0	0	89,000	1,050,000	1,139,000
Glen Rose	259,000	7,838,000	927,000	0	9,024,000
Hensell	1,864,000	1,040,000	114,000	0	3,018,000
Pearsall	235,000	4,441,000	274,000	0	4,950,000
Hosston	8,402,000	37,983,000	1,483,000	0	47,868,000
Williamson County					
Paluxy	0	57,000	1,050,000	1,577,000	2,684,000
Glen Rose	10,412,000	12,929,000	2,450,000	0	25,791,000
Hensell	2,229,000	1,655,000	693,000	74,000	4,651,000
Pearsall	1,212,000	6,113,000	575,000	0	7,900,000
Hosston	11,869,000	30,709,000	17,588,000	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

County and Aquifer Unit	Total Volume (Acre-feet)				
	Fresh	Slightly saline	Moderately saline	Very saline	Total
Hensell	5,717,000	0	0	0	5,717,000
Pearsall	1,823,000	0	0	0	1,823,000
Hosston	4,908,000	0	0	0	4,908,000

Table 12-4 The volumes of fresh, moderately saline, slightly saline, very saline, and total groundwater volumes in the Northern Trinity Aquifer by Groundwater Conservation District.

GCD and Aquifer Unit	Total Volume (Acre-feet)				
	Fresh	Slightly saline	Moderately saline	Very saline	Total
Area with no Groundwater Conservation District					
Paluxy	33,060,000	31,047,000	44,053,000	76,293,000	184,453,000
Glen Rose	19,589,000	55,429,000	69,327,000	62,646,000	206,991,000
Hensell	15,349,000	16,962,000	24,998,000	17,793,000	75,102,000
Pearsall	4,498,000	24,007,000	36,147,000	25,606,000	90,258,000
Hosston	44,621,000	130,290,000	157,221,000	168,102,000	500,234,000
Brazos Valley GCD					
Paluxy	0	0	0	120,000	120,000
GlenRose	0	0	473,000	692,000	1,165,000
Hensell	0	0	0	103,000	103,000
Pearsall	0	0	0	385,000	385,000
Hosston	0	0	0	4,180,000	4,180,000
Central Texas GCD					
Paluxy	0	0	0	0	0
GlenRose	1,796,000	0	0	0	1,796,000
Hensell	2,445,000	103,000	0	0	2,548,000
Pearsall	813,000	3,000	0	0	816,000
Hosston	4,792,000	0	0	0	4,792,000
Clearwater UWCD					
Paluxy	0	1,046,000	1,218,000	340,000	2,604,000
GlenRose	6,071,000	10,694,000	2,955,000	0	19,720,000
Hensell	0	4,384,000	869,000	0	5,253,000
Pearsall	635,000	2,760,000	1,048,000	0	4,443,000
Hosston	4,487,000	23,991,000	837,000	0	29,315,000
Lost Pines GCD					
Paluxy	0	0	0	1,371,000	1,371,000
GlenRose	0	0	8,575,000	5,530,000	14,105,000
Hensell	0	0	413,000	957,000	1,370,000
Pearsall	0	0	1,631,000	2,063,000	3,694,000
Hosston	0	703,000	10,953,000	35,281,000	46,937,000
Middle Trinity GCD					
Paluxy	1,748,000	4,177,000	0	0	5,925,000
GlenRose	15,134,000	9,465,000	0	0	24,599,000
Hensell	24,890,000	6,376,000	0	0	31,266,000
Pearsall	3,333,000	1,757,000	0	0	5,090,000
Hosston	25,105,000	4,818,000	0	0	29,923,000

GCD and Aquifer Unit	Total Volume (Acre-feet)				
	Fresh	**Slightly saline**	**Moderately saline**	**Very saline**	**Total**
Neches & Trinity Valleys GCD					
Paluxy	0	0	13,000	710,000	723,000
GlenRose	0	0	0	1,007,000	1,007,000
Hensell	0	0	0	192,000	192,000
Pearsall	0	0	0	538,000	538,000
Hosston	0	0	0	3,308,000	3,308,000
North Texas GCD					
Paluxy	27,389,000	10,582,000	9,996,000	0	47,967,000
GlenRose	19,795,000	5,882,000	3,787,000	3,896,000	33,360,000
Hensell	14,737,000	4,440,000	4,051,000	0	23,228,000
Pearsall	8,037,000	4,156,000	3,932,000	0	16,125,000
Hosston	15,693,000	16,016,000	20,083,000	0	51,792,000
Northern Trinity GCD					
Paluxy	11,559,000	2,203,000	0	0	13,762,000
Glen Rose	7,893,000	2,086,000	0	0	9,979,000
Hensell	5,886,000	2,705,000	0	0	8,591,000
Pearsall	2,079,000	1,190,000	0	0	3,269,000
Hosston	9,386,000	60,000	0	0	9,446,000
Post Oak Savannah GCD					
Paluxy	0	0	0	2,343,000	2,343,000
Glen Rose	0	6,781,000	14,102,000	4,958,000	25,841,000
Hensell	0	0	803,000	1,528,000	2,331,000
Pearsall	0	2,213,000	3,251,000	2,425,000	7,889,000
Hosston	0	16,160,000	30,386,000	44,837,000	91,383,000
Prairielands GCD					
Paluxy	4,503,000	14,426,000	7,884,000	107,000	26,920,000
Glen Rose	8,122,000	23,850,000	14,894,000	1,146,000	48,012,000
Hensell	6,297,000	14,285,000	2,862,000	74,000	23,518,000
Pearsall	1,658,000	5,824,000	5,976,000	108,000	13,566,000
Hosston	26,644,000	27,094,000	6,312,000	650,000	60,700,000
Red River GCD					
Paluxy	29,807,000	14,022,000	0	0	43,829,000
Glen Rose	13,796,000	8,939,000	0	0	22,735,000
Hensell	4,748,000	10,227,000	179,000	0	15,154,000
Pearsall	3,928,000	8,073,000	0	0	12,001,000
Hosston	4,700,000	23,519,000	7,172,000	0	35,391,000
Saratoga UWCD					
Paluxy	0	0	0	0	0
Glen Rose	624,000	0	0	0	624,000

GCD and Aquifer Unit	Total Volume (Acre-feet)				
	Fresh	**Slightly saline**	**Moderately saline**	**Very saline**	**Total**
Hensell	2,445,000	428,000	0	0	2,873,000
Pearsall	495,000	332,000	0	0	827,000
Hosston	3,251,000	226,000	0	0	3,477,000
Southern Trinity GCD					
Paluxy	0	3,172,000	1,340,000	29,000	4,541,000
Glen Rose	6,656,000	14,530,000	179,000	0	21,365,000
Hensell	2,281,000	3,169,000	472,000	0	5,922,000
Pearsall	1,948,000	2,179,000	446,000	0	4,573,000
Hosston	18,271,000	3,892,000	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	4,408,000	0	0	0	4,408,000
Hosston	14,160,000	0	0	0	14,160,000

Table 12-5 The volumes of fresh, moderately saline, slightly saline, very saline, and total groundwater volumes in the Northern Trinity Aquifer by Groundwater Management Area.

GMA and Aquifer Unit	Total Volume (Acre-feet)				
	Fresh	Slightly saline	Moderately saline	Very saline	Total
Groundwater Management Area 10					
Paluxy	0	0	0	3,000	3,000
Glen Rose	0	18,000	6,000	0	24,000
Hensell	0	3,000	0	0	3,000
Pearsall	0	10,000	0	0	10,000
Hosston	0	111,000	0	0	111,000
Groundwater Management Area 11					
Paluxy	0	0	13,000	7,826,000	7,839,000
Glen Rose	0	0	0	8,559,000	8,559,000
Hensell	0	0	0	2,218,000	2,218,000
Pearsall	0	0	0	3,440,000	3,440,000
Hosston	0	0	0	19,252,000	19,252,000
Groundwater Management Area 12					
Paluxy	0	0	0	2,679,000	2,679,000
Glen Rose	0	0	17,433,000	11,499,000	28,932,000
Hensell	0	0	461,000	2,173,000	2,634,000
Pearsall	0	0	3,326,000	4,851,000	8,177,000
Hosston	0	703,000	14,917,000	79,390,000	95,010,000
Groundwater Management Area 6					
Paluxy	0	0	0	0	0
Glen Rose	0	0	0	0	0
Hensell	8,000	0	0	0	8,000
Pearsall	12,000	0	0	0	12,000
Hosston	543,000	0	0	0	543,000
Groundwater Management Area 8					
Paluxy	114,748,000	80,676,000	64,490,000	70,803,000	330,717,000
Glen Rose	107,622,000	137,618,000	96,853,000	59,817,000	401,910,000
Hensell	94,582,000	63,077,000	34,187,000	16,256,000	208,102,000
Pearsall	31,800,000	52,423,000	49,106,000	22,833,000	156,162,000
Hosston	170,208,000	245,683,000	218,047,000	157,715,000	791,653,000
Groundwater Management Area 9					
Paluxy	0	0	0	1,000	1,000
Glen Rose	0	20,000	0	0	20,000
Hensell	176,000	0	0	0	176,000
Pearsall	22,000	61,000	0	0	83,000
Hosston	358,000	273,000	0	0	631,000

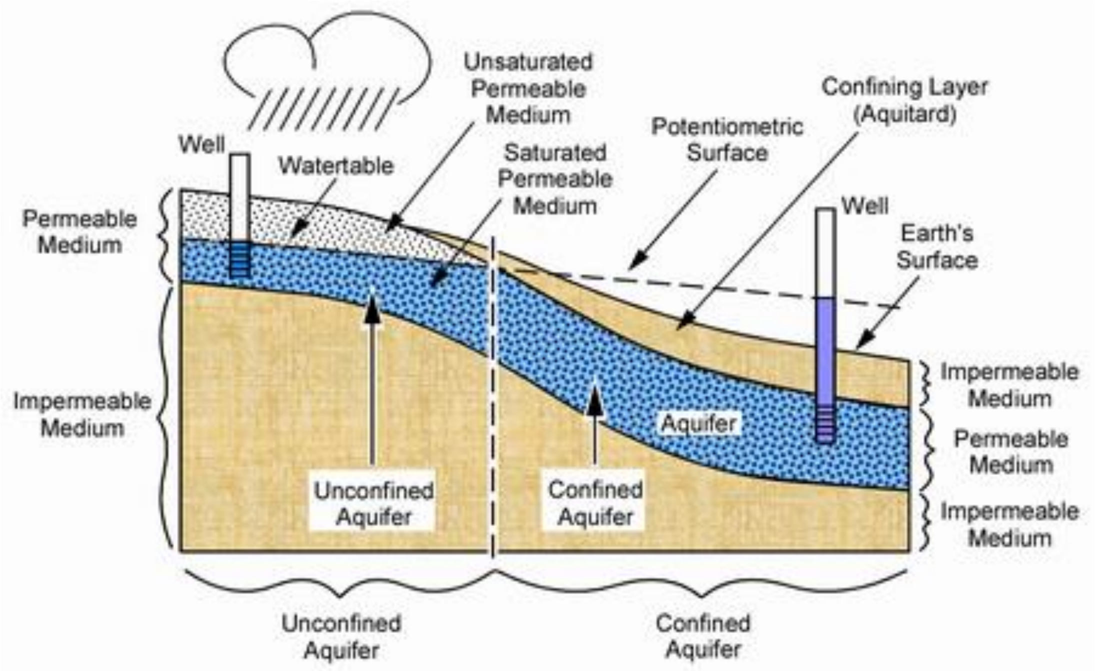

Figure 12-1 **Schematic of aquifer transitioning from an unconfined outcrop region, where recharge from precipitation occurs, to confined conditions in the down dip regions of the aquifer (from Hermance, 2016).**

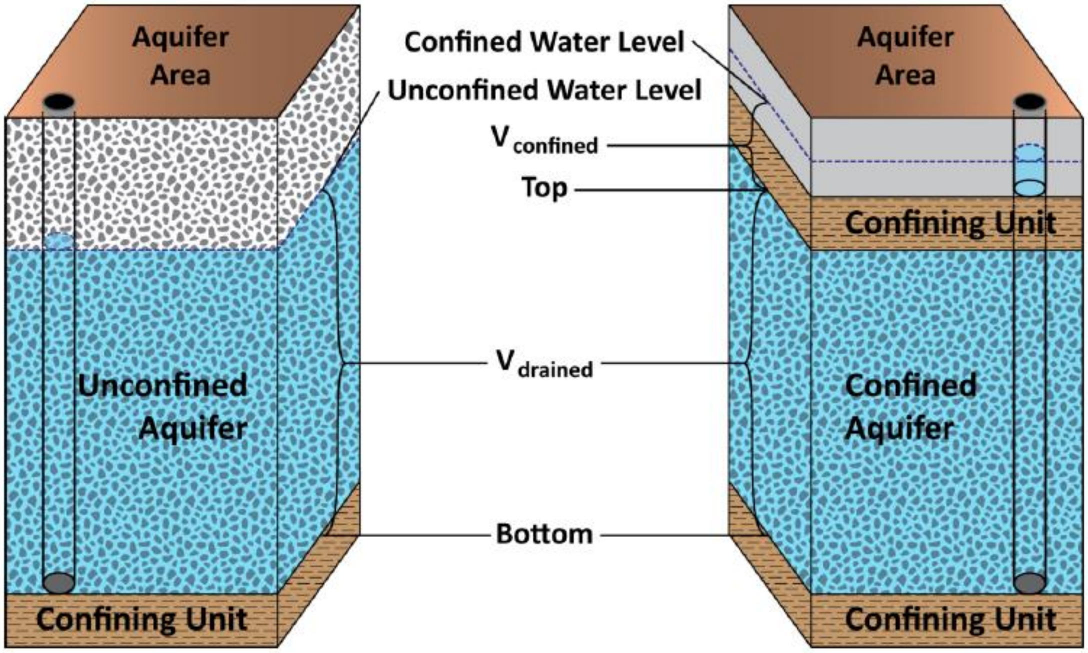

Figure 12-2 **Schematic graph showing the difference between unconfined and confined aquifers (from Shi and others, 2014).**

Table 12-6 **The volumes of fresh, moderately saline, slightly saline, very saline, and total groundwater volumes in the Hill Country Trinity Aquifer.**

Aquifer Unit	Total Volume (Arce-Feet)				
	Fresh	Slightly Saline	Moderately Saline	Very Saline	Total
Cow Creek	174,000	48,000	115,000	104,000	441,000
Glen Rose	719,000	852,000	1,288,000	359,000	3,217,000
Hensell	68,000	87,000	143,000	319,000	617,000
Hosston	1,061,000	723,000	406,000	79,000	2,269,000

Table 12-7 **The volumes of fresh, moderately saline, slightly saline, very saline, and total groundwater volumes in the Hill Country Trinity Aquifer by County.**

County and Aquifer Unit	Total Volume (Acre-feet)				
	Fresh	Slightly saline	Moderately saline	Very saline	Total
Atascosa					
Cow Creek	0	0	2,000	2,000	4,000
Glen Rose	0	0	67,000	1,000	68,000
Hensell	0	0	9,000	4,000	13,000
Hosston	0	0	2,000	0	2,000
Bandera					
Cow Creek	23,000	0	0	0	23,000
Glen Rose	124,000	0	0	0	124,000
Hensell	32,000	0	0	0	32,000
Hosston	222,000	3,000	0	0	225,000
Bastrop					
Cow Creek	0	0	11,000	5,000	16,000
Glen Rose	0	0	183,000	76,000	259,000
Hensell	0	0	6,000	4,000	10,000
Hosston	0	12,000	46,000	11,000	69,000
Bexar					
Cow Creek	22,000	7,000	26,000	3,000	58,000
Glen Rose	78,000	232,000	263,000	0	573,000
Hensell	5,000	22,000	51,000	0	78,000
Hosston	42,000	126,000	90,000	3,000	261,000
Blanco					
Cow Creek	15,000	0	0	0	15,000
Glen Rose	6,000	0	0	0	6,000
Hensell	44,000	0	0	0	44,000
Hosston	113,000	0	0	0	113,000
Burnet					
Cow Creek	0	0	0	0	0
Glen Rose	-1,000	0	0	0	-1,000
Hensell	1,000	0	0	0	1,000
Hosston	5,000	0	0	0	5,000
Caldwell					
Cow Creek	0		15,000	5,000	20,000
Glen Rose	0	22,000	150,000	15,000	187,000
Hensell	0	2,000	11,000	9,000	22,000
Hosston	0	0	35,000	18,000	53,000
Comal					

County and Aquifer Unit	**Total Volume (Acre-feet)**				
	Fresh	**Slightly saline**	**Moderately saline**	**Very saline**	**Total**
Cow Creek	26,000	7,000	2,000	0	35,000
Glen Rose	114,000	105,000	0	0	219,000
Hensell	7,000	8,000	0	0	15,000
Hosston	74,000	44,000	0	0	118,000
Frio					
Cow Creek	0	0	0	27,000	27,000
Glen Rose	0	0	0	118,000	118,000
Hensell	0	0	0	16,000	16,000
Hosston	0	0	0	0	0
Gillespie					
Cow Creek	16,000	0	0	0	16,000
Glen Rose	89,000	0	0	0	89,000
Hensell	102,000	0	0	0	102,000
Hosston	81,000	0	0	0	81,000
Guadalupe					
Cow Creek	0	0	8,000	10,000	18,000
Glen Rose	0	57,000	266,000	0	323,000
Hensell	0	6,000	13,000	12,000	31,000
Hosston	0	1,000	24,000	24,000	49,000
Hays					
Cow Creek	13,000	14,000	6,000	0	33,000
Glen Rose	46,000	159,000	0	0	205,000
Hensell	10,000	8,000	0	0	18,000
Hosston	57,000	0	1,000	0	58,000
Kendall					
Cow Creek	15,000	0	0	0	15,000
Glen Rose	21,000	0	0	0	21,000
Hensell	46,000	0	0	0	46,000
Hosston	166,000	0	0	0	166,000
Kerr					
Cow Creek	27,000	0	0	0	27,000
Glen Rose	156,000	0	0	0	156,000
Hensell	43,000	0	0	0	43,000
Hosston	111,000	0	0	0	111,000
Kimble					
Cow Creek	0	0	0	0	0
Glen Rose	2,000	0	0	0	2,000
Hensell	1,000	0	0	0	1,000
Hosston	1,000	0	0	0	1,000

County and Aquifer Unit	Total Volume (Acre-feet)				
	Fresh	Slightly saline	Moderately saline	Very saline	Total
Lee					
Cow Creek	0	0	0	0	0
Glen Rose	0	0	0	1,000	1,000
Hensell	0	0	0	0	0
Hosston	0	0	0	0	0
Medina					
Cow Creek	2,000	2,000	34,000	45,000	83,000
Glen Rose	32,000	79,000	265,000	136,000	512,000
Hensell	5,000	11,000	42,000	20,000	78,000
Hosston	63,000	348,000	187,000	13,000	611,000
Real					
Cow Creek	1,000	0	0	0	1,000
Glen Rose	6,000	0	0	0	6,000
Hensell	1,000	0	0	0	1,000
Hosston	4,000	0	0	0	4,000
Travis					
Cow Creek	13,000	16,000	7,000	0	36,000
Glen Rose	40,000	191,000	28,000	0	259,000
Hensell	20,000	23,000	1,000	0	44,000
Hosston	83,000	94,000	0	0	177,000
Uvalde					
Cow Creek	2,000	1,000	4,000	2,000	9,000
Glen Rose	0	7,000	23,000	0	30,000
Hensell	0	4,000	3,000	1,000	8,000
Hosston	35,000	97,000	23,000	0	155,000
Williamson					
Cow Creek	0	1,000	0	0	1,000
Glen Rose	9,000	4,000	0	0	13,000
Hensell	2,000	1,000	0	0	3,000
Hosston	7,000	0	0	0	7,000
Wilson					
Cow Creek	0	0	0	2,000	2,000
Glen Rose	0	0	42,000	0	42,000
Hensell	0	0	7,000	0	7,000
Hosston	0	0	1,000	11,000	12,000
Zavala					
Cow Creek	0	0	0	4,000	4,000
Glen Rose	0	0	5,000	13,000	18,000
Hensell	0	0	0	1,000	1,000

County and Aquifer Unit	Total Volume (Acre-feet)				
	Fresh	Slightly saline	Moderately saline	Very saline	Total
Hosston	0	0	0	0	0

Table 12-8 **The volumes of fresh, moderately saline, slightly saline, very saline, and total groundwater volumes in the Hill Country Trinity Aquifer by Groundwater Conservation District.**

GCD and Aquifer Unit	Total Volume (Acre-feet)				
	Fresh	Slightly saline	Moderately saline	Very saline	Total
Area with no Groundwater Conservation District					
Cow Creek	8,000	15,000	8,000	0	31,000
Glen Rose	39,000	153,000	48,000	0	240,000
Hensell	21,000	22,000	3,000	0	46,000
Hosston	87,000	91,000	5,000	0	183,000
Bandera County River Authority					
Cow Creek	23,000	0	0	0	23,000
Glen Rose	124,000	0	0	0	124,000
Hensell	32,000	0	0	0	32,000
Hosston	222,000	3,000	0	0	225,000
Barton Springs/Edwards Aquifer Conservation District					
Cow Creek	10,000	90,000	5,000	0	105,000
Glen Rose	31,000	165,000	2,000	0	198,000
Hensell	1,000	9,000	0	0	10,000
Hosston	5,000	3,000	1,000	0	9,000
Blanco-Pedernales GCD					
Cow Creek	15,000	0	0	0	15,000
Glen Rose	6,000	0	0	0	6,000
Hensell	44,000	0	0	0	44,000
Hosston	113,000	0	0	0	113,000
Central Texas GCD					
Cow Creek	0	0	0	0	0
Glen Rose	-1,000	0	0	0	-1,000
Hensell	1,000	0	0	0	1,000
Hosston	5,000	0	0	0	5,000
Comal Trinity GCD					
Cow Creek	25,000	3,000	0	0	28,000
Glen Rose	46,000	0	0	0	46,000
Hensell	7,000	0	0	0	7,000
Hosston	73,000	39,000	0	0	112,000
Cow Creek GCD					
Cow Creek	15,000	0	0	0	15,000
Glen Rose	20,000	0	0	0	20,000
Hensell	46,000	0	0	0	46,000
Hosston	164,000	0	0	0	164,000
Edwards Aquifer Authority					
Cow Creek	3,000	9,000	39,000	5,000	56,000

GCD and Aquifer Unit	Total Volume (Acre-feet)				
	Fresh	**Slightly saline**	**Moderately saline**	**Very saline**	**Total**
Glen Rose	90,000	381,000	381,000	0	852,000
Hensell	0	33,000	58,000	2,000	93,000
Hosston	0	70,000	121,000	13,000	204,000
Evergreen UWCD					
Cow Creek	0	0	2,000	32,000	34,000
Glen Rose	0	0	109,000	118,000	227,000
Hensell	0	0	16,000	21,000	37,000
Hosston	0	0	3,000	11,000	14,000
Gonzales County UWCD					
Cow Creek	0	0	0	1,000	1,000
Glen Rose	0	0	5,000	8,000	13,000
Hensell	0	0	0	1,000	1,000
Hosston	0	0	0	0	0
Guadalupe County GCD					
Cow Creek	0	0	1,000	9,000	10,000
Glen Rose	0	0	182,000	0	182,000
Hensell	0	0	8,000	12,000	20,000
Hosston	0	0	5,000	23,000	28,000
Hays Trinity GCD					
Cow Creek	8,000	7,000	0	0	15,000
Glen Rose	25,000	3,000	0	0	28,000
Hensell	9,000	0	0	0	9,000
Hosston	55,000	0	0	0	55,000
Headwaters GCD					
Cow Creek	27,000	0	0	0	27,000
Glen Rose	155,000	0	0	0	155,000
Hensell	43,000	0	0	0	43,000
Hosston	110,000	0	0	0	110,000
Hill Country UWCD					
Cow Creek	16,000	0	0	0	16,000
Glen Rose	89,000	0	0	0	89,000
Hensell	102,000	0	0	0	102,000
Hosston	81,000	0	0	0	81,000
Kimble County GCD					
Cow Creek	0	0	0	0	0
Glen Rose	2,000	0	0	0	2,000
Hensell	1,000	0	0	0	1,000
Hosston	1,000	0	0	0	1,000
LOST PINES GCD					

GCD and Aquifer Unit	Total Volume (Acre-feet)				
	Fresh	Slightly saline	Moderately saline	Very saline	Total
Cow Creek	0	0	11,000	5,000	16,000
Glen Rose	0	0	182,000	77,000	259,000
Hensell	0	0	6,000	4,000	10,000
Hosston	0	12,000	45,000	11,000	68,000
Medina County GCD					
Cow Creek	2,000	2,000	34,000	45,000	83,000
Glen Rose	32,000	78,000	264,000	137,000	511,000
Hensell	5,000	11,000	42,000	20,000	78,000
Hosston	63,000	347,000	186,000	13,000	609,000
Plum Creek GCD					
Cow Creek	0	1,000	11,000	3,000	15,000
Glen Rose	0	43,000	89,000	7,000	139,000
Hensell	0	3,000	7,000	5,000	15,000
Hosston	0	0	18,000	8,000	26,000
Real-Edwards Conservation and Reclamation District					
Cow Creek	1,000	0	0	0	1,000
Glen Rose	6,000	0	0	0	6,000
Hensell	1,000	0	0	0	1,000
Hosston	4,000	0	0	0	4,000
Trinity-Glen Rose GCD					
Cow Creek	20,000	2,000	0	0	22,000
Glen Rose	56,000	22,000	0	0	78,000
Hensell	6,000	4,000	0	0	10,000
Hosston	45,000	61,000	0	0	106,000
Uvalde County UWCD					
Cow Creek	2,000	1,000	3,000	2,000	8,000
Glen Rose	0	7,000	23,000	0	30,000
Hensell	2,000	4,000	3,000	1,000	10,000
Hosston	35,000	96,000	22,000	0	153,000
Wintergarden GCD					
Cow Creek	0	0	0	4,000	4,000
Glen Rose	0	0	4,000	12,000	16,000
Hensell	0	0	0	1,000	1,000
Hosston	0	0	0	0	0

Table 12-9 **The volumes of fresh, moderately saline, slightly saline, very saline, and total groundwater volumes in the Hill Country Trinity Aquifer by Groundwater Management Area.**

GMA and Aquifer Unit	Total Volume (Acre-feet)				
	Fresh	Slightly saline	Moderately saline	Very saline	Total
Groundwater Management Area 10					
Cow Creek	11,000	22,000	73,000	15,000	121,000
Glen Rose	30,000	750,000	425,000	47,000	1,252,000
Hensell	2,000	62,000	60,000	4,000	128,000
Hosston	14,000	496,000	291,000	1,000	802,000
Groundwater Management Area 12					
Cow Creek	0	0	11,000	5,000	16,000
Glen Rose	0	1,000	127,000	130,000	258,000
Hensell	0	0	6,000	4,000	10,000
Hosston	0	12,000	45,000	11,000	68,000
Groundwater Management Area 13					
Cow Creek	0	0	28,000	85,000	113,000
Glen Rose	0	0	503,000	451,000	954,000
Hensell	0	0	76,000	60,000	136,000
Hosston	0	0	70,000	67,000	137,000
Groundwater Management Area 7					
Cow Creek	19,000	1,000	0	0	20,000
Glen Rose	97,000	-2,000	0	0	95,000
Hensell	106,000	1,000	0	0	107,000
Hosston	121,000	16,000	0	0	137,000
Groundwater Management Area 8					
Cow Creek	3,000	13,000	3,000	0	19,000
Glen Rose	22,000	125,000	16,000	0	163,000
Hensell	15,000	19,000	1,000	0	35,000
Hosston	45,000	71,000	0	0	116,000
Groundwater Management Area 9					
Cow Creek	142,000	13,000	0	0	155,000
Glen Rose	427,000	67,000	0	0	494,000
Hensell	197,000	5,000	0	0	202,000
Hosston	881,000	128,000	0	0	1,009,000

13 Geophysical Well Log Analysis and Methodology

13.1 Introduction to Total Dissolved Solids

13.1.1 Terms[1]

13.1.1.1 Electrical Conductivity

Electrical conductivity is a measure of water's capability to pass electric current. This capability is directly related to the concentration of dissolved ions in the water. The more ions that are present, the higher the conductivity of water. Likewise, if fewer ions are present in the water, the conductivity of the water will be lower. These ions come from dissolved salts and inorganic materials that comprise the aquifer rock matrix. Compounds that dissolve into ions are also known as electrolytes. Distilled or deionized water has a very low conductivity value. Sea water, on the other hand, has a very high conductivity.

Electrical conductivity is usually measured in micro- or millisiemens per centimeter (μS/cm or mS/cm). The conductivity of water can also be reported in micromhos or millimhos per centimeter, though these units are less common. Conductivity is the reciprocal of resistivity, which is measured in ohms; thus, conductivity units were initially known as mhos. One siemen is equal to one mho. Water conductivity is not only affected by the concentration of ions in solutions but also the type of ions in solution. For example, even at the same total ion concentration, a solution of sodium and chloride ions will have a different conductivity than a solution of calcium and sulfate ions.

13.1.1.2 Specific Conductance

Specific conductance is defined as the measure of water conductivity over a unit length and unit cross-sectional area at 25°C (Hem, 1982; Miller et al., 1988; McCleskey et al., 2012). Probes that measure water conductivity correct for differences in measurement length and area and report conductivity as specific conductance (Miller et al., 1988). For the purposes of this report, conductivity and specific conductance are used interchangeably and have the units of microsiemens per centimeter (μS/cm). The conductivity of water is also affected by temperature. Generally, conductivity increases with increasing temperature. In order for conductivity measurements to be easily compared, instruments typically correct measured values to 25°C (equal to 77°F). However, the change in conductivity due to a change in temperature is also affected by the types of ions present. Thus, the temperature correction methods used by conductivity measuring instruments, which are based on the changes that occur for a standard calibration solution, introduce uncertainties when large temperature corrections are made for waters of significantly different ion compositions.

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[1] Young et al. (2016) provide a thorough introduction to these terms. Although substantially edited and corrected as necessary, much of that information is included in the terms section.

13.1.1.3 Electrical Resistivity

Electrical resistivity is a measurement of water's opposition to the flow of current a unit distance. Electrical resistivity is the reciprocal of conductivity. The standard international unit of electrical resistivity is the ohm-meter (ohm-m). Equation 13-1 provides an equation to calculate electrical resistivity in ohm-m from specific conductance in μS/cm, and Equation 13-2 provides the reverse (e.g., Estepp, 2010). In this report, the electrical resistivity of water is referred to as simply the resistivity of water.

$$R_{w25°C} = \frac{10{,}000}{SC_{w25°C}} \qquad \text{(Equation 13-1)}$$

$$SC_{w25°C} = \frac{10{,}000}{R_{w25°C}} \qquad \text{(Equation 13-2)}$$

Where:

$R_{w25°C}$ = Resistivity of water in ohm-m at 25°C (77°F)
$SC_{w25°C}$ = Specific conductance of water in μS/cm at 25°C (77°F)

13.1.2 Temperature Adjustments to Conductivity and Resistivity

The conductivity and resistivity values of water change with temperature. The effect of temperature on electrical conductivity varies according to the types of ions and their concentrations (Desai and Moore, 1969; Collier, 1993; Hayashi, 2003; McCleskey, 2011).

For many deep borehole geophysical logs, temperature ranges exceed 50°C, and the temperature adjustments to water resistivity must account for that range. Arps (1953) developed a temperature correction equation using measured specific conductance values for sodium chloride waters at various temperatures and concentrations. Unfortunately, even Arps' carefully derived correction introduces some error, especially when correcting resistivities from values at high temperature to values at low temperature (Figure 13-1). However, compared to errors introduced by the simple correction approach suggested for several methods found in Estepp (2010), the relatively small errors introduced by the Arps equation is much preferred (see Table 13-1).

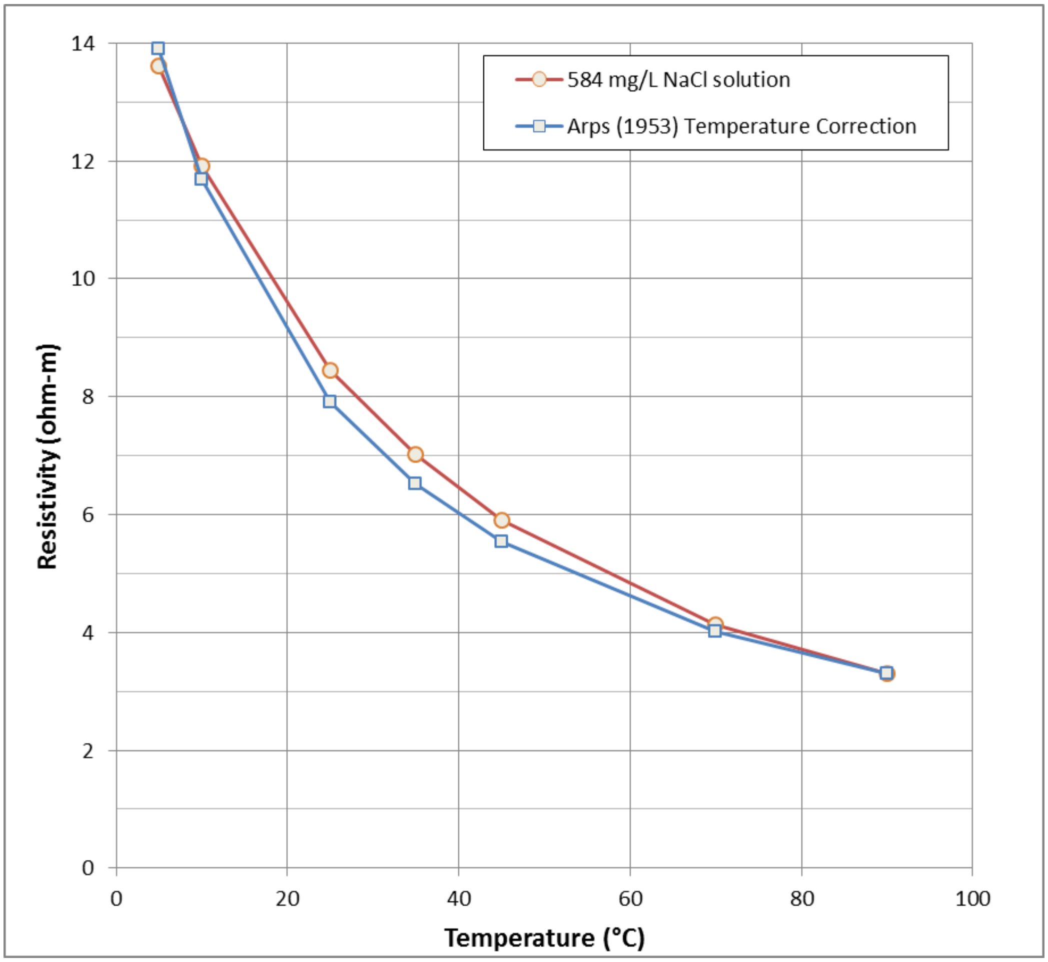


Figure 13-1 **Plot of actual measured resistivity data (circles) for a 584 mg/L NaCl solution at various temperatures from 5° to 90°C (data from McCleskey, 2011) and resistivity values calculated using the Arps (1953) temperature correction when the starting temperature is 90°C (squares). The error in the corrected resistivity at 25°C is about 6%. The magnitude of this error is reduced when correcting from lower starting temperatures (see Table 13-1).**

Table 13-1 **Comparison of errors associated with methods for correction of resistivity values for temperature. The method of Arps (1953) results in much less error than the simplified approach found in Estepp (2010).**

Initial Temperature (T1)	Final Temperature (T2)	Resistivity at Temp. 1 (R1)	Resistivity at Temp. 2 (R2) using Arps†	Resistivity at Temp. 2 (R2) using simple†	% Error Arps	% Error simple
90	25	3.30	7.91	11.88	-6.3	34.0
70	25	4.13	8.13	11.56	-3.7	31.3
45	25	5.90	8.44	10.62	0.1	23.0
35	25	7.01	8.52	9.81	1.0	15.2
25	25	8.43	8.43	8.43	0	0

†Arps (1953) correction using Equation 13-4. Simple correction using equation in Estepp (2010) p. 25.

Thus, the Arps equation was used in this study to correct for temperature differences in measured resistivity values and to convert borehole resistivities to equivalent values at 25°C (77°F). Equations 13-3 and 13-4 provide the corrections for temperature measured in

Fahrenheit and Celsius, respectively.

Temperatures in °F

$$R_2 = R_1 \frac{(T_1+6.77)}{(T_2+6.77)} \qquad \text{(Equation 13-3)}$$

Temperatures in °C

$$R_2 = R_1 \frac{(T_1+21.5)}{(T_2+21.5)} \qquad \text{(Equation 13-4)}$$

Where:

R_1 = Resistivity at Temperature 1
R_2 = Resistivity at Temperature 2
T_1 = Temperature 1
T_2 = Temperature 2

13.1.3 Definition and Measurement of Total Dissolved Solids

The definition of total dissolved solids (TDS) is important because TDS is commonly used as a means to characterize the overall quality of water (LBG-Guyton, 2003). The Texas Administration Code Title 30 (Environmental Quality), Part 1 (Texas Commission on Environmental Quality) and Chapter 307 (Texas Surface Water Quality Standards) Rule 307.3 (ii) (C) (74) defines total dissolved solids as “The amount of material (inorganic salts and small amounts of organic material) dissolved in water and commonly expressed as a concentration in terms of milligrams per liter. The term is equivalent to the term filterable residue, as used in 40 Code of Federal Regulations Part 136 and in previous editions of the publication entitled, *Standard Methods for the Examination of Water and Wastewater”* (Texas Administration Code, 2016). Thus, the total dissolved solids of a water sample provides a single value that represents a measure of all its dissolved constituents. The total dissolved solids value is used as the basis for separating waters into fresh, brackish, and saline categories (see Table 6-1).

The method for measurement of total dissolved solids described in 40 CFR Part 136 involves evaporating an aliquot of filtered water using heat and then weighing the remaining solids. During this process, some dissolved constituents, like bicarbonate, can lose some mass due to conversion of the bicarbonate to water vapor and carbon dioxide gas. The mass of solids per unit water is reported as the total dissolved solids in units of milligrams per liter (mg/L) or parts per million (ppm). The units of ppm and mg/L are equivalent up to about 10,000 mg/L; above this value the increased density of water from the dissolved solids should be accounted for in calculations of ppm. In this report units of total dissolved solids are reported in terms of mg/L, which do not require density correction.

More commonly, total dissolved solids is calculated using the results of chemical analyses of groundwater rather than conducting a separate evaporation test. The sum of laboratory measured concentrations of major constituents such as calcium, sodium, magnesium, potassium, chloride, sulfate, and bicarbonate along with minor constituents like silica and nitrate is used to calculate the total dissolved solids. To remain consistent with the evaporation method, only 49.17% of the bicarbonate concentration is used in the calculation (Collier, 1993). This form of calculated total dissolved solids is the value usually found in the TWDB-GWDB when measured total dissolved solids (by evaporation) are not reported (TWDB, 2016).

However, when conductivity or resistivity of a solution is measured using an electronic probe or borehole geophysical tool, the measured value is impacted by all of the dissolved constituents in solution. Thus, the total dissolved solids value used in conjunction with estimates of salinity from borehole geophysical logs should include 100% of the dissolved bicarbonate (Collier, 1993). Similarly, calculations to estimate the effect on water resistivity from different ions in solution should also include 100% of the dissolved bicarbonate (e.g., McCleskey, 2011; McCleskey et al., 2012).

As might be expected, calculated total dissolved solids values using 49% or 100% of dissolved bicarbonate concentrations differ significantly only for water samples in which bicarbonate is a significant component of the total anion concentration (e.g., Young et al., 2016). For both the Hill Country and Northern segments of the Trinity Aquifer, the change in total dissolved solids due to inclusion of all bicarbonate is about 200 mg/L (Figure 13-2). This difference is important only for samples with total dissolved solids less than 1000 mg/L; and even then, it is important only if a specific conductance versus total dissolved solids correlation is required for estimation of groundwater quality (see the following total dissolved solids and specific conductance discussion).

In this report, 100% bicarbonate values are used in direct calculations of conductivity from water quality data and in corrections of sample total dissolved solids to equivalent sodium chloride total dissolved solids. In other cases where specific conductance is not an intermediate calculated value, such as in maps and other graphical corrections, the 49% bicarbonate or measured total dissolved solids is used in order to make easier comparisons between data and the total dissolved solids values found in the TWDB-GWDB.

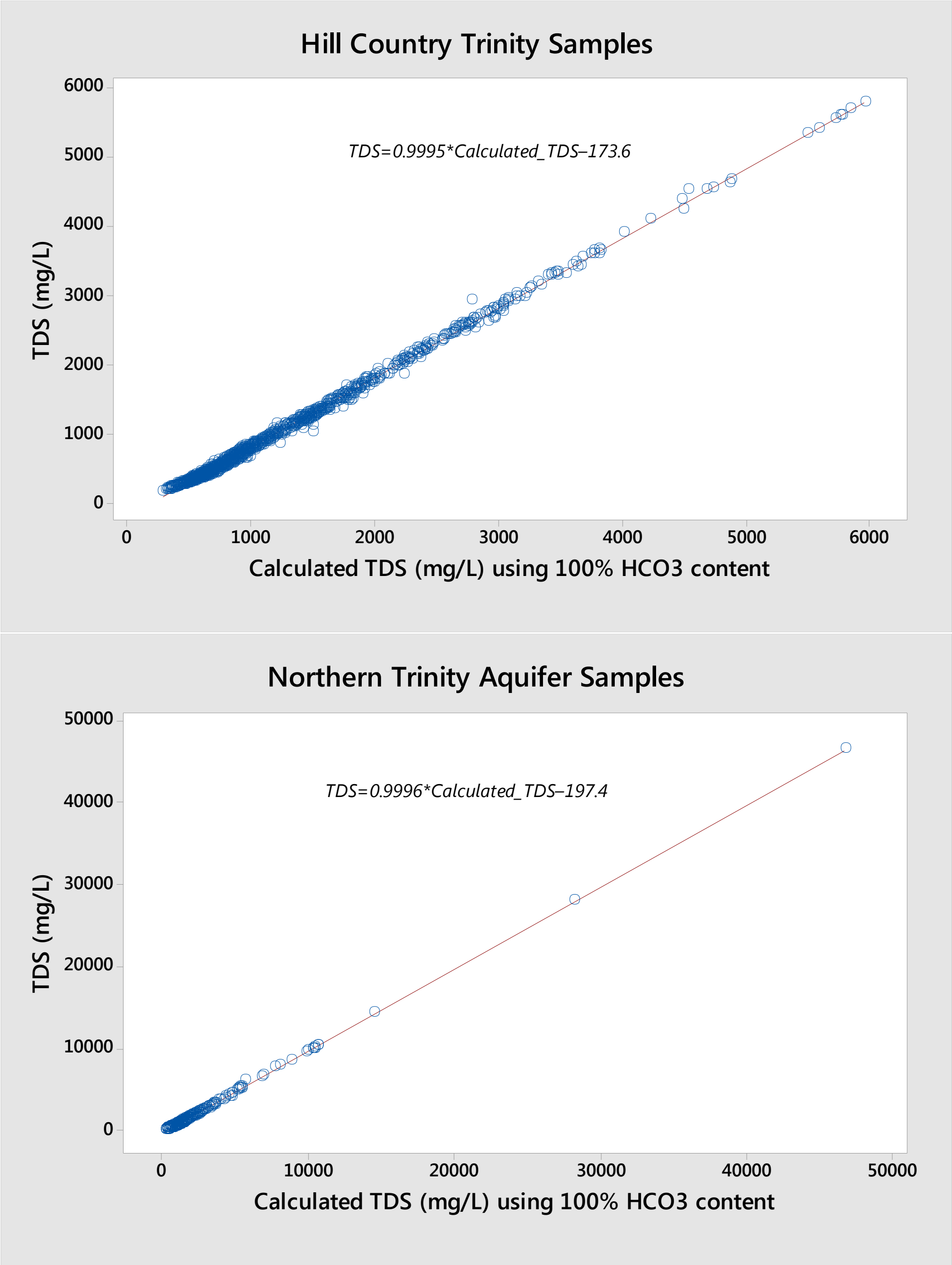


Figure 13-2 **Plots showing total dissolved solids (TDS) data from the TWDB-GWDB and calculated TDS values using 100% of the bicarbonate concentration for all samples in both the Hill Country and Northern segments of the Trinity Aquifer. TDS (49% HCO_3) and calculated TDS (100% HCO_3) have a 1:1 relationship with the calculated TDS values about 200 mg/L greater than the measured or 49%-calculated values.**

13.2 Analysis of Water Quality to Support Geophysical Well-Log Analyses

Determining the extent of potential brackish-water production zones requires an initial assessment of the spatial distribution of water quality, and more specifically, the spatial distribution of total dissolved solids. For major aquifers like the Trinity Aquifer, there is typically a reasonable amount of water-quality data available in areas with good water productivity and high quality (or low total dissolved solids) water. The availability of water-quality sample analyses diminishes rapidly in areas of lesser productivity, poorer water quality, or competition from a water resource that is more easily exploitable. Assessment of water quality in these data-poor areas typically relies upon examination and use of borehole geophysical data, such as resistivity and/or spontaneous potential (SP) measurements, to estimate total dissolved solids. Additionally, some borehole geophysical data in areas of known water quality must be evaluated to develop and validate an appropriate methodology for calculating total dissolved solids from geophysical data.

13.3 TDS Estimation Methods

There are numerous methods for estimating the total dissolved solids of groundwater using geophysical data from borehole logs (e.g., Estepp, 2010; Collier, 1993), and many 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 and others (2016). Many of these applications were performed in the 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,b) and Estepp (1998) both of which have specific examples of calculations performed in the Northern Trinity Aquifer system. Additionally, there have been examples of resistivity and porosity-based methods applied to carbonate aquifers like the Glen Rose and Cow Creek limestones of the Trinity Aquifer (e.g., Schultz, 1994; Kwader, 1986; MacCary, 1980)

Most of these methods rely on three main assumptions: (i) that the resistivity value of formation water can be determined from available resistivity, SP, and other parameters recorded by the borehole electric log, (ii) that the calculated water resistivity can be corrected for variances in formation temperature and water chemistry, and (iii) that an appropriate relationship between corrected water resistivity and total dissolved solids can be determined. As such, this evaluation of potential brackish-water resources in the Trinity Aquifer requires development of an understanding of the distribution of total dissolved solids for water producing units in the Trinity Aquifer and application of borehole geophysical data to estimate total dissolved solids where direct water quality measurements are not available.

A unifying theme of many existing water-quality calculation techniques is that they are all generally applicable to a limited geographic extent within the Trinity Aquifer system. Given the large geographic area and the substantial datasets available in the Northern Trinity Aquifer and Hill Country Trinity Aquifer study areas, an attempt has been made to simplify the calculation of water quality from resistivity signatures. The advantage of this approach is its broad applicability over the entire Trinity Aquifer system.

13.4 Evaluation of Sampled Water Quality

As described in Section 10 (Water Quality Data), water-quality data from multiple sources were assembled and analyzed to examine the distribution of hydrochemistry in the Trinity Aquifer. Water chemistry data for the Hill Country and Northern portions of the Trinity Aquifer were analyzed to characterize the spatial and hydrostratigraphic distributions of chemical constituents and total dissolved solids of the formation water. Evaluation of water quality within the Trinity Aquifer is a challenging exercise even in areas with available data. The Trinity Aquifer as defined is composed of several stratigraphic units, many of which have distinctly different controls on flow and water quality. The stratigraphic units range from calcareous sands to karstic limestone and are interlaced with evaporate-rich strata. Thus, patterns of water quality have significant spatial variability horizontally and with depth (see for example, Figures 10-8 through 10-16). These hydrochemical characteristics not only vary between hydrostratigraphic units, but within the units as well.

To address these issues, a preliminary analysis was conducted to compare the available data with estimates of the spatial extent of total dissolved solids concentrations prepared by LBG-Guyton (2003).The results of these analyses indicated that no significant differences were present between the LBG-Guyton (2003) data and the data assembled for this study. An additional outcome of these preliminary analyses was the realization that the total dissolved solids and specific conductivity relationship for Trinity Aquifer wells in both the Hill Country and Northern regions was non-unique.

Because total dissolved solids is a general measure of the total dissolved and ionic composition of groundwater, total dissolved solids values tend to be directly proportional to specific conductance and inversely proportional to resistivity. As discussed previously, specific conductance and resistivity are dependent not only on total ion concentration and temperature, but also the types of ions in solution. Figure 13-3 shows an example of the total dissolved solids and specific conductance data for all samples of the Hill Country Trinity Aquifer. Two separate trends are noted in the data (one with a slope of ~0.6 and another with a slope >0.8). The two trends suggest that there are at least two distinct populations of water chemistry in the Hill Country Trinity Aquifer, each with a different total dissolved solids versus specific conductivity relationship. This behavior is potentially problematic because it means that a unique conversion from the conductivity of groundwater (C_w, which is often calculated from borehole resistivity values) to total dissolved solids may not be possible for the affected hydrostratigraphic units. The C_w– total dissolved solids correlation is a fundamental component to relate borehole geophysical data with groundwater chemistry for many of the geophysical methods (Estepp, 2010). Following the assignment of water quality data to specific hydrostratigraphic units to be modeled for brackish water production, the C_w – total dissolved solids relationships were analyzed for each unit. Results of that analysis are shown in Figures 13-4 and 13-5.

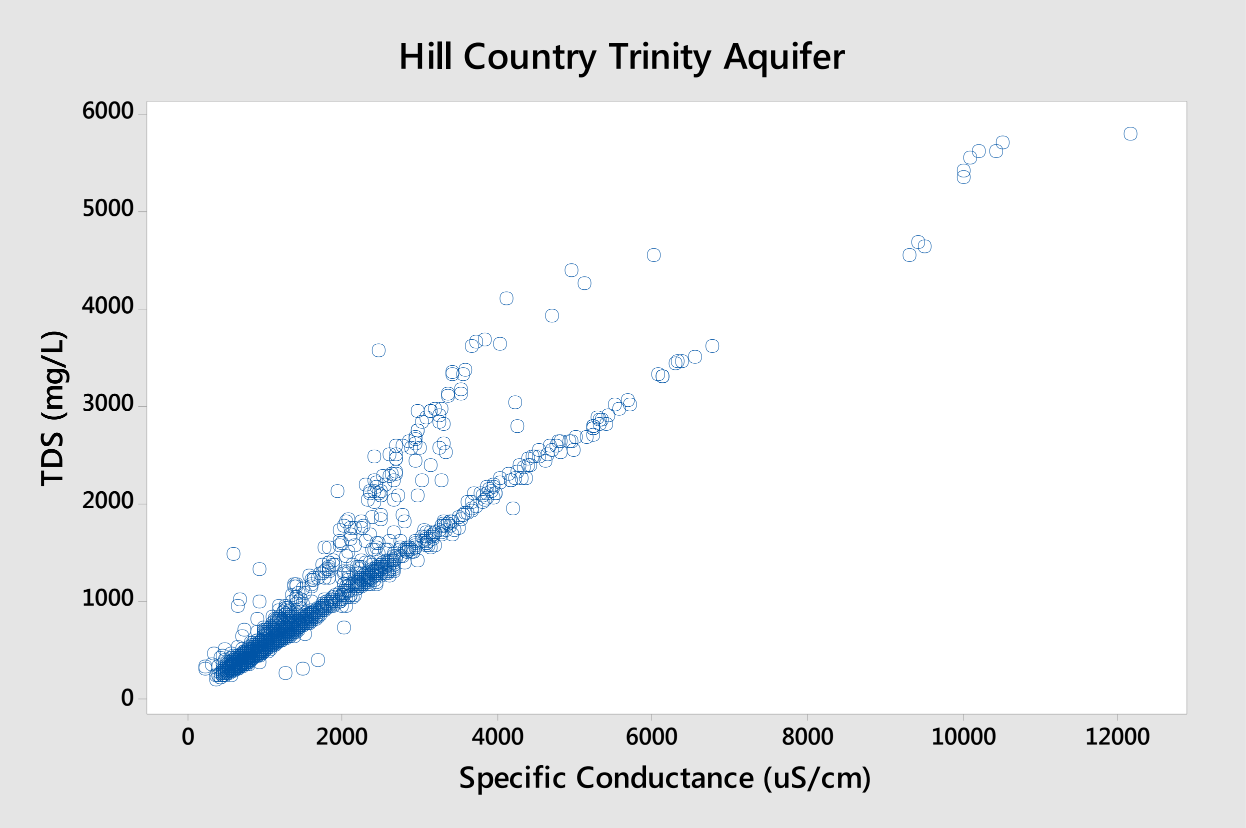


Figure 13-3 Plot of measured conductivity and TDS for water quality samples from the Hill Country region of the Trinity Aquifer. Two separate trends, one with a slope of ~0.6 and the other with slope of >0.8, are apparent. The data suggest water quality is influenced by at least two distinct chemistries.

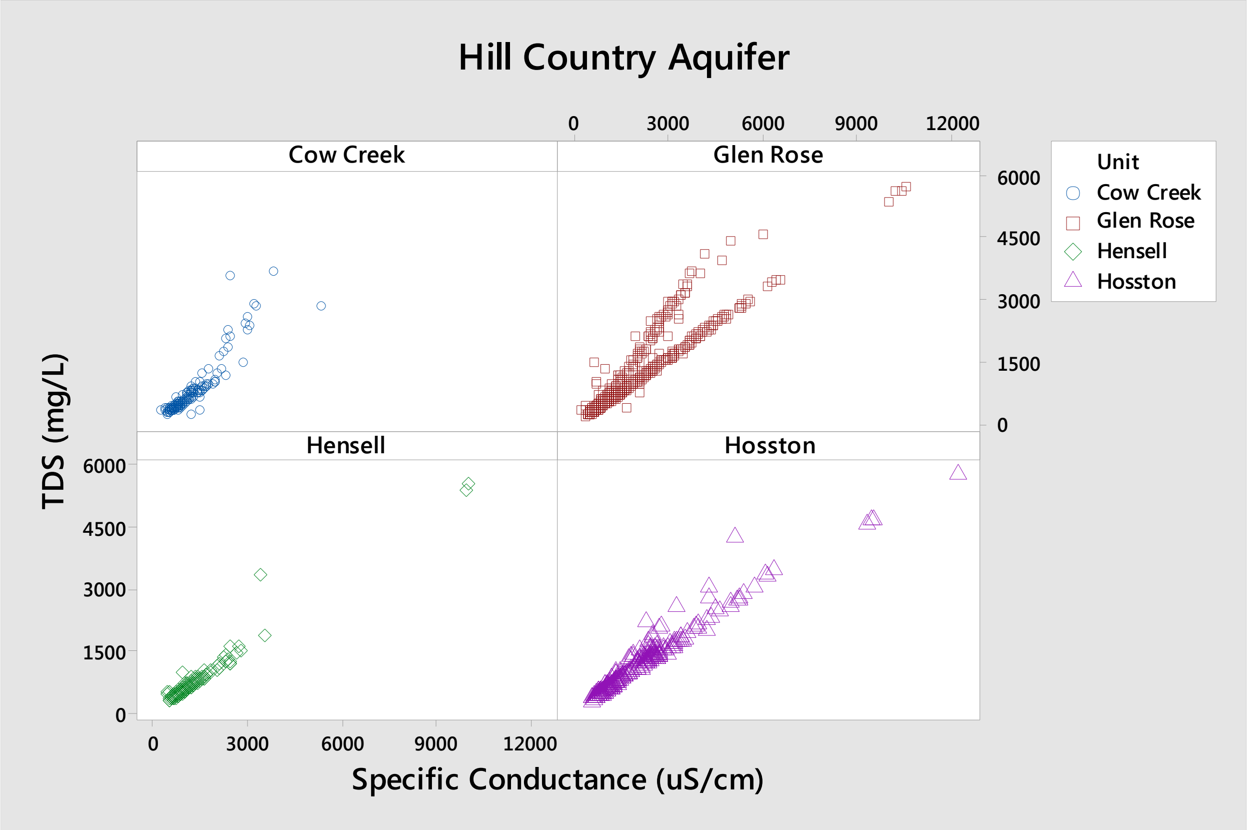


Figure 13-4 **Plot of measured conductivity and TDS for water quality samples for each hydrostratigraphic unit of the Hill Country region of the Trinity Aquifer. The two trends noted for the combined dataset are present in all units, but the Glen Rose unit is most affected.**

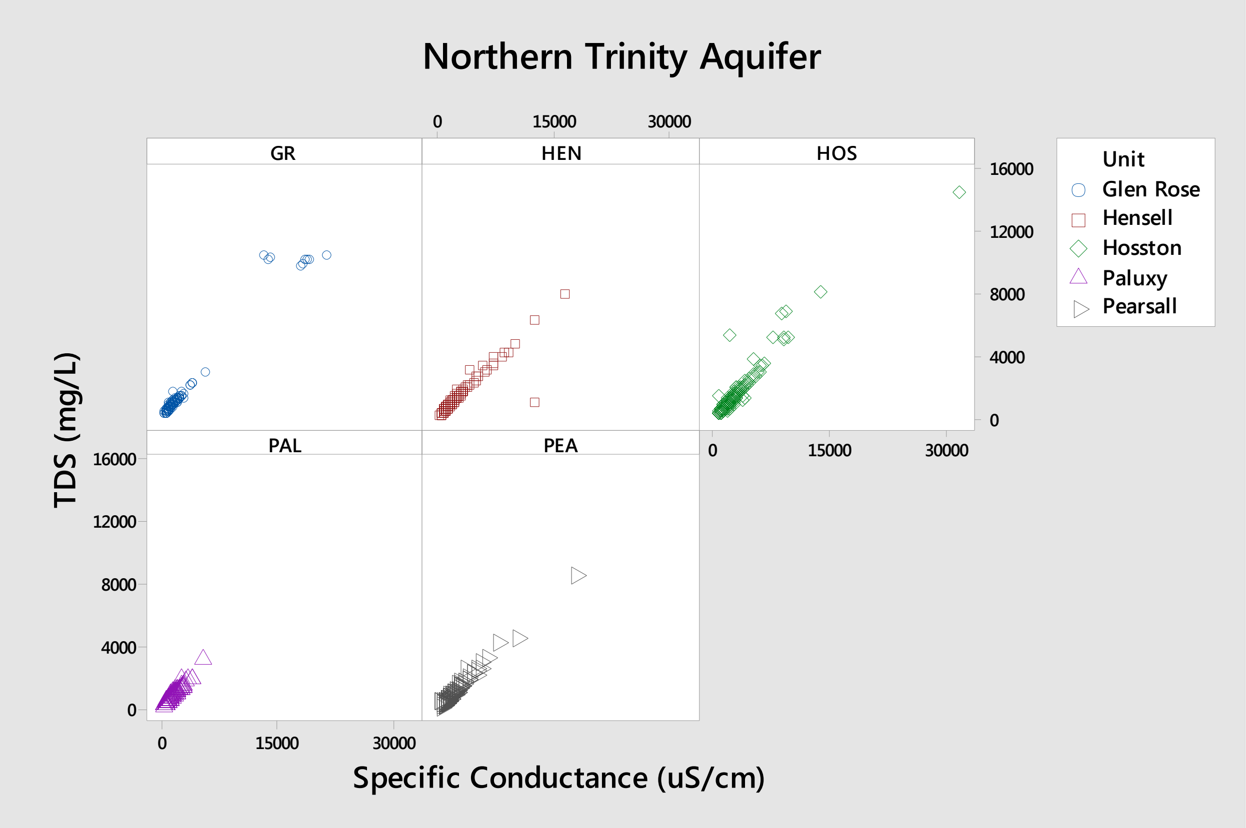


Figure 13-5 **Plot of measured conductivity and TDS for water quality samples for each hydrostratigraphic unit of the Northern region of the Trinity Aquifer. The two trends noted for the Hill Country samples appear to be present only in the Glen Rose and Hosston and to a much smaller degree.**

The results of the additional analyses indicate that this two-pronged trend was not isolated to a particular formation or location. Although the pattern appears in the Glen Rose and Hosston units of the Northern Trinity, it is minor compared to the Hill Country data (Figures 13-4 and 13-5).

A spatial analysis indicated that the high (>0.8) C_w– total dissolved solids slopes were associated with regions of high sulfate concentrations. As an example, a map of measured sulfate concentrations for the Glen Rose unit of the Hill Country Trinity is provided in Figure 13-6. By comparing this map to Figure 10-13, one can observe the apparent spatial correlation between areas of high total dissolved solids and sulfate. This is consistent with the strong data correlation shown in Figure 10-17. The implication is that sulfate content of the groundwater is causing the separation of trends.

Additional analyses of the groundwater sample data indicated that the number of measurements with high C_w /TDS ratios varied over time, with an absence of high ratio values between 1970 and 1990. Collier (1993) reviewed issues of specific conductance measurement data in the TWDB-GWDB and noted that many measurements of specific conductance associated with the Texas Department of Health (TXDoH) laboratory were questionable. A quick inspection of samples from the Glen Rose unit of the Hill Country Trinity Aquifer indicated that more than 82% were analyzed by the TXDoH laboratory between 1970 and 1990.

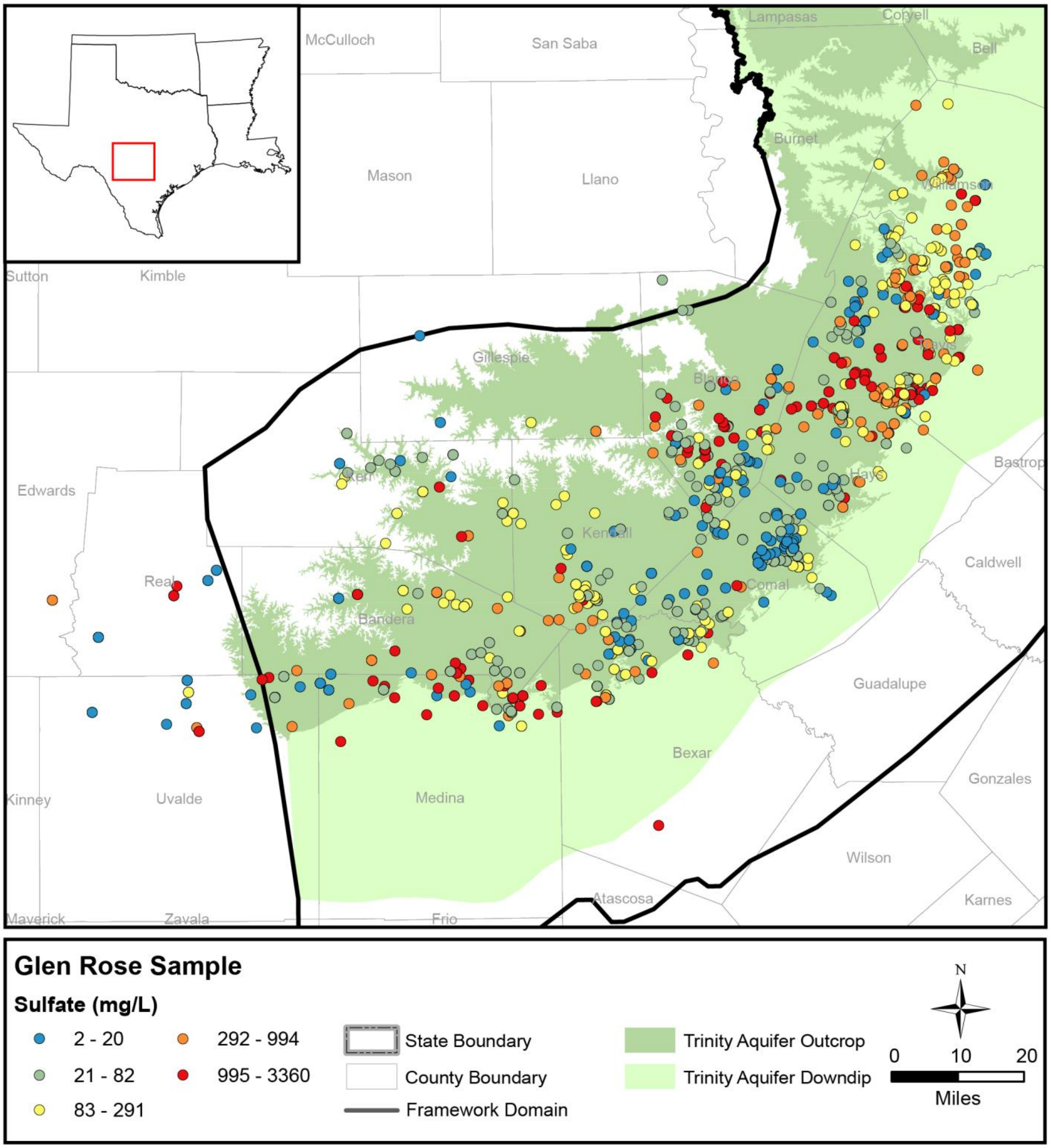


Figure 13-6 **Map of sulfate concentrations for water quality samples from the Glen Rose unit of the Hill Country Trinity Aquifer. A comparison to Figure 10-13 indicates sulfate and TDS are spatially correlated.**

To evaluate the impact of specific conductance measurements on the observed C_w– total dissolved solids correlations, all groundwater samples from the Hill County and Northern Trinity units were modeled using a geochemical software package that calculated specific conductance at 25°C (Ball and Nordstrom, 1991; U.S. Geological Survey, 2012).

The results of the geochemical modeling showed that there were numerous instances of reported specific conductance values that were too high based on the chemical composition of the groundwater samples. As examples, Figures 13-7 and 13-8 depict the differences in reported and calculated specific conductance values for the Glen Rose unit of both the Hill Country and Northern Trinity aquifers. These results are particularly interesting because they (i) demonstrate the magnitude of the effect of ions other than sodium chloride on specific conductivity, (ii) reveal the large number of specific conductance values in the TWDB-GWDB that are incorrect, and (iii) show that the effects of sulfate and bicarbonate on specific conductivity (and resistivity) are present in the Glen Rose Formation for total dissolved solids values up to 10,000 mg/L.

Hydrostratigraphic units such as the Hensell Formation of the Northern Trinity Aquifer, which has less sulfate and bicarbonate, are less impacted but do show different C_w– total dissolved solids relationships when the calculated specific conductance values are used (e.g., the Northern Trinity Hensell C_w– total dissolved solids slope changes from ~0.5 to ~0.6).

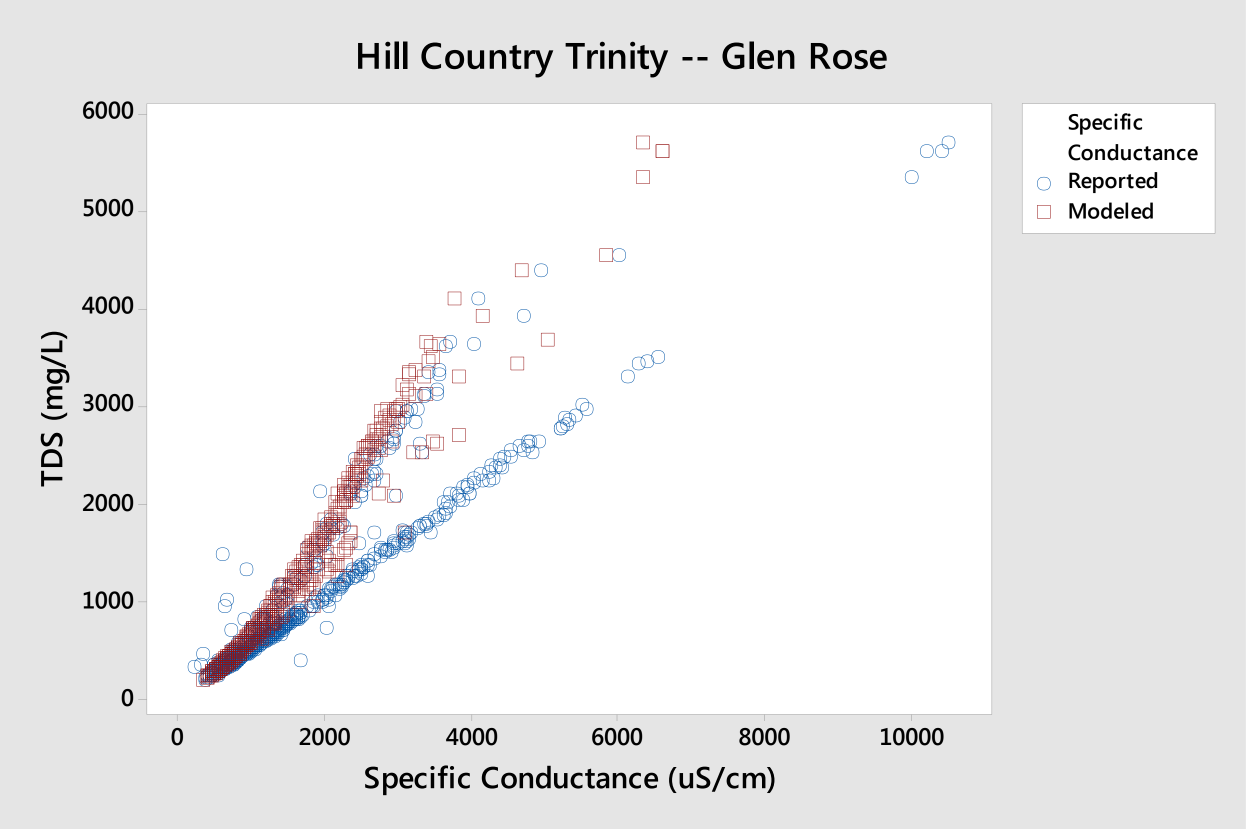


Figure 13-7 **Plots of TDS (mg/L), reported specific conductance (µS/cm) (circles), and geochemical model calculated specific conductance (µS/cm) (squares) for water quality samples from the Glen Rose unit of the Hill Country Trinity Aquifer. For TDS>1000 mg/L, only one calculated specific conductance value actually lies on the low (~0.6) slope trend.**

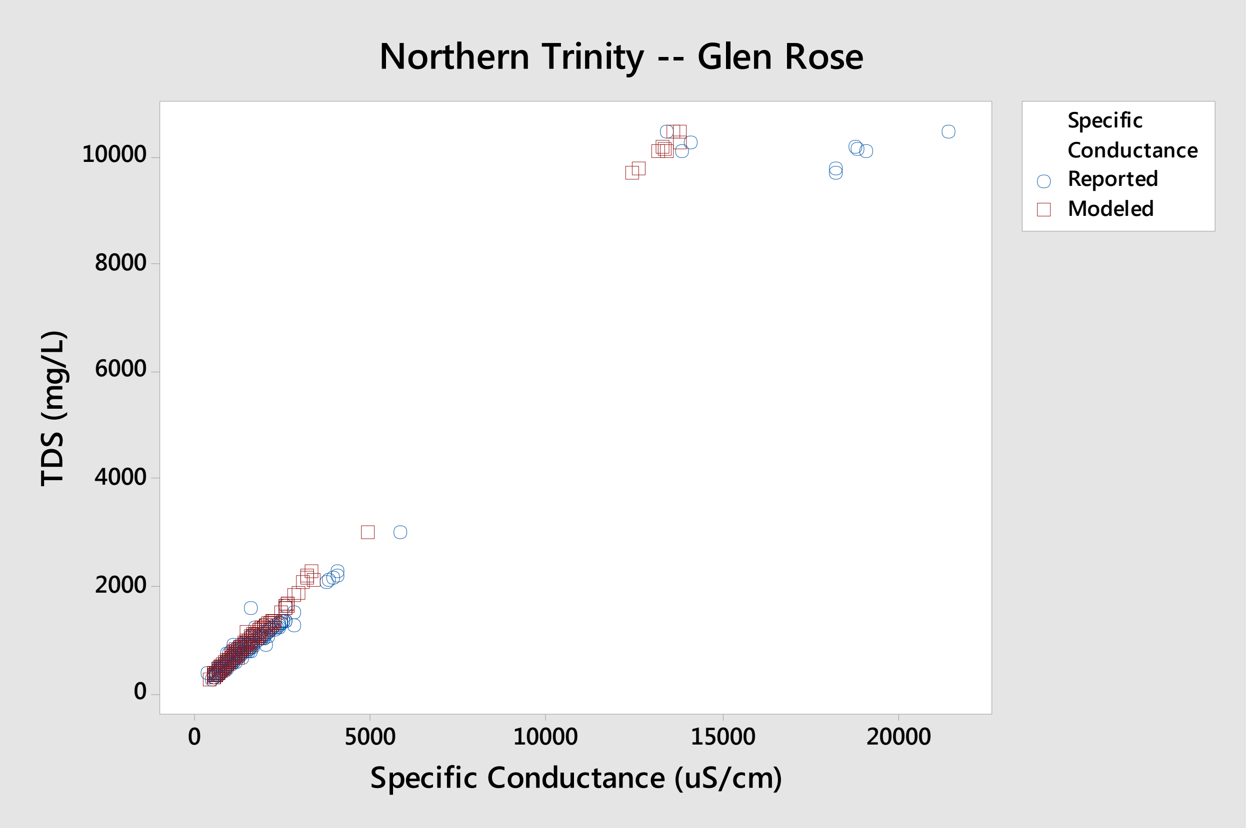


Figure 13-8 **Plots of TDS (mg/L), reported specific conductance (µS/cm) (circles), and geochemical model calculated specific conductance (µS/cm) (squares) for water quality samples from the Glen Rose unit of the Northern Trinity Aquifer. For the TDS values near 10,000 mg/L, all reported specific conductance values on the incorrect lower slope (~0.55) trend were analyzed prior to 1999.**

Methods that use the C_w– total dissolved solids relationship as a final step in estimating water quality from borehole geophysics must account for the prevalence of erroneous specific conductance data. Ways to address the issue without expressly calculating specific conductance include using chemical correction factors to correlate reported total dissolved solids directly to equivalent sodium chloride total dissolved solids and methods to calculate equivalent sodium chloride total dissolved solids directly from borehole resistivities (e.g., Bateman and Konen, 1977). These methods do not rely on reported specific conductance values.

13.5 Estimating TDS from Existing Groundwater Quality Data and 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., sthe 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. 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 SP, deep and flushed zone (or shallow) resistivity (R_{deep} and 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 the formation R_t value (e.g., 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

$$F = \frac{R_o}{R_w} \qquad \text{(Equation 13-5)}$$

where F is the formation factor which is related to porosity by the equation

$$F = \frac{a}{\phi^m} \qquad \text{(Equation 13-6)}$$

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 et al., 1952). Combining Equations 13-5 and 13-6 produces

$$R_w = R_o \times \phi^m \qquad \text{(Equation 13-7)}$$

which 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 composed of sodium chloride, 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 13-7 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.

13.5.1 Evaluation of Potential TDS Estimation Methods

Appropriate selection of methods to estimate the total dissolved solids of Trinity Aquifer groundwater in downdip areas is dependent on several factors including (i) aquifer lithology, (ii) aquifer groundwater chemistry, and (iii) the types of parameters available in borehole geophysical logs.

Limestone is a major component of the lithologies that comprise the Trinity Aquifer. The use of methods to calculate R_w that rely on SP data is discouraged in limestone aquifers (e.g., Collier, 1993). Challenges in using SP data arise because the hydrochemistry of the Trinity Aquifer is quite variable and includes significant concentrations of calcium, bicarbonate, sulfate, and magnesium, all of which have potentially significant impacts on the calculation of R_w and specific conductivity values. Thus, calculated values of R_w, as well as some intermediate resistivity values used in some methods, such as mud and mud filtrate resistivity (R_m and R_{mf}), likely need corrections for the effects of chemistry. Finally, availability of data from borehole geophysical logs varies significantly between the updip (fresh) and downdip (brackish) areas of the Trinity Aquifer. Review of available logs from multiple sources indicated that porosity measurements in the fresh water zones were rare.

In both the Northern Trinity Aquifer and Hill Country Trinity Aquifer extents, the majority of the available logs contain SP, resistivity, and induction logs. While there are some gamma, neutron porosity, and density porosity logs, their availability, both geographically and vertically, is poor and confined to hydrocarbon producing formations. In addition, given the high variability in the porosity and cementation exponent within the Trinity Aquifer, it is not likely that data from these logs would be broadly applicable outside of the immediate area of the geophysical log. Additionally, the review of available geophysical logs indicated that there were very limited geophysical data that included R_m or R_{mf} information, especially for the Hill Country region of the Trinity Aquifer where many wells were drilled using water as the drilling fluid.

The implications of the lack of some geophysical data in the Hill Country are twofold:

(1) R_w calculation methods that have been shown to be useful in limestone aquifers, such as the Estepp and R_{wa} methods (Estepp, 2010, Schultz, 1994, Collier, 1993), are mostly unusable in the fresh-water zone because of a lack of porosity measurements (porosities are used with resistivity ratios to estimate the cementation exponent, m, in the Estepp technique). Conversely, geophysical logs from wells in the downdip area, which has more petroleum exploration and production activity, have porosity values, but it is difficult to validate these R_w methods due to a lack of associated water-quality data. Porosity values and cementation exponents can be estimated for the fresh-water zone with an associated large increase in uncertainty.

(2) The presence of some R_m and R_{mf} data indicates that the resistivity ratio, or Alger-Harrison method (Estepp, 2010; Collier, 1993; Alger and Harrison, 1989), is most useful for the Hill Country region of the Trinity Aquifer. Unfortunately, geophysical data are limited in the Hill Country Trinity Aquifer so there are few opportunities to validate the method using known water quality (and total dissolved solids) values. However, there are

> sufficient available geophysical data to indicate that the resistivity ratio method is appropriate for the Northern Trinity Aquifer region. Thus, the resistivity ratio method is the primary method selected for use in brackish groundwater assessment for both the Hill Country Trinity Aquifer and the Northern Trinity Aquifer regions.

Other techniques to determine groundwater total dissolved solids in areas where water-quality data are lacking include empirical relationships, such as R_o- total dissolved solids graphs (e.g., Collier, 1993). As discussed below, preliminary analyses of data for the Northern Trinity Aquifer indicated that the R_o- total dissolved solids technique was unsuitable, consistent with previous results of Northern Trinity Aquifer groundwater (Collier, 1993).

Given the paucity of data with which to determine porosity or the cementation exponent, two approaches that are not dependent on explicit estimates of porosity and cementation exponent were examined to characterize water quality in the Northern Trinity Aquifer study area. The first of these two approaches is the Mean $\mathrm{R_o}$ method (Estepp, 1998, 2010). This approach has been successfully implemented in unconsolidated sands of the Gulf Coast Basin (e.g., Ayers and Lewis, 1985; Fogg, 1980; Fogg and Kreitler, 1982; Fogg and Blanchard, 1986; Hamlin, 1988; Collier, 1993; Estepp, 1998; Meyer, 2012; Young et al., 2016) but has yet to be proven in consolidated rock formations such as the Cretaceous Units that make up the Trinity Aquifer system. Collier (1993) states that the Mean $\mathrm{R_o}$ 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 $\mathrm{R_o}$ analysis technique 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 Trinity Aquifer.

Sampled water quality and geophysical log data compiled by Kelley et al. (2014) for the Northern Trinity Aquifer GAM provided a test dataset to evaluate the potential use of the Mean $\mathrm{R_o}$ method. Within the dataset, there were 38 public water-supply wells that had a water-quality measurement and a geophysical log that included either deep resistivity and/or induction (applied similarly to deep resistivity for the purposes of this analysis), in addition to screen location information. Using structural picks made on the logs as part of the Kelley et al. (2014) study, it was determined that all of these wells were screened exclusively in the Hosston Formation, with the exception of one well that was co-completed in the Hosston and Pearsall formations.

The sand units within the screened intervals for all of these wells were identified, and the average and 80th percentile resistivity values for each of the sand units were derived from the digitized log. The 80th percentile was used to see if using the higher amplitude portions of the resistivity kick would produce a better match. 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 13-2 provides a summary of the results. Figures 13-9a and 13-9b show the plots of total dissolved solids values against each of the sands that were screened by each of the wells. As illustrated, there is no evident trend that could be used to correlate R_o and sampled total dissolved solids. Figures 13-10a and 13-10b show the combined average resistivity for all of the sands screened by any one well (i.e. instead of plotting the resistivity of each individual sand unit, the average was taken for the resistivity of all sands matched against the well screen) plotted against the sampled total dissolved solids from the same well. Averaging the results by well does not improve the correlation.

Table 13-2 **Average observed resistivity and total dissolved solids values for wells used in Mean R_o Analysis.**

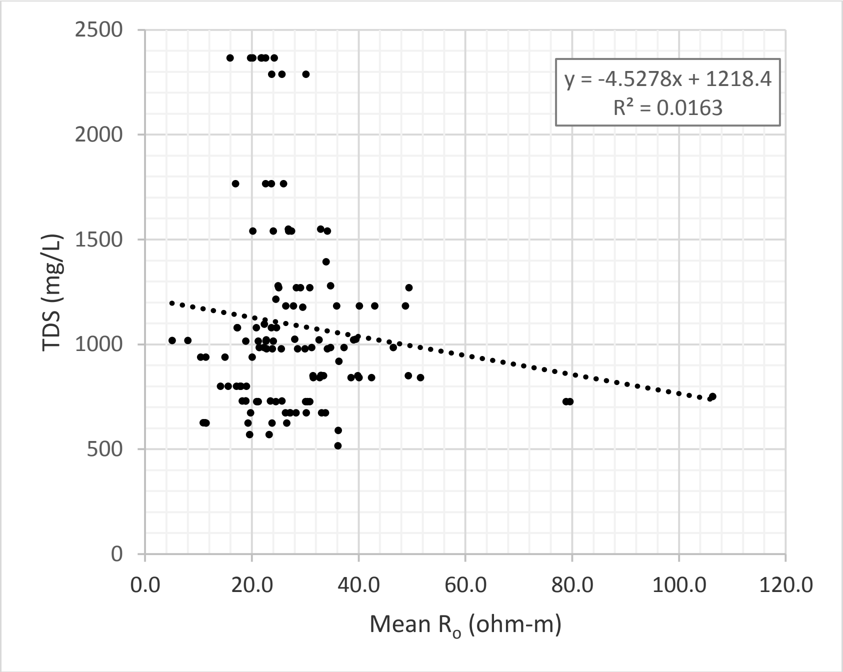
API	Depth (ft)		Mean R_o (ohm-m)		80th Percentile R_o (ohm-m)		TDS (mg/L)
	TOP	BOT	Sand Interval	Average Over Screen Interval	Sand Interval	Average Over Screen Interval	Average Over Screen Interval
4055701	2,494	2,611	33	33	42	42	852
4061501	665	734	36	37	49	46	1183
	836	924	49		60		
	912	956	26		41		
	1,136	1,208	28		32		
	1,212	1,226	43		49		
	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		

API	Depth (ft)		Mean R_o (ohm-m)		80th Percentile R_o (ohm-m)		TDS (mg/L)
	TOP	BOT	Sand Interval	Average Over Screen Interval	Sand Interval	Average Over Screen Interval	Average Over Screen Interval
	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		
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

API	Depth (ft)		Mean R_o (ohm-m)		80th Percentile R_o (ohm-m)		TDS (mg/L)
	TOP	BOT	Sand Interval	Average Over Screen Interval	Sand Interval	Average Over Screen Interval	Average Over Screen Interval
4007301	1,515	1,540	34	28	48	34	673
	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		
	1,682	1,690	35		37		

API	Depth (ft)		Mean R_o (ohm-m)		80th Percentile R_o (ohm-m)		TDS (mg/L)
	TOP	BOT	Sand Interval	Average Over Screen Interval	Sand Interval	Average Over Screen Interval	Average Over Screen Interval
	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		

A)



B)

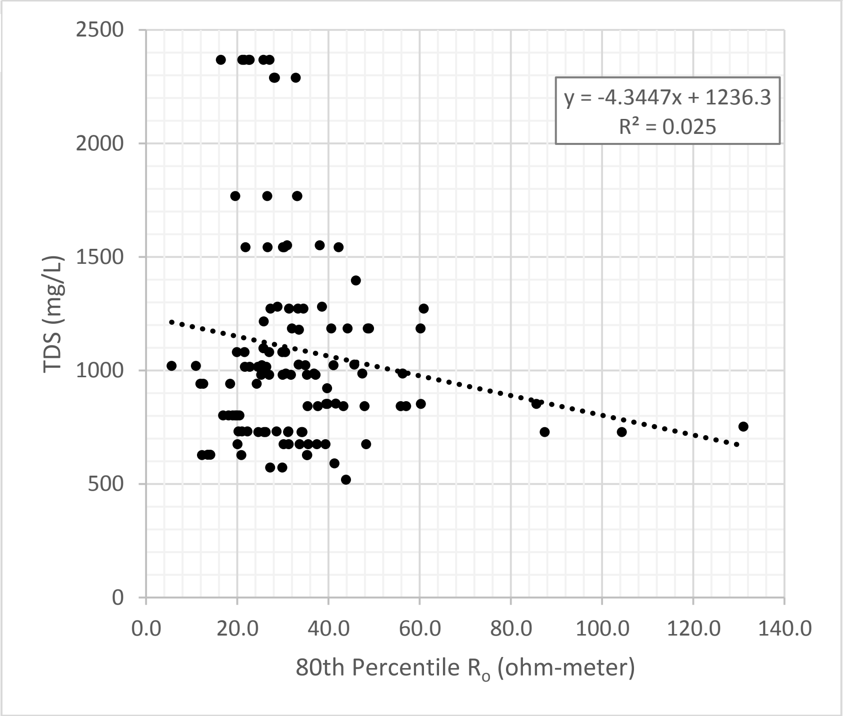


Figure 13-9 **A) Sampled total dissolved solids (TDS) plotted against average observed resistivity (R_o) for all sands identified in the screened portion of the water well. B) Sampled total dissolved solids (TDS) plotted against the 80th percentile of the observed resistivity (R_o) for all sands identified in the screened portion of the water well.**

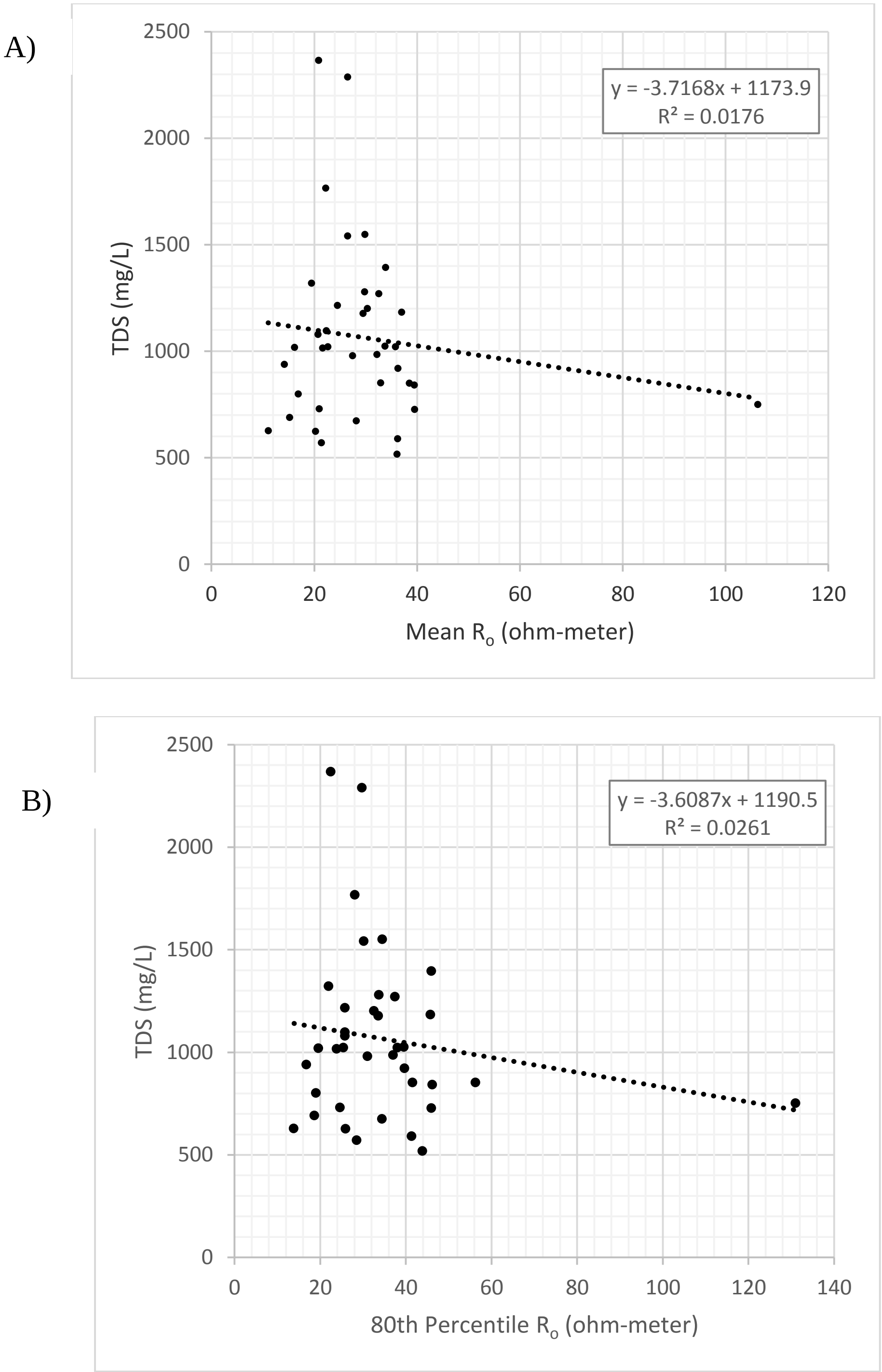


Figure 13-10 **A) Sampled total dissolved solids (TDS) plotted against average observed resistivity (R_o) and averaged over all sands identified in the screened portion of the water well and B) Sampled total dissolved solids (TDS) plotted against 80th percentile of the observed resistivity (R_o) and averaged over all sands identified in the screened portion of the water well.**

While multiple publications have shown successful use of the Mean R_o technique, 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. Additionally, these studies are rarely performed on the up-dip water saturated portions of geologic formations.

13.6 Application of the Resistivity Ratio Approach

Given the variability of the formation factor and the inability to identify and subsequently predict its variability, a different approach was attempted to predict the formation factor in Archie's (1942) resistivity relationships (Equations 13-5 to 13-7). For both the Northern and Hill Country regions of the Trinity Aquifer, total dissolved solids of groundwater in areas lacking water-quality measurements were estimated from borehole geophysical logs using the resistivity ratio or modified Alger-Harrison technique (Estepp, 2010; Collier, 1993; Alger and Harrison, 1989). Application of this technique requires values for the parameters R_t (equivalent to R_o), R_{xo}, and R_{mf}.

In a typical borehole environment, like the one shown in Figure 13-11, 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 that develops 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}). All of this information, along with the bottom-hole temperature (BHT), is recorded on the header of the geophysical log along with various other 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} is calculated using the methods outlined in Collier (1993).

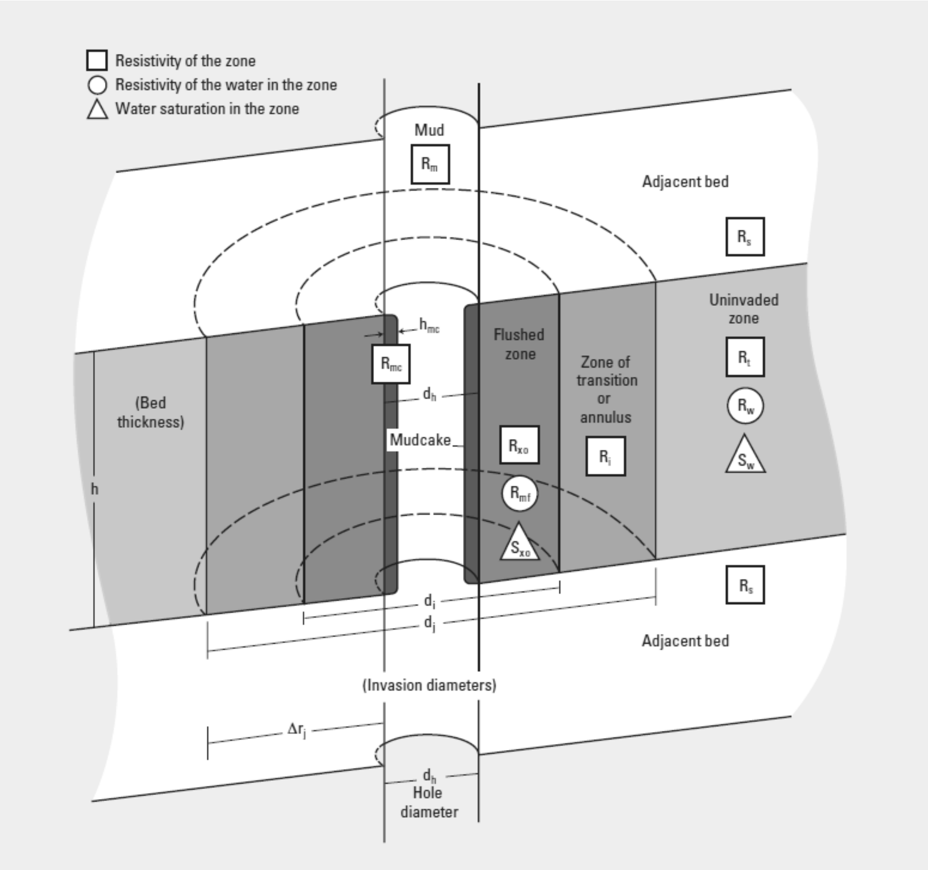


Figure 13-11 Wellbore shown traversing a zone of interest (Schlumberger, 2009).

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

$$R_{mf} = \Phi^m \times R_{xo} \qquad \text{Equation 13-8}$$

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 13-7 into Equation 13-8 to produce

$$R_{we} = R_{mf} \times \frac{R_o}{R_{xo}} \qquad \text{Equation 13-9}$$

Advantages of the resistivity ratio method include (i) specific formation factor parameters do not need to be measured or estimated, and (ii) once R_{mf} is corrected for temperature to 25°C, formation temperatures are not needed. As discussed previously, R_{mf} temperature corrections were conducted using the Arps (1953) equations. Thus, after temperature correction the final R_{we} calculation becomes

$$R_{we25} = R_{mf25} \times \frac{R_o}{R_{xo}} \qquad \text{Equation 13-10}$$

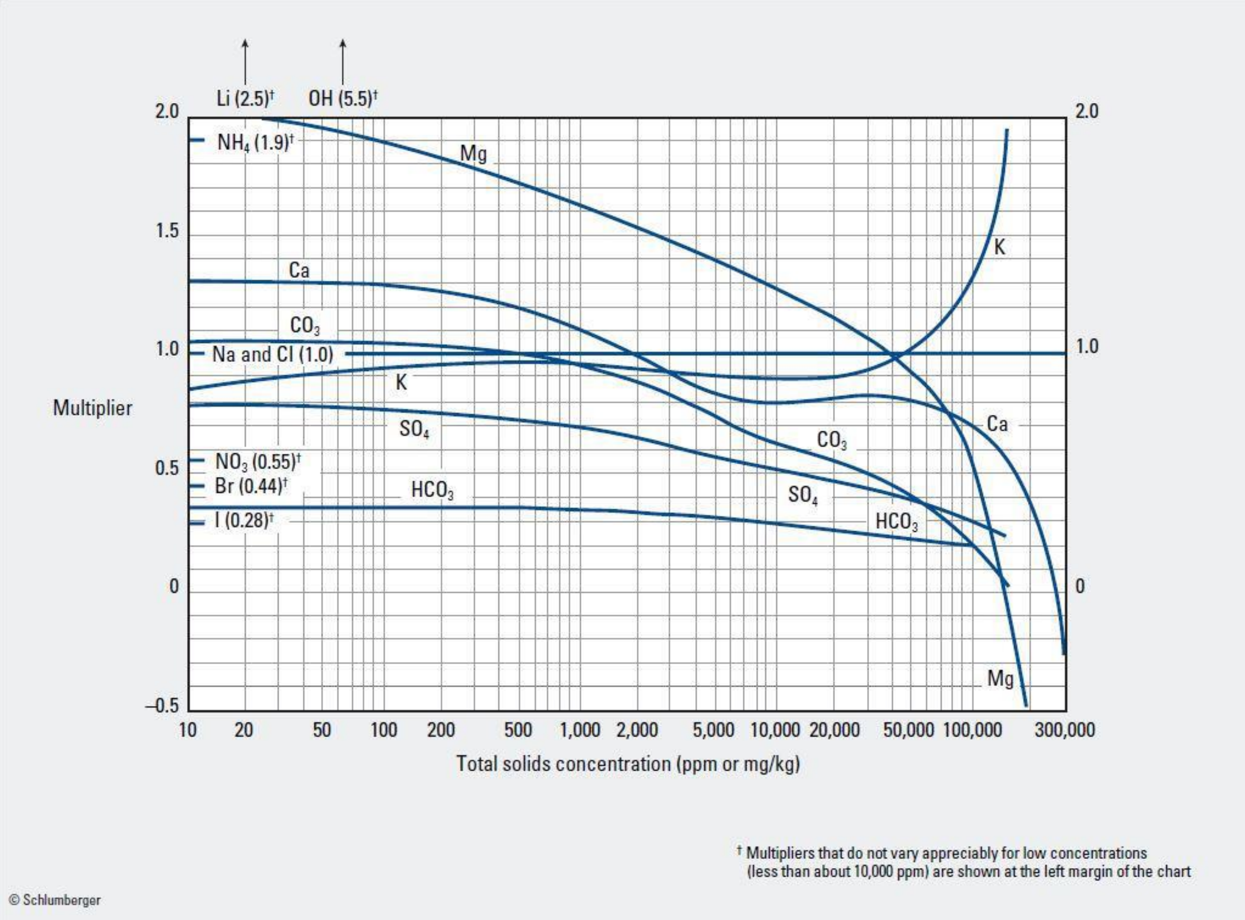
where R_{we25} and R_{mf25} are the equivalent formation water and mud-filtrate resistivities at 25°C.

Alternatively, resistivity values can be corrected to formation temperature in Equation 13-9 and then converted to equivalent resistivities at 25°C during the calculation of $\mathrm{TDS}_{\mathrm{NaCl}}$ (see discussion for Equation 13-11 below). This approach was used in the Northern Trinity Aquifer region.

As discussed previously, the calculated R_{we25} value is also impacted by variations in chemistry within the brackish- and fresh-water zones. Discussions of techniques for correcting R_{we25} (and R_{mf25}) for the effects of chemistry are found in Estepp (2010) and Collier (1993). 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} correlation.

An alternative approach to correcting for chemistry is to calculate the sodium chloride (NaCl)-equivalent total dissolved solids ($\mathrm{TDS}_{\mathrm{NaCl}}$) (estimated total dissolved solids value if the groundwater was a simple sodium chloride solution) for known water wells using measured water-quality data. Water-quality data from the Northern Trinity Aquifer and Hill Country Trinity Aquifer regions were used to calculate $\mathrm{TDS}_{\mathrm{NaCl}}$ values using the ionic concentration of the groundwater and the conversion scheme provided in Schlumberger's GEN-4 Chart (Figure 13-12) (Desai and Moore, 1969; Collier, 1993; 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 $\mathrm{TDS}_{\mathrm{NaCl}}$. 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.

The correlation between total dissolved solids and $\mathrm{TDS}_{\mathrm{NaCl}}$ for each hydrostratigraphic horizon 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.



† Multipliers that do not vary appreciably for low concentrations (less than about 10,000 ppm) are shown at the left margin of the chart

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Figure 13-12 **Schlumberger chart GEN-4 (Schlumberger, 2009) used to calculate equivalent sodium chloride total dissolved solids from a known water chemistry sample. "ppm" stands for parts per million. "mg/kg" stands for milligrams per kilogram.**

The R_{we25} calculated from the resistivity ratio method (Equation 13-10) is converted into a TDS_{NaCl} value using the equation of Bateman and Konen (1977) [also found in Bigelow (1992) and Western Atlas (1992)].

$$TDS_{NaCl} = 10^{\left(\frac{3.562-\log_{10}[R_{we25}-0.0123]}{0.955}\right)} \qquad \text{Equation 13-11}$$

Where TDS_{NaCl} is the equivalent sodium chloride total dissolved solids in mg/L and R_{we25} is the equivalent formation water resistivity in ohm-m. This calculated TDS_{NaCl} value is then converted into an appropriate $\text{TDS}_{AquiferUnit}$ (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, which also have a geophysical log with relevant header parameters, screen information, and water-quality samples were examined. In total, there were 32 wells that fit the criteria (Table 13-3). For the 32 wells, there were a total of 113 screened sand intervals. Average calculated total dissolved solids values from the resistivity ratio technique were plotted against sampled total dissolved solids values for all the wells (Figure 13-13a). As can be seen from the plot, the measured and estimated total dissolved solids values are somewhat poorly correlated. An additional 4 Hosston Formation wells with 8 screened intervals from the Hill Country Trinity were also examined (Table 13-4). Results from these wells were only slightly better than the Northern Trinity Aquifer evaluation, but were constrained to a very limited total dissolved solids range. The poor correlation observed for the test calculations may be due to the relatively small range over which the measured data is available. That is, there are only four sample measurements that exceed 2,000 mg/L, and most of the measurements cluster between 500 and 1,500 mg/L total dissolved solids. Because this technique has a sound theoretical basis, we would expect it to be broadly applicable over a wide water-quality range.

Table 13-3 Calculated total dissolved solids using the resistivity ratio method for Northern Hosston water wells that have a sampled water quality and geophysical log.

Well ID	Depth (ft)		Resistivity (ohm-m)				F	TDS_{NaCl}	TDS_{NaCl} to TDS Multiplier	Calculated TDS		Measured TDS
	TOP	BOT	R_o	R_s	R_{mfz}	R_w				Sand Interval	Average Over Screen Interval	
4055701	2,494	2,611	33	34	4	4	0.12	869	1.20	1,045	1,045	852
4061501	1,136	1,208	28	27	3	3	0.11	1,258	1.14	1,432	1,628	2,047
	1,212	1,226	43	52	3	2	0.06	1,604	1.14	1,826		
	1,237	1,252	40	44	3	3	0.07	1,428	1.14	1,626		
4062801	2,209	2,307	33	27	1	1	0.03	3,454	1.16	3,999	4,034	1,021
	2,326	2,358	39	33	1	1	0.03	3,513	1.16	4,068		
5805902	2,191	2,287	26	24	2	2	0.07	1,914	1.17	2,242	2,203	2,288
	2,293	2,310	24	23	2	2	0.08	1,964	1.17	2,301		
	2,321	2,418	30	26	2	2	0.07	1,764	1.17	2,066		
1850501	2,278	2,295	27	14	1	1	0.04	3,148	1.09	3,439	3,476	1,541
	2,298	2,321	27	14	1	1	0.04	3,084	1.09	3,370		
	2,350	2,392	34	17	1	1	0.04	2,999	1.09	3,276		
	2,404	2,466	24	13	1	1	0.05	3,166	1.09	3,459		
	2,479	2,493	20	12	1	1	0.05	3,509	1.09	3,834		
4026102	565	612	36	38	13	12	0.34	349	1.14	398	398	920
3224306	1,892	2,000	33	30	5	5	0.15	732	1.19	874	925	2,098
	2,009	2,043	40	39	5	5	0.11	818	1.19	977		
3301301	2,016	2,066	23	19	2	3	0.11	1,706	1.16	1,980	2,063	1,766
	2,068	2,076	17	16	2	2	0.14	1,840	1.16	2,136		
	2,088	2,172	24	20	2	3	0.11	1,681	1.16	1,951		
	2,186	2,268	26	24	2	2	0.09	1,882	1.16	2,184		
3309102	1,926	1,948	17	20	2	2	0.13	2,120	1.22	2,578	2,468	1,079
	1,957	1,971	17	19	2	2	0.13	1,975	1.22	2,401		
	1,988	2,036	24	24	2	2	0.10	1,890	1.22	2,298		

Well ID	Depth (ft)		Resistivity (ohm-m)				F	TDS_{NaCl}	TDS_{NaCl} to TDS Multiplier	Calculated TDS		Measured TDS
	TOP	BOT	R_o	R_s	R_{mfz}	R_w				Sand Interval	Average Over Screen Interval	
	2,054	2,084	25	28	2	2	0.09	2,059	1.22	2,504		
	2,092	2,122	21	24	2	2	0.10	2,103	1.22	2,557		
3309403	1,924	1,943	25	27	4	4	0.16	977	1.22	1,189	1,155	979
	1,965	1,981	24	24	4	4	0.18	936	1.22	1,138		
	1,990	2,009	34	35	4	4	0.12	948	1.22	1,154		
	2,017	2,037	29	31	4	4	0.14	996	1.22	1,212		
	2,044	2,050	30	29	4	4	0.15	887	1.22	1,079		
	2,056	2,079	23	23	4	4	0.18	951	1.22	1,157		
3309503	2,115	2,178	35	27	2	3	0.08	1,030	1.22	1,260	1,400	1,279
	2,189	2,215	25	23	2	2	0.10	1,259	1.22	1,540		
3320101	3,615	3,742	27	22	2	2	0.08	1,487	1.21	1,793	1,843	1,549
	3,756	3,838	33	28	2	2	0.06	1,569	1.21	1,893		
3326301	2,956	2,982	31	16	1	2	0.07	1,777	1.16	2,069	2,419	1,270
	2,999	3,028	28	17	1	2	0.07	2,141	1.16	2,493		
	3,054	3,104	29	19	1	2	0.06	2,262	1.16	2,634		
	3,116	3,139	25	17	1	2	0.07	2,400	1.16	2,795		
	3,153	3,162	49	26	1	2	0.04	1,809	1.16	2,106		
1857404	1,706	1,771	19	20	2	2	0.12	2,038	1.11	2,257	2,233	1,015
	1,783	1,811	24	24	2	2	0.09	1,979	1.11	2,192		
	1,816	1,829	21	22	2	2	0.10	2,043	1.11	2,262		
	1,834	1,878	23	23	2	2	0.10	2,007	1.11	2,222		
1857602	2,231	2,396	22	26	2	1	0.07	2,849	1.14	3,246	3,246	1,021
1962204	951	1,019	36	42	10	8	0.23	499	1.19	595	595	517
1964201	1,621	1,643	33	25	3	3	0.11	1,147	1.16	1,334	1,305	841
	1,650	1,664	40	31	3	4	0.09	1,141	1.16	1,327		
	1,675	1,683	52	36	3	4	0.08	1,019	1.16	1,186		
	1,686	1,693	31	25	3	3	0.11	1,189	1.16	1,383		
	1,697	1,706	39	29	3	4	0.09	1,112	1.16	1,294		
	1,710	1,727	42	32	3	4	0.08	1,125	1.16	1,308		
3333101	2,174	2,214	20	19	3	3	0.13	1,697	1.19	2,023	1,929	570
	2,228	2,354	23	21	2	3	0.12	1,539	1.19	1,835		
3342702	2,750	2,798	24	28	2	2	0.07	1,859	1.13	2,099	2,099	1,215
3263802	1,441	1,480	11	20	2	1	0.12	3,488	1.21	4,233	4,089	627
	1,493	1,614	11	18	2	1	0.13	3,251	1.21	3,946		
3909902	3,066	3,095	14	17	1	1	0.07	3,520	1.19	4,187	3,972	800
	3,103	3,113	16	17	1	1	0.07	3,134	1.19	3,728		
	3,119	3,145	18	20	1	1	0.06	3,238	1.19	3,851		

Well ID	Depth (ft)		Resistivity (ohm-m)				F	TDS_{NaCl}	TDS_{NaCl} to TDS Multiplier	Calculated TDS		Measured TDS
	TOP	BOT	R_o	R_s	R_{mfz}	R_w				Sand Interval	Average Over Screen Interval	
	3,156	3,182	17	20	1	1	0.06	3,510	1.19	4,175		
	3,194	3,203	18	21	1	1	0.06	3,390	1.19	4,032		
	3,212	3,219	19	21	1	1	0.06	3,246	1.19	3,861		
3910201	3,490	3,557	22	20	1	1	0.06	2,427	1.19	2,886	2,886	1,096
4007301	1,515	1,540	34	40	2	2	0.06	2,290	1.21	2,769	2,718	673
	1,571	1,585	33	38	2	2	0.06	2,211	1.21	2,673		
	1,604	1,631	27	32	2	2	0.07	2,223	1.21	2,687		
	1,642	1,670	26	29	2	2	0.08	2,136	1.21	2,583		
	1,678	1,690	28	32	2	2	0.07	2,164	1.21	2,616		
	1,697	1,712	27	29	2	2	0.08	2,052	1.21	2,481		
	1,719	1,738	30	33	2	2	0.07	2,061	1.21	2,492		
	1,741	1,747	20	29	2	2	0.08	2,848	1.21	3,444		
3238904	1,488	1,497	36	29	3	4	0.11	1,019	1.20	1,227	1,227	589
3925402	2,525	2,580	24	20	1	2	0.07	2,180	1.25	2,731	2,718	727
	2,619	2,644	31	22	1	2	0.06	1,913	1.25	2,396		
	2,649	2,678	30	22	1	2	0.06	1,910	1.25	2,393		
	2,700	2,730	21	19	1	1	0.07	2,403	1.25	3,010		
	2,758	2,795	21	20	1	1	0.07	2,548	1.25	3,192		
	2,822	2,854	30	25	1	2	0.05	2,229	1.25	2,792		
	2,868	2,919	80	57	1	2	0.02	1,930	1.25	2,418		
	2,928	2,946	79	66	1	2	0.02	2,246	1.25	2,814		
4024301	2,644	2,805	34	30	1	2	0.05	2,419	1.09	2,628	2,628	1,394
5807901	3,219	3,240	24	36	3	2	0.08	1,858	1.23	2,288	2,140	2,366
	3,246	3,254	16	20	3	2	0.15	1,561	1.23	1,923		
	3,260	3,283	20	30	3	2	0.10	1,885	1.23	2,321		
	3,286	3,307	22	29	3	2	0.11	1,633	1.23	2,011		
	3,313	3,367	20	27	3	2	0.11	1,624	1.23	2,000		
	3,383	3,394	22	33	3	2	0.09	1,894	1.23	2,332		
	3,398	3,447	23	31	3	2	0.10	1,708	1.23	2,104		
3214110	876	891	15	17	1	1	0.05	6,396	1.23	7,893	7,310	939
	904	917	10	12	1	1	0.07	6,232	1.23	7,691		
	930	941	11	11	1	1	0.07	5,448	1.23	6,724		
	957	1,020	20	20	1	1	0.04	5,616	1.23	6,932		
3216203	1,588	1,604	21	26	4	3	0.14	1,468	1.21	1,772	1,370	985
	1,607	1,619	22	22	4	4	0.16	1,211	1.21	1,462		
	1,625	1,651	37	29	4	5	0.12	905	1.21	1,093		
	1,656	1,675	31	34	4	3	0.10	1,321	1.21	1,595		

Well ID	Depth (ft)		Resistivity (ohm-m)				F	TDS_{NaCl}	TDS_{NaCl} to TDS Multiplier	Calculated TDS		Measured TDS
	TOP	BOT	R_o	R_s	R_{mfz}	R_w				Sand Interval	Average Over Screen Interval	
	1,682	1,690	35	30	4	4	0.12	1,028	1.21	1,242		
	1,695	1,722	46	35	4	5	0.10	877	1.21	1,059		
3222602	1,052	1,075	24	32	4	3	0.11	1,510	1.24	1,865	1,501	625
	1,088	1,094	27	20	4	5	0.18	813	1.24	1,004		
	1,110	1,122	11	18	4	2	0.21	1,732	1.24	2,140		
	1,133	1,145	19	14	4	5	0.25	806	1.24	996		
3222903	1,068	1,081	19	20	3	3	0.16	1,202	1.21	1,456	1,426	730
	1,087	1,110	18	19	3	3	0.17	1,136	1.21	1,376		
	1,116	1,154	23	22	3	3	0.15	1,020	1.21	1,236		
	1,194	1,243	19	23	3	3	0.14	1,350	1.21	1,637		
	1,250	1,290	26	27	3	3	0.11	1,176	1.21	1,425		
5813503	2,468	2,488	30	31	2	2	0.08	1,636	1.14	1,864	1,882	1,201
	2,500	2,528	24	24	2	2	0.09	1,586	1.14	1,808		
	2,539	2,589	32	32	2	2	0.07	1,562	1.14	1,780		
	2,606	2,621	35	40	2	2	0.06	1,819	1.14	2,074		

Table 5-4. Calculated total dissolved solids using the resistivity ratio method for Hill Country Hosston water wells that have a sampled water quality and geophysical log.

Well ID	Depth (ft)[†]		Resistivity (ohm-m)				TDS_{NaCl}	TDS_{NaCl} to TDS Multiplier	Calculated TDS		Measured TDS
	TOP	BOT	R_o	R_s	R_{mf}	R_w			Sand Interval	Average Over Screen Interval	
6924202	742	842	148.1	156.7	10.5	10.3	468.6	1.16	540	587	644
	742	760	155.6	166.7	10.5	10.1	474.8	1.16	547		
	792	816	260.2	317.6	10.5	8.9	544.3	1.16	628		
5664601	600	634	670.2	291.1	4.9	11.7	409.7	1.16	472	472	818
5663606	605	655	421.2	349.4	3.2	3.4	1476.7	1.16	1709	1709	475
5664701	528	638	190.6	80.6	8.9	21.3	218.3	1.16	250	250	414
	528	554	400.1	116.2	8.9	29.5	155.5	1.16	177		
	565	578	318.8	114	8.9	26.1	183.1	1.16	209		

[†] Depth of screened or water producing interval

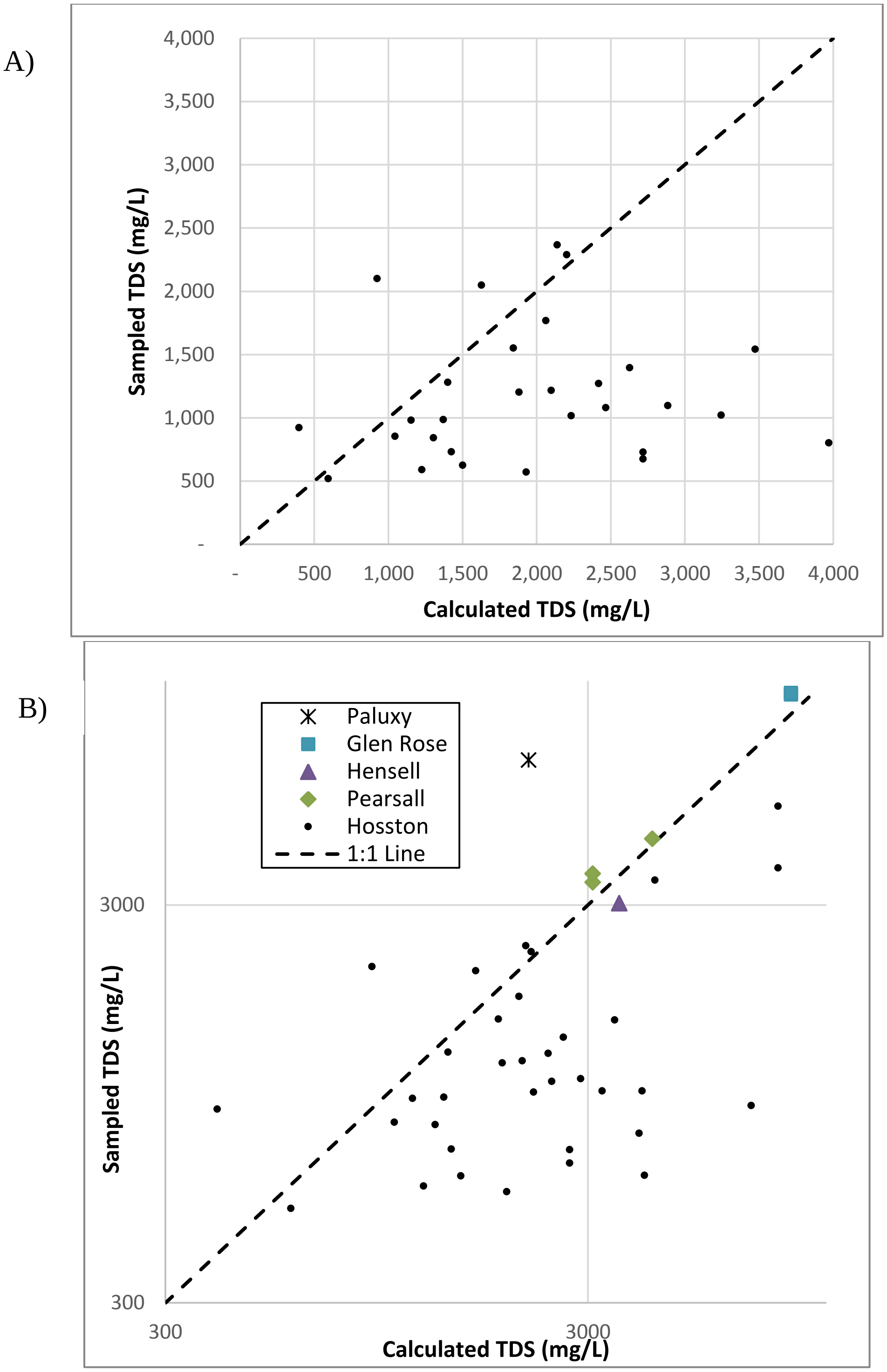

Figure 13-13 **A) Sampled total dissolved solids (TDS) plotted against calculated total dissolved solids using the resistivity ratio method and B) sampled total dissolved solids (TDS) plotted against calculated total dissolved solids using the resistivity ratio method, with higher sampled concentration well pair results added.**

To assess the performance of the technique over wider total dissolved solids ranges, the few water-quality samples that exceed 3,000 mg/L 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. The results are shown on Figure 13-13b, added to the existing Hosston Formation dataset. Because of the expanded range, the data are not plotted on a logarithmic scale. Figure 13-13b indicates that the approach, while still showing scatter around the 1:1 line, the expanded total dissolved solids range improves significantly at 3,000 to 10,000 mg/L total dissolved solids. Because the 1,000 mg/L total dissolved solids line can largely be determined based on sampled water quality, the improvement in the resistivity ratio approach at higher total dissolved solids ranges allows for a complementary approach: i.e., the resistivity ratio method allows estimates of the location of the 3,000 mg/L total dissolved solids and 10,000 mg/L total dissolved solids transition lines, while sampled water quality is considered to be the best data source for estimating the location of the 1,000 mg/L total dissolved solids transition line.

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

Broad application of this approach involved acquiring log header parameters and digitized shallow and deep resistivity/induction curves for a geographically and stratigraphically distributed log dataset. The logs had lithologic picks in the formations of interest so that the average short and deep resistivity value could be calculated from digitized curves over the sand/limestone (avoiding clay/shale) portions of the formations. For the Northern Trinity Aquifer region, lithologic picks on a sub 5-foot basis were made by Scott Hamlin as part of the Northern Trinity Aquifer GAM study. The lithologic intervals were used as the top and base of a zone to average the shallow and deep resistivity values that were ultimately used in Equations 13-10 and 13-11.

13.6.1 TDS–TDS_{NaCl} equations and fits for Northern and Hill Country Trinity Aquifer regions

The TDS–TDS_{NaCl} equations for the five hydrostratigraphic units modeled for the Northern Trinity Aquifer are listed in Equations 13-12 through 3-16 below. Data and regression are shown in Figures 13-14 through 13-18.

$$TDS_{Paluxy} = 1.0559\left(TDS_{NaCl\ Paluxy}\right) + 67.946 \qquad \text{Equation 13-12}$$
$$TDS_{Glen\ Rose} = 1.2238(TDS_{NaCl\ Glen\ Rose}) - 21.92 \qquad \text{Equation 13-13}$$
$$TDS_{Hensell} = 1.0272(TDS_{NaCl\ Hensell}) + 67.404 \qquad \text{Equation 13-14}$$
$$TDS_{Pearsall} = 1.0879(TDS_{NaCl\ Pearsall}) + 36.409 \qquad \text{Equation 13-15}$$
$$TDS_{Hosston} = 1.1597(TDS_{NaCl\ Hosston}) - 3.5185 \qquad \text{Equation 13-16}$$

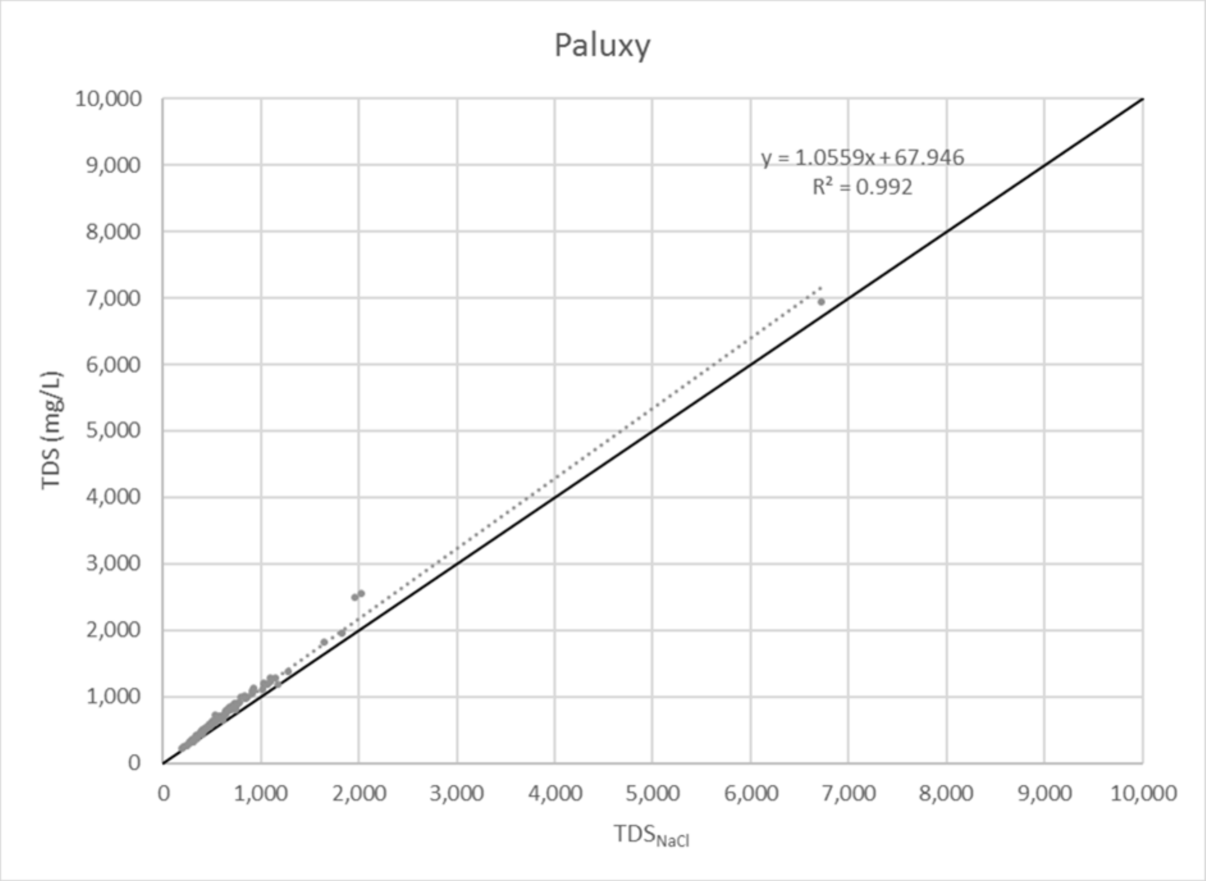

Figure 13-14 Sampled total dissolved solids (TDS) in milligrams per liter (mg/L) plotted against sodium chloride equivalent total dissolved solids in milligrams per liter (mg/L) for the Paluxy Formation. Solid line indicating 1:1 relationship is shown for comparison.

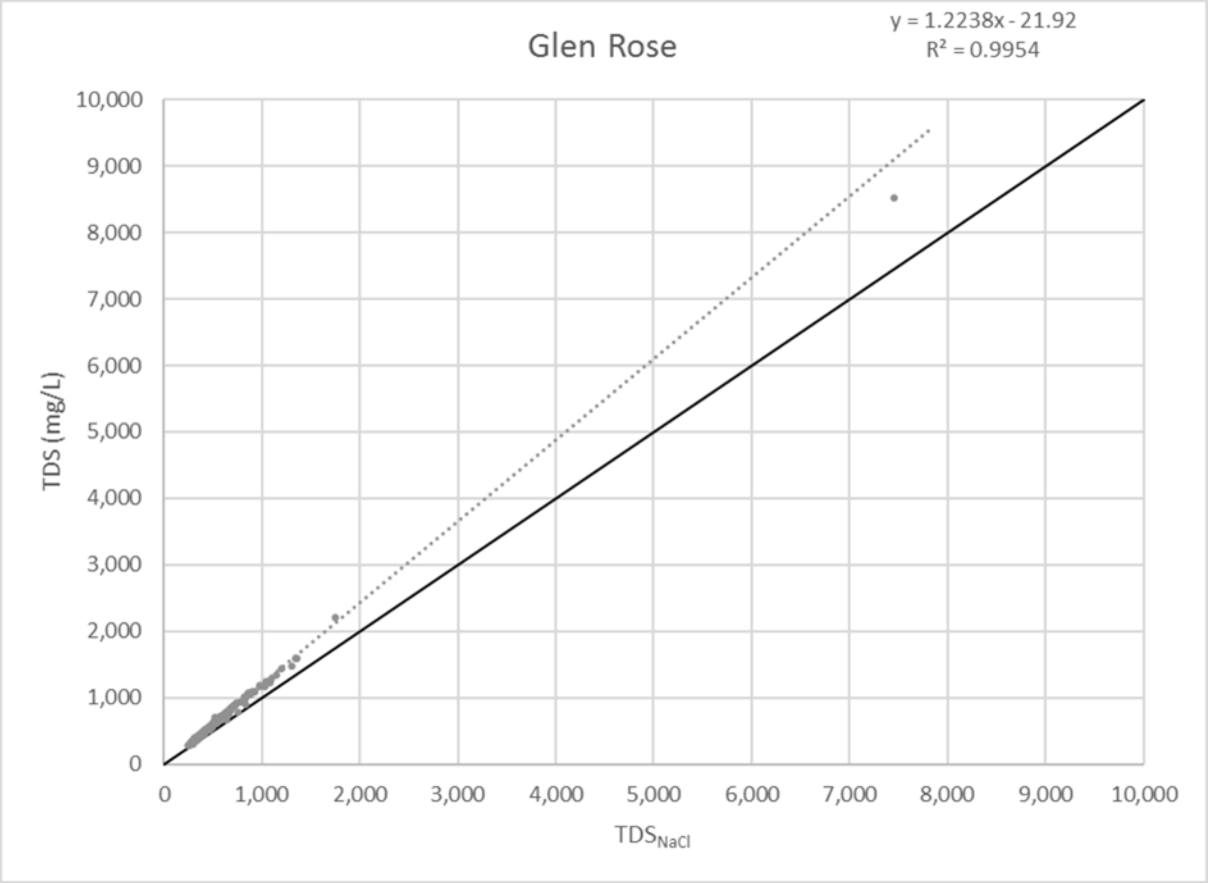

Figure 13-15 **Sampled total dissolved solids (TDS) in milligrams per liter (mg/L) plotted against sodium chloride equivalent total dissolved solids in milligrams per liter (mg/L) for the Glen Rose Formation. Solid line indicating 1:1 relationship is shown for comparison.**

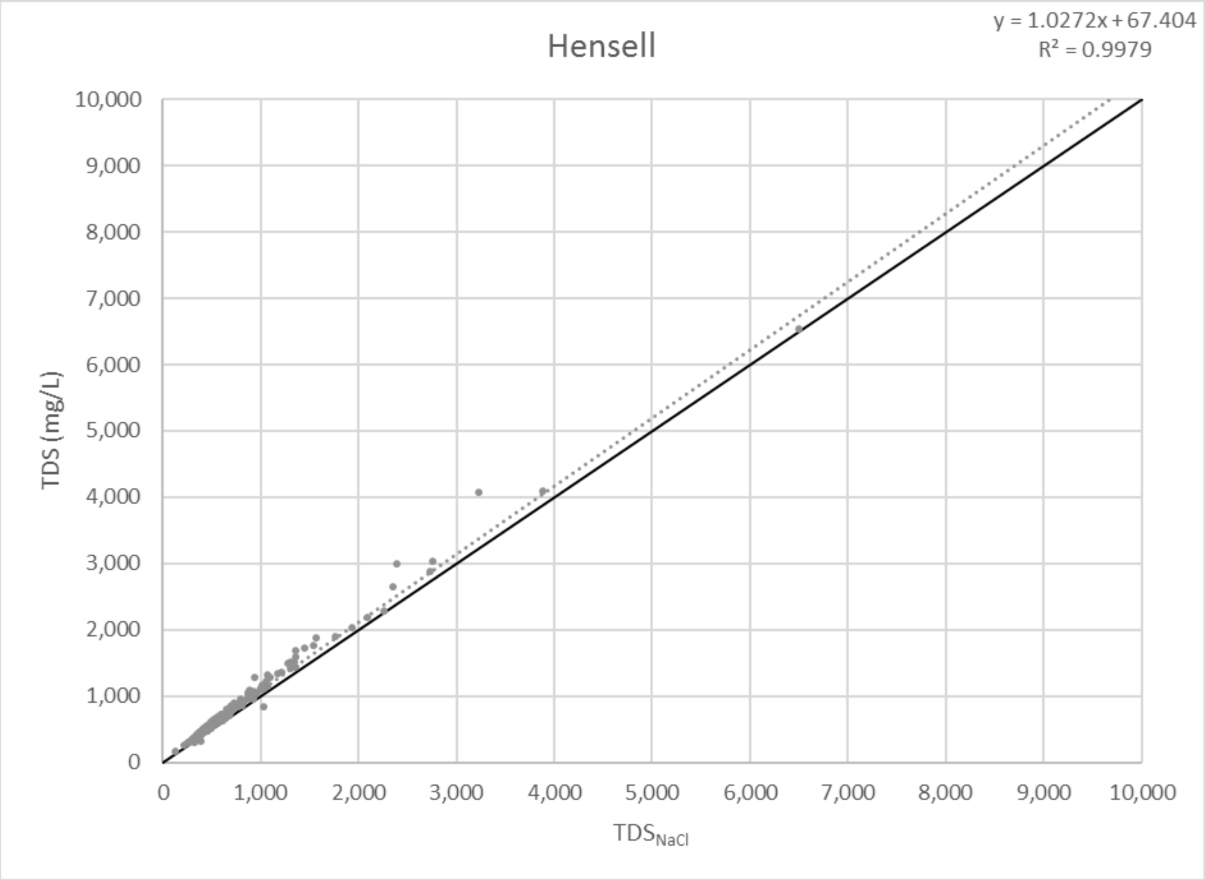

Figure 13-16 **Sampled total dissolved solids (TDS) in milligrams per liter (mg/L) plotted against sodium chloride equivalent total dissolved solids in milligrams per liter (mg/L) for the Hensell Formation. Solid line indicating 1:1 relationship is shown for comparison.**

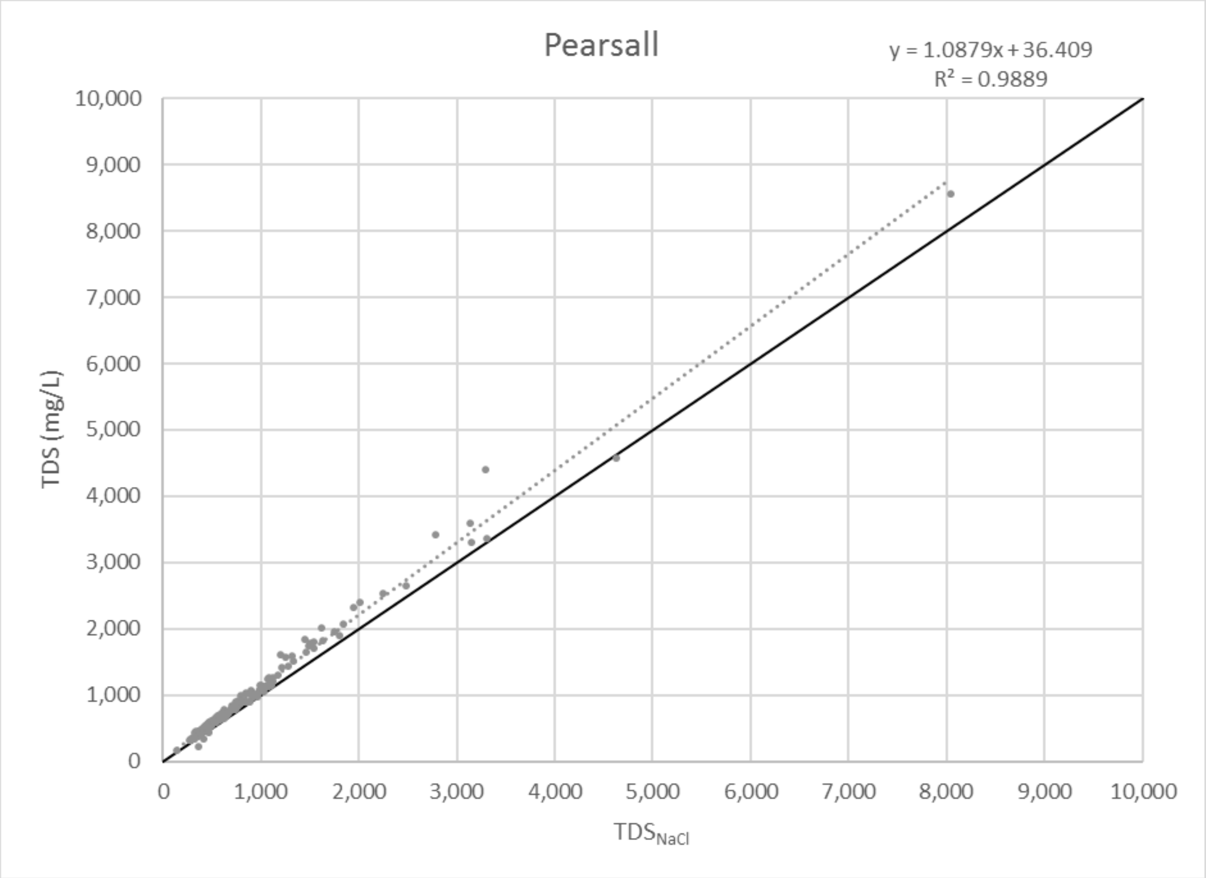

Figure 13-17 **Sampled total dissolved solids (TDS) in milligrams per liter (mg/L) plotted against sodium chloride equivalent total dissolved solids in milligrams per liter (mg/L) for the Pearsall Formation. Solid line indicating 1:1 relationship is shown for comparison.**

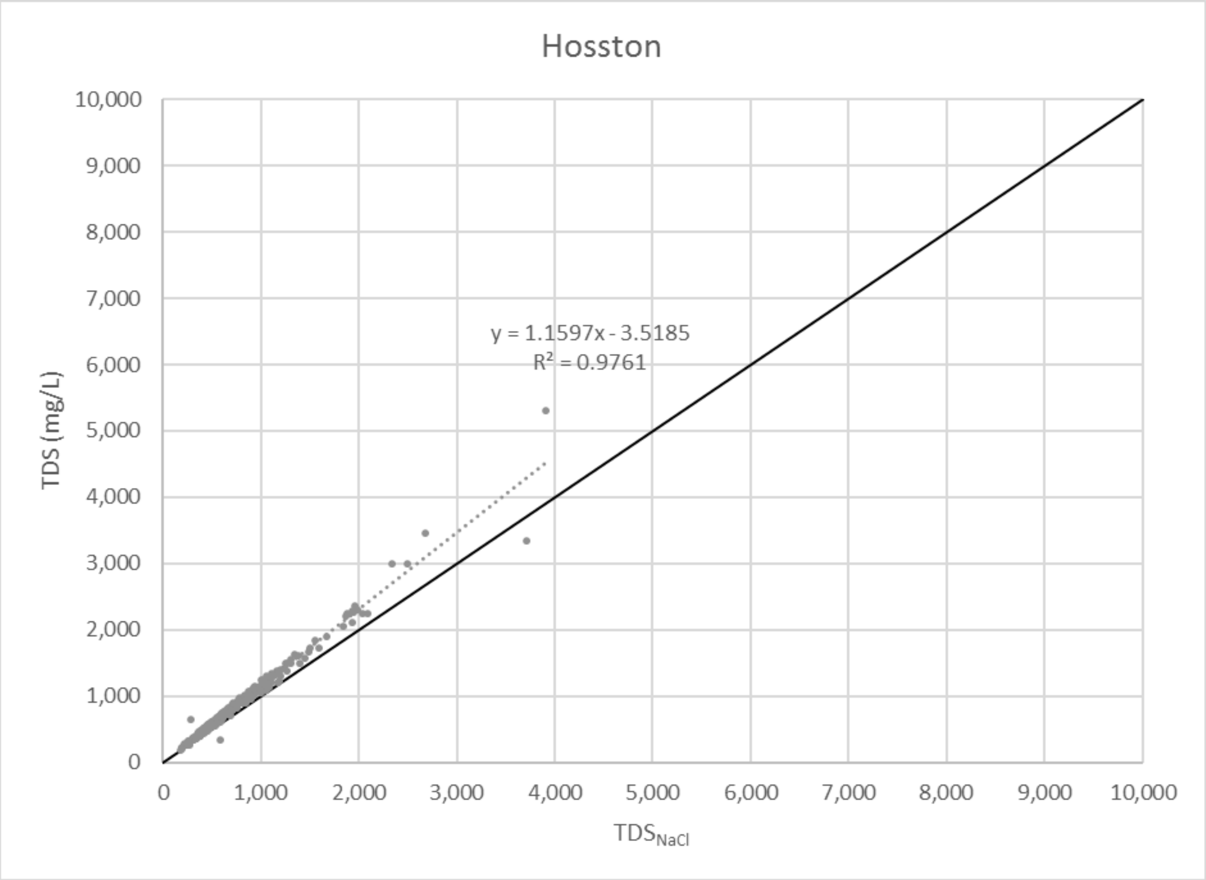

Figure 13-18 **Sampled total dissolved solids (TDS) in milligrams per liter (mg/L) plotted against sodium chloride equivalent total dissolved solids in milligrams per liter (mg/L) for the Hosston Formation. Solid line indicating 1:1 relationship is shown for comparison.**

The TDS–TDS$_{NaCl}$ equations for the four hydrostratigraphic units modeled for the Hill Country Trinity Aquifer are listed in Equations 13-17 through 13-20 below. Data and regression are shown in Figures 13-19 through 13-22.

$TDS_{Glen\ Rose} = 1.334 \times (TDS_{NaCl\ Glen\ Rose}) - 84.392$ Equation 13-17

$TDS_{Hensell} = 1.2942 \times (TDS_{NaCl\ Hensell}) - 83.24$ Equation 13-18

$TDS_{Cow\ Creek} = 1.3195 \times (TDS_{NaCl\ Cow\ Creek}) - 81.251$ Equation 13-19

$TDS_{Hosston} = 1.1434 \times (TDS_{NaCl\ Hosston}) + 10.494$ Equation 13-20

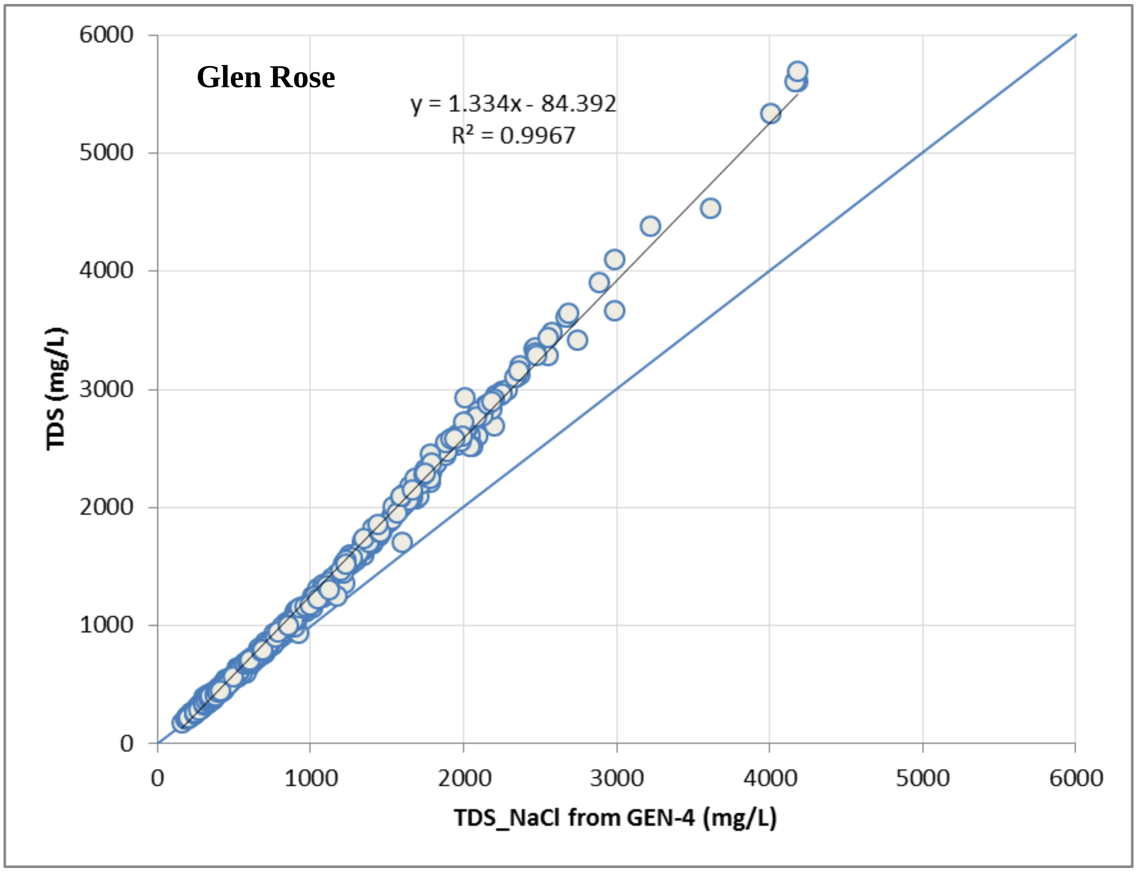

Figure 13-19 Sampled total dissolved solids (TDS) in milligrams per liter (mg/L) plotted against sodium chloride equivalent total dissolved solids in milligrams per liter (mg/L) for the Hill Country Glen Rose unit. Blue line indicating 1:1 relationship is shown for comparison.

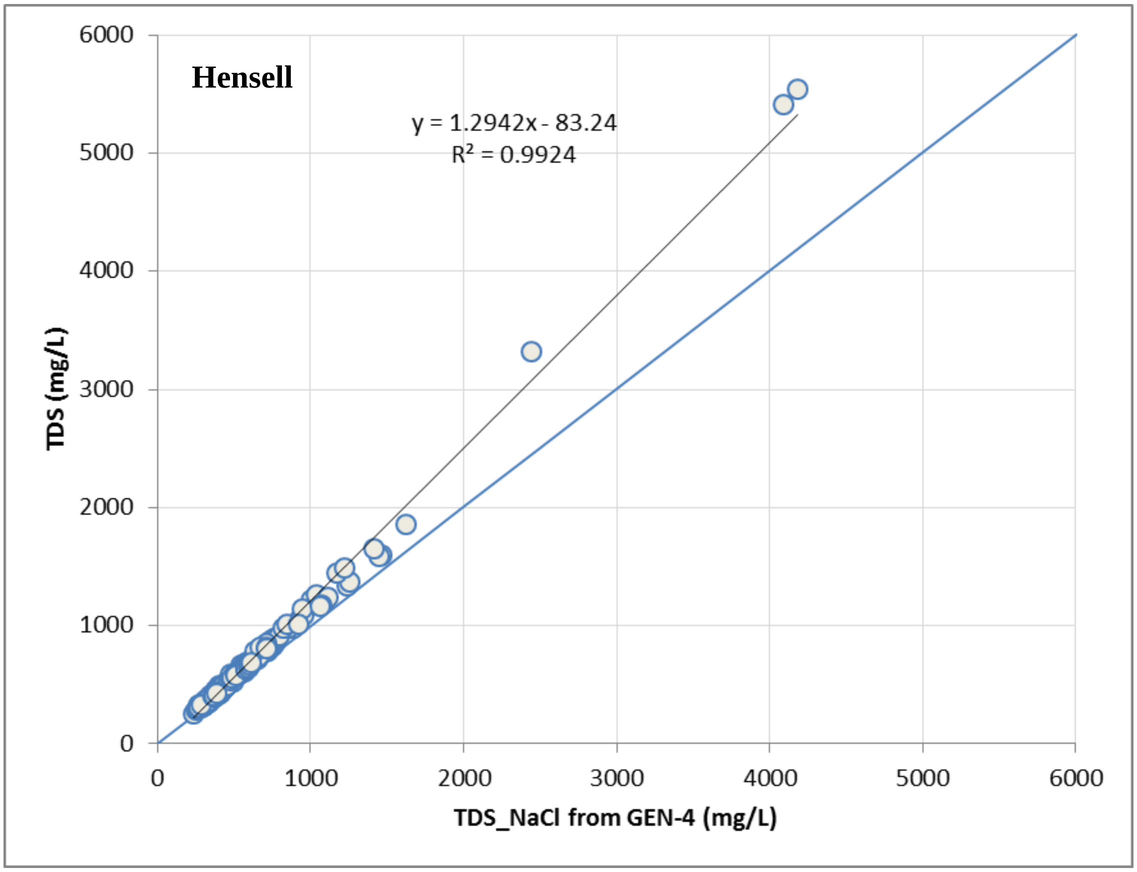

Figure 13-20 Sampled total dissolved solids (TDS) in milligrams per liter (mg/L) plotted against sodium chloride equivalent total dissolved solids in milligrams per liter (mg/L) for the Hill Country Hensell unit. Blue line indicating 1:1 relationship is shown for comparison.

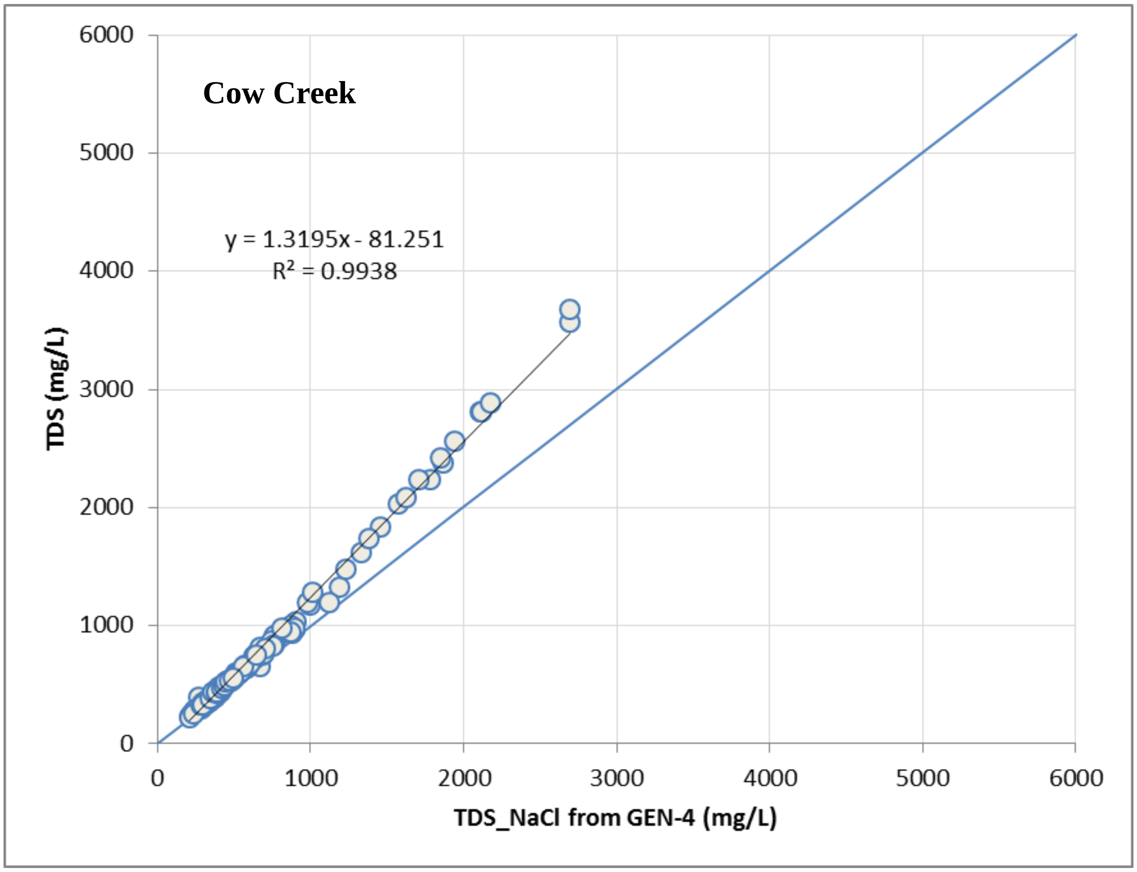

Figure 13-21 Sampled total dissolved solids (TDS) in milligrams per liter (mg/L) plotted against sodium chloride equivalent total dissolved solids in milligrams per liter (mg/L) for the Hill Country Cow Creek unit. Blue line indicating 1:1 relationship is shown for comparison.

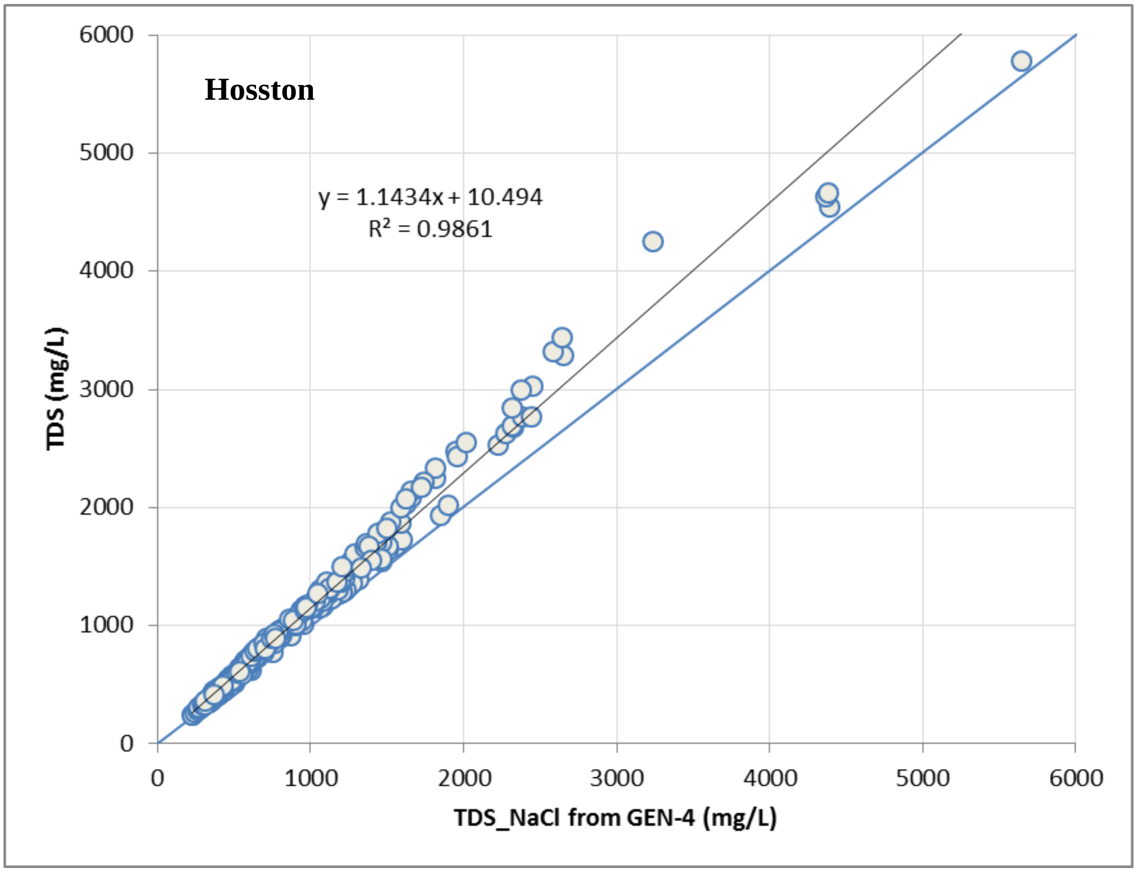

Figure 13-22 **Sampled total dissolved solids (TDS) in milligrams per liter (mg/L) plotted against sodium chloride equivalent total dissolved solids in milligrams per liter (mg/L) for the Hill Country Hosston unit. Blue line indicating 1:1 relationship is shown for comparison.**

13.6.2 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 13-21) and the formation temperature (Equation 13-22). Calculation of mud-temperature at formation depth:

$$T_m(z) = T(z_1) + \frac{T(z_2)-T(z_1)}{z_2-z_1}(z-z_1) \qquad \text{Equation 13-21}$$

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

The calculated $T_m(z)$ value is used in the correction of R_{mf} in Equation 13-10.

Calculation of formation temperature at depth (T_z) using values from the PRISM Climate Group's 30-year Normal Mean Annual Temperature Map (1981–2010) and bottom-hole temperatures:

$$T(z) = T(z_1) + \frac{T(z_2) - T(z_1)}{z_2 - z_1}(z - z_1) \qquad \text{Equation 13-22}$$

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: temperature of mud filtrate (taken directly from the geophysical log header) and average annual surface temperature (taken from a raster map of PRISM temperature data) (PRISM Climate Group, 2016). For each well location, mean annual surface temperature between 1981 and 2010 were obtained from the PRISM Climate Group (2016) raster dataset. This raster dataset uses the PRISM (Parameter-elevation Relationships on Independent Slopes Model) interpolation method (Daly et al., 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 et al., 2011).

For the mud temperature (Equation 13-21) used to convert the resistivity of mud filtrate at surface temperature to the resistivity of mud filtrate at depth, it was determined that the most representative dataset would be the surface temperature and bottom hole temperature recorded on the log header. There remains considerable question as to whether this dataset is most ideal 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, given standard practices in the oil and gas industry, waiting until the temperature returns to ambient conditions before measuring is uncommon. Therefore, in calculating the mud-temperature gradient, it is assumed that the borehole was continually circulated up to the point that the logging engineer(s) arrived to take the mud-temperature/resistivity measurement and subsequently log the borehole.

For the formation temperature (Equation 13-22), 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 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 et al., 2011)

Calculated TDS_{NaCl} results by formation were plotted for the three separate scenarios (Table 13-5 and Figure 13-23). 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 the TWDB staff and the results of this analysis, it was decided to use Scenario #2 to calculate the formation temperature in Equation 13-22. 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 (Dr. Carlos Torres-Verdin, 2016, personal communication) 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 13-4 Average sodium chloride equivalent total dissolved solids calculated using the resistivity ratio method for the three geothermal gradient scenarios.

Formation	S1	S2	S3	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

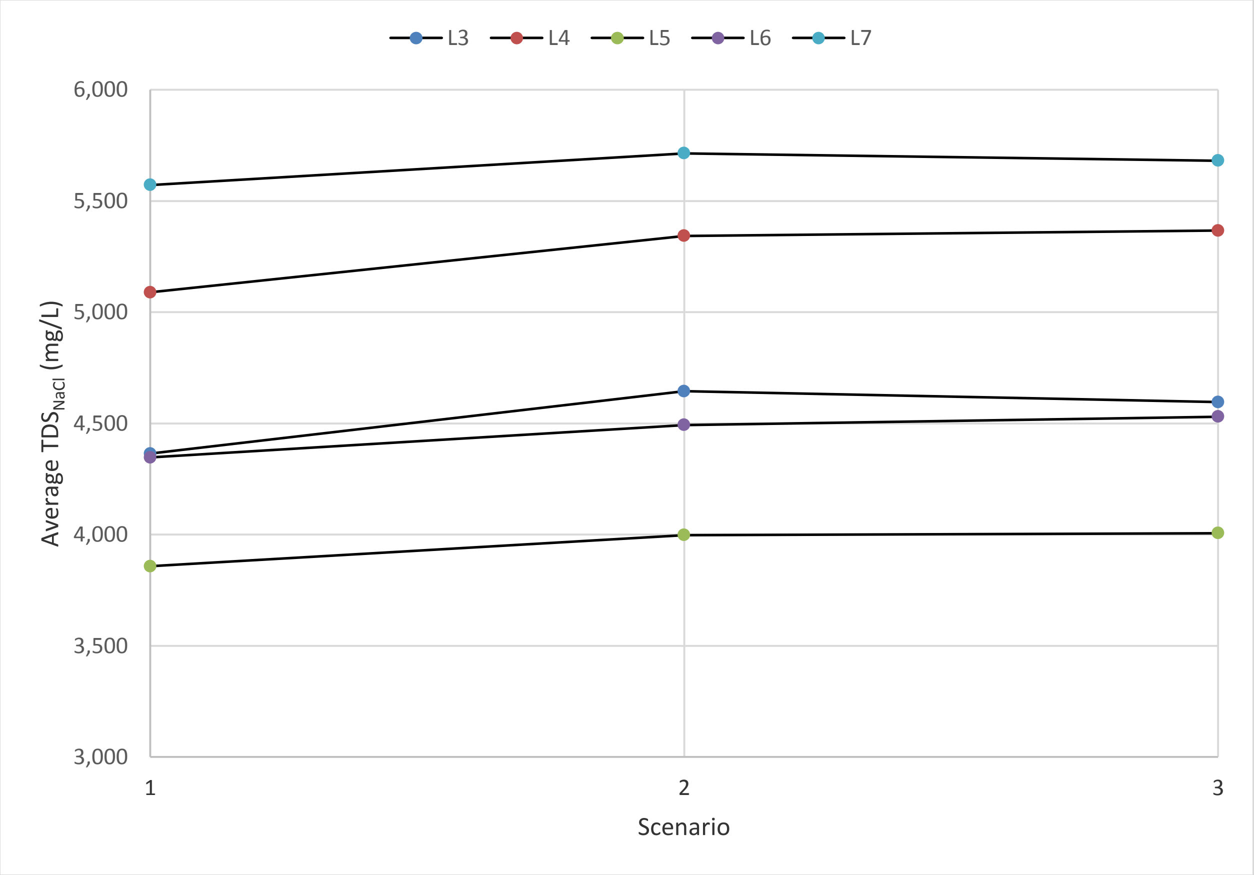

Figure 13-23 **Average sampled total dissolved solids (TDS) in milligrams per liter (mg/L) plotted by calculated geothermal gradient scenario.**

The water quality (TDS) for every sand and limestone unit for the Paluxy, Glen Rose, Hensell, Pearsall, and Hosston formations in the Northern Trinity Aquifer was calculated using this methodology. These calculated water-quality values were averaged by formation and subsequently plotted on maps of the study area along with sampled water quality by formation. All of the data were used to parameterize each unit within the northern portion of the Trinity Aquifer into fresh (0-1,000 mg/L bottom-hole temperature), slightly saline (1,000-3,000 mg/L bottom-hole temperature), moderately saline (3,000-10,000 mg/L bottom-hole temperature), and very saline (>10,000 mg/L bottom-hole temperature).

14 Potential Brackish Groundwater Production Area Analysis and Groundwater Modeling Methodology

14.1 Selection of Potential Production Areas

House Bill 30 provides direction to 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 14-1 defines the criteria set forth in House Bill 30 to be used for designation of brackish groundwater production zones. It is important to note that TWDB officially designates brackish groundwater production zones. This report uses the information presented here and the criteria defined below to define potential production areas that will be considered for designation as brackish groundwater production zones by TWDB.

Table 14-1 House Bill 30 Criteria for designation of potential production areas.

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.

The approach to definition of potential production areas (PPAs) was mostly similar for the Hill Country Trinity Aquifer and the Northern Trinity Aquifer, however, because of hydrogeologic differences between the two regions, there were differences in the approaches. These differences are detailed in the following subsections.

14.1.1 Hill Country Trinity Aquifer

The delineation of Hill Country Potential Production Areas was predominately a process of exclusion based on interpretation of the criteria in H.B. 30. The exclusion zones were established using the process described in the following sections. This exercise was performed via spatial geoprocessing routines included in ESRI ArcGIS version 10.4.

14.1.1.1 Exclusion of Fresh Water Sources

Areas of the Hill Country Trinity Aquifer with fresh water where water quality is less than 1,000 mg/L TDS were excluded from Potential Production Areas. Measured water quality and calculated water quality were used to designate the transition of fresh water to brackish water for the Hill Country Trinity Aquifer as shown in Figure 14.1. The portion of the Hill Country Trinity Aquifer that is updip of this transition is excluded from Potential Production Areas (Figure14.1). It is important to note that there are zones of brackish water within exclusion zones in formations that comprise the Trinity Aquifer. However, these zonesare not hydraulically separated from fresh water production zones. Brackish water in this area is also in production for agriculture.

14.1.1.2 Existing Production Exclusion Zones

Areas where there is production from wells completed in the Trinity Aquifer were excluded from the Potential Production Areas. Production wells were identified using the TWDB groundwater database, the submitted drillers reports (SDR) database, and the TCEQ Public Water Supply (PWS) intake database. A spatial query and metadata query were performed on these databases to limit the analysis to wells that were completed in the Trinity Aquifer. Wells in the SDR database were also limited to wells completed in the Trinity with uses implying production of water. Test borings and environmental boreholes in the SDR database were excluded from the analysis. A three-mile buffer was created around each of the Trinity Aquifer wells used for water production. These buffers were merged to create one continuous exclusion zone across the study domain (Figure 14.2). It should be noted that the majority of wells from the SDR database in the confined portion of the Trinity Aquifer are completed below the Hammett Shale in the Hosston Formation.

14.1.1.3 Political and Administrative Exclusion Zones

There are two administrative exclusion zones as enumerated in H.B. 30 that fall within the Hill Country portion of the Trinity Aquifer: the Barton Springs Edwards Aquifer Conservation District and the Edwards Aquifer Authority Jurisdiction (Figure 14.3). The entire Trinity Aquifer within the Barton Springs Edwards Aquifer Conservation District is excluded from potential brackish water production. Within the Edwards Aquifer Authority jurisdiction, H.B. 30 excludes only the “Area of the Edwards Aquifer”. This exception is interpreted to allow production from formations either under or above the Edwardsaquifer if those formations are hydraulically separated from the Edwards Aquifer. In practice, we removed all Trinity Aquifer units within the footprint of the Edwards Aquifer recharge zone and all formations above the Hammett Shale within the confined portion of the Edwards Aquifer from being categorized as exclusion zones (Figure 14.3).

14.1.1.4 Injection Well Exclusion Zones

Formations that are being used for or considered for waster-water disposal through injection wells, or formations in direct hydraulic communication with these formations, are excluded from the Potential Production Areas (Figure 14.4). There are no injection wells in the Hill Country Portion of the Trinity Aquifer with the exception of Aquifer Storage and Recovery (ASR) wells associated with an ASR project in Kerrville, TX. The Kerrville wells are already located in an existing production exclusion zone. There are several wastewater injection and stimulation injection wells in the Edwards group where TDS values exceed 10,000 mg/L. A 15 mile buffer has been applied to all these locations to create exclusion zones for injection wells.

14.1.1.5 Potential Production Area Delineation

Potential Production Areas in the Trinity Aquifer are determined by the extent of the exclusion zones. Most areas in the Trinity Aquifer with water quality < 3,000 mg/L TDS are excluded from the Production Areas. To determine the Potential Production Areas, the exclusion zones were merged onto one map. Potential Production Areas were then drawn by freehand for areas that were not in exclusion zones. The Upper and Middle Trinity formations were assumed to be in partial hydraulic communication with the Edwards Aquifer. Therefore, the Potential Production Areas were drawn for the Hosston/Sligo units and from the Glen Rose Formation down to the top of the Hammett Shale Formation. Figure 14.5 and 14.6 show the Potential ProductionAreas within the study area split into the Hosston/Sligo formations and the Trinity Aquifer above the Hammett Shale Formation.

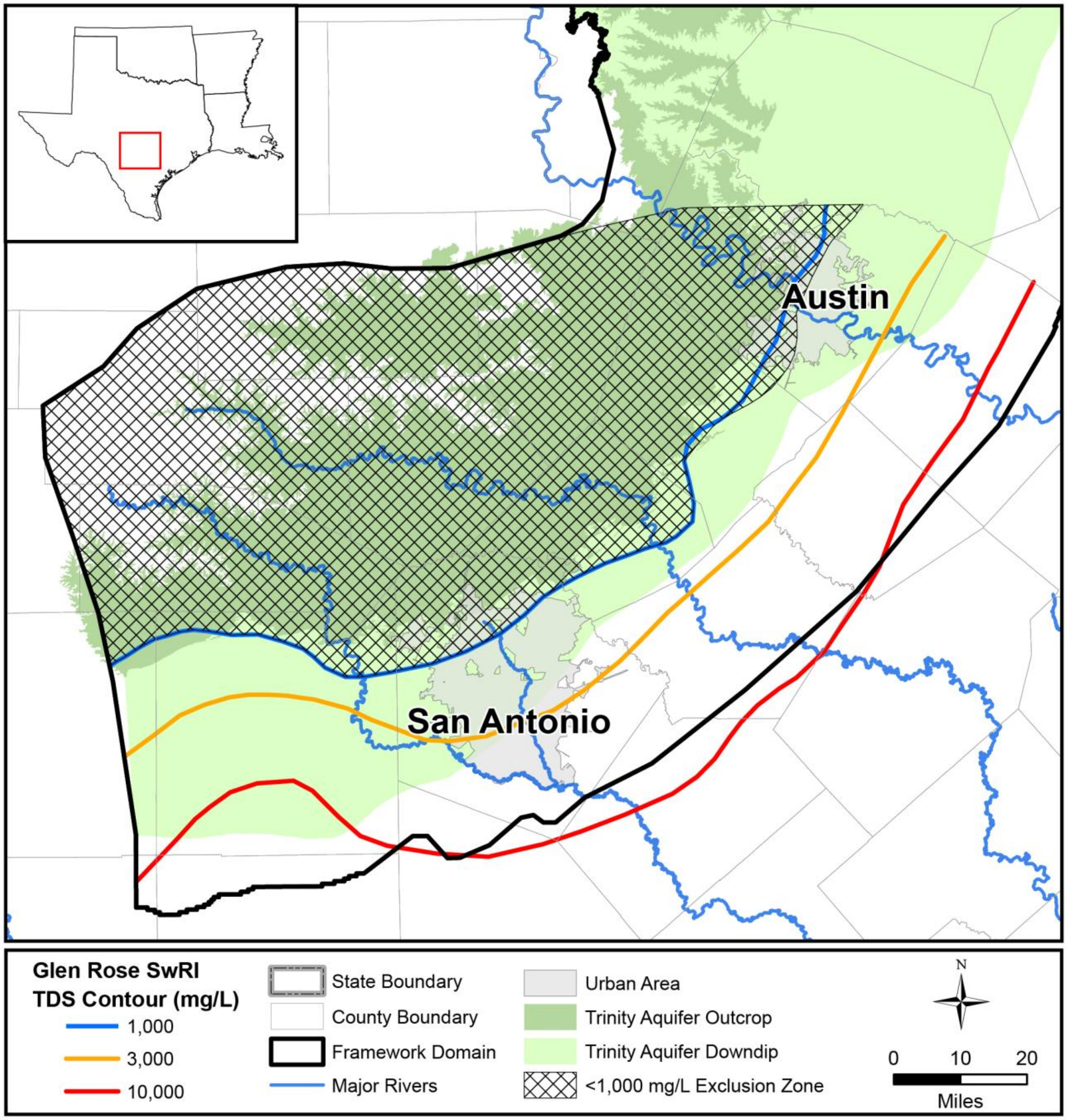

Figure 14-1 Hill Country Trinity Aquifer Potential Production Area area excluded due to fresh water (TDS < 1,000 mg/L)

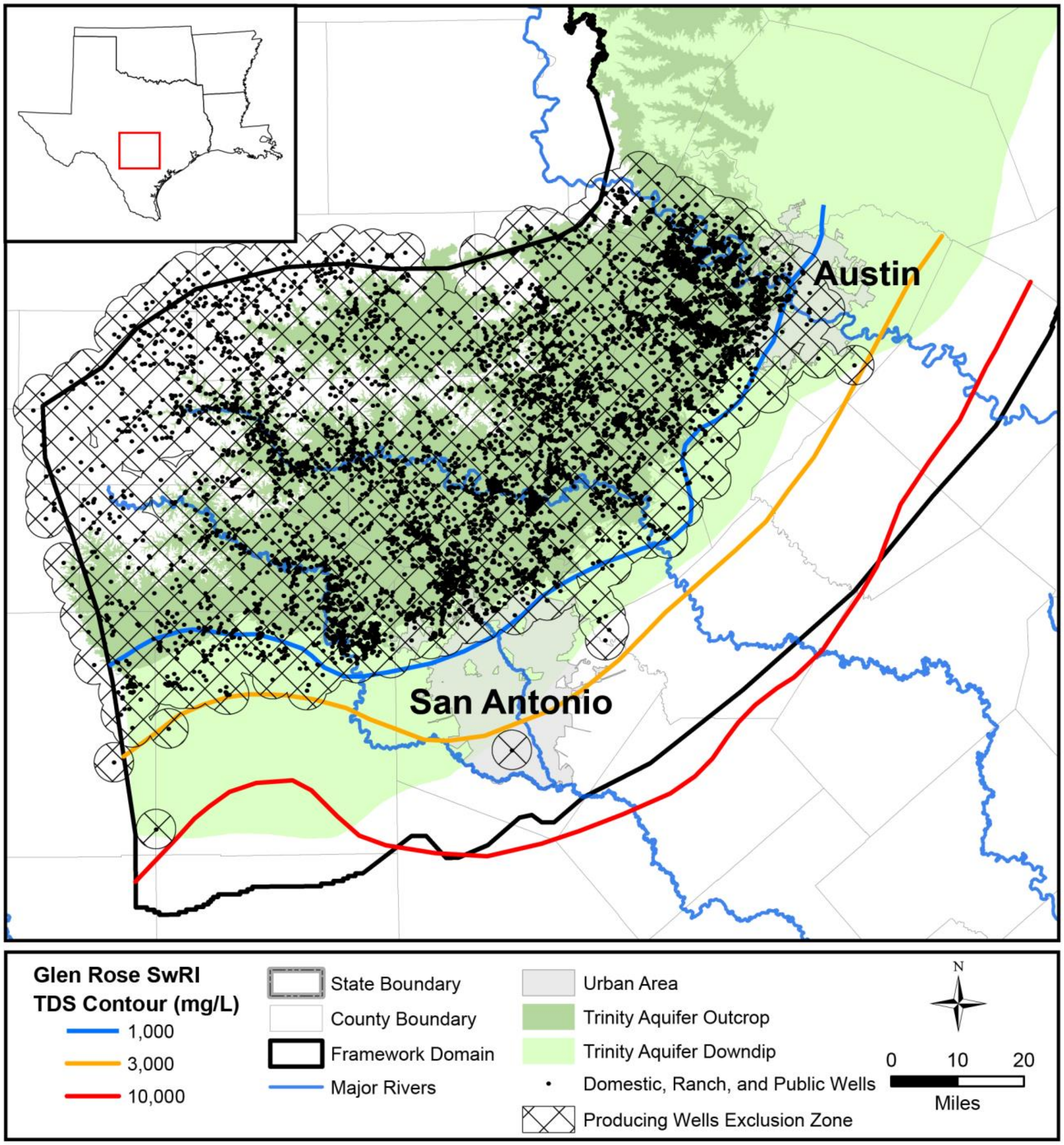

Figure 14-2 Hill Country Trinity Aquifer Potential Production Area zone excluded due to existing production wells.

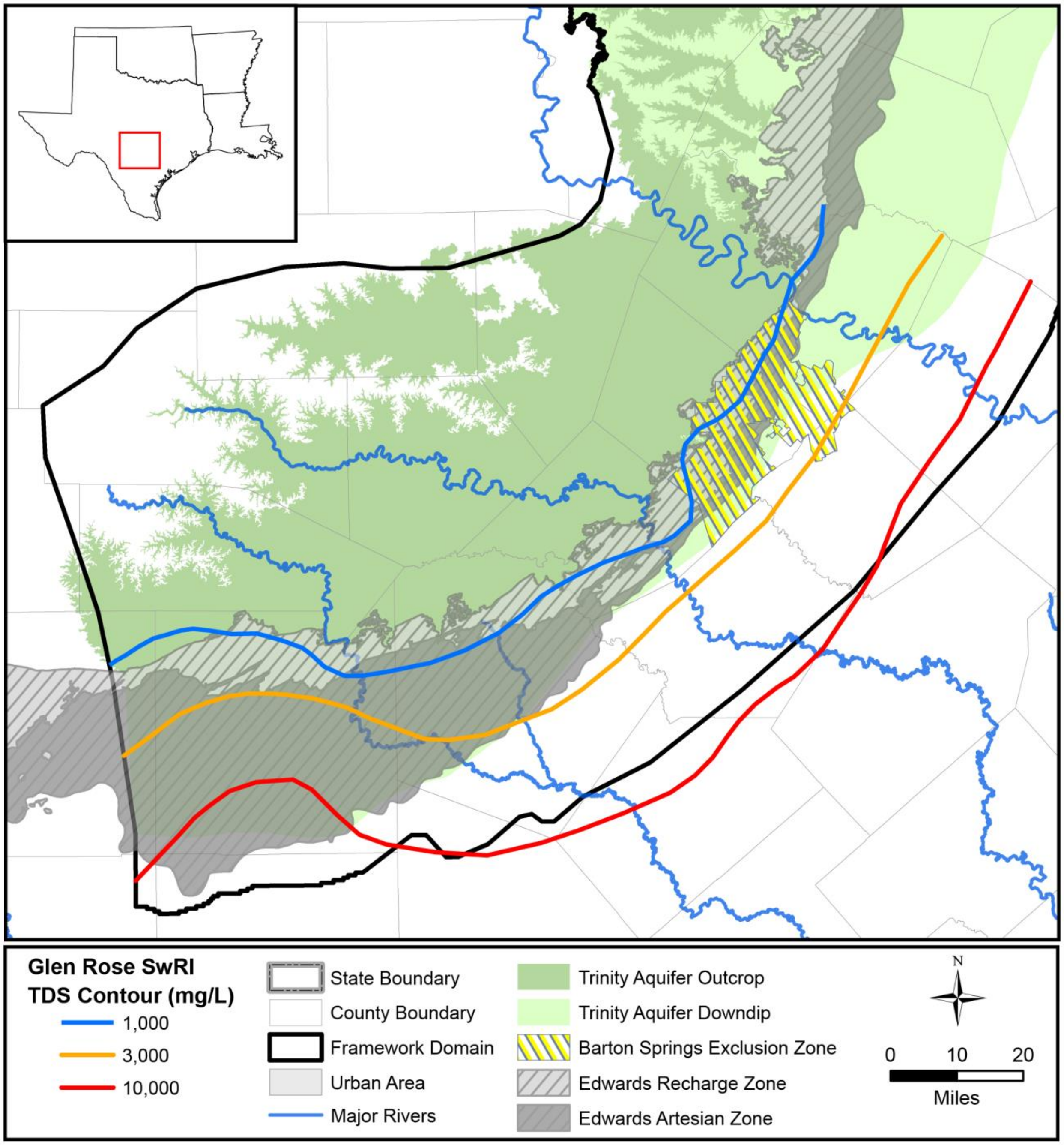

Figure 14-3 **Hill Country Trinity Aquifer Potential Production Area area excluded due to administrative boundary exclusion zones.**

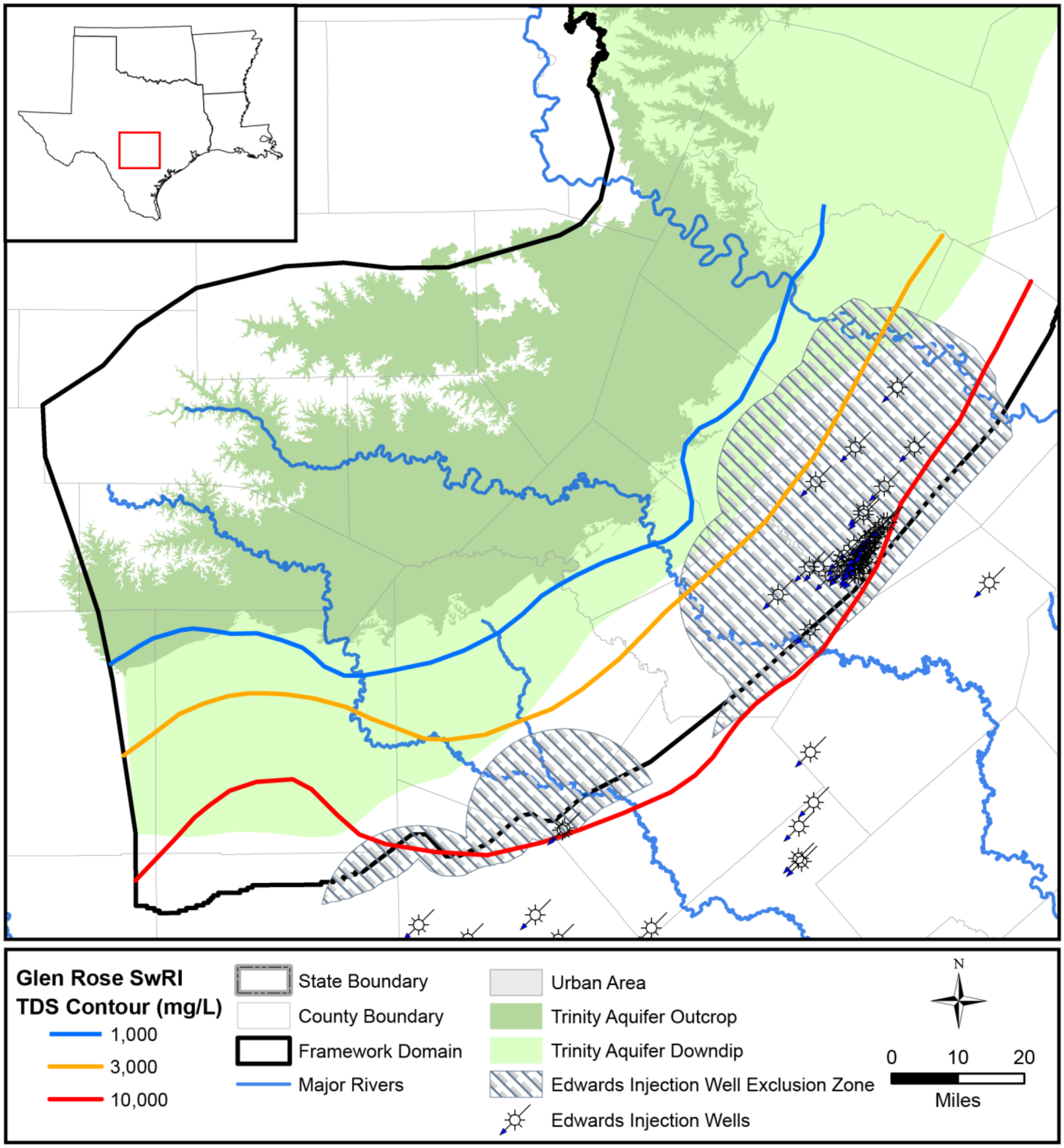

Figure 14-4 **Hill Country Trinity Aquifer Potential Production Area areas excluded due to injection well exclusion zones.**

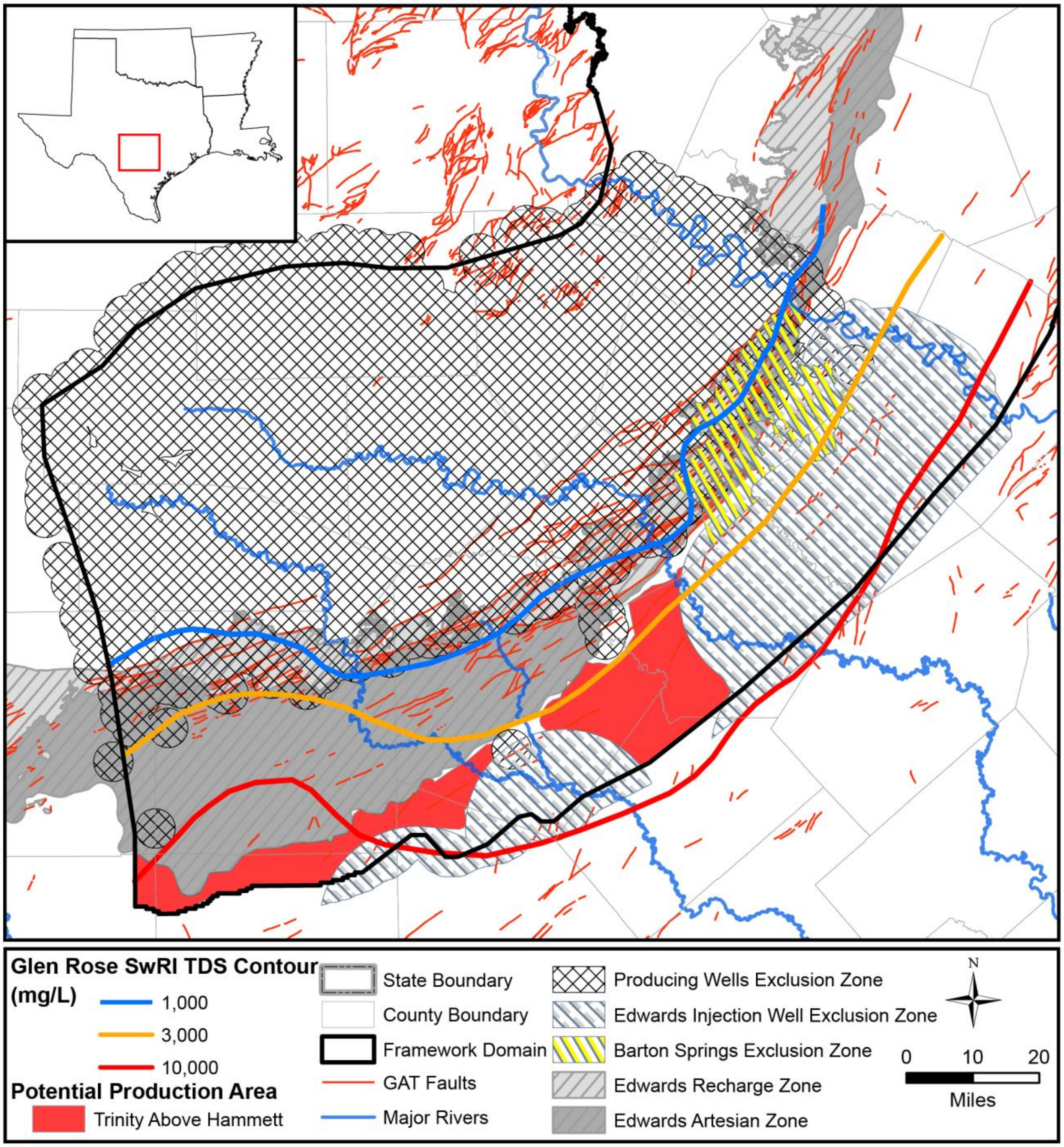

Figure 14-5 **Hill Country Trinity Aquifer Potential Production Areas for the middle and upper Trinity.**

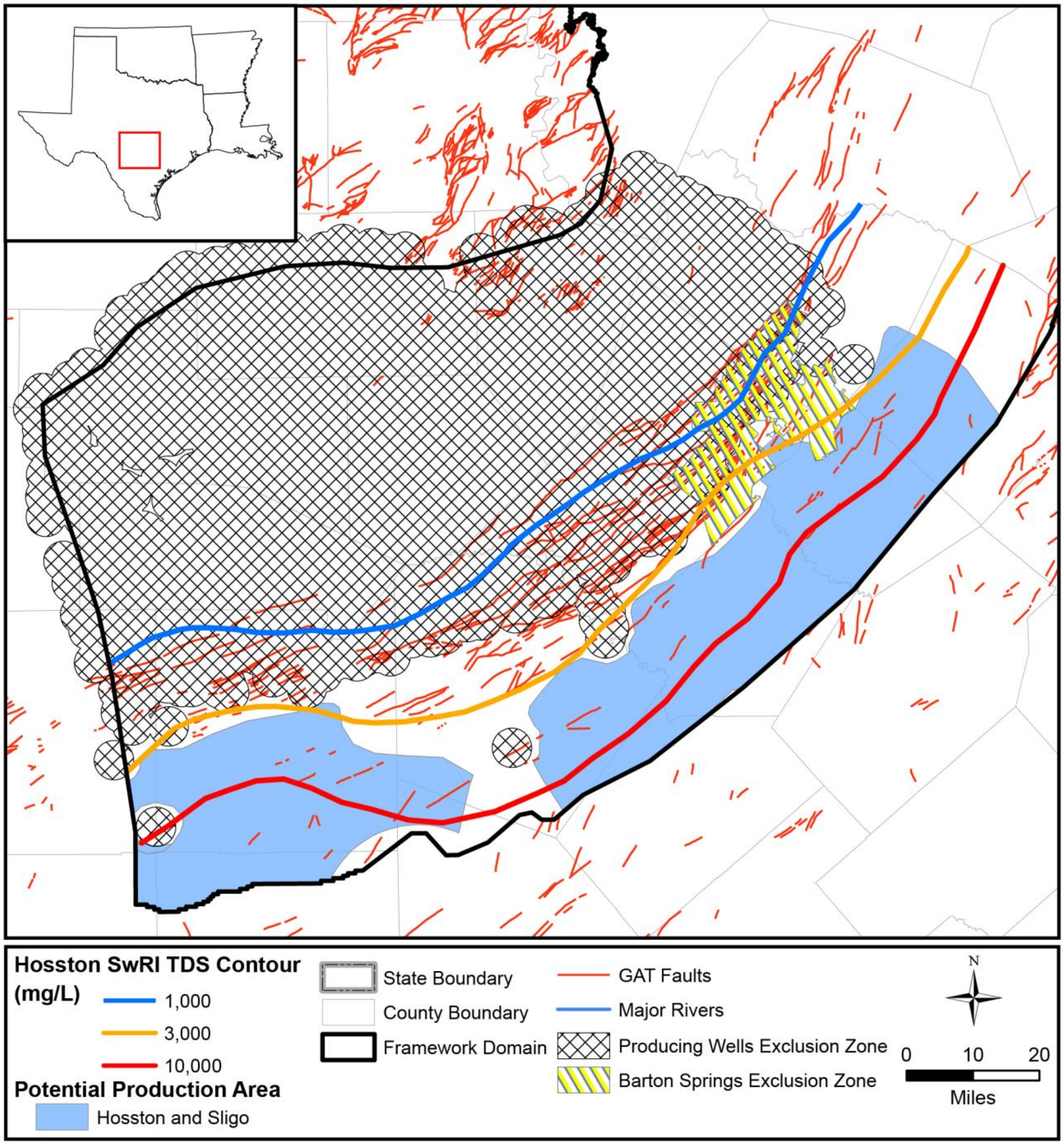

Figure 14-6 **Hill Country Trinity Aquifer Potential Production Areas for the Hosston and Sligo formations.**

14.1.2 Northern Trinity

The approach to selection of potential production areas was similar for the Northern Trinity Aquifer as was taken for the Hill Country Trinity Aquifer. In this subsection, we discuss the potential barriers to flow that exist in the Northern Trinity Aquifer, where the productive areas may exist in the brackish portions of the aquifer, and the presence of the exclusion zones previously discussed.

14.1.2.1 Barriers to Flow

The potential barriers to flow in the Northern Trinity Aquifer include both horizontal and vertical barriers. The potential horizontal barriers are primarily faults that occur, mostly along strike, in the downdip portions of the aquifer. The Mexia-Talco fault zone represents a significant barrier to horizontal flow and defines the downdip extent of the study area.

Many of the faults updip of the Mexia-Talco fault zone occur in the brackish areas, as shown in Figures 6-5 through 6-9 which show the locations of the brackish zones for each of the formations that comprise the Northern Trinity Aquifer. However, because the thickness of the units is typically larger than the fault throw, and the faults are not laterally extensive on a regional scale, it cannot be demonstrated that the faults pose significant horizontal resistance to flow (Kelley et al., 2014).

The primary vertical barriers to flow are laterally extensive clays or shales that occur in the formations. None of the formations are considered to be true aquitards, as evidenced by well completions that occur in all of the formations that comprise the Northern Trinity Aquifer. And while some of the formations (i.e. the Pearsall Formation) have a higher percentage of clay content than other, more productive formations, the clays are interbedded with sand and/or limestone. Because these clays and shales cannot be demonstrated to be laterally extensive on a regional basis, they are not considered to be significant barriers to vertical flow, when considering another formation that is directly above or below a formation of interest. For example, while the Paluxy Formation might be considered to be substantially vertically isolated from the Hosston Formation due to the hundreds of feet of interbedded clays that occur between the two formations, the Paluxy Formation would not be considered to be significantly isolated from the Glen Rose Formation that lies directly beneath.

Because no evidence of significant horizontal or vertical isolation exists for the formations that comprise the Northern Trinity Aquifer, the primary constraint on impacts will be the conductivity of the formation in question, and the distance of the pumping centers from the impacted areas. Assessing these impacts is the primary goal of the modeling, which is described in the following section.

14.1.2.2 Aquifer Productivity

As noted in the previous section, production wells exist in all of the formations that make up the Northern Trinity Aquifer. Most of the wells are completed in or near the freshwater portions of the formations, with well density generally decreasing downdip in a given formation. Kelley et al. (2014) conceptualized aquifer hydraulic conductivity as decreasing with depth, so generally decreasing downdip.

Because H.B. 30 asks that Proposed Production Areas be productive, we set a lower conductivity cutoff at 0.1 ft/d. Whether an aquifer is “productive” is somewhat dependent on the needs of the user. A well with a 500 foot open section in a 0.1 ft/d aquifer could produce about 50 gpm with 200 feet of drawdown. This is a relatively small amount of water for the amount of drawdown, so a 0.1 ft/d cutoff could be considered conservative, i.e. including portions of the aquifer that are of lower productivity.

To define areas of formations that were less than 0.1 ft/d, we used the calibrated horizontal hydraulic conductivity from the Northern Trinity and Woodbine Aquifer Groundwater Availability Model (Kelley et al., 2014).

14.1.2.3 Exclusion Zones

The approach to designating exclusion zones was similar to the Hill Country Trinity Aquifer approach. Areas in a formation that were determined to be fresh water were excluded. Because of the lack of vertical barriers to flow described previously, the freshwater areas for formations directly above or directly below a formation were also excluded. For example, for the Hensell Formation, the freshwater portion of the Glen Rose Formation was projected downward into the Hensell Formation as an exclusion zone, while the freshwater section of the Pearsall Formation was projected upward as an exclusion zone in the Hensell Formation.

Injection wells (with screen completions in the formation of interest) were buffered with a radius of 30 miles. Existing water wells were assigned a buffer radius of 3 miles. Many of the existing water wells that were part of the study dataset did have construction information and water wells in the Northern Trinity Aquifer are commonly completed across multiple formations. For this reason, if a well had a total depth that was in or below a formation, we considered that well to be completed in that formation. The result of this is that shallower formations had more water-well buffers than deeper formations.

14.1.2.4 Potential Production Areas

The potential production areas defined for the Northern Trinity Aquifer are shown in Figures 14.7 – 14.11, for the Paluxy, Glen Rose, Hensell, Pearsall, and Hosston formations, respectively. The Potential Production Areas are labeled using a two-letter prefix that represents the formation, and then numbered sequentially for each formation starting in the northeast, and moving along strike to the southwest.

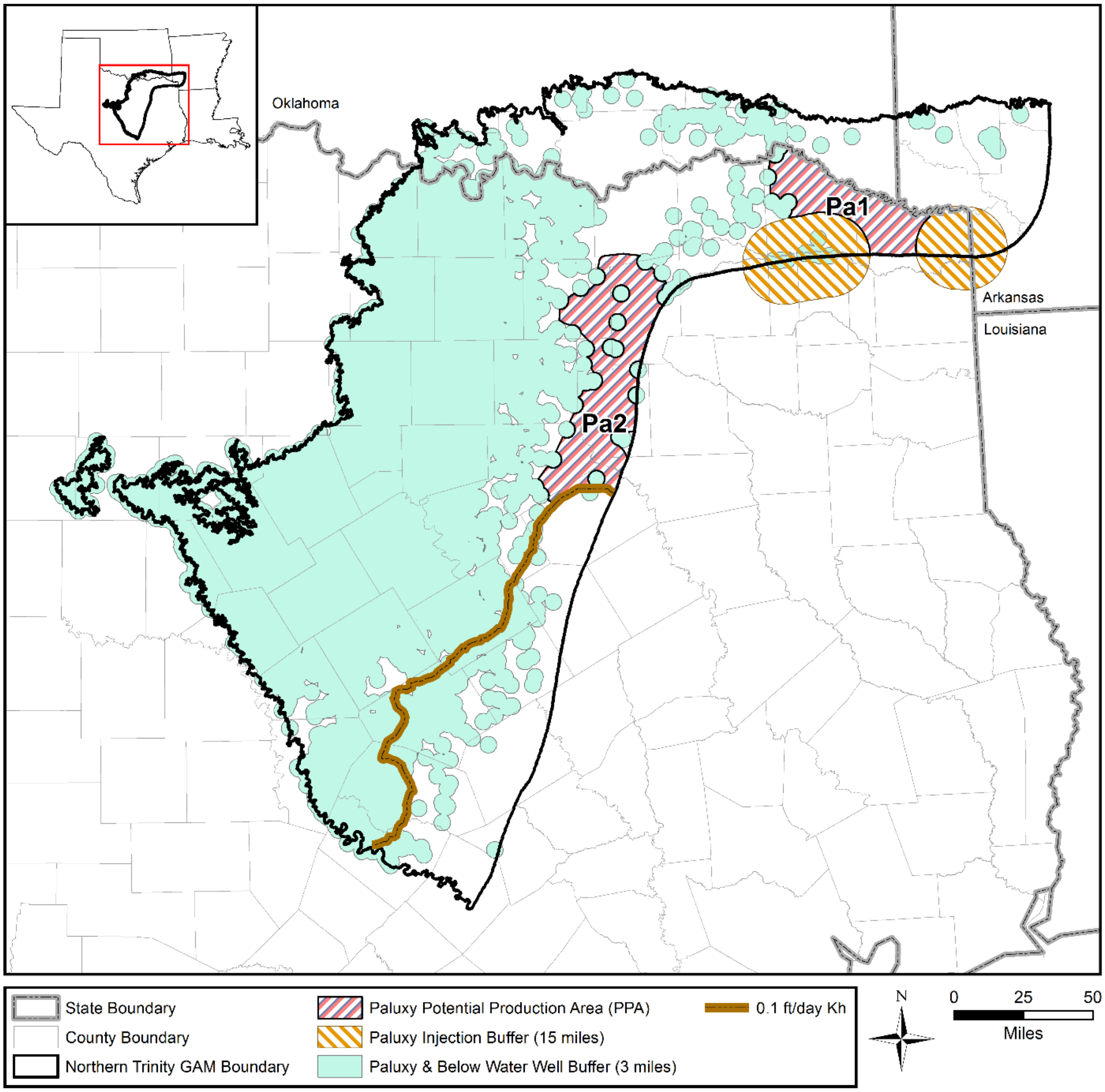

Figure 14-7 **Northern Trinity Potential Production Areas in the Paluxy Formation**

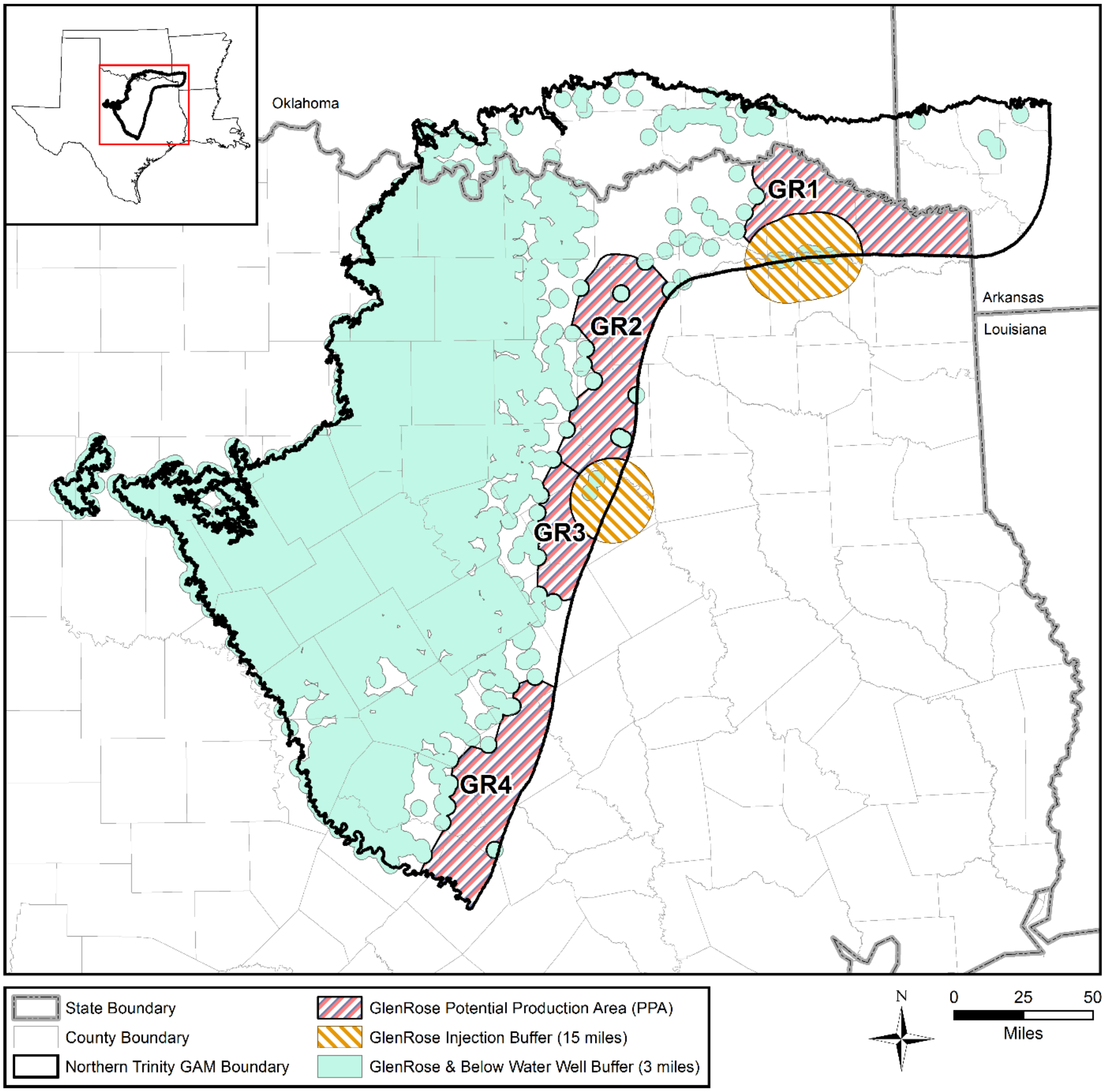

Figure 14-8 Northern Trinity Potential Production Areas in the Glen Rose Formation

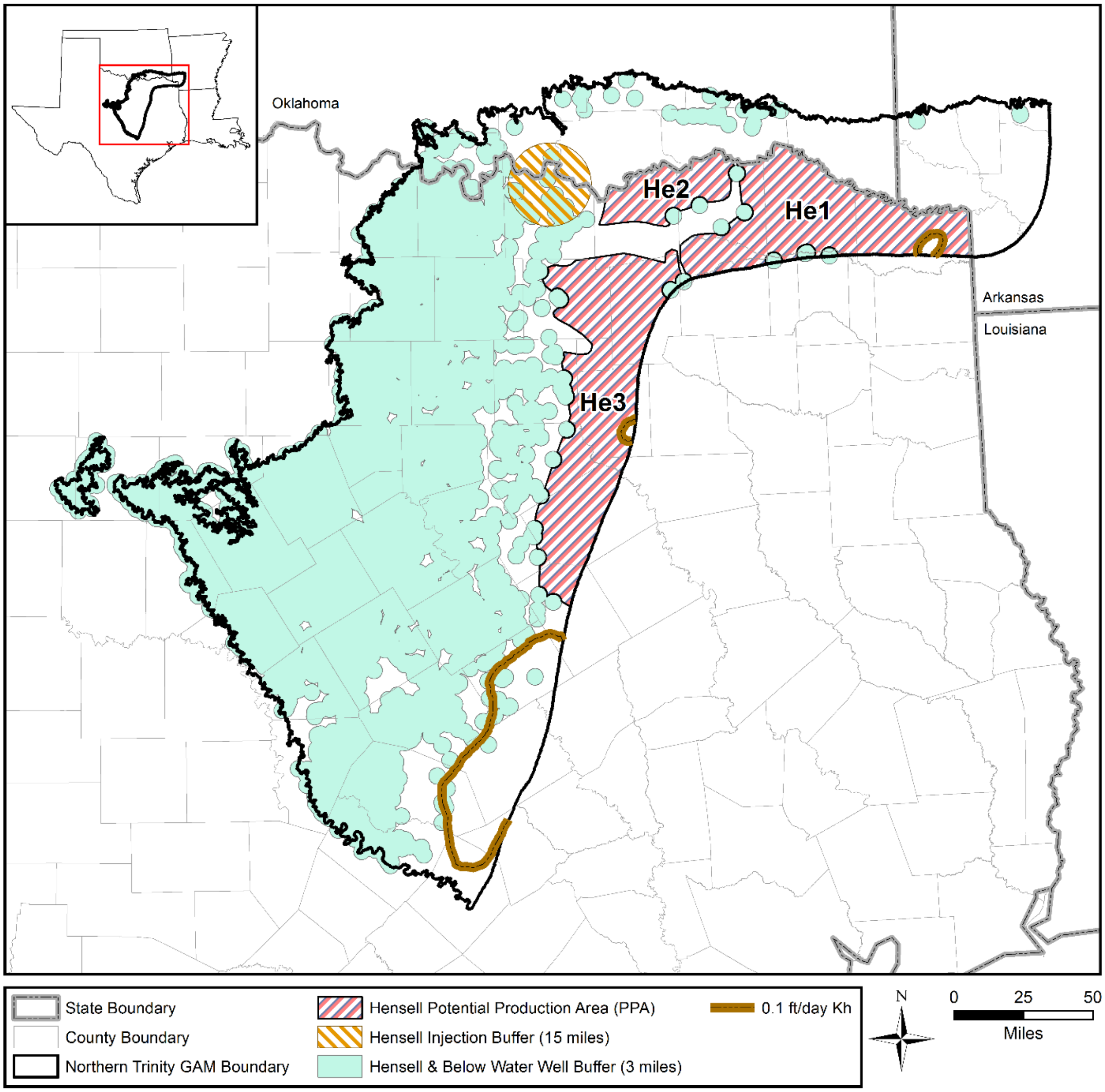

Figure 14-9 **Northern Trinity Potential Production Areas in the Hensell Formation**

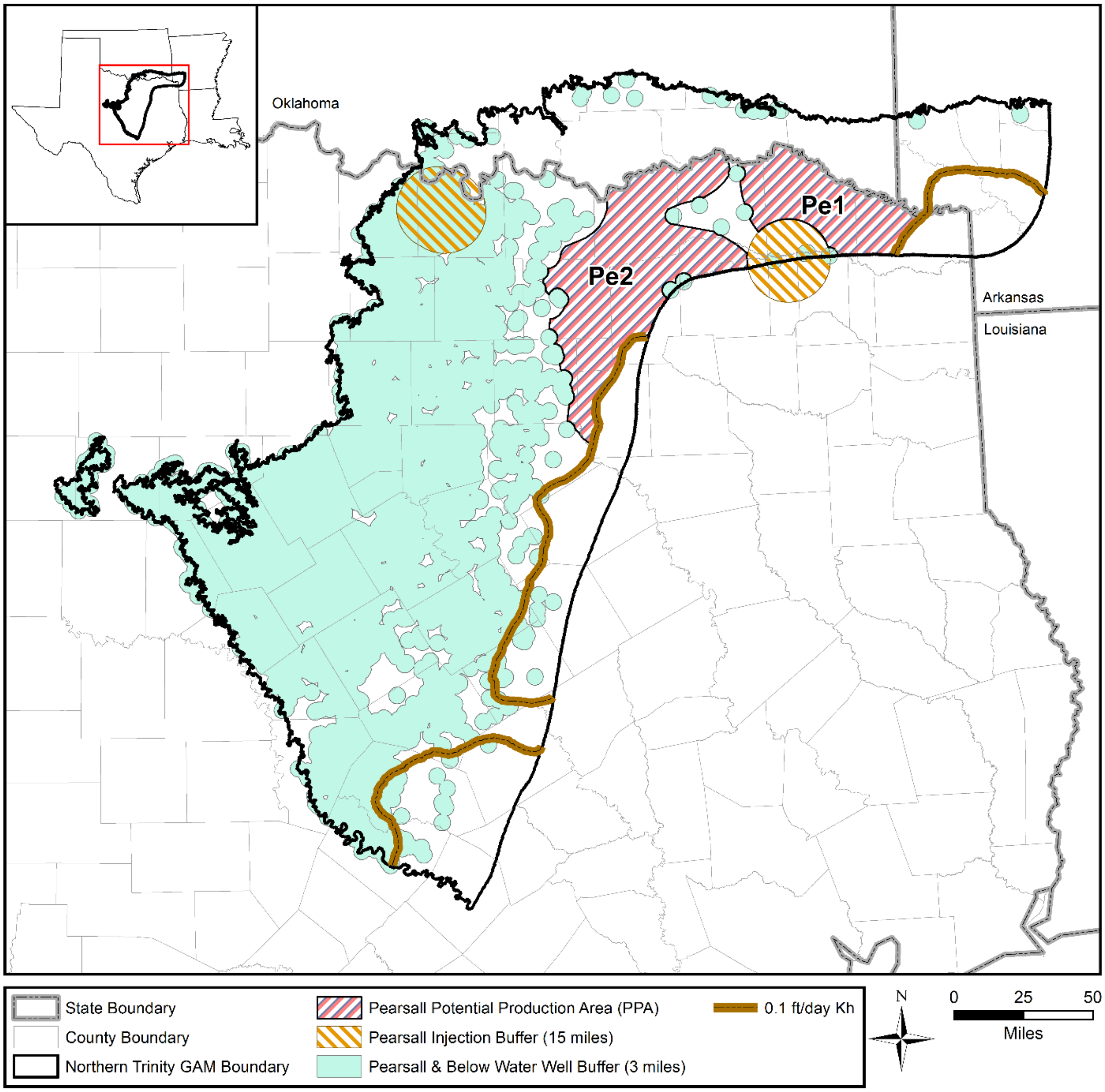

Figure 14-10 Northern Trinity Potential Production Areas in the Pearsall Formation

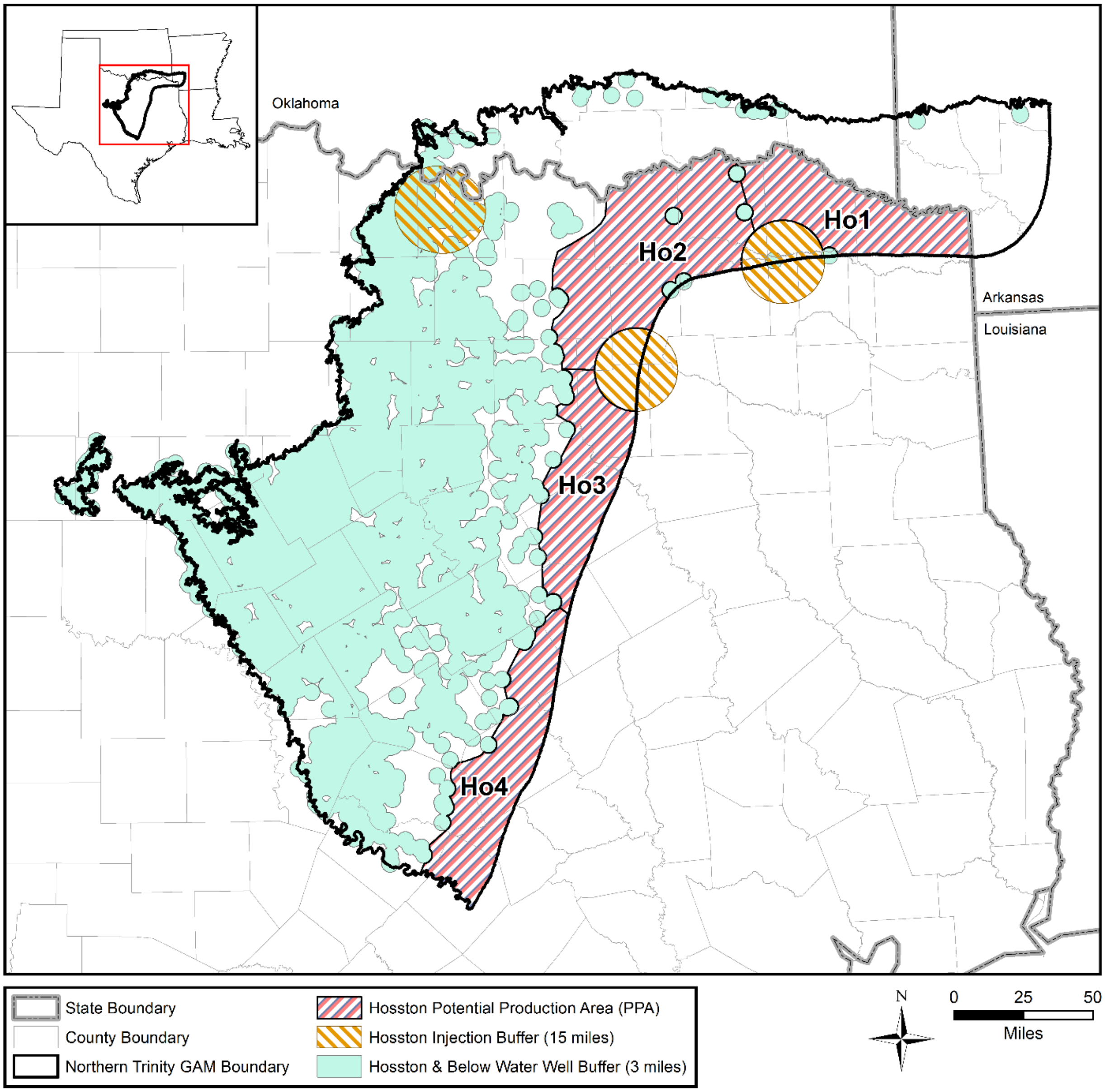

Figure 14-11 Northern Trinity Potential Production Areas in the Hosston Formation

14.2 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 is capable of producing over 30-year and 50-year periods without causing significant impacts to fresh water availability. The modeling approach is based upon four primary features: (i) the modeling tool used; (ii) the well field assumptions; (iii) the metrics used to assess drawdown; and (iv) the metrics used to assess change in water quality. Due to the different modeling approaches that were taken for the Hill Country and Northern Trinity portions of the aquifer, the approaches are discussed in separate subsections, starting with the Hill Country Trinity Aquifer

14.2.1 Hill Country Trinity Aquifer Modeling Approach

14.2.1.1 Modeling Tool Used

The Hill Country portion of the Trinity Aquifer GAM (Jones et al., 2011) is the primary state-accepted tool for assessing groundwater availability in the Hill Country Trinity Aquifer. Unfortunately, this model only covers the freshwater portion of the Hill Country Trinity Aquifer. It is not an appropriate tool for assessing the availability of brackish water since the brackish portion of the aquifer falls outside of the model domain. The time and resources available for this project did not allow for an extension to the existing GAM. To overcome these limitations, simple three-dimensional models were created for three cross sections in the Hill Country Trinity Aquifer study domain. Locations of the three cross sections are shown in Figure 14.12. Stratigraphic sections were created for each of the locations. The stratigraphy was then extruded 50 miles on each side of the cross section using MODFLOW-USG (Panday and Others, 2013), creating simplified three-dimensional model grids. The models were constructed with a 1 mile-by-1 mile grid resolution (Figure 14.13). Model layering was based on the hydrostratigraphy from the Hill Country Trinity Aquifer GAM (Jones et al., 2011). Parameter values were selected from the low range of calibrated parameters used in the Hill Country Trinity Aquifer GAM. Parameter values used in the section models are presented in Table 14.2. For each model, a constant head boundary was applied to the up-dip boundary of the section. A general head boundary was applied to the downdip boundary. This boundary represented the head projected 25 miles farther downdip than the downdip boundary. Boundary values were selected from hydraulic head values extracted from composite water level data extracted from the TWDB groundwater database. In downdip areas where no data are present, well data from more shallow zones are used. Hydrostatic conditions are assumed at the boundaries. Each model was run until steady state conditions were achieved to establish initial head conditions. The ensuing transient model simulations resulted in non-hydrostatic conditions.

14.2.1.2 Wellfield Assumptions

One pumping well was desigated for each wellfield located in each Potential Production Area. Well locations were chosen by inspection, since the shape of the PPAs were not sufficiently regular to allow for a distance or area-based location strategy. In general, each pumping well was locally centered with respect to the updip and downdip boundaries of a Potential Production Area. A single well configuration was designated in the model. Well locations for each simulation are shown in Figures 14.14 – 14.17. Although Potential Production Areas were defined for each formation, wellfields were screened in multiple formations consistent with the hydrostratigraphy of the Hill Country Trinity Aquifer GAM.

A separate simulation was performed for each Potential Production Area and only one well was active in any simulation. Production rates were varied based on the relative productivity of the formation at each well location. These rates were estimated by trial and error by running the model in increasing multiples of 750 afy of pumping until over 400 ft of maximum drawdown was obtained or a maximum rate of 9,000 afy was reached. In this way, the pumping rates for wellfields in areas with higher conductivity were comparatively higher.

Production rates estimated from the trial simulations resulted in average well drawdowns ranging from approximately 100 to 570 feet, depending on the conductivity of the formation. Two additional simulations with 25% and 50% of these rates were also performed. The 25% simulation is referred to as the “low” case, the 50% simulation is refered to as the “medium” case, and the 100% simulation is referred to as the “high” case.

14.2.1.3 Drawdown Metrics

Drawdown impacts were assessed by subtracting a “with brackish wellfield” simulated head from the “steady-state” simulated head. Maximum drawdowns were tabulated for the overall grid (maximum drawdown at the well itself), at the fresh water/brackish-water transition (the line defining an estimated 1,000 mg/L total dissolved solids), and the overlying fresh Edwards Aquifer.

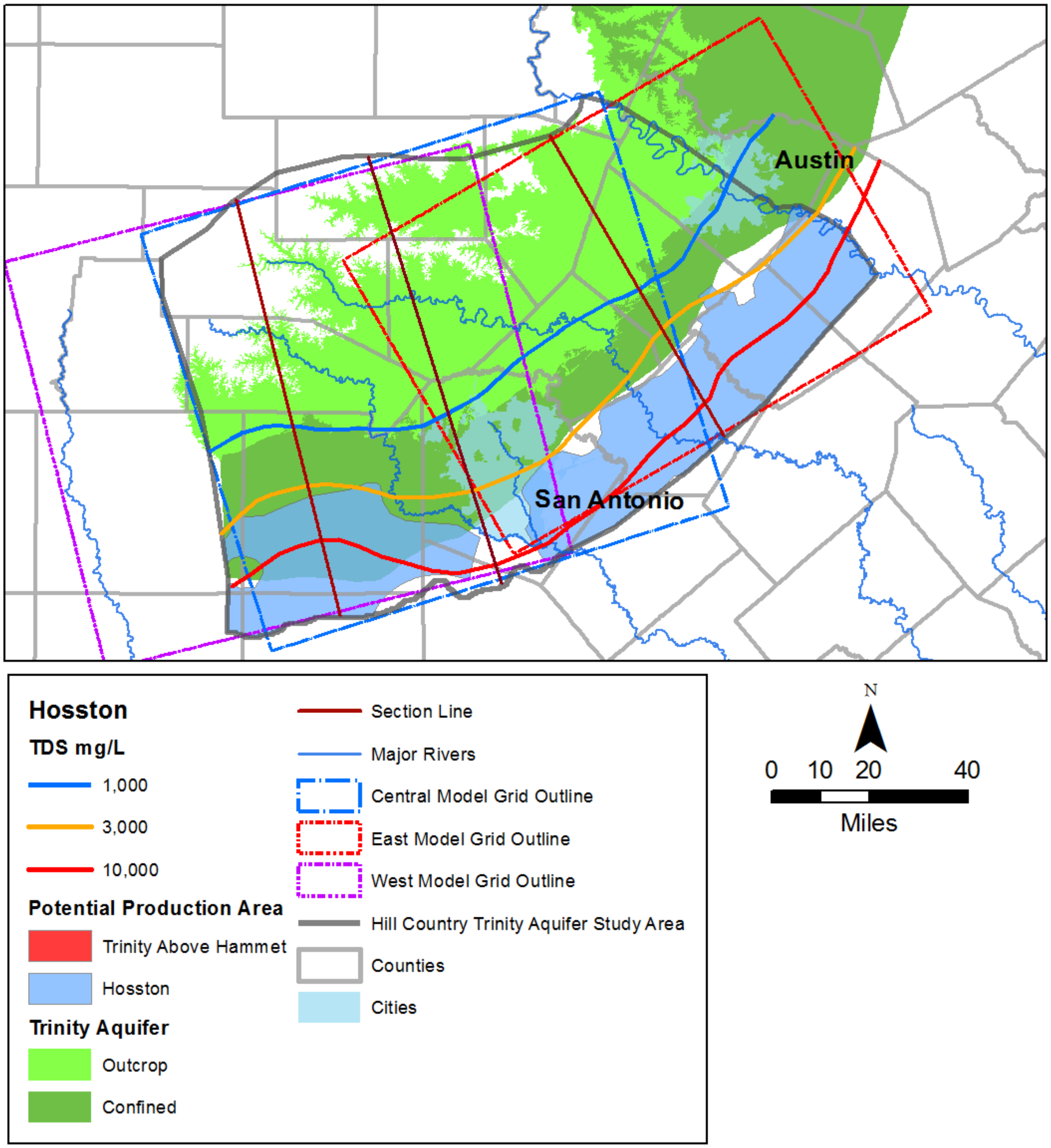

Figure 14-12 Locations of the sections selected for modeling Potential Production Areas of brackish water from the Trinity Aquifer. Outlines for each extruded section model are illustrated with dashed lines.

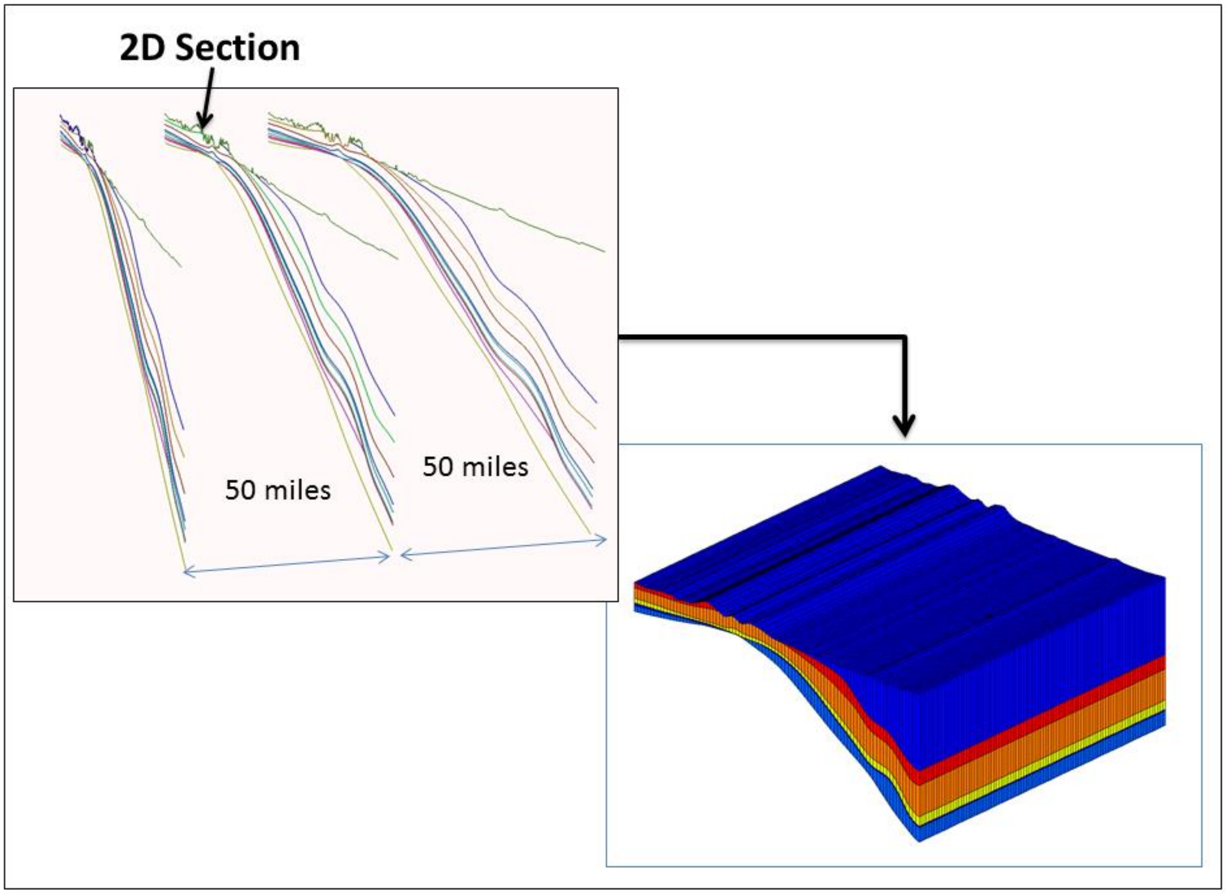

Figure 14-13 **Diagram of the three-dimensional extruded model construction process.**

14.2.2 Northern Trinity Aquifer Modeling Approach

14.2.2.1 Modeling Tool Used

The Northern Trinity and Woodbine Aquifer Groundwater Availability Model (Kelly et al., 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 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 Formation 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 (LBG Guyton, 2016) that had been created to support the adoption of desired future conditions in GMA-8 for the 2016 round of state-wide planning. This predictive simulation was called “Run 10” and contained estimates of future pumping supplied by the 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.

14.2.2.2 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 one 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, as shown in Figure 14.18 Given the potential costs of very deep brackish wells, we reasoned that the decrease in per-well productivity would not be favorable to potential users, so we chose the single well configuration to perform the final modeling. The locations of the wells for each simulation are shown in Figures 14.19 – 14.37 Because Potential Production Area were defined for each formation, wellfields were isolated to a single formation, 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 formation at each wellfield location. These rates were estimated by placing drains (MODFLOW DRN package) at the potential well locations and setting the drain elevation at 500 feet below the initial head in the formation at that location. The drains conductances were set to 10,000 ft^2/d. 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. 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 formation and interference from “existing” pumping (the pumping that was in the baseline Run 10 simulation). Two additional simulations with 25% and 50% of these rates were also performed. The 25% simulation was referred to as the “low” case, the 50% simulation was referred to as the “medium” case, and the 100% simulation was referred to as the “high” case.

14.2.2.3 Drawdown Metrics

Drawdown impacts were assessed by subtracting a “with brackish wellfield” simulated head from the “baseline” (Run 10) simulated head. Maximum drawdowns were tabulated for the overall grid (maximum drawdown at the wellfield itself), at the nearest existing well, and at the fresh water/brackish -water transition (defined as 1,000 mg/L total dissolved solids).

14.2.2.4 Change in Water Quality Metric

The potential change in water quality due to a simulated wellfield was assessed using particle tracking. Particles were placed in every grid cell that intersected the fresh water/brackish-water transition, at three vertical locations within the cell. Particles were tracked in the forward direction. The distance traveled by the particles were compared between the baseline simulation (Run 10) and each “with wellfield” simulation, for the “high” pumping case. Particle distances were assessed after 50 years of travel time.

14.3 Potential Production Area Pumping Analysis and Results for 30 and 50 Year Periods

The series of predictive simulations for the scenarios described above were performed to evaluate the potential of the Potential Production Areas to serve as water sources within the Trinity Aquifer. The results are presented separate for the two regions, first for the Hill Country Trinity Aquifer and second for the Northern Trinity Aquifer.

14.3.1 Simulated Results for the Hill Country Trinity Aquifer

14.3.1.1 Drawdown Impacts

Figures 14.14 – 14.17 show the simulated drawdown compared to the basecase at each wellfield after 30 and 50 years of production. Tables 14.3 and 14.4 summarize the drawdown results of the simulations for each wellfield after 30 and 50 years of production. Maximum drawdowns in both the unit being pumped (occurring at the production well), and in the overlying freshwater Edwards Aquifer are reported at the transition from fresh water to brackish water. Simulated maximum drawdown at the production well is the value averaged over the mile square grid cell, so actual drawdown at a well would be higher than the simulated value.

Maximum drawdown and production rate varies by well, depending on the productivity of the formation. Maximum drawdown at 50 years (for the “high” production case) for all units ranges from 118 feet (GLR/HEN/CC Central Well) to 570 feet (Hosston West Well). Total production rate (for the “high” production case) varies from 3,000 afy (Hosston West Well) to 9,000 afy (GLR/HEN/CC Central Well).

Analysis of the relationship between drawdown and production rate at a given well indicates that the relationship is linear. That is, for a given well, the ratio between drawdown and production rate is constant for the low, medium, and high production cases. This is expected for confined aquifers. This linearity allows us to use a limited number of simulations to use this linearity to predict the drawdown for any production rate, without having to complete simulations for each production rate.

14.3.1.2 Change in Water Quality

Changes in water quality of the Potential Production Areas were simulated using the extruded three-dimensional model sections.

Table 14-2 Summary of hydraulic properties assingned to numerial groundwater flow models.

Model Layer	Aquifer	Specific Yield	Specific Storage (per ft)	Hydraulic Conductivity (ft/day)	Confining Bed
1	Overbuden	Inactive			Conductance (0.03ft/d)
2	Edwards Group	0.008	1.0E-05	11.15	
3	Upper Trinity	0.0005	1.0E-06	9	
4	Middle Trinity	0.0008	1.0E-07	8.2	
5	Hammett Shale	0.0008	1.0E-07	0.003	Conductance (0.003ft/d)
6	Lower Trinity/Hosston	0.0008	1.0E-07	1.6	

Table 14-3 Drawdown Metrics 30 years of pumping at potential production areas.

				Pumping Rate (afy)			Max. Drawdown at Fresh Water Line (ft)			Max. Drawdown in Unit (ft)			Max. Drawdown in Edwards Aquifer (ft)		
Formation	**Label**	**Section Line**	**Depth to Unit Top**	**low**	**med.**	**high**	**low**	**med.**	**high**	**low**	**med.**	**high**	**low**	**med.**	**high**
Hosston	Hosston West	West	1148.04	750	1500	3000	0.69	1.40	2.9	142.1	284.8	568.4	2.1	4.3	8.6
Hosston	Hosston Central	Central	937.8	1500	3000	6000	0.82	1.936	3.839	132.5	265	530.5	3.609	7.316	14.87
Glen Rose/ Hennsel/ Cow Creek	GLR/ HEN/ CC Central	Central	751.4	3000	6000	9000	2.198	3.904	5.545	37.57	75.13	112.7	8.53	16.44	26.25
Hosston	Hosston East	East	967.35	750	1500	3000	NA**	NA**	NA**	120.6	241	484.6	1.542	2.854	8.858

**Hosston is not continuous on this section

Table 14-4 Drawdown metrics after pumping Potential Production Areas for 50 yrs.

Formation	Label	Section Line	Depth to Unit Top (ft)	Pumping Rate (afy)	Max Drawdown at Fresh Water Line (ft)	Max Drawdown in Unit (ft)	Max. Drawdown in Edwards Aquifer (ft)
Hosston	Hosston West	West	1,148	3,000	3.8	569.6	9.7
Hosston	Hosston Central	Central	937.8	6,000	5.2	533.1	18.1
Glen Rose/ Hennsel/ Cow Creek	GLR/ HEN/ CC Central	Central	751.4	9,000	19.7	117.5	31.5
Hosston	Hosston East	East	967.35	3,000	NA*	484.2	2.4

*Hosston is not continuous on this section

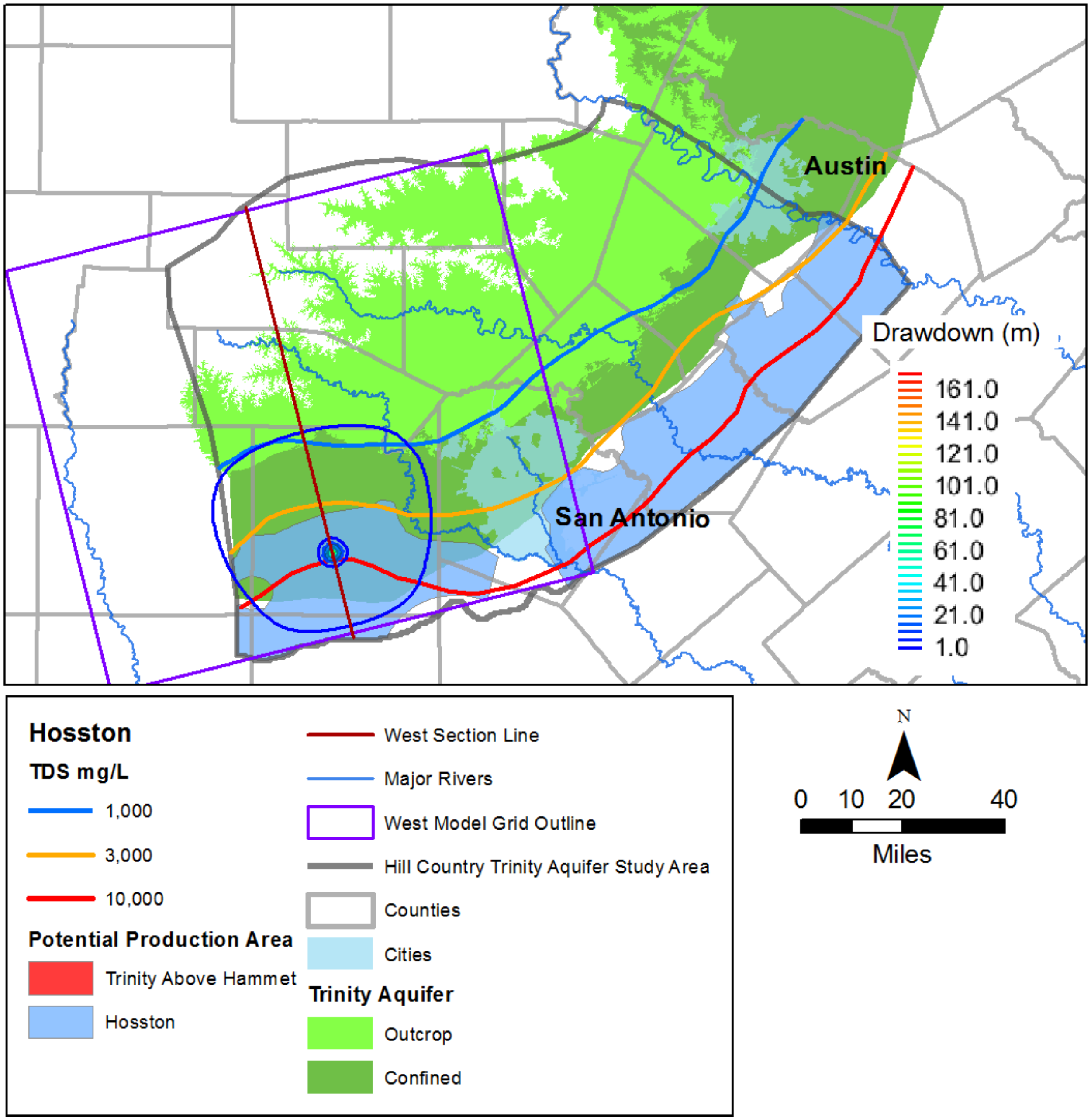

Figure 14-14 **Simulated drawdown in West section model from pumping the Hosston Formationat 3,000 afy for 50 years.**

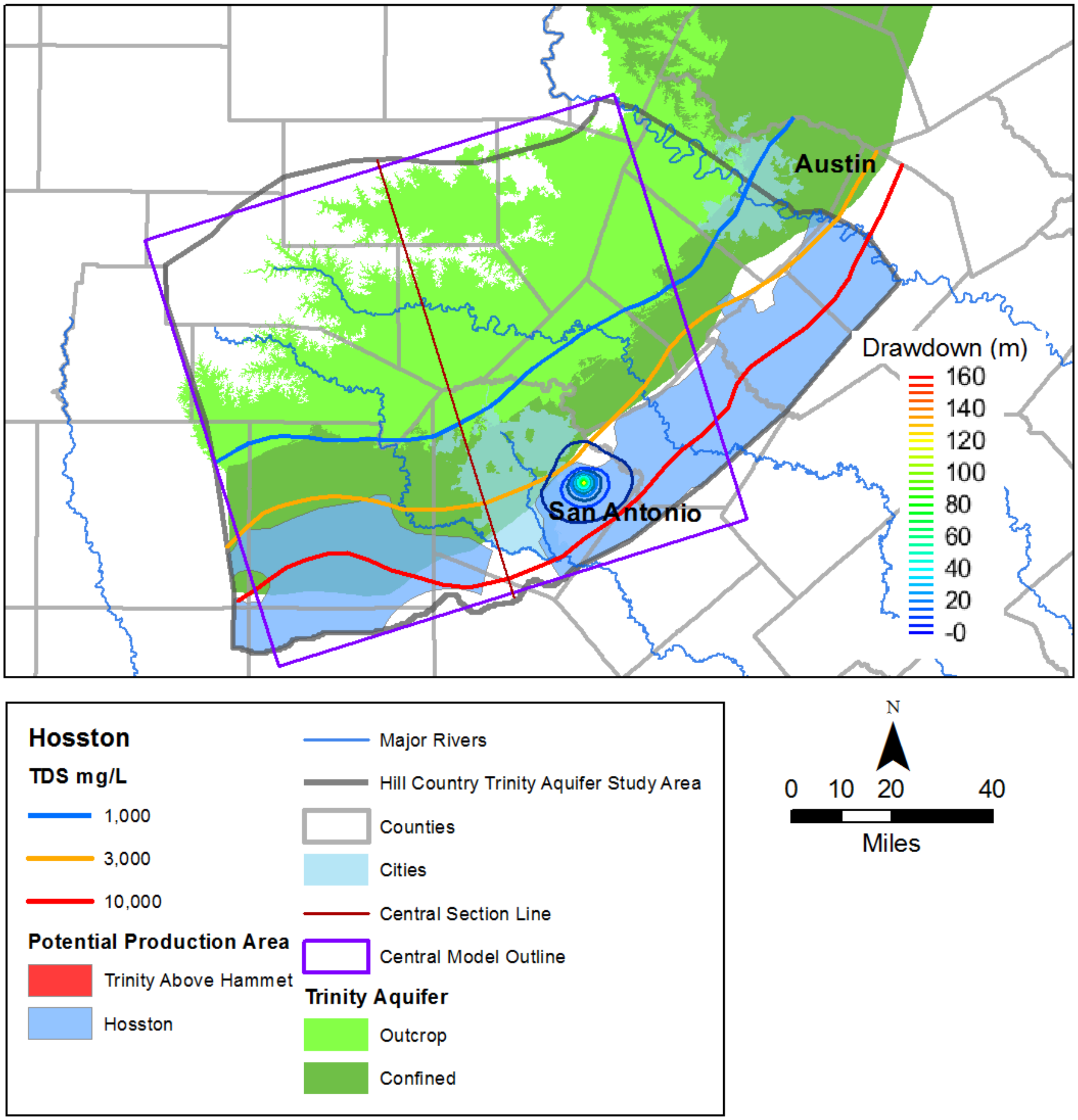

Figure 14-15 **Simulated drawdown in Central section model from pumping the Hosston Formation at 6,000 afy for 50 years.**

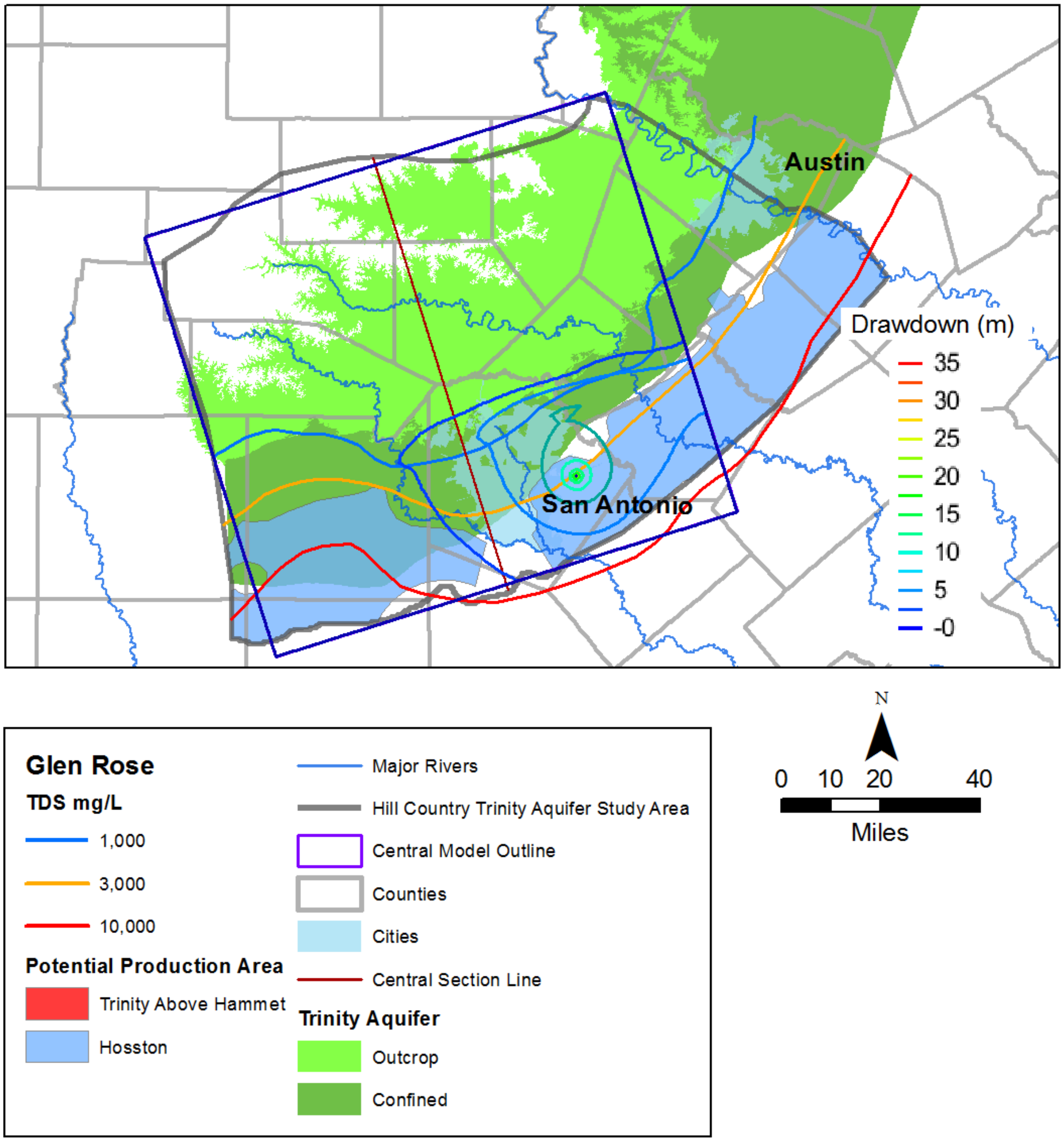

Figure 14-16 Simulated drawdown in Central section model from pumping the Upper and Middle Trinity (Upper Glen Rose, Lower Glen Rose, Hennsell, and Cow Creek) at 9,000 afy for 50 years.

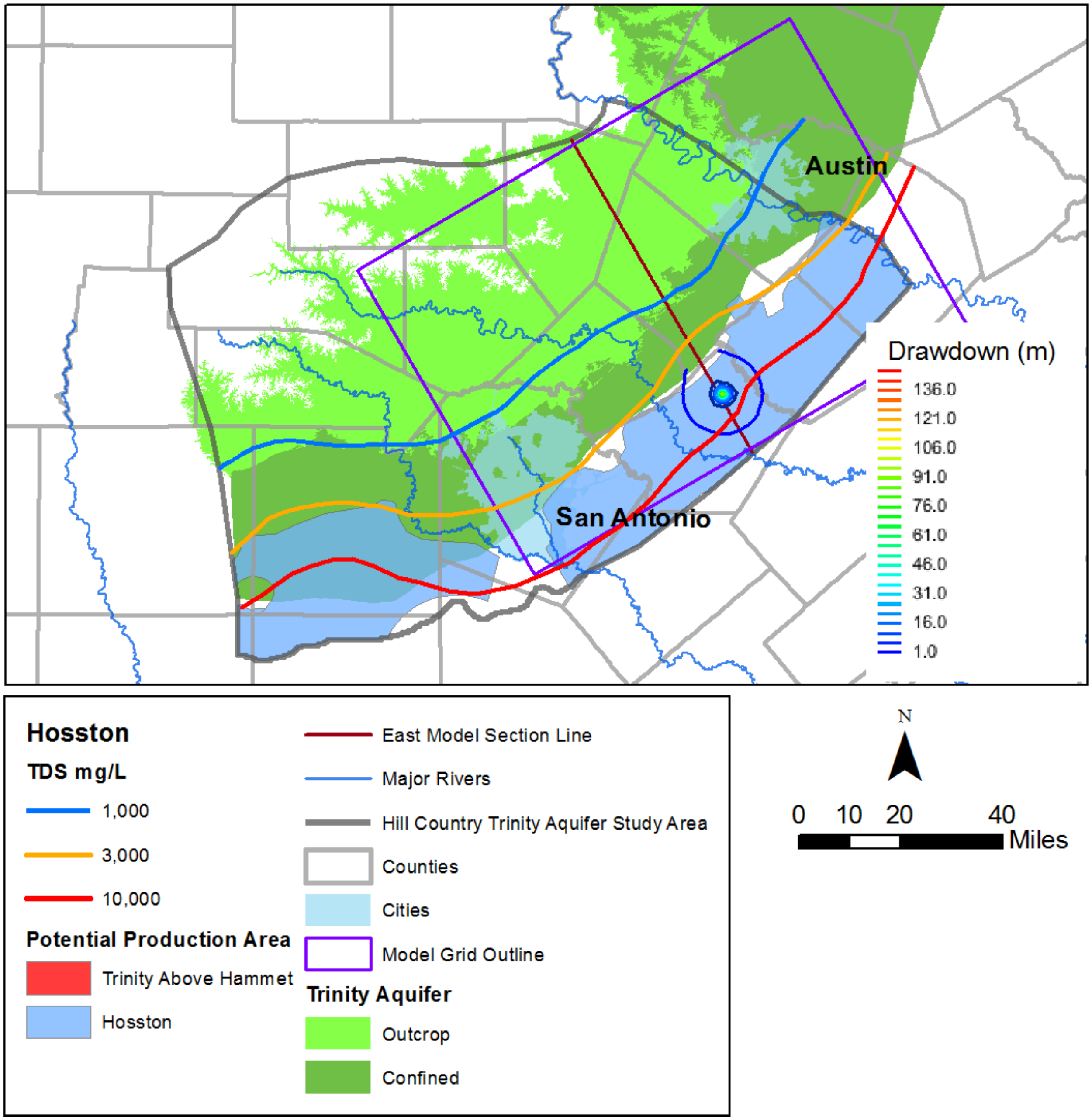

Figure 14-17 Simulated drawdown in East section model pumping at 3,000 afy for 50 years.

14.3.2 Simulated Results for the Northern Trinity Aquifer

The series of predictive scenarios described above were developed to evaluate the potential of the Northern Trinity Aquifer to serve as a water source within the Potential Production Areas.

14.3.2.1 Drawdown Metrics

Figures 14.19 – 14.37 show the simulated drawdown at each wellfield after 50 years of production, compared to the basecase. Tables 14.5 and 14.6 summarize drawdown results of the simulations for each wellfield after 30 and 50 years of production, respectively. 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.

Maximum drawdown and production rate varies by wellfield, depending on the productivity of the formation, 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 (Hensell PPA #3, Wellfield #1) to 411 feet (Glen Rose PPA #1, Wellfield #1). Total production rate (for the “high” production case) varies from 39 afy (Hensell PPA #3, Wellfield #2) to 2,796 afy (Hosston PPA #3, Wellfield #2).

Analysis of the relationship between drawdown and production rate at a given wellfield indicates that the relationship is exactly 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. Table 14.7 shows the predicted drawdown impacts for each wellfield, for a production rate of 1,000 acre-feet per year. The predicted drawdown for Hensell PPA #3, Wellfield #2 exceeds the depth to the unit top, and so would not be physically possible to achieve.

14.3.2.2 Change in Water Quality

Table 14.8 shows a summary of the results of the particle tracking simulations. For each wellfield simulation, the distance between the starting and ending point for each particle was compared to the basecase. In some cases, the “with project” distance was greater than basecase, and in some cases it was less. Table 14.8 shows the maximum and minimum difference in distance, where positive numbers indicate that the “with project” simulated particle distance was greater than the basecase distance.

Whether the particle moves a shorter 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 basecase. Although under natural conditions in the Trinity Aquifer, flow is generally downdip toward the Mexia-Talco fault zone, under the simulated future pumping conditions, large drawdowns updip result in reversal of gradients. Figure 14.38 shows the head contours in the Hosston Formation at the end of the base case simulation, which illustrates this effect.

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) and that the difference between the basecase and "with project" case is also small. Figure 14.39 shows the tracks for one particle for the basecase and "with project" case. Note that for this example, the project pumping has caused the particle to move less distance, since the particle was moving updip under base case conditions, while the brackish production is occurring downdip.

Table 14-5 Simulation of drawdown in the North 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)		
Formation	**PPA#**	**Well Field**	**Label**	**Depth to Unit Top (ft)**	**low**	**med.**	**high**	**low**	**med.**	**high**	**low**	**med.**	**high**	**low**	**med.**	**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

Table 14-6 Simulation results 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)**		
Formation	**PPA#**	**Well Field**	**Label**	**Depth to Unit Top (ft)**	**low**	**med.**	**high**	**low**	**med.**	**high**	**low**	**med.**	**high**	**low**	**med.**	**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 Rose	1	1	GR151	2,808	164	328	657	4	9	17	1	1	2	103	205	411
Glen Rose	2	1	GR251	4,527	65	129	258	6	12	24	7	14	28	65	130	260
Glen Rose	3	1	GR351	2,754	121	242	483	11	22	44	1	3	6	76	153	306
Glen Rose	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

Table 14-7 Estimated drawdown for a 1,000 acre-feet per year wellfield after 50 years of production.

Formation	PPA #	Well Field	Label	Depth to Unit Top (ft)	Total Pumping Rate (afy)	Max. Drawdown at Existing Well (ft)	Max Drawdown at Fresh Water Line (ft)	Max 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

*exceeds available drawdown

Table 14-8 Minimum and maximum change in simulated travel distances at 50 years.

				Maximum Difference in Distance				**Minimum Difference in Distance**			
Formation	**PPA#**	**Well Field**	**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

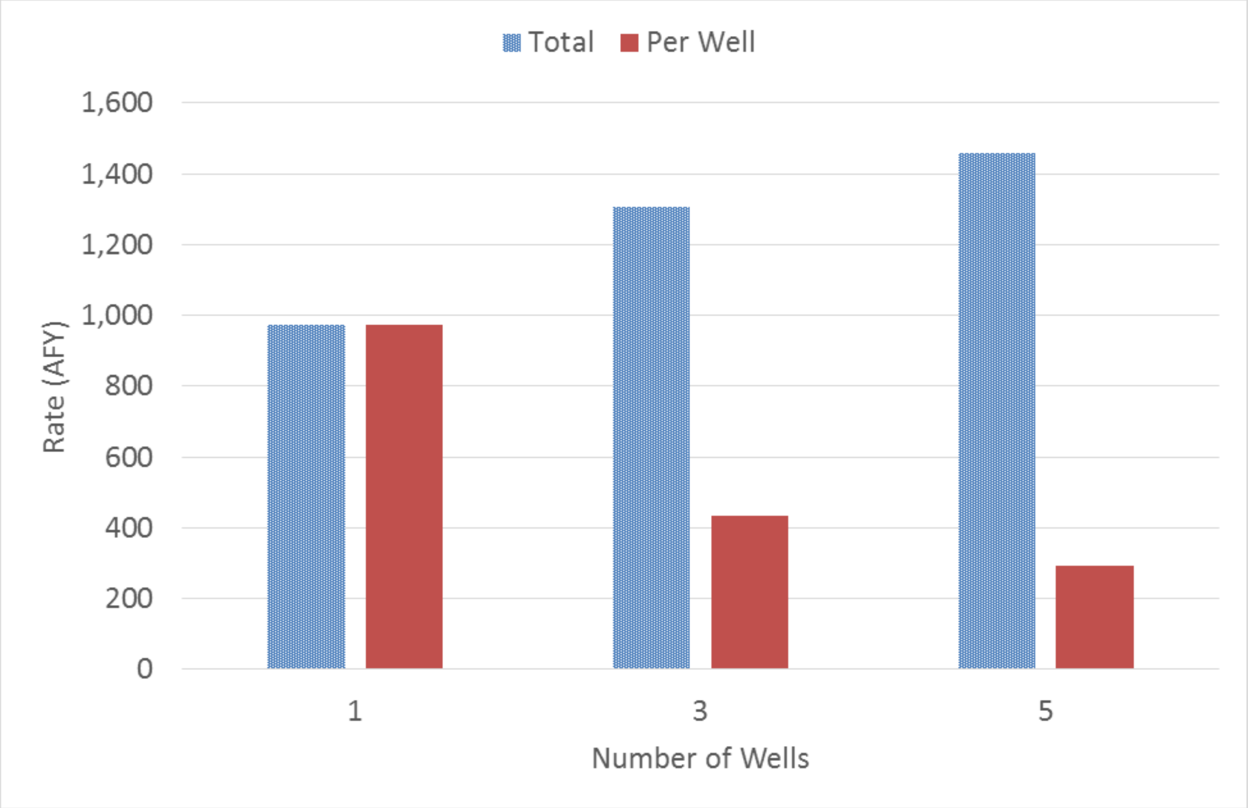

Figure 14-18 **Average wellfield and per-well productivity for 1, 3, and 5 well configurations.**

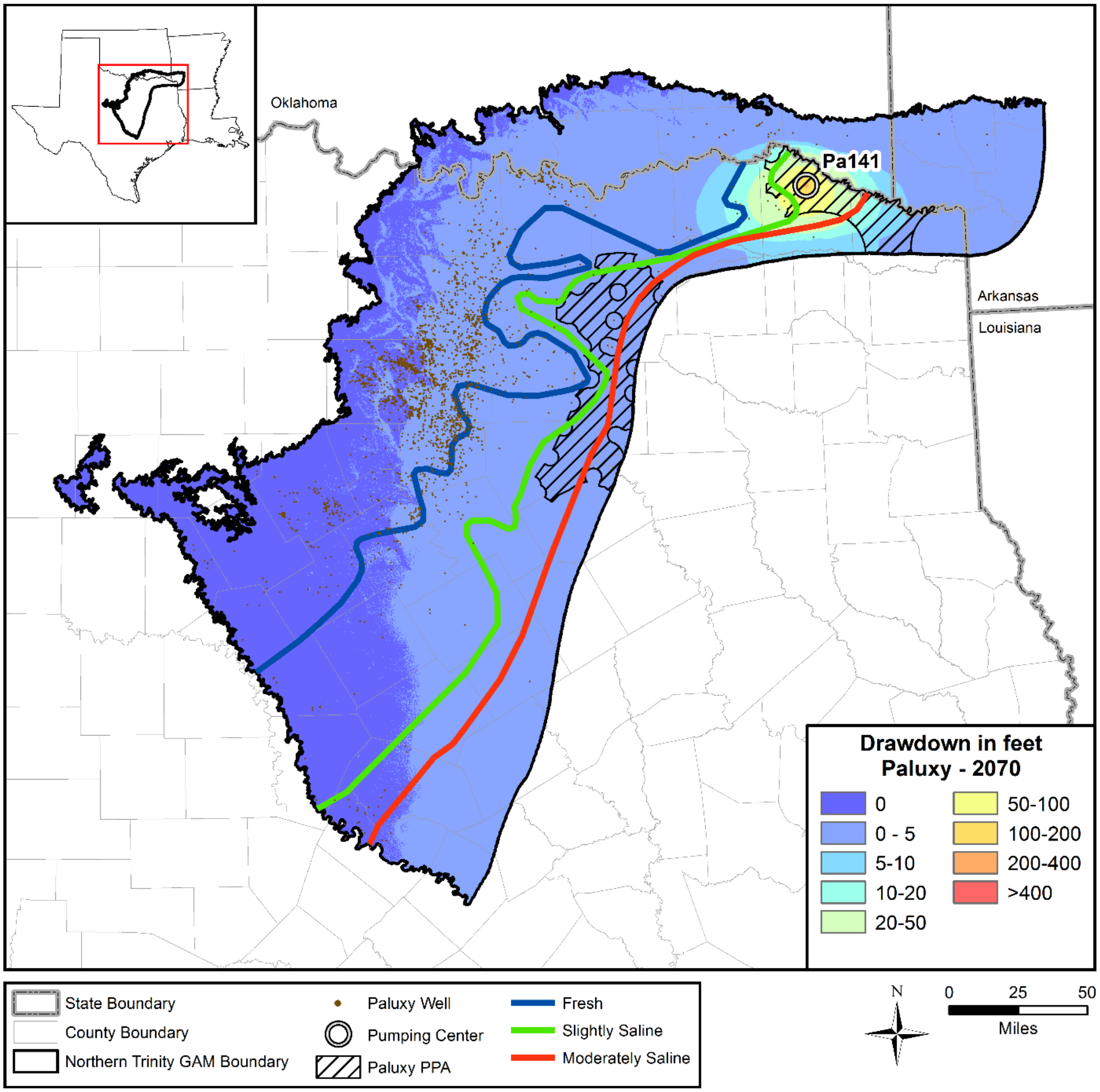

Figure 14-19 **Estimated drawdown in the Paluxy Formation in the North Trinity Aquifer after 50 years of production in PPA 1, Wellfield 1.**

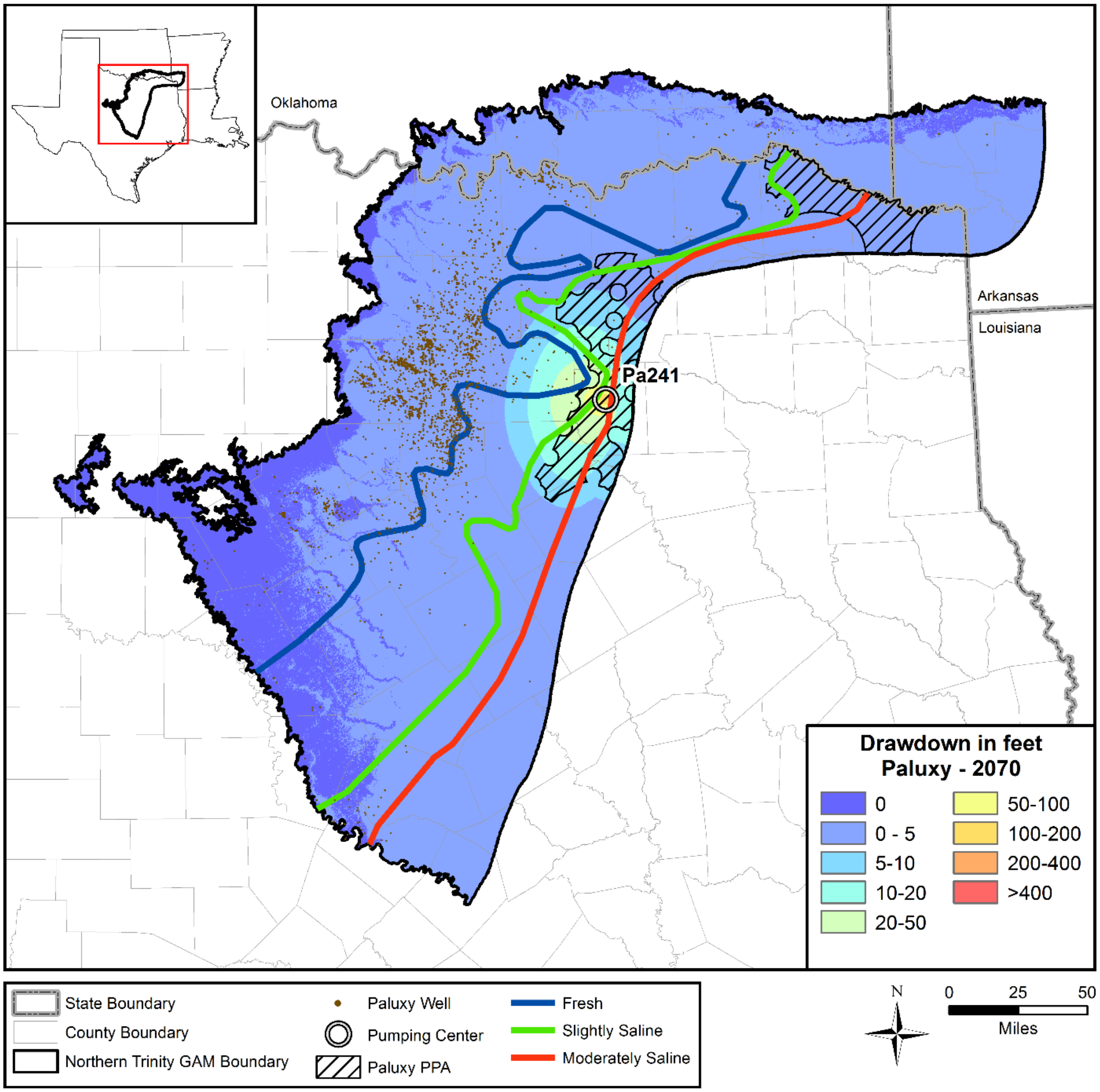

Figure 14-20 Estimated drawdown in the Paluxy Formation in the North Trinity Aquifer after 50 years of production in Paluxy PPA 2, Wellfield 1.

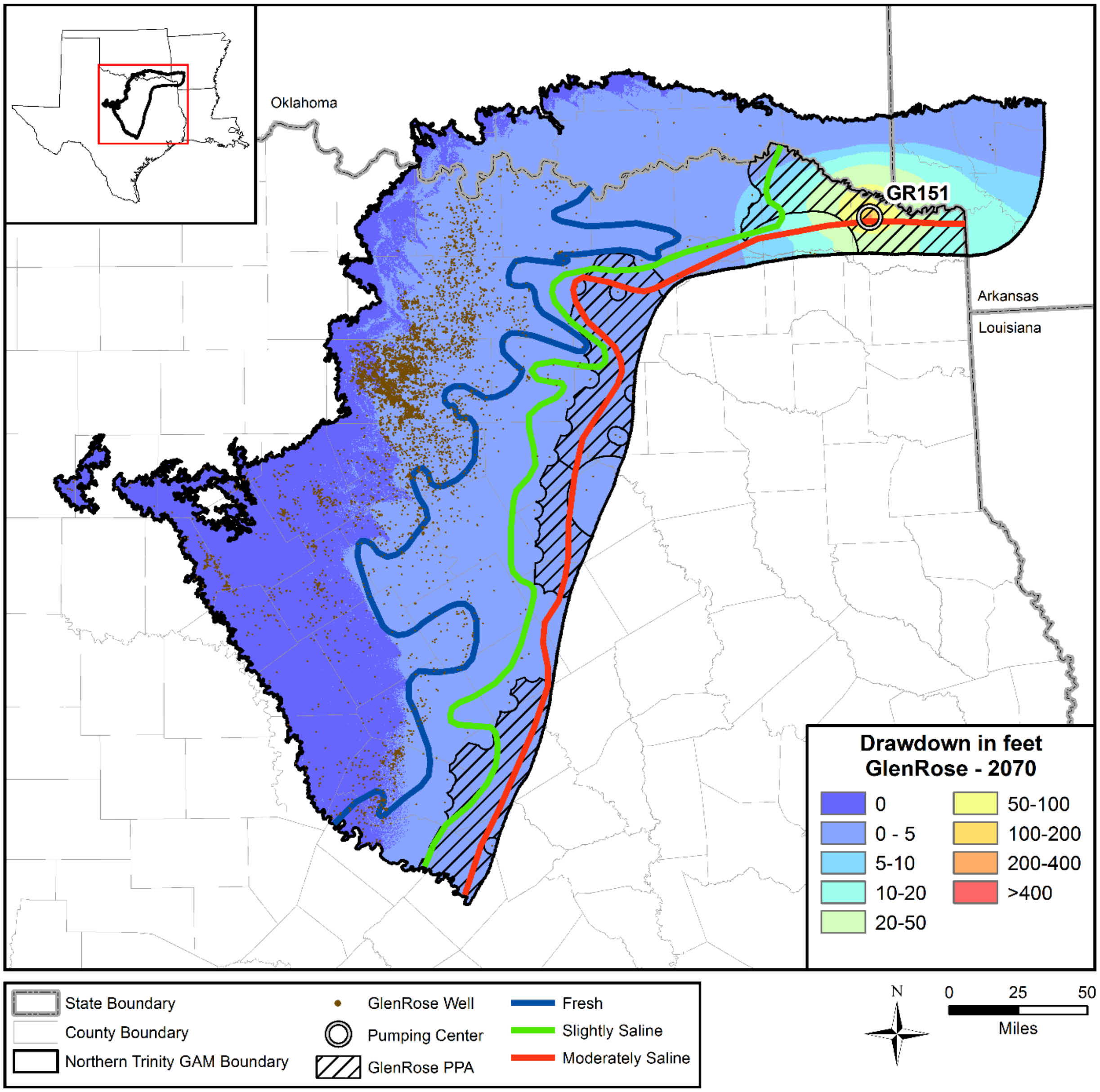

Figure 14-21 **Estimated drawdown in the Glen Rose Formation in the North Trinity Aquifer after 50 years of production in Glen Rose PPA 1, Wellfield 1.**

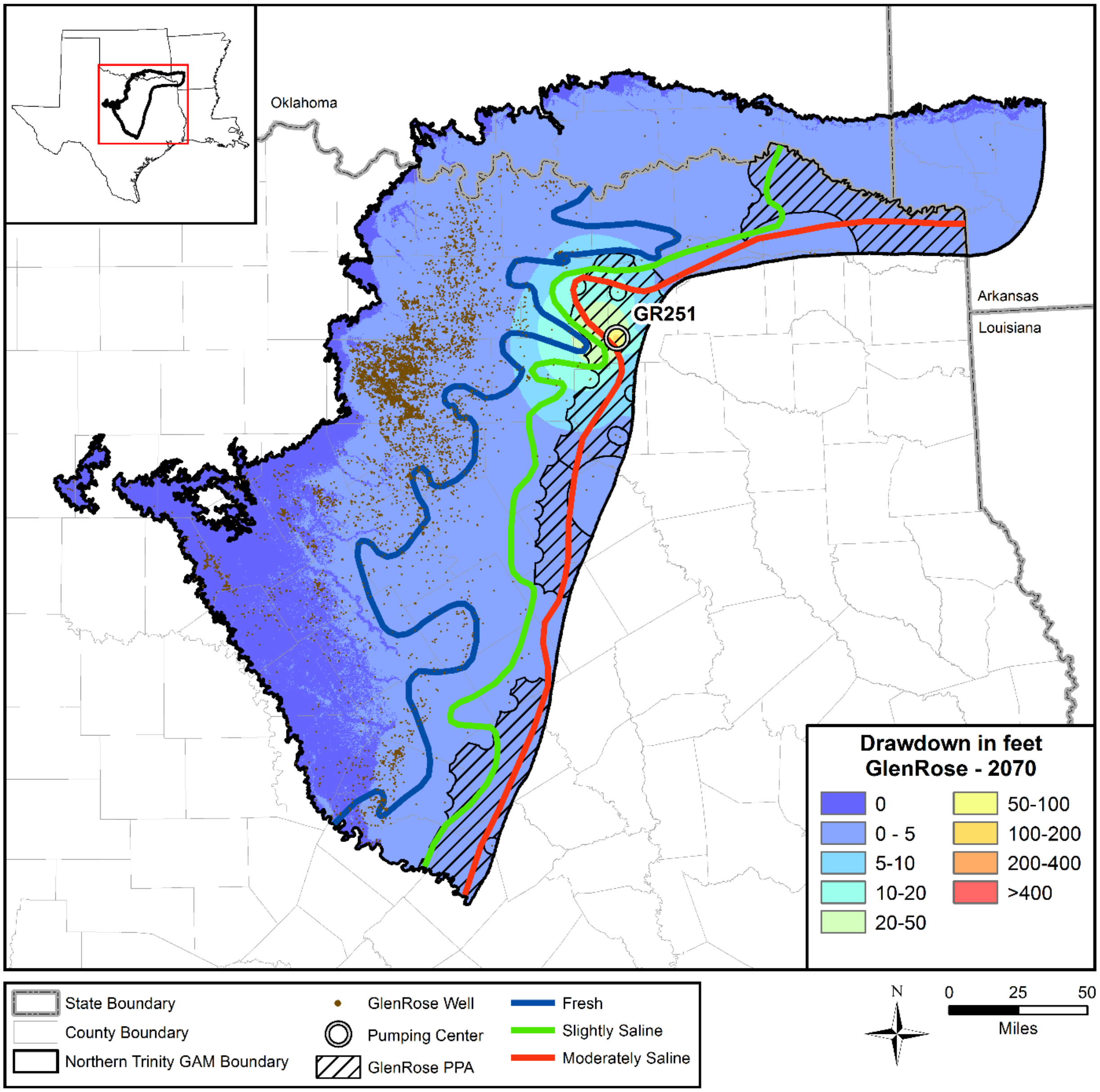

Figure 14-22 Estimated drawdown in the Glen Rose Formation in the North Trinity Aquifer after 50 years of production in Glen Rose PPA 2, Wellfield 1.

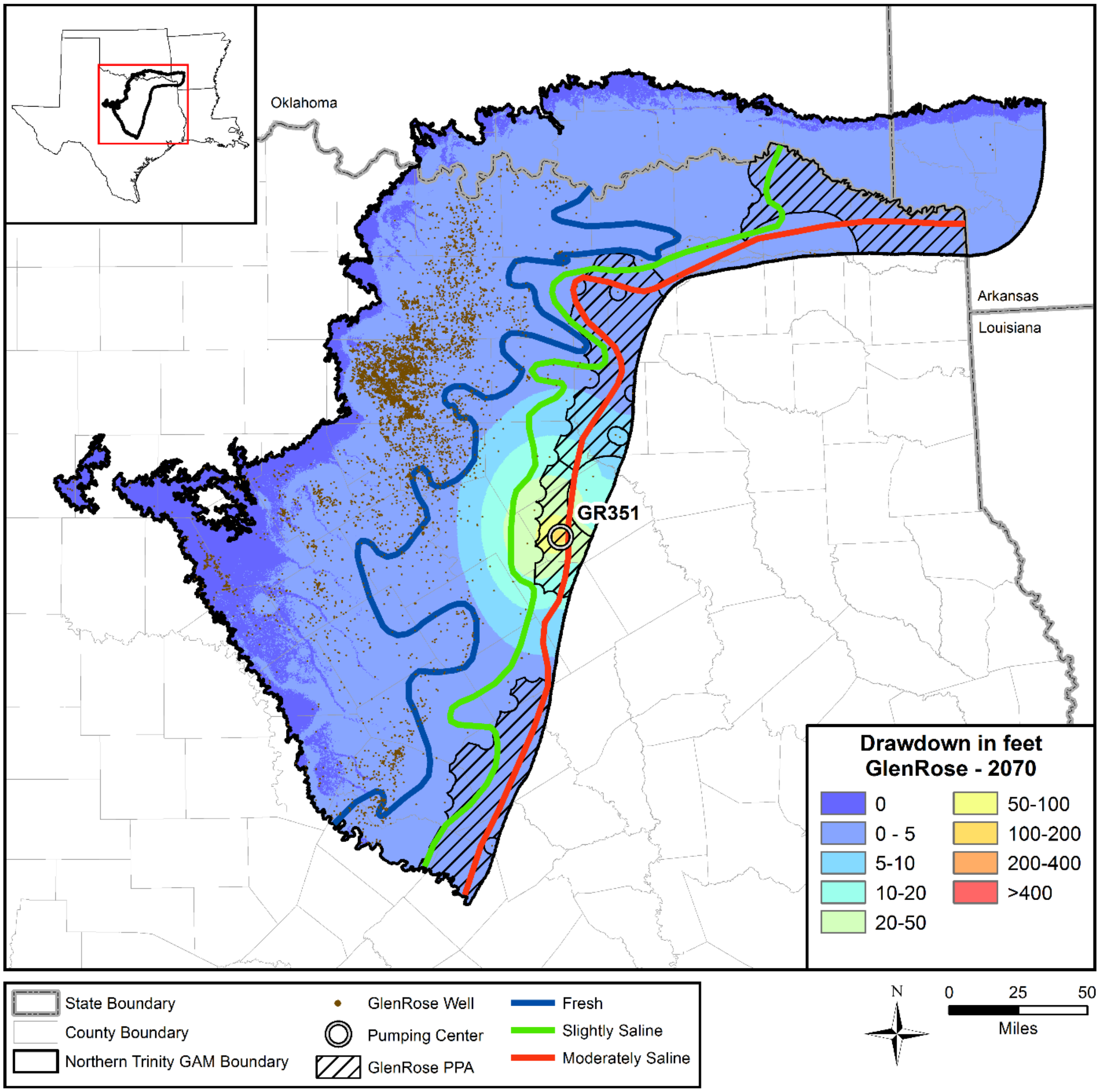

Figure 14-23 Estimated drawdown in the Glen Rose Formation in the North Trinity Aquifer after 50 years of production in Glen Rose PPA 3, Wellfield 1.

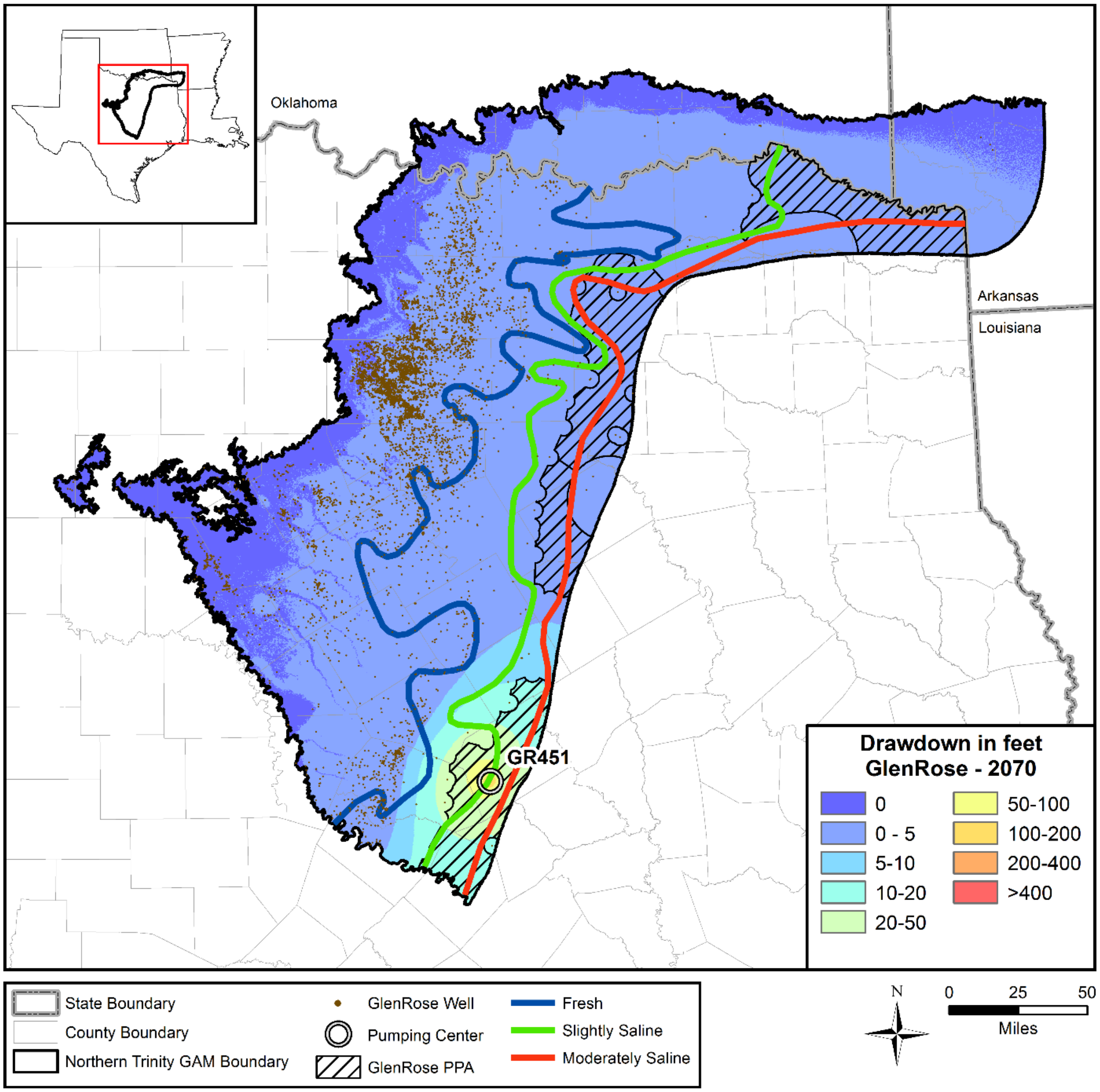

Figure 14-24 **Estimated drawdown in the Glen Rose Formation in the North Trinity Aquifer after 50 years of production in Glen Rose PPA 4, Wellfield 1.**

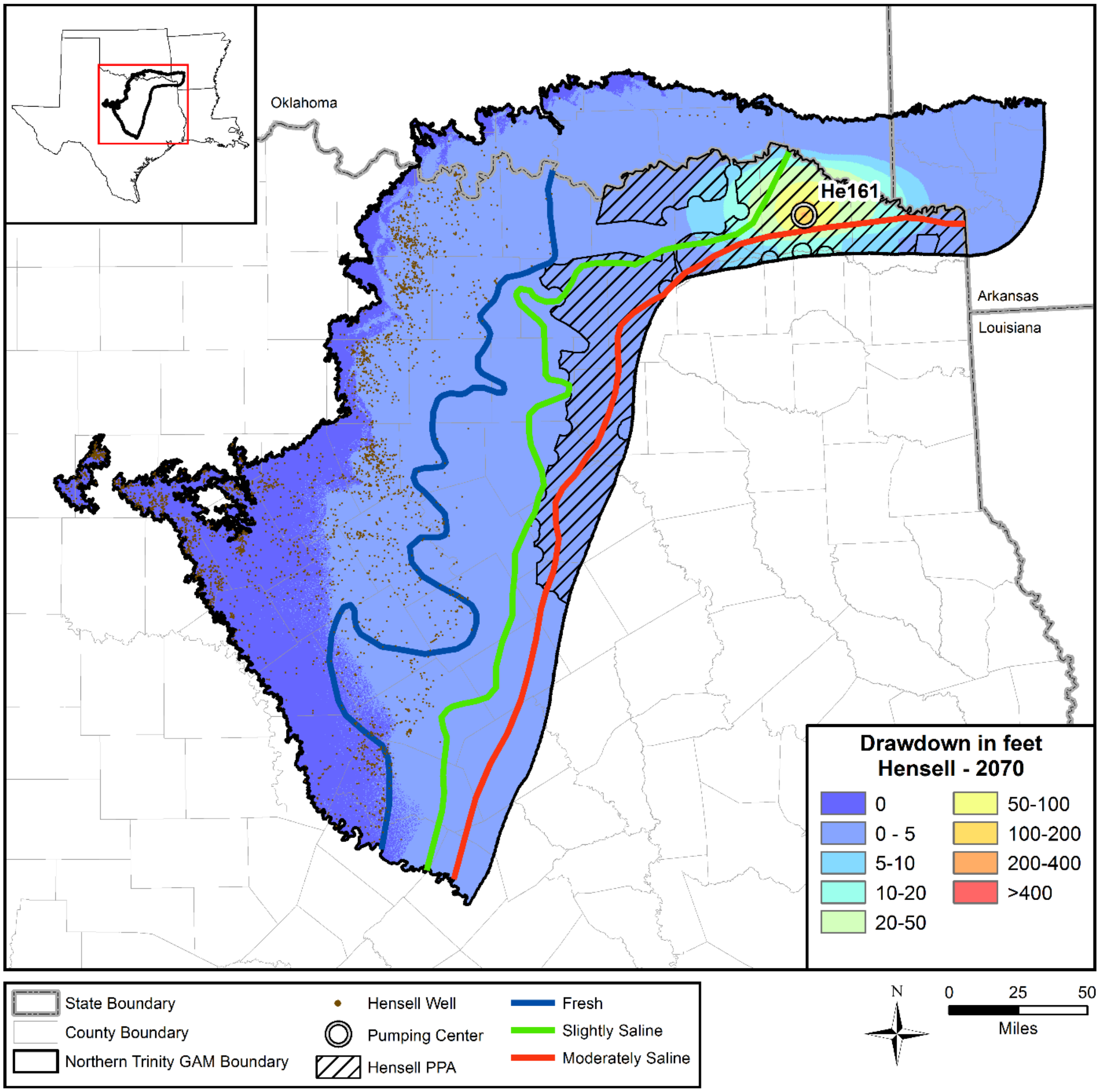

Figure 14-25 Estimated drawdown in the Hensell Formation in the North Trinity Aquifer after 50 years of production in in Hensell PPA 1, Wellfield 1.

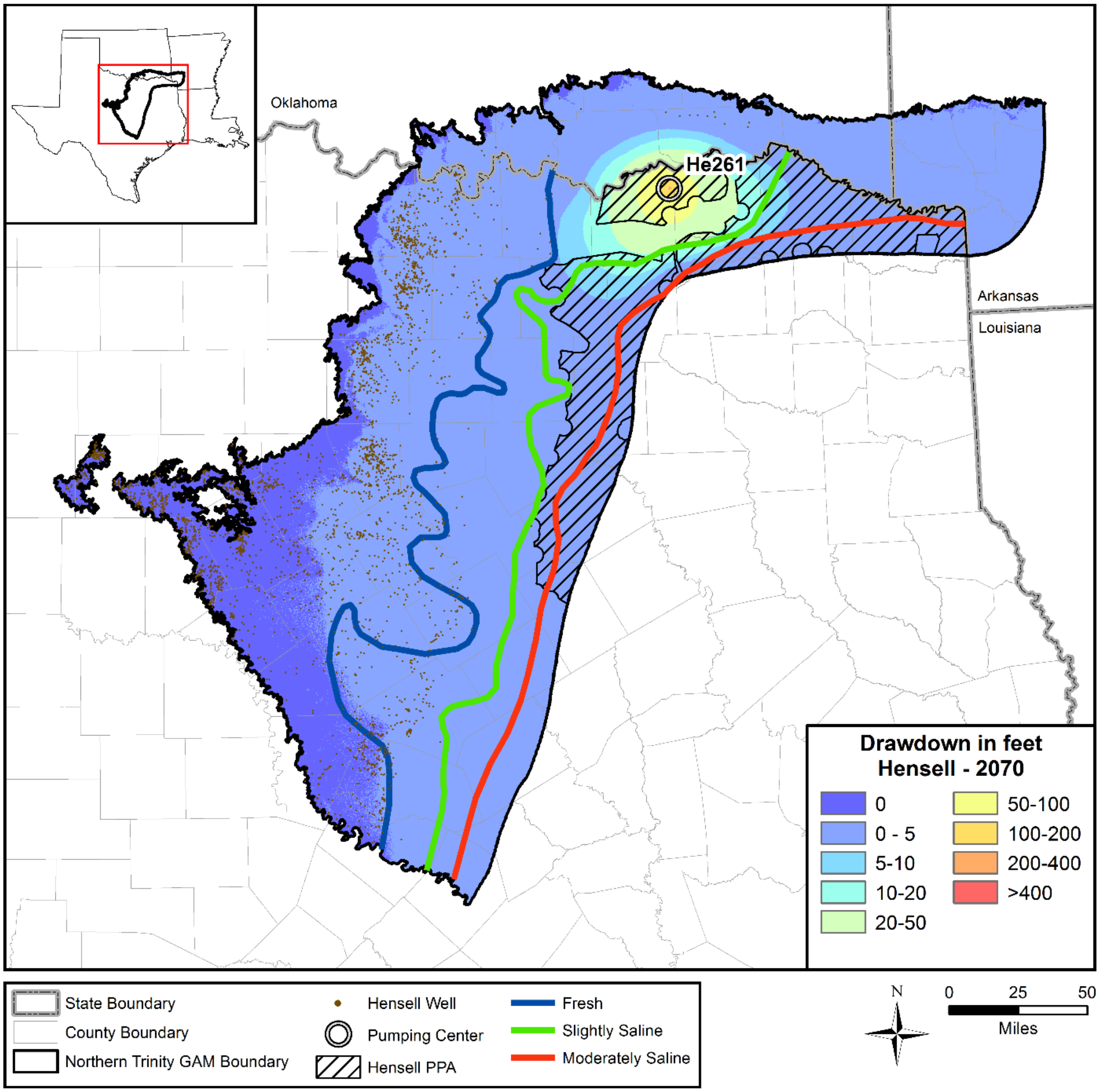

Figure 14-26 **Estimated drawdown in the Hensell Formation in the North Trinity Aquifer after 50 years of production in Hensell PPA 2, Wellfield 1.**

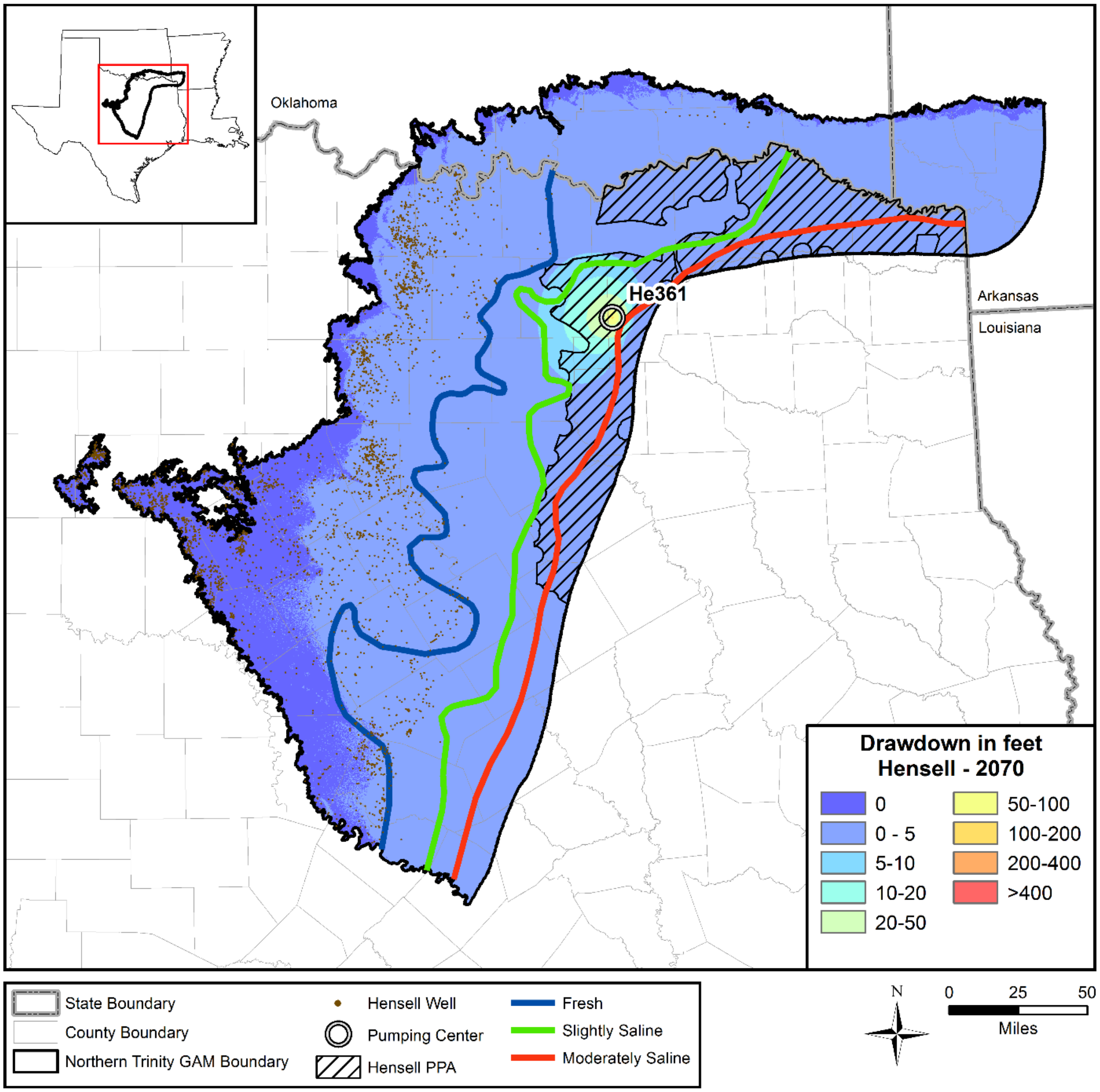

Figure 14-27 Estimated drawdown in the Hensell Formation in the North Trinity Aquifer after 50 years of production in in Hensell PPA 3, Wellfield 1.

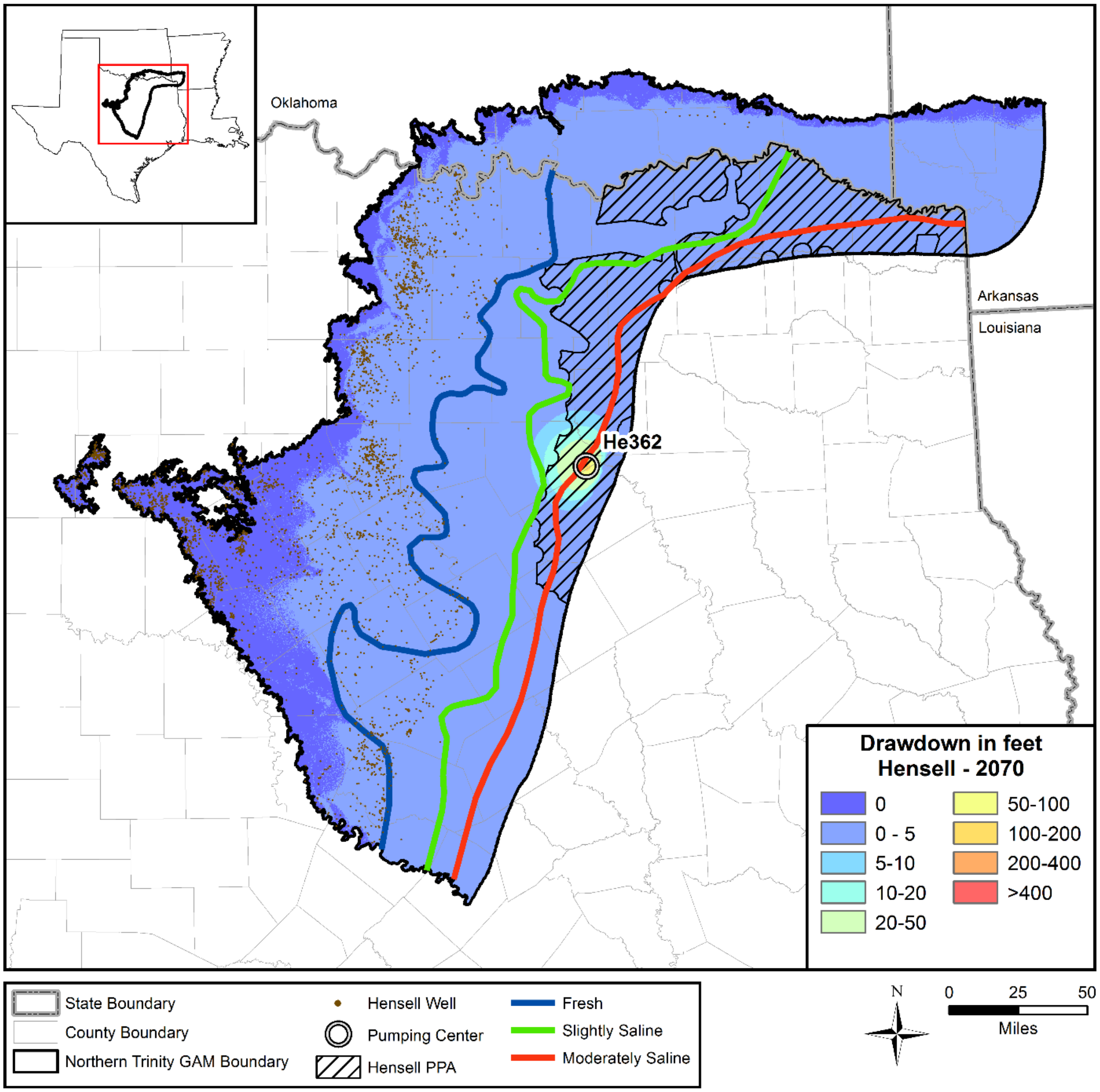

Figure 14-28 **Estimated drawdown in the Hensell Formation in the North Trinity Aquifer after 50 years of production in in Hensell PPA 3, Wellfield 2.**

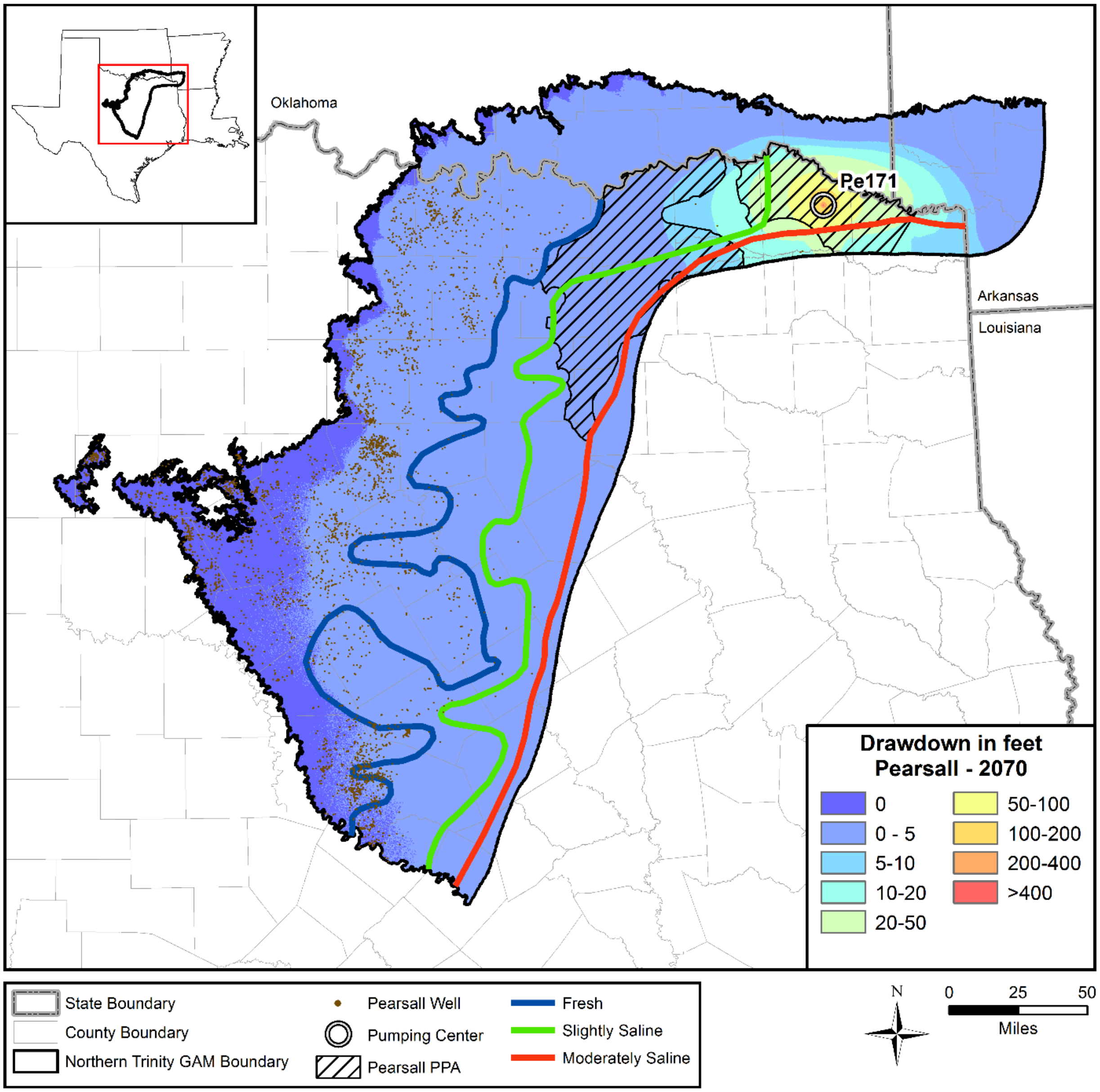

Figure 14-29 Estimated drawdown in the Pearsall Formation in the North Trinity Aquifer after 50 years of production in Pearsall PPA 1, Wellfield 1.

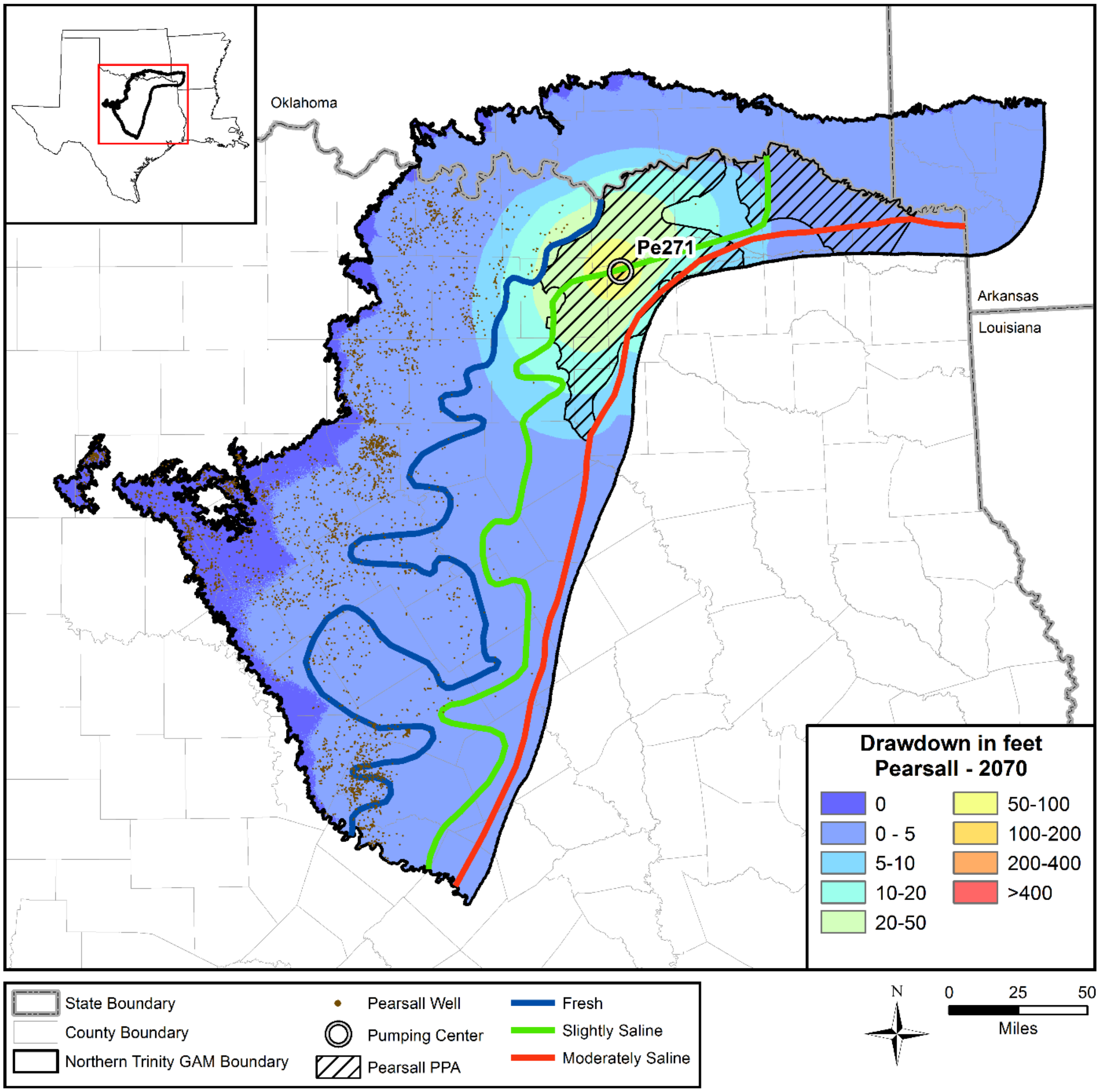

Figure 14-30 Estimated drawdown in the Pearsall Formation in the North Trinity Aquifer after 50 years of production in in Pearsall PPA 2, Wellfield 1.

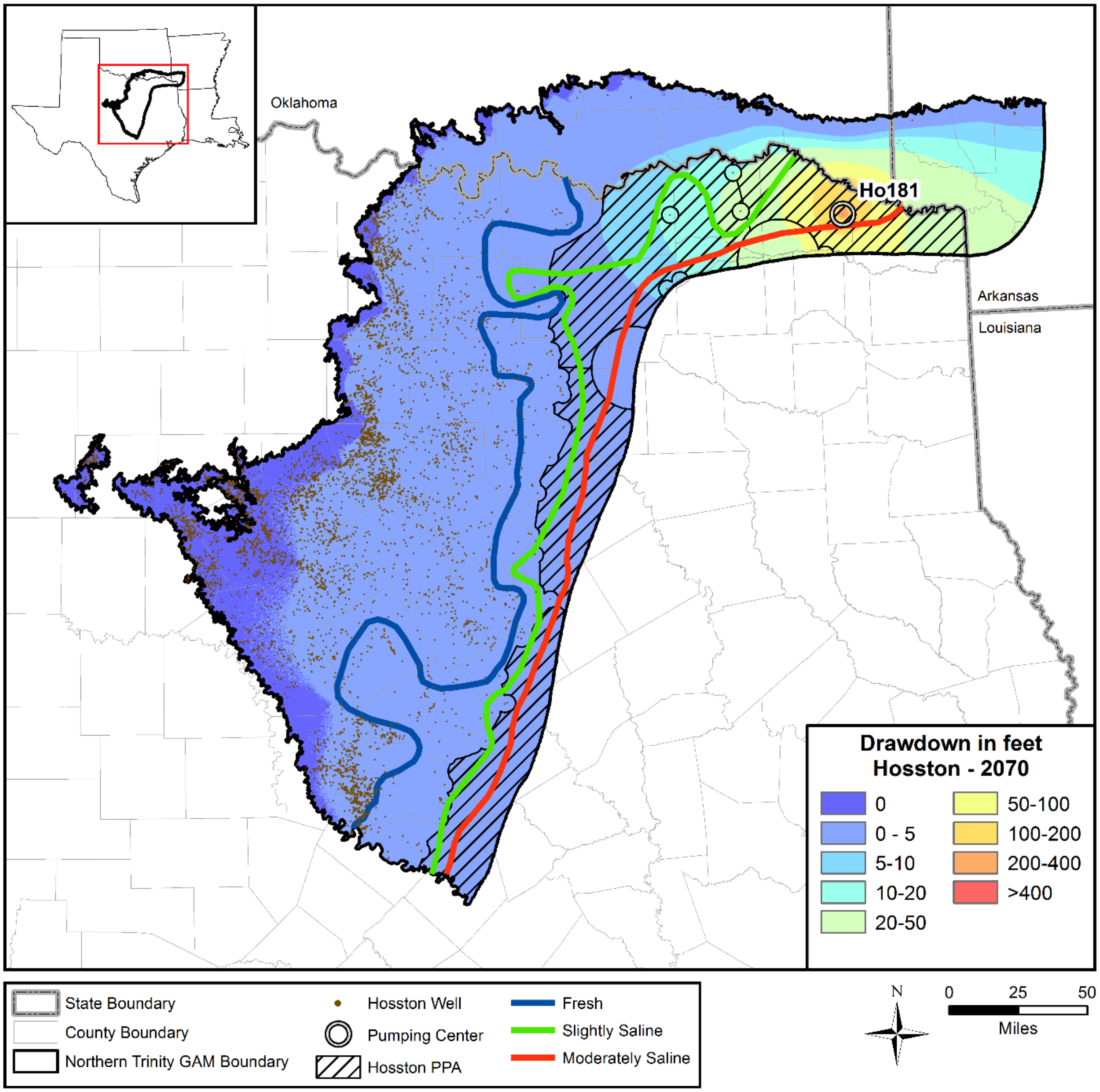

Figure 14-31 Estimated drawdown in the Hosston Formation in the North Trinity Aquifer after 50 years of production in Hosston PPA 1, Wellfield 1.

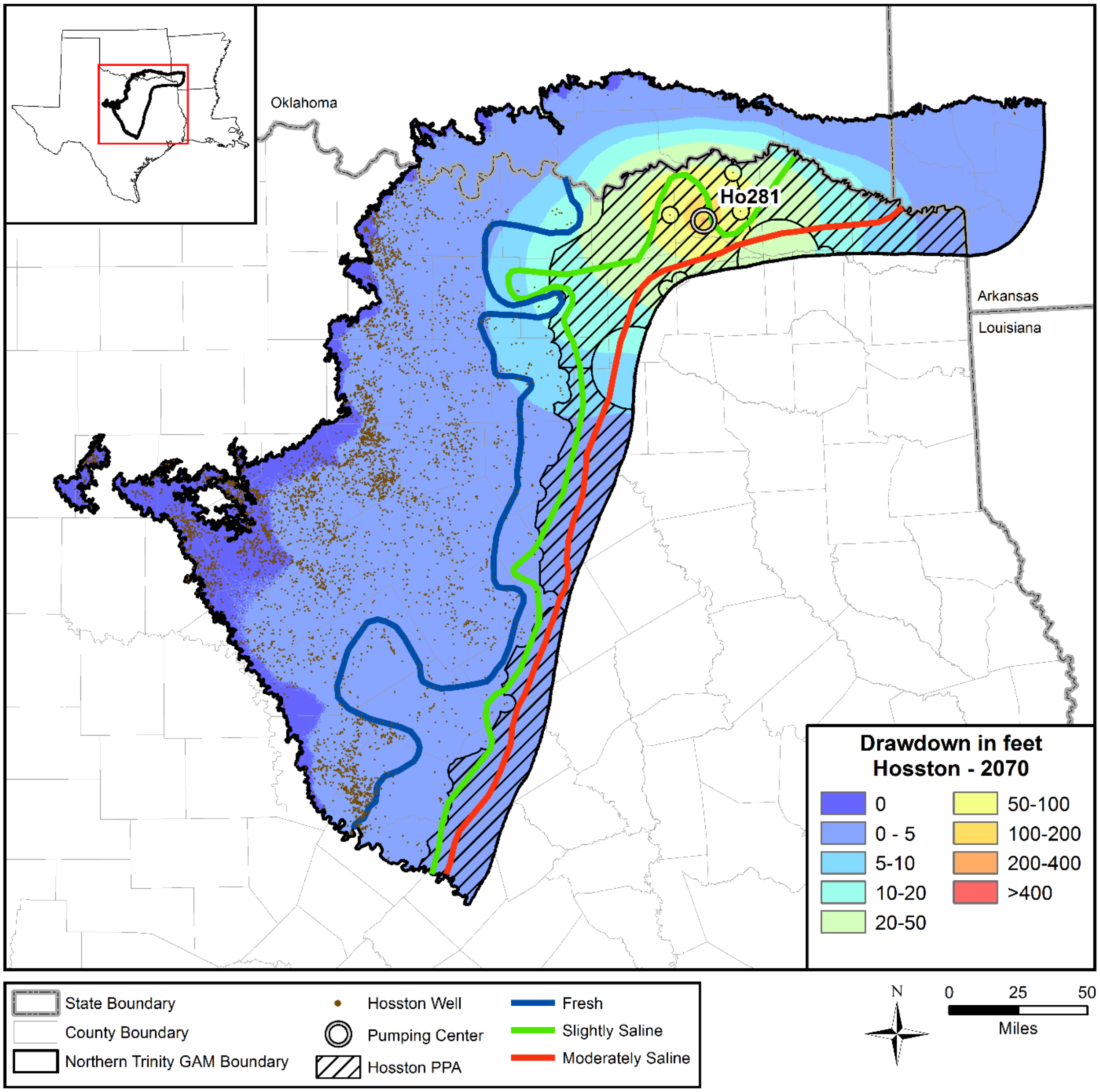

Figure 14-32 Estimated drawdown in the Hosston Formation in the North Trinity Aquifer after 50 years of production in Hosston PPA 2, Wellfield 1.

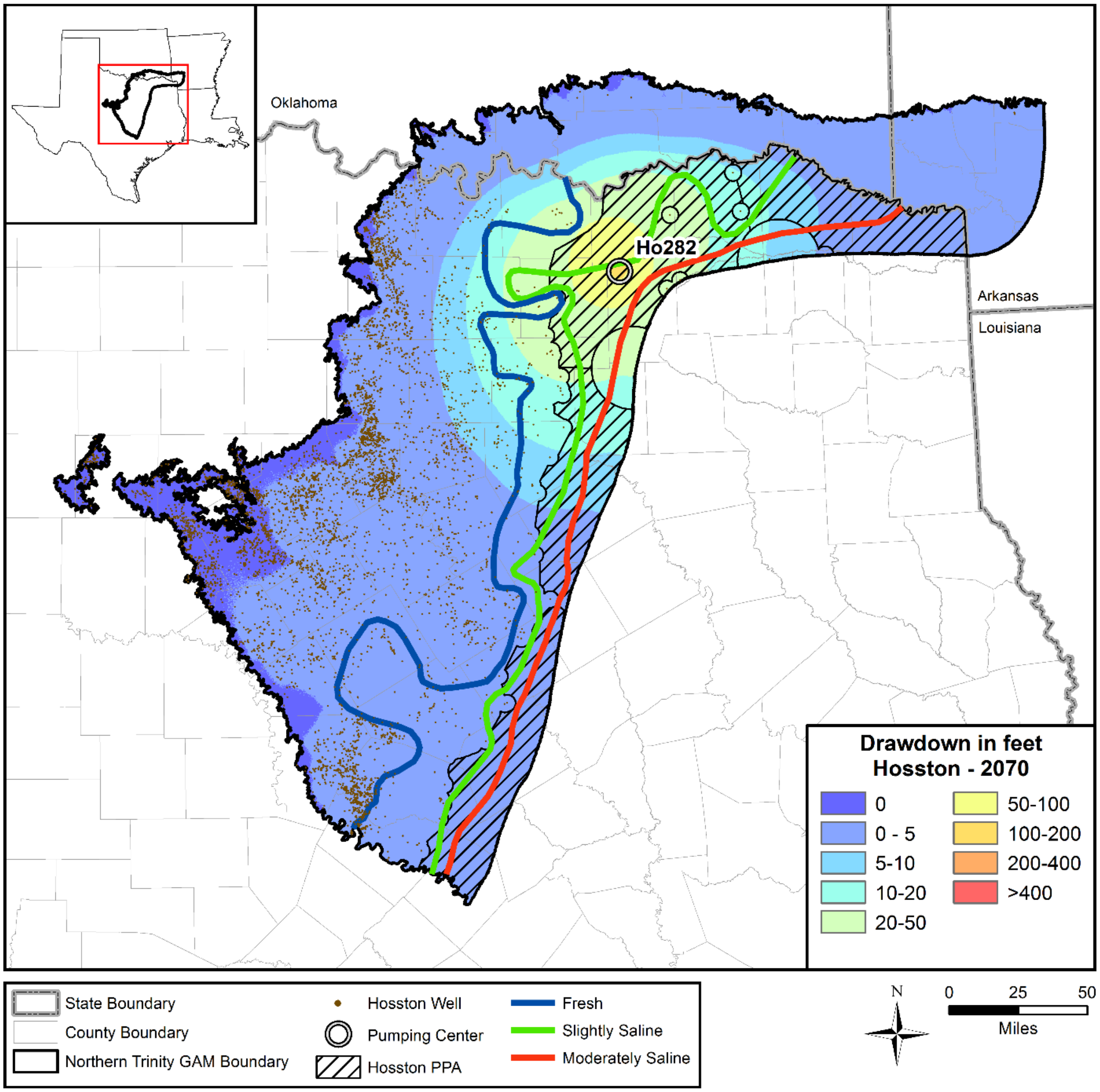

Figure 14-33 Estimated drawdown in the Hosston Formation in the North Trinity Aquifer after 50 years of production in Hosston PPA 2, Wellfield 2.

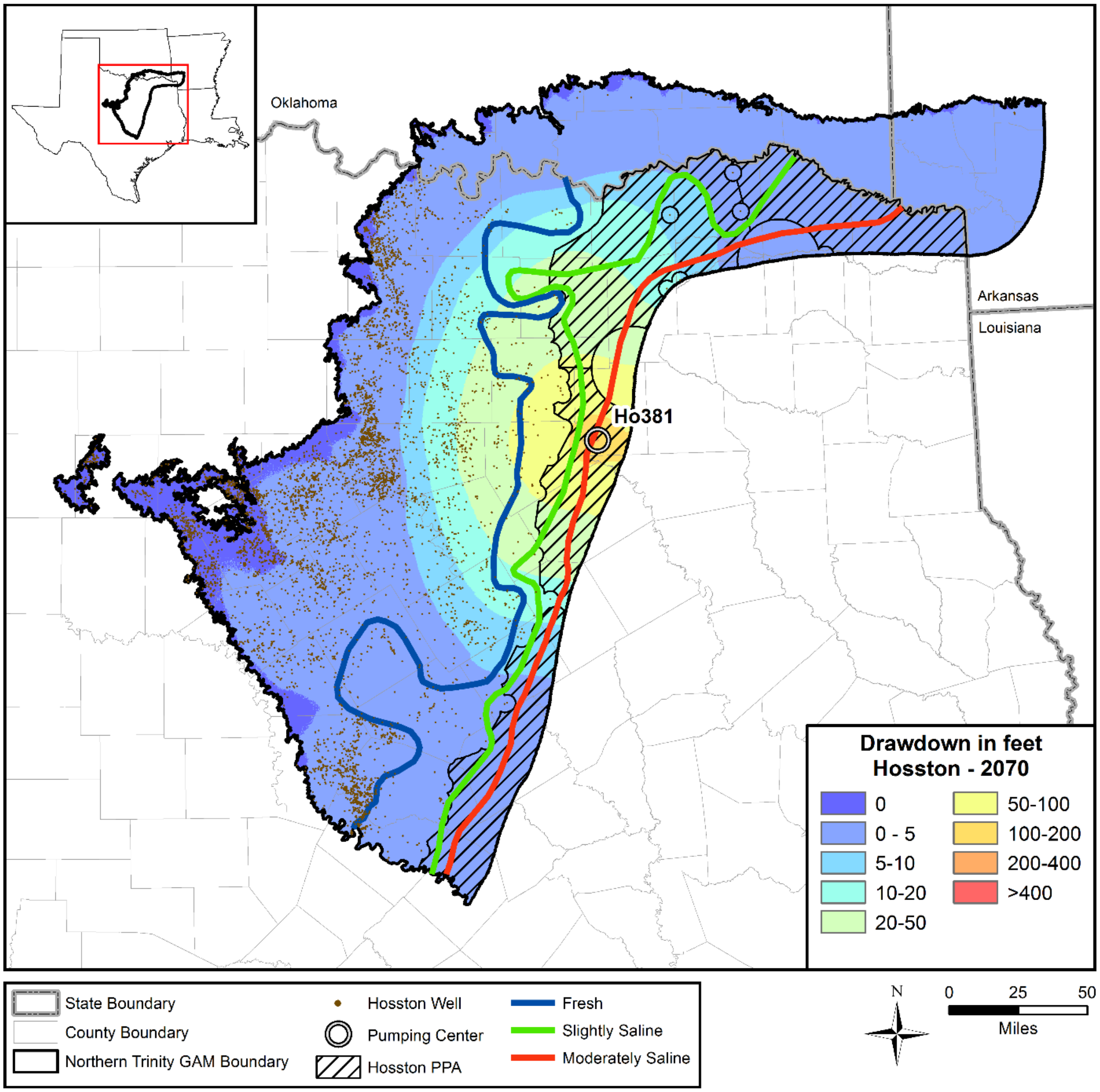

Figure 14-34 Estimated drawdown in the Hosston Formation in the North Trinity Aquifer after 50 years of production in Hosston PPA 3, Wellfield 1.

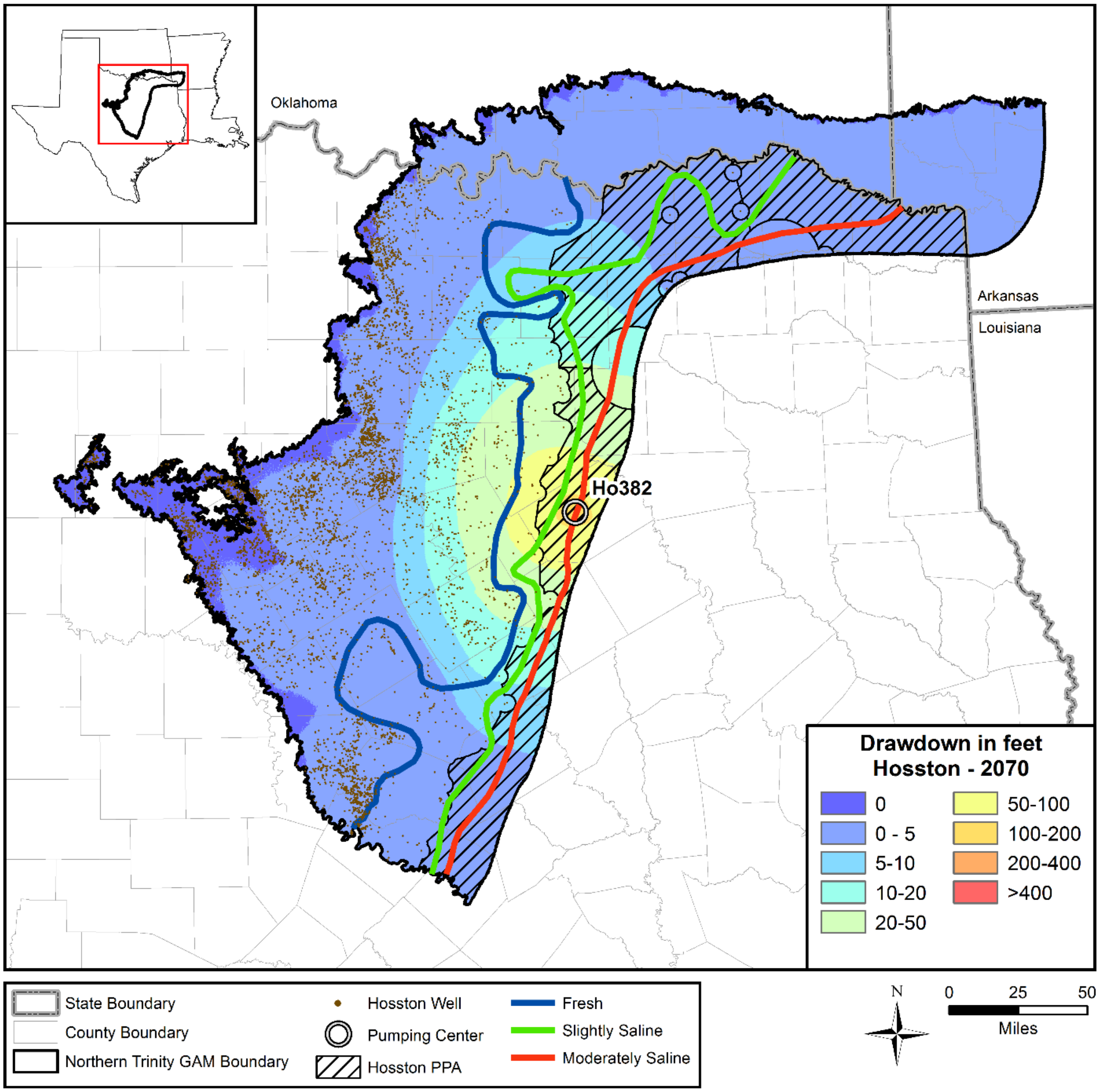

Figure 14-35 **Estimated drawdown in the Hosston Formation in the North Trinity Aquifer after 50 years of production in Hosston PPA 3, Wellfield 2.**

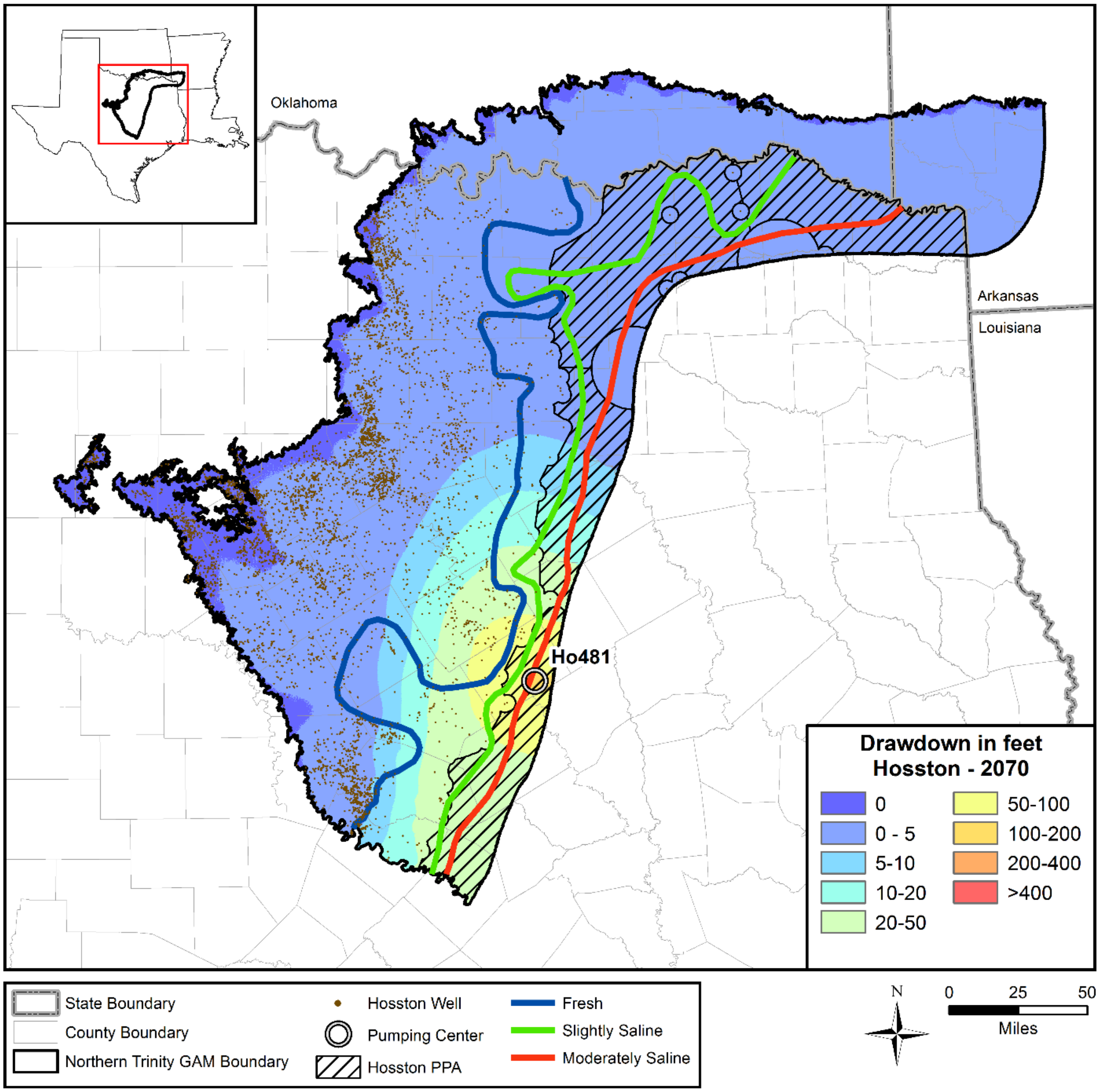

Figure 14-36 Estimated drawdown in the Hosston Formation in the North Trinity Aquifer after 50 years of production in Hosston PPA 4, Wellfield 1.

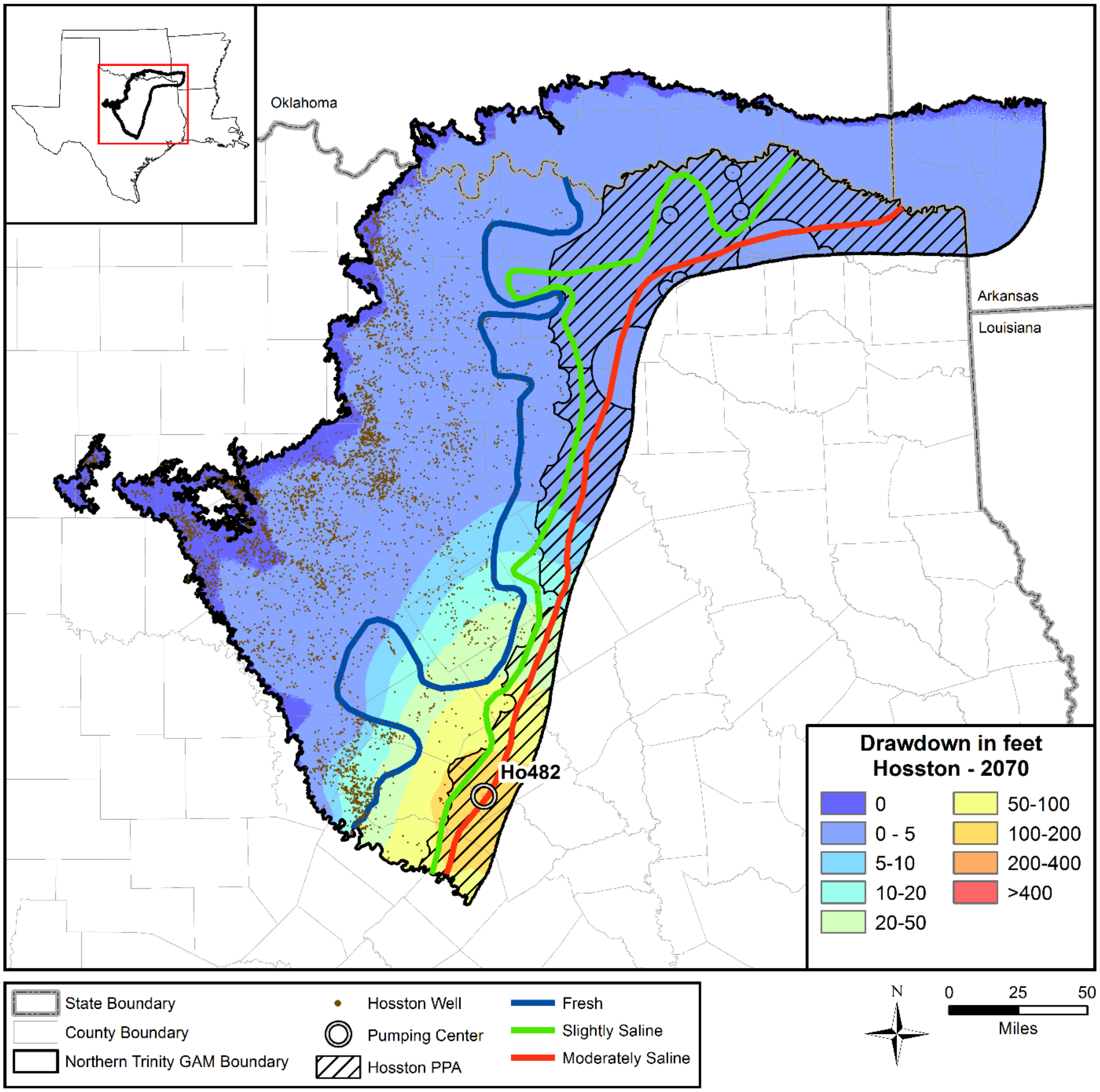

Figure 14-37 Estimated drawdown in the Hosston Formation in the North Trinity Aquifer after 50 years of production in Hosston PPA 4, Wellfield 2.

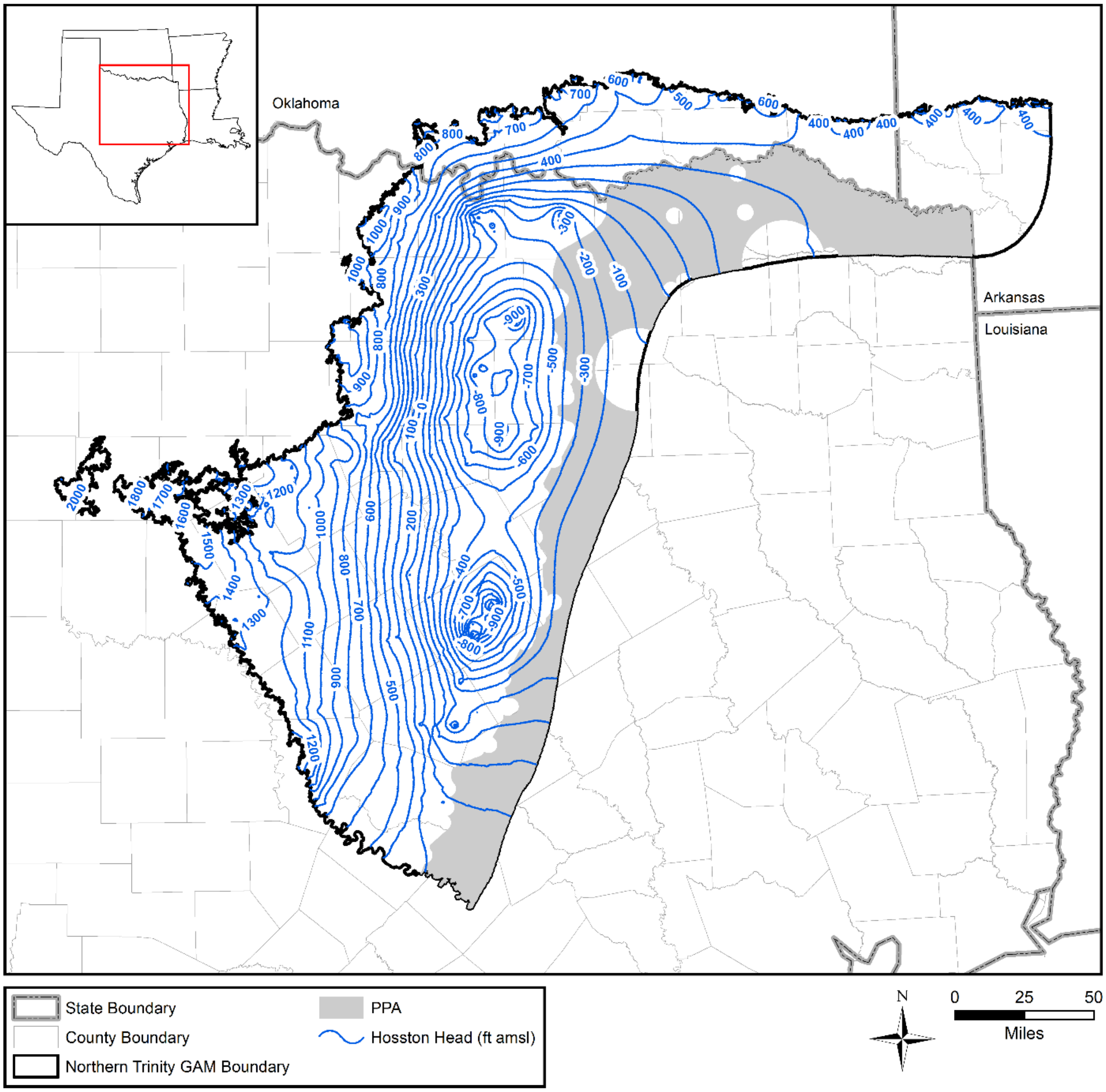

Figure 14-38 Head contours in the Hosston Formation at the end of the basecase simulation.

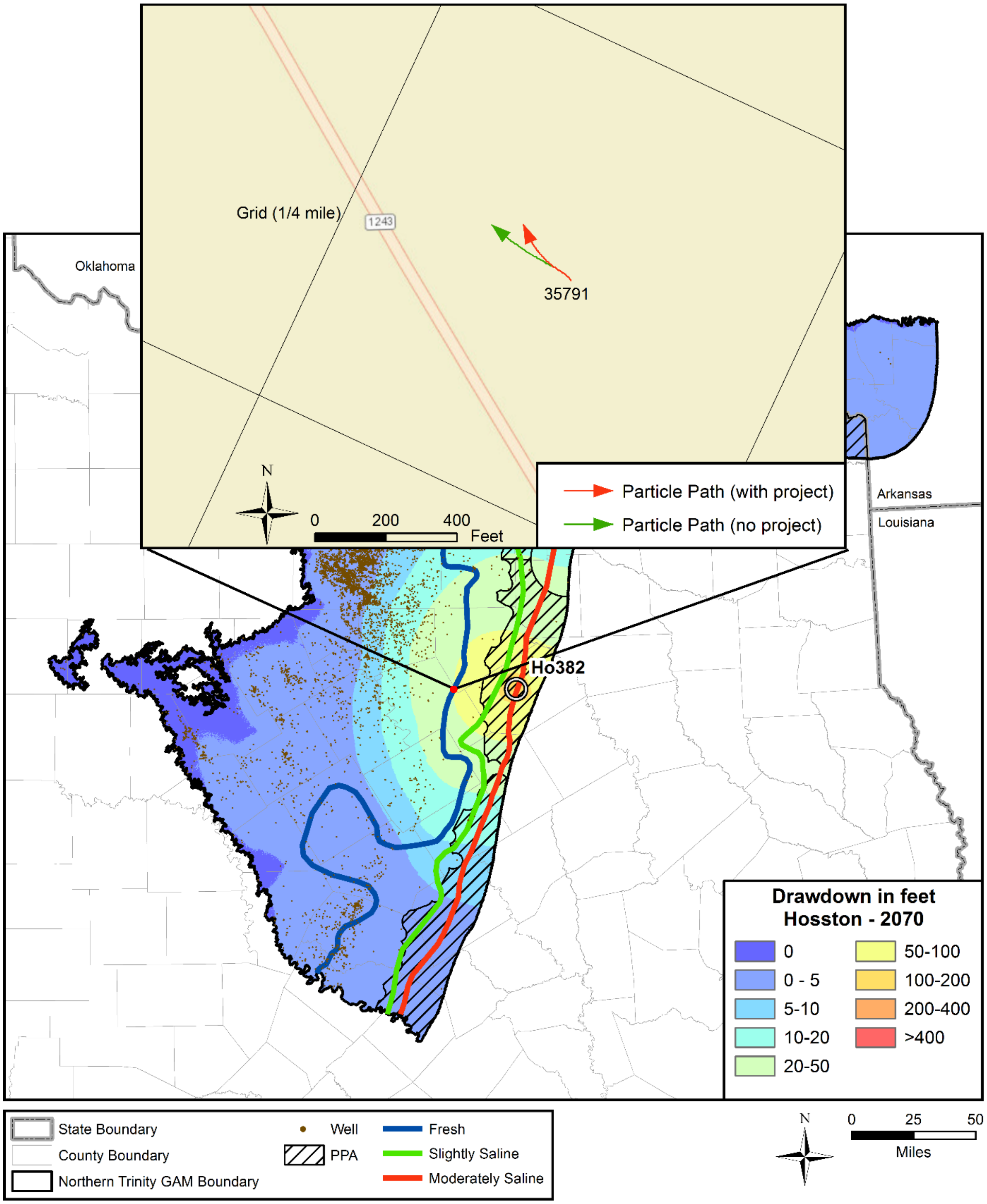

Figure 14-39 Example of particle tracks after 50 years for simulation of pumping Hosston PPA #3 Wellfield #2.

15 Future Improvements

This study was performed for and funded by the TWDB’s Innovative Water Technologies section to support their Brackish Resources Aquifer Characterization System. Key to their mission is the collection and organization of basic aquifer data to support the understanding and delineation of brackish groundwater resources in Texas. This specific study was authorized under H.B. 30 passed by the 84th Texas Legislative Session and is specific to the Trinity Aquifer in Texas. Our proposed list of potential future improvements focuses both on the larger mission of the TWDB Innovative Water Technologies section’s Brackish Resources Aquifer Characterization System, and further study in the Trinity Aquifer specifically.

The following are future improvements that we propose for consideration by the TWDB:

- There is a general lack of data in the brackish aquifers in Texas, but there is an extreme lack of good hydrogeologic data that can be used to describe aquifer hydraulic properties in the Trinity Aquifer, especially in the downdip portions of the aquifer.
- To evaluate the methods used to estimate groundwater salinity from geophysical log data, we recommend that the TWDB set up a few small-scale pilot studies in coordination with drilling and logging companies with the goal of providing data to ground truth the methods used to interpret geophysical logs to estimate total dissolved solids concentrations.
- The geologic cross-sections developed in this study provide evidence of the lithologic and structural complexity of this aquifer. Future investigators should be aware that this study has not mapped all of the faults in this system, nor can interpolated surfaces be locally accurate in a structural setting with this amount of complexity over such a large project area. Future investigators of the brackish resources of the Trinity Aquifer will need to perform their own drilling and mapping to better understand the local aspects of the aquifer and how local variations in structure and lithology may impact brackish resources. Local investigators are urged to provide local characterization data to the TWDB to support the improvement in understanding of the aquifer.
- The evaluation of pumping impacts for the Northern Trinity portion of the study area relied on the existing Groundwater Availability Model. The model had less calibration data in the brackish portion than in the fresh portion, so the hydraulic parameters were not as well-constrained in the brackish portion. As additional aquifer testing occurs during continued development of the brackish portion of the aquifer, the model parameterization in the brackish portion should be revisited.

16 Conclusions

The Trinity Aquifer is a TWDB designated major aquifer in the state of Texas and underlies all or parts of 52 counties in central to northern Texas (Figure 2-1 and 2-2). The Trinity Aquifer is designated as a major aquifer because it provides large quantities of water in large areas of the state. The Trinity Aquifer consists of several water-producing formations or aquifers (the Paluxy, Glen Rose, Hensell, Pearsall, Cow Creek, and Hosston formations), as shown in Figure 2-3.

This study was performed under contract to the TWDB to support work authorized under House Bill 30, passed by the 84th Texas Legislative Session. This bill requires the TWDB to identify and designate brackish groundwater production zones in Texas aquifers, and the Trinity Aquifer was designated as one of the aquifers requiring an investigation. The objective of this study is to characterize the quantity and quality of groundwater within the Trinity Aquifer and to evaluate potential production areas that can be used by the TWDB staff to make recommendations to the Executive Administrator and the Board on designation of brackish groundwater production zones.

The following conclusions can be drawn from this study:

- In order to estimate water quality from geophysical logs in this study, the Alger-Harrison (1989) or resistivity ratio methods were found to be most suitable. This method requires resistivity values of mud filtrate (R_{mf}) from the log header and deep (R_t) and shallow resistivities (R_{xo}) from the borehole data. Advantages of using this method are that it does not require calculation of formation temperatures, and the method minimizes the effect of surface conductance. The disadvantages of this method include that it often requires adjustments of resistivity values due to tool differences, and values must be adjusted for influence of variable chemistry. This study has documented that calculation and analysis of water quality from geophysical logs in the Trinity Aquifer is very complex and requires advanced petrophysical techniques to accurately derive water quality (total dissolved solids) estimates. This study provides a groundwork for these techniques.

- We analyzed TDS concentrations estimated from 123 geophysical well logs along with measured TDS concentrations from 2519 water wells to define TDS boundary lines across the study area. These lines allowed us to delineate the geometry of five salinity classes in each hydrogeologic formation: freshwater, slightly saline, moderately saline, very saline, and brine waters.

- We used these TDS boundary lines, the geometry of the binned TDS zones, our hydrogeological analysis, and criteria set forth by House Bill 30 to identify 19 potential brackish production areas (four in the Hill Country Trinity Aquifer and fifteen in the Northern Trinity Aquifer).

- There is a general lack of hydrogeologic data in the brackish portions of the Trinity Aquifer. The absence of data is significant and especially limiting in the downdip area of both the Northern Trinity and Hill Country Trinity Aquifers.

- The volume of the Trinity Aquifer defined for this study contains approximately 2 billion acre feet of groundwater. Out of the 2 billion acre feet of groundwater, 552 million acre feet is freshwater, 582 million acre feet is slightly saline groundwater, 501 million acre feet is moderately saline groundwater, and 470 million acre feet is very saline groundwater. These groundwater volumes are tabulated by groundwater management areas, groundwater conservation districts, and counties for each geological formation in section 12 of this report.

17 Acknowledgements

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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 Bull., 36, 253–277.

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

Young, K., 1972, Mesozoic history, Llano region: in Barnes, V. E., Bell, W. C., Clabaugh, S. E., and Cloud, P. E., eds., Geology of the Llano region and Austin area, field excursion, The University of Texas at Austin, Bureau of Economic Geology Guidebook 13, 77 p.

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, Gulf Coast Report. . Identification of Potential Brackish Groundwater Production Areas – Gulf Coast Aquifer System: Prepared for the Texas Water Development Board, 664p. https://www.twdb.texas.gov/publications/reports/numbered_reports/doc/R318/R318.pdf

19 Appendices

19.1 Hill Country Trinity Aquifer Lithologic Fence Diagrams

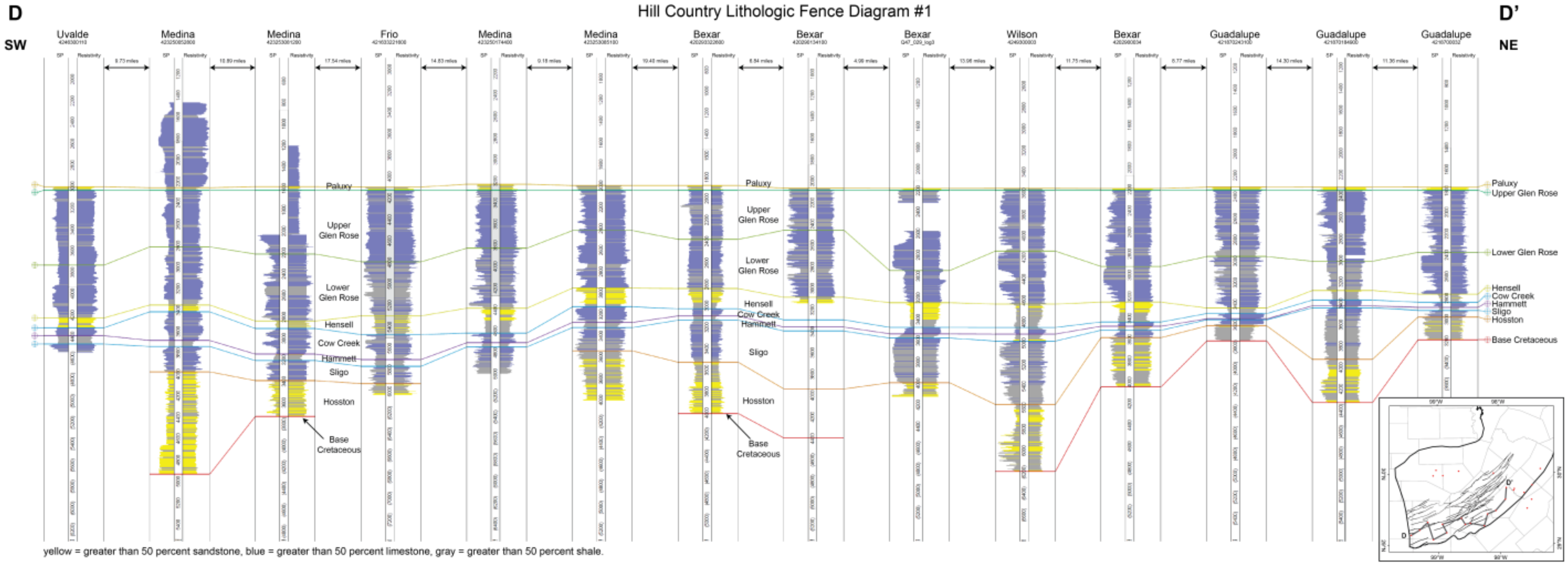
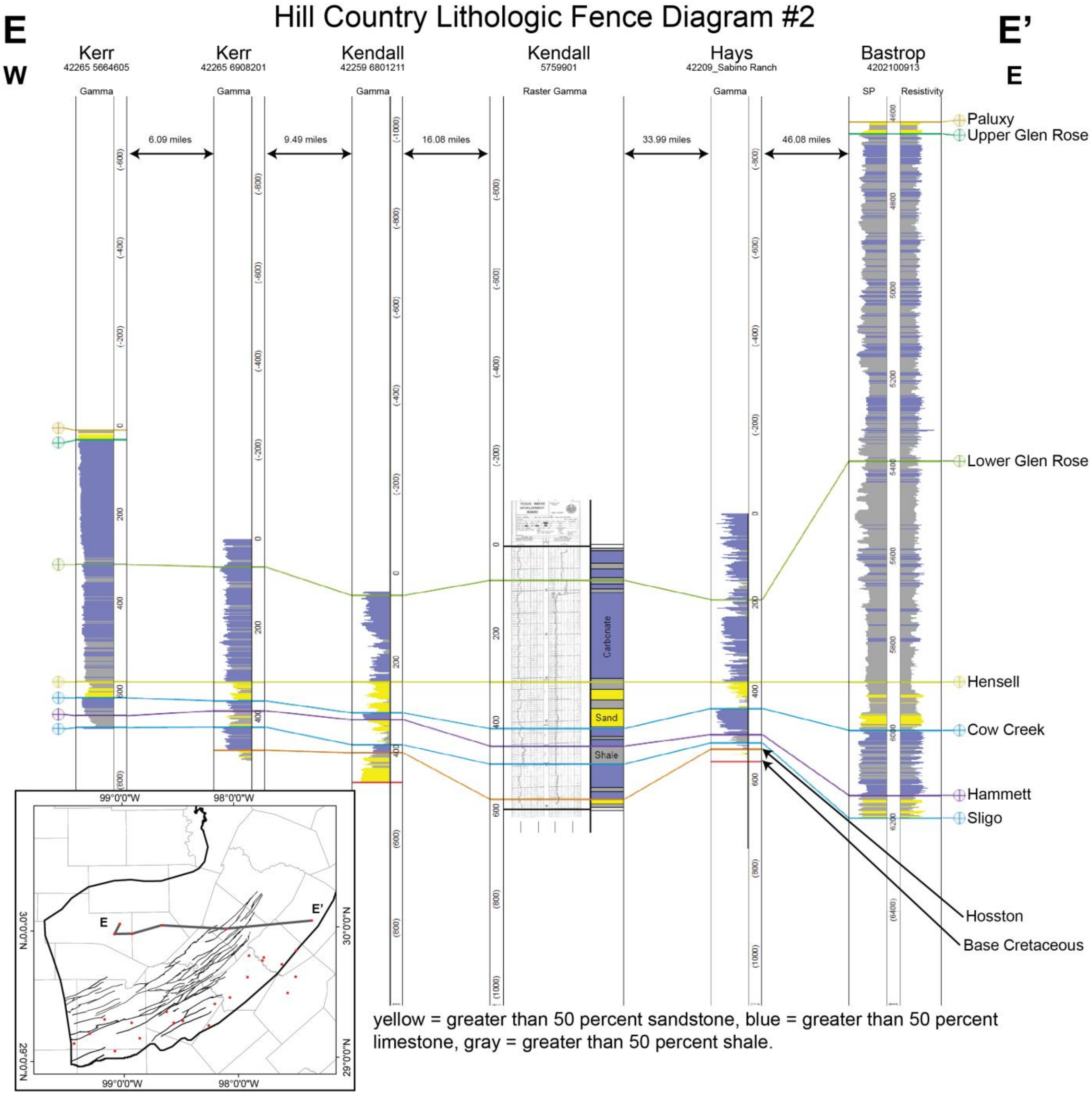
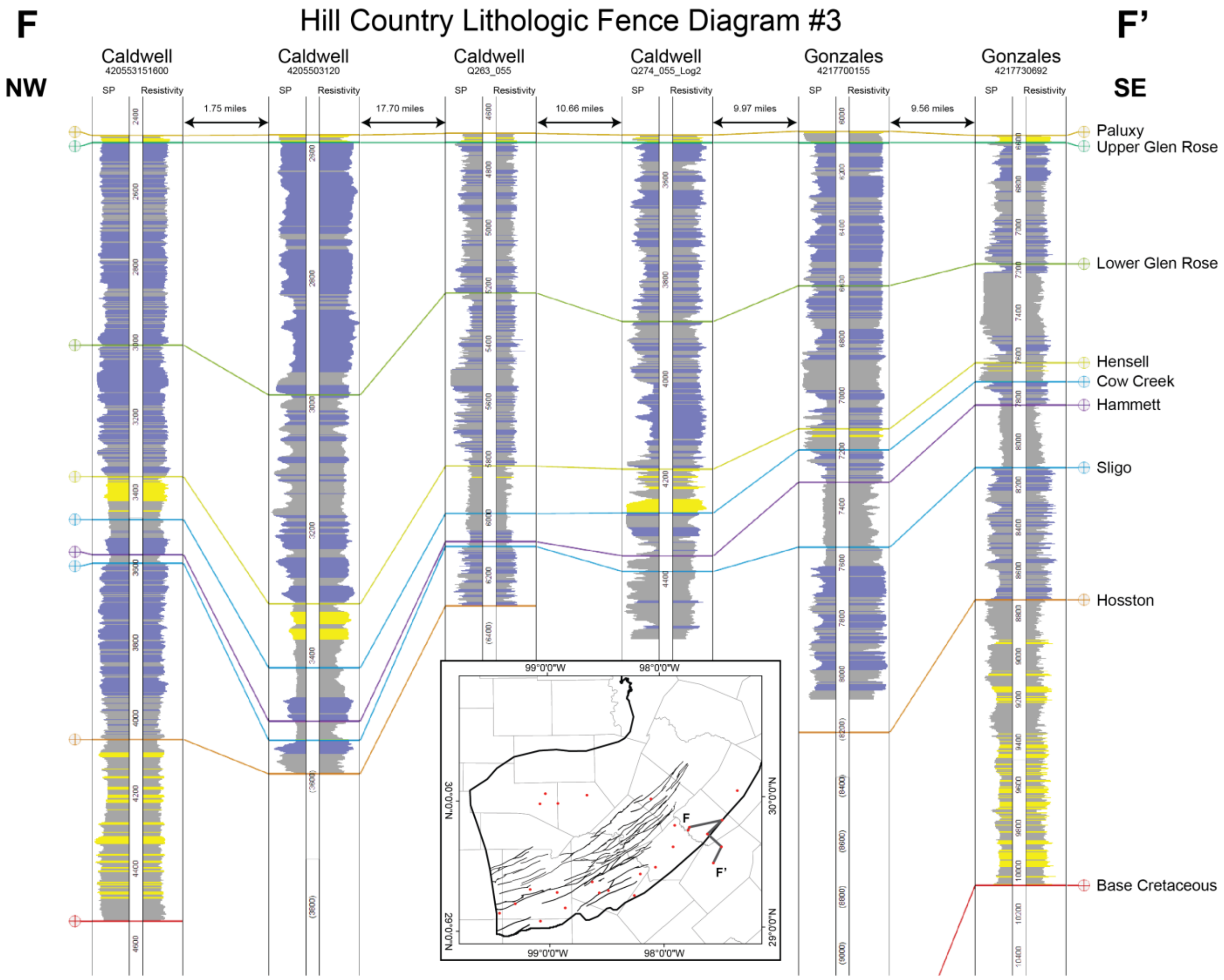


Figure 19-1-1:Lithologic fence diagram D-D'



yellow = greater than 50 percent sandstone, blue = greater than 50 percent limestone, gray = greater than 50 percent shale.

Figure 19-2 **Lithologic fence diagram E-E'**



yellow = greater than 50 percent sandstone, blue = greater than 50 percent limestone, gray = greater than 50 percent shale.

Figure 19-3 **Lithologic fence diagram F-F’**

19.2 Thickness table for Hill Country Trinity Stratigraphic Units

This table was created from literature evaluated for use in this project in order to help constrain the top and bottom depths as well as thicknesses of each stratigraphic unit based on previously reported information.

[Thickness Table page 1]

[Thickness Table page 2]

[Thickness Table page 3]

[Thickness Table page 4]

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[Thickness Table page 6]

[Thickness Table page 7]

[Thickness Table page 8]

[Thickness Table page 9]

[Thickness Table page 10]

[Thickness Table page 11]

[Thickness Table page 12]

[Thickness Table page 13]

[Thickness Table page 14]

19.3 Northern Trinity Aquifer Thickness and Isopach Maps

These maps were created using data utilized to create the Northern Trinity GAM (Kelley et al., 2014), but were not included in that report.

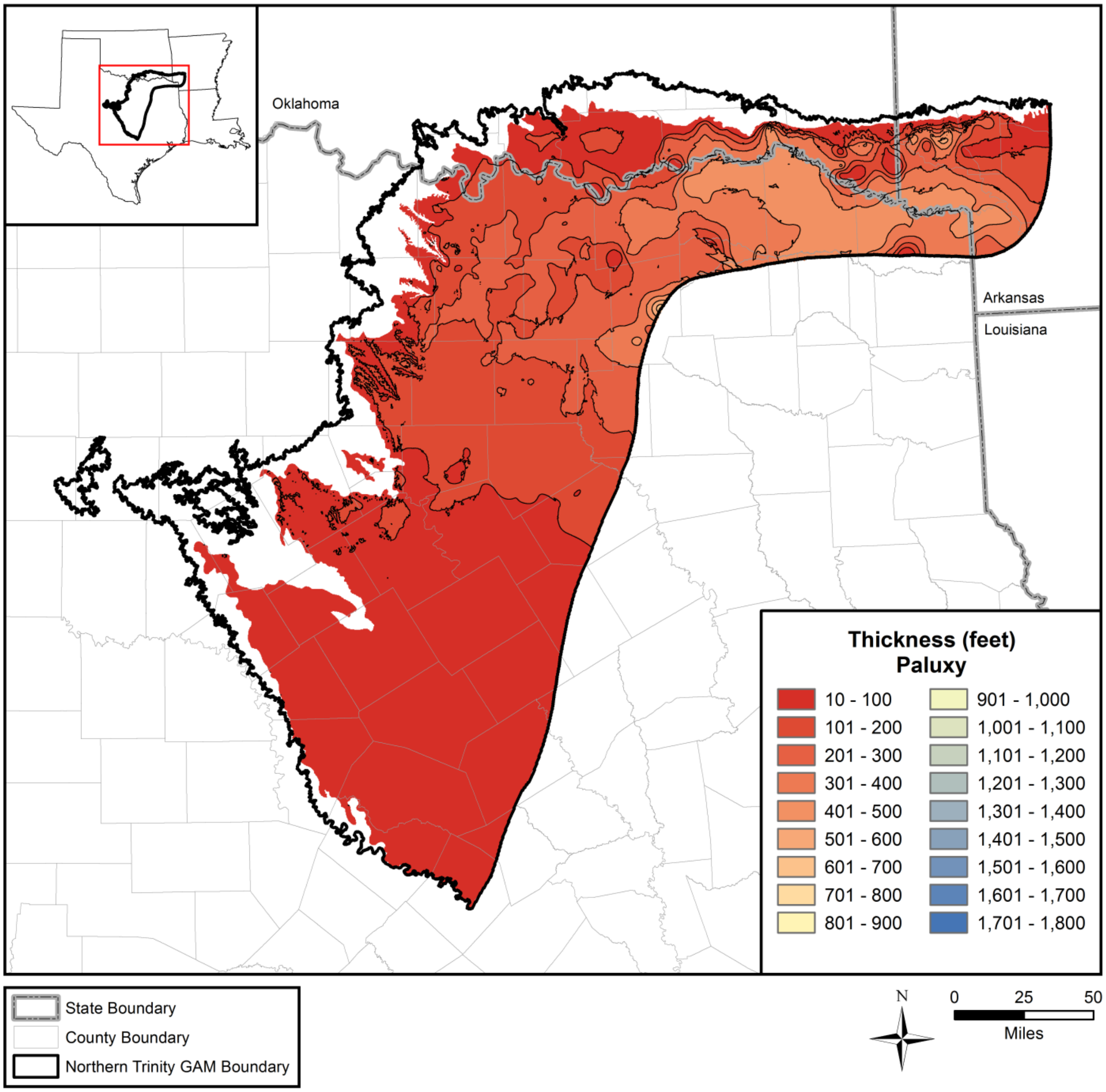

Figure 19-4 Isopach map of the Paluxy Sand in the Northern Trinity Aquifer.

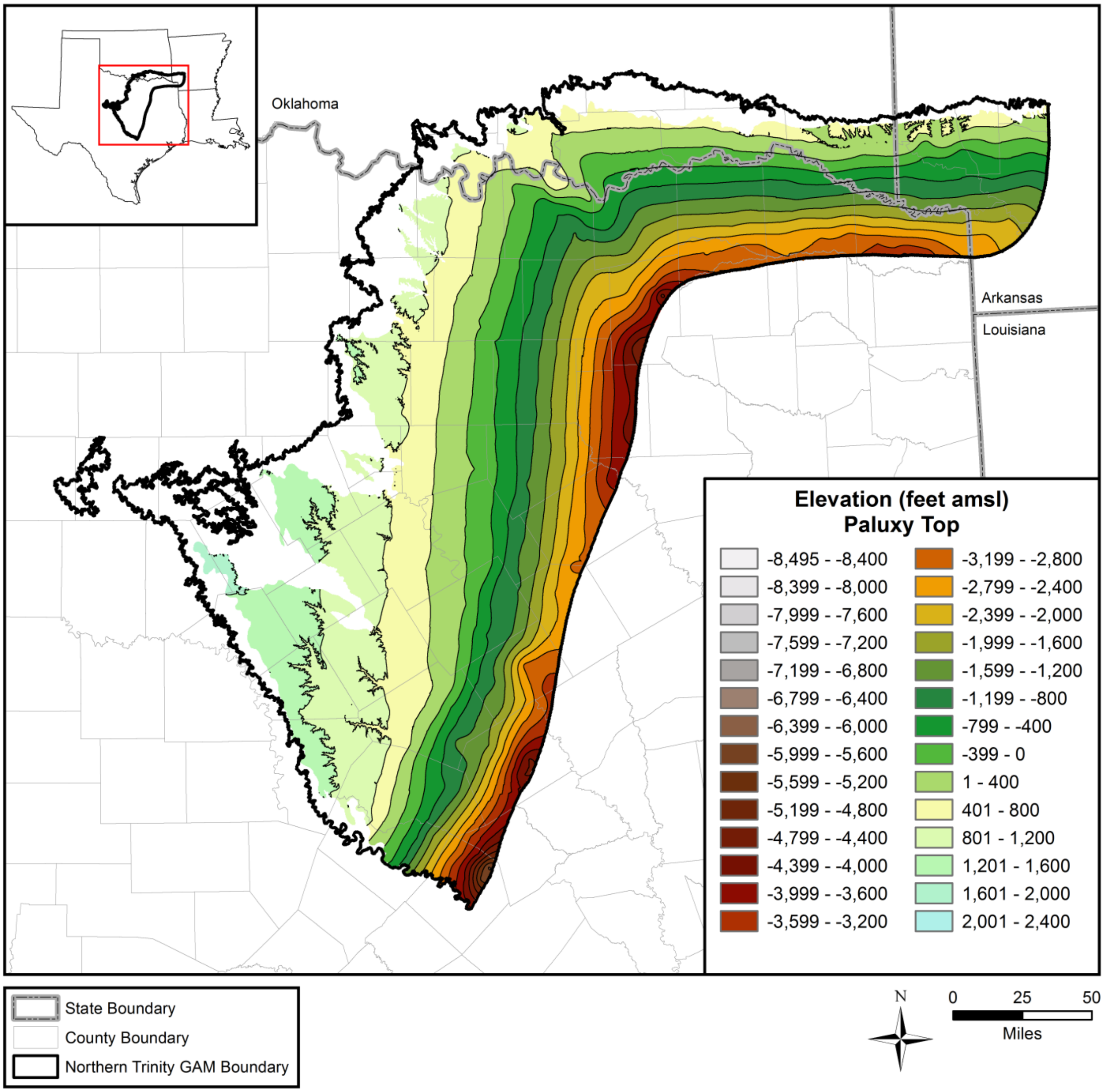

Figure 19-5 Top elevation of the Paluxy Sand in the Northern Trinity Aquifer.

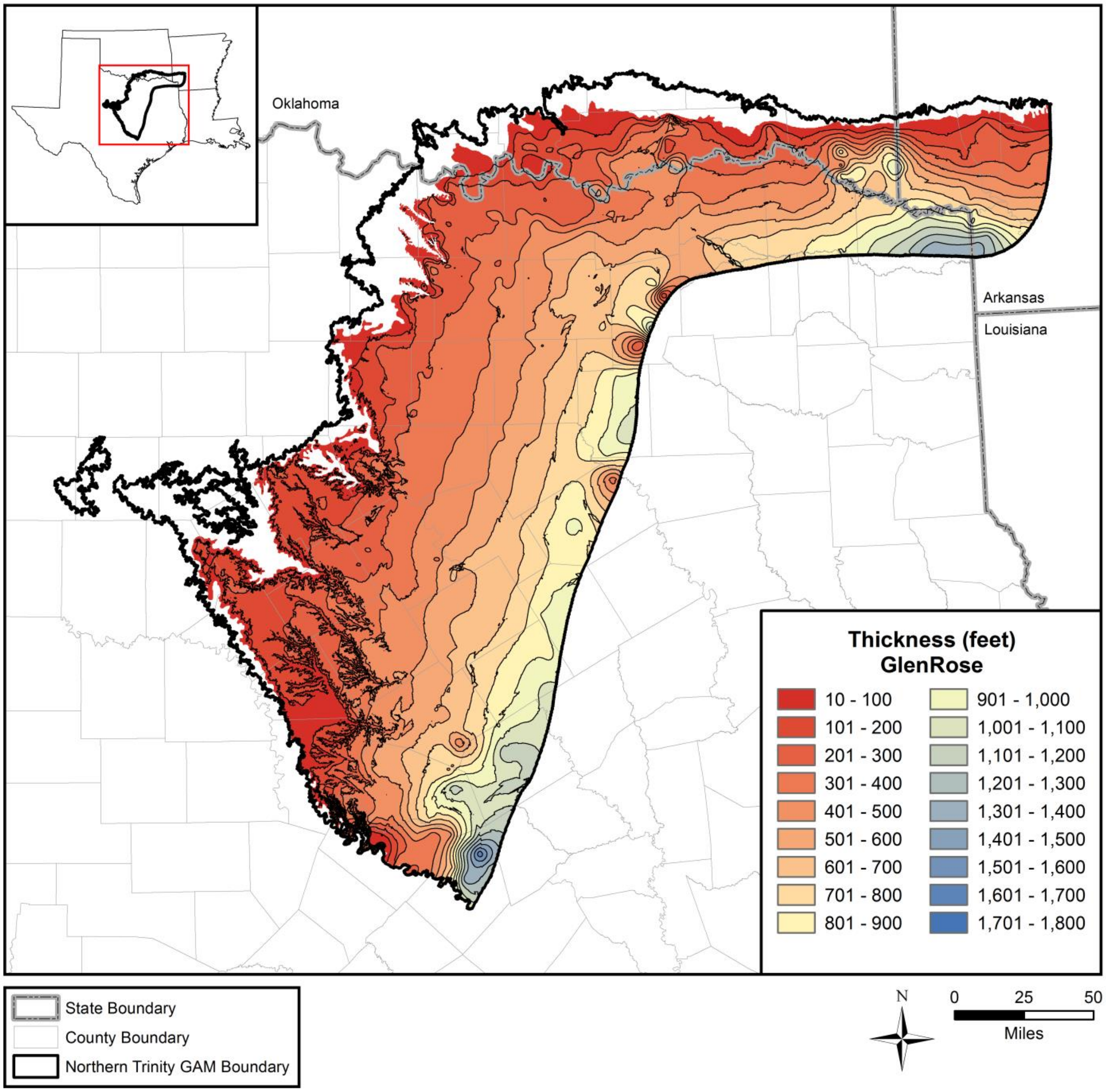

Figure 19-6 **Isopach map of the Glen Rose Limestone in the Northern Trinity Aquifer**

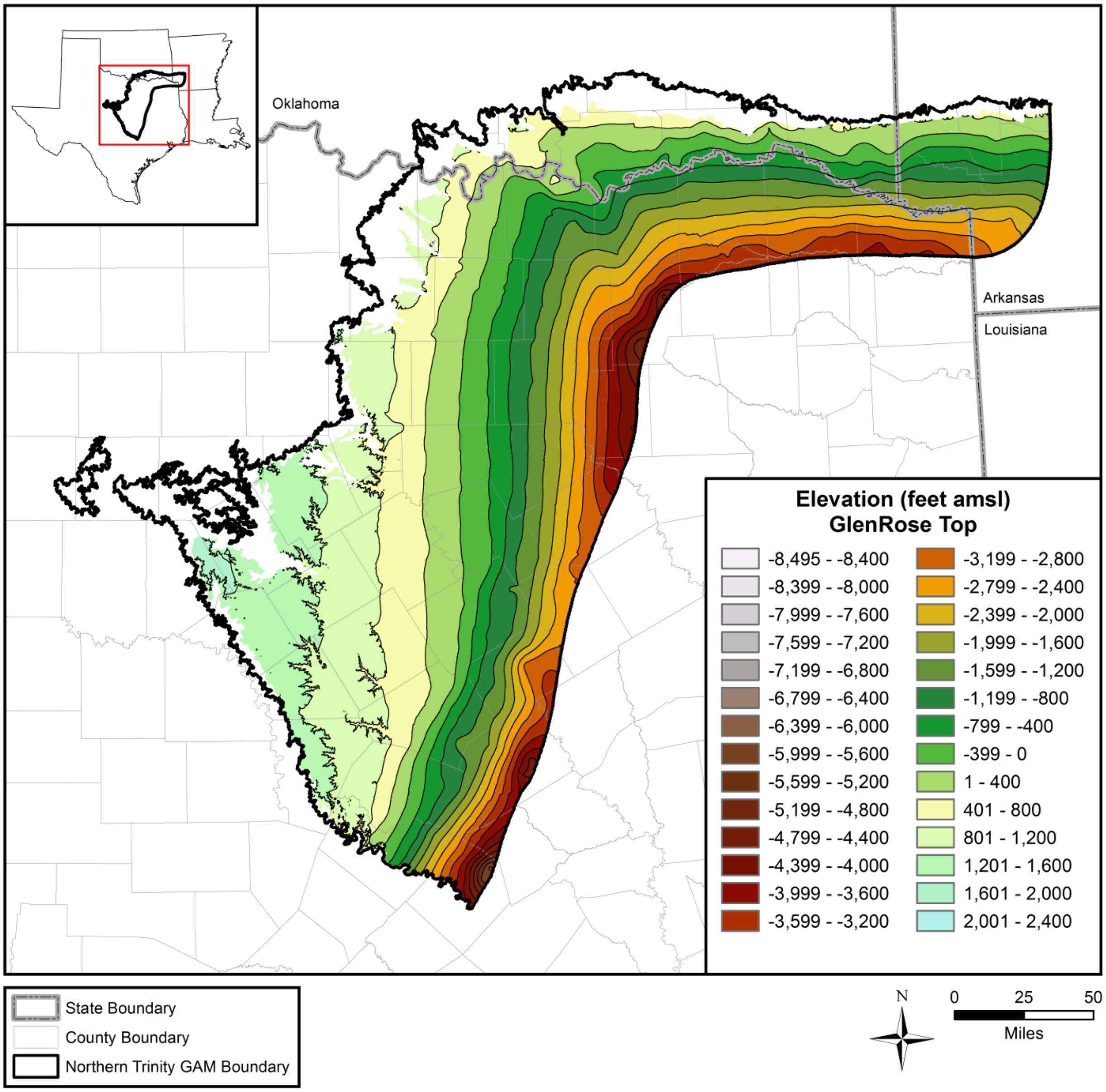

Figure 19-7 **Top elevation of the Glen Rose Limestone in the Northern Trinity Aquifer**

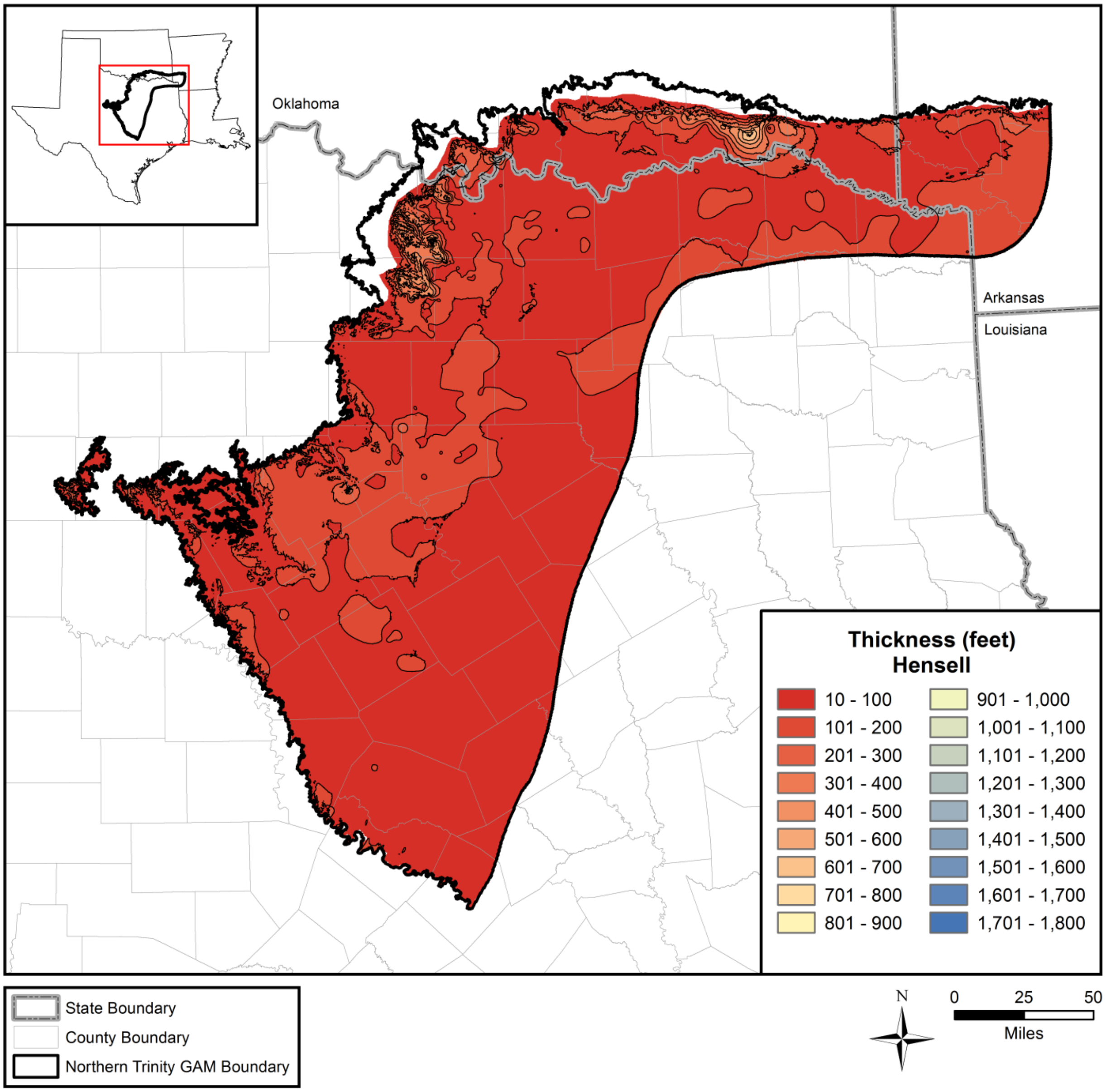

Figure 19-8 Isopach map of the Hensell Sand in the Northern Trinity Aquifer

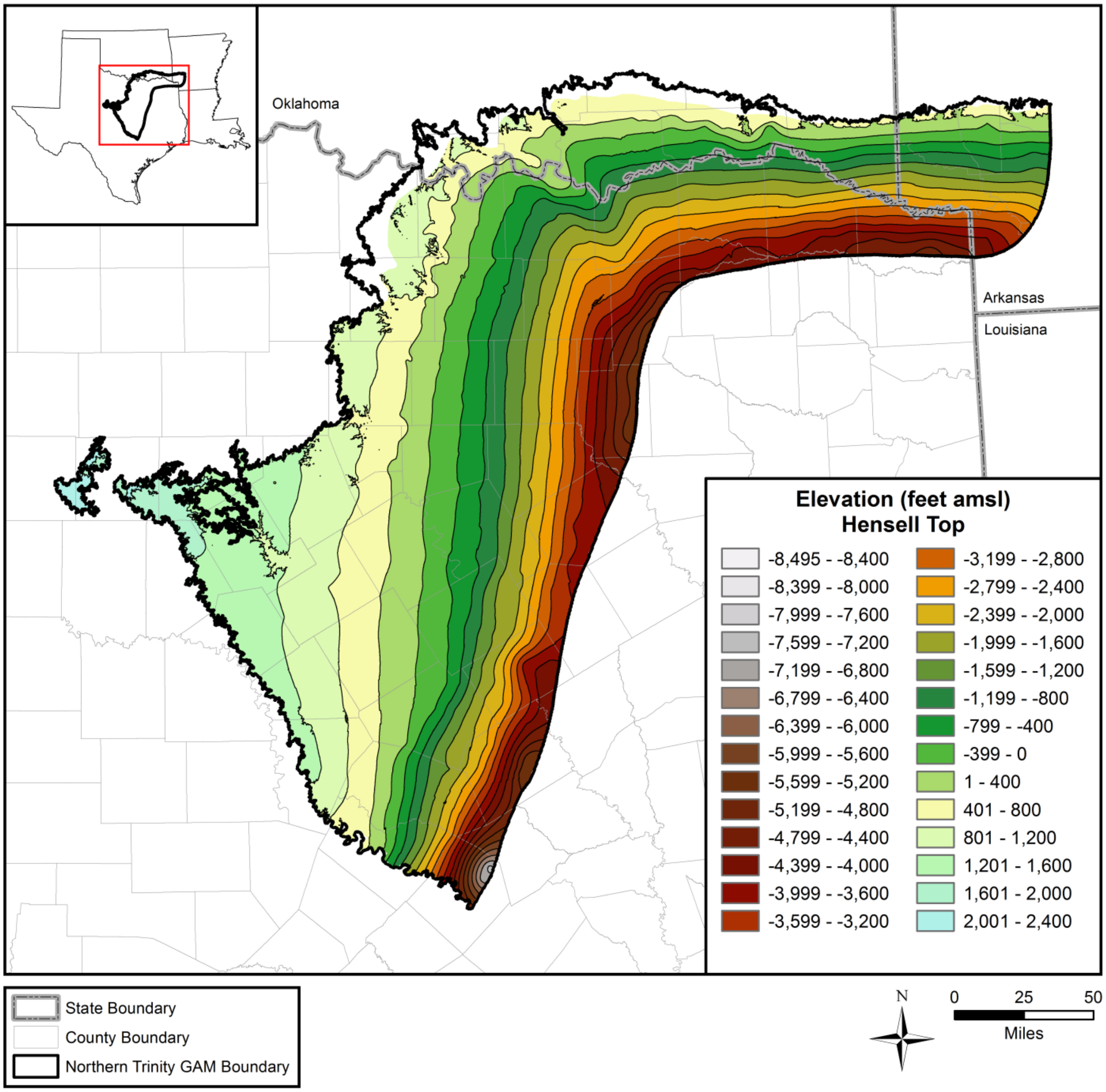

Figure 19-9 **Top elevation of the Hensell Sand in the Northern Trinity Aquifer**

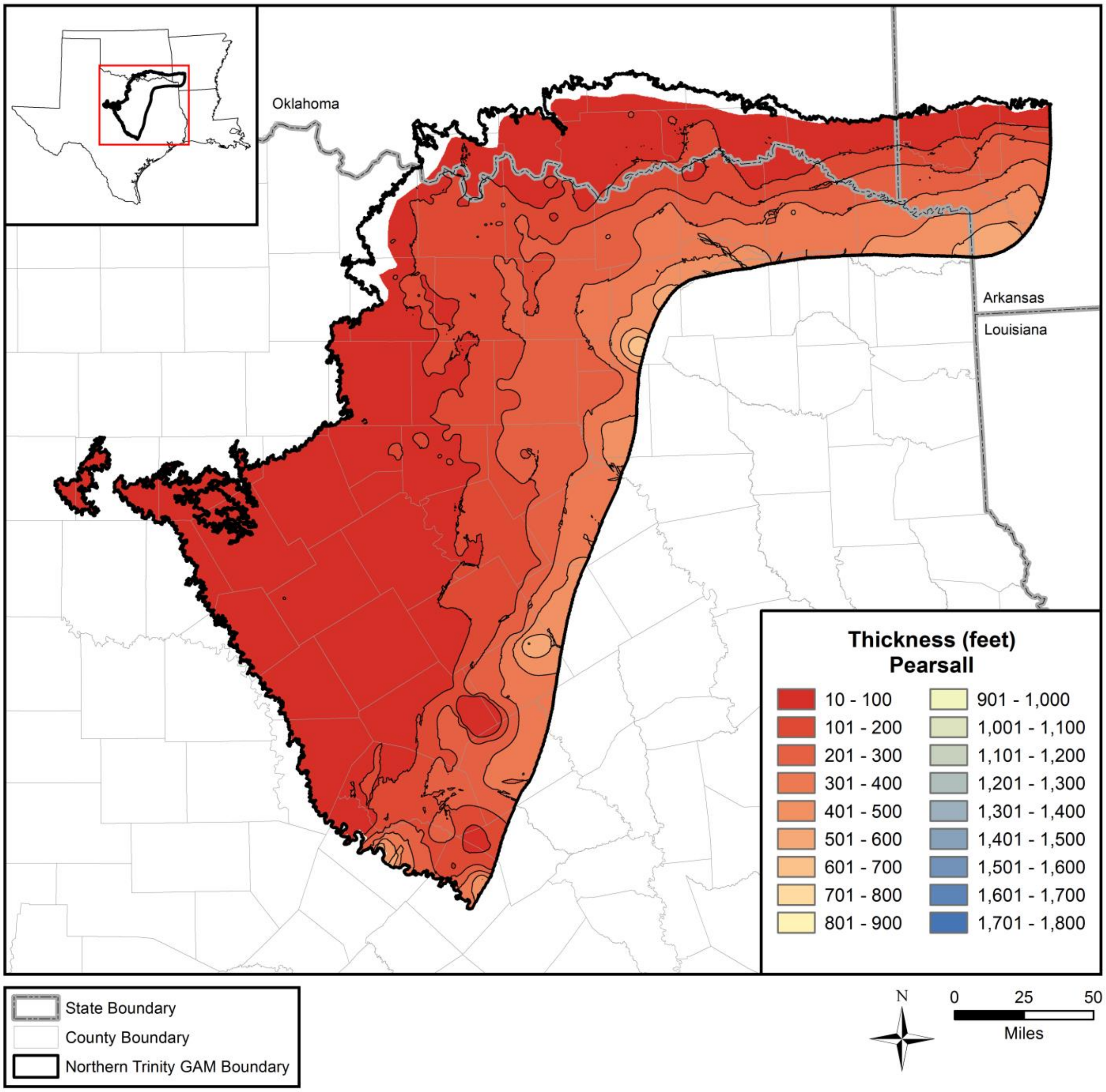

Figure 19-10 **Isopach map of the Pearsall Shale in the Northern Trinity Aquifer**

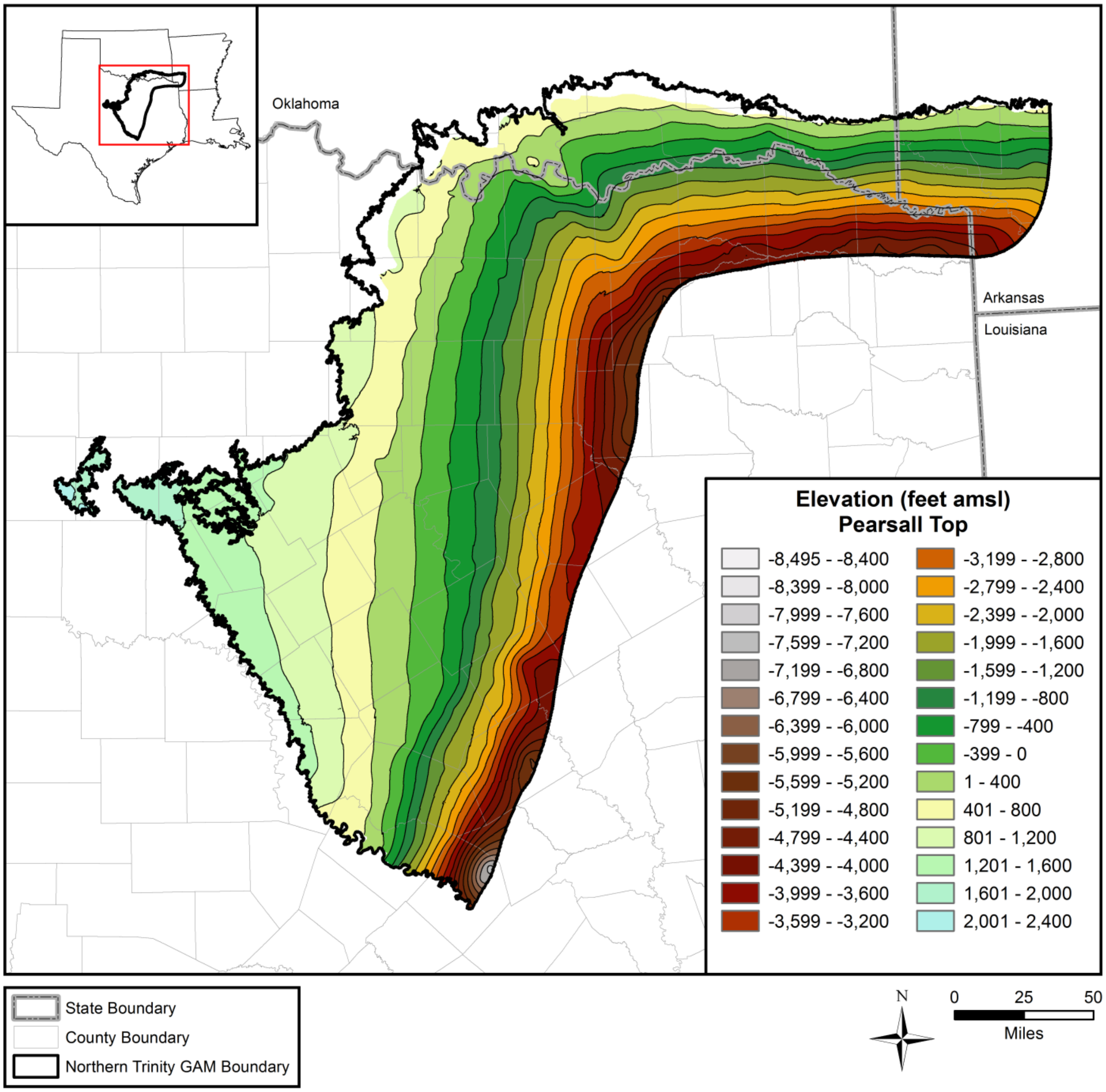

Figure 19-11 Top elevation of the Pearsall Shale in the Northern Trinity Aquifer

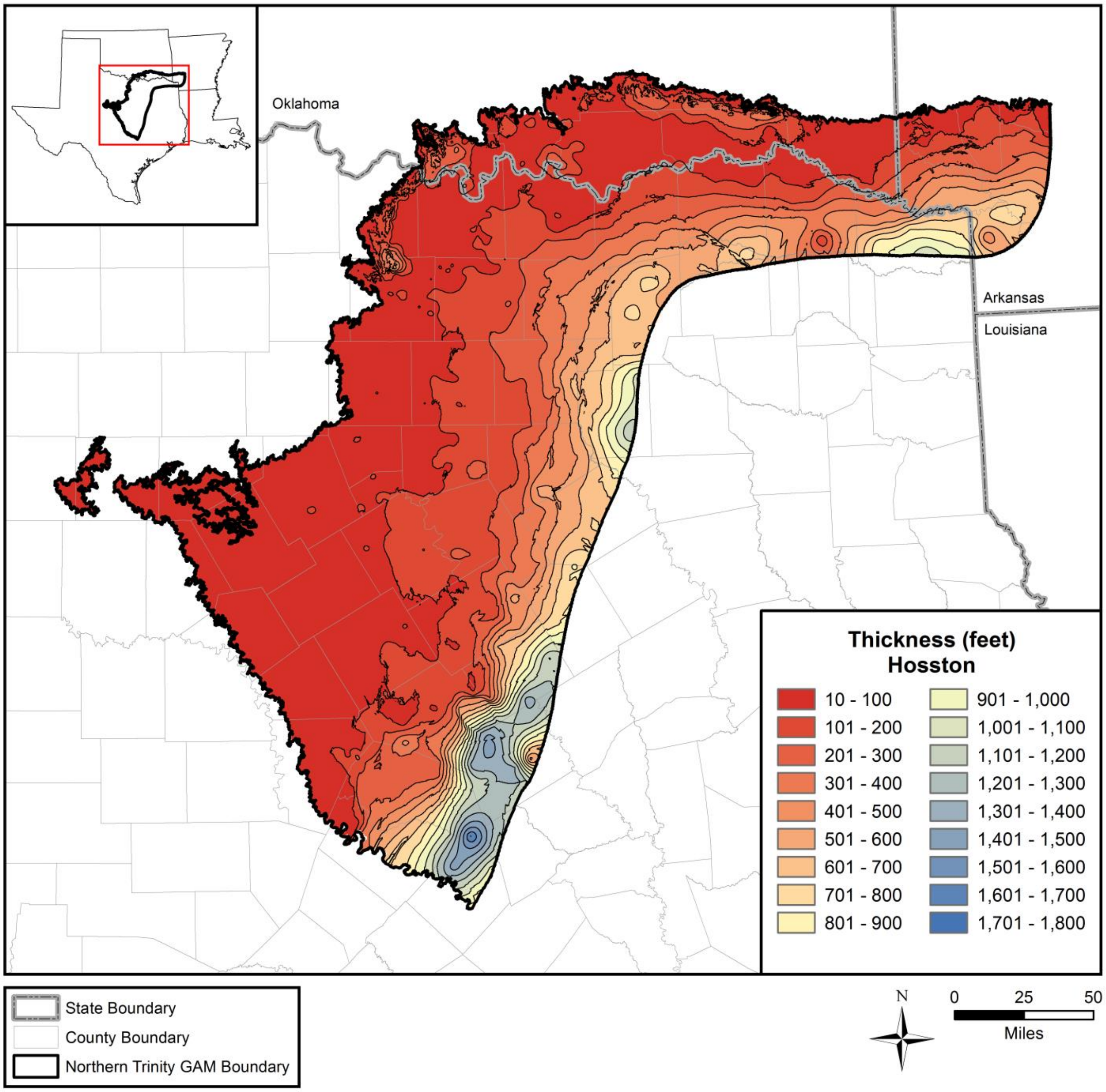

Figure 19-12 Isopach map of the Hosston Sand in the Northern Trinity Aquifer

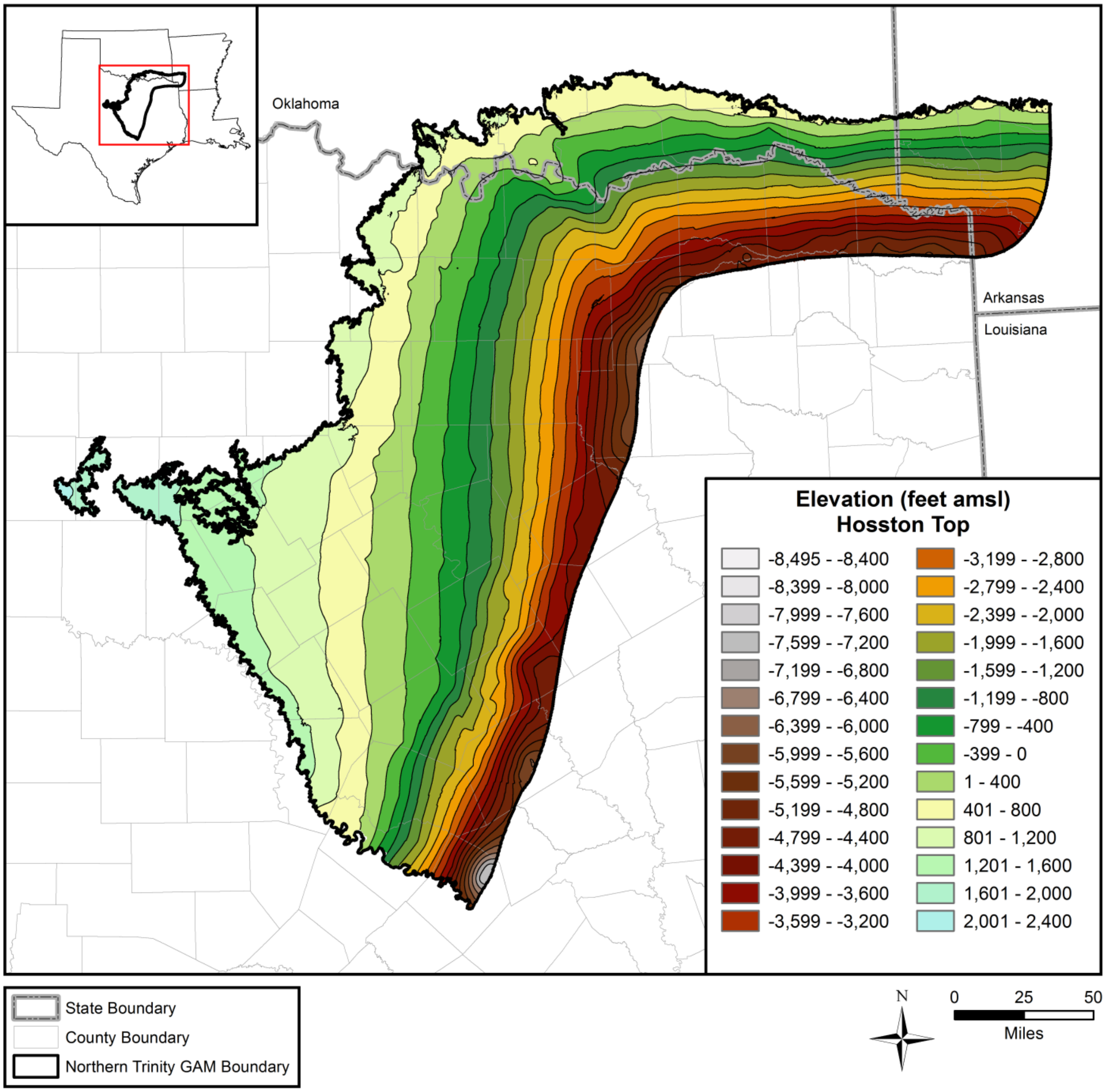

Figure 19-13 Top elevation of the Hosston Sand in the Northern Trinity Aquifer

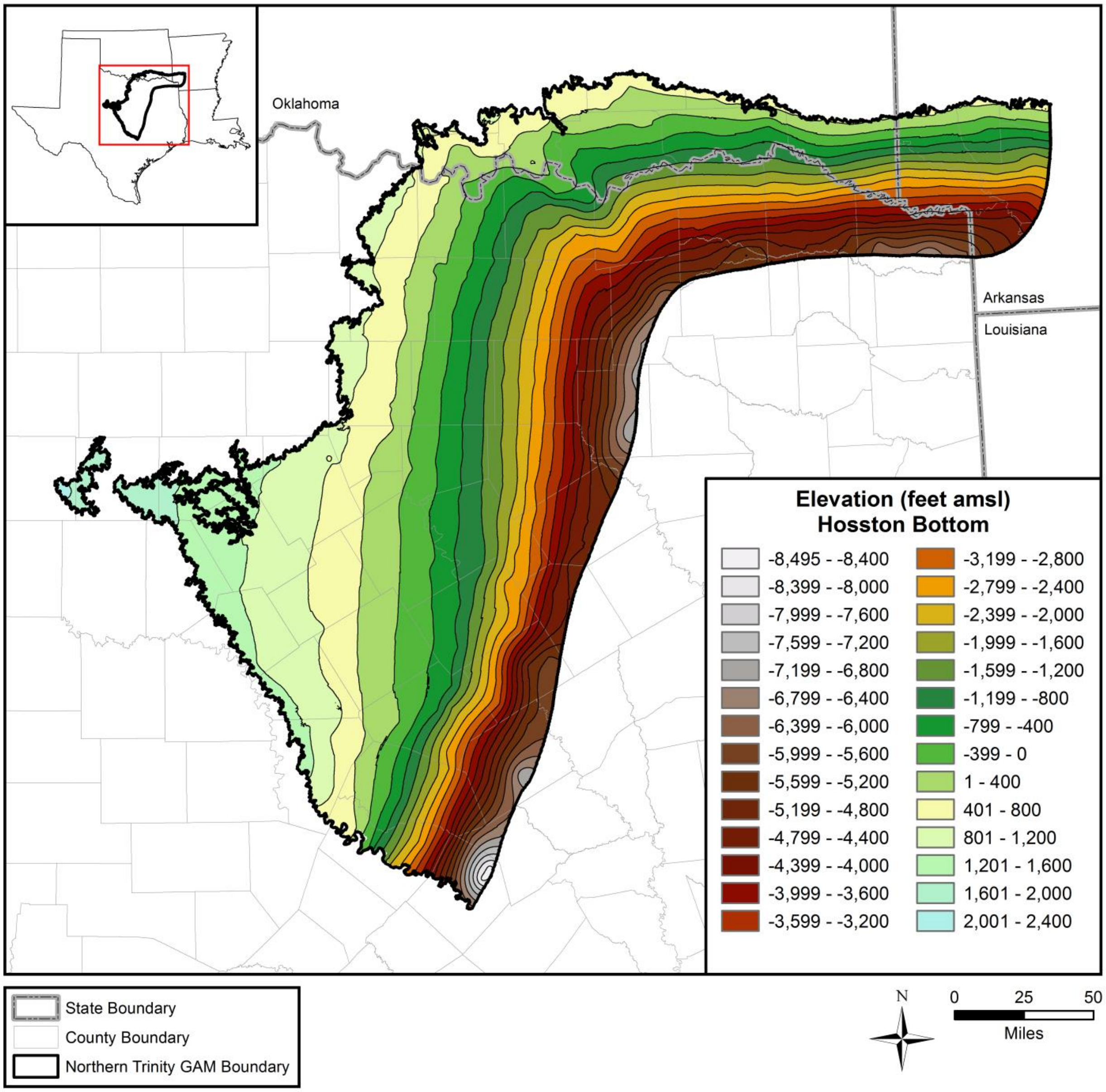

Figure 19-14 **Bottom of elevation of the Hosston Sand in the Northern Trinity Aquifer**

19.4 GIS file name codes

During the course of this study, spatial analyses heavily relied on the use of ESRI ArcGIS 10.4. Table 19-1 outlines seven different categories of feature datasets and raster catalogs used in report figures for this study. Tables 19-2 – 19-8 describe the contents of each feature dataset or raster catalog in further detail, specifically the file types and names and their associated descriptions. Feature datasets include any combination of point, polyline, and polygon shapefiles. Similarly, raster catalogs include raster datasets. All files in the geodatabase are projected in TWDB's Groundwater Availability Model (GAM) coordinate system.

Table 19-1 Feature datasets and raster catalogs, along with descriptions, used in this study and included in geodatabase deliverable.

Name	Type	General Description
Boundaries	Feature Dataset	Shapefiles with boundaries for various information displayed on figures
Framework_Rasters	Raster Catalog	Rasters with formation thickness, surface elevation, and formation top elevation
Geology	Feature Dataset	Shapefiles with geologic information
Previous_Investigations	Feature Dataset	Rasters with total dissolved solids and recharge data from previous studies
Salinity_Zones	Feature Dataset	Shapefiles with salinity zone contour lines
Water_Quality_Data	Feature Dataset	Shapefiles with water quality data
Wells_Lines_Zones	Feature Dataset	Shapefiles with well point locations, section lines, and potential production area zones

Table 19-2 Shapefiles included in the Boundaries feature dataset.

Description	File type	File Name
Outcrop and Subcrop of the Trinity Aquifer	Polygon	TrinityAquifer
Model Boundary for this project	Polygon	ModelBoundary
River authority boundaries	Polygon	TWDB_RiverAuthorities
River basin boundaries	Polygon	TWDB_MRBs_2014
Regional water planning group boundaries	Polygon	TWDB_RWPAs_2014
Groundwater conservation district boundaries within the study area	Polygon	GCDs_Study_Area
County boundaries	Polygon	CountyBoundary
State Boundary	Polygon	StateBoundary
Barton Springs Groundwater Conservation Districts	Polygon	Barton_Springs_GCD
Edwards Aquifer	Polygon	Edwards_Aquifer
SwRI Data acquisition domain for the Hill Country study area	Polyline	HCT_Data_Acquisition_Domain
Northern Trinity GAM boundary (Kelley et al., 2014) and data acquisition/model boundary for Intera	Polygon	NT_GAM_Boundary
Framework model domain for the Hill Country study area	Polygon	HCT_Framework_Domain
Model boundary for Hill Country GAM (Jones et al., 2011)	Polygon	Hill_Country_Trinity_GAM_Boundary

Table 19-3 Raster datasets included the in the Framework_Rasters raster catalog.

Description	File type	File Name*
Isopach showing the thickness of the Georgetown Formation	Raster	George_iso
Isopach showing the thickness of the Edwards Group	Raster	Edwards_iso
Isopach showing the thickness of the Paluxy Formation	Raster	Paluxy_iso
Isopach showing the thicknessof the Upper Glen Rose Formation	Raster	ugr_iso
Isopach showing the thickness of the Lower Glen Rose Formation	Raster	lgr_iso
Isopach showing the thickness of the Hensell Sands	Raster	hensell_iso
Isopach showing the thickness of the Cow Creek Limestone	Raster	cc_iso
Isopach showing the thickness of the Hammett Shale	Raster	hammett_iso
Isopach showing the thickness of the Sligo Formation	Raster	sligo_iso
Isopach showing the thickness of the Hosston Formation	Raster	hosston_iso
Digital Elevation model for the Hill country model area	Raster	HCT_DEM
Structural surface of the top of the Georgetown Formation	Raster	George_clip
Structural surface of the top of the Edwards Group	Raster	Edwards_clip
Structural surface of the top of the Paluxy Formation	Raster	Paluxy_clip
Structural surface of the top of the Upper Glen Rose Formation	Raster	ugr_clip
Structural surface of the top of the Lower Glen Rose Formation	Raster	lgr_clip
Structural surface of the top of the Hensell Sands	Raster	hensell_clip
Structural surface of the top of the Cow Creek Limestone	Raster	cc_clip
Structural surface of the top of the Hammett Shale	Raster	hammett_clip
Structural surface of the top of the Sligo Formation	Raster	sligo_clip
Structural surface of the top of the Hosston Formation	Raster	hosston_clip
Structural surface of the top of Pre-Cretaceous strata	Raster	prek_clip

* In the file name structure, ‘iso’ is an abbreviation for ‘isopach’. File names ending in ‘clip’ were clipped in ArcGIS to the Model Boundary described in Table 19-1-2.

Table 19-4 Shapefiles included in the Geology feature dataset.

Description	File type	File Name
Surface Geology	Polygon	Surface_Geology_NT
Surface Geology	Polygon	Pre_Cretaceous_NT
Surface Geology	Polygon	Travis_Peak_NT
Surface Geology	Polygon	Surface_Water
Surface Geology	Polygon	Quaternary_Alluvium
Surface Geology	Polygon	Tertiary_Aged_Sediments
Surface Geology	Polygon	K_Igneous
Surface Geology	Polygon	Gulfian_Above_Woodbine
Surface Geology	Polygon	Washita_Group
Surface Geology	Polygon	Fredericksburg_Group
Surface Geology	Polygon	Glen_Rose_all
Surface Geology	Polygon	Travis_Peak_Formation
Surface Geology	Polygon	Pre_Cretaceous_Undifferentiated

Table 19-5 Shapefiles included in the Previous Investigations feature dataset.

Description	File type	File Name
LBG Guyton TDS Contours, 2003	Polyline	LBG_Guyton_TDS_Contours_2003
Hill Country GAM (Jones et al., 2011)	Polygon	HCTrinity_GAM
Northern Trinity GAM (Kelley et al., 2014)	Polygon	NTrinity_GAM

Table 19-6 Shapefiles included in the Salinity feature dataset.

Description	File type	File Name
SwRI Calculated TDS Contour Glen Rose Formation	Polyline	GlenRose_SwRI_TDS_Contours
SwRI Calculated TDS Contour Hensell Formation	Polyline	Hensell_SwRI_TDS_Contours
SwRI Calculated TDS Contour Cow Creek Formation	Polyline	CowCreek_SwRI_TDS_Contours
SwRI Calculated TDS Contour Hosston Formation	Polyline	Hosston_SwRI_TDS_Contours
Intera Calculated TDS Contour Paluxy Formation	Polyline	PaluxyTDSLines
Combined HCT/NT Calculated TDS Contour Glen Rose Formation	Polyline	GlenRose_Combined_TDS_Contour
Combined HCT/NT Calculated TDS Contour Hensell Formation	Polyline	Hensell_Combined_TDS_Contour
Combined HCT/NT Calculated TDS Contour Pearsall Formation	Polyline	CowCreek_Combined_TDS_Contour
Combined HCT/NT Calculated TDS Contour Hosston Formation	Polyline	Hosston_Combined_TDS_Contour

Description	File type	File Name
Wells with geophysical logs considered for Glen Rose Formation TDS calculations, Hill Country Trinity Aquifer	Point	GlenRose_TDS_Calc_Pts_final
Wells with geophysical logs considered for Hensell Formation TDS calculations, Hill Country Trinity Aquifer	Point	Hensell_TDS_Calc_Pts_final
Wells with geophysical logs considered for Cow Creek Formation TDS calculations, Hill Country Trinity Aquifer	Point	CowCreek_TDS_Calc_Pts_final
Wells with geophysical logs considered for Hosston Formation TDS calculations, Hill Country Trinity Aquifer	Point	Hosston_TDS_Calc_Pts_final

Table 19-7 Shapefiles included in the Water Quality Data feature dataset.

Description	File type	File Name
Hill Country Trinity Glen Rose Limestone water quality sample from TWDB-GWDB	Point	GlenRoseSampleHCT
Hill Country Trinity Hensell Sand water quality sample from TWDB-GWDB	Point	HensellSampleHCT
Hill Country Trinity Cow Creek Limestone water quality sample from TWDB-GWDB	Point	CowCreekSampleHCT
Hill Country Trinity Hensell Sand water quality sample from TWDB-GWDB	Point	HosstonSampleHCT
Northern Trinity Paluxy water quality sample from TWDB-GWDB	Point	PaluxySampleNT
Northern Trinity Glen Rose Limestone water quality sample from TWDB-GWDB	Point	GlenRoseSampleNT
Northern Trinity Hensell Sand water quality sample from TWDB-GWDB	Point	HensellSampleNT
Northern Trinity Pearsall Shale water quality sample from TWDB-GWDB	Point	PearsallSampleNT
Northern Trinity Hosston Sand water quality sample from TWDB-GWDB	Point	HosstonSampleNT

Table 19-8 Shapefiles included in the Wells Lines Zones feature dataset.

Description	File type	File Name
Image logs used for constructing the framework model	Point	Image_Logs
Digitaized logs used for constructing the framework model	Point	Digital_Logs
Digitized logs interpreted for lithology	Point	Digital_Lithology_Wells_GAM
Data sources for the wells used in the framework model	Point	Well_Source
Wells from Submitted Drillers Report database	Point	SDR_Wells
Ranch and Public wells producing from the Trintiy Aquifer	Point	Domestic_Ranch_and_Public_Wells
Public well producing from the Trinity Aquifer	Point	Public_Water_Supply_Wells
Faults used in the framework model (after Fratesi et al., 2015)	Polyline	Modeled_Faults
Faults from the Geologic Atlas of Texas	Polyline	GAT_Faults
Lithologic Cross Section	Polyline	Lithology_Cross_Section_1
Lithologic Cross Section	Polyline	Lithology_Cross_Section_2
Lithologic Cross Section	Polyline	Lithology_Cross_Section_3
Geologic Cross Section	Polyline	Trinity_A-APrime
Geologic Cross Section	Polyline	Trinity_B-BPrime
Geologic Cross Section	Polyline	Trinity_C-CPrime
Freshwater exclusion zone	Polygon	Freshwater_Exclusion_Zone
Producing wells exclusion zone	Polygon	Producing_Wells_Exclusion
Edwards Injection well exclusion zone	Polygon	Edwards_Injection_Well_Exclusion
Potential Production areas for the Hosston formation and above the Hammett shale portion of the Trintiy Aquifer	Polygon	Potential_Production_Areas
Outline of San antonio and Austin Urban Areas	Polygon	Cities_HCT
Major Rivers in Texas	Polyline	Major_Rivers
Model Boundary for the western portion of the Hill Country study area	MultiPatch	West_Model_Grid_Outline
Model Boundary for the central portion of the Hill Country study area	MultiPatch	Central_Model_Grid_Outline
Model Boundary for the eastern portion of the Hill Country study area	MultiPatch	East_Model_Grid_Outline
West Section model used to simulate drawdown in Hill Country Trinity Aquifer	Polyline	West_Section_Line
Central Section model used to simulate drawdown in Hill Country Trinity Aquifer	Polyline	Central_Section_Line
East Section model used to simulate drawdown in Hill Country Trinity Aquifer	Polyline	East_Section_Line

Description	**File type**	**File Name**
Drawdown contours developed when simulating pumping from the Lower Trinity (Hosston) using West Section Line	Polyline	Drawdown_Contours_West_Hosston
Drawdown contours developed when simulating pumping from the Lower Trinity (Hosston) using Central Section Line	Polyline	Drawdown_Contours_Central_Hosston
Drawdown contours developed when simulating pumping from the Lower Trinity (Hosston) using East Section Line	Polyline	Drawdown_Contours_East_Hosston
Drawdown contours developed when simulating pumping from the Middle and Upper Trinity using Central Section Line	Polyline	Drawdown_Contours_Central_MUT

19.5 Groundwater Volume GIS Tool Documentation

As part of the Brackish Resources Aquifer Characterization System Program, INTERA developed a series of Python scripts to calculate 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.

19.5.1 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, moderately saline, slightly saline, and very saline), and aquifer units (Paluxy, Glen Rose, Hensell, Pearsall, Hosston).

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

If Aquifer is Outcrop

$$Volume_{unconfined_{aq}} = \left(WL_{aq} - Bottom_{aq}\right) \times Area_{cell} \times S_y$$
$$Volume_{confined_{aq}} = 0$$
$$Volume_{total_{aq}} = Volume_{unconfined_{aq}} + Volume_{confined_{aq}}$$

else if Aquifer is Subcrop

$$Volume_{confined_{aq}} = \left(WL - Top_{aq}\right) \times Area_{cell} \times S_s \times Thickness_{aq}$$
$$Volume_{unconfined_{aq}} = Thickness_{aq} \times Area_{cell} \times S_y$$
$$Volume_{total_{aq}} = Volume_{unconfined_{aq}} + Volume_{confined_{aq}}$$

else

$$Volume_{unconfined_{aq}} = 0$$
$$Volume_{confined_{aq}} = 0$$

$$Volume_{total_{aq}} = Volume_{unconfined_{aq}} + Volume_{confined_{aq}}$$

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
S_s = specific storage (1/feet)
$Surface$ = Elevation of stratigraphic unit surface (feet)
S_y = specific yield (unitless)
$Thickness_{aq}$= thickness of aquifer unit (feet)
Top_{aq}= elevation of top of aquifer unit (feet amsl)
WL = water level elevation (feet amsl) modeled for the last year of calibration (beginning of 2010) in the Northern Trinity GAM (Kelley and others, 2014).

19.5.2 Python Scripts

The Electronic Deliverable contains the following 5 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

19.5.2.1 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*)

19.5.2.2 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*)

19.5.2.3 4_Trinity_MakeReportTables_byAQ

Purpose:
- Formats output files from 3_CombiningAquiferFiles.py into report format
- outputs a .csv that corresponds to Table 12-2 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 12-2 in the report (*Electronic_deliverable\Volume_Calculator\Results\Aq_forReport_gmaCheck.csv*)

19.5.2.4 5_Trinity_MakeReportTables

Purpose:
- Formats output files from 3_CombiningAquiferFiles.py into report format
- outputs .csv files that corresponds to Tables 12-3, 12-4, and 12-5 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 12-3 (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 12-4 (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 12-5 (table of volumes per aquifer tabulated by water quality zone and GMA) (*Electronic_deliverable\Volume_Calculator\Results\GMA_forReport.csv*)