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Conceptual Model Report: Groundwater Availability Model for Northern Portion of the Queen City, Sparta, and Carrizo-Wilcox Aquifers

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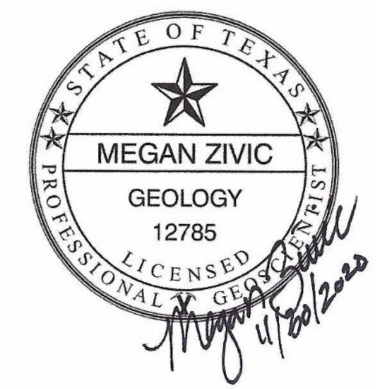

This document is released under the authority of Megan Zivic, P.G.

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EXECUTIVE SUMMARY

The northern portion of the Queen City, Sparta, and Carrizo-Wilcox aquifer system is an important groundwater resource in northeastern Texas. A groundwater availability model (GAM) was developed previously for this aquifer system in order to provide a tool for predicting groundwater availability into the future and assessing water management strategies developed by state water planners, Groundwater Conservation Districts, Regional Water Planning Groups, and other stakeholders. The groundwater availability model was updated previously in 2004 when the Queen City and Sparta aquifers were added to the Carrizo-Wilcox groundwater availability model. This study provides an additional update to the groundwater availability model, with particular focus on improving the hydrostratigraphic framework to better represent the variable confined and unconfined aquifer conditions in outcrop areas. This report summarizes the conceptual hydrogeologic model for the aquifer system, which will provide the foundation for construction of the updated groundwater model. This report does not reproduce documentation available on the construction of the previous groundwater availability models, except as necessary to describe the development of the updated groundwater availability model.

The conceptual model described herein provides the hydrogeologic framework and characterization of the aquifer of interest in the study area. This investigation involved evaluation of information regarding physiography, climate, hydrogeology, groundwater levels and groundwater movement, surface water features, recharge, hydraulic properties for the aquifer units, discharge (including well pumping), and groundwater quality. The conceptual model relies on the results of previous groundwater availability model studies by Fryar and others (2003) and Kelley and others (2004). The conceptual model was updated with hydrogeologic information, such as water levels, pumping, and precipitation, collected after the previous studies were conducted. In addition to updating hydrogeologic datasets and interpretations, considerable effort was made towards verifying and updating the hydrostratigraphic framework of the aquifer system for input to the updated groundwater model.

The conceptual model for the updated northern portion of the Queen City, Sparta, and Carrizo-Wilcox groundwater availability model comprises nine hydrostratigraphic units, including (from top to bottom) river alluvium, Sparta Sand, Weches Formation, Queen City Sand, Reklaw Formation, Carrizo Sand, and the upper, middle, and lower units of the Wilcox Group. All layers except the river alluvium are southward-dipping sedimentary deposits. The river alluvium layer comprises narrow deposits along the major rivers and tributaries that overlay all the outcrop areas of all layers. The top of the aquifer system of interest for this study is overlain by a wedge of younger sedimentary deposits, including the Gulf Coast Aquifer System.

The flow system is bounded by the Red River to the east, by the boundary between the Brazos and Trinity river basins to the west, and by the up-dip extent of the Wilcox Group to

the north. The southern model boundary is the down-dip extent of the Wilcox growth fault zone.

The conceptual model includes two hydrogeologic conditions: initial conditions and transient conditions. The transient model period represents historical hydrogeologic conditions from 1984 through 2015. This time period was selected principally based on pumping data availability. Initial conditions for the transient model represent conditions prior to 1984.

Regional groundwater movement in the study area is generally from the upland areas in the north to the south towards the Gulf of Mexico. Groundwater withdrawals since the early 1980s have occurred predominantly for municipal uses and, to a lesser degree, industrial supplies. Total annual groundwater withdrawals have generally remained larger than 140,000 acre-feet (AF) since 1980, with peak withdrawals of about 170,000 acre-feet per year (AF/yr) during the mid- to late 1990s. Groundwater levels in the aquifers have declined and rebounded in areas in response to local pumping and recharge. Aquifer recharge occurs from percolation of precipitation and infiltration of impounded water in reservoirs and lakes. Shallow groundwater levels contribute to streamflows and flowing springs along the major drainages in the area. All major rivers and tributaries have gaining streamflow conditions along their lengths within the study area. Springs often occur in topographically low areas along river valleys and in outcrop areas. The number of springs in the area is a result of humid climate, gently dipping aquifer layers, and a dissected topography, all of which contribute to rejected recharge and runoff in the region. Although pumping in the study area has resulted in a decline and drying of spring flows, numerous springs still discharge to the surface.

Information from the conceptual model described herein will be incorporated in the groundwater model. Details about the construction and calibration of the groundwater model will be summarized in the Model Calibration Report.

1 INTRODUCTION

The Texas Water Development Board (TWDB) recognizes nine major aquifers and twenty-two minor aquifers in Texas (George and others, 2011). These aquifers are shown on Figure 1-1 and Figure 1-2. Major aquifers produce large quantities of groundwater over large areas, while minor aquifers produce small quantities of groundwater over large areas or large quantities of groundwater over small areas. Groundwater models developed in Texas through the Groundwater Availability Model (GAM) program have been used in numerous ways to advance groundwater planning and management of the aquifers in the state. When the program began about 15 years ago, one of the objectives was that the models were to be used as living tools that would be updated as data and modeling technology improved.

The Carrizo-Wilcox Aquifer is a classified as a major aquifer in Texas. The aquifer extends from the Rio Grande region in south Texas to northeast Texas and into Louisiana and Arkansas. For groundwater modeling purposes, the TWDB divided the aquifer into three areas: the southern portion, central portion, and northern portion. Each of these areas is modeled by separate groundwater availability models.

The Sparta and Queen City aquifers are classified as minor aquifers in Texas. These minor aquifers extend from the Frio River region in south Texas to east Texas. The Sparta Aquifer continues into Louisiana where it is mapped as Sparta Sand and in Arkansas where it is included with the Claiborne Group. The Queen City Aquifer continues into Arkansas and the northwest area of Louisiana as part of the Cane River Formation of the Claiborne Group. For groundwater modeling purposes, the TWDB divided the Sparta and Queen City aquifers into the same south, central, and north model areas as the Carrizo-Wilcox Aquifer.

The primary objective of this project is to update the existing groundwater availability model for the northern portions of the Queen City, Sparta, and Carrizo-Wilcox Aquifers. The groundwater availability model is used to simulate impacts of groundwater pumping on groundwater resources in northeast Texas. The study area is shown on Figure 1-3. This model will build from two primary sources of data and information: (1) the existing groundwater availability models for the Queen City and Sparta Aquifers (Kelley and others, 2004), and (2) the existing groundwater availability model for the northern Carrizo-Wilcox Aquifer (Fryar and others, 2003). The resulting numerical model developed for this project will provide the means to assess future impacts (both local and regional) from current pumping and projected increases in pumping. Model results will be used for evaluating groundwater impacts, surface water impacts, and the potential for ground subsidence that may occur in the area due to long-term withdrawal of groundwater. The groundwater availability model will also be used to assist the groundwater conservation districts in Groundwater Management Area 11 to develop and/or revise their desired future conditions.

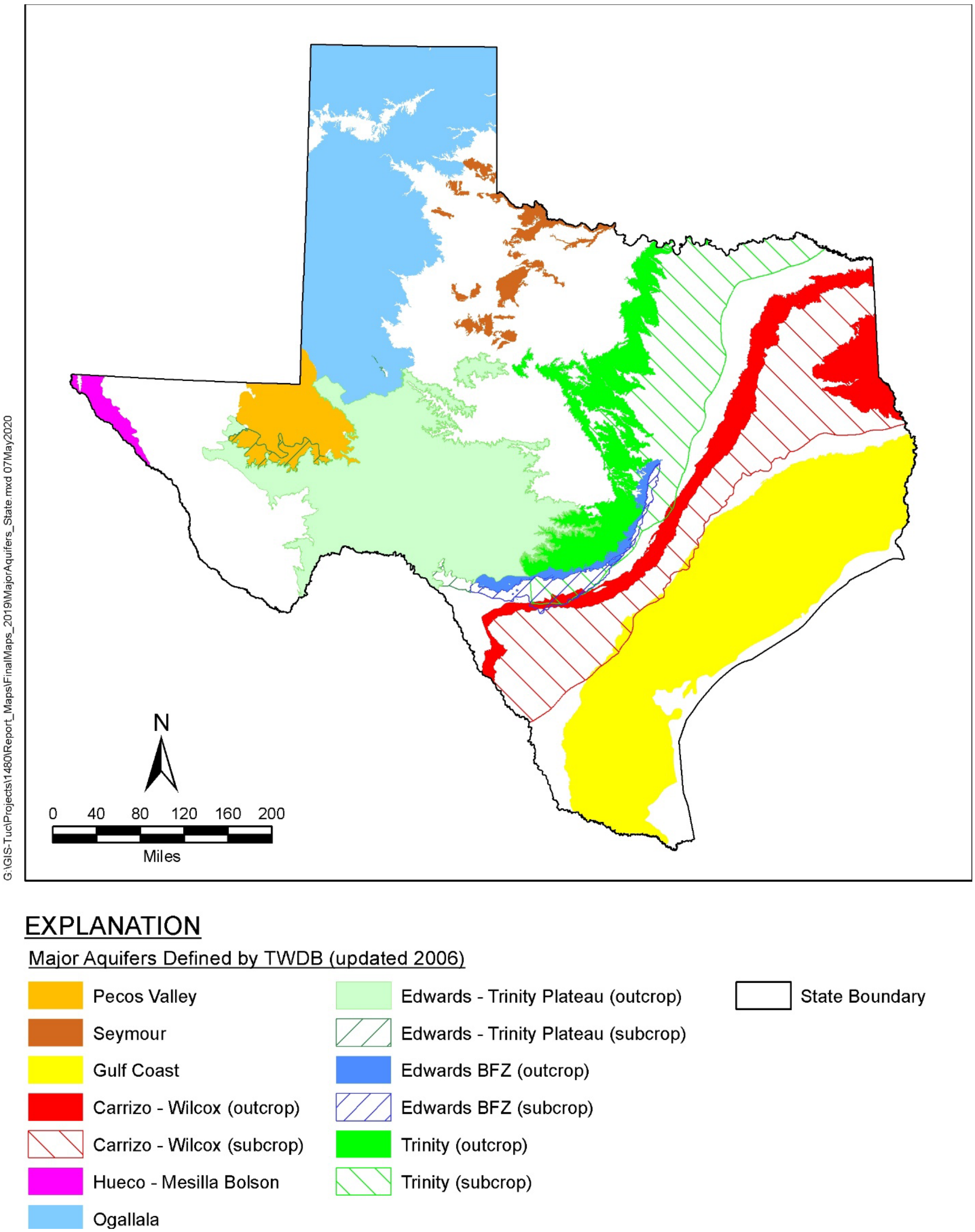


Figure 1-1. Major Aquifers in Texas

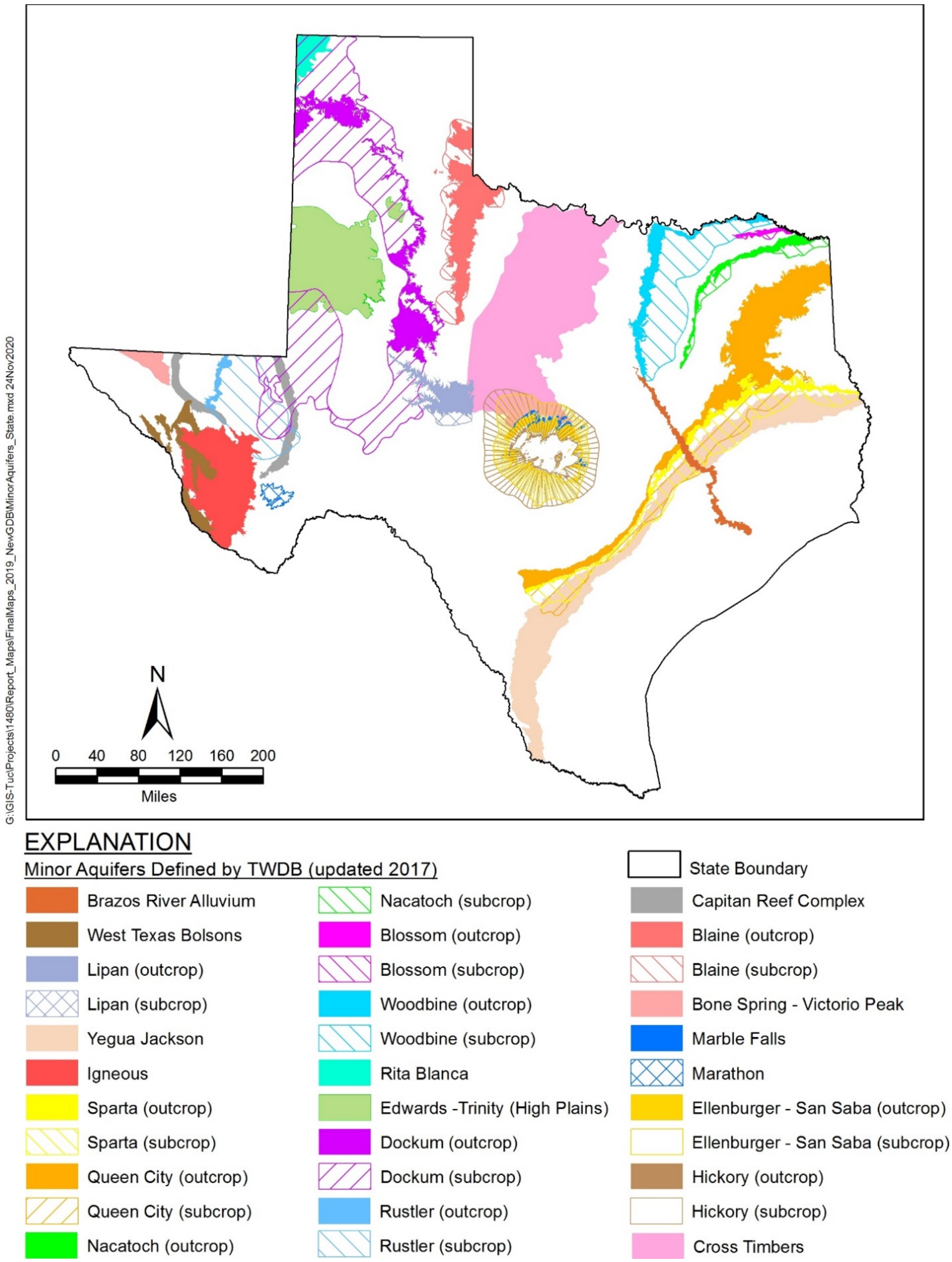


Figure 1-2. Minor Aquifers in Texas

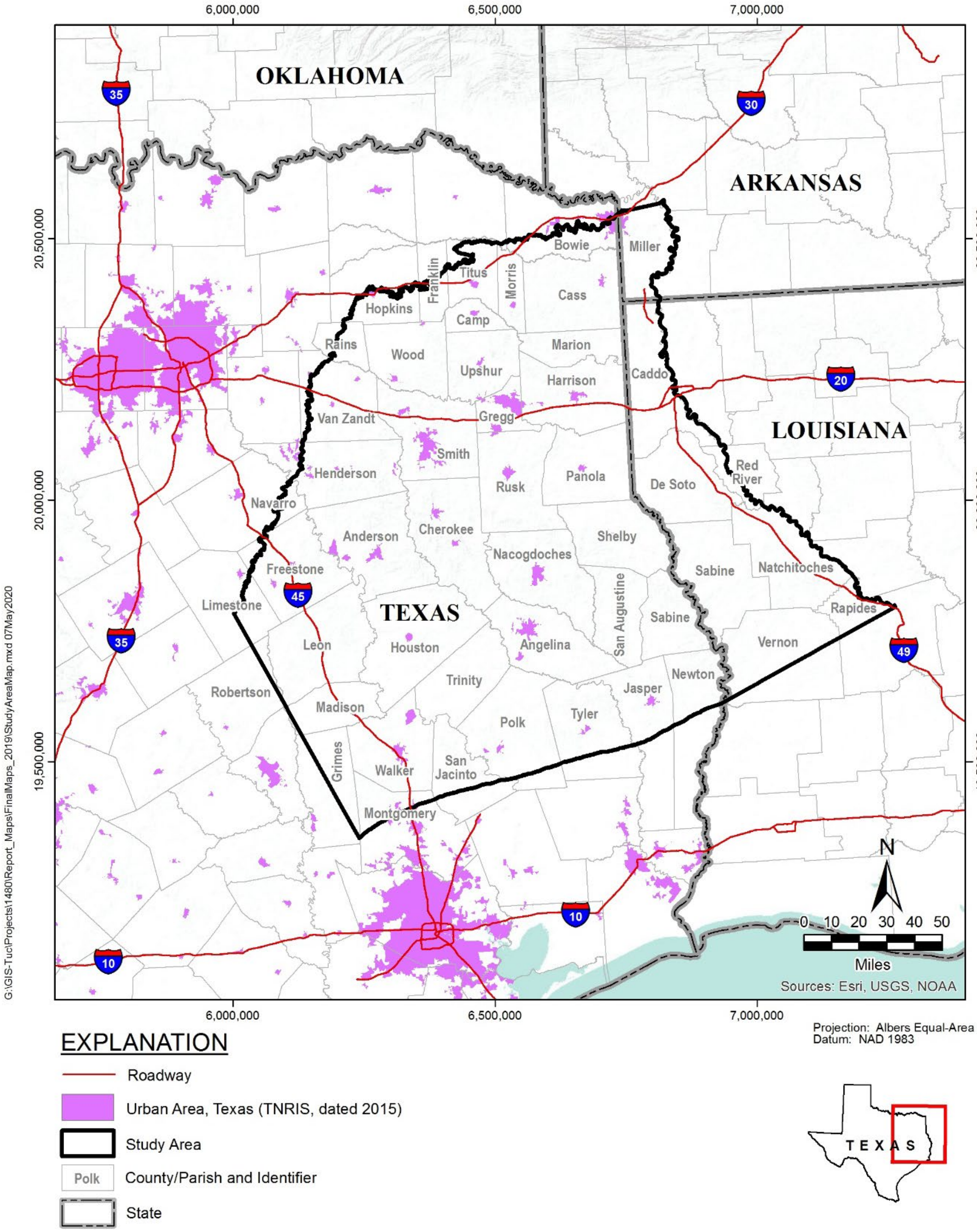


Figure 1-3. Location of Study Area

The model for this study will be developed specifically to address the objectives summarized above. The model domain extent and actively simulated aquifers were selected to encompass the water extractions of interest in the region. The model will be calibrated to observed annual conditions (groundwater levels and flows) from 1984 through 2015. The model period begins in 1984 because of maximum availability of reliable data, especially pumping information, begins at about 1984. The model will use annually averaged recharge and pumping stresses for all simulations because of the long-term nature of the objectives and the slow movement of groundwater in an aquifer. Details for the design and implementation of the calibrated model will be summarized in the Model Calibration Report.

This project is conducted in two phases. Phase 1 is the update of the conceptual hydrogeologic model for the northern portion of the Queen City, Sparta, and Carrizo-Wilcox aquifers in support of the numerical model. Phase 2 is the development and calibration of a transient numerical groundwater flow model.

This conceptual hydrogeologic model provides the hydrogeologic framework and characterization of the groundwater system in the study area. This investigation involved evaluation of information regarding physiography, climate, hydrogeology, groundwater levels and groundwater movement, surface water features, recharge, hydraulic properties for the aquifer units, discharge (including well pumping), and groundwater quality.

This report summarizes the conceptual hydrogeologic model developed for the northern portion of the Queen City, Sparta, and Carrizo-Wilcox aquifers for Phase 1 of this project. An overview of the study area is provided in Chapter 2. Previous investigations are summarized in Chapter 3. The hydrostratigraphy of the aquifer system, aquifer properties, groundwater recharge and discharge, surface water system, and water quality are described in detail in Chapter 4. The general conceptual model for development of the groundwater model is summarized in Chapter 5. The information provided in this report will be used to update the numerical groundwater model in Phase 2 of this project.

2 OVERVIEW OF STUDY AREA

The study area for this investigation is located predominantly in northeast Texas and extends into western Louisiana and the southwestern tip of Arkansas (Figure 1-3). The study area is essentially the same as the previous groundwater availability model by Fryar and others (2003); slight adjustments were made to the northern boundary of the Wilcox Aquifer for this model update based on the outcrop contact with the older Midway Group. The area includes all or portions of Anderson, Angelina, Bowie, Brazos, Camp, Cass, Cherokee, Franklin, Freestone, Gregg, Grimes, Harrison, Henderson, Hopkins, Houston, Jasper, Leon, Limestone, Madison, Marion, Montgomery, Morris, Nacogdoches, Navarro, Newton, Panola, Polk, Rains, Robertson, Rusk, Sabine, San Augustine, San Jacinto, Shelby, Smith, Titus, Trinity, Tyler, Upshur, Van Zandt, Walker, and Wood counties in Texas; Caddo, De Soto, Natchitoches, Rapides, Red River, Sabine, and Vernon parishes in Louisiana; and Miller county in Arkansas. Cities and major surface water drainages are shown on Figure 2-1. Major and minor aquifers that occur in the study area are shown on Figure 2-2 and Figure 2-3. The Yegua-Jackson Aquifer (minor) and Gulf Coast Aquifer System (major) overly the aquifers of interest for this study.

Groundwater administrative areas located in Texas within the study area are shown on Figure 2-4, Figure 2-5, and Figure 2-6. The boundaries for these areas were obtained from TWDB (2017b). The study area extends across portions of five Regional Water Planning Areas (Figure 2-4): Region C, the North East Texas Region (Region D), Region H, the East Texas Region (Region I), and a small portion of Region G. Ten Groundwater Conservation Districts (GCDs) are located within the study area (Figure 2-5): Bluebonnet GCD, Lower Trinity GCD, Mid-East Texas GCD, Neches and Trinity Valleys GCD, Panola County GCD, Pineywoods GCD, Rusk County GCD, Southeast Texas GCD, and small portions of the Brazos Valley GCD and Lone Star GCD. In addition, the study area encompasses Groundwater Management Area 11, and also extends across portions of Groundwater Management Areas 12 and 14 (Figure 2-6).

Figure 2-7 shows the major rivers and associated drainage basins in the study area, based on geospatial datasets obtained from the United States Geological Survey's National Hydrography Dataset (USGS, 2016) and the Texas Natural Resources Information System (TNRIS, 2017). Major drainage basins present in the study area include Trinity, Neches, Sabine, Big Cypress-Sulphur, and Red-Saline

The study area was delineated based on hydrologic boundaries, lateral extents of aquifers, and locations of pumping centers. The study area is bounded laterally by the surface water basin divide between the Trinity and Brazos rivers in the southwest, and by the Red River in Arkansas and Louisiana in the northeast. The north boundary is the northern extent of the Wilcox Aquifer outcrop. The south boundary extends into the down-dip portions of the Carrizo-Wilcox Aquifer. This study area is essentially the same as the boundaries in the previous groundwater availability models developed by Fryar and others (2003) and Kelley and others (2004).

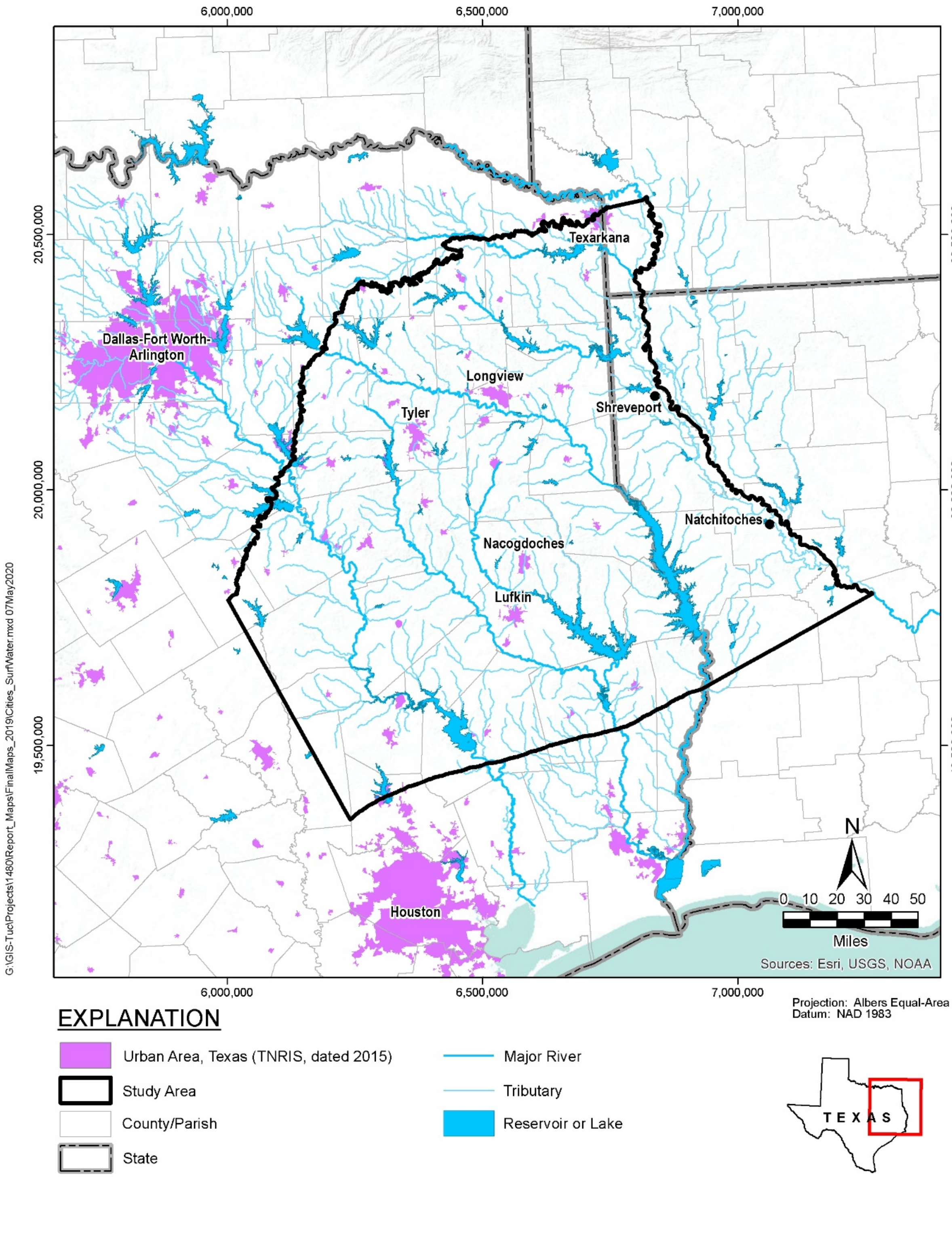


Figure 2-1. Cities and Surface Water Features in Study Area

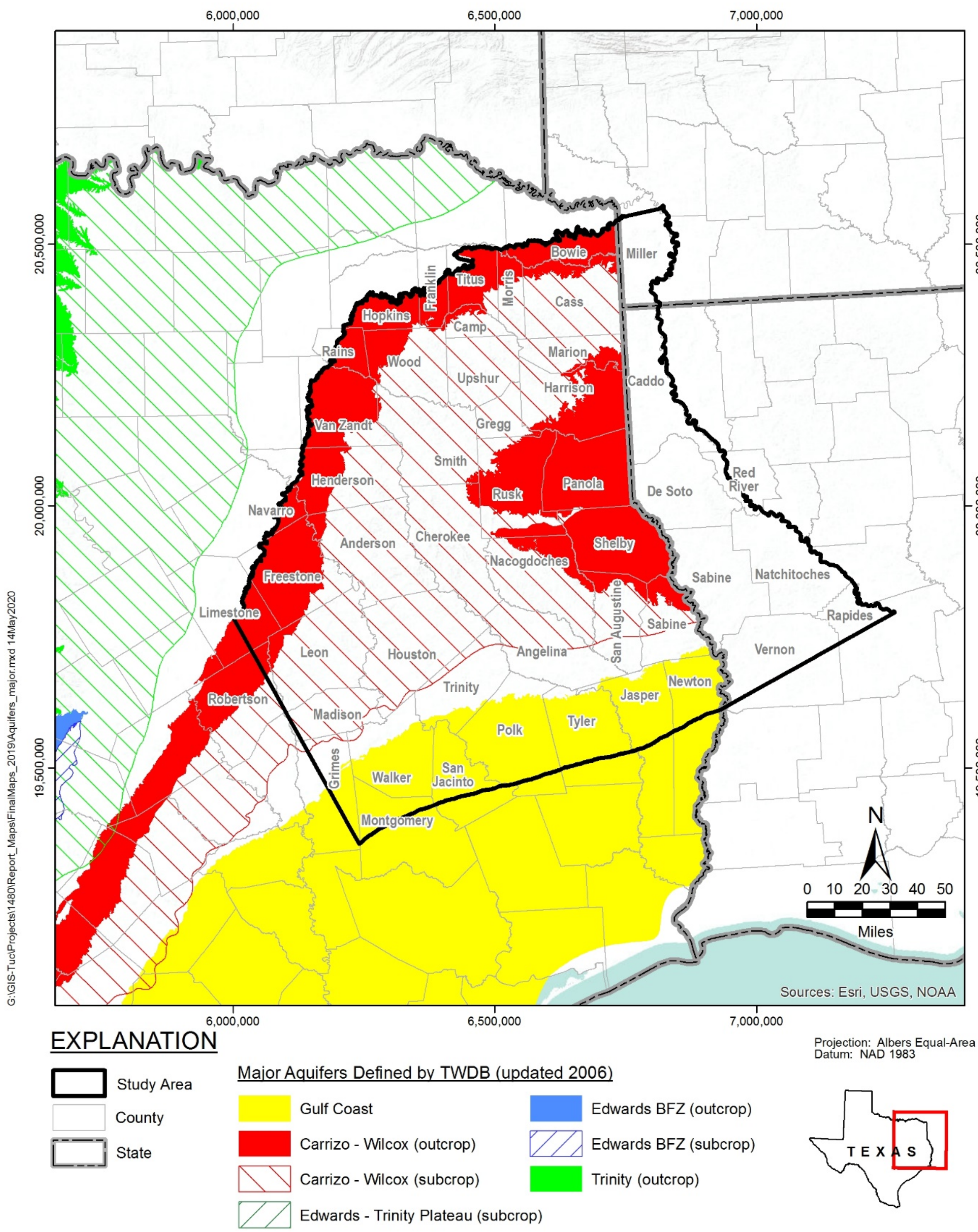


Figure 2-2. Major Aquifers in Study Area

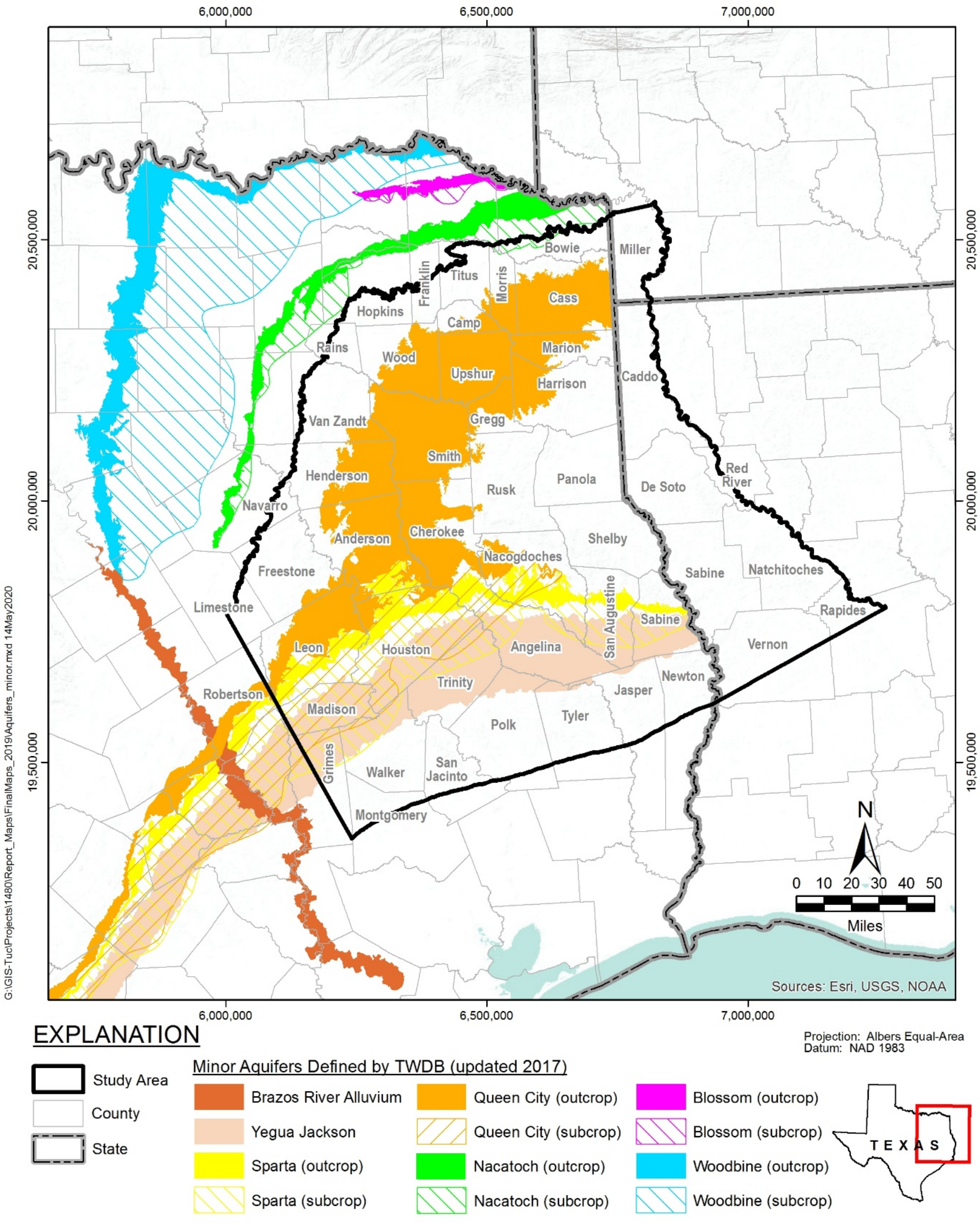


Figure 2-3. Minor Aquifers in Study Area

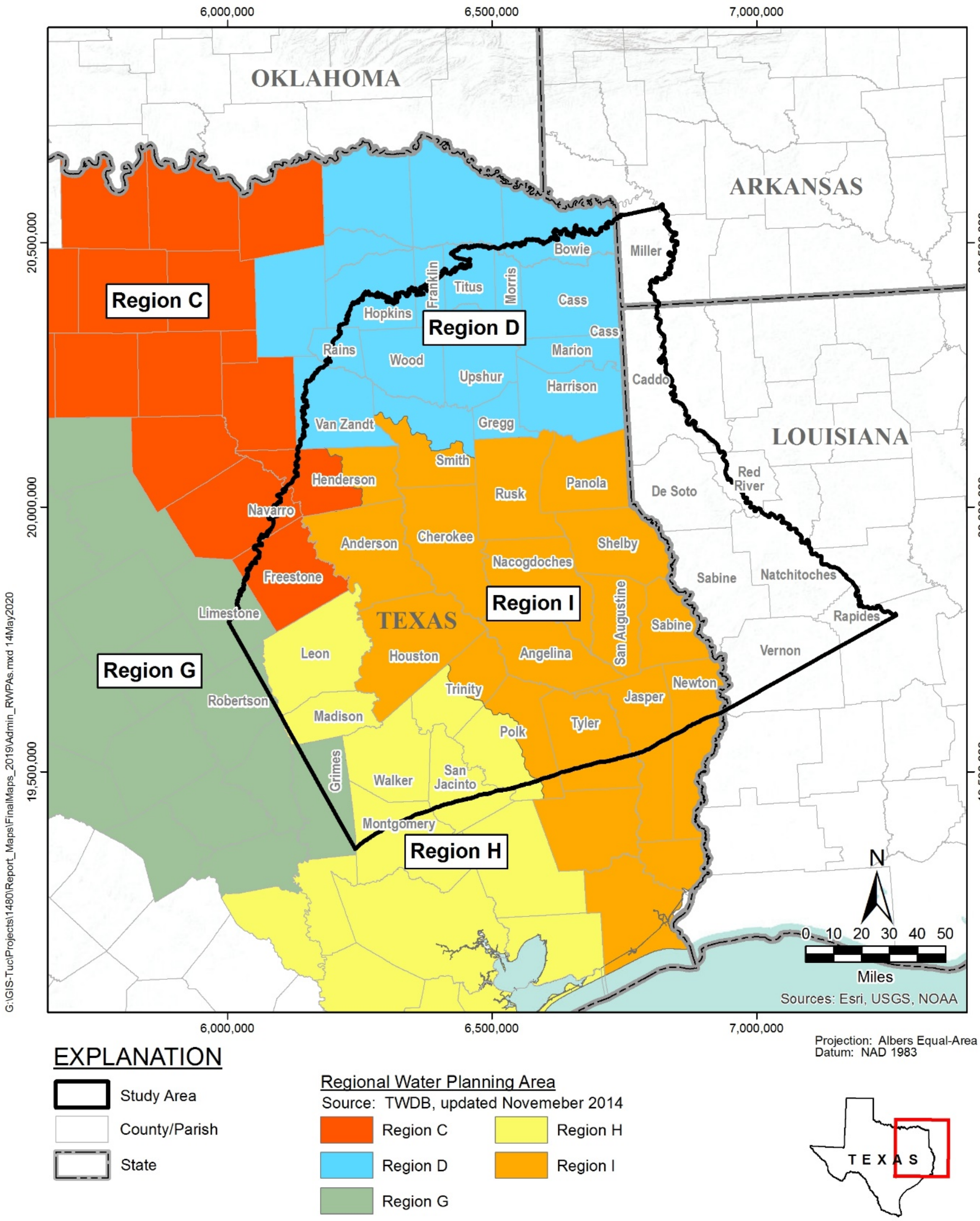


Figure 2-4. Regional Planning Areas in Study Area

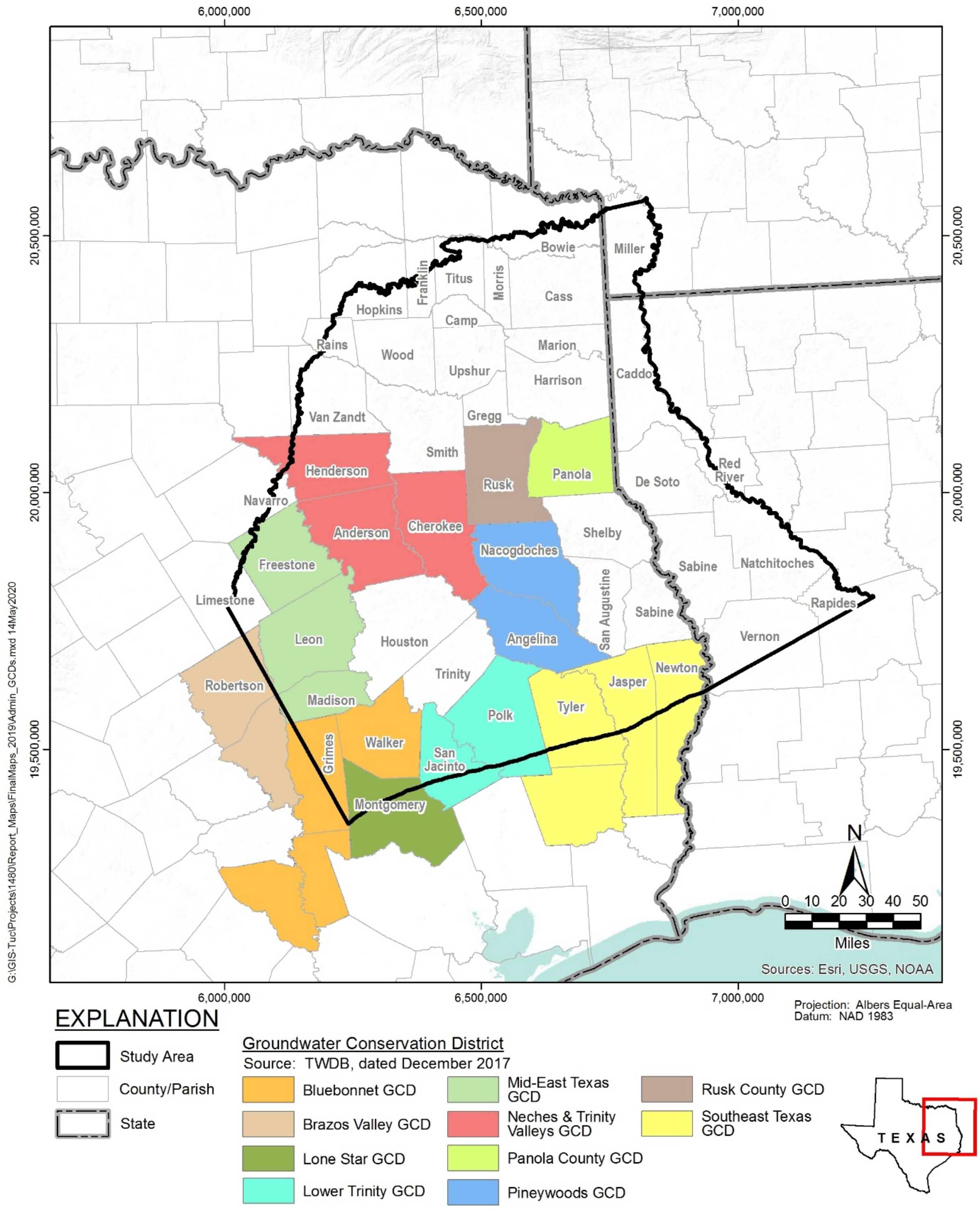


Figure 2-5. Groundwater Conservation Districts in Study Area

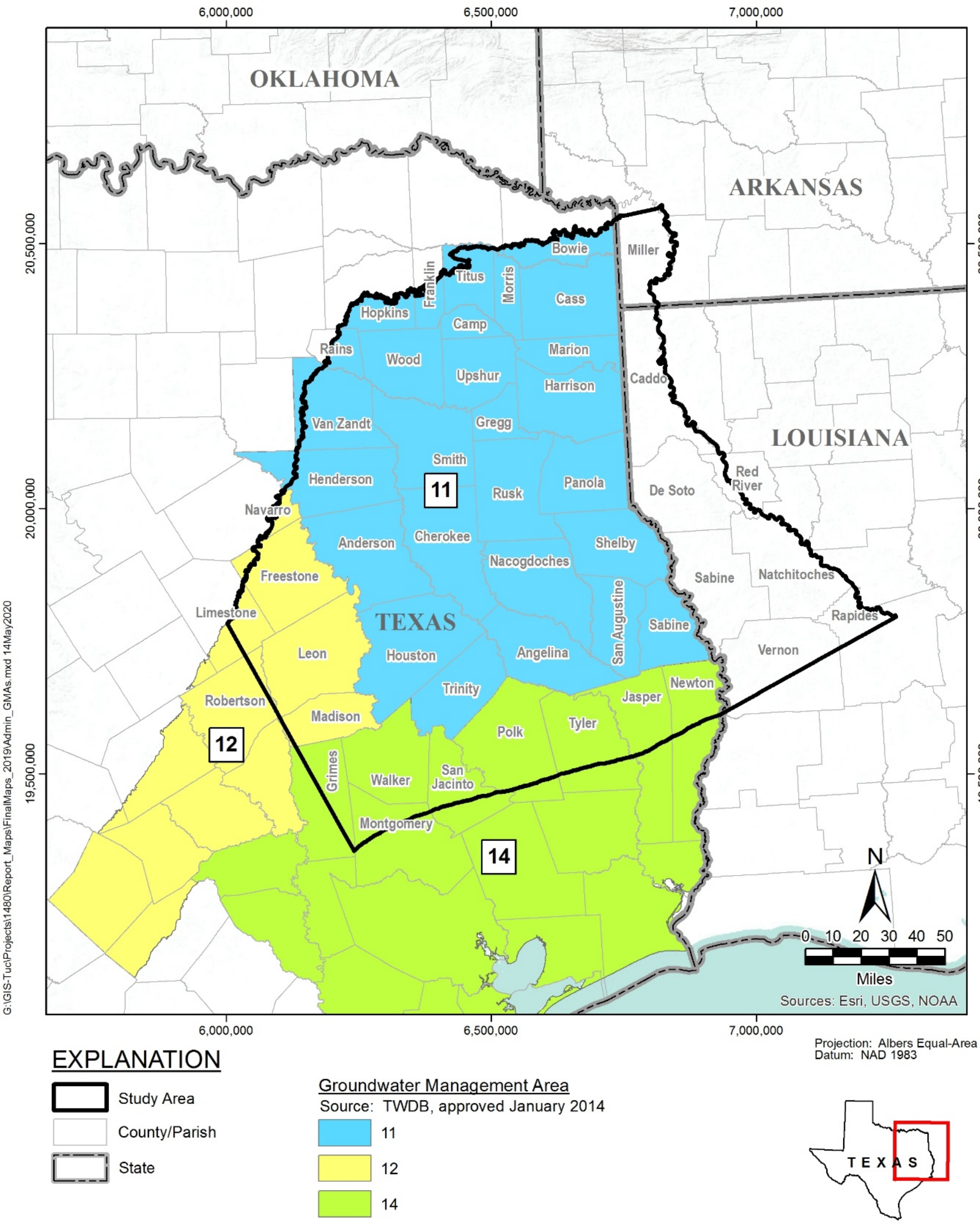


Figure 2-6. Groundwater Management Areas in Study Area

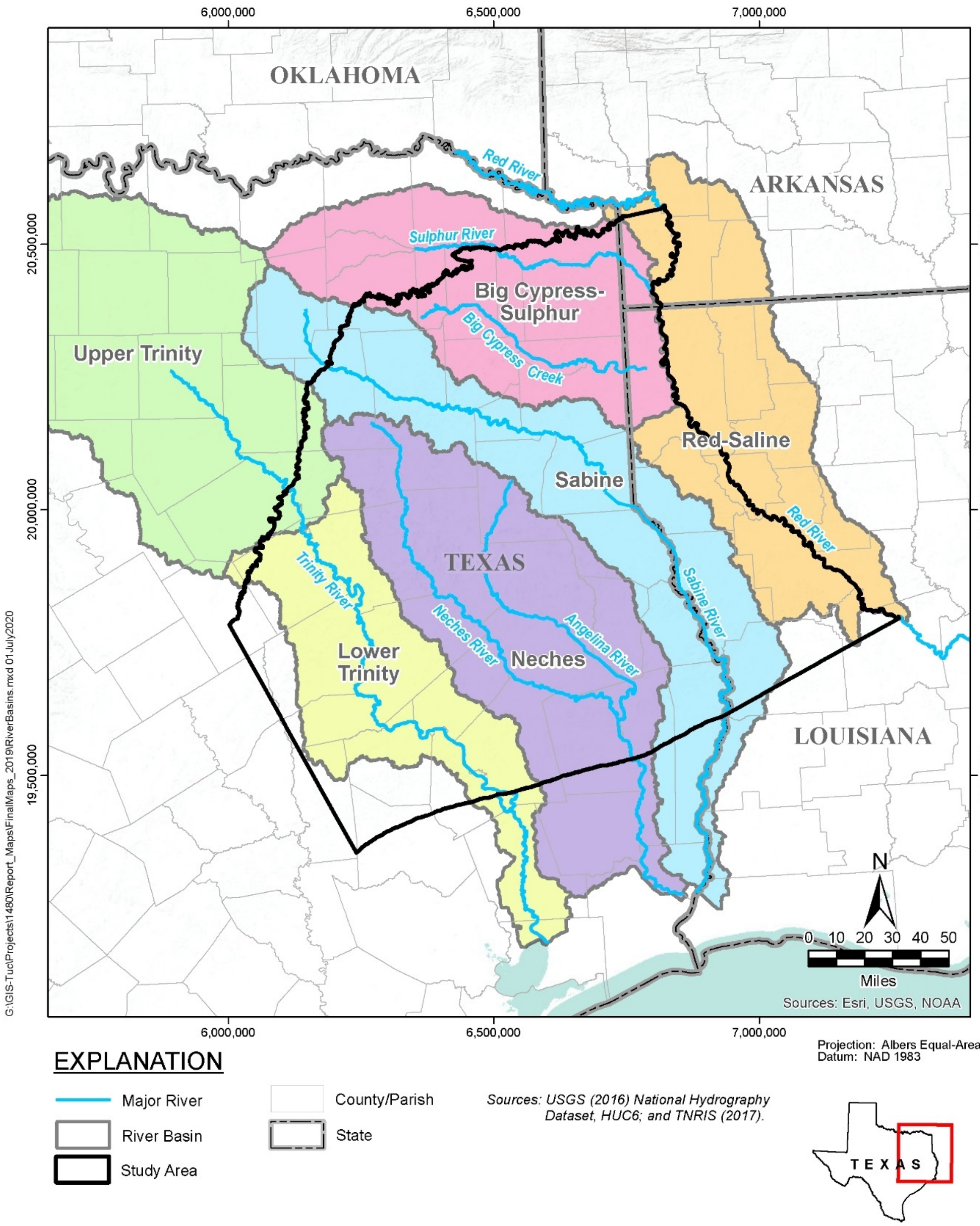


Figure 2-7. Major River Basins in Study Area

2.1 Physiography and Climate

Digital elevation model datasets (1 arc-second resolution, or 30 meters) were obtained for the study area from United States Geological Survey (USGS, 2002) National Elevation Datasets. Land surface elevation in the study area is shown on Figure 2-8. In general, land surface elevation in the study area decreases from the northwest to the east and south. Land surface elevations range from about 775 feet above mean sea level along isolated river basin divides to less than 100 feet above mean sea level along major river valleys. The land surface is substantially dissected by streams and drainages.

The study area is located within the Interior Coastal Plain physiographic province in Texas (Texas Bureau of Economic Geology, 1996). The province is divided into different ecoregions based on topography and vegetation. Ecoregions in the study area include Piney Woods, Oak Woods and Prairies, Blackland Prairie in Texas, and South-Central Plains in Louisiana and Arkansas (Figure 2-9) (United States Environmental Protection Agency, 1998). Piney Woods is the dominant ecoregion in the study area and comprises gently rolling hills with large tracts of pine forest and hardwood and pine trees in bottomlands along rivers and creeks. According to the Texas Parks & Wildlife Department (McMahan and others, 1984), the dominant vegetation types in the valley are pine hardwood forest, oak forest, and grasslands. Vegetation types are shown on Figure 2-10. Similar vegetation maps for Louisiana and Arkansas were not discovered for this study.

The climate in the study area is subtropical humid. Climate divisions delineated by the National Oceanic and Atmospheric Administration's (2018) National Climate Data Center are shown on Figure 2-11. Average annual temperature in the area is about 65 degrees Fahrenheit (°F). Mean high temperature is in the low 90s °F in July, and the mean low temperature is in the low 30s °F in January (TWDB, 2015a, b). Thirty-year averages (1981 through 2010) for precipitation and temperature were computed using climate data obtained from the PRISM Climate Group (2017). The 30-year average annual temperatures range slightly over the study area from about 64°F in the north to about 68°F in the southwest, as shown on Figure 2-12.

The 30-year average annual precipitation in the study area increases from about 39 inches in the west to about 60 inches in the southeast, as shown on Figure 2-13. Winter rainfall occurs infrequently and generally over short durations (TWDB, 2015a, b). Total average annual precipitation for the study area for 1981 through 2015 is shown on Figure 2-14. Monthly precipitation data for individual rain gauges in the study area were downloaded from the National Oceanic and Atmospheric Administration's (2019) National Climate Data Center. Average monthly precipitation measured at selected rain gauges in the study area is shown on Figure 2-15.

Information on net lake evaporation was obtained from the TWDB (2017c) for 1-degree quadrangles in the study area. Average lake evaporation across the valley is shown on Figure 2-16. Average annual net lake evaporation is generally smaller than 50 inches in the eastern portions of the study area and larger than 50 inches in the western portions.

Hydrologic Soil Groups were classified from gridded Soil Survey Geographic Database soils datasets downloaded from the U.S. Department of Agriculture (USDA) National Resources Conservation Service (NRCS, 2007) Web Soil Survey website (https://websoilsurvey.nrcs.usda.gov/app/). The National Resources Conservation Service defines the Hydrologic Soil Groups as:

> *Hydrologic soil groups are based on estimates of runoff potential. Soils are assigned to one of four groups according to the rate of water infiltration when the soils are not protected by vegetation, are thoroughly wet, and receive precipitation from long-duration storms. The soils in the United States are assigned to four groups (A, B, C, and D) and three dual classes (A/D, B/D, and C/D). The groups are defined as follows: Group A. Soils having a high infiltration rate (low runoff potential) when thoroughly wet. These consist mainly of deep, well drained to excessively drained sands or gravelly sands. These soils have a high rate of water transmission. Group B. Soils having a moderate infiltration rate when thoroughly wet. These consist chiefly of moderately deep or deep, moderately well drained or well drained soils that have moderately fine texture to moderately coarse texture. These soils have a moderate rate of water transmission. Group C. Soils having a slow infiltration rate when thoroughly wet. These consist chiefly of soils having a layer that impedes the downward movement of water or soils of moderately fine texture or fine texture. These soils have a slow rate of water transmission. Group D. Soils having a very slow infiltration rate (high runoff potential) when thoroughly wet. These consist chiefly of clays that have a high shrink-swell potential, soils that have a high water table, soils that have a claypan or clay layer at or near the surface, and soils that are shallow over nearly impervious material. These soils have a very slow rate of water transmission. If a soil is assigned to a dual hydrologic group (A/D, B/D, or C/D), the first letter is for drained areas and the second is for undrained areas. Only the soils that in their natural condition are in group D are assigned to dual classes.*

The dominant hydrologic soil groups in the study area are shown on Figure 2-17. Fine-grained to clayey soils with slow infiltration rates occur throughout the majority of the valley. Areas with sands and gravels with high infiltration rates are present in the western and southern portions of the study area.

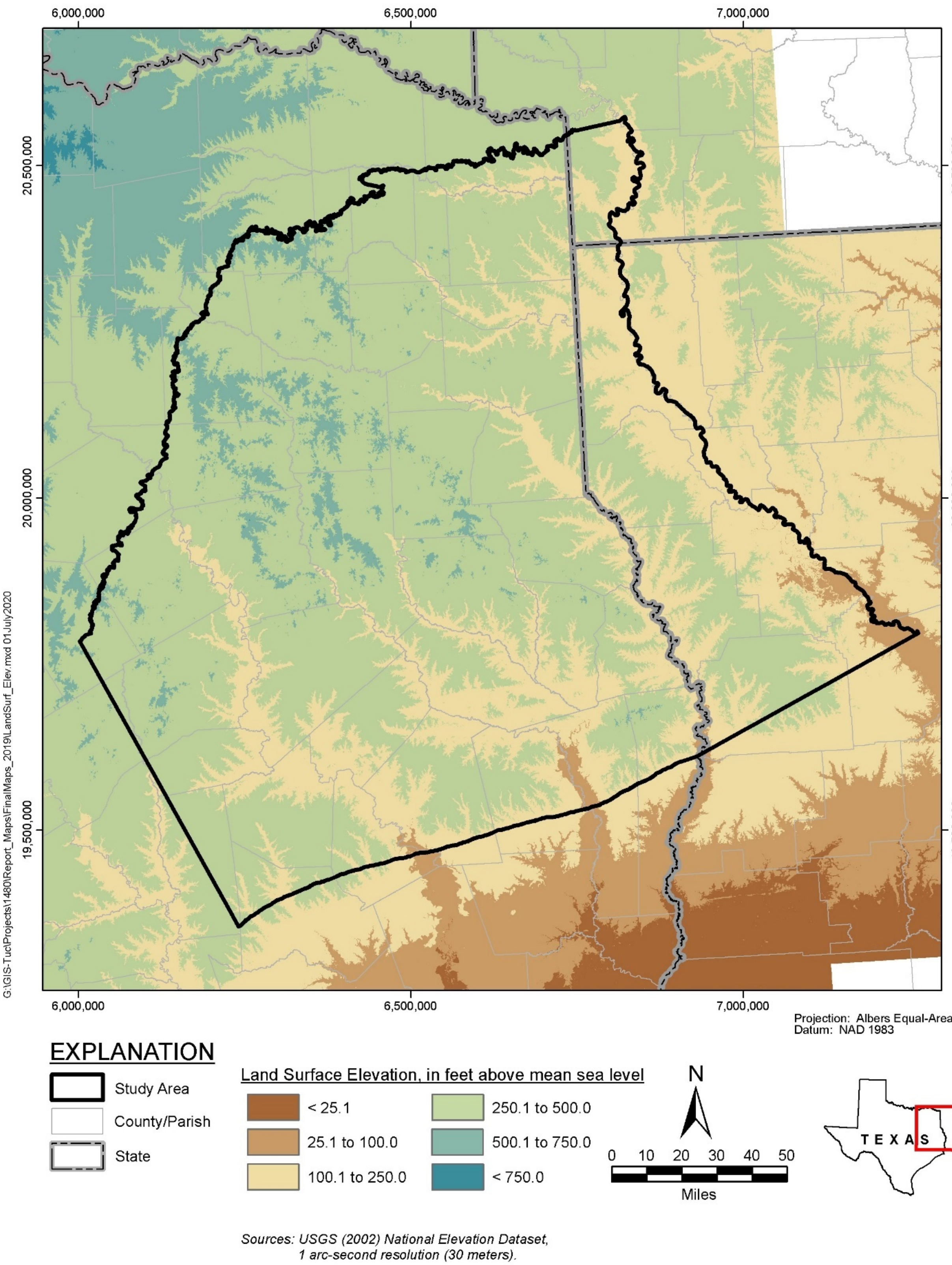
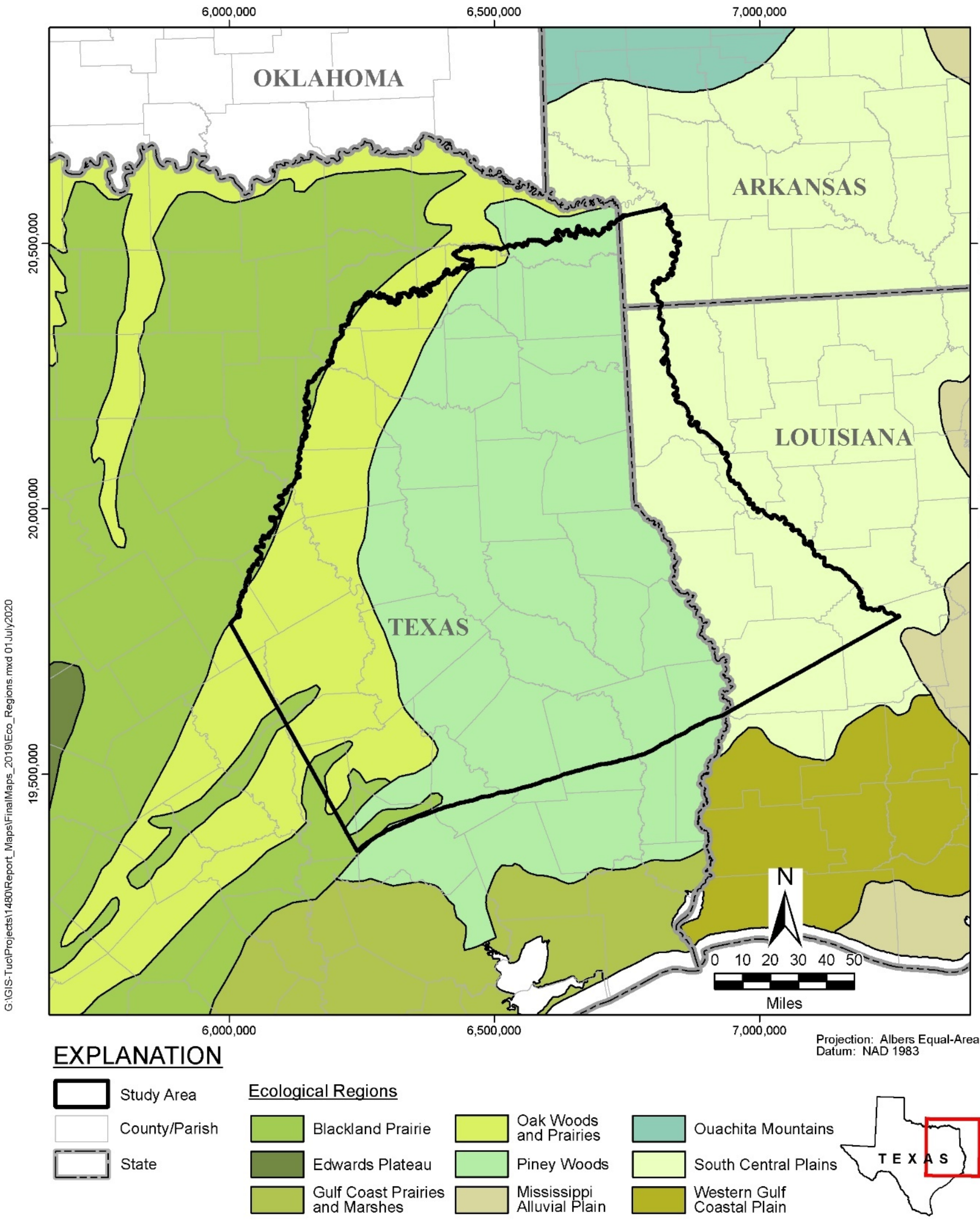


Figure 2-8. Land Surface Elevation in Study Area



Sources: U.S. Environmental Protection Agency (1998).

Figure 2-9. Ecological Regions in Study Area

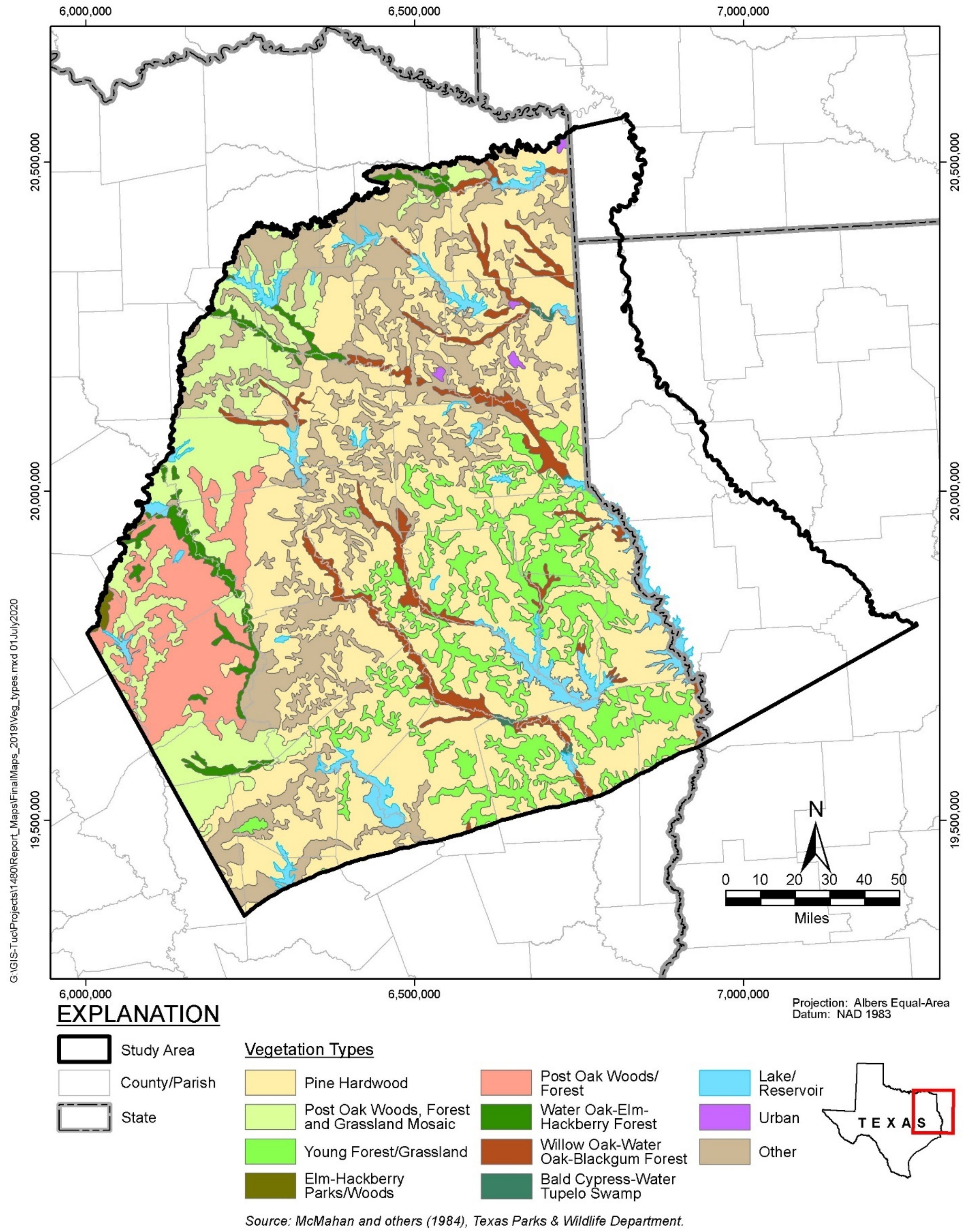
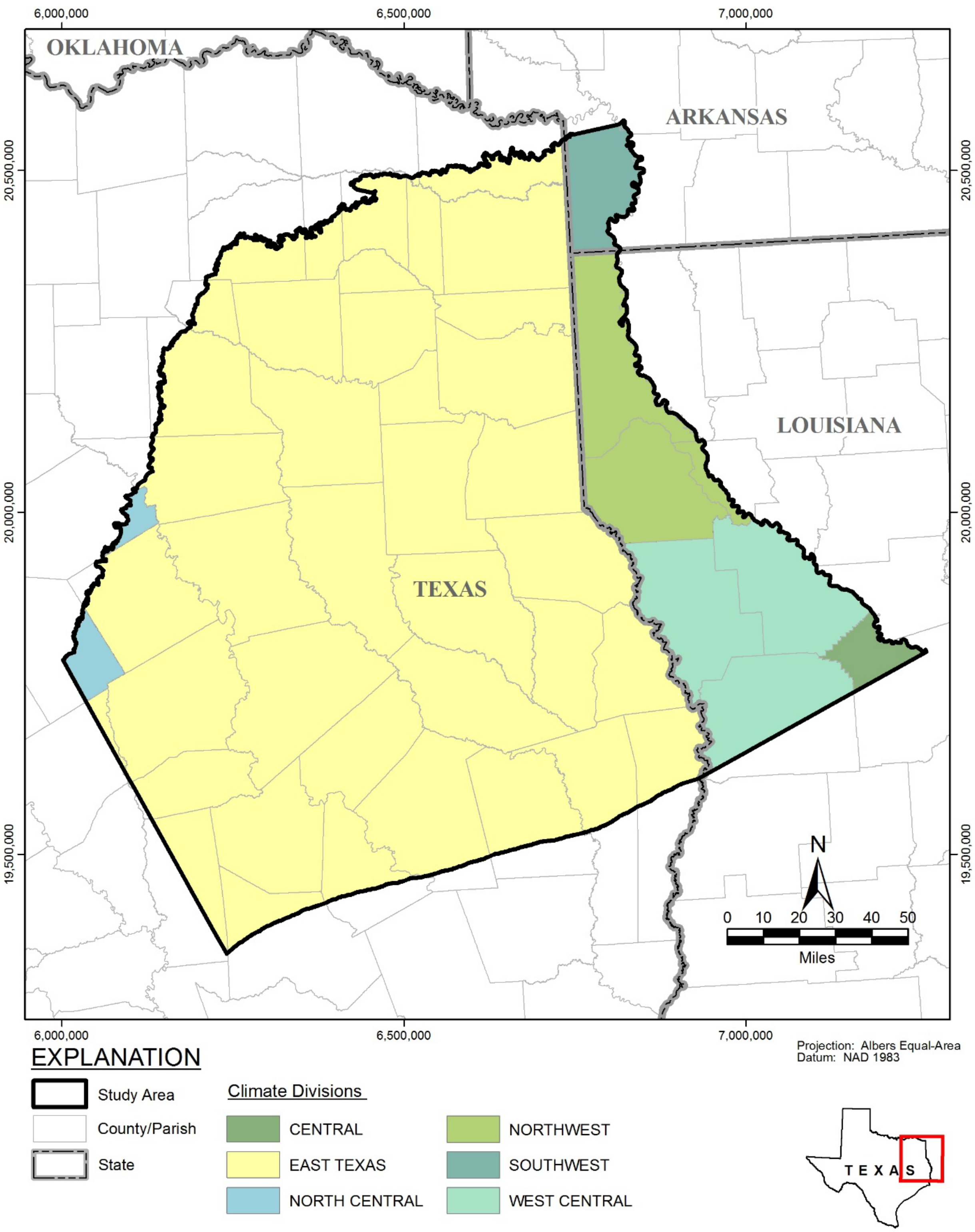


Figure 2-10. Vegetation Types in Study Area



Source: NOAA (2018) National Climate Data Center

Figure 2-11. Climate Divisions in Study Area

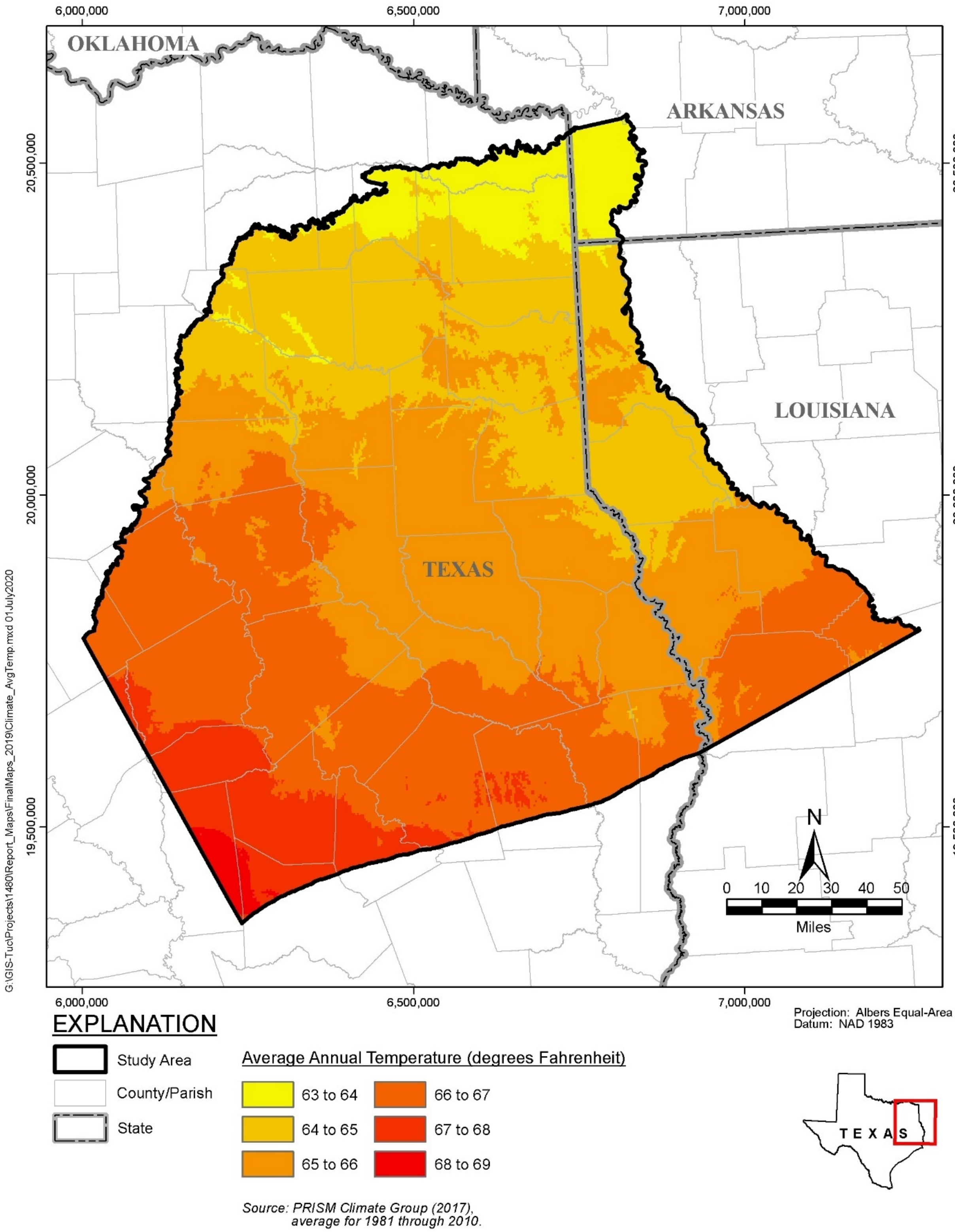


Figure 2-12. Average Annual Temperature in Study Area

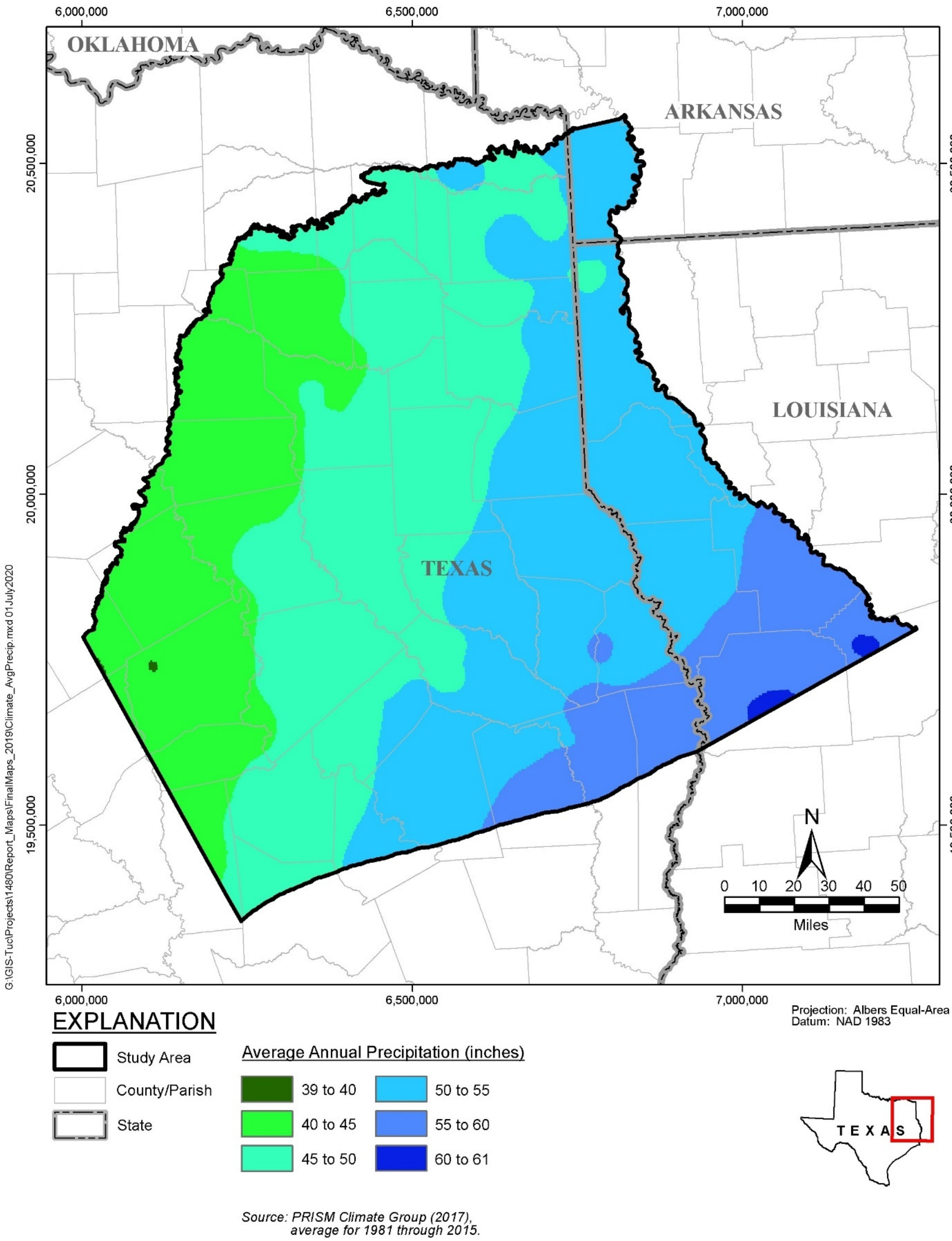


Figure 2-13. Average Annual Precipitation in Study Area

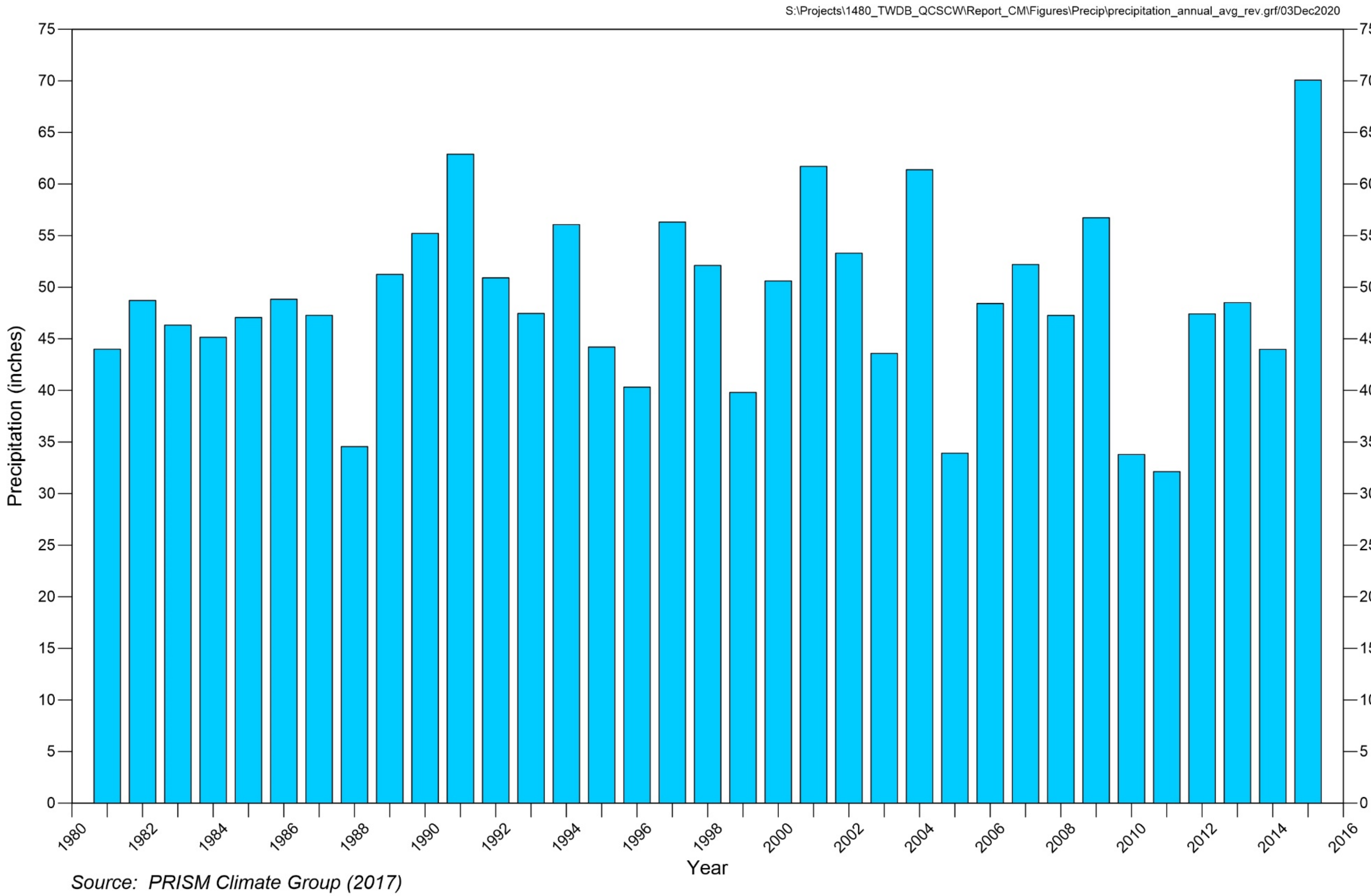


Figure 2-14. Annual Precipitation in Study Area

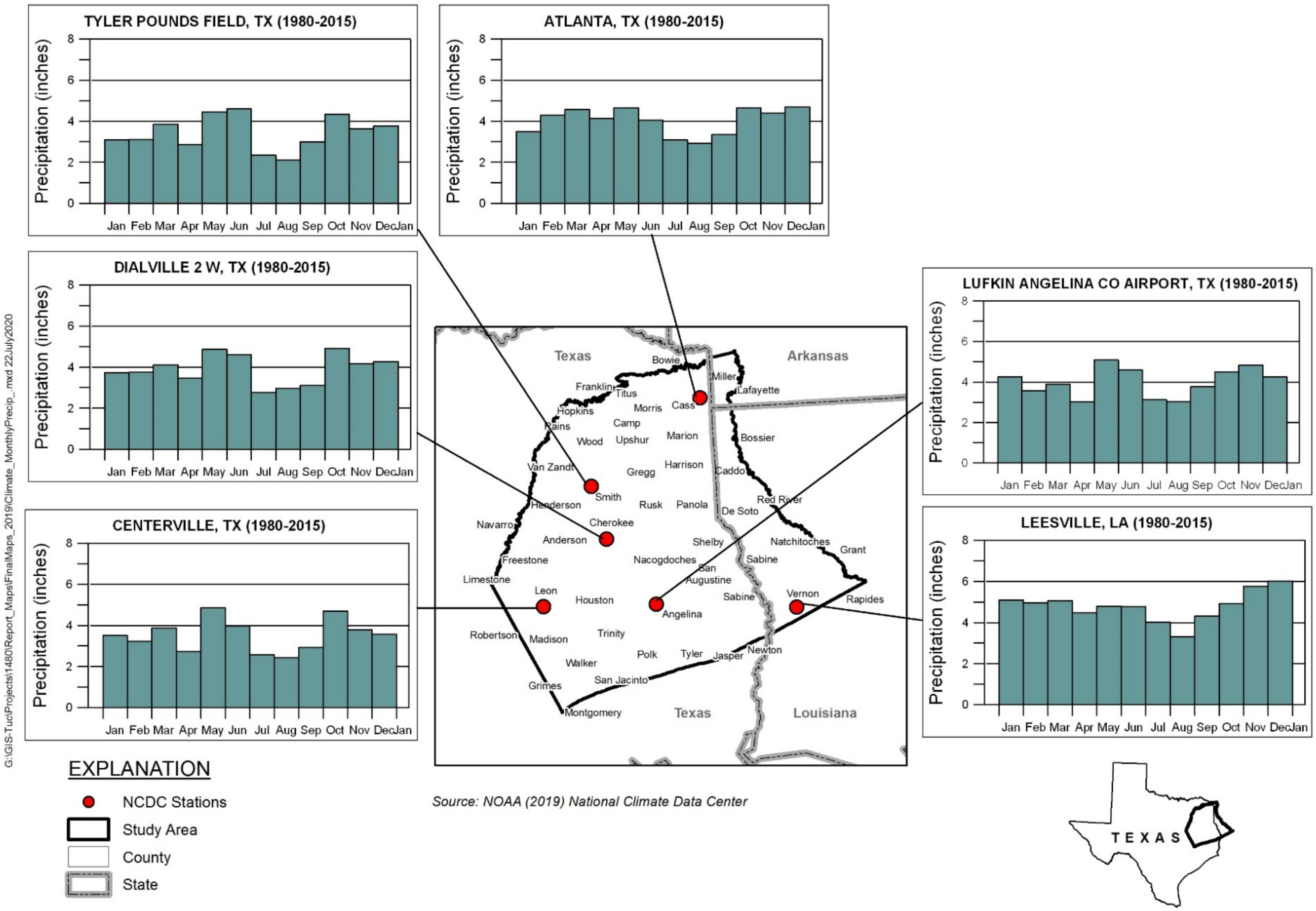


Figure 2-15. Average Monthly Precipitation at Selected Rain Gauges

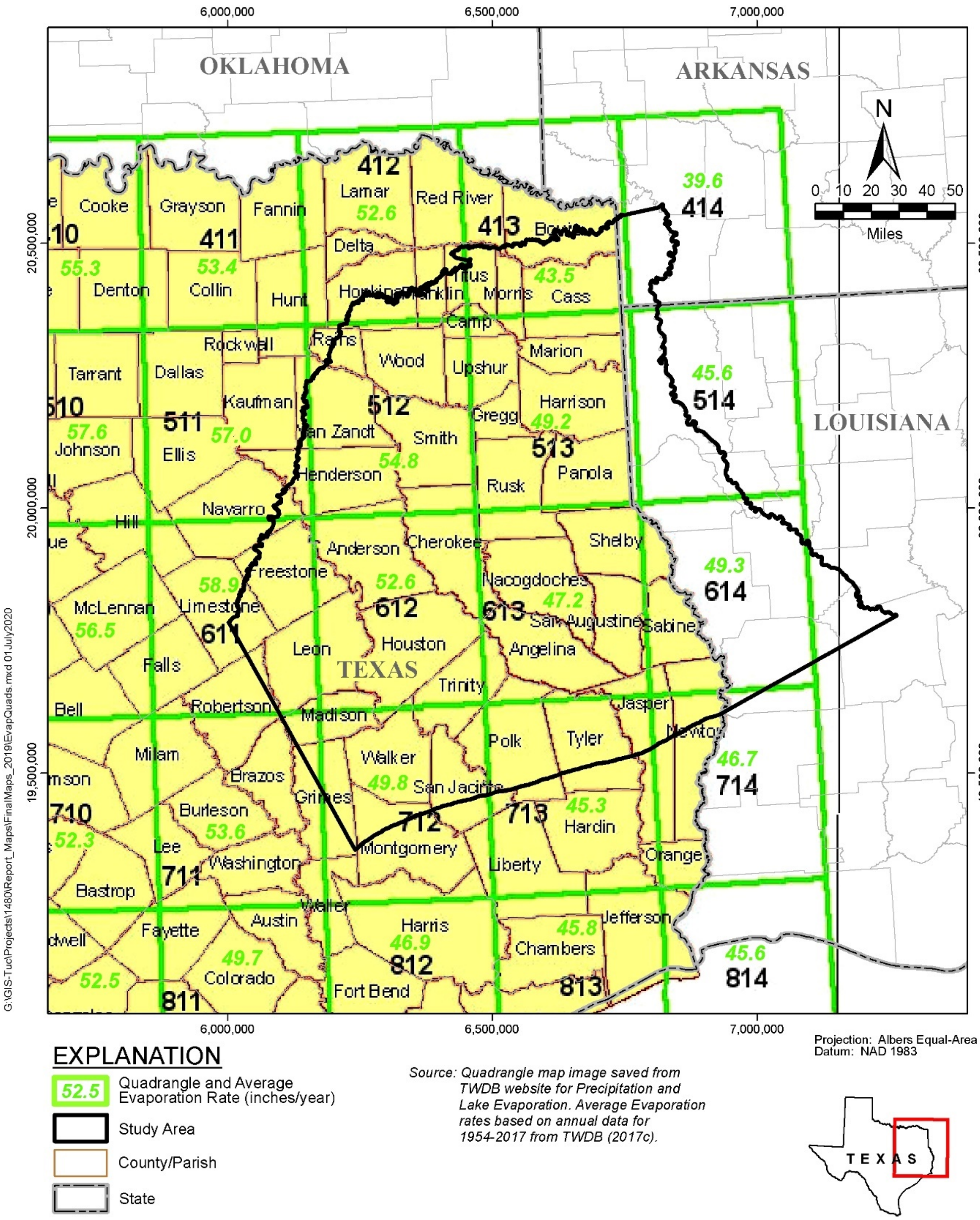
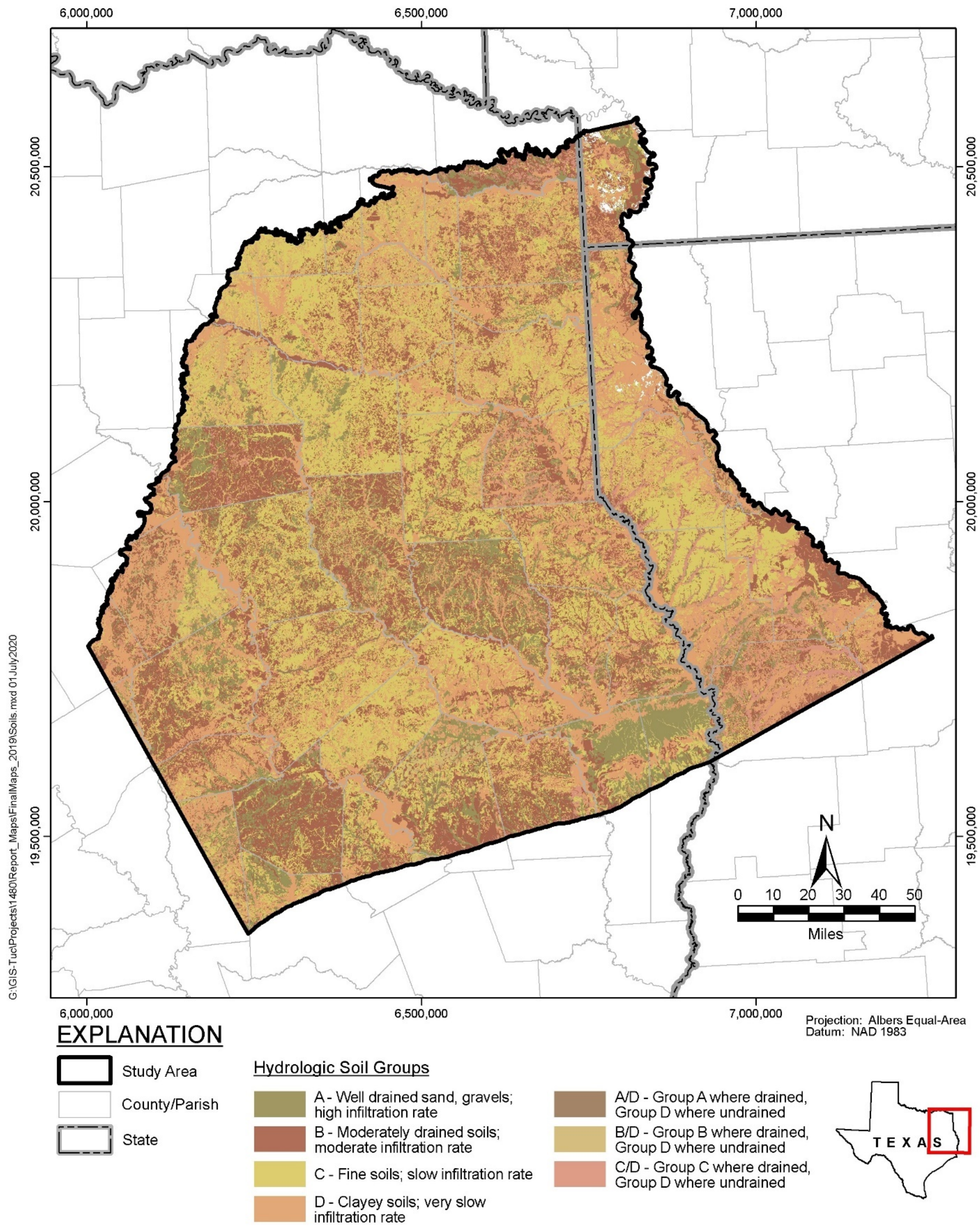


Figure 2-16. Average Annual Lake Evaporation



Source: National Resources Conservation Service (2007).

Figure 2-17. Hydrologic Soil Groups in Study Area

2.2 Geologic Setting

Fryar and others (2003) provide a comprehensive description of the general geologic setting of the study area. This section relies heavily on information presented in that report. The geologic units in the study area comprise of sediments that are part of a gulfward thickening wedge of Cenozoic sediments deposited in the Houston Embayment and East Texas Basin in the northwest portion of Gulf Coast Basin. Regional subsidence, episodes of sediment inflow from outside the Gulf Coast Plain, and eustatic sea level change have influenced the deposition of these sediments (Grubb, 1997). According to Galloway and others (1994), deposition of Cenozoic sequences is characterized as an offlapping progression of successive, gulfward thickening wedges. Deposition occurred along continental margin deltaic depocenters within embayments (the Houston Embayment in this study area) and was modified by development of salt domes and growth faults.

In ascending stratigraphic order, the principle depositional sequences are the Wilcox group, Carrizo Sand, Queen City Sand, Sparta Sand, Yegua-Cockfield, Jackson, and Vicksburg-Frio formations (Galloway and others, 1994). These depositional sequences are bounded by marine shales and finer-grained sediments deposited by marine transgressions. The sequences of interest for this study are the Wilcox Group, Carrizo Sand, Queen City Sand and Sparta Sand. The finer-grained bounding units of interest in the study area include the Reklaw and Weches formations, which overly the Carrizo Sand and Queen City Sand, respectively.

Surficial geology in the study area, obtained from a United States Geological Survey integrated geologic database (Stoeser and others, 2007), is shown on Figure 2-18 and major structural features are shown on Figure 2-19. The Carrizo and Wilcox units outcrop along a belt along the northern extent of the study area. These units also outcrop in the Sabine Uplift in the eastern portion of the study area and continue eastward into Louisiana. The Sparta and Queen City units outcrop in much of the central portion of the study area. In the southern portion of the study area, surface geology and the pattern of outcrops are oriented southwest-northeast, which is coincident with depositional strike (Fryar and others, 2003).

The dominant structural features in the model area include the Houston Embayment in the west, East Texas Embayment to the north, the Sabine Uplift in the east, the Sabine Arch in the south, and the Elkhart-Mount Enterprise Fault Zone (Figure 2-19). The embayments focus sediment input and are a central area of deposition. The East Texas Embayment includes significant deposits of halite which have been displaced to form salt ridges and salt domes due to subsidence, tilting, and differential loading of younger sediments (Jackson, 1982). The East Texas Embayment sediment deposition was influenced by the topographic expression of the Sabine Uplift, a broad structural dome, to the east (Fogg and others, 1991). The Elkhart-Mount Enterprise Fault Zone is composed of the Elkhart Graben on the western end and the Mount Enterprise Faults to the east. The Elkhart Graben consists of parallel, normal faults which define a graben approximately 25 miles long. The Mount Enterprise Fault Zone is east-northeast of the Elkhart Graben and is composed of an array of parallel and en échelon normal faults downthrown to the north (Jackson, 1982). Some of the displacement of this fault zone is syndepositional with the Wilcox Group which thickens as a result (Jackson, 1982).

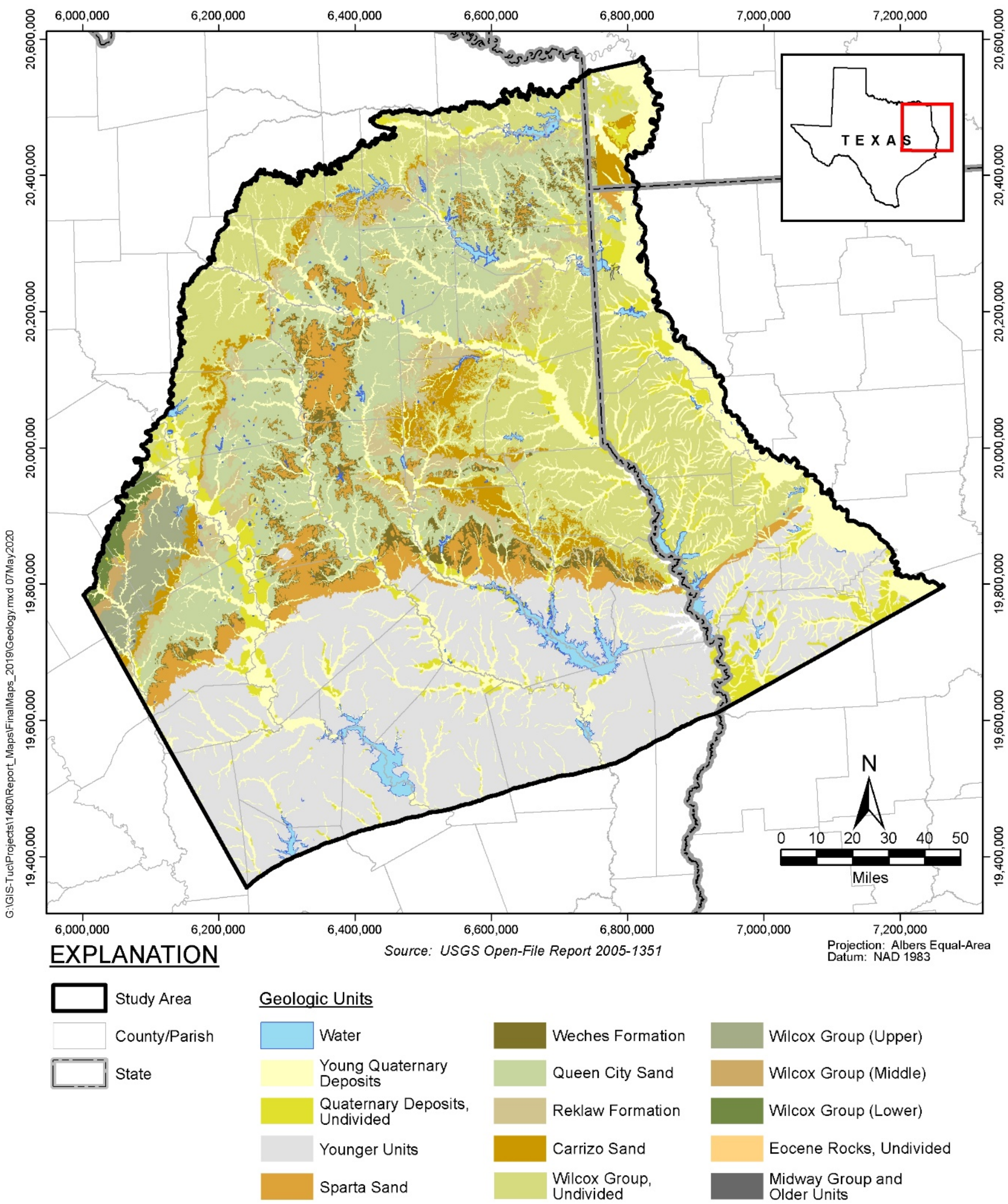


Figure 2-18. Surface Geology of the Northern Portions of The Queen City, Sparta, and Carrizo-Wilcox Aquifers

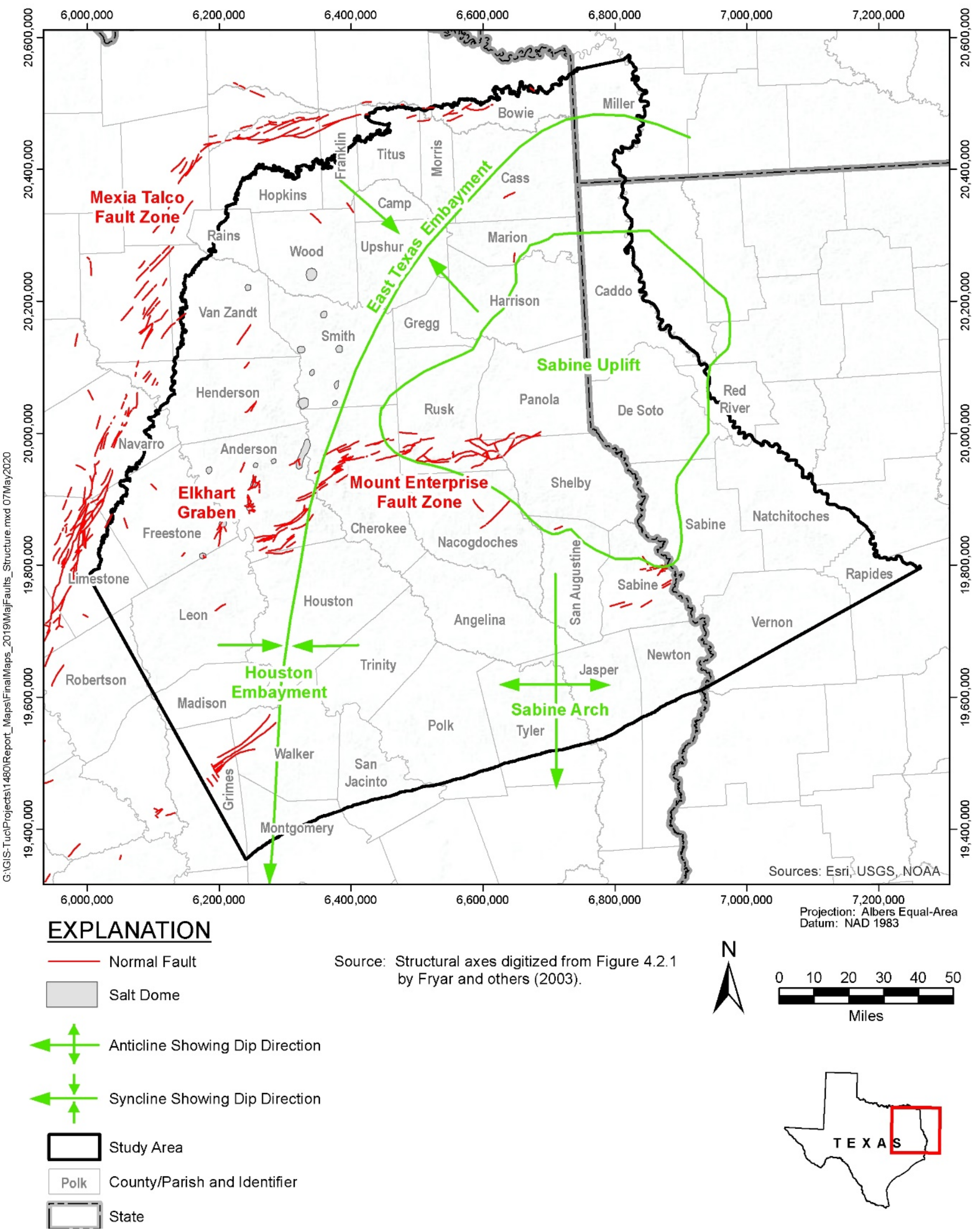


Figure 2-19. Major Fault and Structural Features in Study Area

3 PREVIOUS STUDIES

The northern Queen City, Sparta, and Carrizo-Wilcox aquifer system has been studied by numerous investigations and groundwater modeling. This investigation relies heavily on the hydrogeologic interpretations and results of studies conducted by Fryar and others (2003) and Kelley and others (2004) for the previous groundwater availability models for the northern portions of the Queen City, Sparta, and Carrizo-Wilcox aquifers.

Fryar and others (2003) developed the groundwater availability model for the northern portions of the Carrizo-Wilcox Aquifer with the purpose of providing a tool for making predictions of groundwater availability through 2050. The study involved comprehensive literature reviews and analyses for developing the conceptual model for the aquifer system. Hydrogeologic information, including sand geometry and hydraulic properties, compiled from Kaiser (1974), Kaiser (1978), Fogg and Kreitler (1982), and Kaiser (1990) were most relied upon for the study. The model comprised of six layers and was calibrated to transient conditions from 1980 through 1989. The model layers included, from top to bottom, Queen City, Reklaw, Carrizo, upper Wilcox, middle Wilcox, and lower Wilcox. Grid cells have uniform dimensions of 1 mile by 1 mile. The steady-state model was calibrated to predevelopment conditions. The transient model was calibrated to conditions from 1980 through 1989, with a subsequent model verification period from 1990 through 1999. The verified model was used to predict changes to groundwater conditions to the year 2050 based on future groundwater demands developed by Regional Water Planning Groups and Groundwater Conservation Districts.

The Carrizo-Wilcox groundwater availability model was updated in 2004 when the Queen City and Sparta aquifers were added to the model by Kelley and others (2004). The model included eight layers and was calibrated to the same period as the Carrizo-Wilcox groundwater availability model. The Sparta Sand and Weches Formation were added to the model as new layers. The Weches Formation layer is between the underlying Queen City Sand and the overlying Sparta Sand. The model grid, boundary conditions, and simulation periods of this groundwater availability model are the same as specified in the northern Carrizo-Wilcox groundwater availability model. Principal limitations of this groundwater availability model include poor representation of discontinuous outcrops of Sparta Sand and their associated confined aquifer conditions, as well as the inability of the model to properly accommodate increased recharge rates that have occurred after the model verification period. However, the current study described herein relies on aspects on the conceptual model developed by Kelley and others (2004).

The thicknesses of the Sparta Sand in outcrop areas and their importance to the aquifer system were reviewed for the current study. Several previous studies characterize the discontinuous, smaller, and isolated Sparta Sand deposits in the outcrop areas north of the main Sparta Aquifer (Broom 1968; Broom, 1969; Broom, 1971; Dillard, 1963; Sandeen, 1987; Guyton & Associates, 1971). Results of these studies, along with surficial geologic maps, were used to delineate the discontinuous Sparta Sand outcrops in the hydrostratigraphic framework constructed for this groundwater availability model study.

4 HYDROGEOLOGIC SETTING

The hydrogeologic setting summarizes the information required for the development of the conceptual groundwater model. This section provides information on the hydro-stratigraphic layering framework, groundwater levels and flows, recharge, discharge, groundwater-surface water interactions, aquifer hydraulic properties, and groundwater quality in terms of salinity.

The study area is located over the northern portion of the Queen City, Sparta, and Carrizo-Wilcox Aquifer System, a major aquifer system that extends from the Texas-Mexico international border in the south to Arkansas and Louisiana in the northeast. The principal geologic sequences are Paleogene in age and are from oldest to youngest the Lower Wilcox, Middle Wilcox, Upper Wilcox, Carrizo Sand, Reklaw Formation, Queen City Sand, Weches Formation, and Sparta Sand. These units were deposited in altering progradation sequences and transgressive sequences. The progradation sequences are depositional episodes resulting in basin-ward thickening wedges, aggradation of the continental platform and progradation of the shelf margin and continental slope (Galloway and others, 2000). The progradation sequences include the following units in ascending stratigraphic order: the Lower Wilcox, Upper Wilcox, Carrizo, Queen City Sand, and Sparta Sand. Each of the progradation sequences are separated by the regional marine shales: the Middle Wilcox, the Reklaw Formation and the Weches Formation and are typically made up of clay, silt, and fine, discontinuous sand mixtures. Although not considered a substantial aquifer in the study area, river alluvium deposits are also incorporated into the aquifer system in this study.

The Sparta, Queen City, Carrizo, and Wilcox formations, in descending order, generally comprise thick, laterally continuous, and permeable fluvio-deltaic sands. The Weches and Reklaw formations typically comprise clay, silt, and discontinuous sand mixtures.

4.1 Hydrostratigraphy and Layering Framework

Hydrostratigraphy refers to the layering of aquifers and associated confining units of a study area. Hydrostratigraphic units are geologic sub-units with similar hydrogeologic properties or geologic units with distinct hydrogeologic properties. The hydrostratigraphic framework of an aquifer system is composed of the elevation surfaces of the hydrostratigraphic units in chronostratigraphic order. The stratigraphic column for the Sparta, Queen City, and Carrizo-Wilcox aquifer system is presented on Figure 4-1.

The hydrostratigraphy evaluated for the groundwater model comprises the following aquifer units, from youngest to oldest: river alluvium, Sparta Sand, Weches Formation, Queen City Sand, Reklaw Formation, Carrizo Sand, and the Wilcox Group. The hydrostratigraphy for this investigation is based on interpretations by several sources summarized in Table 4.1.

PERIOD	EPOCH	HYDROSTRATIGRAPHIC UNITS
Quaternary	Post-Eocene	Quaternary Alluvium
Tertiary		Younger Units
	Eocene	Sparta Sand
		Weches Formation
		Queen City Sand
		Reklaw Formation
		Carrizo Sand
		Upper Wilcox
		Middle Wilcox
	Paleocene	Lower Wilcox
	Post-Paleocene	Midway Group and Older Units

GIS-Tuc\Projects\1480\Report_Maps\FinalMaps_2019\Stratigraphic_Section.ai

Figure 4-1. Generalized Stratigraphic Section of Hydrostratigraphic Units

Table 4.1. Subsurface Data Sources for the Hydrostratigraphic Framework

Hydro-stratigraphic Unit	Ayers and Lewis (1985)	Rusk County GCD[a]	Wilson & Hosman (1987) (USGS RASA)[b]	East Texas Model (TWDB, unpublished)	M&A and Brackish Resources Aquifer Characterization System[c]	Kaiser (1990)	Central Carrizo-Wilcox GAM[d]
Top of Sparta Sand	X		X	X	X		X
Top of Weches Fm.	X			X	X		X
Top of Queen City	X	X	X	X	X		X
Top of Reklaw Fm.	X	X	X	X	X		X
Top of Carrizo Sand	X	X	X	X	X		X
Top of Upper Wilcox	X	X	X	X	X		X
Top of Middle Wilcox	X	X		X			
Top of Lower Wilcox	X	X		X		X	
Base of Wilcox	X	X	X	X	X		X

[a] Contacts provided by Rusk County GCD in an unpublished letter from Maloukis, A. (2017)
[b] USGS Regional Aquifer-System Analysis data from Wilson and Hosman (1987)
[c] Brackish Resources Aquifer Characterization System electrical logs reviewed by Montgomery & Associates
[d] Data sources for the Central Carrizo-Wilcox groundwater availability model include: Payne (1968), Garcia (1972), Guevara and Garcia (1972), Guevara (1972), Ricoy (1976), and Ricoy and Brown (1977)

The hydrostratigraphic framework for the groundwater model is principally based on the subsurface geospatial data sets listed in Table 4.1 and also utilized surficial geologic map information from the United States Geological Survey integrated geologic database (Stoeser and others, 2007) available from the Texas Natural Resources Information System.

4.1.1 Outcrop Analysis

The thicknesses of the Sparta Sand in outcrop areas and their importance to the aquifer system were reviewed for this study. Geologic information provided in geologic maps, well data, and cross-sections from previous studies were used to characterize the formation thickness for this study. In particular, the discontinuous, smaller Sparta Sand outcrops north of the main Sparta aquifer were delineated based on thicknesses described in literature (Broom 1968; Broom, 1969; Broom, 1971; Dillard, 1963; Sandeen, 1987; Guyton & Associates, 1971) and the aerial extent shown on the United States Geological Survey surficial geologic map. In the northern portion of the model, the discontinuous Sparta Sand outcrops are a maximum thickness of 50 feet in Cass and Marion counties (Broom, 1969), 250 feet in southwest Upshur County (Broom, 1971), and 250 feet in Wood County (Broom, 1968). In the central portion of the study area, the discontinuous Sparta Sand outcrops are a maximum thickness of 280 feet in Smith County (Dillard, 1963), 100 feet in the Mount Enterprise Fault area and have limited thickness in Rusk County (Sandeen, 1987). In the southern portion of the study area, the discontinuous Sparta Sand outcrops have a maximum documented thickness of 50 feet in Cherokee County near the city of Jacksonville (Guyton & Associates, 1971). Although Guyton & Associates (1971) documented thicknesses of the Sparta Sand at up to 255 feet thick, these areas are part of the continuous Sparta Sand outcrop belt included in the previous groundwater availability model.

Geologic cross-sections from literature review (Sandeen, 1987; Kaiser, 1990) suggested displacement along the Mount Enterprise Fault Zone ranging from 100 to 400 feet with a level of uncertainty. The surficial geologic map and available subsurface contact data were primarily used to distinguish displacement along the Mount Enterprise Fault Zone. Subsurface geologic data for this area are limited.

4.1.2 Review of Borehole Geophysical Logs

Borehole geophysical logs were used to verify the hydrostratigraphic layering control points used for the previous groundwater availability models. The principal data source for this analysis are electrical logs (elogs) provided by the Brackish Resources Aquifer Characterization System in July 2017. These elogs were used to verify hydrostratigraphic unit contacts provided by various data sources for 607 locations. These 607 locations were selected based on their proximity within 1,500 feet of a well location provided by the Brackish Resources Aquifer Characterization System. Of the well locations reviewed, 453 wells with hydrostratigraphic unit contacts provided by a data source were confirmed with an elog. In some cases, the data source distinguished only a few hydrostratigraphic units necessary for their study, but other contacts were apparent in the elog. Where possible, additional hydrostratigraphic unit contacts were identified for these locations. The remaining 261 elogs did not match the hydrostratigraphic unit contacts and suggests the data source may be different than the proximal Brackish Resources Aquifer Characterization System elog. In addition to these verified locations, 107 additional locations were identified and reviewed to fill spatial gaps of available elogs in support of the geologic model. Figure 4-2 shows elog locations in support of the geologic model.

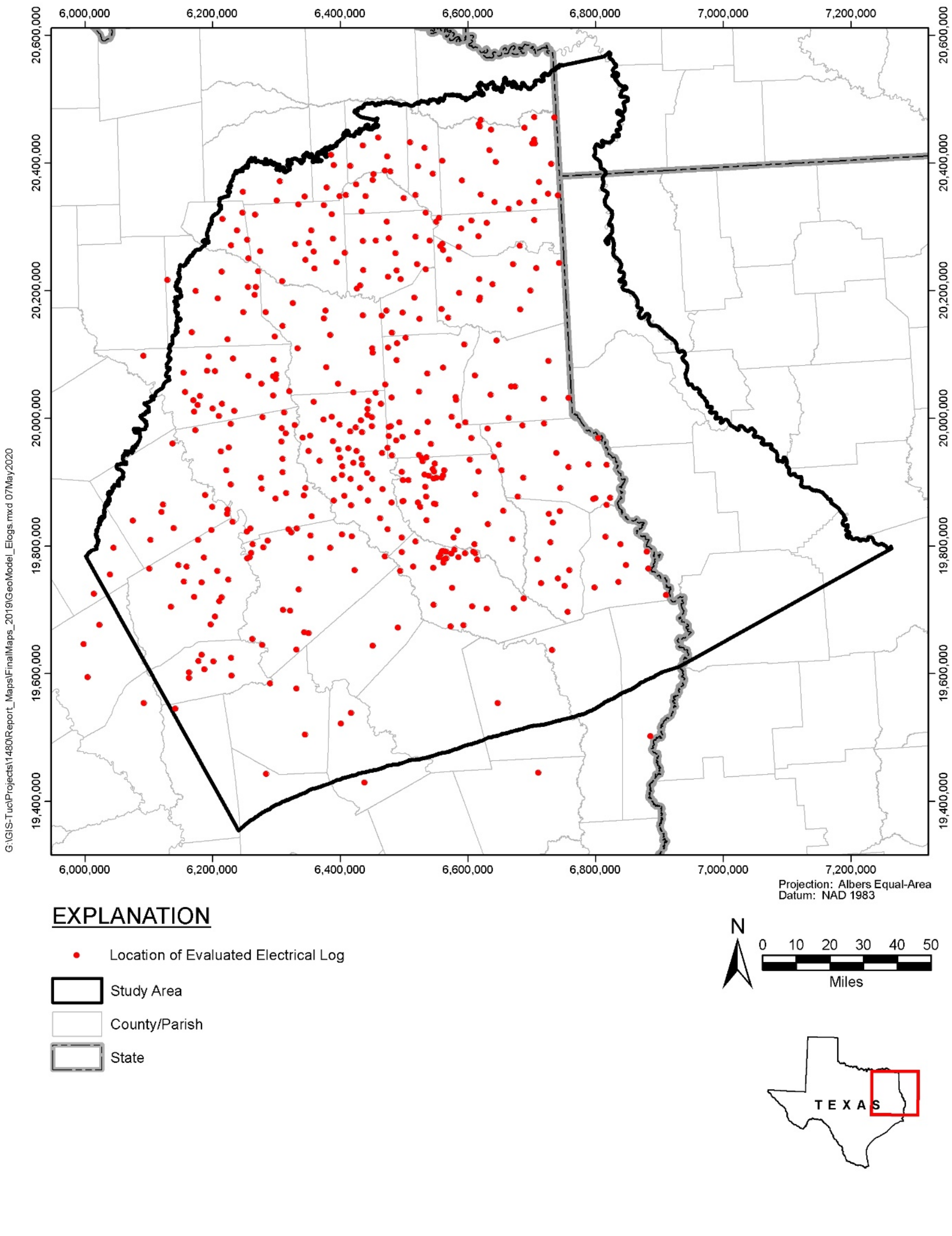


Figure 4-2. Locations of Evaluated Borehole Geophysical Logs

The method for reviewing elogs involved the following steps:

1. Review available reports to determine the elog curve characteristics for each hydrostratigraphic unit in a given county. These reports include the following:
    a. TWDB Reports: Anders (1967), Baker and Follet (1974), Baker (1979), Broom (1968), Broom (1969), Broom (1971), Broom and Myers (1966), Preston and Moore (1991), Sandeen (1987), Thompson (1972), Thorkildsen and Price (1991), White (1973), Guyton & Associates (1970), Guyton & Associates (1971)
    b. TWDB Bulletins: Broom and others (1965), Dillard (1963)
    c. USGS Open File Report: Baker (1995), Wilson and Hosman (1987)
    d. USGS Professional Paper: Payne (1968)
    e. Bureau of Economic Geology Papers: Guevara and Garcia (1972); Kaiser (1990); Ricoy and Brown (1977); Hobday and others (1980)
2. Review well locations from the various data sources within 1,500 feet of a Brackish Resources Aquifer Characterization System elog location to determine if the hydrostratigraphic unit contacts correlate with the elog. M&A added additional contacts if apparent on the elog.
3. After the hydrostratigraphic unit contacts were verified for each county, additional elogs were analyzed to fill in spatial gaps.

The elog characteristics for the hydrostratigraphic units change from the southern to the northern part of the study area. In the southernmost part of the study area, the hydrostratigraphic units are at depth and in brackish water which results in the elog characteristics becoming substantially muted. The distinguishing elog characteristics for each hydrostratigraphic unit outside of the brackish area is summarized as followed:

- Sparta Sand
    - South: High resistivity peak with fluctuations. Spontaneous potential also increases.
    - North: Sparta outcrops in the north are not thick enough to be included on the elogs.
- Weches Formation
    - South: Resistivity decreases and is more stable compared to the Sparta Sand. spontaneous potential also decreases.
    - North: Weches Formation outcrops in the north are not thick enough to be included on the elogs.
- Queen City Sand
    - South: Resistivity increases with some fluctuation and the spontaneous potential decreases. The unit is relatively thin in the south.
    - North: Resistivity is higher and fluctuates more in the north. The Queen City Sand is thicker in the north.

- Reklaw Formation
    - South: Resistivity is significantly lower and is more stable than the overlying Queen City Sand and underlying Carrizo Sand. A resistivity spike at the base is often included in the Reklaw Formation. Spontaneous potential steadily increases.
    - North: The resistivity fluctuates and is higher than the Reklaw characteristic in the south but still lower than the Queen City and Carrizo Sand. The Reklaw Formation in the north is thinner compared to the south.
- Carrizo Sand
    - South: Resistivity increases significantly and is easy to distinguish in any freshwater log where the Carrizo Sand is present. The base of the Carrizo is determined by a sharp decrease in resistivity. Spontaneous potential is not a good indication for this hydrostratigraphic unit since it varies.
    - North: In the northernmost part of the study area, the resistivity of the Carrizo Sand fluctuates more and often includes two small resistivity peaks compared to the large resistivity peak in the southern part of the study area.
- Wilcox Group
    - South: The top of the Wilcox Group includes a low resistivity interval and is easily distinguished between the high resistivity spike of the overlying Carrizo Sand and the low resistivity of the underlying Midway Group. The resistivity is moderately high and fluctuates throughout the unit.
    - North: The resistivity characteristics for the Wilcox Group are the same in the north, but the unit is thinner.
    - The Wilcox Group is composed of the following subunits: Upper, Middle, and Lower Wilcox. Although several reports show elogs defining the Wilcox Group, only a few reports discern the subunits of the Wilcox Group by showing their elog characteristics in or near the model domain which presented limited references for verifying the subunit contacts from previous data sources. These reports are focused on the west side of the model mostly around Houston County (Ayers and Lewis, 1985; Baker, 1995, Thorkildesn and Price, 1991) and around the Sabine Uplift (Kaiser, 1990; Lupton and others, 2015). The reports focused on the west side of the model often discern the subunits only outside of this reports' study area. The reports focused around the Sabine Uplift do not distinguish the Upper Wilcox from the Middle Wilcox but instead group these together as "upper". In many of the logs, a clear delineation of the subunits is difficult to determine.
    - The Upper Wilcox can be distinguished by the sawtooth pattern in the resistivity log (Kaiser, 1990).
    - The Middle Wilcox tends to have an increase in resistivity with a blocky characteristic.
    - The top contact for the Lower Wilcox can be distinguished by a sharp decrease in resistivity which then recovers to a lower, declining resistivity compared to other Wilcox units. Kaiser (1990) describes the resistivity characteristic as an inverted Christmas tree pattern for the Lower Wilcox.

4.1.3 Hydrostratigraphic Framework

A continuous three-dimensional (3D), volumetric representation of the hydrostratigraphic framework for the study area was prepared using the geologic modeling software Leapfrog® Geo, developed by Seequent. The Leapfrog geologic model was developed using the framework geospatial datasets for unit top elevations from various data sources shown in Table 4.1 and outcrop extent polylines from the digital United States Geological Survey geology map datasets.

The hydrostratigraphic framework model is data driven and focuses on the original data sources outlined in Table 4.1 with review and some elog verification by M&A. As such, the model was not rectified to the decisions made in the previous groundwater availability model for the sub-units of the Wilcox Group which are only apparent in the MODFLOW grid files. These changes to the MODFLOW grid files and the decisions behind the changes were not documented in the previous groundwater availability model report and were brought to M&A's attention during the comment phase of this report. To address the comment, M&A did a thorough review of the previous MODFLOW grid file compared to the current hydrostratigraphic framework model to understand the differences since both models used the same structure contact datasets. The differences between the Upper, Middle, and Lower Wilcox for the hydrostratigraphic framework model and the previous groundwater availability model are summarized as follows:

- Structure contact datasets obtained from the previous groundwater availability model include Lower Wilcox contacts in the northern portion of the model domain, but the old MODFLOW grid pinches this unit out in the north. The pinchout contact is similar to the contact by Kaiser (1990) which focused on the Sabine Uplift area and was almost certainly delineated prior to the structure contact datasets. The structure contact datasets show variable thicknesses in the north of the subunits for the Wilcox Group, so it is assumed these are reviewed contacts from elogs rather than an equal separation of the Wilcox Group into its sub-units. The hydrostratigraphic framework model honors the structure contact datasets and includes the Lower Wilcox in the northern portion of the model.

- The aquifer unit surfaces from the previous groundwater availability model show the Upper Wilcox is largely absent in the Sabine Uplift; however, the structure contact datasets show a top contact for the Middle Wilcox in the following counties: Harrison, Panola, and Shelby. These datasets show therefore that there is more Upper Wilcox within the footprint of the Sabine Uplift than portrayed in the previous groundwater availability model. The hydrostratigraphic framework model honors the structure contact datasets and includes more Upper Wilcox within the Sabine Uplift.

- The aquifer unit surfaces from the previous groundwater availability model show the thickness of the Lower Wilcox is significantly reduced in the Sabine Uplift. The structure contact datasets support a reduced thickness in the Sabine

Uplift but also includes some intervals of the Lower Wilcox up to 300 feet thick. As a result of the supporting dataset, the hydrostratigraphic framework shows the Lower Wilcox thicker than the previous groundwater availability model in the Sabine Uplift.

The hydrostratigraphic framework model focused on the available datasets and did not rectify the model to undocumented decisions made during the last model initiative. The outcrop areas of the main hydrostratigraphic units and the Quaternary river alluvium within the stream channels and tributaries in the study area are shown on Figure 4-3. The footprints of the hydrostratigraphic units differ from the aquifer footprints due to the incorporation of small, discontinuous outcrops, including areas outside of Texas, and due to the footprint including the downdip portion of the layer to the model boundary unlike the aquifer footprint. In some areas, this framework has blank or null portions in the base elevation surfaces indicating locations where the interpolation of the unit has pinched out primarily due to salt domes, river alluvium eroding into the underlying layers, or outcrop delineations. This framework was converted into the unstructured grid of the numerical groundwater availability model, which does not require a minimum layer thickness and allows for groundwater flow between any adjacent grid cell. Geologic cross-sections of this detailed framework are presented on Figure 4-4. The sections were intentionally oriented in a manner to illustrate the stacking of the generally wedge-shaped aquifer units. The surficial river alluvium layer is too thin to be visible in regional-scale cross-section view.

Each hydrostratigraphic unit and the Quaternary Alluvium are described from youngest to oldest in the following sections. The geologic model also includes volumes for the units younger than the Sparta Sand and Quaternary deposits along the major rivers and tributaries.

<u>Quaternary Deposits (River Alluvium)</u>

The Quaternary Deposits (river alluvium) were distinguished from other hydrostratigraphic units for the groundwater model. The extent of the river alluvium deposits along the major river channels was simplified from the Quaternary unit extents mapped from Texas Natural Resources Information System. Available lithologic or elog data for boreholes did not provide contacts for the river alluvium, so a literature review was conducted to provide some basis for the thickness. None of the major rivers within the study area had documentation for the Quaternary unit thickness; however, the Brazos River to the west of the study area is documented with a thickness of up to 100 feet for the Quaternary units with an average thickness of 45 feet and the North Fork Red River to the north of the study area is up to 195 feet thick with an average thickness of 70 feet (Ryder, 1996). For the hydrostratigraphic framework, the Quaternary Deposits were assigned a thickness of up to 80 feet in the major river channels with a flat bottom since the location of the active channel over time is unknown and likely changed over time.

To aid with the groundwater modeling, the major tributary drainages were also modeled as river alluvium. These areas also had no contacts from borehole data and no documentation for unit thickness found in literature. The location of each tributary centerline was relocated, as necessary, to ensure they occurred in the topographic low of each drainage.

This centerline was then buffered 2,000 feet to determine the aerial extent of the unit since Quaternary units were often not mapped in the drainages. An approximate, interpretive thickness of 15 feet was assigned to the tributaries based on the conceptual idea that the tributaries are thinner than the major river channels. Thicknesses of river alluvium deposits represented in the hydrostratigraphic framework are shown on Figure 4-5.

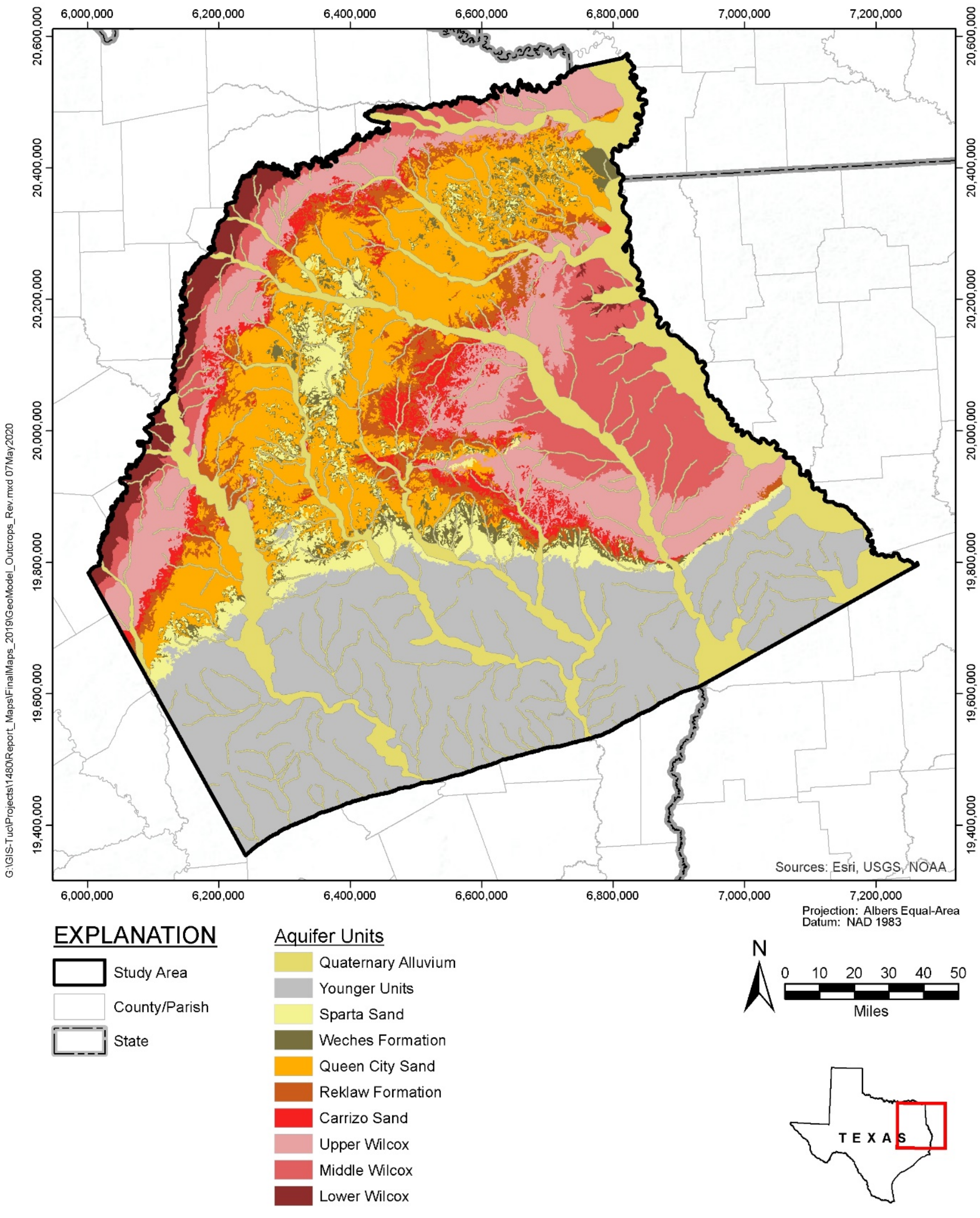


Figure 4-3. Aquifer Outcrops from Geologic Model

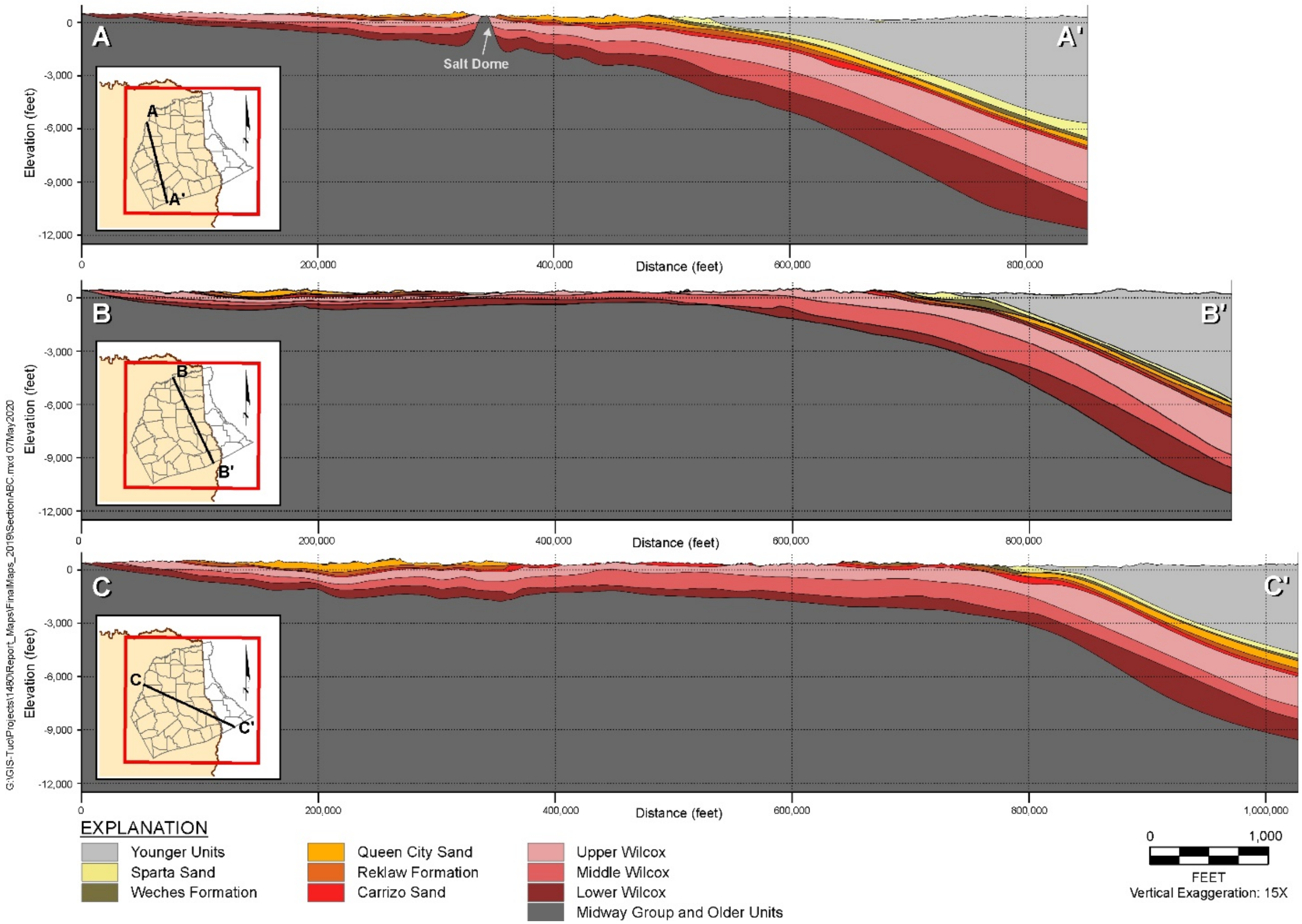


Figure 4-4. Hydrogeologic Sections A-A', B-B', and C-C'

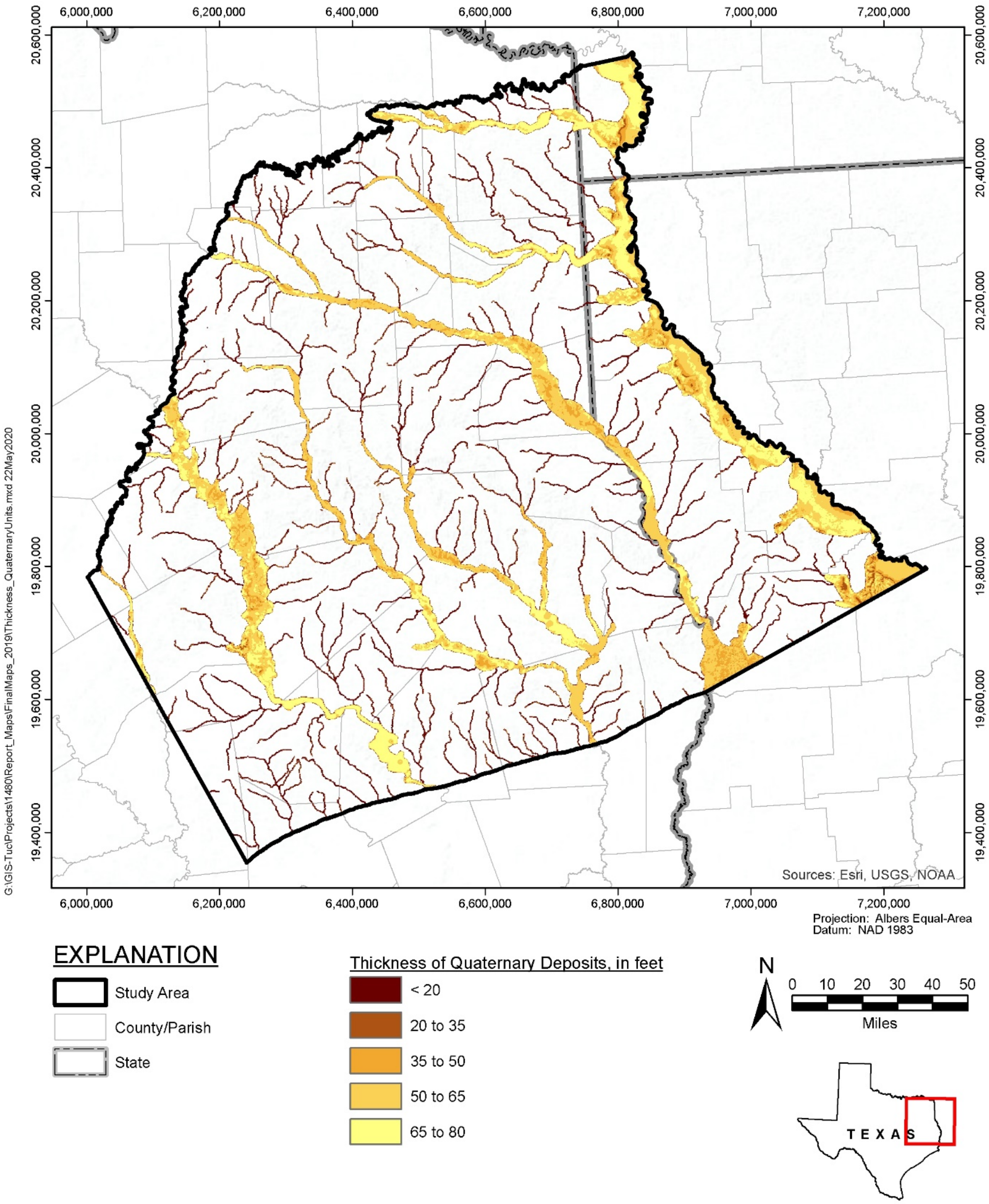


Figure 4-5. Thickness of Quaternary Deposits

Sparta Sand

The Sparta Sand is a distinct sand rich unit identified as a high-constructive delta facies in east Texas (Ricoy and Brown, 1977). This hydrostratigraphic unit is easily distinguished from the younger Cook Mountain Formation and older Weches Formation, which are both marly marine transgressive units. Figure 4-6 shows the top elevation of the Sparta Sand (or base of overlying Younger Units in down dip areas), which ranges from about 765 feet above mean sea level in the northern portion of the study area to -6,300 feet above mean sea level in the southern portion. A negative value for "above mean sea level" represents an elevation below mean sea level. The bottom (base) elevations and thickness of the Sparta Sand are shown on Figure 4-7 and Figure 4-8, respectively. The bottom elevation of the Sparta Sand is 735 feet above mean sea level in the north and decreases to about -6,750 feet above mean sea level in the south (Figure 4-7). The thickness of the Sparta Sand is up to 940 feet in the south and thins to zero in the north (Figure 4-8).

Weches Formation

The Weches Formation is composed of glauconitic muds and represents a marine transgression between the overlying Sparta Sand and underlying Queen City Sand. This hydrostratigraphic unit is considered a confining layer to the Queen City Sand. Figure 4-7 shows the top elevation of the Weches Formation (base of overlying Sparta Sand), which ranges from about 735 feet above mean sea level in the northern portion of the study area to -6,750 feet above mean sea level in the southern portion. The bottom (base) elevations and thickness of the Weches Formation are shown on Figure 4-9 and Figure 4-10, respectively. The bottom elevation of the Weches Formation is about 720 feet above mean sea level in the north and decreases to about -6,900 feet above mean sea level in the south (Figure 4-9). The thickness of the Weches Formation is up to 565 feet in the south and thins to zero in the north (Figure 4-10).

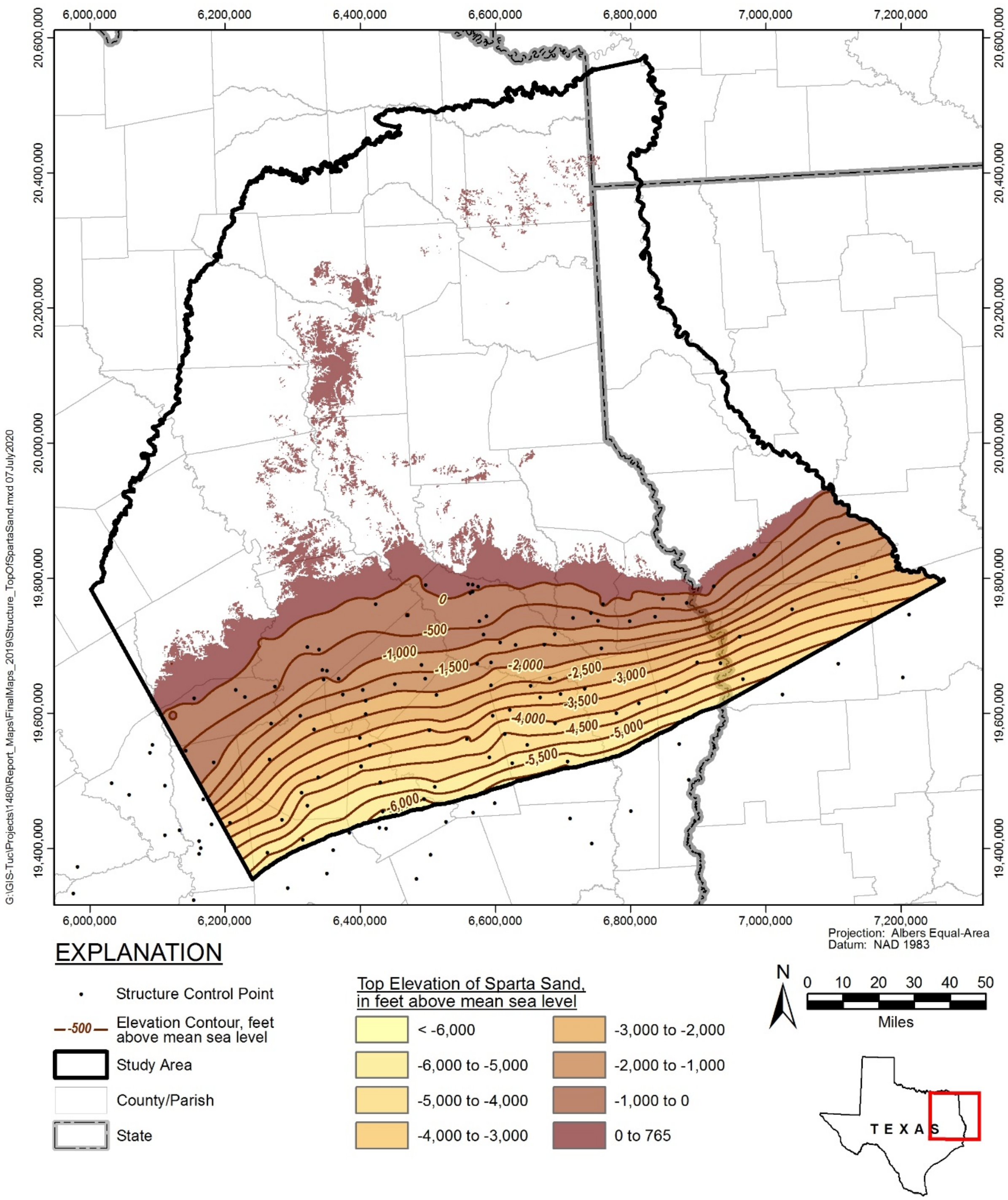


Figure 4-6. Top Elevation Contours for Sparta Sand

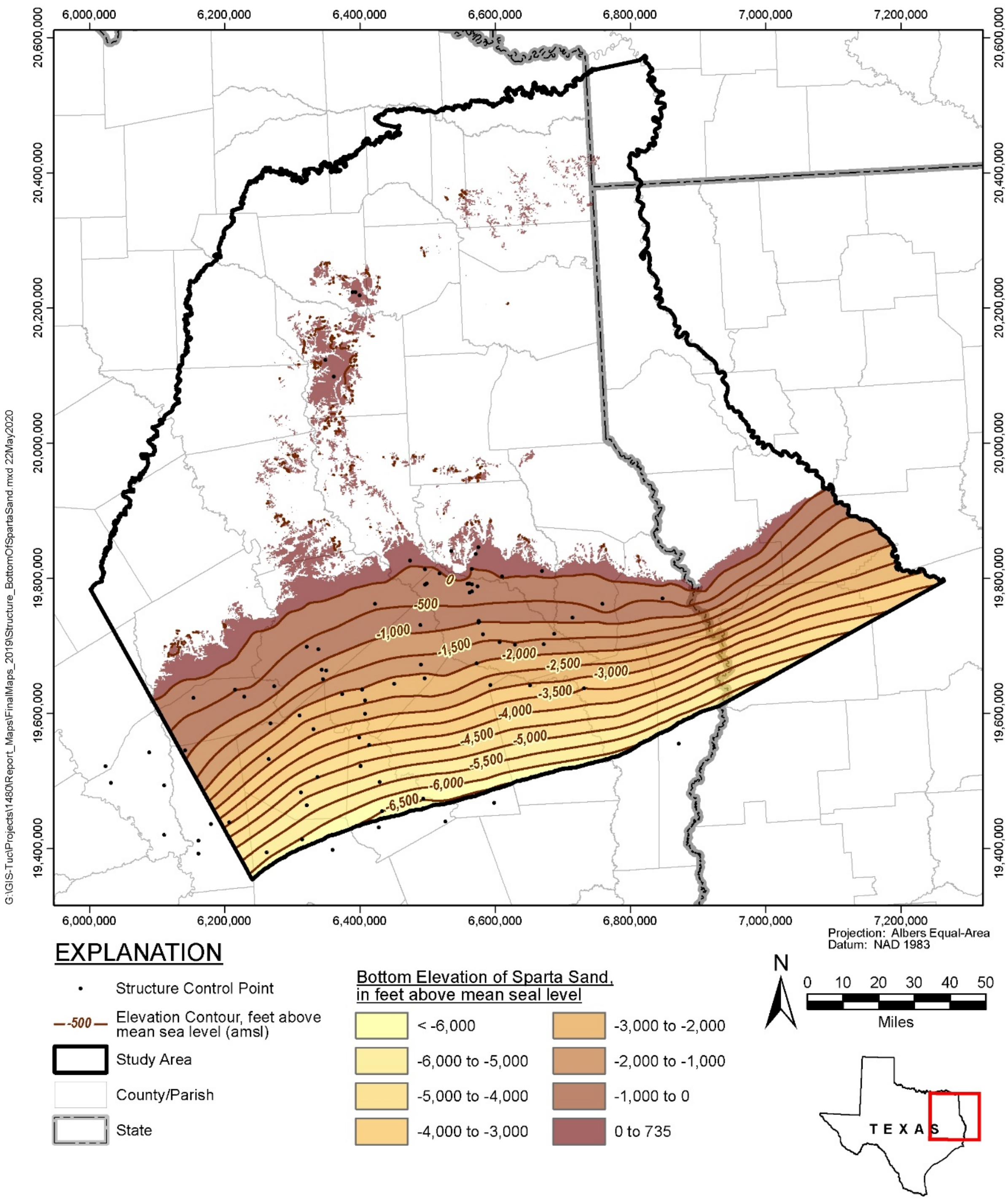


Figure 4-7. Bottom Elevation Contours for Sparta Sand

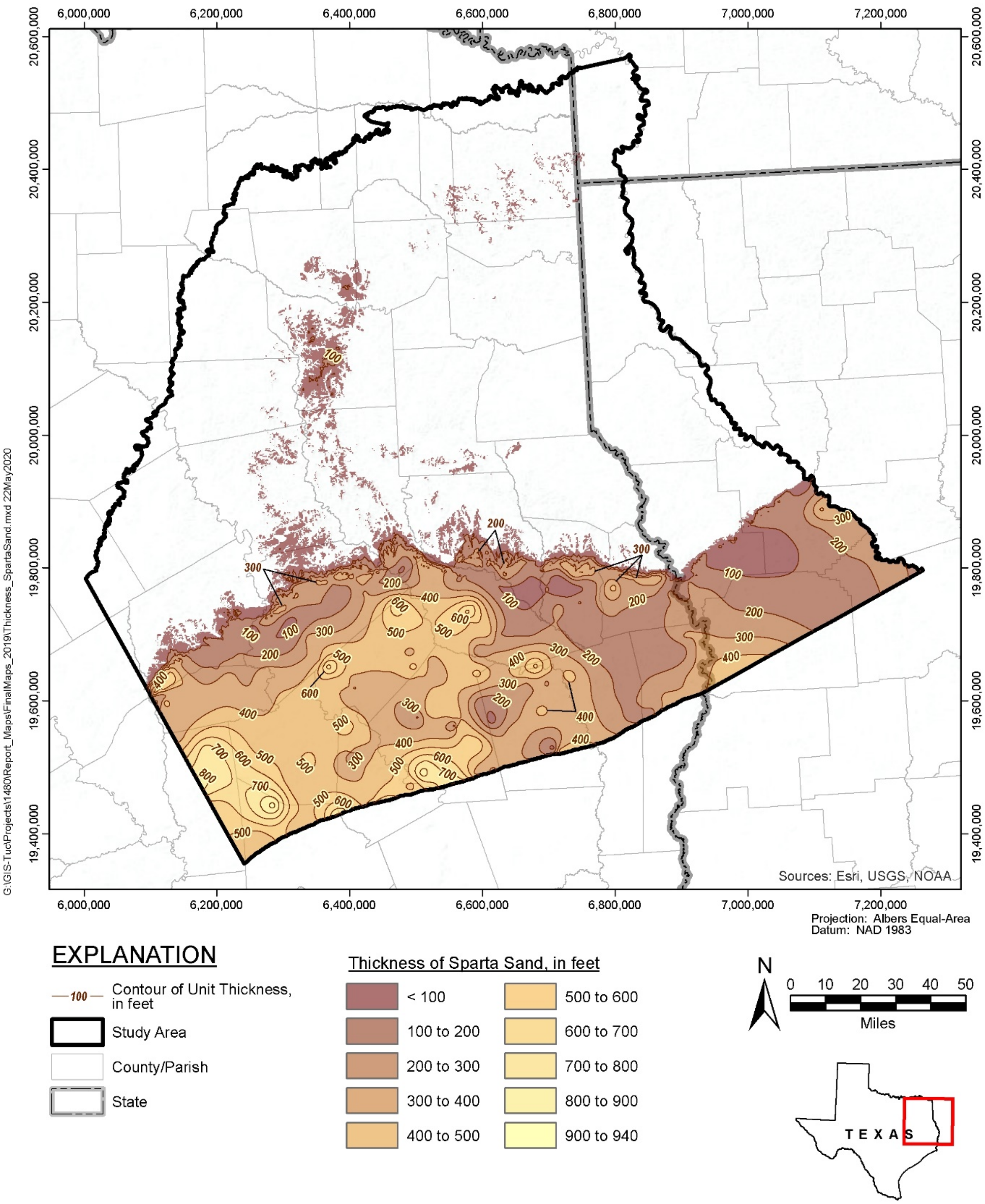


Figure 4-8. Thickness of Sparta Sand

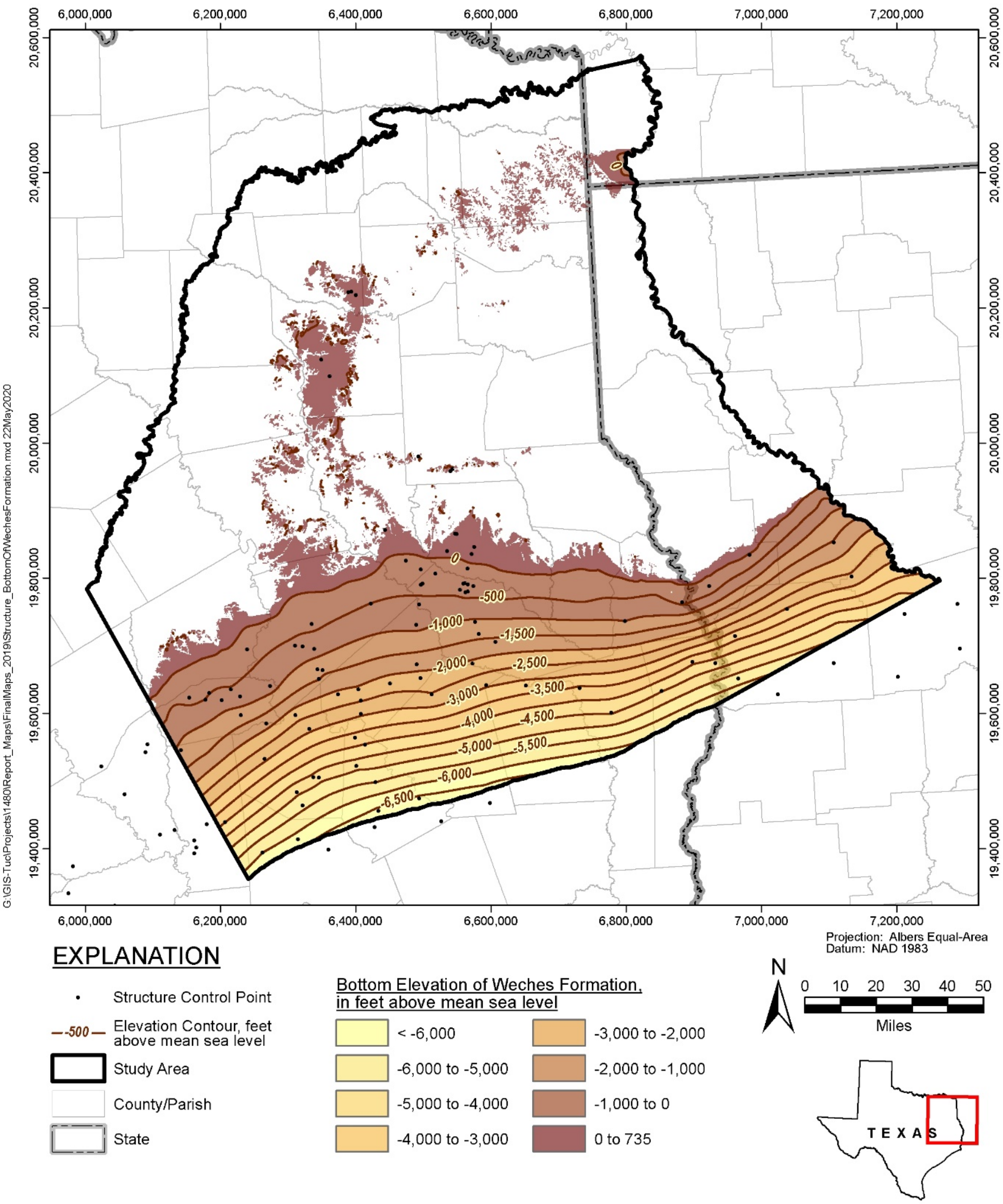


Figure 4-9. Bottom Elevation Contours for Weches Formation

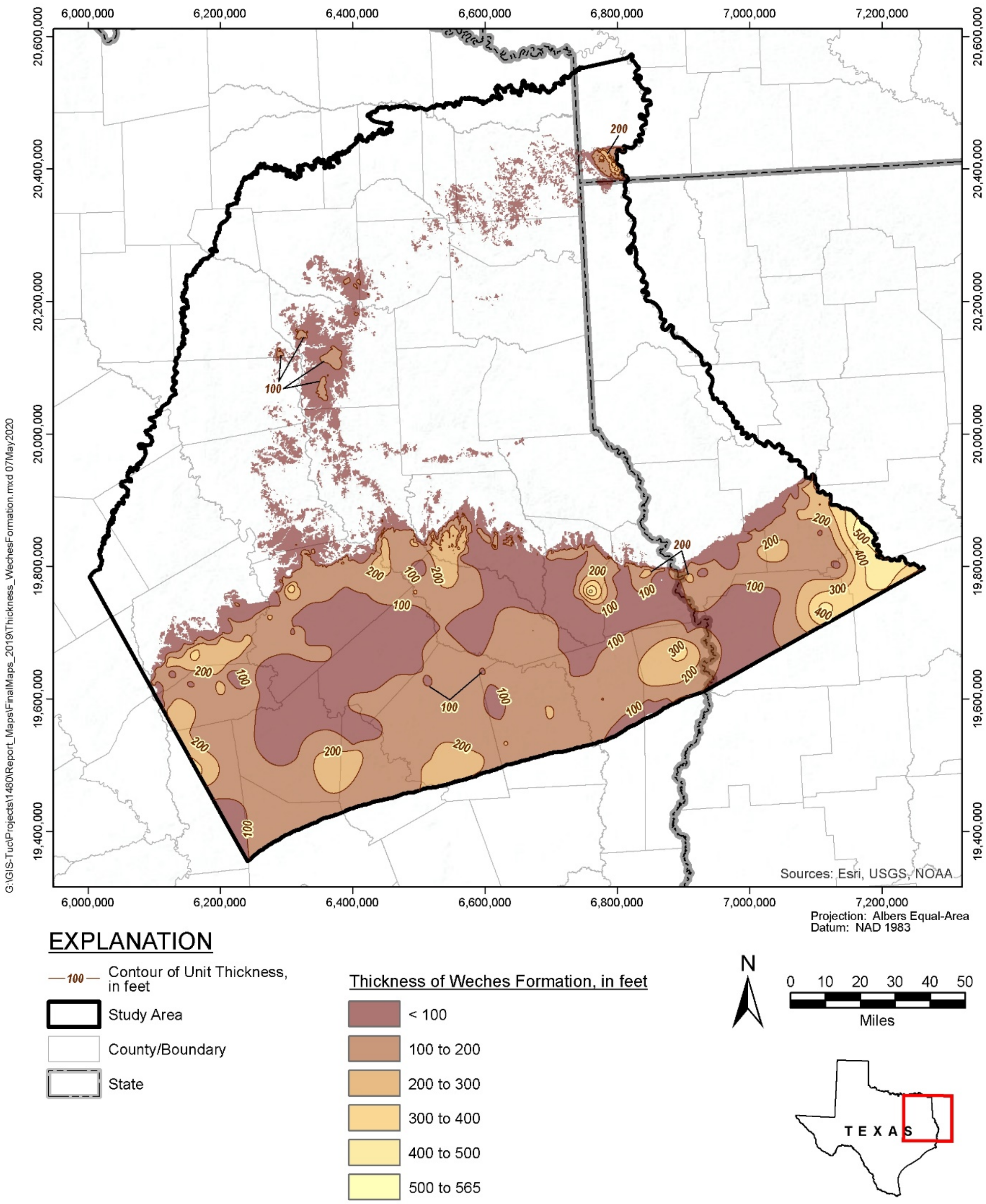


Figure 4-10. Thickness of Weches Formation

Queen City Sand

The Queen City Sand is composed of deltaic sands deposited as a high-constructive, lobate delta system (Guevara and Garcia, 1972). Figure 4-10 shows the top elevations of the Queen City Sand (or base of overlying Weches Formation), which ranges from about 720 feet above mean sea level in the northern portion of the study area to -6,900 feet above mean sea level in the southern portion. The bottom (base) elevations and thickness of the Queen City Sand are shown on Figure 4-11 and Figure 4-12, respectively. The bottom elevation of the Queen City Sand is about 565 feet above mean sea level in the north and decreases to about -7,000 feet above mean sea level in the south (Figure 4-11). The thickness of the Queen City Sand is up to 695 feet (Figure 4-12).

Reklaw Formation

The Reklaw Formation is composed of mud and sand is considered as a confining unit to the Carrizo and Wilcox hydrostratigraphic units. Figure 4-11 shows the top elevation of the Reklaw Formation (or base of overlying Queen City Sand), which ranges from about 570 feet above mean sea level in the northern portion of the study area to -7,000 feet above mean sea level in the southern portion. The bottom (base) elevations and thickness of the Reklaw Formation are shown on Figure 4-13 and Figure 4-14, respectively. The bottom elevation of the Reklaw Formation is about 565 feet above mean sea level in the north and decreases to about -7,130 feet above mean sea level in the south (Figure 4-13). The thickness of the Reklaw Formation is up to 490 feet (Figure 4-14).

Carrizo Sand

The Carrizo Sand unconformably overlies the Wilcox Group and is composed of homogenous fluvial sands with interbedded muds locally in the northernmost area. Figure 4-13 shows the top elevation of the Carrizo Sand (or base of overlying Reklaw Formation), which ranges from about 565 feet above mean sea level in the northern portion of the study area to -7,130 feet above mean sea level in the southern portion. The bottom (base) elevations and thickness of the Carrizo Sand are shown on Figure 4-15 and Figure 4-16, respectively. The bottom elevation of the Carrizo Sand is about 640 feet above mean sea level in the north and decreases to about -7,230 feet above mean sea level in the south (Figure 4-15). The thickness of the Carrizo Sand is up to 485 feet (Figure 4-16).

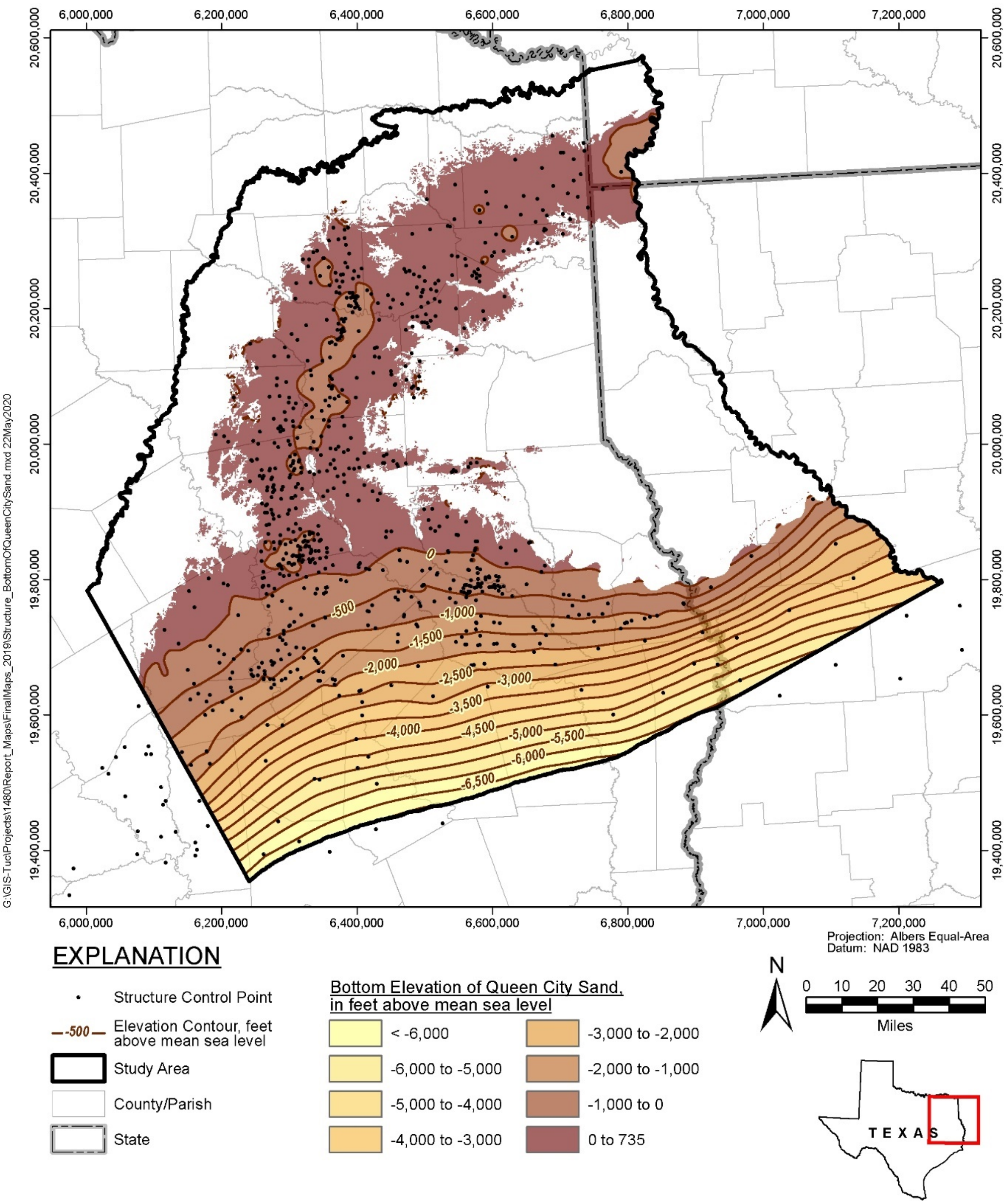


Figure 4-11. Bottom Elevation Contours for Queen City Sand

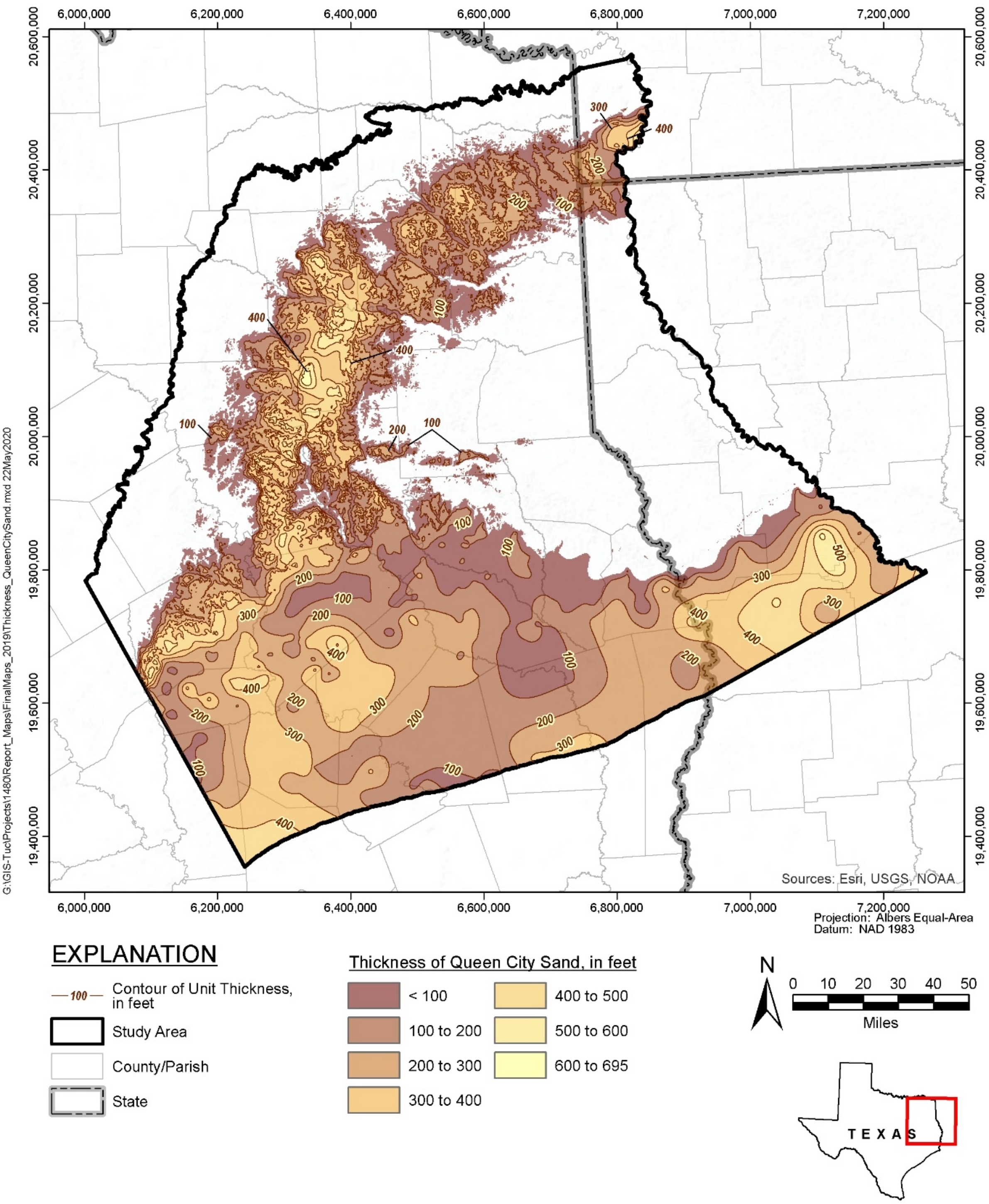


Figure 4-12. Thickness of Queen City Sand

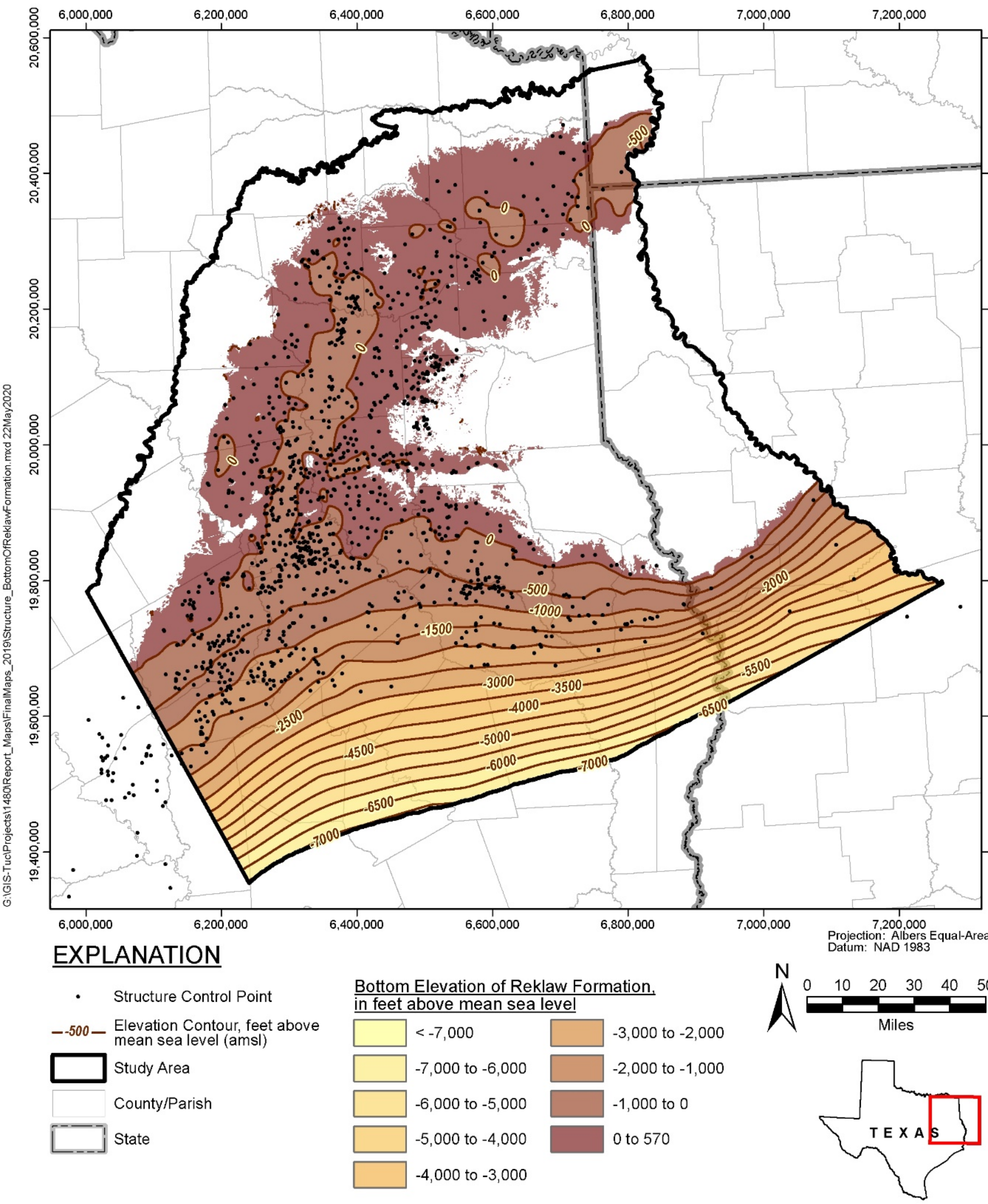


Figure 4-13. Bottom Elevation contours for Reklaw Formation

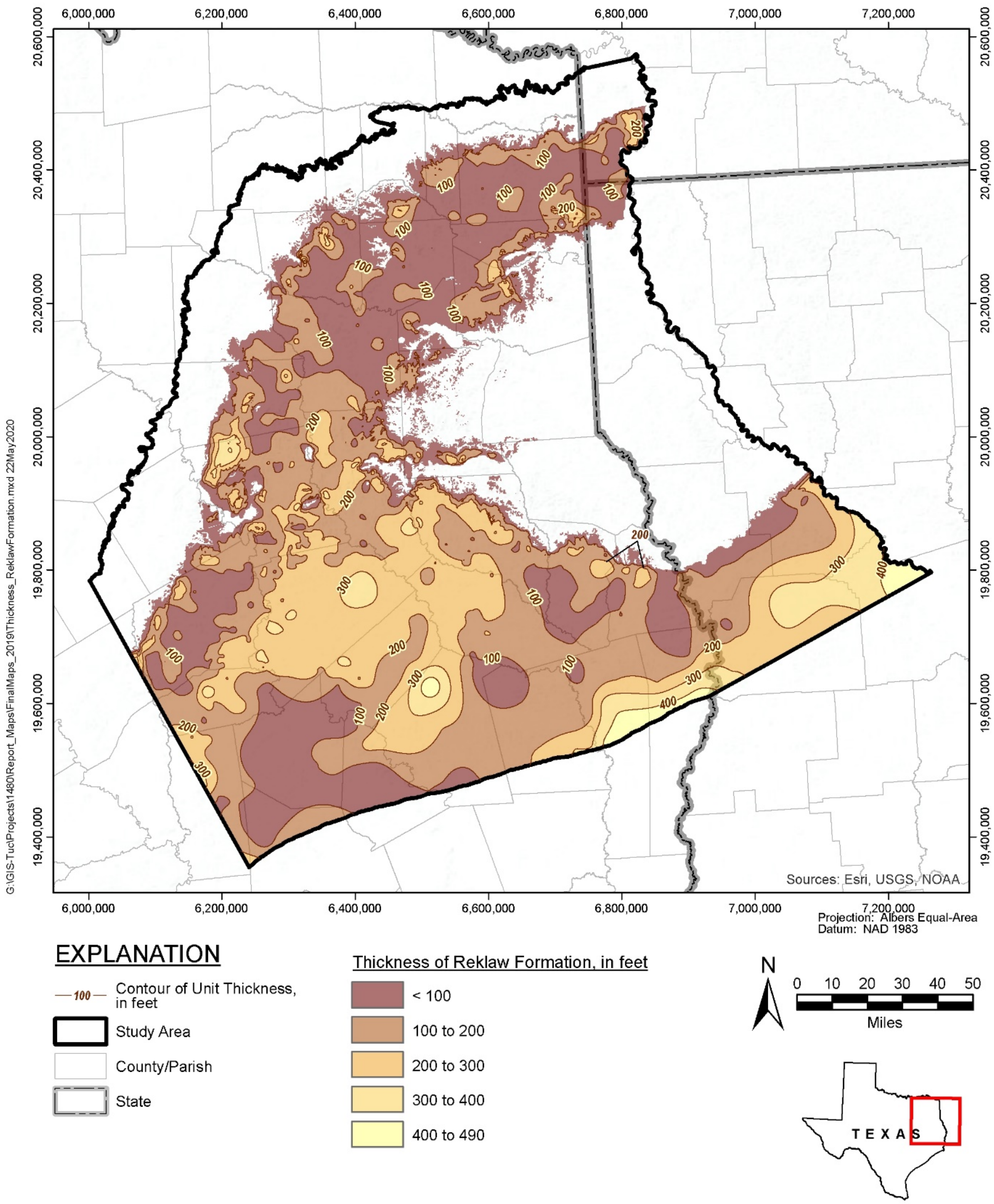


Figure 4-14. Thickness of Reklaw Formation

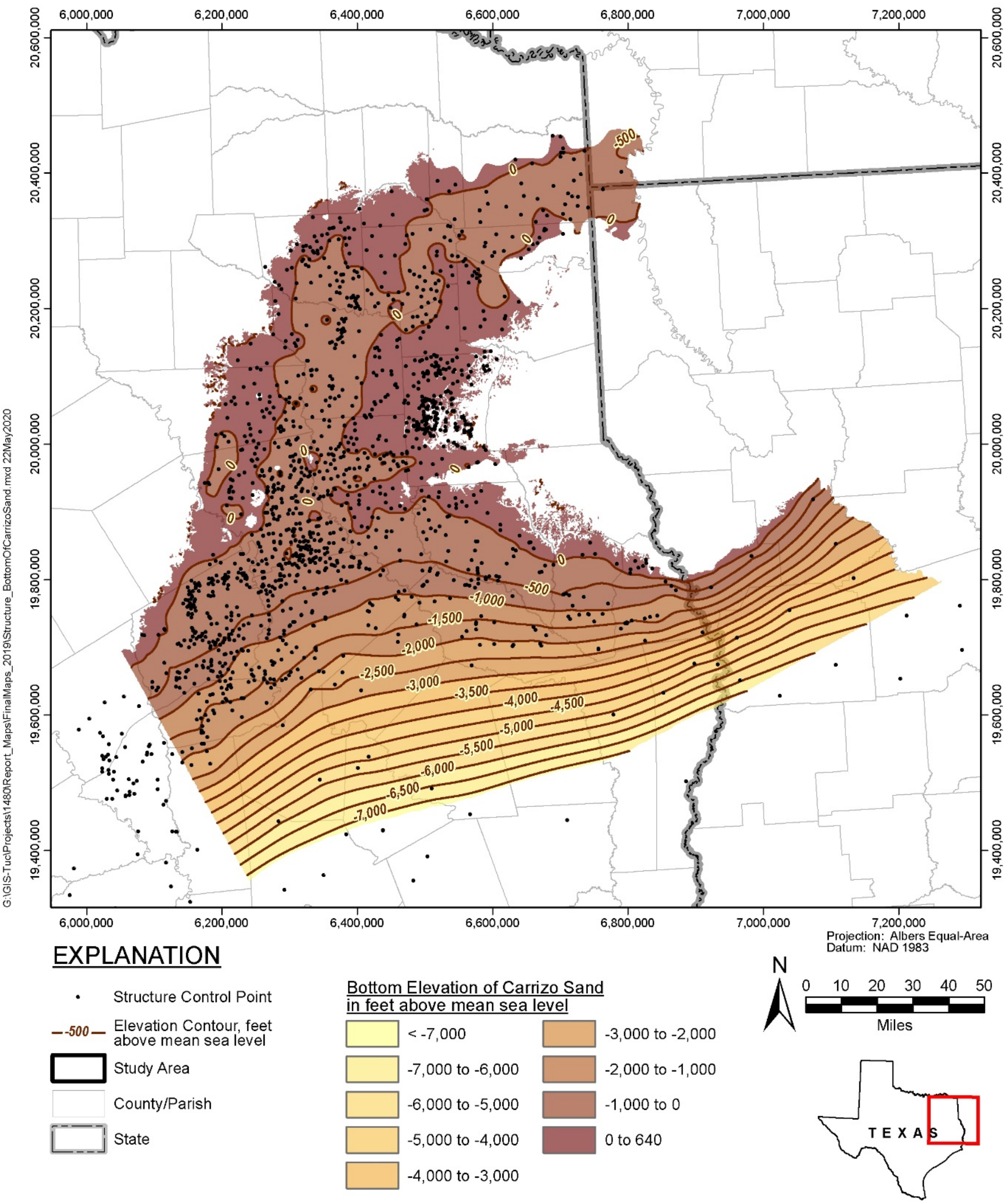


Figure 4-15. Bottom Elevation Contours for Carrizo Sand

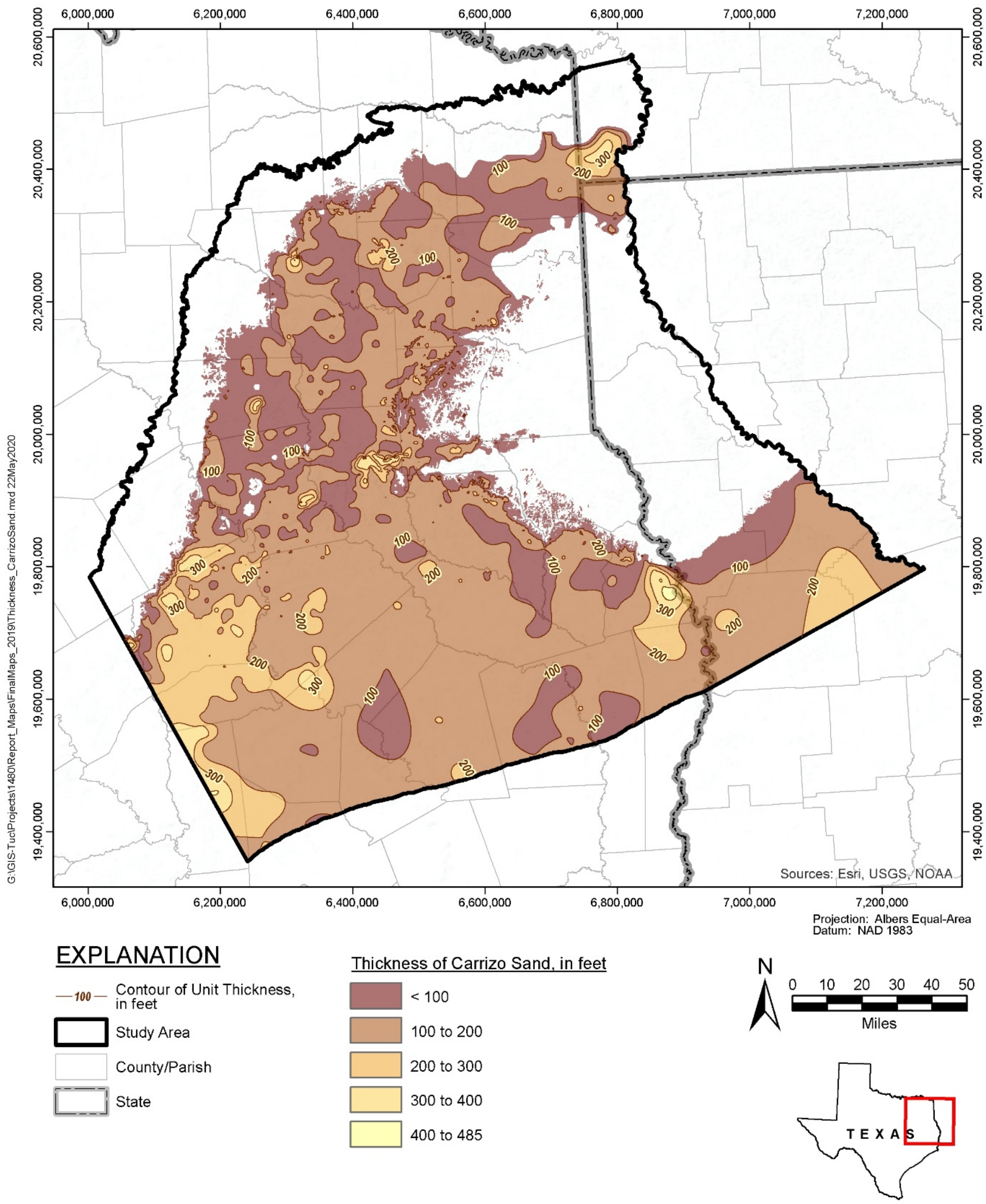


Figure 4-16. Thickness of Carrizo Sand

Wilcox Group

The Wilcox Group is subdivided as three layers (Upper, Middle, and Lower) based on the Hooper, Simsboro, and Calvert Bluff formations which are mapped west of the Trinity River. The depositional environments for these subunits correspond to deltaic, fluvial, and fluvial-deltaic facies for the Upper, Middle, and Lower Wilcox, respectively (Kaiser, 1974).

Several data sources distinguish the structure of the subunits of the Wilcox Group (Ayers and Lewis, 1985; Maloukis, 2017; TWDB, unpublished). The spatial distribution of the top structure points for the Upper Wilcox (or base of the Carrizo Wilcox) are shown on Figure 4-15 and the base structure points for the Upper, Middle, and Lower Wilcox are shown on Figure 4-17, Figure 4-18, and Figure 4-19, respectively. Only a few reports demonstrate the differences with elogs. These reports are focused on the west side of the model mostly around Houston County (Ayers and Lewis, 1985; Baker, 1995, Thorkildesn and Price, 1991) and around the Sabine Uplift (Kaiser, 1990; Lupton and others, 2015). The reports focused on the west side of the model often discern the subunits only outside of this reports' study area. The reports focused around the Sabine Uplift do not distinguish the Upper Wilcox from the Middle Wilcox but instead group these together as "upper".

In the Sabine Uplift area, the hydrostratigraphic framework model distinguishes between the Upper and Middle Wilcox due to structure points from the TWDB (unpublished). However, the reports which show the contacts with the support of elogs (Kaiser 1990; Lupton and other, 2015) do not distinguish between these subunits. The hydrostratigraphic framework model uses the structure points from the TWDB and delineates a boundary some distance within the Sabine Uplift for these two subunits based on the expression of the uplift. The footprints of the Upper and Middle Wilcox are similar to the previous groundwater availability model (Fryar and others, 2003; Kelley and others, 2004). Although the hydrostratigraphic framework model distinguishes these two subunits of the Wilcox Group in the Sabine Uplift, these two layers will be modeled under similar conditions in the numeric groundwater model to effectively treat them as undifferentiated. Figure 4-20 shows geologic cross-sections focused on the Wilcox Group in the Sabine Uplift.

The hydrostratigraphic framework model also differs from the previous groundwater availability model by including the Lower Wilcox in the north portion of the model based on available structure contact datasets. The previous groundwater availability model pinched out the Lower Wilcox, so it did not reach the northern portion of the model.

The top of the Upper Wilcox includes a thin regional marine-transgressive unit which separates the Wilcox Group from the Carrizo Sand. Figure 4-15 shows the top elevation of the Upper Wilcox unit (or base of the overlying Carrizo Sand), which ranges from about 640 feet above mean sea level to -7,230 feet above mean sea level. In the area of the Sabine Uplift, the Upper Wilcox is delineated in the hydrostratigraphic framework model but will be treated as undifferentiated with the Middle Wilcox for the purposed of the numeric groundwater model. The bottom (base) elevations and thickness of the Upper Wilcox unit are shown on Figure 4-17 and Figure 4-18, respectively. The bottom elevation of the Upper

Wilcox unit is about 570 feet above mean sea level in the north and decreases to about -9,550 feet above mean sea level in the south (Figure 4-17). The thickness of the Upper Wilcox unit is up to 2,680 feet (Figure 4-18).

Figure 4-17 shows the top elevation of the Middle Wilcox unit (or base of the overlying Upper Wilcox unit), which ranges from about 570 feet above mean sea level to -9,550 feet above mean sea level. In the area of the Sabine Uplift, the Upper Wilcox is delineated in the hydrostratigraphic framework model based on supporting structure contact datasets but will be treated as undifferentiated with the Middle Wilcox for the purpose of the numeric groundwater model. The bottom (base) elevations and thickness of the Middle Wilcox unit are shown on Figure 4-19 and Figure 4-20, respectively. The bottom elevation of the Middle Wilcox unit is about 565 feet above mean sea level in the north and decreases to about -10,430 feet above mean sea level in the south (Figure 4-19). The thickness of the Middle Wilcox unit is up to 1,560 feet (Figure 4-20).

Figure 4-19 shows the top elevation of the Lower Wilcox unit (or base of the overlying Middle Wilcox unit), which ranges from about 565 feet above mean sea level to -10,430 feet above mean sea level. The Lower Wilcox is present in the northern portion of the model based on available structure contact datasets. The bottom (base) elevations and thickness of the Lower Wilcox unit are shown on Figure 4-21 and Figure 4-22, respectively. The bottom elevation of the Lower Wilcox unit is about 560 feet above mean sea level in the north and decreases to about -11,700 feet above mean sea level in the south (Figure 4-21). The thickness of the Lower Wilcox unit is up to 2,735 feet (Figure 4-22).

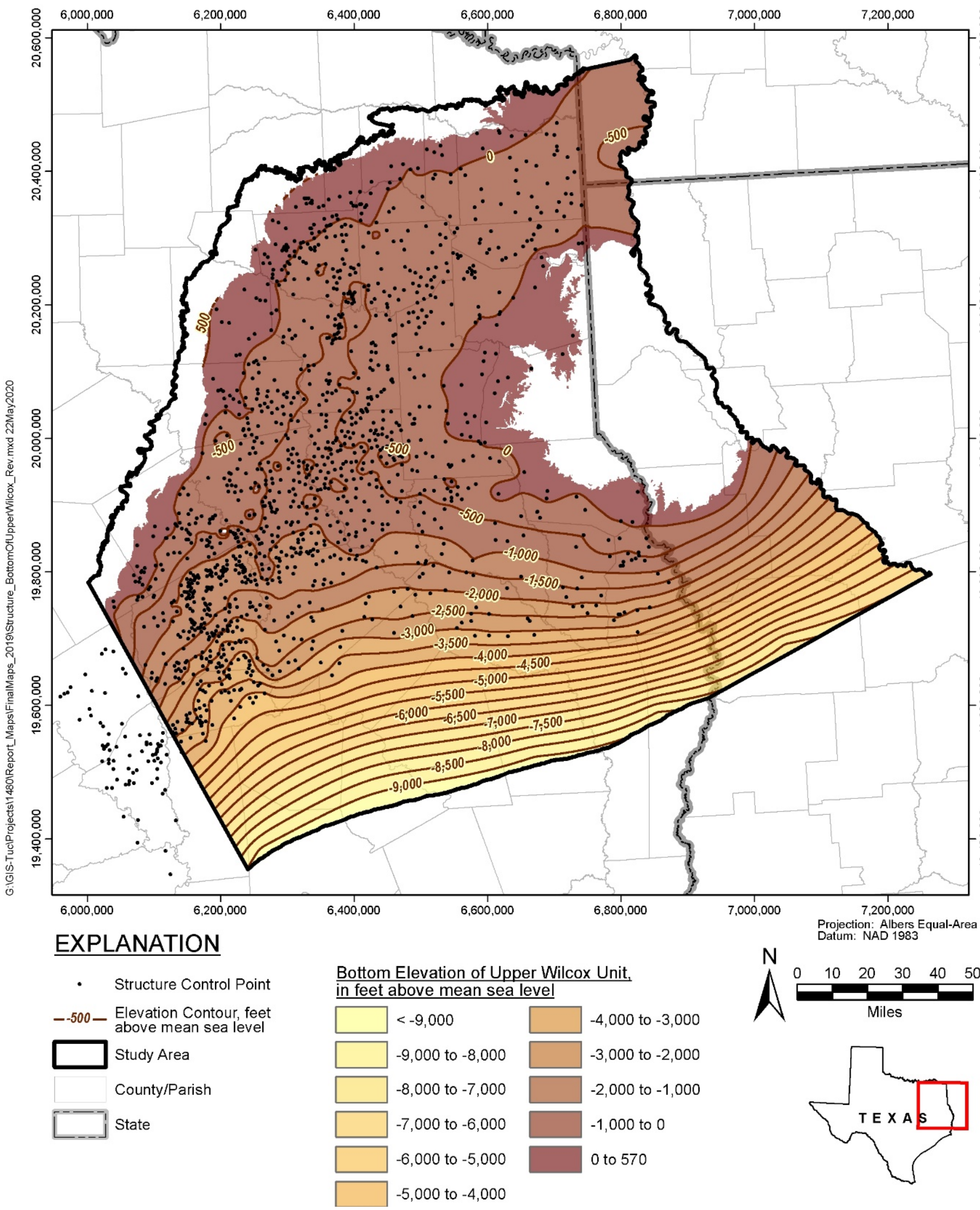


Figure 4-17. Bottom Elevation Contours for Upper Wilcox Unit

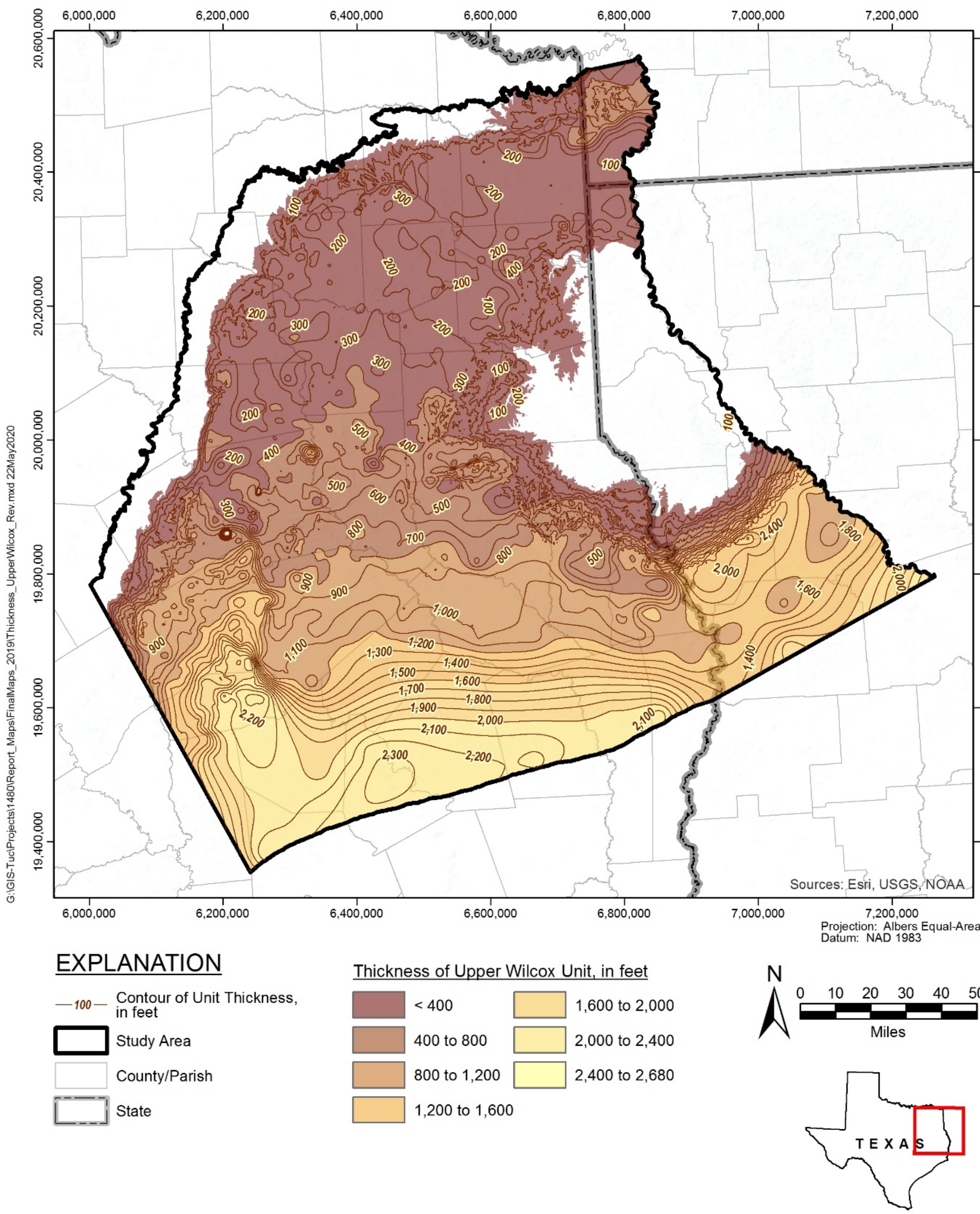


Figure 4-18. Thickness of Upper Wilcox Unit

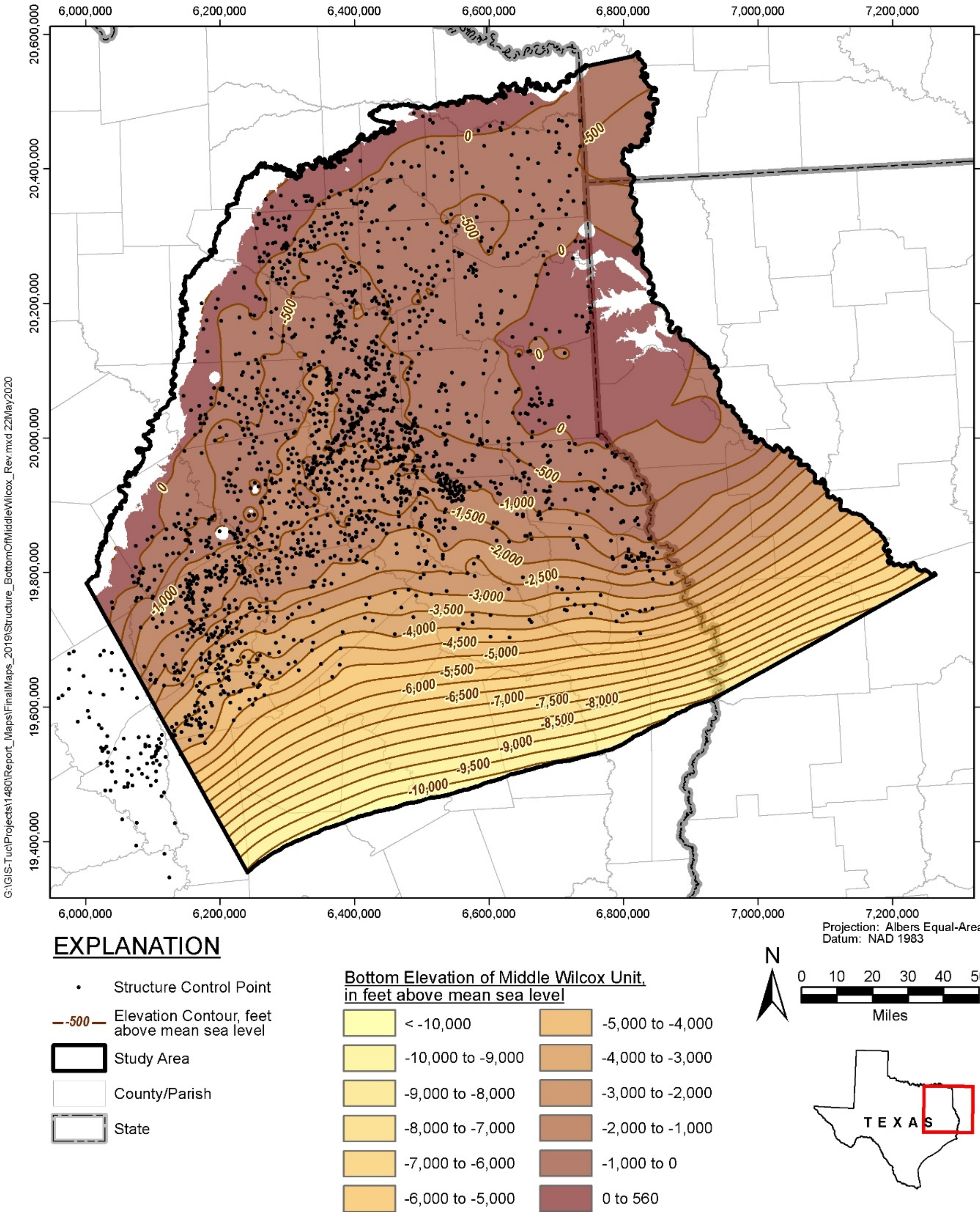


Figure 4-19. Bottom Elevation Contours for Middle Wilcox Unit

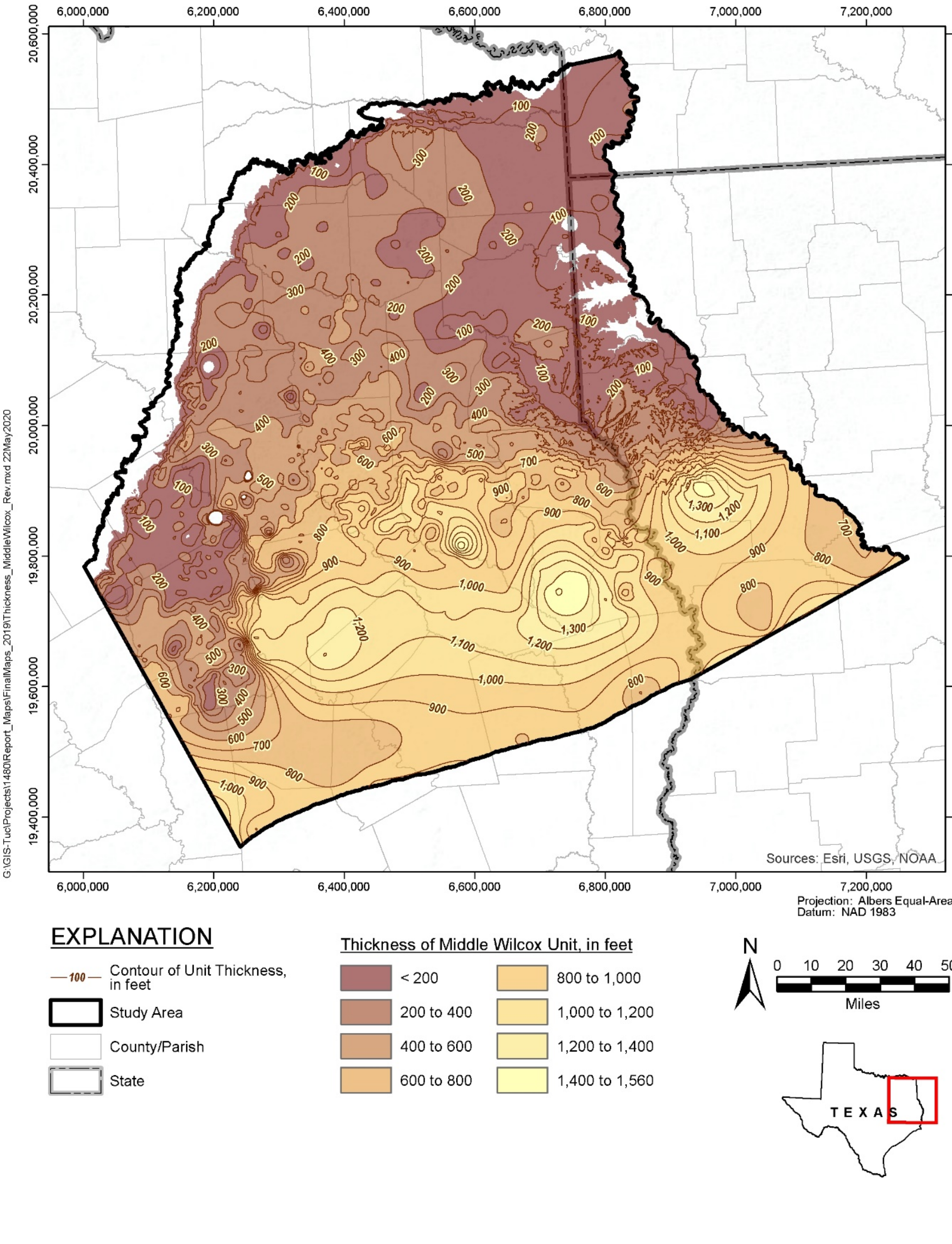


Figure 4-20. Thickness of Middle Wilcox Unit

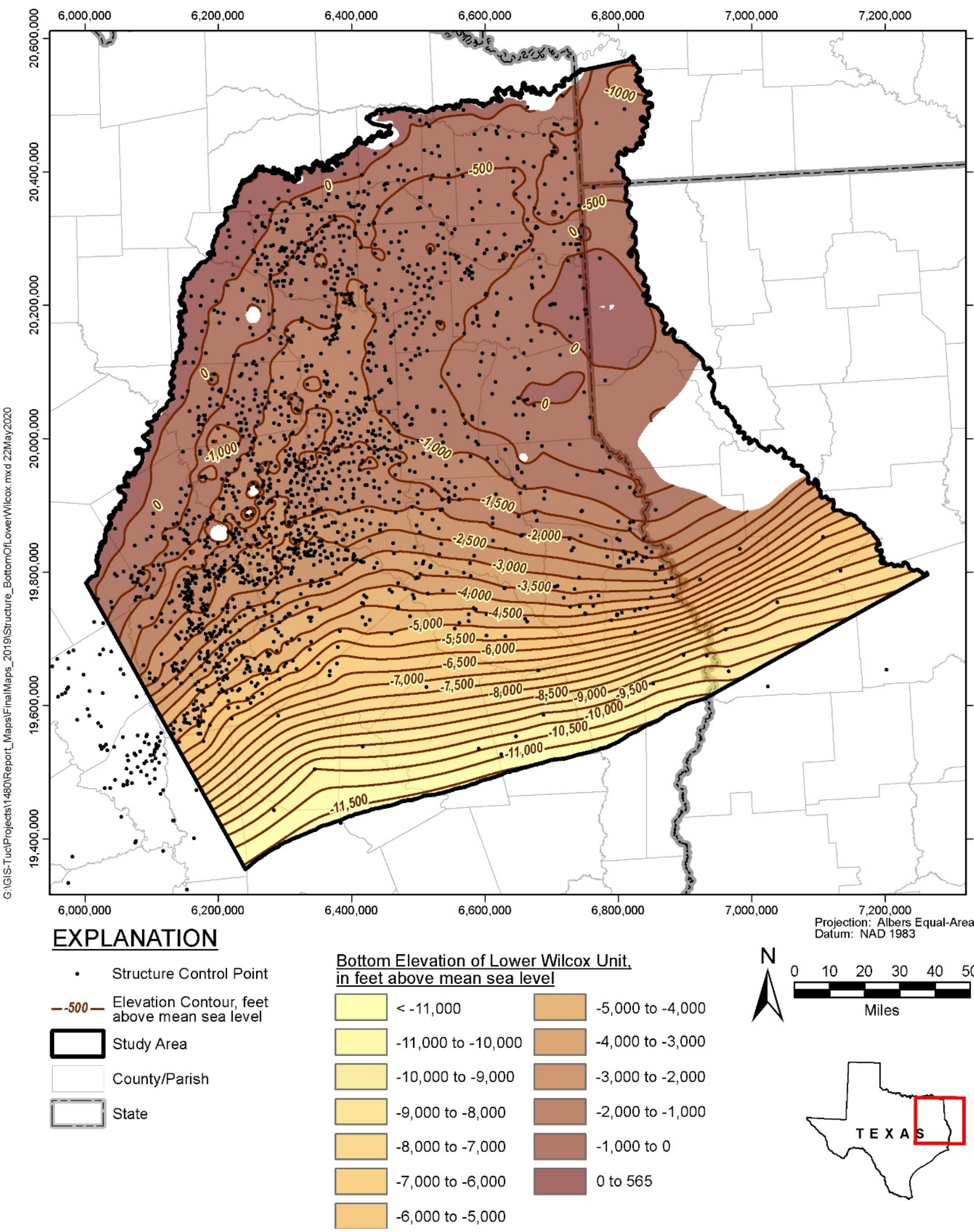


Figure 4-21. Bottom Elevation Contours for Lower Wilcox Unit

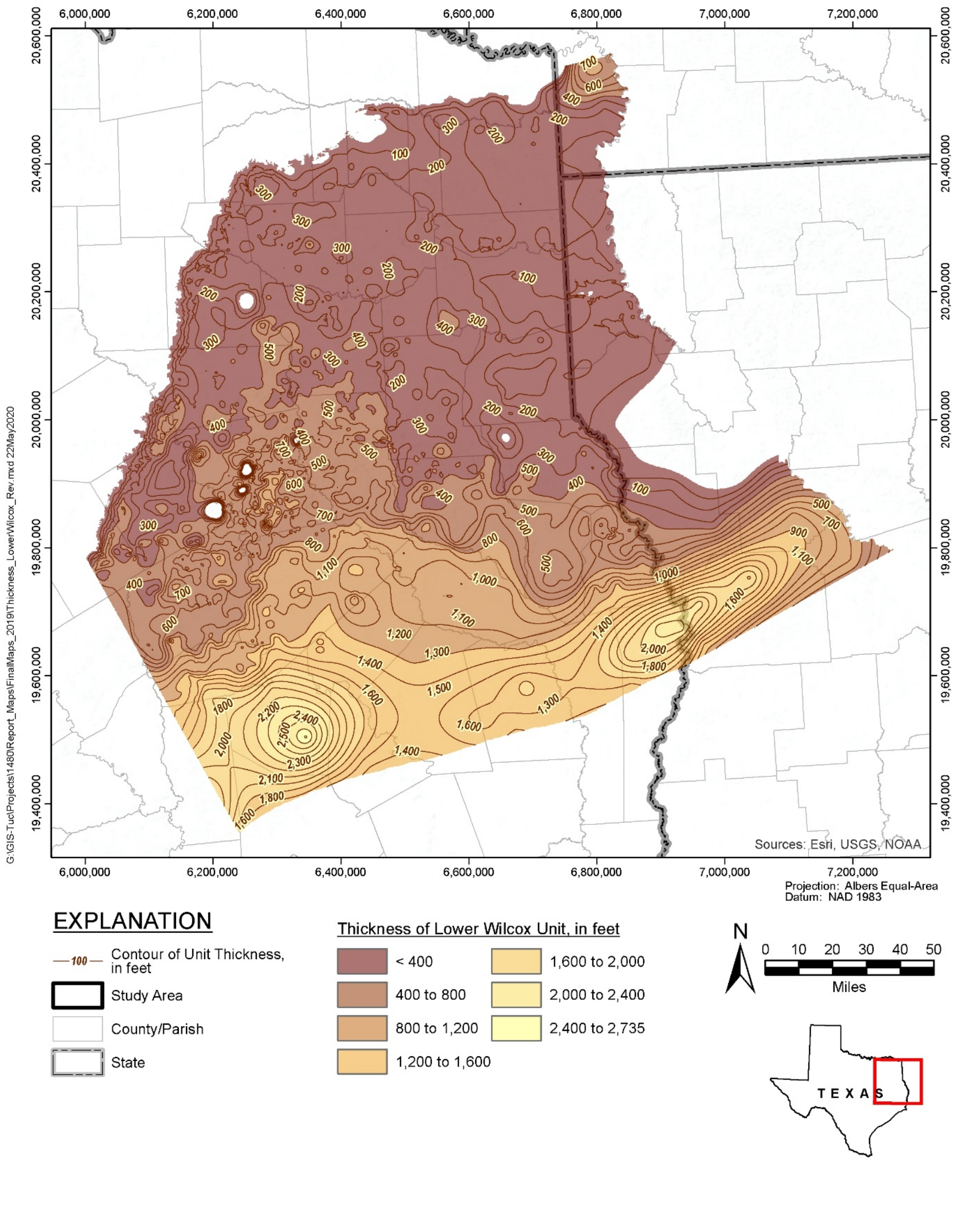


Figure 4-22. Thickness of Lower Wilcox Unit

4.2 GROUNDWATER LEVELS AND FLOW

Groundwater in the northern portions of the Queen City, Sparta, and Carrizo-Wilcox aquifer system occurs under unconfined (or water-table) conditions in the outcrop areas and confined conditions in down-dip areas. Confined conditions also occur in the northern parts of the Queen City unit where it is overlain by the Weches and Sparta units. In many areas, hydraulic pressures within the aquifers where confined conditions occur have been sufficient to allow for groundwater discharge to land surface to contribute inflow to the rivers. Groundwater flows to the surface along the Trinity and Sabine rivers and tributaries in the confined portions of the aquifer system, indicating upward flow in these areas (Fryar and others, 2003; Kelley and others, 2004). Regional groundwater movement is generally from higher elevations in the north to lower elevations along drainages and to the south towards the Gulf of Mexico. As described by Fryar and others (2003), the relationship between the Carrizo Sand and the sand intervals of the Wilcox Group varies throughout the study area. The sands of the Wilcox, Carrizo, Reklaw, and Queen City units are generally hydraulically connected and behave as a single aquifer in the northern-most margins of the study area. The sands of the Wilcox and Carrizo units are hydraulically connected and behave as a single aquifer in counties throughout the northwest and southeast portions of the study area. The Carrizo and Wilcox units behave as separate aquifers in the remaining portions of the study area.

4.2.1 PREVIOUS STUDIES

An extensive literature search and analysis was conducted by Fryar and others (2003) and Kelley and others (2004) to understand the regional groundwater flow in the aquifer system and the history of groundwater use from the aquifers through 2000. The groundwater level information summarized herein relies heavily on the results of these two previous analyses. Groundwater level information was updated through 2016 for this study.

The investigations by Fryar and others (2003) and Kelley and others (2004) conducted a pressure versus groundwater level depth analysis, developed by Fogg and Kreitler (1982), using measurement data obtained from the TWDB website. The analysis used data from wells with both groundwater level and screened interval data. The goal of the analysis was to evaluate vertical hydraulic gradients between hydrostratigraphic units in the aquifer system. The analysis used the maximum groundwater level measured at each well. Results of the studies indicate that vertical pressure gradients are generally upward to near "hydrostatic" (no gradient) in the southern and central portions of the study area and are smaller than hydrostatic in the northern portion of the study area. A smaller than hydrostatic gradient indicates downward pressure gradients. Downward gradients generally occur where the underlying aquifer unit has been substantially developed. Furthermore, temporal changes to vertical gradient were assessed using data from pre-1950 and post-1950. Evidence was found suggesting a decrease in upward gradients in the central portions of the study area through time, and an increase in downward gradients in the northern portions. Increasing downward gradients through time in

Nacogdoches and Angelina counties are a result of substantial depressurization of deeper aquifer units relative to shallower units between 1950 and 2000. The trends observed in Nacogdoches and Angelina counties are likely due to the large cone of depression in the Carrizo Sand due to groundwater production by the cities of Nacogdoches and Lufkin and by a paper mill (formerly Southland Paper Mill) located near the Nacogdoches-Angelina county line.

4.2.2 DISTRIBUTION OF GROUNDWATER LEVEL MEASUREMENTS

Information for well locations, well construction, and groundwater level measurements was obtained from the TWDB Groundwater Database (GWDB) (TWDB, 2017a), the Brackish Resources Aquifer Characterization System database (TWDB, 2017d), and monitoring locations from the United States Geological Survey (2017a) National Water Information System in Louisiana. For many wells, the Brackish Resources Aquifer Characterization System database includes the state identification number for linking to the groundwater database. This identification number was used to remove duplicate wells from the water level dataset. If no state identification number was available, well location coordinates were used to identify duplicate wells for the dataset. Any remaining wells were assumed to be unique wells and were included in the evaluation for this investigation. A total of 50,368 groundwater level measurement records are available from 6,410 wells located in the study area, beginning in the early 1900s. These data will be used as groundwater level targets for calibration of the historical transient groundwater model.

Available well screen information was compared to the hydrostratigraphic framework (base elevation surfaces) to determine the aquifer unit(s) that each well penetrates. If no information on screened interval was available for a well, the well was assumed to be fully screened to its reported well depth. Due to large reported screened intervals or well depths, the vast majority of wells are believed to intersect multiple aquifer units. If a well was identified as penetrating multiple aquifers and also was used as a calibration target location for the previous groundwater availability model, the same model layer was assigned for this analysis. For other wells screened in multiple units, the measurement value was used for contouring if it was consistent with measurements from nearby single-unit wells in a particular aquifer unit or locations included in the previous groundwater availability model. Large well screens and well depths prevent this study from assigning measurements to aquifers with a high level of certainty.

Locations of all wells with available groundwater measurements for the aquifers of interest in the study area are shown on Figure 4-23. The spatial distributions of selected groundwater level measurements for the Sparta Sand and Queen City Sand and the Carrizo Sand and Wilcox Group are shown on Figure 4-24 and Figure 4-25, respectively. Measurements at these locations were selected to evaluate and prepare the time-series groundwater level contours for 1980, 1999, and 2015, as discussed in the next section of this report. All available groundwater level measurements will be used for calibration of the groundwater model. The majority of the wells are located in the outcrop areas of the units in the central and northern portions of the study area, and many have just one or a few measurements available. No measurements are available for the deep, down-dip portions of the aquifers of interest in the south (Figure 4-23).

4.2.3 GROUNDWATER LEVELS AND FLOW THROUGH TIME

The water table surface in the study area generally follows land surface topography, with higher groundwater level elevations occurring in the upland areas in the north and northwest and lower groundwater level elevations occurring to the south and southeast.

Contours of regional groundwater level elevation were evaluated for each aquifer unit for four time periods: (1) 1936 to represent predevelopment conditions; (2) 1980 to represent initial conditions for the groundwater model transient calibration period; (3) 1999 to represent conditions within the model calibration period; and (4) 2015 to represent conditions at the end of the groundwater model calibration period. Contours for predevelopment, 1980, and 1999 were prepared by Fryar and others (2003) and Kelley and others (2004) for the previous groundwater availability models for the aquifer system. The previously-prepared contours and associated control data were compared with groundwater level measurement data compiled for this study, and it was determined that the previous contours were representative of the available historic data and, thus, are sufficient for use in this study. However, certain portions of contours were reclassified as "approximate" in the deep, downdip portions of the aquifers where no measured data exist. These contour datasets will be used as guides during calibration of the historical transient groundwater model.

Contours for 2015 were prepared for this study using groundwater level measurements obtained from TWDB Groundwater Database (TWDB, 2017a) the Brackish Resources Aquifer Characterization System database (TWDB, 2017d), and monitoring locations from the United States Geological Survey (2017a) National Water Information System in Louisiana. The spatial coverage of groundwater level measurement data for a given month of year is generally sparse because the data are not available at regular intervals in every well. The majority of available measurements were taken during winter months (November through February); therefore the 2015 contours generally represent winter conditions which may have less pumping interference. Since the amount of data specifically for winter 2014-2015 was insufficient for developing regional contours, data within the period of 2012 to 2016 were used based on the following criteria:

1. Highest priority given to a measurement collected during winter 2014-2015. If a well had multiple measurements for this winter time period, then a measurement value was selected chronologically from available data;
2. If no data were available for winter 2014-2015, then winter measurements for adjacent years were used, first going back one year then forward one year;
3. If no winter measurements were available for the four-year window, then summer measurements were used.

Predevelopment groundwater conditions are defined as the conditions of the groundwater system prior to the start of disturbances to natural groundwater flows as a result of groundwater development (pumping withdrawals). Predevelopment groundwater level elevation contours maps were developed by Kelley and others (2004) for the Sparta Aquifer and Queen City Aquifer (Figure 4-26 and Figure 4-27). Very few data are available for the Carrizo-Wilcox Aquifer and therefore predevelopment groundwater level contours were not developed for the previous groundwater availability model. Locations of predevelopment groundwater level measurements compiled by Fryar and others (2003) are shown on Figure 4-28. The predevelopment groundwater levels contours could be used as a guide for calibration of a steady-state groundwater model.

Groundwater level elevation contour maps for 1980, 1999, and 2015 for each of the Sparta, Queen City, Carrizo, Upper Wilcox, Middle Wilcox, and Lower Wilcox aquifer units are shown on Figure 4-29 through Figure 4-34, respectively. Contours were not drawn for the Weches and Reklaw confining units due to the lack of data for these units.

The groundwater elevation contour maps show that regional groundwater movement in the study area is generally to the south from the upland areas in the north. The highest groundwater level elevations in the study area occur in the northwest in Van Zandt and Henderson counties. In general, relatively steep hydraulic gradients occur between outcrop and down-dip areas, and also at cone of depression caused by groundwater pumping. Although the steep gradients in groundwater levels immediately south of Rusk County generally coincide with the location of the Mount Enterprise Fault Zone (Figure 2-19), it is unclear whether the change in gradients in this area is a result of the fault or other factors such as the pumping centers in Nacogdoches and Angelina counties. Some of the changes in groundwater elevations presented on Figure 4-29 through Figure 4-34 are likely a result of available measurements and inconsistent monitoring schedules. However, some of the changes could be a result of changes in groundwater pumping in a given area through time.

In addition to using groundwater level data from TWDB, Fryar and others (2003) used some artificial control points to prepare groundwater level contours for the Carrizo, Upper Wilcox, and Middle Wilcox aquifer units for 1980 and 1999 (Figure 4-31 through Figure 4-33). These control points were needed to help define the cone of depression resulting from municipal groundwater pumping for the cities of Nacogdoches and Lufkin; actual measurement data were not available south of these pumping centers. The same control points were used for preparing the 2015 contours, assuming that down-dip conditions did not change through time.

Inspection of groundwater level data and results of previous groundwater availability models suggest that regional hydraulic connections occur between the aquifer units in certain areas in the study area. The similarity of groundwater levels in adjacent aquifers suggests that the aquifers are hydraulically connected, particularly at or near outcrop areas. Simulation results by the previous groundwater availability models suggest that groundwater movement is upward from the Middle Wilcox into the overlying Upper Wilcox and Carrizo Sand in the down-dip, central-south portions of the aquifer system.

In addition to time-series contour maps, changes in groundwater levels in the aquifer system were assessed using hydrographs of groundwater levels from 1980 through 2016.

Wells with measurements for long periods of time were selected for evaluation and characterization of each aquifer unit. Selected groundwater level elevation hydrographs for the Sparta, Queen City, Carrizo, and Wilcox aquifers are shown on Figure 4-35 through Figure 4-41.

Groundwater levels have remained relatively stable in the Sparta Aquifer, with variations generally less than 10 feet at most wells (Figure 4-35). Measurements at a well in Nacogdoches County indicate a gradual decline in groundwater levels of less than 10 feet since 1980. Measurements from a well in Walker County show groundwater level declines of about 40 feet since 1980; this well is down-dip from the outcrop area in the confined portions of the aquifer.

Similar to the Sparta Aquifer, groundwater levels have remained relatively stable in the Queen City Aquifer, with variations generally less than 20 feet at most wells (Figure 4-36 and Figure 4-37). However, groundwater level declines have occurred at a few wells in the aquifer between 1980 and 2016. Groundwater levels at a well in Wood County have declined by approximately 100 feet during that time period. Groundwater levels at a well in Gregg County have gradually risen since the 1980s. Large fluctuations in a hydrograph, such as shown for a well in Cass County, could indicate influence by nearby groundwater pumping or recharge.

Groundwater levels in the Carrizo Aquifer unit have declined through time at most hydrograph locations (Figure 4-38 and Figure 4-39). The largest groundwater level declines in the Carrizo and Wilcox aquifers are a result of municipal groundwater withdrawals by the cities of Nacogdoches and Lufkin, and industrial withdrawals for a paper mill located at the Nacogdoches-Angelina county border (Fryar and others, 2003) (Figure 4-39). Hydrographs for wells in that area show substantial decline in groundwater levels (on the order of 200 to 300 feet) since the 1950s, followed by a dramatic rise in groundwater levels (on the order of 200 to 250 feet) that starts in the 1980s and 1990s. Hydrographs for wells located in the northern portions of the aquifer generally show relatively stable groundwater levels. Large declines have also occurred in Smith, Anderson, and Leon counties in the confined portions of the aquifer.

Groundwater levels in the Wilcox Aquifer have remained stable or rising in some areas and declined in other areas of the study area (Figure 4-40 and Figure 4-41). Hydrographs for wells located in the Sabine Uplift in the eastern portion of the study area indicate that groundwater levels in that area have remained relatively stable through time, with variations generally less than 15 feet; except for one well in Panola County which experienced highly variable groundwater levels before stabilizing in the late 1990s. Groundwater levels west of the Sabine Uplift area have declined as much as 40 feet since the 1980s.

Analysis of seasonal groundwater fluctuations was attempted for this study. However, such an analysis could not be conducted because of insufficient available data. Frequent and regular measurements are needed at many individual locations for such an analysis to be conducted.

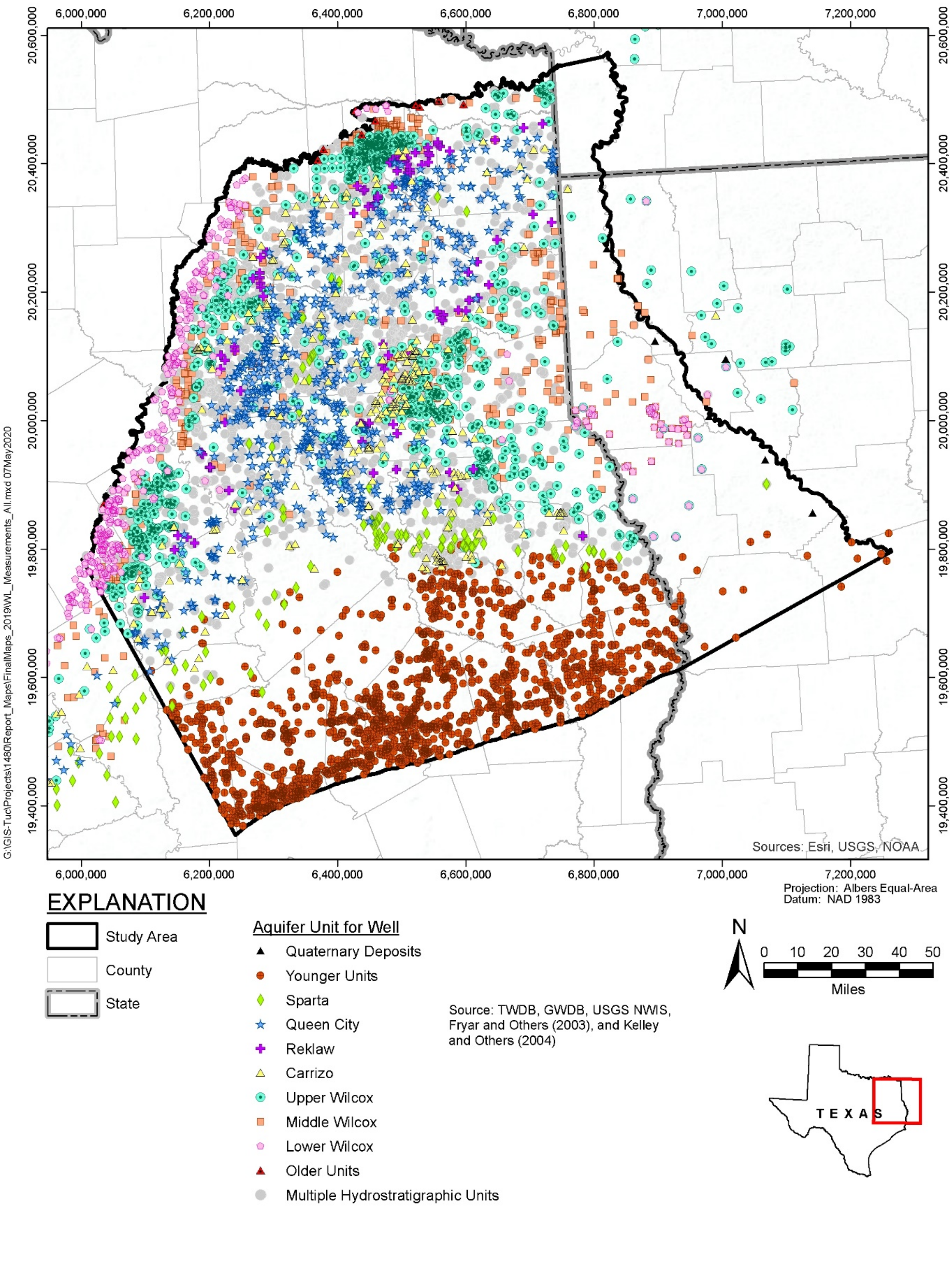


Figure 4-23. Locations of Wells with Groundwater Level Measurements in Texas Water Development Board Groundwater Database

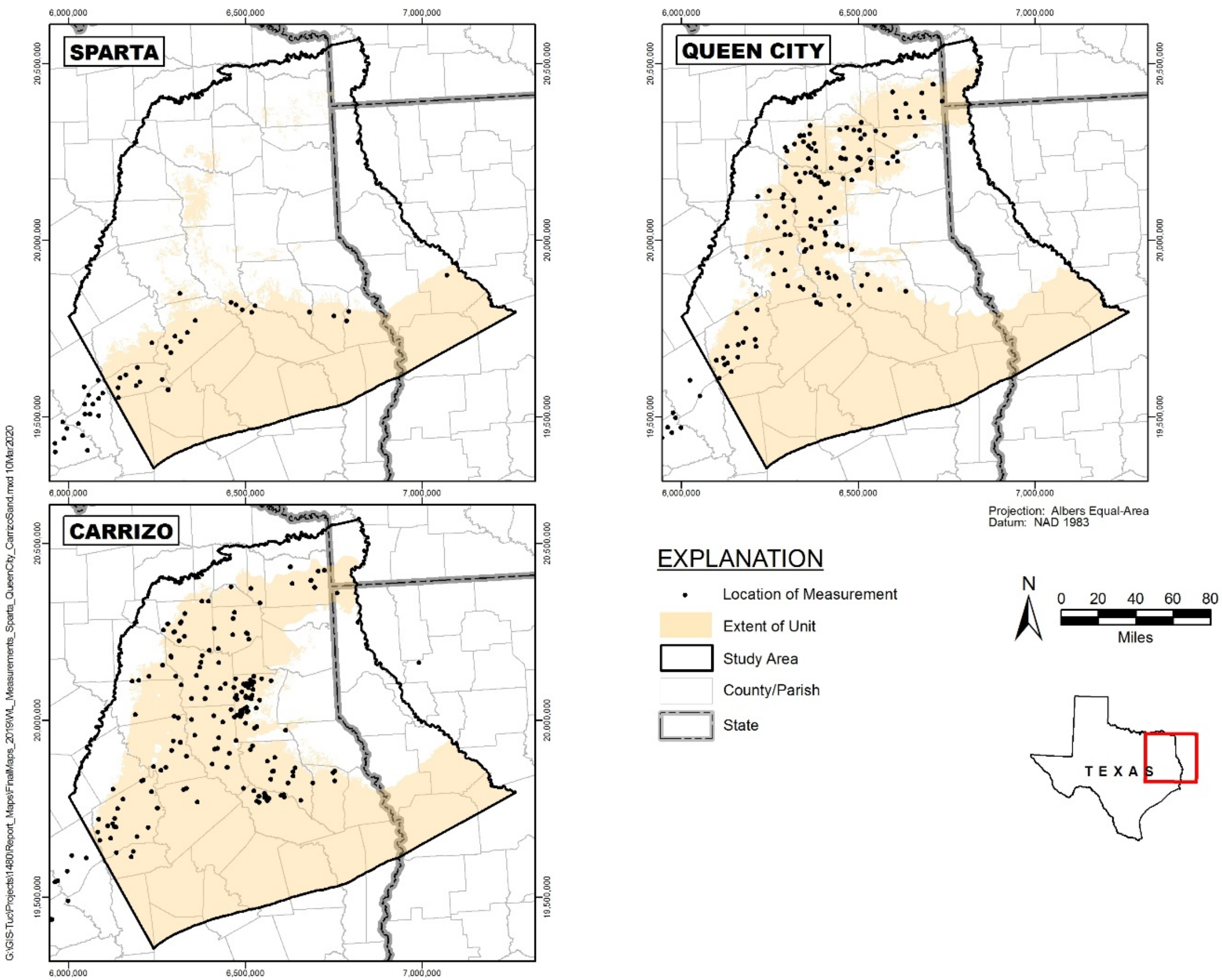


Figure 4-24. Locations of Selected Groundwater Level Measurements for Sparta, Queen City, and Carrizo Aquifers

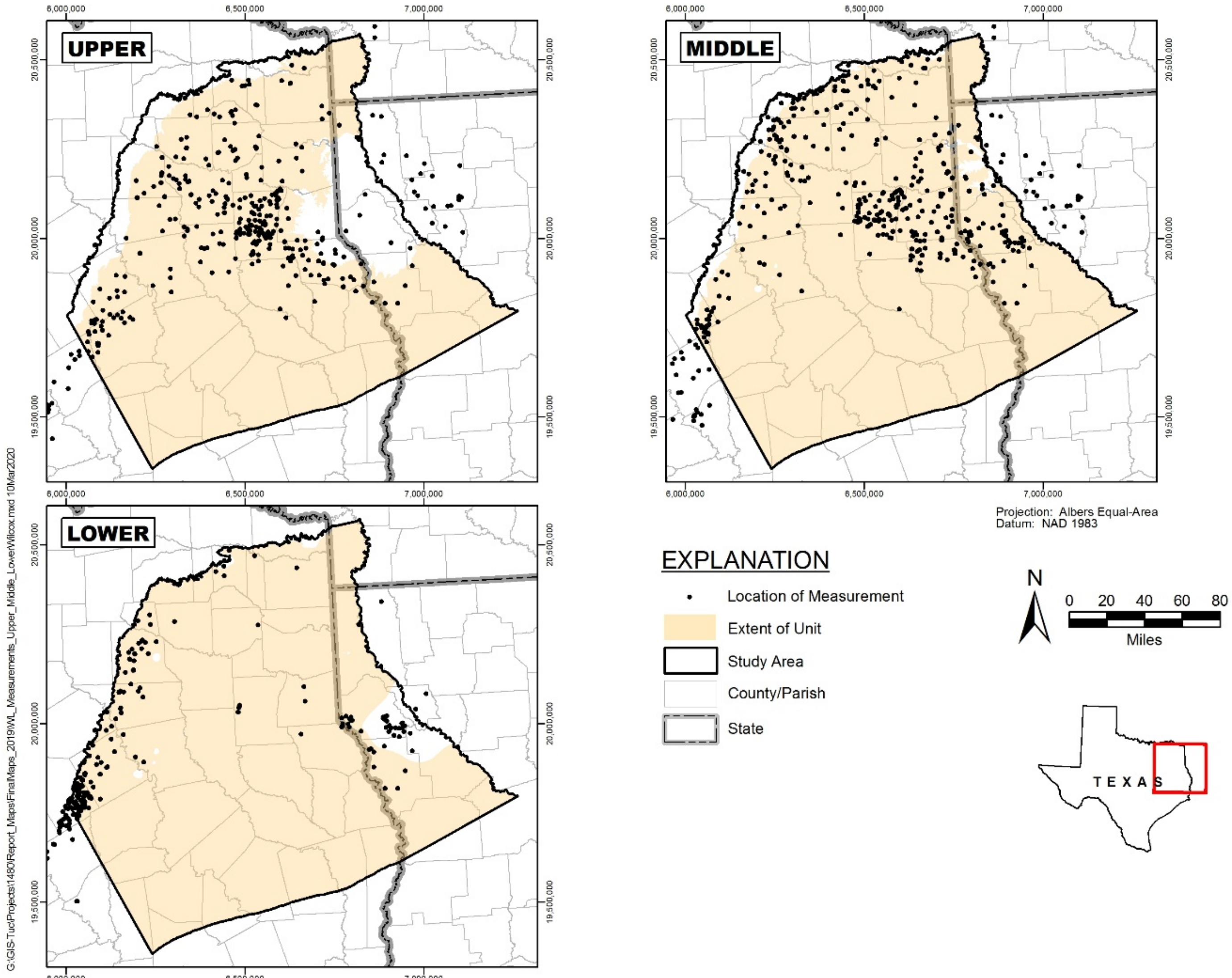
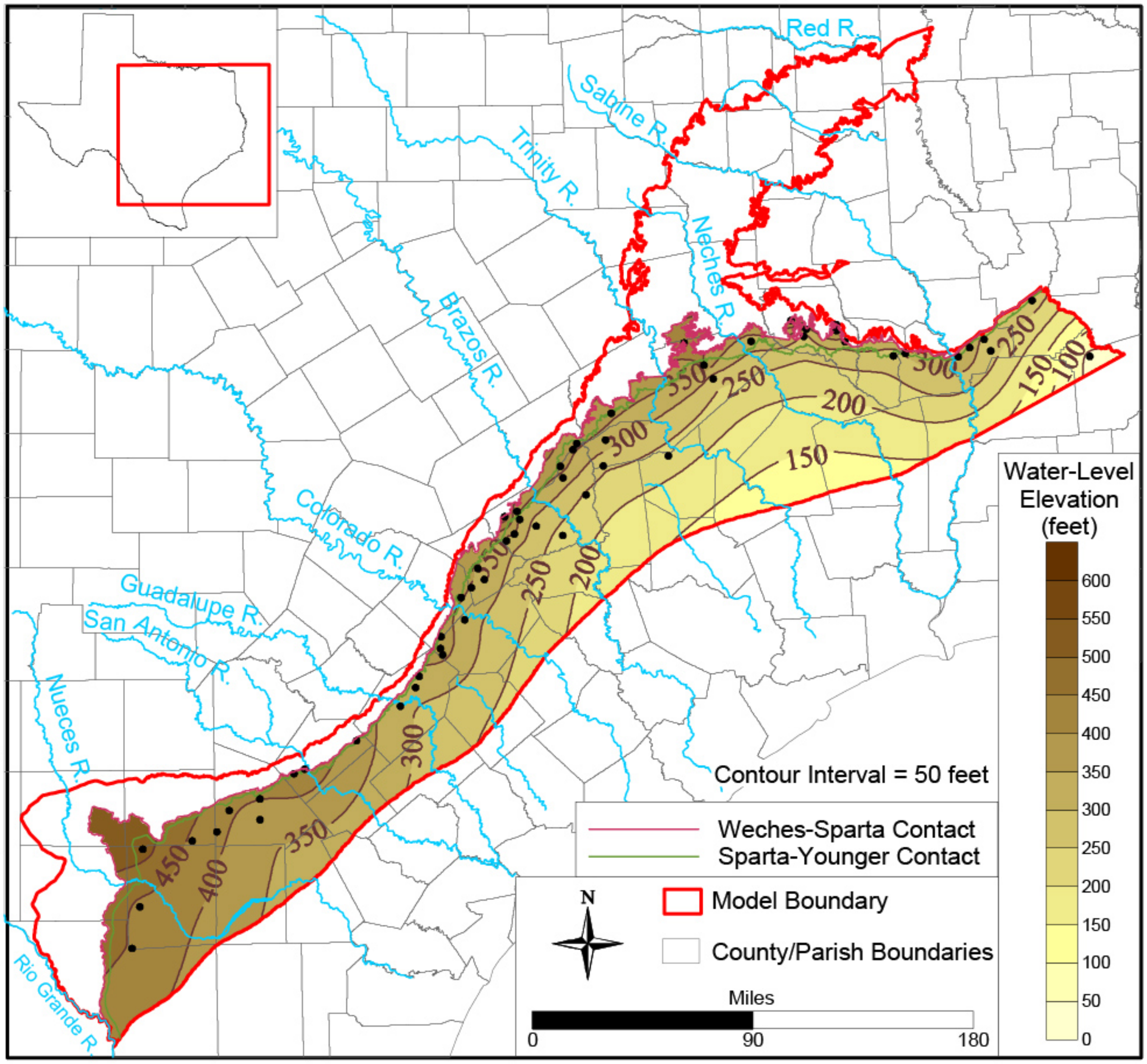
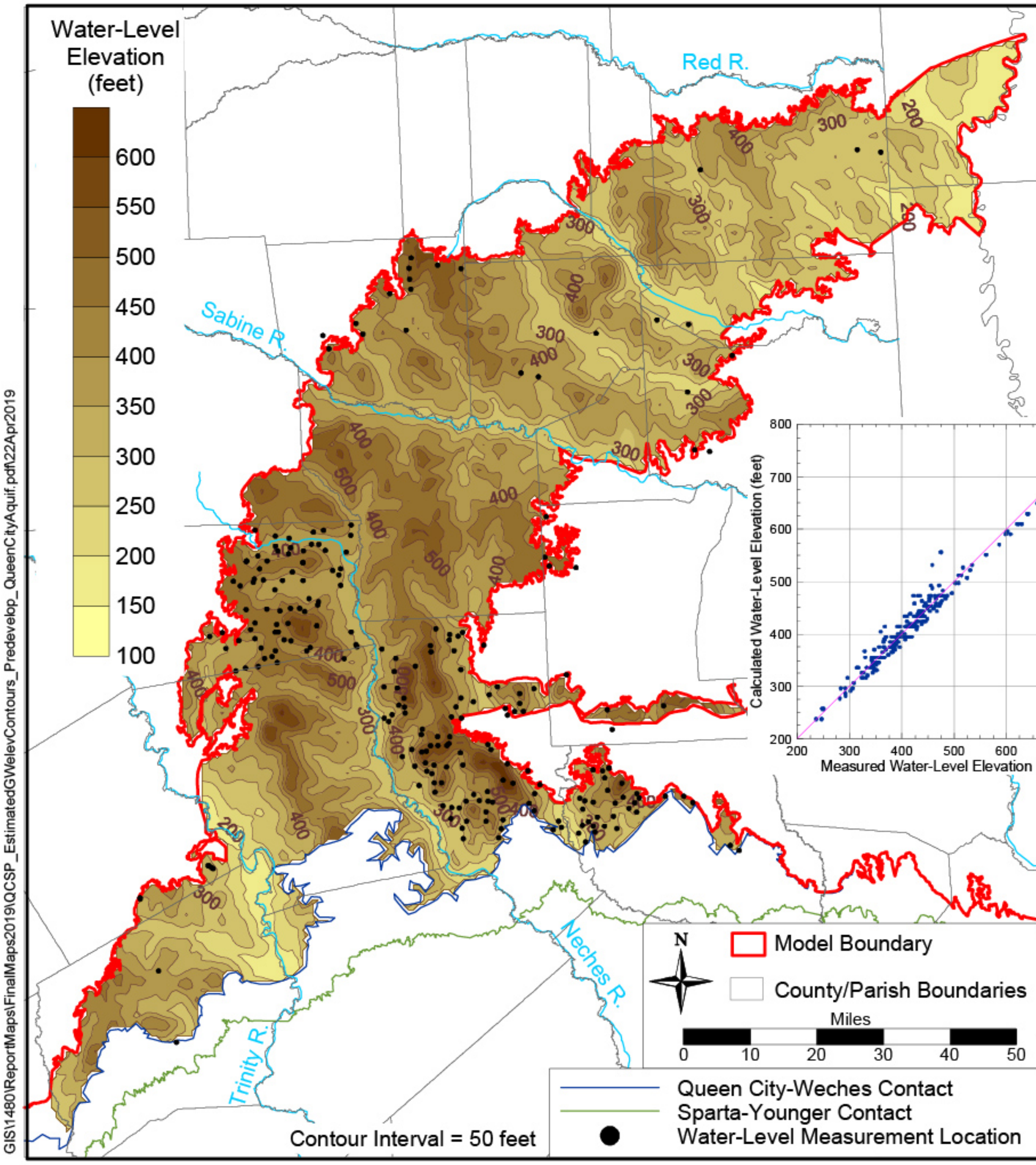


Figure 4-25. Locations of Selected Groundwater Level Measurements for Upper, Middle, and Lower Wilcox Aquifers



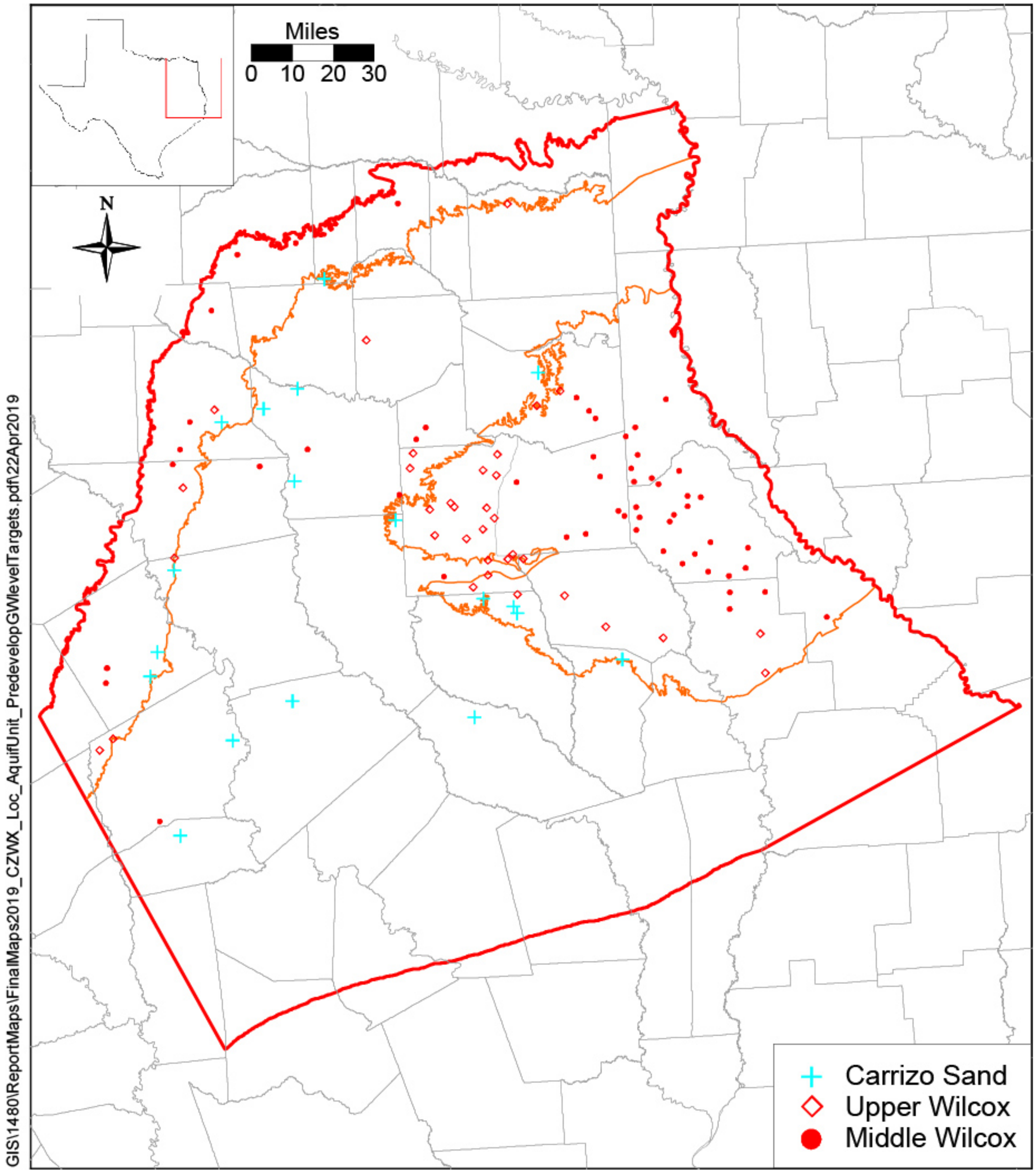
Source: Figure 4.4.8 from final report for Groundwater Availability Models for the Queen City and Sparta Aquifers (Kelley and others, 2004)

Figure 4-26. Estimated Groundwater Level Elevation Contours for Predevelopment Conditions in Sparta Aquifer



Source: Figure 4.4.5 from final report for Groundwater Availability Models for the Queen City and Sparta Aquifers (Kelley and others, 2004)

Figure 4-27. Estimated Groundwater Level Elevation Contours for Predevelopment Conditions in Northern Portion of Carrizo-Wilcox Aquifer



Source: Figure 4.4.4 from final report for Groundwater Availability Model for the Northern Carrizo-Wilcox Aquifer (Fryar and others, 2003)

Figure 4-28. Location and Aquifer Unit for Predevelopment Groundwater Level Elevation Targets in Carrizo-Wilcox Aquifer

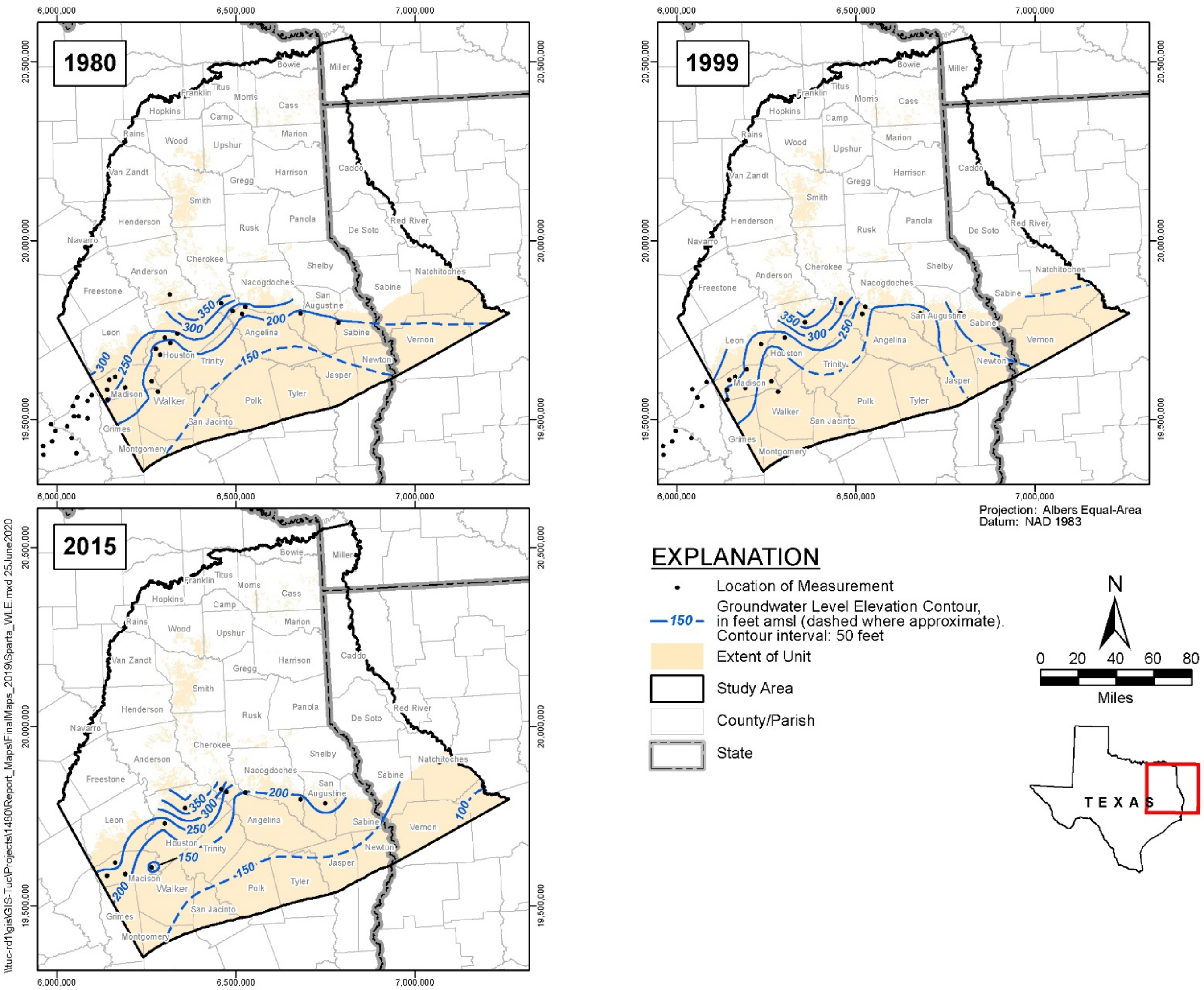


Figure 4-29. Groundwater Level Elevation Contours for Sparta Aquifer

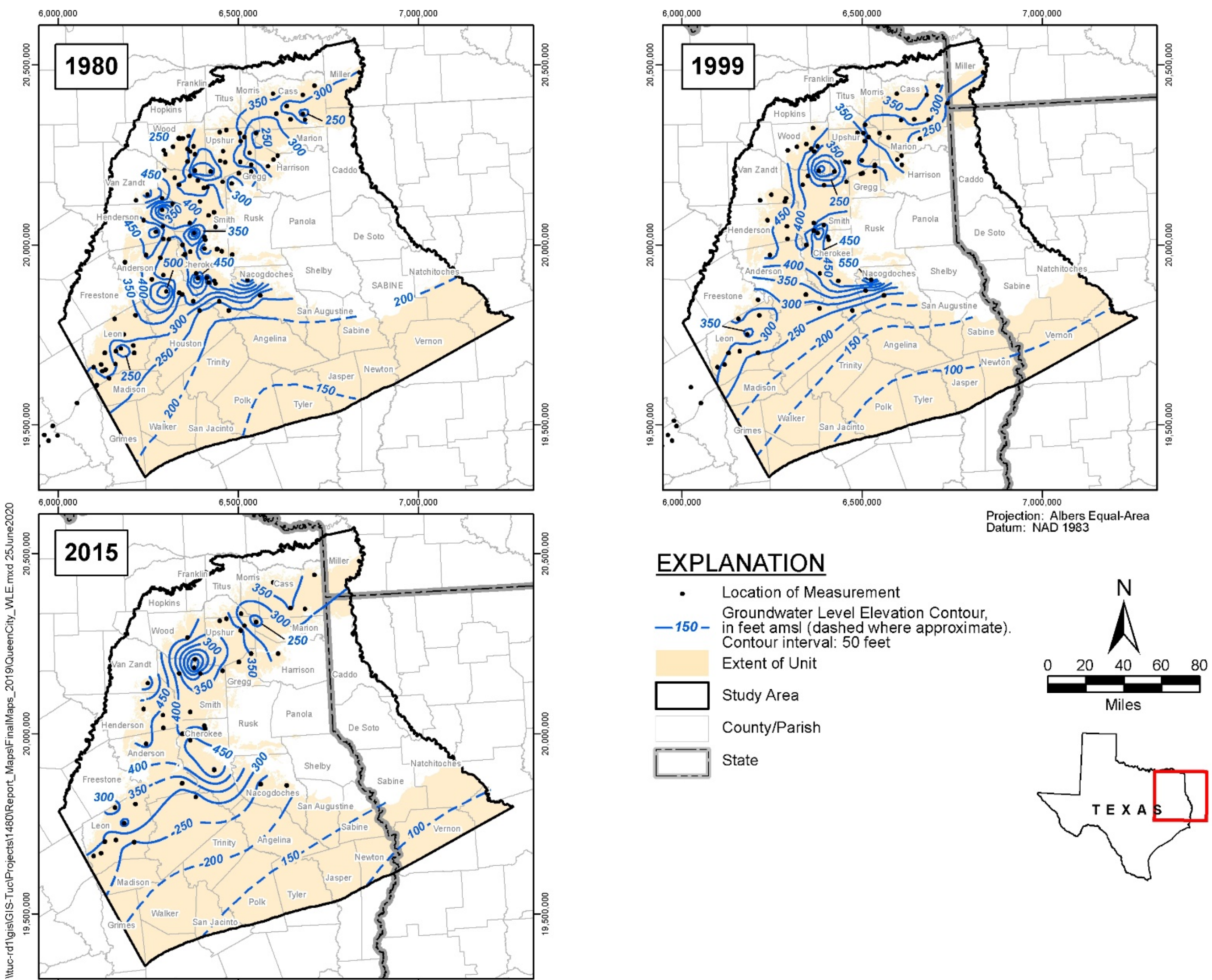


Figure 4-30. Groundwater Level Elevation Contours for Queen City Aquifer

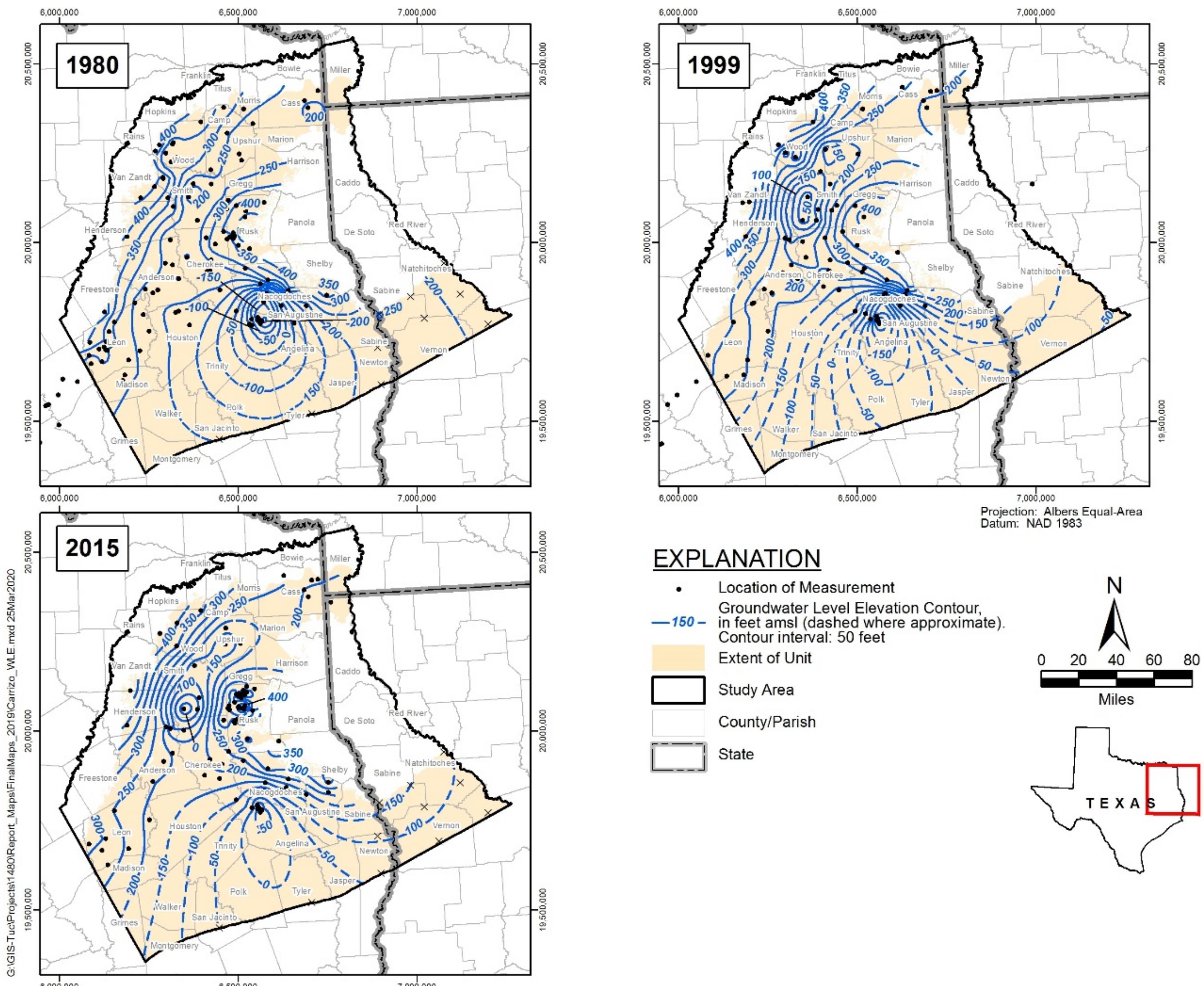


Figure 4-31. Groundwater Level Elevation Contours for Carrizo Aquifer

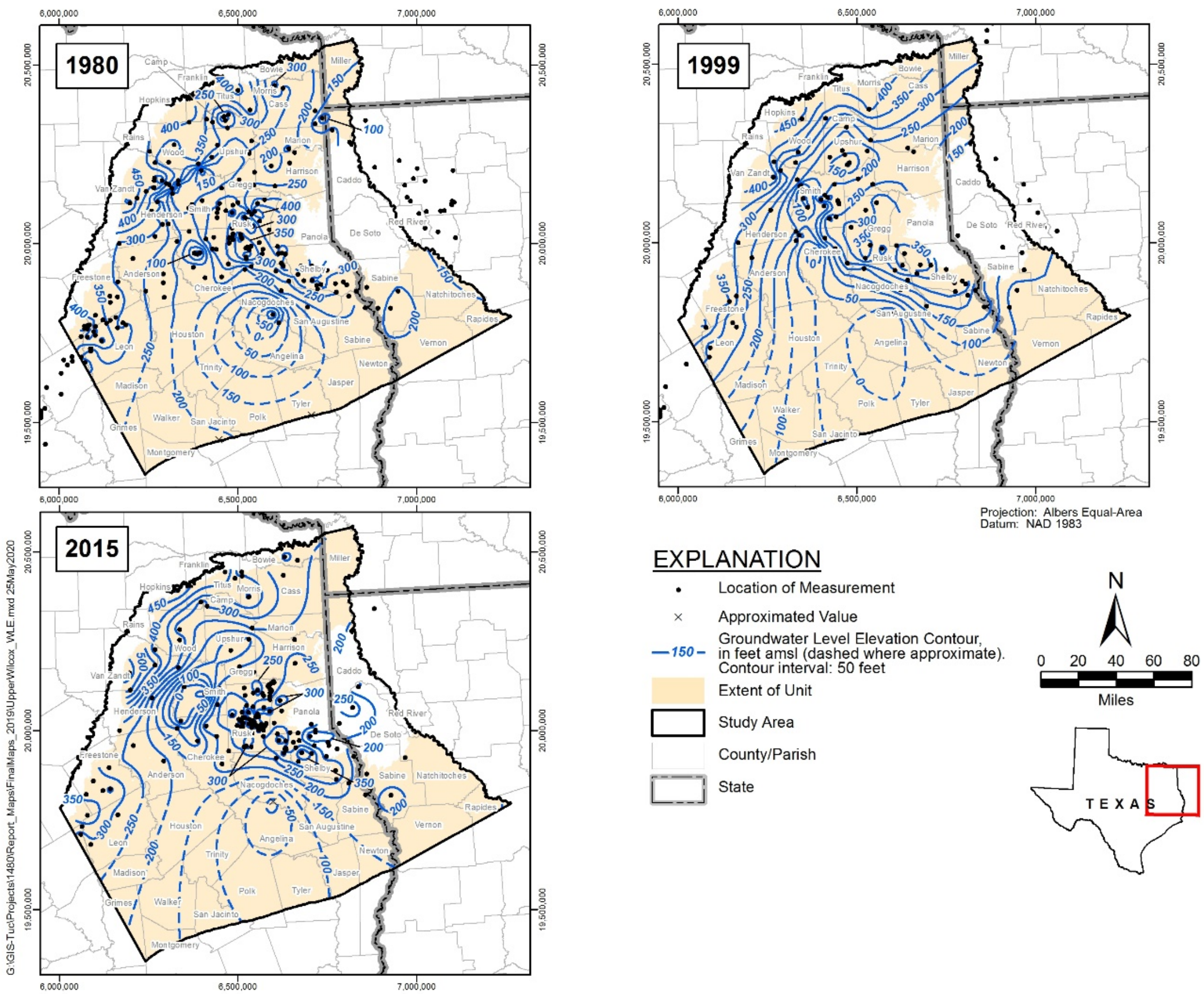


Figure 4-32. Groundwater Level Elevation Contours for Upper Unit of Wilcox Aquifer

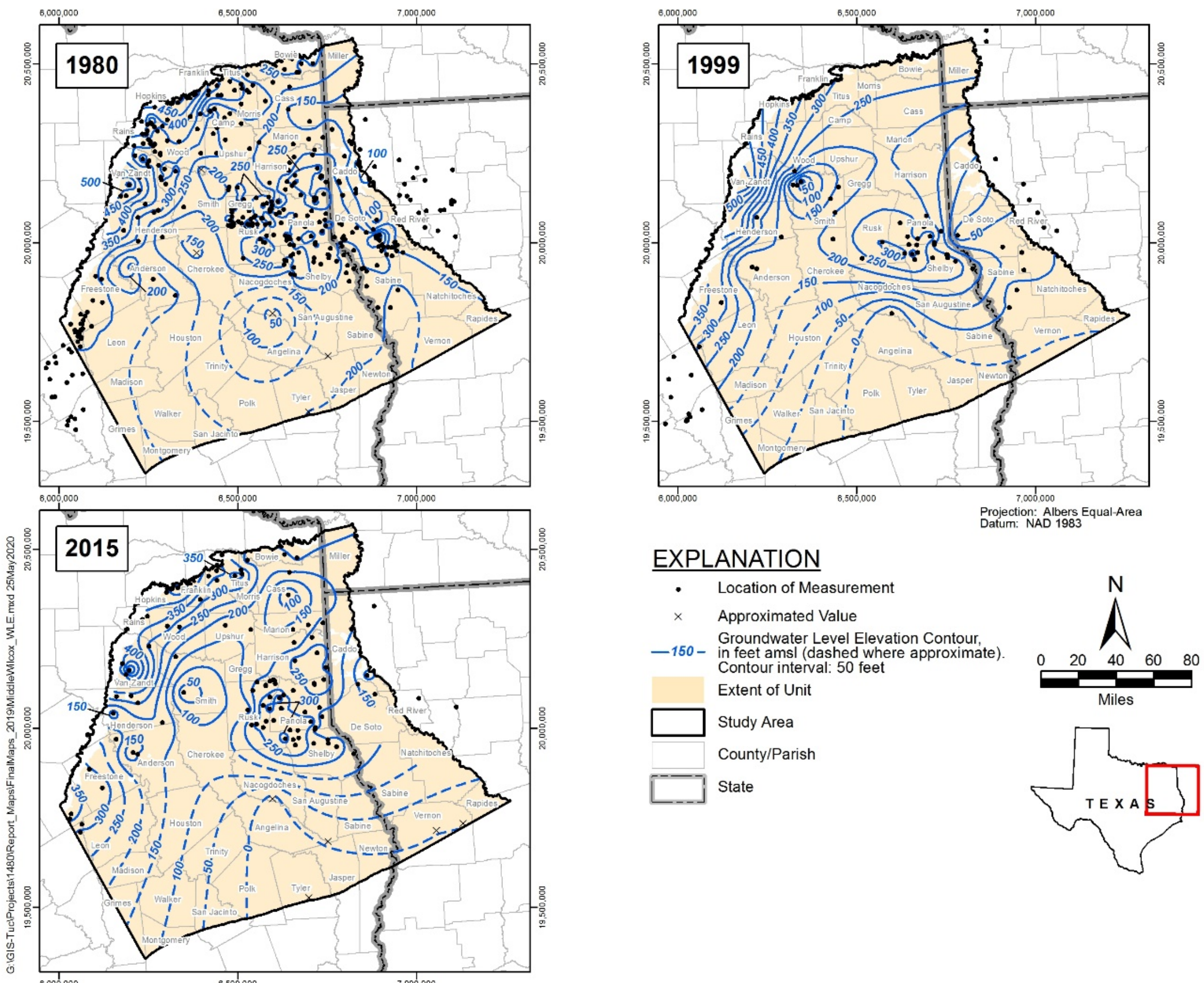


Figure 4-33. Groundwater Level Elevation Contours for Middle Unit of Wilcox Aquifer

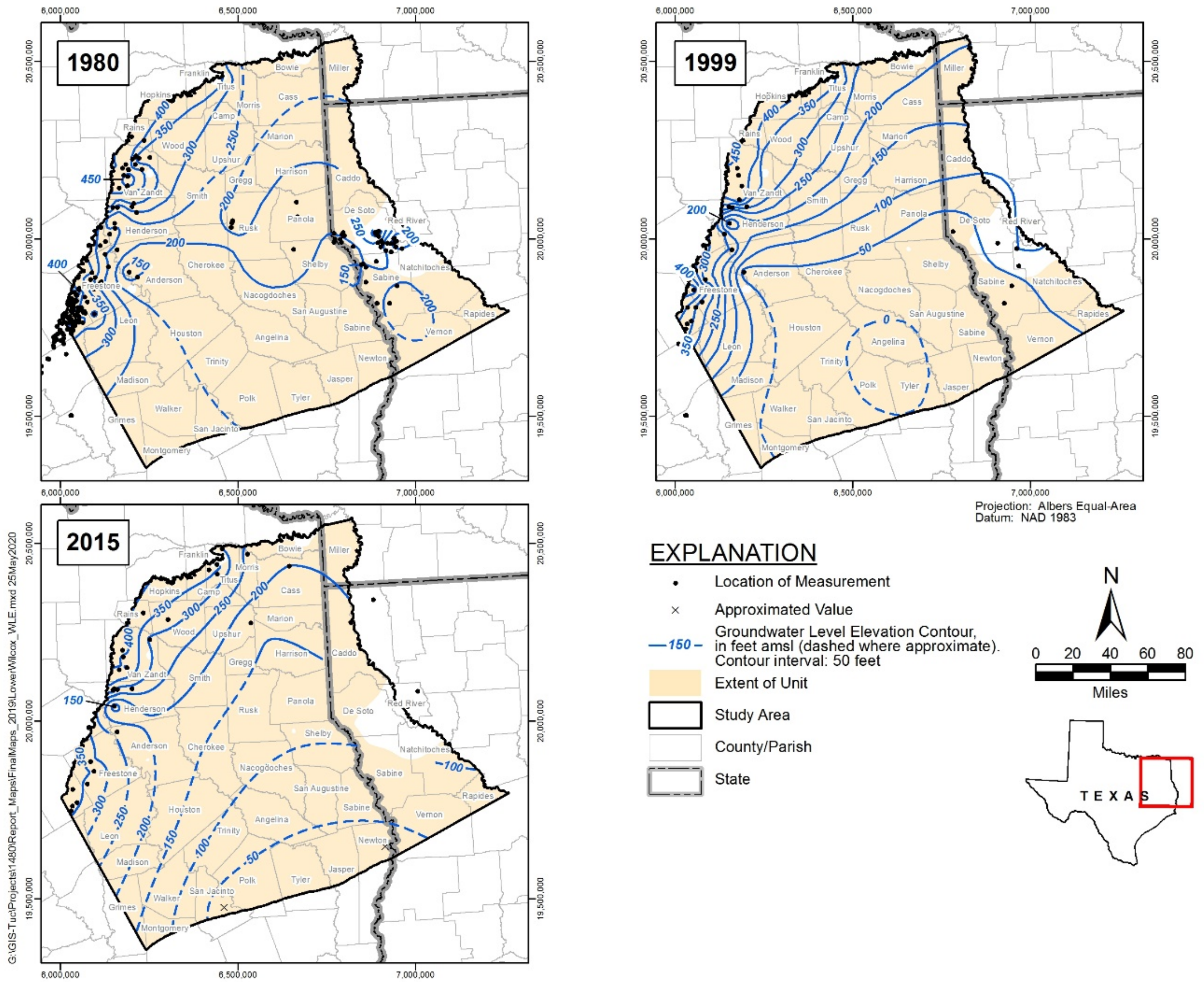


Figure 4-34. Groundwater Level Elevation Contours for Lower Unit of Wilcox Aquifer

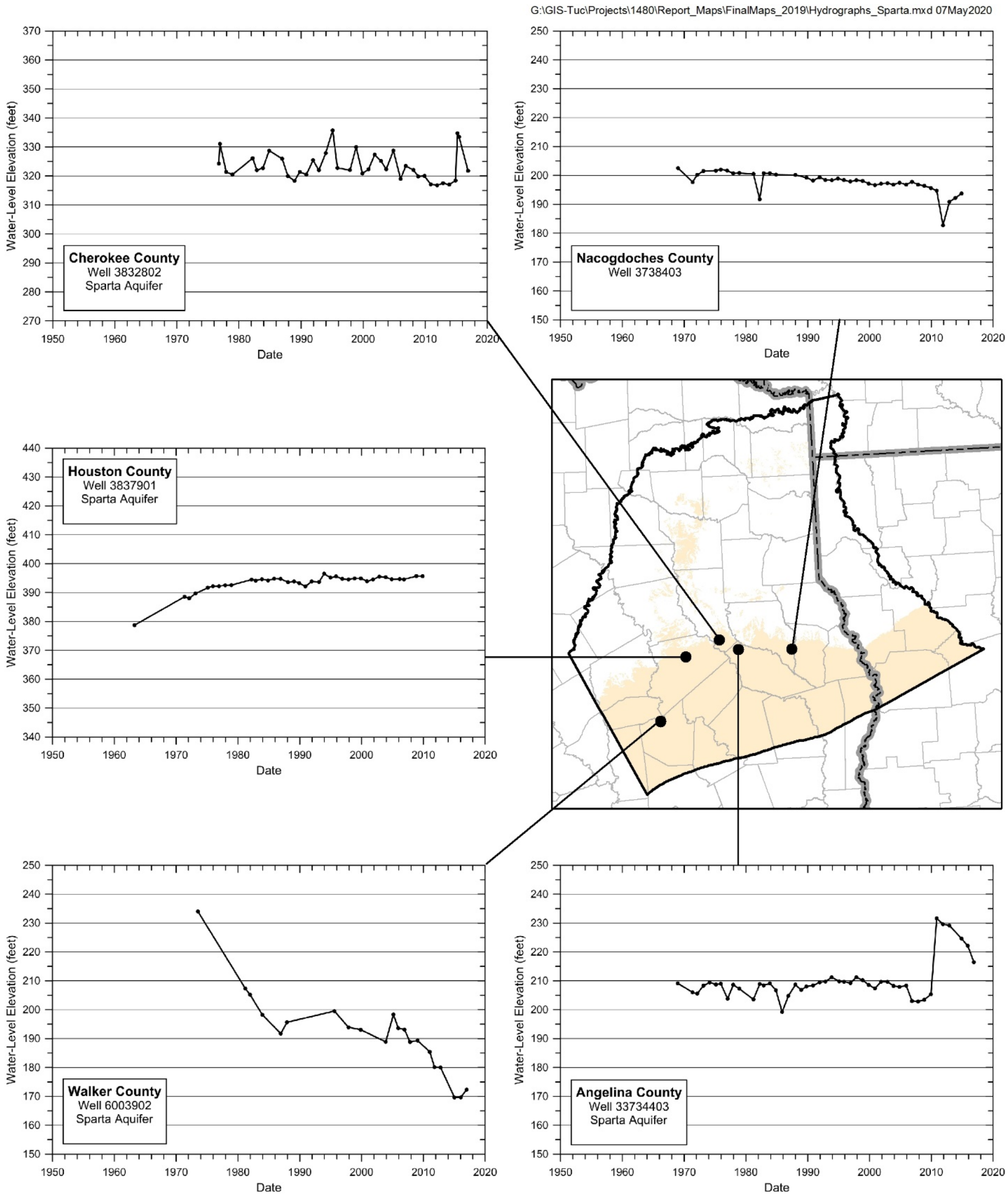


Figure 4-35. Selected Groundwater Level Elevation Hydrographs for Sparta Aquifer

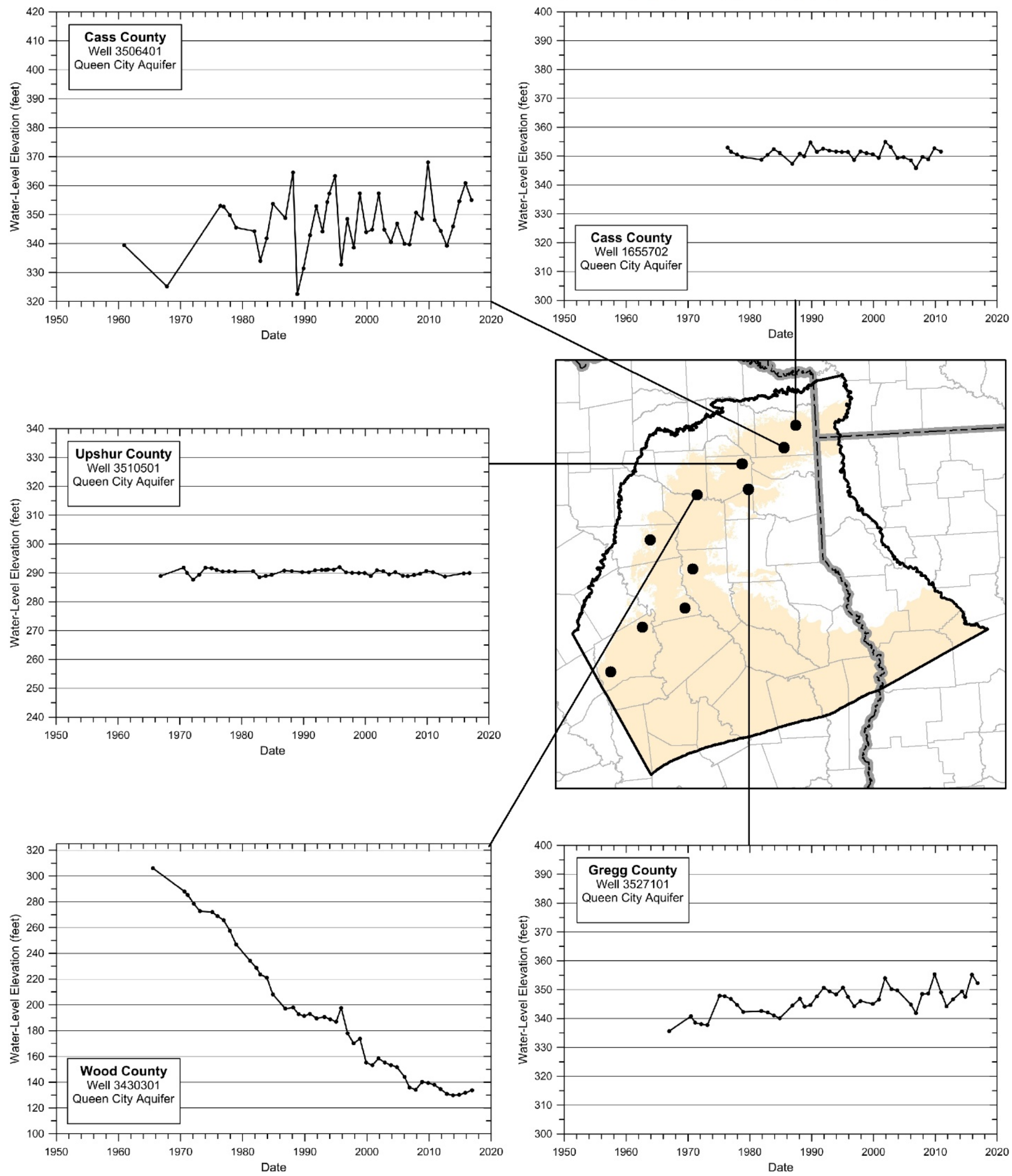


Figure 4-36. Selected Groundwater Level Elevation Hydrographs for Queen City Aquifer in the Northern Portions of Study Area

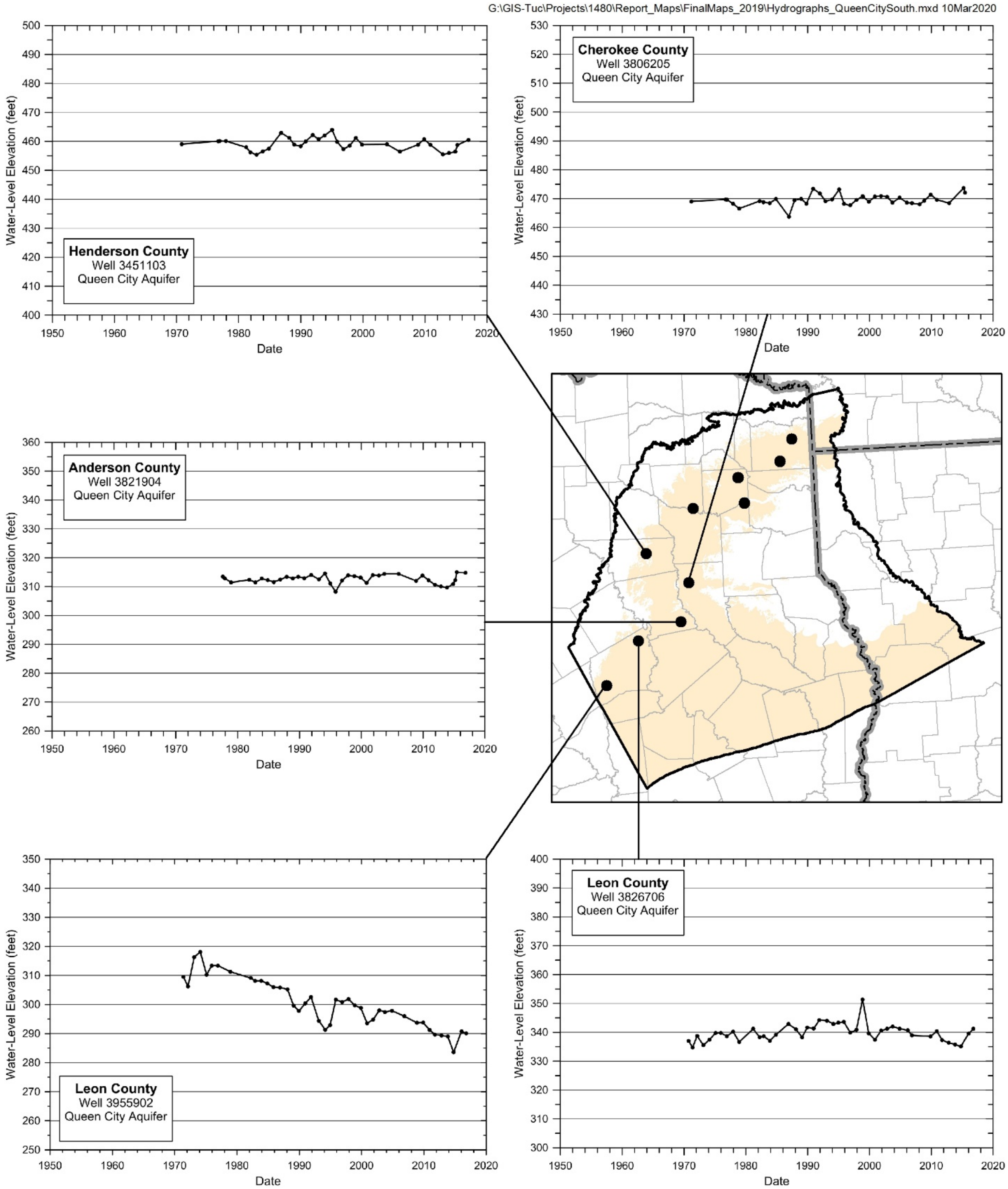


Figure 4-37. Selected Groundwater Level Elevation Hydrographs for Queen City Aquifer in the Southern Portions of Study Area

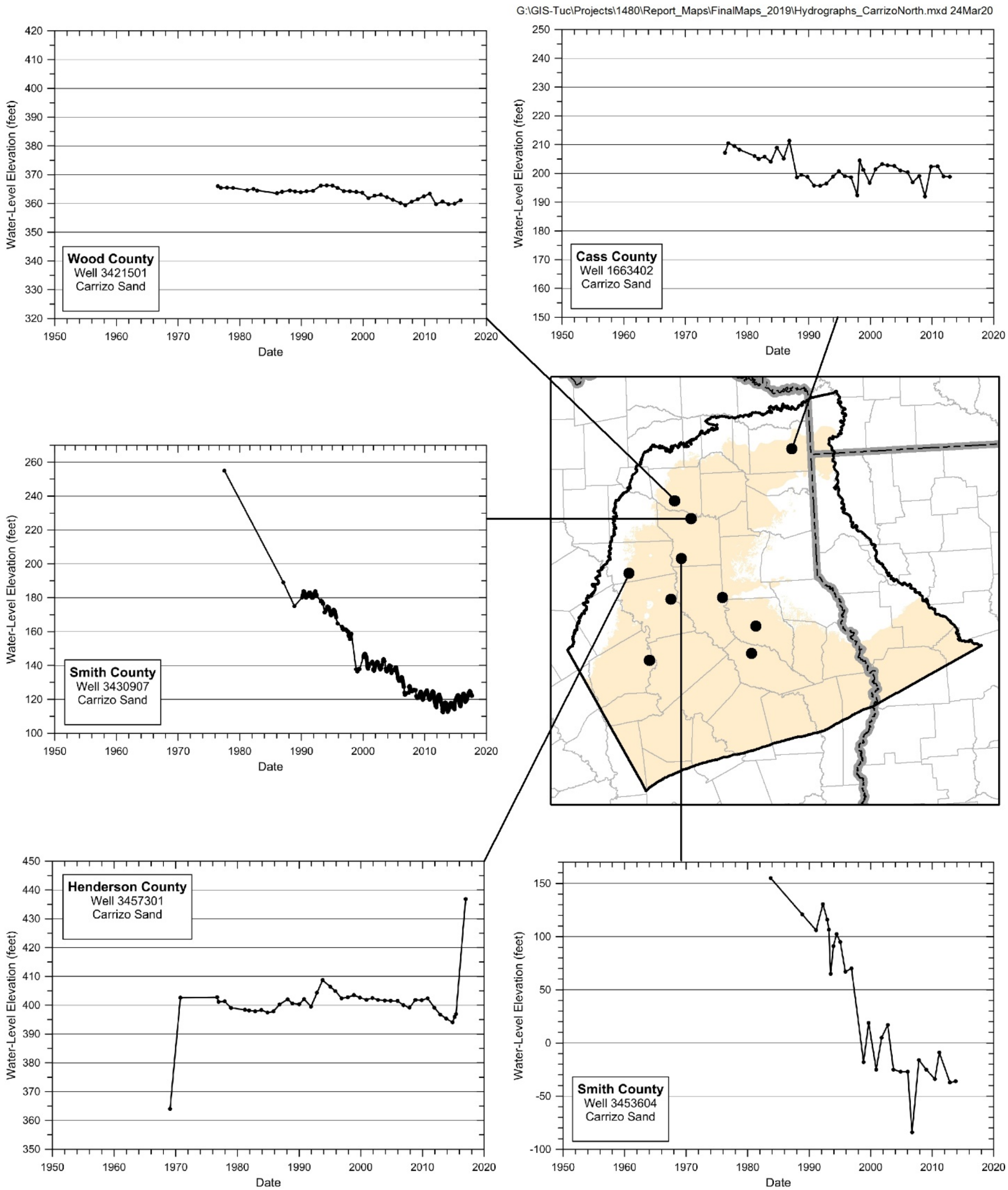


Figure 4-38. Selected Groundwater Level Elevation Hydrographs for Carrizo Aquifer in the Northern Portions of Study Area

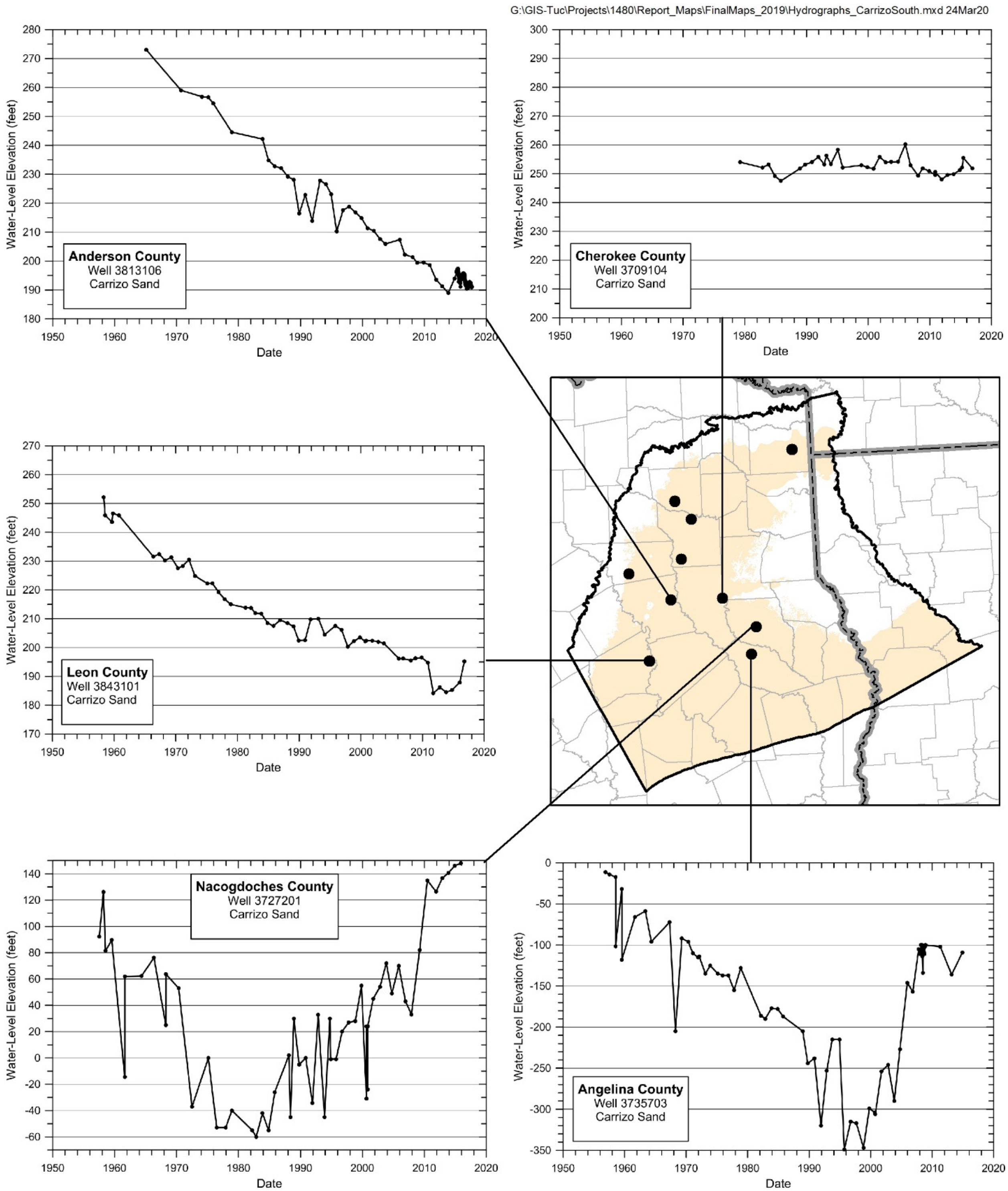


Figure 4-39. Selected Groundwater Level Elevation Hydrographs for Carrizo Aquifer in the Southern Portions of Study Area

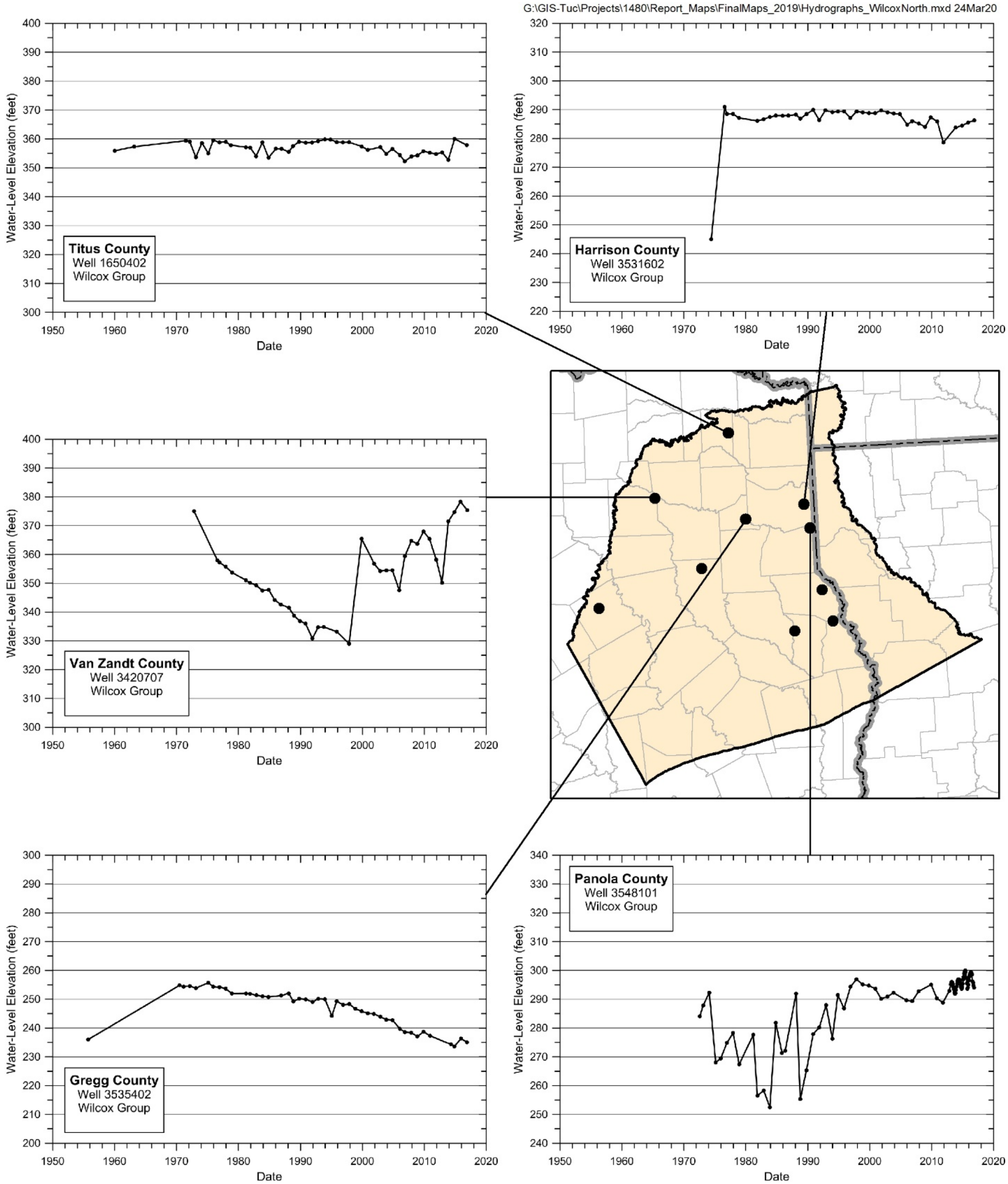


Figure 4-40. Selected Groundwater Level Elevation Hydrographs for Wilcox Aquifer in the Northern Portions of Study Area

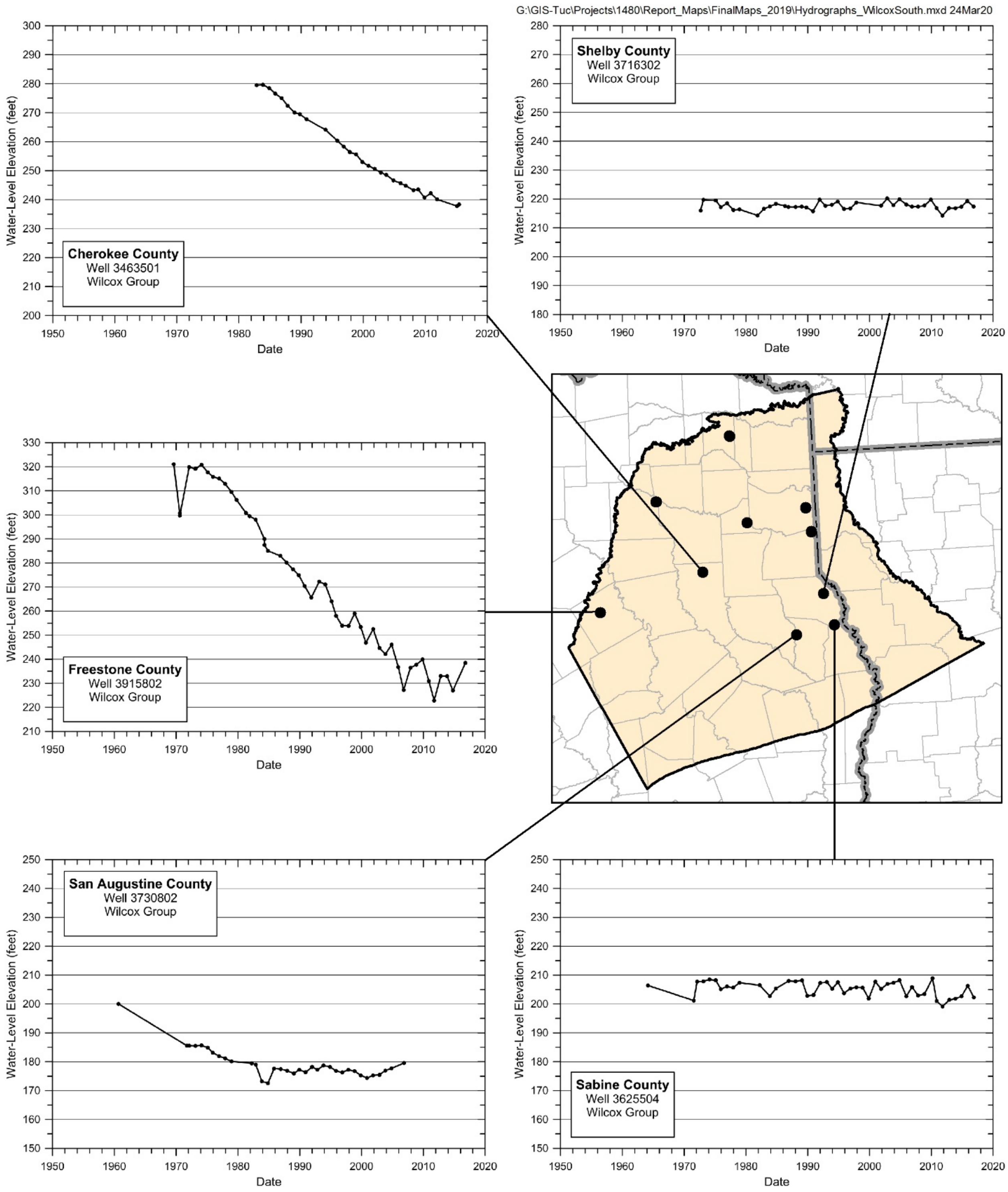


Figure 4-41. Selected Groundwater Level Elevation Hydrographs for Wilcox Aquifer in the Southern Portions of Study Area

4.3 RECHARGE

Recharge to the Sparta, Queen City, and Carrizo-Wilcox aquifers in the study area occurs from (1) percolation of precipitation in the outcrop areas and (2) percolation of impounded water at reservoirs. Percolation of precipitation is the principal recharge mechanism in the study area. Recharge from infiltration along rivers and tributaries could occur in localized areas in the study area; however, groundwater discharges to surface waters in the vast majority of the study area.

Aquifer recharge from Class II injection wells occurs below or in the deep, down-dip portions of the aquifers of interest in the study area and is assumed to occur at relatively small rates. Data for injection wells were requested from the Railroad Commission of Texas. However, after discussions with TWDB personnel, it was decided that any recharge from injection wells in the study area occurs below the base of useable quality water and would not impact groundwater conditions related to the groundwater availability model. For these reasons, injection wells are not included in the groundwater model for this study.

Springs often occur in topographically low areas along river valleys and in outcrop areas where hydrogeologic conditions generally preferentially reject recharge (Kelley and others, 2004). The number of flowing springs and gaining stream reaches in the study area is a result of humid climate, gently dipping topography, and dissected topography, which contribute to rejected recharge and runoff in the study area and greater East Texas Basin (Fryar and others, 2003).

4.3.1 RECHARGE FROM PRECIPITATION

Groundwater recharge from percolation of precipitation is difficult to estimate on a regional scale. Research has been conducted to improve these estimates for the study area. Previous estimates of recharge rates for the northern Queen City, Sparta, and Carrizo-Wilcox aquifers vary substantially due to varied hydraulic conductivity, rainfall distribution, evapotranspiration rates, groundwater-surface water interactions, and model grid cell size. Previous estimates of recharge rates for the aquifers range from nearly zero inches per year (in/yr) to about 2.5 in/yr. Kelley and others (2004) calibrated recharge rates for the previous groundwater availability model for the Queen City, Sparta, and Carrizo-Wilcox aquifers in the study area. Figure 4-42 shows varying distributions of recharge to the aquifers of interest based on different estimation methods. Note that no values are shown for areas south of the interface between the Sparta and the Younger units because the Younger units were not simulated in the model. Recharge presumably still occurs over the Younger aquifer units; it is just not accounted for in this study. An empirical relationship between recharge and precipitation was fit to reported data, excluding the highest point, from Scanlon and others (2003) (Figure 4-42 (a)), which averaged about 2 in/yr in the study area (Figure 4-43(a)). Scanlon performed extensive unsaturated zone simulations using the widely used Unites States Department of Agriculture National Resources Conservation Service State Soil Geographic database and Soil Survey Geographic Database for soils information along with weather and vegetation data for the major aquifers in Texas in 14 study areas. Kelley and others (2004) then scaled recharge up in local topographic highs and down at local topographic lows to account for discharge to the stream channels. This was then scaled by geology depending on each layer's hydraulic properties. Final calibrated recharge rates for the northern model ranged from 0.5 to 2.6 in/yr.

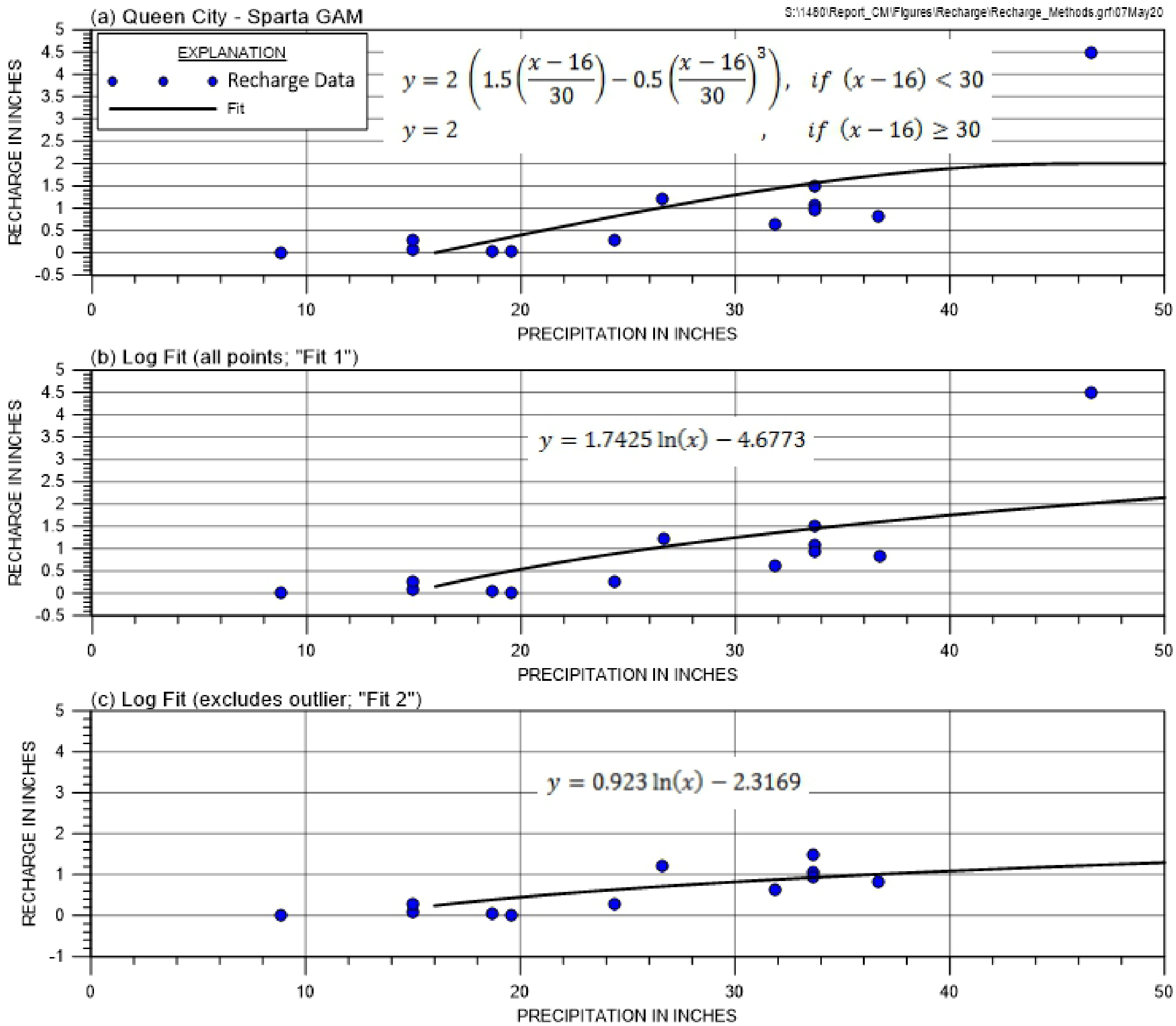


Figure 4-42. Estimated Recharge as a Function of Precipitation

Several methods were developed to update recharge estimates for the aquifer of interest in the study area. Two new logarithmic empirical relationships (fit 1 and fit 2) were developed by fitting to the Scanlon and others (2003) data, one including all points (Figure 4-42 (b)) and one excluding the highest point (Figure 4-42 (c)). The third method used the chloride mass balance approach presented in Scanlon and others (2012) and was applied using TWDB wells in the study area that had chloride information and chloride deposition data from National Atmospheric Depositional Program. PRISM data for the 30-year normal average (1981 through 2010) for precipitation was used to calculate estimates of recharge based on these three methods and the relationship (pre-calibration) presented by Kelley and others (2004) (Figure 4-43). The Kelley and others (2004) method and the first log fit (fit 1, all points) had the highest estimated average of recharge at 2 in/yr followed by the second log fit (fit 2, high point excluded) at 1.25 in/yr. Chloride mass balance approach had the most spatial variability, but had the lowest average recharge at about 1 in/yr. Regional recharge estimates based on groundwater chloride data should be considered a lower bound because various processes can add chloride to groundwater, but no process can remove chloride from groundwater in the aquifer system.

Volumetric comparisons of the recharge estimation methods are presented in Table 4.2. The previous study by Kelley and others (2004) estimated annual recharge volumes for each aquifer unit based on an assumed rate of 2 in/yr and the surface area of the outcrop of each unit. This method results in volumes of about 165,000 AF/yr, 825,000 AF/yr, and 1,200,000 AF/yr for the Sparta, Queen City, and Carrizo aquifers, respectively. This agrees with their pre-calibration estimates which are about 170,000 AF/yr, 850,000 AF/yr, and 1,125,000 AF/yr, respectively, for the same aquifers. The first logarithmic fit (all points) provides the most similar estimates while the second logarithmic fit (high point excluded) and chloride mass balance approach set a lower bound of volumetric recharge (Table 4.2).

Table 4.2. Summary of Annual Recharge from Reported or Interpolated Estimates

Formation	QCSP GAM (estimated)[a]	QCSP GAM (pre-calibration)[b]	Chloride Mass Balance[c]	Fit 1[d]	Fit 2[e]
Sparta	165,224	172,640	109,011	177,782	108,078
Weches		267,303	164,293	275,792	167,611
Queen City	824,600	849,637	452,896	858,820	523,430
Reklaw		1,044,771	541,402	1,059,602	645,524
Carrizo	1,200,520	1,122,723	590,672	1,137,472	693,087
Upper Wilcox		1,870,665	868,235	1,936,126	1,176,421
Middle Wilcox		1,948,096	881,464	2,012,159	1,222,976
Lower Wilcox		1,900,480	859,786	1,947,394	1,184,968

All values in acre-feet per year

[a] Values from Table 4.6.2 of previous GAM report by Kelley and others (2004). Based on assumed recharge rate of 2 inches per year.
[b] Interpolated values using empirical equation developed by Kelley and others (2004), without scaling for topography and geology.
[c] Interpolated values using empirical equation developed by Scanlon and others (2012).
[d] Interpolated values using empirical equation developed by Scanlon and others (2003).
[e] Interpolated values using empirical equation developed by Scanlon and others (2003), except one outlier.

The recharge estimation approaches presented in this section could be used as a starting point for calibration of recharge. All methods use relationship with precipitation which allow variation of recharge through time. Annual scaling factors were applied to the distribution of average recharge from Kelley and others (2004), shown on Figure 4-43. Adjustment factors were adjusted during calibration of the numerical model to match calibration targets, such as groundwater levels and streamflows. The calibration process is described in the model calibration report.

The recharge distribution simulated for each layer in the previous calibrated groundwater availability model developed by Kelley and others (2004) was assessed for this study. Steady-state recharge varied for each layer. In that model, steady-state recharge rates are approximately 140,000 AF/yr for Sparta; 11,000 AF/yr for Weches; 275,000 AF/yr for Queen City; 33,000 AF/yr for Reklaw; 132,000 AF/yr for Carrizo; 167,000 AF/yr for Upper Wilcox; 274,000 AF/yr for Middle Wilcox; and 18,000 AF/yr for Lower Wilcox. Recharge in the previous groundwater availability model varied from year to year. In that model, recharge in 1999 was simulated as approximately 97,000 AF/yr for Sparta; 7,000 AF/yr for Weches; 159,000 AF/yr for Queen City; 18,000 AF/yr for Reklaw; 67,000 AF/yr for Carrizo; 94,000 AF/yr for Upper Wilcox; 185,000 AF/yr for Middle Wilcox; and 11,000 AF/yr for Lower Wilcox.

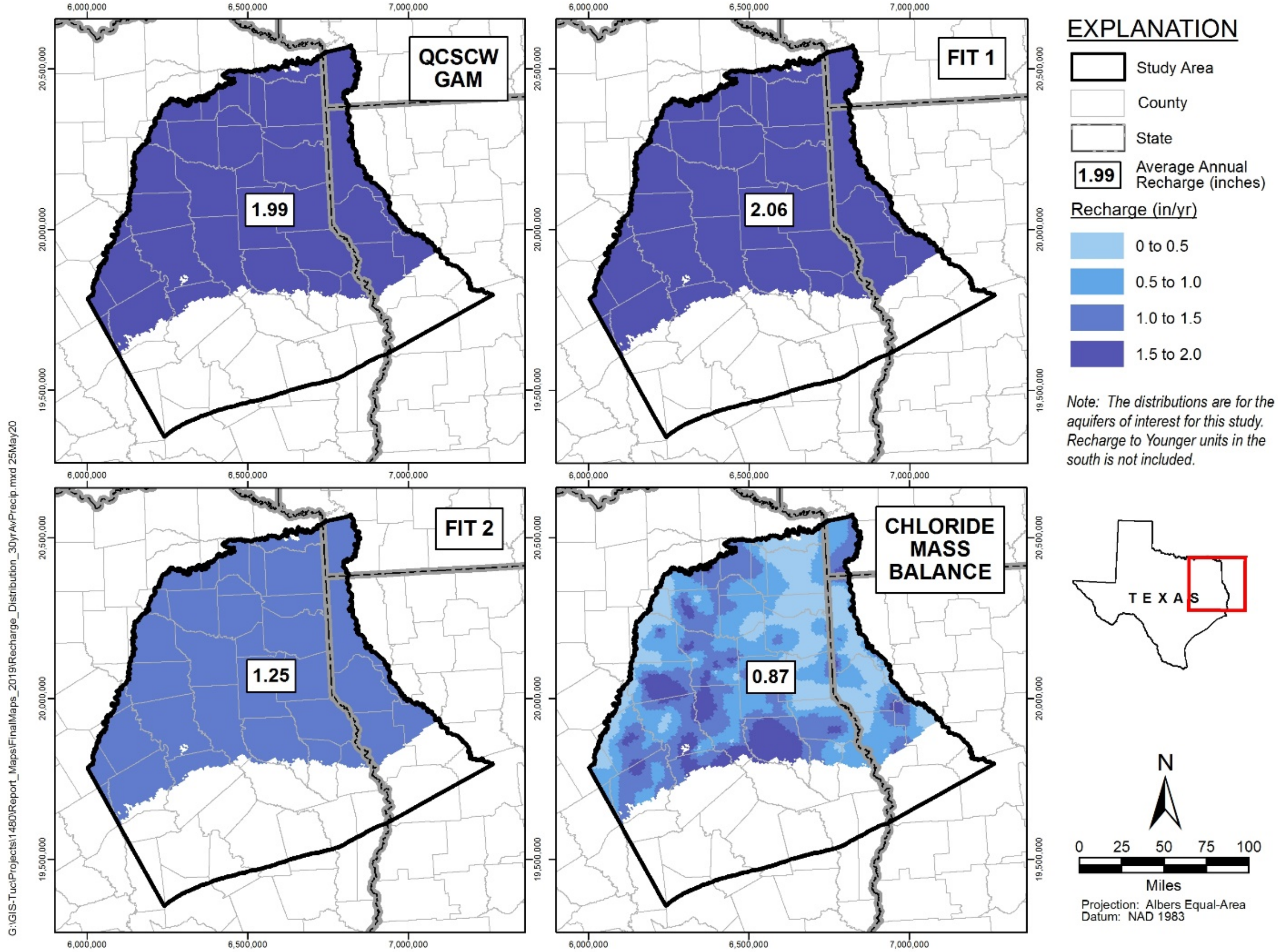


Figure 4-43. Recharge Distribution from Various Methods Based on 30-Year Average Precipitation

4.3.2 RECHARGE FROM RESERVOIRS

In total there are 41 reservoirs with surface areas greater than half a square mile in the study area in the outcrops of the Sparta, Queen City, and Carrizo-Wilcox aquifers (Figure 4-44). These reservoirs provide potential areas of focused recharge to the underlying aquifers of interest. Table 4.3 lists the names, owners, and year impounded for each reservoir. This information was sourced from the Texas Water Development Board (2017g) and Fryar and others (2003). Only one natural lake was historically present in the study area, Caddo Lake, which was drained in the 1870s and later impounded in 1914. Figure 4-45 includes historic lake stage (water level) elevations obtained from the TWDB (2017g) and source data from the previous groundwater availability model by Fryar and others (2003). The hydrographs show only minor variations in lake levels over the period of interest. Reservoir locations and stage measurements will be incorporated in the groundwater model.

Table 4.3. Major Reservoirs in the Study Area

Reservoir	Reservoir Name	Owner	Date Impounded
1	Black Bayou Lake	State of Louisiana	1955
2	Caddo Lake	Caddo Levee District	1914
3	Cedar Creek Reservoir	Tarrant Regional Water District	1965
4	Clear Lake	---	---
5	Clinton Lake	---	---
6	Cross Lake	City of Shreveport	1925
7	Eastman Lakes	---	---
8	Ellison Creek Reservoir	Lone Star Steel Company	1943
9	Fairfield Lake	Texas Utilities Generating Company	1969
10	Houston County Lake	Houston County WCID #1	1966
11	Johnson Creek Reservoir	Southwestern Electric Power Company	1961
12	Lake Athens	Athens Municipal Water Authority	1962
13	Lake Bob Sandlin	Titus County Water District	1977
14	Lake Cherokee	Cherokee Water Company	1948
15	Lake Cypress Springs	Franklin County Water District & T.W.D.B	1970
16	Lake Fork Reservoir	Sabine River Authority	1979
17	Lake Gilmer	City of Gilmer	---
18	Lake Gladewater	City of Gladewater	1952
19	Lake Hawkins	Wood County	1962
20	Lake Holbrook	Wood County	1962
21	Lake Jacksonville	City of Jacksonville	1957
22	Lake Limestone	Brazos River Authority	1978
23	Lake Nacogdoches	City of Nacogdoches	1976
24	Lake O the Pines	U.S. Army Corps of Engineers	1957
25	Lake Palestine	Upper Neches River Authority	1962
26	Lake Quitman	Wood County	1962
27	Lake Striker	Angelina-Nacogdoches WCID #1	1957
28	Lake Tyler	City of Tyler	1966

Reservoir	Reservoir Name	Owner	Date Impounded
29	Lake Winnsboro	Wood County	1962
30	Martin Lake	Texas Utilities Generating Company	1974
31	Murvaul Lake	Panola County GWSD #1	1957
32	Pinkston Reservoir	City of Center	1977
33	Richland-Chambers Reservoir	Tarrant County WCID #1	1987
34	Rogers Lake	Southwestern Electric Power Company	1983
35	Sibley Lake	State of Louisiana	1962
36	Smithport Lake	State of Louisiana	---
37	Toledo Bend Reservoir	Sabine River Authority	1966
38	Trinidad Lake	---	1925
39	Wallace Lake	U.S. Army Corps of Engineers	1946
40	Welsh Reservoir	Southwestern Electric Power Company	1975
41	Wright Patman Lake	U.S. Army Corps of Engineers	1956

--- = Not available

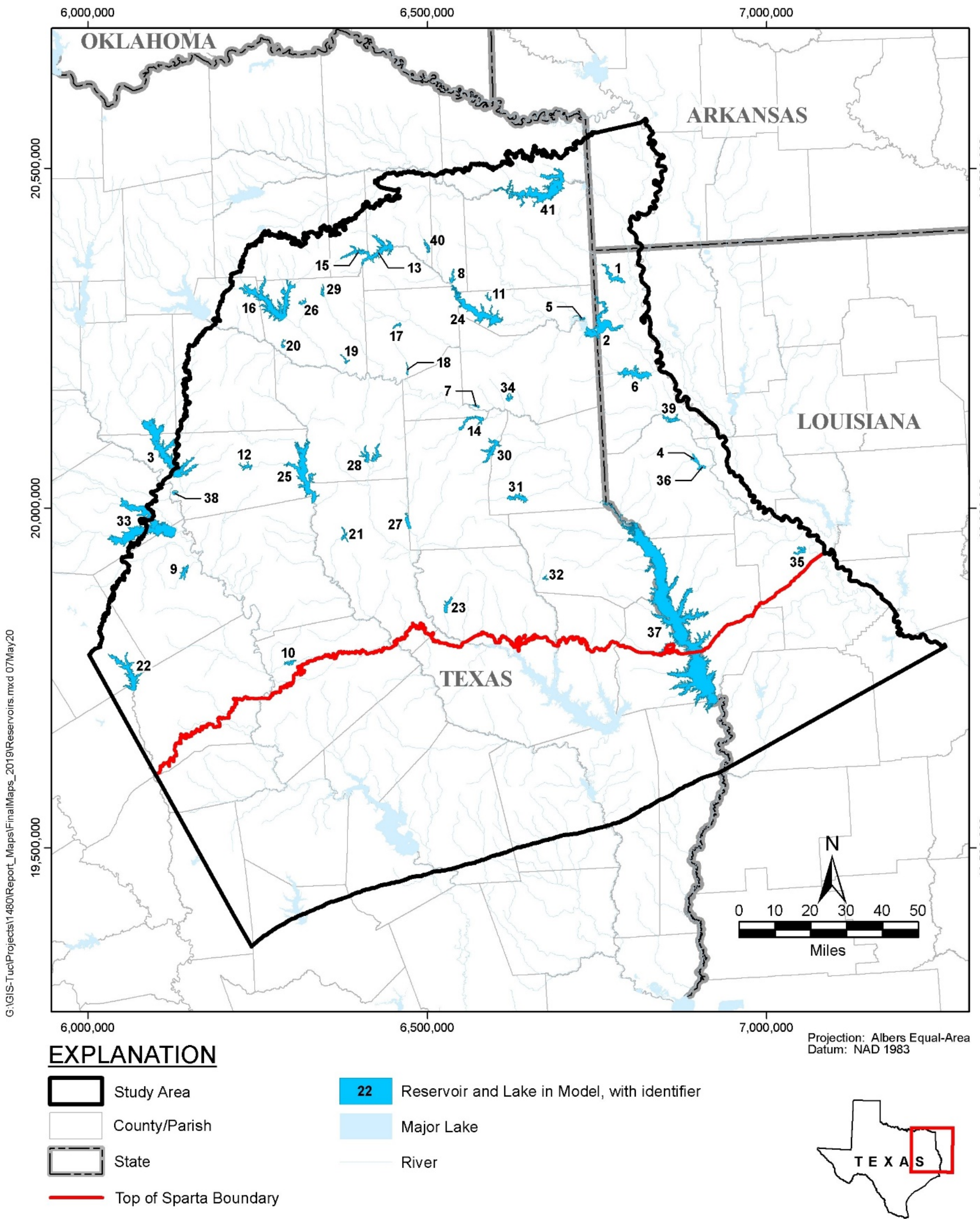


Figure 4-44. Locations of Major Reservoirs in Study Area

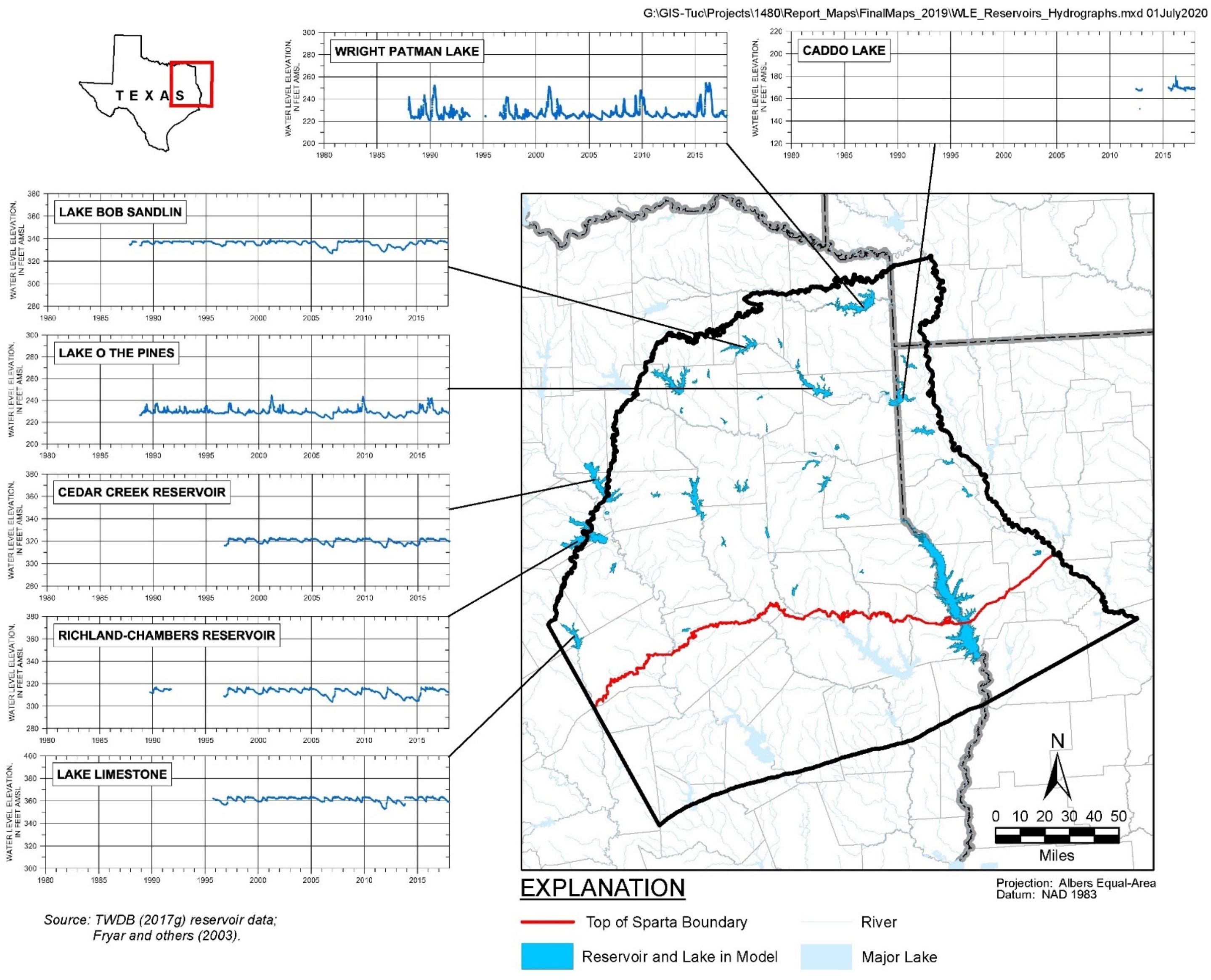


Figure 4-45. Water Level Hydrographs for Selected Reservoirs in Study Area

4.4 SURFACE WATER NETWORK

Important surface water features within the study area include several major rivers and tributaries, numerous lakes and reservoirs, and springs. The following sections describe the surface water network in the study area.

4.4.1 RIVER FLOWS

The major rivers intersecting the study area include the Trinity River, Neches River, Angelina River, Sabine River, Big Cypress Creek, Sulphur River, and Red River (Figure 4-46). Big Cypress Creek and Sulphur River are major tributaries to Red River. Angelina River is a major tributary to Neches River. Many other smaller rivers and streams are also included in the study area.

Numerous stream gain/loss studies have been conducted for rivers and tributaries in the study area, particularly for the Carrizo-Wilcox Aquifer. Fryar and others (2003) and Kelley and others (2004) provide a comprehensive summary of these studies. A literature search conducted for this investigation did not discover any new relevant studies completed for recent years in the study area. Studies have been conducted on the Sabine River, Angelina River, Neches River, Sulphur River, Trinity River, Grays, Little Cypress, and Sugar creeks in the Red River Basin, Lake Fork Creek in the Sabine River Basin, and Big and Little Elkhart creeks in the Trinity River Basin within the study area. The majority of surveys conducted in this study area observed gaining flow conditions along the studied stream. The one exception was the survey for Lake Fork Creek which indicated losing flow conditions; however, this result is reported to be anomalous. The results of these gain/loss surveys indicate that most major rivers and tributaries have gaining streamflows.

Flows along the rivers are measured by the United State Geological Survey (USGS, 2017a) at several streamflow gages in the study area. Daily streamflow data are available from the United States Geological Survey for the period of 1903 through 2016. Annual streamflows are assessed for this study because annual stress periods will be simulated in the updated groundwater availability model. Measured river flows will be used as a guide during calibration of the groundwater model. Annual streamflows at selected gaging stations along the major rivers in the study area are shown on Figure 4-47 through Figure 4-51. These hydrographs indicate that gaining flow conditions occur along most rivers in the study area.

Historical annual streamflows along the Trinity River vary substantially from year to year, ranging from about 550,000 to over 6,000,000 AF/yr. Streamflow measurements indicate a general increase in flow along its length (Figure 4-47). Annual flows are general larger than 1,500,000 AF/yr in the upper reaches near Trinidad, Texas and increase to mostly larger than 2,000,000 AF/yr near Goodrich, Texas.

Historical annual streamflows along the Neches River vary substantially from year to year, ranging from about 80,000 to over 6,000,000 AF/yr. Streamflow measurements indicate a general increase in flow along its length (Figure 4-48). Annual flows are general smaller than 1,000,000 AF/yr in the upper reaches near the city of Neches, Texas and increase to larger than 2,000,000 AF/yr near Town Bluff, Texas, which is downstream from the confluence with the Angelina River.

Historical annual streamflows along the Sabine River vary substantially from year to year, ranging from about 25,000 to over 8,000,000 AF/yr. Streamflow measurements indicate a general increase in flow along its length (Figure 4-49). Annual flows are smaller than 2,000,000 AF/yr in the upper reaches near Mineola, Texas and increase to larger than 2,000,000 AF/yr near Burkeville, Texas, which is downstream from the Toledo Bend Reservoir.

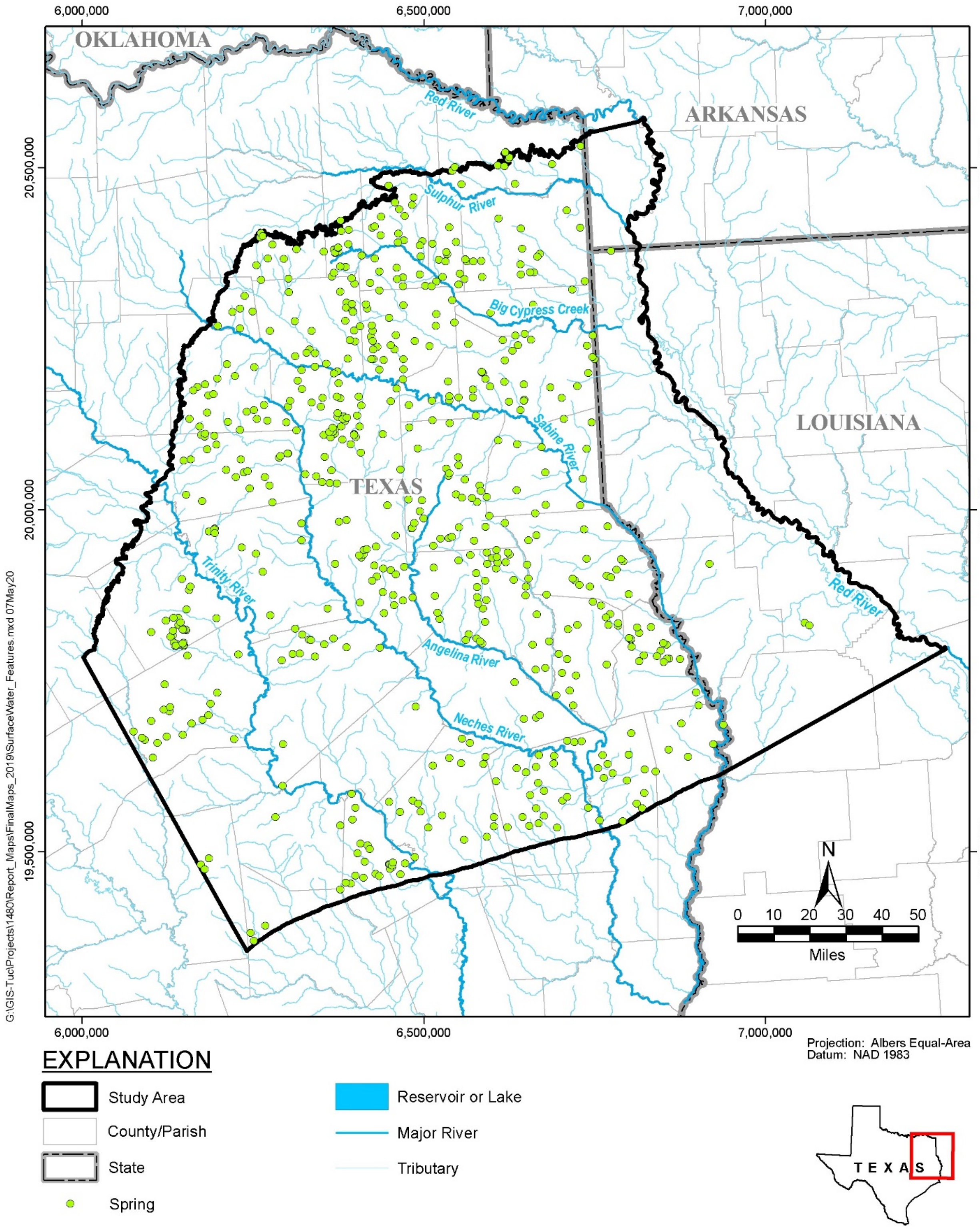
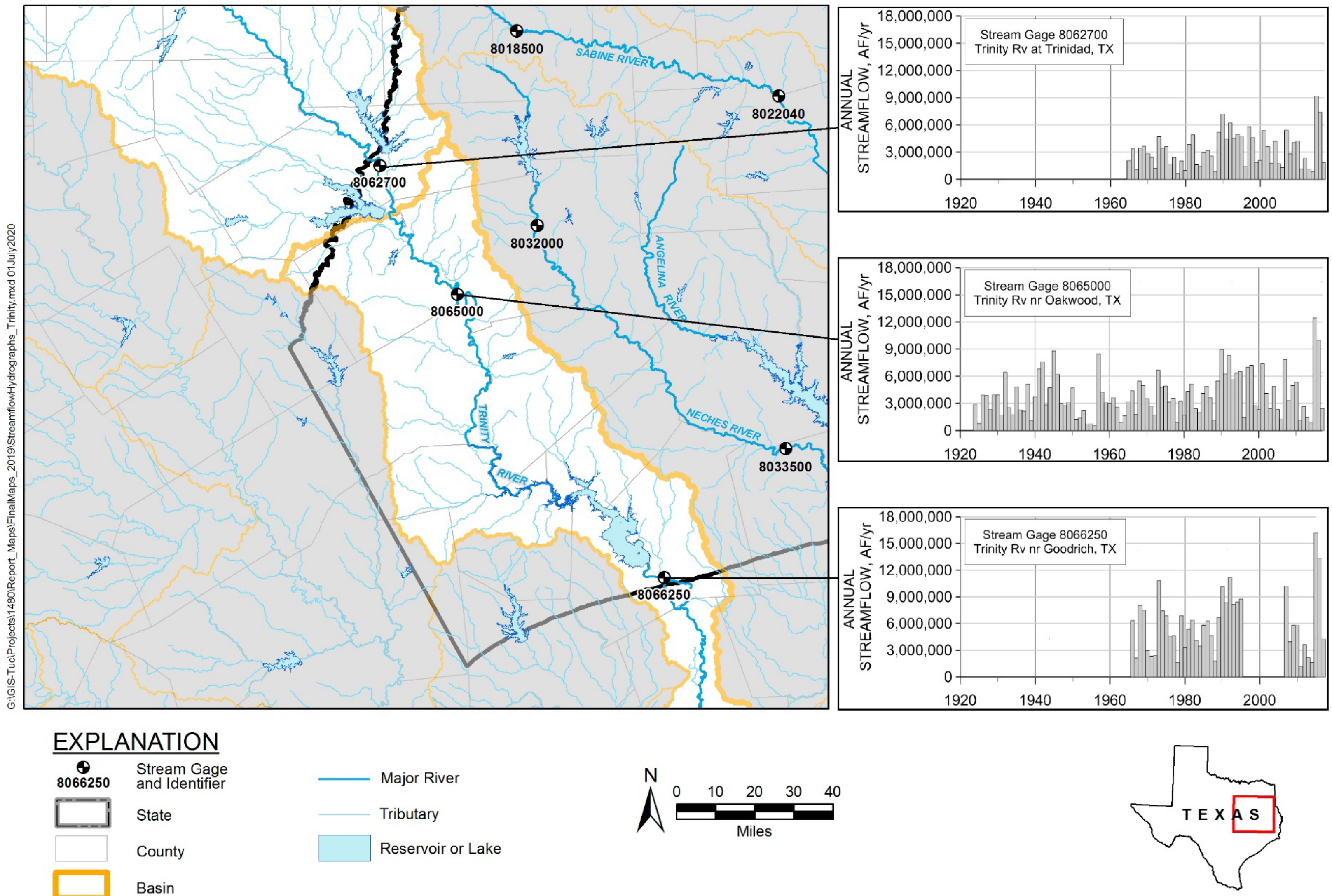
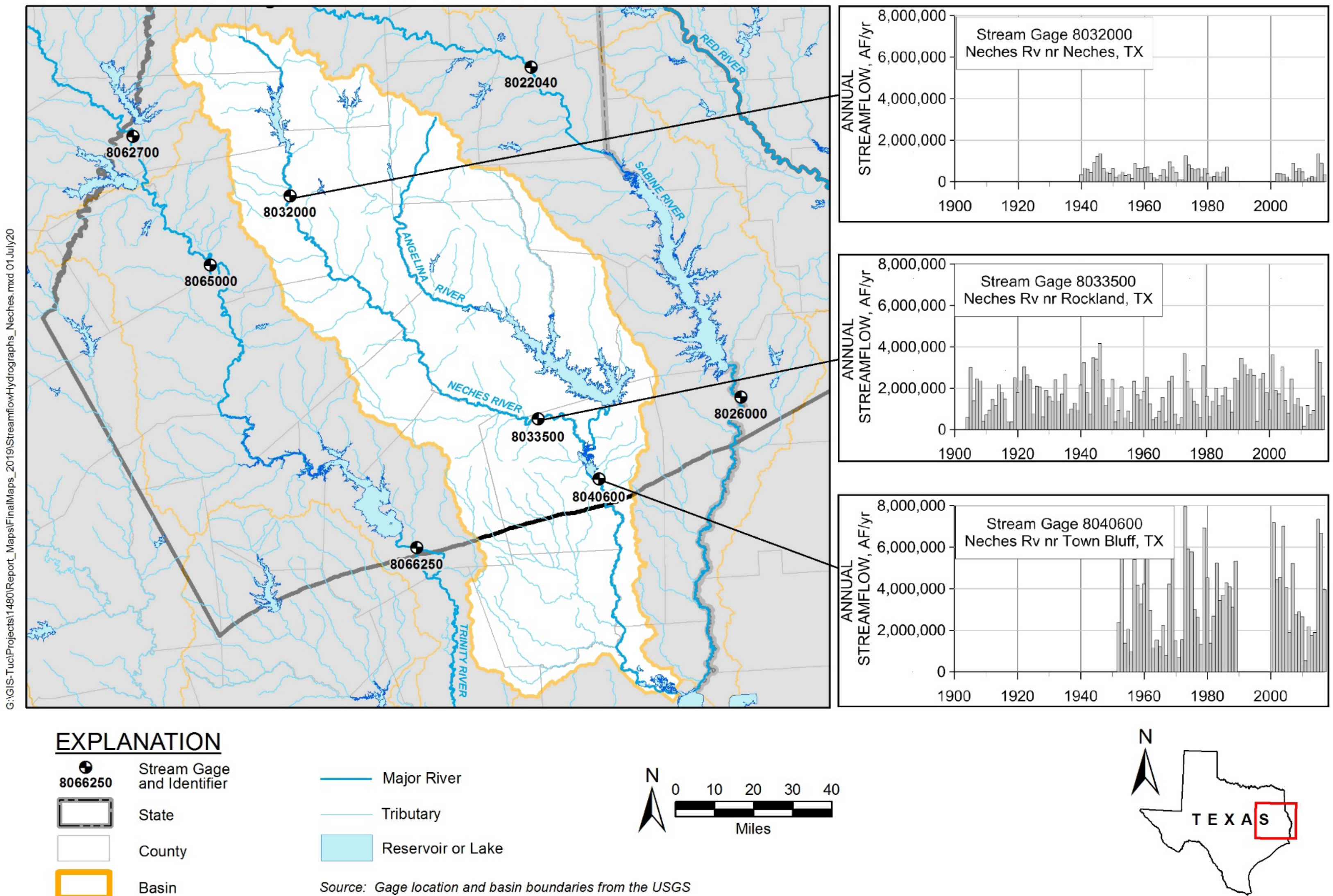


Figure 4-46. Surface Water Features in Study Area



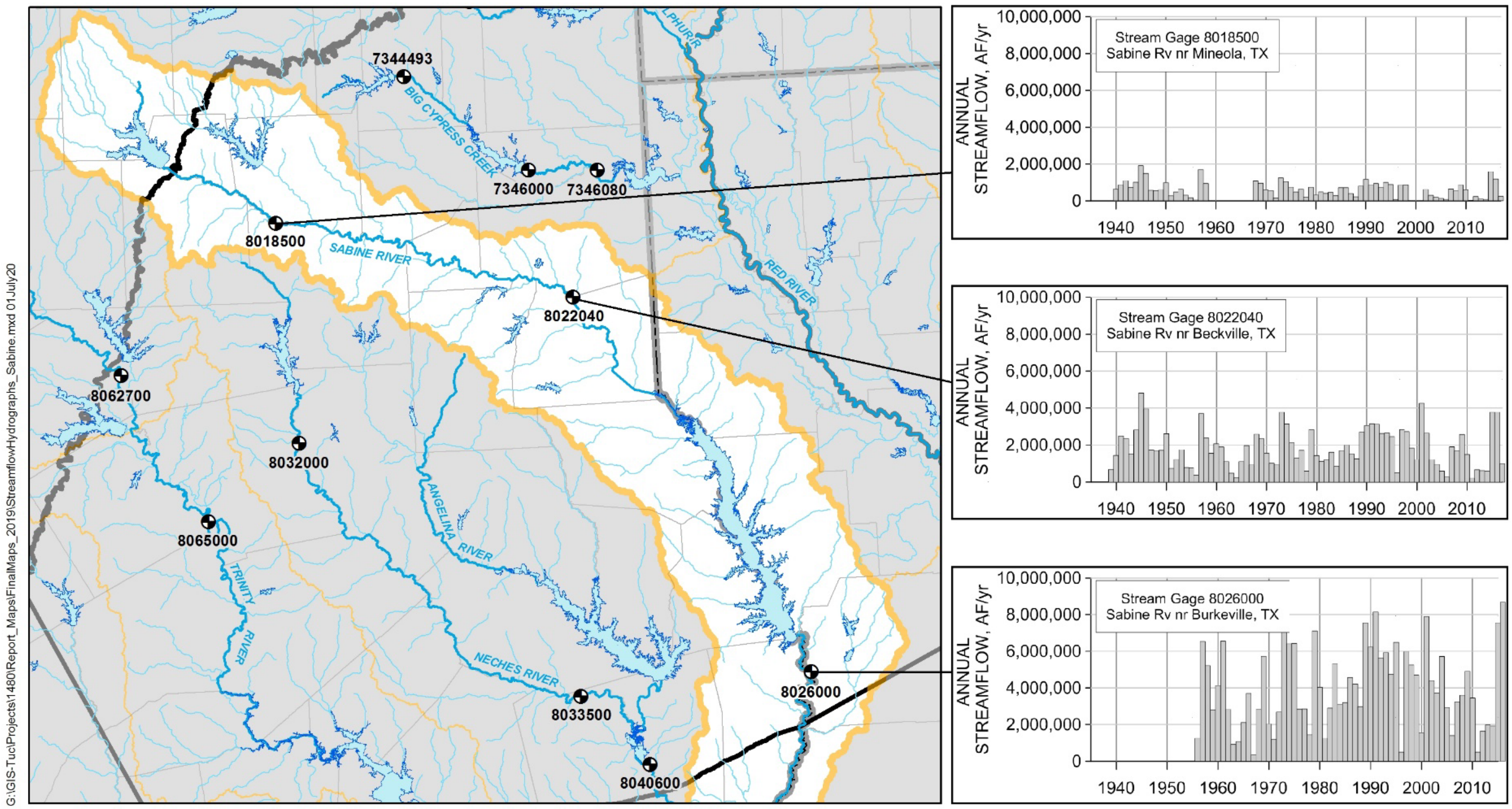
Source: Gage location and basin boundaries from the USGS (2016) National Hydrography Dataset. Basins are Hydrologic Unit Code 6 boundaries. Annual streamflows from the USGS (2017a).

Figure 4-47. Annual Streamflows along Trinity River



Source: Gage location and basin boundaries from the USGS (2016) National Hydrography Dataset. Basins are Hydrologic Unit Code 6 boundaries. Annual streamflows from the USGS (2017a).

Figure 4-48. Annual streamflows along Neches River



EXPLANATION

8032000 Stream Gage and Identifier

State

County

Basin

Major River

Tributary

Reservoir or Lake

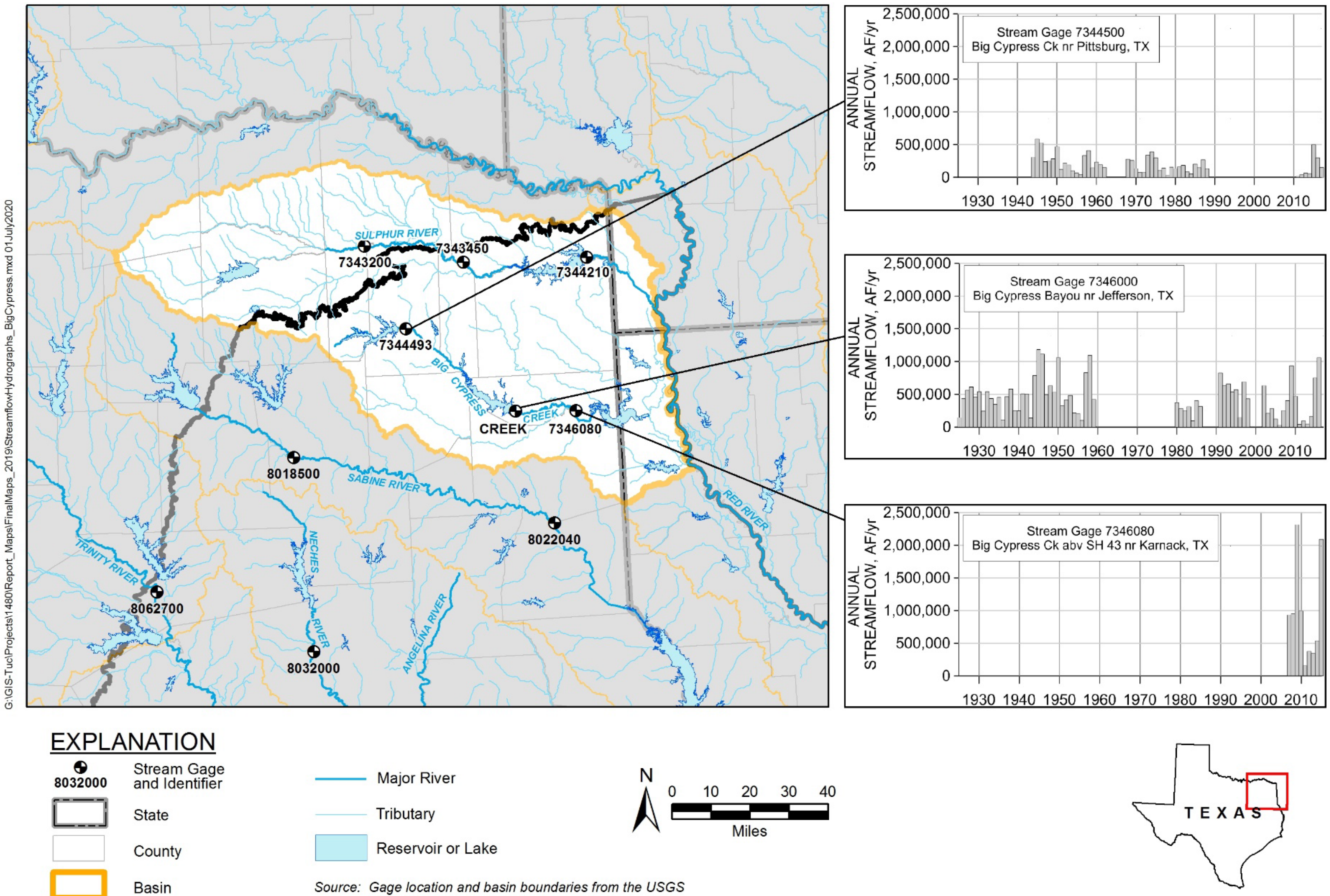
N

0 10 20 30 40

Miles

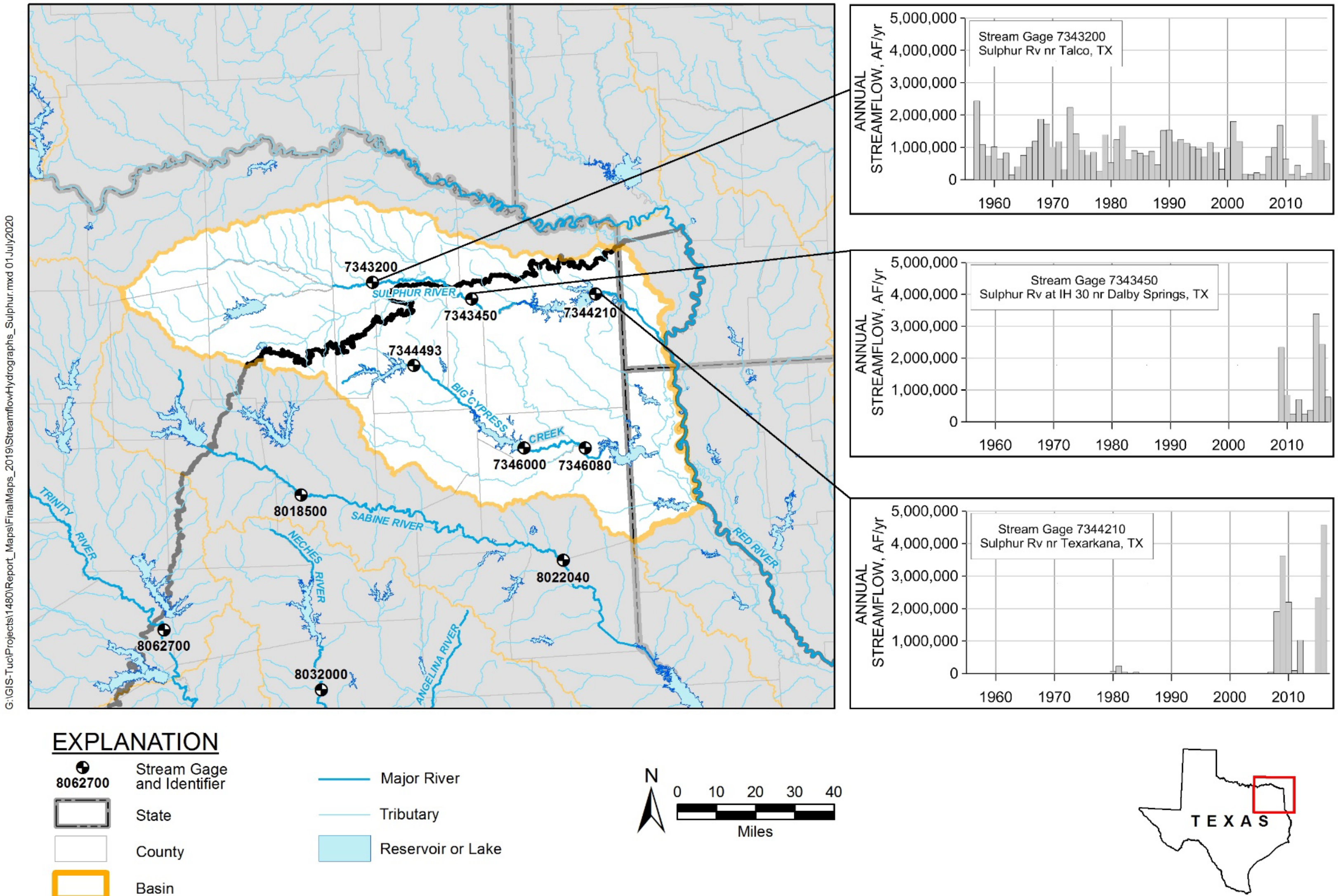
Source: *Gage location and basin boundaries from the USGS (2016) National Hydrography Dataset. Basins are Hydrologic Unit Code 6 boundaries. Annual streamflows from the USGS (2017a).*

Figure 4-49. Annual Streamflows along Sabine River



Source: Gage location and basin boundaries from the USGS (2016) National Hydrography Dataset. Basins are Hydrologic Unit Code 6 boundaries. Annual streamflows from the USGS (2017a).

Figure 4-50. Annual Streamflows along Big Cypress Creek



Source: Gage location and basin boundaries from the USGS (2016) National Hydrography Dataset. Basins are Hydrologic Unit Code 6 boundaries. Annual streamflows from the USGS (2017a).

Figure 4-51. Annual Streamflows along Sulphur River

Historical annual streamflows along the Big Cypress Creek vary from year to year, ranging from about 300 to over 2,000,000 AF/yr (Figure 4-50). Flows are generally smaller than 500,000 AF/yr along the upper and middle reaches of the creek. The downstream gage near Karnack, Texas has a relatively short period of record; flows at this gage are more variable than the upstream gages.

Historical annual streamflows along the Sulphur River vary from year to year, ranging from about 1,200 to over 3,000,000 AF/yr (Figure 4-51). The two downstream gages have relatively short periods of record; flows at these gages are more variable than the upstream gage.

Differences in measured annual streamflows were evaluated to note overall gains or losses along a specific river during the model simulation period from 1980 through 2016. Gages along unregulated reaches of the major rivers were selected for this evaluation. The annual differences between selected upstream and downstream gages along the major rivers are summarized in Table 4.4. Monitoring data show an increase in flows between gages along the major rivers since 1980, which suggests gaining flow conditions. These streamflow data do not represent baseflows; however, the data are useful as a general guide regarding annual flow conditions along the rivers for model calibration.

Table 4.4. Difference in Annual Streamflows Along Major Rivers

Year	Trinity River Difference between Upstream Gage (8062700) and Downstream Gage (8065000)	Neches River Difference between Upstream Gage (8032000) and Downstream Gage (8033500)	Sabine River Difference between Upstream Gage (8018500) and Downstream Gage (8022040)	Big Cypress Creek Difference between Upstream Gage (7346000) and Downstream Gage (7346080)	Sulphur River Difference between Upstream Gage (7343200) and Downstream Gage (7343450)
	Acre-feet per year				
1980	733,351	1,241,886	1,120,389	---	---
1981	469,566	401,467	642,742	---	---
1982	202,031	1,096,009	794,499	---	---
1983	800,404	1,557,673	1,158,328	---	---
1984	537,816	940,176	579,243	---	---
1985	1,083,754	1,161,861	980,470	---	---
1986	1,711,768	1,343,266	1,293,325	---	---
1987	1,045,431	---	1,128,706	---	---
1988	223,072	---	1,043,928	---	---
1989	260,536	---	1,908,260	---	---
1990	1,657,918	---	1,895,939	---	---
1991	1,816,922	---	2,279,446	---	---
1992	2,094,569	---	2,188,064	---	---
1993	1,144,837	---	1,894,759	---	---
1994	1,362,890	---	1,654,467	---	---
1995	1,783,230	---	1,561,036	---	---
1996	70,721	---	439,170	---	---
1997	1,153,871	---	1,999,762	---	---
1998	2,609,106	---	1,845,885	---	---
1999	855,658	---	1,369,706	---	---
2000	234,473	---	---	---	---
2001	2,046,079	---	---	---	---
2002	462,493	1,487,907	---	---	---
2003	601,001	1,346,074	919,549	---	---
2004	705,850	2,655,626	761,287	---	---
2005	594,805	1,170,117	454,648	---	---
2006	-71,824	716,843	205,966	---	---
2007	2,421,136	1,557,670	1,249,730	675,551	---
2008	481,935	685,990	1,133,496	546,034	---
2009	905,996	868,981	1,711,966	1,377,043	655,256
2010	1,093,447	600,215	910,693	520,536	196,511
2011	13,031	86,898	183,112	104,071	83,298
2012	341,519	987,344	427,661	273,010	253,464
2013	262,410	466,365	499,592	294,785	130,475
2014	96,266	680,755	520,428	369,931	172,309
2015	3,211,977	2,518,080	2,188,581	1,332,558	1,388,595
2016	2,573,379	2,338,927	2,599,085	1,084,341	1,203,301

Note: Difference in flows between gages are not calculated for initial years of record; record likely are not complete. --- = data not available for calculation

4.4.2 RESERVOIRS, LAKES, AND SPRINGS

Reservoirs, lakes, and springs can be found throughout the study area (Figure 4-46). Reservoirs overlying the aquifers of interest in the study area larger than one-half square mile in area are summarized in Section 4.3.2 of this report and shown on Figure 4-44. Daily discharge flows from reservoirs in the study area were obtained from the United States Army Corps of Engineers (2018). Reservoirs with available data are shown on Figure 4-52. Peak average daily discharges are generally on the order of 10,000 cubic feet per second (cfs) or smaller from reservoirs in the north. Discharges are more variable in the western portions of the study area, with peak flows generally larger than 10,000 cfs.

Hundreds of springs are documented within the study area (Figure 4-46). Springs are important to understanding the surface-groundwater interaction because they occur where groundwater intersects the land surface. Springs often occur in topographically low areas along river valleys and in outcrop areas where hydrogeologic conditions generally preferentially reject recharge (Kelley and others, 2004). The number of flowing springs in the study area is a result of humid climate, gently dipping topography, and dissected topography, which contribute to rejected recharge and runoff in the study area and greater East Texas Basin (Fryar and others, 2003). Spring discharges are summarized in Section 4.7.2 of this report.

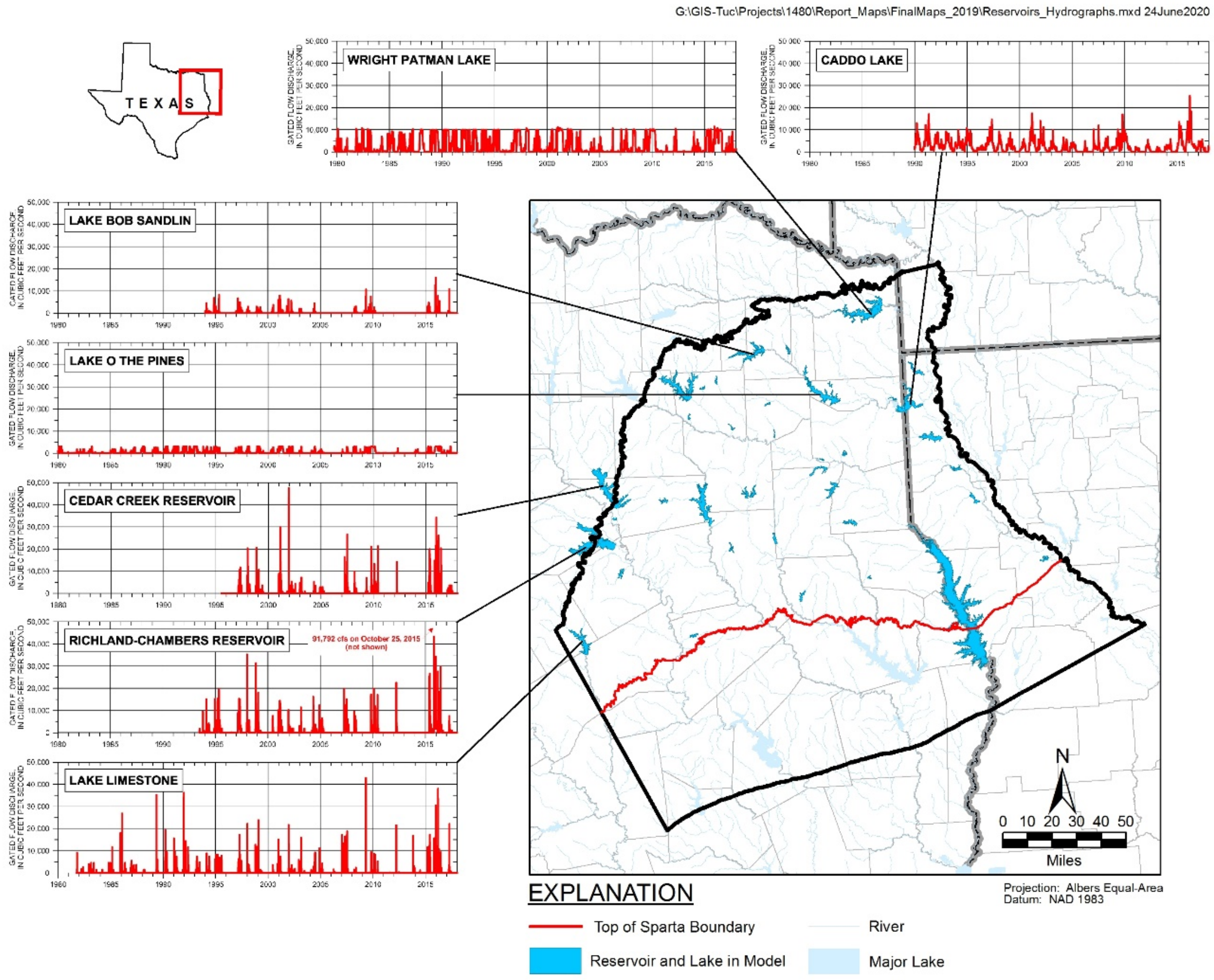


Figure 4-52. Daily Discharge Flows for Selected Reservoirs in Study Area

4.5 HYDRAULIC PROPERTIES

The movement and storage of groundwater through an aquifer is dependent on the structural and geological characteristics that are then described through hydraulic parameters. Important aquifer hydraulic parameters include transmissivity, hydraulic conductivity, specific yield, and specific storage. Transmissivity is the rate of groundwater movement under a 1:1 hydraulic gradient through a unit section of an aquifer 1 foot wide and extending the full saturated thickness of the aquifer (Theis, 1935). Transmissivity is a measure of the ability of an aquifer to transmit groundwater and is equal to the product of hydraulic conductivity and saturated aquifer thickness. Units for transmissivity are feet squared per day (ft^2/day). Hydraulic conductivity is the rate of groundwater movement, under a 1:1 hydraulic gradient, through a unit area of aquifer material (Heath, 1989). Units for hydraulic conductivity are feet per day (ft/day).

Specific yield is the ratio of the volume of water which a saturated porous medium will yield by gravity drainage to the volume of the porous medium (Lohman, 1972). Specific yield is generally applied to unconfined or "water table" aquifers. Specific storage is the volume of water released from or taken into storage per unit volume of the aquifer per unit change in head (units of 1/length) (Lohman, 1972).

Previous studies along with an additional analysis using updated well test data from TWDB were used to calculate the hydraulic properties for the Sparta Sand, Weches Formation, Queen City Sand, Reklaw Formation, Carrizo Sand, Upper Wilcox, Middle Wilcox, and Lower Wilcox. The previous studies included Mace and others (2002) and Kelley and others (2004).

A database developed for a previous study conducted by Mace and others (2002) was obtained and processed for this study. The Railroad Commission Texas slug test and bailing test measurements were removed, as recommended in the associated report, because they tend towards lower values. Well log estimate measurements were also removed due to their bias towards higher values. The remaining measurements in the database were from the TWDB and the Texas Commission on Environmental Quality. Each measurement was assigned to an aquifer layer based on well screen or well depth information and elevations of the hydrostratigraphic framework described in Section 4.1 of this report. This process yielded 3,140 unique values of transmissivity and 2,985 values of hydraulic conductivity. Additional measurements were compiled from the Texas Commission on Environmental Quality wells processed by Kelley and others (2004) and TWDB. A total of 44 TWDB measurements from the TWDB (2017a) Groundwater Database were added using data collected since the previous groundwater availability model investigation. TWDB well transmissivity was determined by using the estimation method developed by Driscoll (1986) for unconfined aquifers because yield and drawdown were the only available data. Transmissivity values were converted to hydraulic conductivity values by dividing by the screen length at the measurement well location.

4.5.1 TRANSMISSIVITY AND HYDRAULIC CONDUCTIVITY

Aquifer transmissivity and hydraulic conductivity values from previous studies and current analysis are summarized in Table 4.5. Histograms for estimated hydraulic conductivity values for each aquifer unit are shown on Figure 4-53. The hydraulic properties for each aquifer unit are summarized below. The aquifer properties reported herein are based on available aquifer testing results from datasets previously described, except for the river alluvium which is described using values reported in literature. The range and geometric mean values are representative of the aquifer testing data and might not represent actual properties throughout the entire aquifer layer. The testing data provide a range of possible values for constraining model calibration. Vertical conductance will be evaluated during model calibration. Distributions of aquifer property measurements in the upper aquifer units (Sparta, Weches, Queen City, and Reklaw) and the lower aquifer units (Carrizo and Wilcox Group) are shown on Figure 4-54 and Figure 4-55, respectively. The vast majority of data available for all aquifer units are from wells located at or very near outcrop areas. No data are available for deep, down-dip portions of the aquifer system.

Table 4.5. Summary of Aquifer Testing Results from Wells in the Northern Portions of Queen City, Sparta, and Carrizo-Wilcox Aquifers

	Transmissivity (ft^2/day)[a]				Hydraulic Conductivity (ft/day)[b]			
Aquifer	**Count**	**Minimum**	**Maximum**	**Geometric mean**	**Count**	**Minimum**	**Maximum**	**Geometric mean**
Sparta Sand	24	27.56	7,266.26	337.51	24	0.92	807.36	14.26
Weches Formation	29	5.68	2,627.27	132.24	29	0.19	65.68	4.70
Queen City Sand	642	1.25	11,180.03	277.75	1,047	0.12	451.38	4.83
Reklaw Formation	293	2.72	19,311.82	260.00	270	0.06	386.24	5.46
Carrizo Sand	170	6.86	11,857.29	230.01	170	0.28	197.62	5.61
Upper Wilcox	1193	2.26	11,036.12	184.58	1136	0.06	278.07	3.83
Middle Wilcox	547	4.67	26,850.12	176.66	527	0.04	671.25	3.63
Lower Wilcox	286	1.48	2,432.89	126.31	271	0.01	96.72	2.72

[a] ft^2/day = square feet per day
[b] ft/day = feet per day

Source: Mace and others (2002), Kelley and others (2004), TWDB Groundwater Database (2017a).

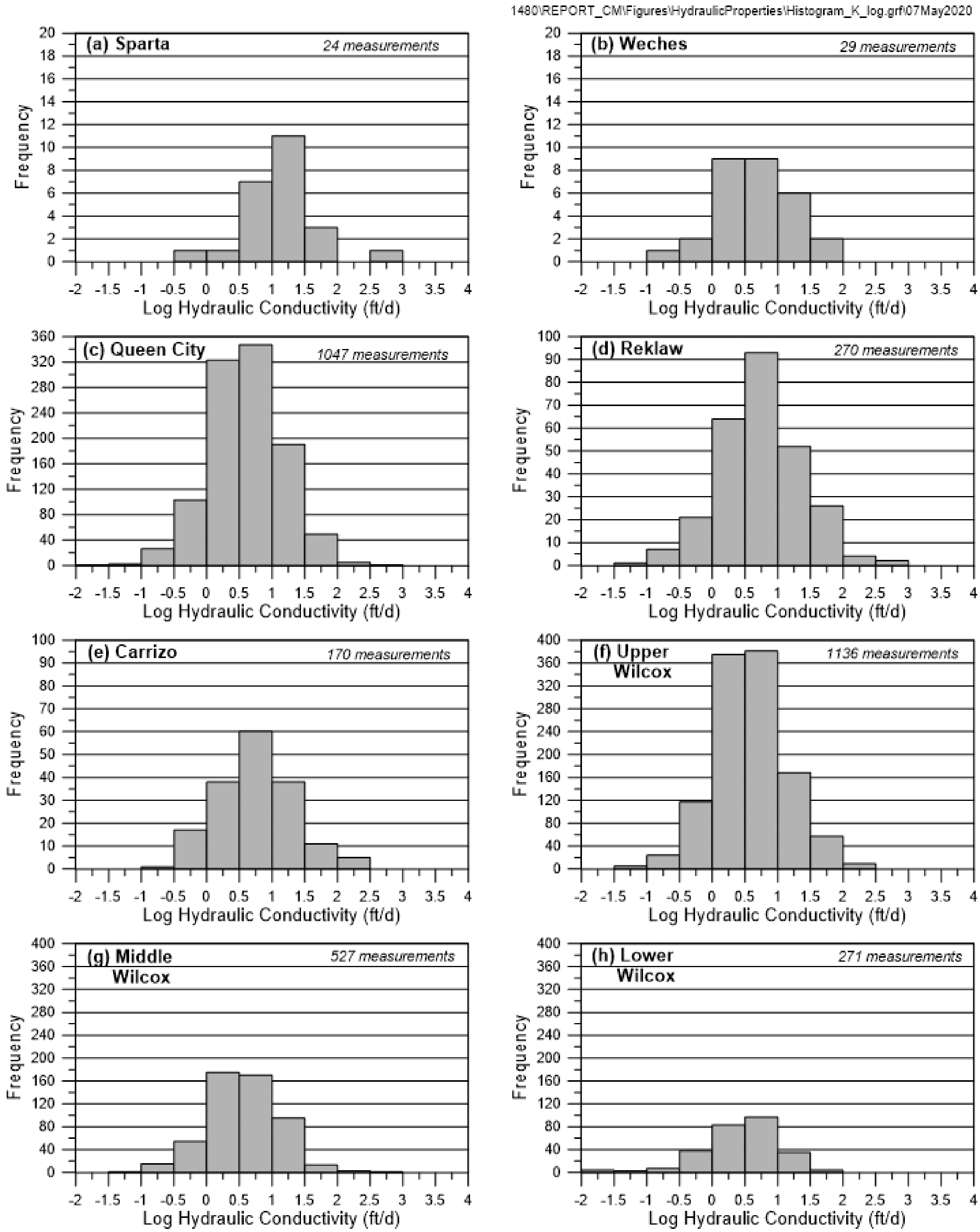


Figure 4-53. Histograms of Measured Hydraulic Conductivity for the Northern Queen City, Sparta, and Carrizo-Wilcox Aquifers

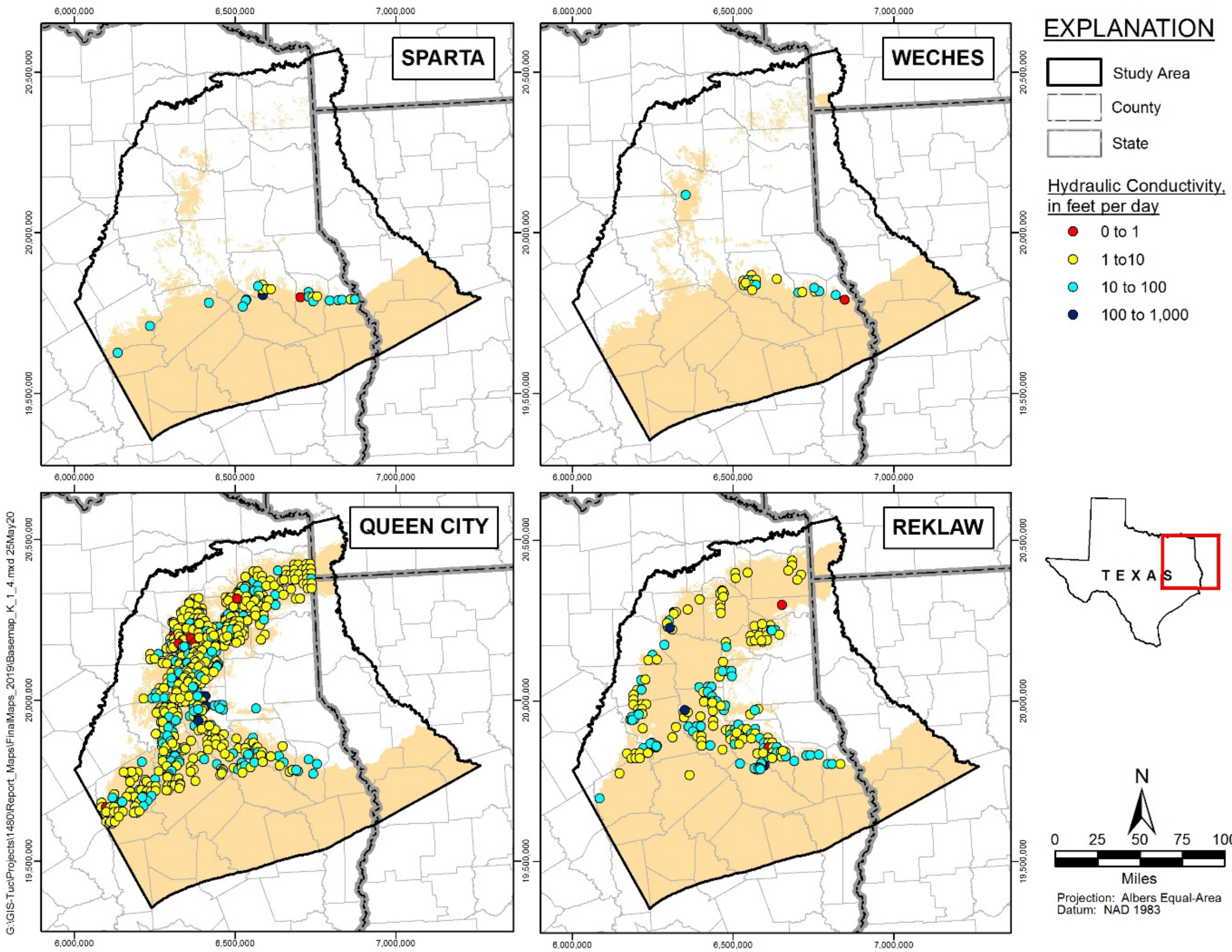


Figure 4-54. Hydraulic Conductivity for Upper Aquifer Units

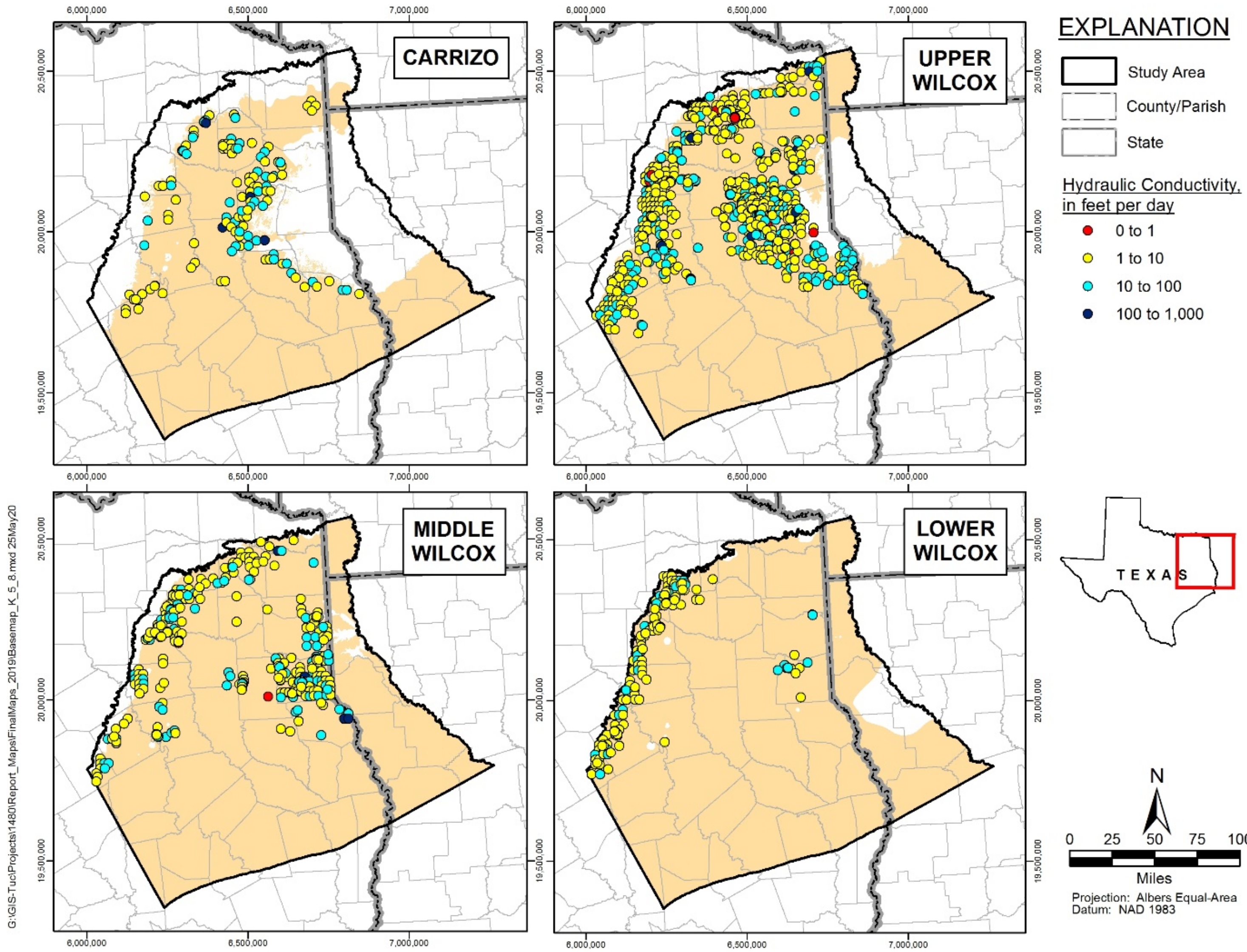


Figure 4-55. Hydraulic Conductivity for Lower Aquifer Units

River Alluvium

No measurements of hydraulic properties for river alluvium were available for the study area. Assuming a lithology of sandy gravel, the hydraulic conductivity of the river alluvium deposits range from approximately 10 ft/day to 1,000 ft/day (Freeze and Cherry, 1979). Hydraulic conductivity simulated for the Brazos River Alluvium Aquifer groundwater availability model by Ewing and others (2016) ranged from 1 ft/day to 1,000 ft/day, with a median of approximately 165 ft/day.

Sparta Sand

Based on a limited number of data (24 measurements), hydraulic conductivity values estimated from aquifer testing results are generally largest in the Sparta Sand compared to the other aquifer units (Table 4.5). Measured transmissivity values for the Sparta Sand range from 28 ft^2/day to 7,265 ft^2/day, with a geometric mean of 338 ft^2/day. Estimated hydraulic conductivity values range from 1 ft/day to 808 ft/day, with a geometric mean of approximately 14 ft/day. Most available hydraulic property measurements are from wells located near the outcrop edges (Figure 4-54).

Weches Formation

Measured transmissivity values for the confining Weches Formation range from 6 ft^2/day to 2,625 ft^2/day, with a geometric mean of 132 ft^2/day. Estimated hydraulic conductivity values for the Weches Formation range from 0.2 ft/day to 65 ft/day, with a geometric mean of 5 ft/day. The measured values are more concentrated towards the center of the study area in Nacogdoches County (Figure 4-54). Hydraulic conductivity values for the Weches Formation, on average, are much smaller than measured values for the Sparta Sand.

Queen City Sand

Measured transmissivity values for the Queen City Sand range from 1 ft^2/day to 11,180 ft^2/day, with a geometric mean of 278 ft^2/day. Estimated hydraulic conductivity values for the Queen City Sand range from 0.1 ft/day to 451 ft/day, with a geometric mean of 5 ft/day. The measurement values are distributed throughout the area, resulting in full coverage in the aquifer layer (Figure 4-54). The Queen City Sand yields similar average hydraulic conductivity to Sparta Sand, but has a much broader range of values, largely due to the significantly larger number of points (1,047 measurements) (Figure 4-53).

Reklaw Formation

Measured transmissivity values for the confining Reklaw Formation range from 3 ft^2/day to 19,310 ft^2/day, with a geometric mean of 260 ft^2/day. Estimated hydraulic conductivity values range from 0.05 ft/day to 385 ft/day, with a geometric mean of 5 ft/day. Measured values are primarily located at the outcrop edges of the Reklaw Formation but are also largely concentrated in Nacogdoches County (Figure 4-54). Hydraulic conductivity values in Reklaw Formation have a more log-normal distribution than other layers (Figure 4-53).

Carrizo Sand

Measured transmissivity values for the Carrizo Sand range from 7 ft^2/day to 11,860 ft^2/day, with a geometric mean of 230 ft^2/day. Estimated hydraulic conductivity values for the Carrizo Sand range from 0.3 ft/day to 198 ft/day, with a geometric mean of 6 ft/day. The measurements are located mostly around Rusk County and near the outcrops of the aquifer layer area (Figure 4-55). Like the Reklaw Formation, the Carrizo Sand has a more log-normal distribution of hydraulic conductivity than other units (Table 4.5).

Upper Wilcox

Measured transmissivity values for the Upper Wilcox within the study area range from 2 ft^2/day to 11,000 ft^2/day, with a geometric mean of 185 ft^2/day. Estimated hydraulic conductivity values for the Upper Wilcox range from 0.06 ft/day to 278 ft/day, with a geometric mean of 4 ft/day. The Upper Wilcox has the greater number of measurements (1,136 points) mostly focused at the outcrop areas (Figure 4-55).

Middle Wilcox

Measured transmissivity values for the Middle Wilcox within the study area range from 5 ft^2/day to 26,850 ft^2/day, with a geometric mean of 177 ft^2/day. Estimated hydraulic conductivity values for the Middle Wilcox range from 0.04 ft/day to 671 ft/day, with a geometric mean of 4 ft/day. Locations of measured data for the Middle Wilcox are close to the outcrop edge with less points inwards than Upper Wilcox (Figure 4-55).

Lower Wilcox

Measured transmissivity values for the Lower Wilcox within the study area range from 1 ft^2/day to 2,450 ft^2/day, with a geometric mean of 125 ft^2/day. Estimated hydraulic conductivity values for the Lower Wilcox range from 0.01 ft/day to 97 ft/day, with a geometric mean of 3 ft/day. Locations of measured data for the Lower Wilcox are limited to only the edges of the outcrops as compared to the more spread-out distribution of the Middle and Upper Wilcox (Figure 4-55).

Most available measurements for all aquifers are within logarithmic values near 0 and up to 1 which represents a more constrained distribution of hydraulic conductivity, with the exception for the Sparta Sand. There is still a degree of variation in hydraulic conductivity that suggests levels of heterogeneity within the layers. There was abundant data for most layers except for the Sparta Sand and Weches Formation.

Although numerous wells in the study area have measurements of hydraulic properties, there are large areas where data are not available which prevents a comprehensive understanding of hydraulic properties of the aquifer system as a whole. This is especially true for the deep, down-dip portions of the aquifer units.

The previous groundwater availability model by Kelley and others (2004) scaled initial hydraulic conductivities as a function of sand fraction and representative conductivities for clay and sand. Values were generally unchanged during calibration, except for the Reklaw and Carrizo aquifer layers. Vertical conductivity throughout the Reklaw Formation was decreased to better represent a confining unit. Horizontal conductivity in the Carrizo aquifer layer for areas running through Upshur, Smith, and Cherokee counties and a small area in Angelina County were decreased to maintain measured drawdown and to reduce water level rebound in the Carrizo layer, respectively.

Calibrated hydraulic conductivity distributions from the previous groundwater availability model by Kelley and others (2004) were evaluated for this study. Hydraulic conductivities for the Sparta Sand ranged from about 0.00012 to 5.5 ft/day, with an average of 1.6 ft/day. Specified hydraulic conductivities in the Queen City Sand unit are similar to the Sparta Sand, with a range from about 0.0001 to 20 ft/day, with an average of 1.6 ft/day. The Carrizo Sand was specified with the largest hydraulic conductivities, ranging from about 0.2 to 60 ft/day, with an average of about 12 ft/day. The Upper and Middle Wilcox both have minimum specified hydraulic conductivities of 1 ft/day, but with maximums of 7 and 10 ft/day, respectively, along with averages of about 2 ft/day for both units. The Lower Wilcox unit has the second highest specified hydraulic conductivities in the model area, ranging from 2 ft/day to 30 ft/day, with an average of 2.2 ft/day. The confining layers of Weches and Reklaw both were specified with a hydraulic conductivity of 1 ft/day.

Hydraulic conductivity and storativity for the Wilcox aquifer in Panola County were estimated by Lupton and others (2015) for the Panola County Groundwater Conservation District. Results of 30 aquifer tests were evaluated for that study. Hydraulic conductivity estimates ranged from 1 to 12 ft/day.

Data for vertical hydraulic conductivity within the northern portions of the Queen City, Sparta, and Carrizo-Wilcox aquifer system are not available for this study. Groundwater models are often used to estimate vertical hydraulic conductivity at a regional scale. A typical ratio of horizontal to vertical hydraulic conductivity (vertical anisotropy) ranges from 1 to 1,000 for model applications. The previous groundwater availability model estimated vertical hydraulic conductivity based on sand and clay fractions. In that model, a vertical hydraulic conductivity value of $1x10^{-4}$ ft/day was specified for confining units, which is equivalent to the approximate conductivity for a clay material. This value was selected based on the expectation that vertical hydraulic conductivity is controlled by depositional environmental and lithofacies (Kelley and others, 2004). Model input datasets for the previous groundwater availability model for the northern portions of the Queen City and Sparta aquifers indicate horizontal isotropic hydraulic conductivity properties, which means horizontal conductivity is equal in all directions.

4.5.2 STORAGE PROPERTIES

No measurements of aquifer storage properties are available for the northern portions of the Queen City, Sparta, and Carrizo-Wilcox aquifer system. Fryar and others (2003) and Kelley and others (2004) specified values for specific yield and specific storage that allowed the model to reproduce measured changes in groundwater levels throughout the study area. Specific yield values for the Sparta, Queen City, Carrizo, and Wilcox aquifer layers were specified with a specific yield value of 0.15. A specific yield value of 0.10 is specified for the Weches and Reklaw confining layers. Typical specific yields for sedimentary materials range from 0.1 to 0.3 (Freeze and Cherry, 1979).

Storativity values from the previous groundwater availability model by Kelley and others (2004) were unchanged during calibration. For the Weches, Queen City, Reklaw, and Carrizo aquifer layers, storativity was estimated for the model by calculating specific storage as a function of sand fraction, specific storage of sand and clay, and depth and then multiplying by layer thickness. Average storativity values specified for these layers are 0.0012, 0.00025, 0.00073, 0.00064, and 0.00049 (dimensionless), respectively. Average specified specific storage values for these layers are $3.0x10^{-6}$, $4.5x10^{-6}$, $4.0x10^{-6}$, $5.5x10^{-6}$, and $3.6x10^{-6}$ 1/ft, respectively. Storativity values specified for the three Wilcox layers in a previous groundwater availability model by Fryar and others (2003) were also specified in the groundwater availability model by Kelley and others (2004). Storativity for the Wilcox layers is not explicitly reported by Kelley and others (2004); however, specific storage is reported to be $4.5x10^{-6}$ 1/ft at all these layers. Median storativity of the Wilcox aquifer was estimated to be 0.0003 (dimensionless) by Lupton and others (2015).

4.5.3 NET SAND THICKNESS

The aquifer units in the study area comprise thick, laterally continuous permeable fluvio-deltaic sands. Groundwater movement predominantly occurs within the sand intervals. Net sand fraction information could be used to scale aquifer hydraulic properties during model calibration. The model calibration report will summarize the use, if any, of this information in the model.

Net sand distributions for aquifer units within the study area were determined by previous studies. Net sand distributions were obtained from geospatial datasets for previous groundwater availability models developed by Kelley and others (2004) for the Sparta and Queen City aquifers and by Fryar and others (2003) for the Wilcox aquifer. The Carrizo unit contains dominantly sand (Fryar and others, 2003).

Net sand distributions for the northern portions of the Sparta, Queen City, and Wilcox aquifers are shown on Figure 4-56, Figure 4-57, and Figure 4-58. Net sand thicknesses in the Sparta and Queen City aquifers (Figure 4-56 and Figure 4-57) generally decrease to the south in the direction of the formation dip as sand intervals are progressively replaced by mud (Kelley and others, 2004). Contours of net sand thickness in the Carrizo aquifer are available for only a small outcrop area in the western portion of the study area and, thus, are not shown on a figure in this report. Based on the limited dataset, net sand thicknesses in the Carrizo Aquifer range from 50 feet to 200 feet, with thicknesses generally increasing downdip. The Wilcox Group consists of 50 percent sand on average; however, the sand bodies are embedded in fine-grained matrix and might have poor interconnection (Fryar and others, 2003). Contours of percent sand for the Wilcox Group is shown on Figure 4-58. Percent sand is much more variable in the north than the south and east in the study area. Similar to the Sparta and Queen City aquifers, net sand generally decreases to the south in the deep, down-dip portions of the aquifer.

The net sand distributions prepared for the previous groundwater availability models could be used to determine effective hydraulic properties values for model cells thus constraining model heterogeneities according to the sand fraction distributions. For the current model, the net sand fraction for areas with no available information from previous studies is assumed to be equal to the average value of available data for the respective aquifer layer. A net sand fraction value of 0.5 is assumed for portions of aquifer units where net sand fractions were not available.

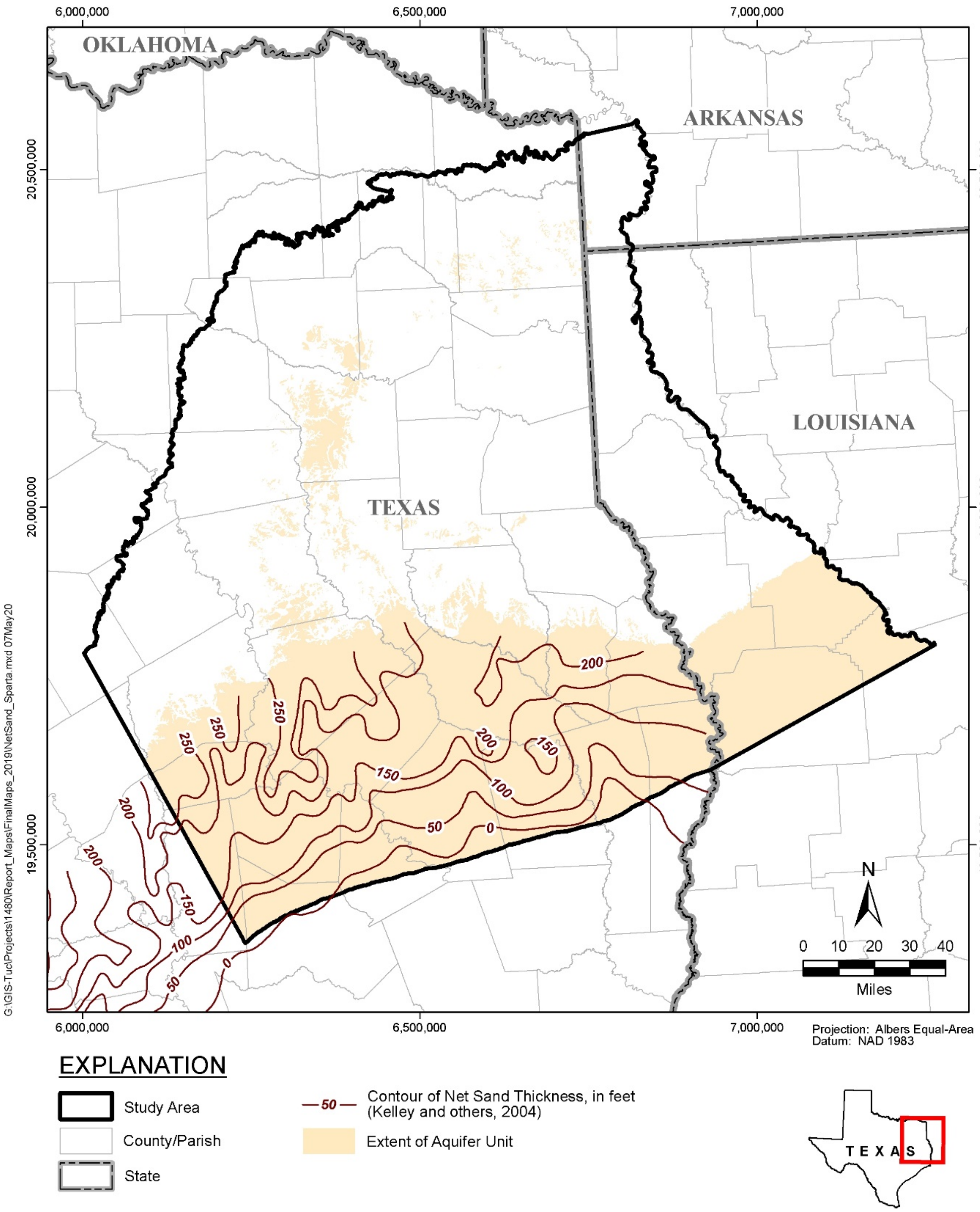


Figure 4-56. Net Sand Thickness Contours for Sparta Aquifer

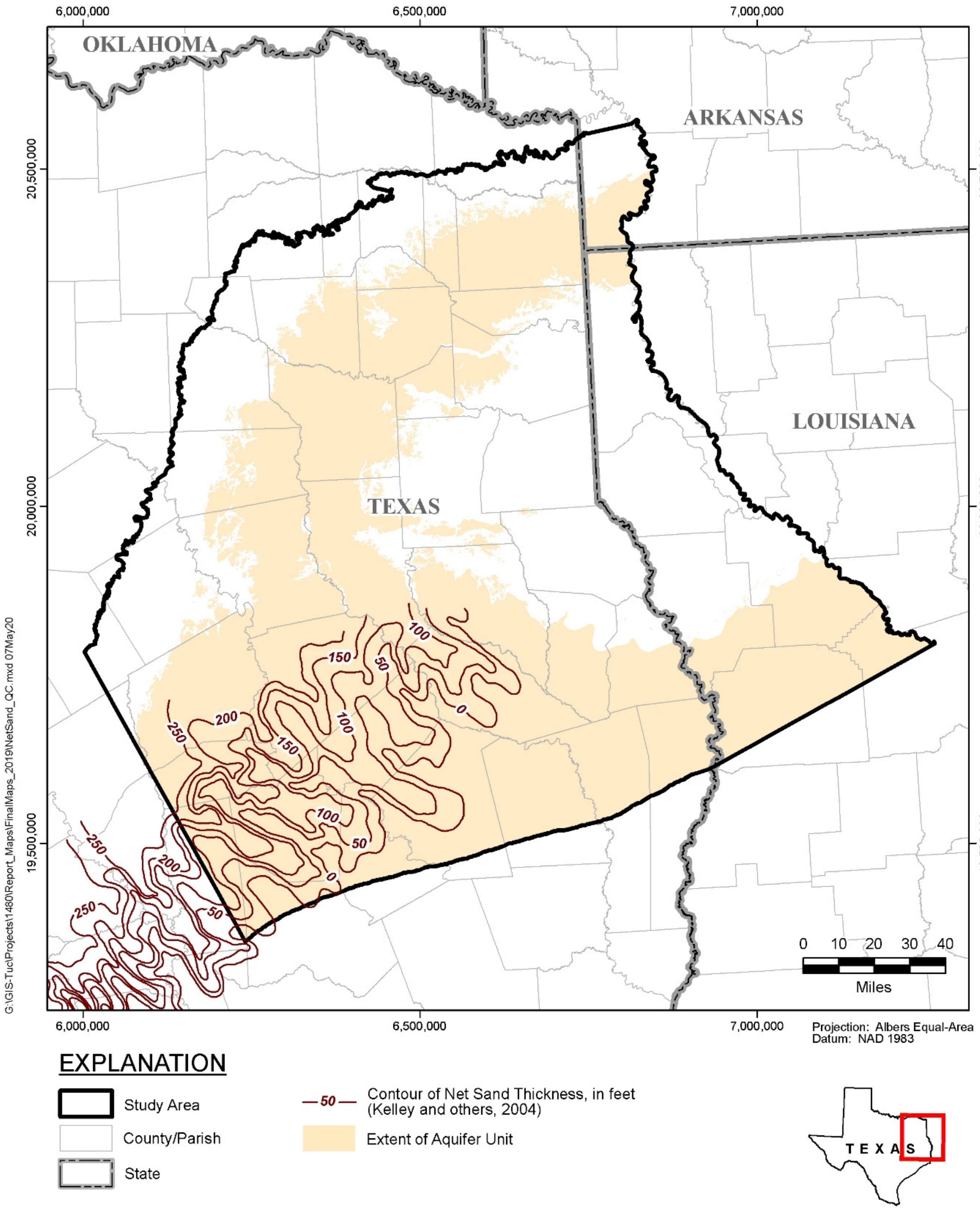


Figure 4-57. Net Sand Thickness Contours for Queen City Aquifer

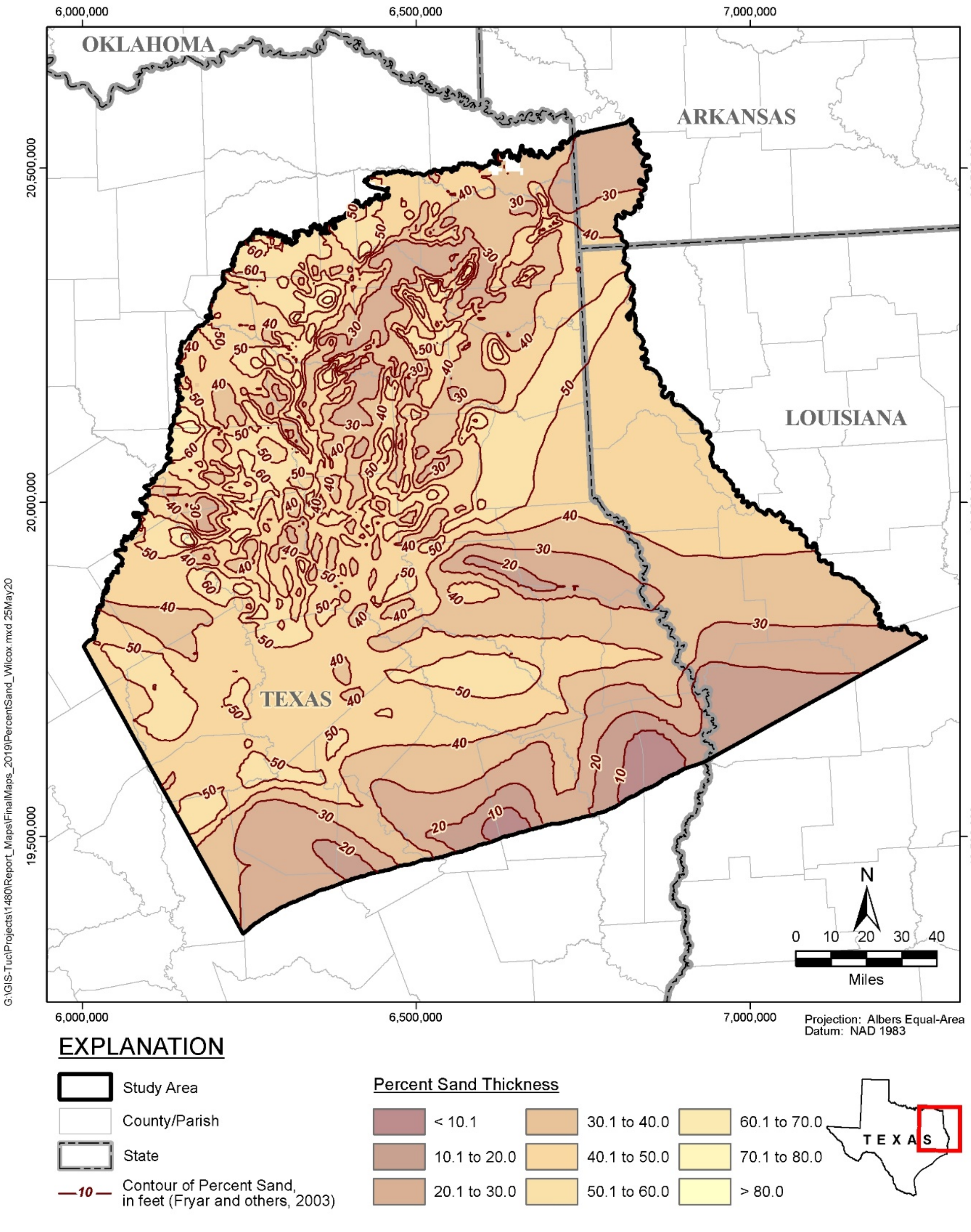


Figure 4-58. Percent Sand Contours for Wilcox Aquifer

4.6 POTENTIAL FOR SUBSIDENCE

Subsidence is the gradual lowering of land surface elevation and typically occurs when large amounts of groundwater have been extracted from unconsolidated aquifers where compressible intervals exist. The northern portion of the Queen City, Sparta, and Carrizo-Wilcox aquifer system comprises hydrostratigraphic units containing interbedded, water-bearing sand and clay intervals. Land subsidence occurs when groundwater pumping results in substantial depressurization of the aquifer, thus causing compaction of clays. The compaction of aquifer layers could propagate to the surface causing land surface subsidence. Concerns with respect to land subsidence principally relates to potential damage to infrastructure, such as roadways, pipelines, and canals.

Land subsidence due to excessive groundwater pumping has not been documented in the northeast Texas study area. A Subsidence District is not present in the study area. Land subsidence will be evaluated during the numerical modeling process if model results indicate large groundwater level drawdown will occur from increased pumping in the region.

A study on variability of Texas aquifers to pumping-induced subsidence was recently conducted by Furnans and others (2017) for the TWDB. That study estimated the risk for subsidence for major and minor aquifers throughout Texas, including the Sparta, Queen City, and Carrizo-Wilcox aquifers. Subsidence risk was evaluated by developing a risk matrix that incorporated three factors: (1) distribution, thickness, and compressibility of clay layers, (2) amount and timing of water level changes, and (3) lowest historical water level. Subsidence risk value was assigned to individual wells with data. Subsidence risks at well locations throughout the Sparta Aquifer, the Queen City Aquifer, and the Carrizo-Wilcox Aquifer are shown on Figure 4-59, Figure 4-60, and Figure 4-61, respectively. Results of the Furnans and others (2017) study suggest that the northern portion of the Carrizo-Wilcox Aquifer has a medium to high risk for future subsidence due to pumping and the northern portion of the Queen City and Sparta aquifers have a medium risk.

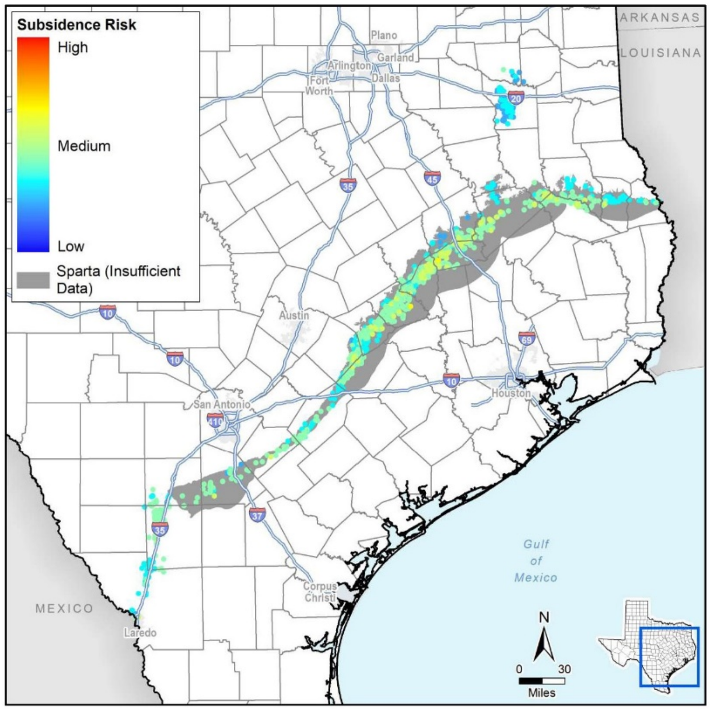


Figure 4-59. Sparta Aquifer subsidence risk vulnerability at well locations, extracted from Figure 4.163 by Furnans and others (2017).

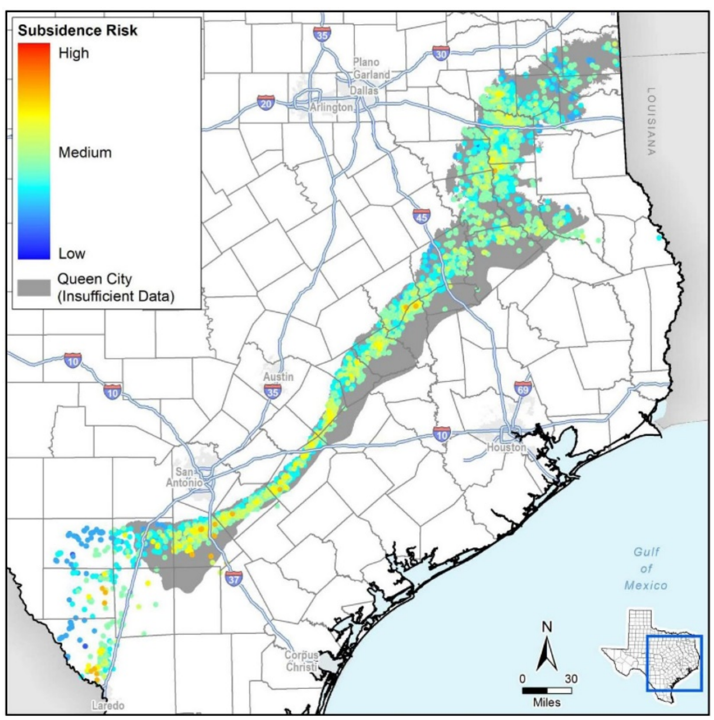


Figure 4-60. Queen City Aquifer subsidence risk vulnerability at well locations, extracted from Figure 4.122 by Furnans and others (2017)

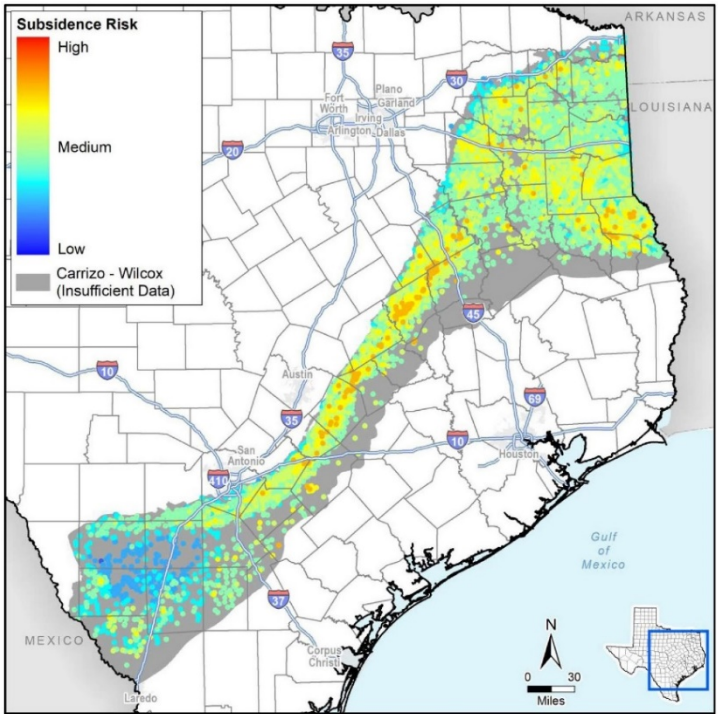


Figure 4-61. Carrizo-Wilcox Aquifer subsidence risk vulnerability at well locations, extracted from Figure 4.7 by Furnans and others (2017).

4.7 AQUIFER DISCHARGE

Aquifer discharge refers to the groundwater exiting a groundwater system. Groundwater discharge mechanisms in the northern portion of the Queen City, Sparta, and Carrizo-Wilcox aquifers include groundwater pumping withdrawals, discharges to surface water features, evapotranspiration, and groundwater movement into adjacent aquifer units. Under predevelopment conditions, recharge to the aquifer is balanced by the same amount of discharge from the aquifer. Kelley and others (2004) estimate that groundwater evapotranspiration consumes 50 percent of recharge in the study area and groundwater discharge to streams consumes 48 percent of recharge; these discharges are components of rejected recharge. The following sections describe the components of groundwater discharge that occur in the study area.

4.7.1 GROUNDWATER WITHDRAWALS BY PUMPING

Groundwater pumping data were compiled for this study from multiple data sources. Pumping estimates for Texas counties were obtained from TWDB and pumping estimates for parishes in Louisiana and counties in Arkansas were obtained from the United States Geological Survey National Water Information System. In addition, pumping records were obtained from GCDs and the Railroad Commission of Texas to help refine the TWDB pumping estimates. Data obtained from each data source are summarized herein. These data will be processed and distributed to individual well locations for the groundwater flow model. Implementation of groundwater pumping in the groundwater model will be discussed in the model calibration report.

Groundwater pumping estimates from annual TWDB water use surveys were obtained for the years 1980 through 2016 for counties in Texas within the study area (TWDB, 2017e, f) with the exception of the time period of 1981 through 1983 where data was not available. For counties that are located partially outside the study area, annual pumping estimates for the entire county are reported. The water use surveys collect pumping estimates for six water use sectors: municipal, irrigation, manufacturing, steam-electric generation, livestock, and mining. Domestic pumping estimates are not included in the TWDB water use surveys. Data attributes of the annual TWDB datasets allow pumping estimates to be evaluated by aquifer source, county, and water use sector for this study.

TWDB water use estimates indicate that total annual groundwater pumping from the Queen City, Sparta, and Carrizo-Wilcox aquifers has remained relatively stable in the study area since 1980 (Figure 4-62). Total annual groundwater withdrawals are generally larger than 140,000 AF, ranging from approximately 138,000 AF in 1980 to approximately 173,000 AF in 1996. The peak in 1996 coincided with abnormally large estimates for irrigation water use that occurred from 1994 through 1999. Pumping is estimated to be approximately 143,000 AF in 2016 and has followed a gradual declining trend since 2011.

The Carrizo-Wilcox Aquifer has been the principal source of groundwater supply in the study area over the period of record for pumping estimates (Figure 4-62). The Sparta and Queen City aquifers are relatively minor sources of total groundwater supply in the study area; however, they are important sources of groundwater in areas.

Estimated annual pumping by water use sector from 1980 to 2016 for the study area within Texas is shown on Figure 4-63. Annual pumping is summarized by water use and aquifer source in Table 4.6. Groundwater withdrawals during this time period occurred predominantly for municipal uses and, to a lesser degree, manufacturing, mining, and livestock uses. According to TWDB water use surveys, groundwater withdrawals for municipal water use have generally increased through time from approximately 85,000 AF in 1980 to approximately 120,000 AF in 2011. Pumping for municipal use has increased from about 62 percent of total annual pumping in 1980 to approximately 75 percent in 2016, peaking at 80 percent in 2005. Withdrawals for manufacturing decreased from 18 percent of total withdrawals in 1980 to 3 percent in 2016, with a peak at 21 percent in 1989. Mining withdrawals have been relatively stable at an average of 6 percent of total withdrawals. It is likely that mining groundwater withdrawals are underestimated in the TWDB water use surveys, based on additional data compiled from the United States Geological Survey, Rusk County GCD, and the Railroad Commission of Texas, as described in the following sections of this report. Livestock withdrawals have accounted for an average of 9 percent of total withdrawals in the study area since 1980, according to the TWDB water use surveys.

Annual pumping is summarized by county and water use in Table 4.7. Based on the TWDB water use surveys, the majority of groundwater pumping from the Queen City, Sparta, and

Carrizo-Wilcox aquifers has occurred in Angelina County and Smith County since 1980. Groundwater use in Angelina County has been predominantly for municipal and manufacturing purposes. Pumping for manufacturing purposes in Angelina County began to gradually decrease in the 1990s and eventually stopped in 2008.

Groundwater withdrawal estimates were obtained from United States Geological Survey five-year water use reports (USGS, 2011a, b, c, 2014) for counties and parishes in Arkansas and Louisiana for the years 1960 through 2015 and are summarized on Figure 4-64. The United States Geological Survey reports summarize groundwater pumping by water use sectors, including domestic, livestock, industrial, municipal, and irrigation. Based on the water use reports, the majority of pumping in the Louisiana study area has been for municipal use. The only Arkansas county fully included in the study area, Miller County, has pumped groundwater primarily for irrigation use. The annual groundwater pumping estimates for each county or parish included within the study area are summarized in Table 4.8 and Table 4.9. Aquifer sources were not reported in the available data. It is assumed the United States Geological Survey pumping estimates include withdrawals from all aquifer sources in addition to the Queen City, Sparta, or Carrizo-Wilcox aquifers within each county or parish. Furthermore, it is assumed that groundwater withdrawal estimates for Texas counties within the study area were also compiled from the five-year water use reports, and thus, were compared to the water use estimates obtained from TWDB (Figure 4-65) for this study. For this comparison, TWDB pumping estimates for all reported aquifer sources, in addition to the Queen City, Sparta, and Carrizo-Wilcox aquifers in the study area, are included in the total pumping estimates. This is necessary because the United States Geological Survey dataset does not report aquifer source in their county estimates. Furthermore, TWDB manufacturing, mining, and steam electric power sectors were grouped into an “industrial” category for comparison with the United States Geological Survey estimates of industrial pumping. Total pumping volumes shown on Figure 4-65 are larger than those shown on Figure 4-62 and Figure 4-63 in part because the data includes pumping estimates for all aquifers in the study area. Based on TWDB data, substantial pumping occurs from the Gulf Coast and Brazos River Alluvium aquifers for industrial and irrigation uses, respectively, in southern counties of the study area.

In general, the United States Geological Survey data compare reasonably well with the TWDB data. However, the United States Geological Survey water use estimates for municipal/public supply are consistently smaller than the TWDB estimates; and the TWDB estimates for industrial supplies are consistently smaller than United States Geological Survey estimates. Groundwater pumping varies from year to year and has generally increased since the early 1990s. Pumping has gradually decreased since 2011, which has the highest estimated pumping volume in the observed time period.

Average annual pumping volumes vary between counties and parishes and by aquifer in the study area (Figure 4-66). Average pumping values for Texas counties are based on the TWDB water use surveys which include aquifer source information. Average pumping values for Arkansas counties and Louisiana parishes are based on the United States Geological Survey water use reports, which do not include aquifer source information. For Texas counties, average pumping volumes from Queen City, Sparta, and Carrizo-Wilcox aquifers are represented as a percentage of the total average pumping for a particular county. The largest amount of groundwater pumping from the aquifers of interest in the Texas portion of the study area has occurred in Angelina and Smith counties. Very small amounts of pumping have occurred in Rains, Marion, San Augustine, and Sabine counties. Pumping in the counties in the southern portion of the study area is sourced from the Gulf Coast Aquifer which is not an aquifer of interest for this study. A large majority of groundwater pumping in the Louisiana study area has occurred in Rapides Parish, but only a small portion of the parish is located within the study area and all pumping has likely been from aquifer sources other than the Queen City, Sparta, and Carrizo-Wilcox aquifers (USGS, 2011a). Similarly, the Queen City, Sparta, Carrizo-Wilcox aquifer system does not appear to be a significant groundwater resource for Vernon Parish and Grant Parish although moderate amounts of pumping have occurred in the area over the study time period. The adjacent Texas counties along the southern boundary also indicate a majority of pumping from other aquifer sources, based on the TWDB data. The Carrizo-Wilcox units are much deeper in this southeast portion of the study area. In other portions of the Louisiana study area, the Carrizo-Wilcox Aquifer is the primary source of groundwater withdrawals for parishes such as Caddo, Bossier, and De Soto (USGS, 2011b, 2011c, 2014). For input to the groundwater model, total pumping in Louisiana and Arkansas will be proportioned to the aquifers of interest based on aquifer source proportions recorded in Texas counties.

Domestic pumping estimates were reported in the United States Geological Survey five-year water use reports; however, they are not included in TWDB water use survey estimates. The United States Geological Survey estimates for domestic pumping were used to estimate annual domestic pumping for each county using well records obtained from the TWDB Groundwater Database. For example, an average production volume of 2.9 AF per well in Wood County in 1990 was calculated by dividing the United States Geological Survey reported domestic pumping volume of 146 AF for that county by 50, the number of domestic wells reported in the TWDB Groundwater Database to be located in that county as of the year 1990. The average production volume was then multiplied by the number of domestic wells listed in the individual years prior to each five-year report to generate an annual pumping estimate for each year. The TWDB Groundwater Database likely underestimates the total number of domestic wells for a given year; however, the data does provide a means for spatially distributing the pumping using reported well locations. The discrepancy in the number of wells is likely accounted for in the generated annual domestic estimates based on notably high average yield per well calculations using the United States Geological Survey reported volumes.

Data requests were submitted to all GCDs in the study area for current and historical groundwater production information. Districts provided well information and pumping data for 2001 through 2017. All groundwater production data obtained from the districts were compiled together and summarized by water use sector in Table 4.10**.** Data provided by each GCD contain more detail than TWDB records with regards to pumping at individual well locations and for specific water uses.

Additional pumping data were acquired from the Railroad Commission of Texas, which monitors groundwater production by mines. Annual groundwater production by mines in the study area is summarized in Table 4.11. The Railroad Commission of Texas data provide annual pumping volumes for Texas lignite mine dewatering purposes from individual mining entities and permits spanning the years 2008 through 2016. As indicated in the table, some entities include pumping volumes for a property that comprises multiple counties. The reported pumping volumes indicate a significant underestimation of pumping for mining use by TWDB water use surveys, particularly for Rusk County in years 2001 through 2014, Freestone County in years 2008 through 2016, and Robertson County in years 2011 through 2014. Pumping records obtained from Groundwater Conservation Districts and the Railroad Commission of Texas were incorporated into the pumping dataset for input into the groundwater model.

Locations of groundwater production wells in the study area were obtained from the TWDB groundwater database (TWDB, 2017a) and the Louisiana Department of Natural Resources' geospatial dataset (Louisiana DNR, 2018). In addition to well locations, these datasets include information for well construction and well use. The well uses were categorized into the following groups: municipal, irrigation, industrial, domestic, and stock. For example, domestic wells were determined by selecting records for wells with well use designated as "domestic". The industrial category includes multiple sub-uses, including mining, manufacturing, industrial, and others. Locations of reported groundwater production wells located in the study area are shown on Figure 4-67. The majority of municipal wells are located in the northern portions of the study area, and in clusters near cities such as Nacogdoches and Lufkin. Irrigation wells and numerous domestic wells are scattered throughout the study area. However, well information shown on Figure4-67 are not verified and some of the wells may not actually exist. The coverage of reported wells is much denser in Louisiana than in Texas. Presumably, this is a result of how the data are managed and do not actually represent active pumping wells, although only records listed with "active" status are shown on Figure 4-67.

These source data were merged into a single dataset and distributed to individual well locations for input to the numerical groundwater model. Annual pumping for each county was summarized by water use and distributed to wells located within the respective county based on the well's reported water use. For example, countywide total municipal pumping was distributed evenly among all reported municipal wells in the county. Well and pumping information provided by the Groundwater Conservation Districts and Railroad Commission were considered priority and replaced TWDB well locations and water use estimates where overlap of the datasets occurred. District pumping data and well locations were used instead of TWDB information for all water uses other than mining and domestic.

Pumping estimates were adjusted during calibration of the numerical model to address inconsistencies between the conceptual pumping dataset and groundwater level measurements. Model simulations using the conceptual pumping dataset, which was principally based on TWDB pumping estimates, could not match trends in groundwater level measurements. To improve model calibration, the pumping data compiled for this conceptual report were replaced with the pumping data from the previous groundwater availability model for 1980 through 2005, and scaling factors were applied to the conceptual dataset from 2006 through the remaining simulation period. The final total simulated pumping from the calibrated numerical model is shown on Figure 4-68, and pumping hydrographs for each county are included in Appendix A. The adjustments to pumping made during model calibration are described in the model calibration report.

Table 4.6. Annual Estimated Groundwater Pumping by Water Use Sector and Aquifer Source for Texas Counties in Study Area

Aquifer Source	1980	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
Municipal																																
Carrizo-Wilcox	77,412	83,124	84,737	82,464	85,161	94,767	86,465	81,826	79,157	83,248	85,992	88,310	92,596	93,403	93,636	100,371	98,126	105,100	105,637	104,840	112,847	110,632	100,717	105,244	96,176	99,244	108,679	109,653	103,028	98,454	98,379	96,447
Queen City	6,098	4,871	4,709	4,507	4,241	3,839	4,114	5,380	5,269	5,495	5,753	5,450	5,645	6,362	5,954	6,241	6,030	2,576	2,635	2,588	2,789	4,510	3,667	4,179	5,024	6,466	6,434	6,175	5,396	4,668	3,775	3,464
Sparta	2,487	2,759	2,616	2,833	2,089	1,887	2,240	2,333	2,309	2,091	2,170	2,214	1,983	2,608	2,161	2,320	2,183	1,902	1,779	1,886	2,057	3,123	2,967	3,064	3,820	4,762	6,519	5,978	5,645	5,424	4,808	4,463
Manufacturing																																
Carrizo-Wilcox	24,197	22,649	22,143	21,356	21,255	18,998	32,847	23,431	21,802	14,291	14,149	14,207	14,619	13,915	13,111	12,574	12,474	15,573	16,459	8,072	7,223	8,299	7,649	7,160	11,407	1,864	2,292	2,193	2,657	2,045	1,764	2,701
Queen City	52	65	56	53	0	0	0	0	0	0	1	0	0	1	3	3	3	0	0	0	0	0	0	0	0	36	58	59	70	1,026	1,094	926
Sparta	0	40	72	73	70	69	70	70	69	69	74	74	148	181	156	136	217	185	188	191	204	216	197	192	212	0	0	0	0	0	0	0
Mining																																
Carrizo-Wilcox	6,410	10,306	10,039	14,411	9,434	9,470	8,306	7,060	9,288	10,230	10,194	10,235	10,720	11,698	11,290	9,473	10,081	8,527	8,700	8,661	8,741	8,906	8,640	8,112	7,843	8,849	1,500	2,604	2,108	2,255	6,975	6,603
Queen City	4,902	4,288	3,957	3,201	2,720	2,488	2,462	3,579	3,213	2,860	2,897	2,988	776	778	706	488	488	0	0	0	0	0	0	0	0	0	0	0	0	0	0	74
Sparta	112	32	33	32	29	30	27	27	38	38	37	37	37	37	37	37	37	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Electric Power																																
Carrizo-Wilcox	499	891	1,156	1,519	1,517	1,418	1,862	4,640	4,281	4,365	4,738	4,609	4,446	5,179	5,164	4,830	4,941	1,137	1,519	1,303	1,207	1,546	1,582	1,513	1,679	1,658	7,160	4,855	5,534	6,032	6,199	5,889
Queen City	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Sparta	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Irrigation																																
Carrizo-Wilcox	1,850	2,490	2,802	2,393	2,005	2,647	1,992	2,393	2,427	2,120	2,412	17,138	15,972	20,384	13,493	19,763	17,471	2,353	1,901	2,951	3,776	4,221	4,051	3,612	4,762	9,105	8,613	7,548	9,747	9,345	5,788	7,512
Queen City	236	507	425	412	570	438	151	131	122	122	206	128	116	139	139	139	139	452	278	546	761	851	1,025	607	947	1,055	1,173	1,251	2,050	1,848	1,162	1,268
Sparta	186	198	160	144	144	144	12	11	11	11	45	84	73	96	96	96	96	595	292	384	555	601	590	492	529	587	790	680	902	645	418	578
Livestock																																
Carrizo-Wilcox	8,660	10,655	9,485	9,213	9,267	9,351	9,257	11,017	11,047	11,551	11,488	12,144	12,010	12,271	11,474	10,862	11,350	7,671	7,882	8,625	6,249	6,378	5,530	5,895	5,743	11,703	11,661	10,998	11,215	11,121	11,280	11,494
Queen City	3,676	3,811	3,542	3,528	3,468	3,645	3,587	3,944	3,979	4,480	4,486	4,364	4,335	4,587	4,001	3,859	4,057	2,554	2,612	1,641	992	1,027	1,012	879	985	1,406	1,408	1,176	1,262	1,311	1,233	1,261
Sparta	1,225	1,330	1,307	1,138	1,217	1,269	1,184	1,246	1,266	1,386	1,365	1,256	1,246	1,384	1,166	1,167	1,215	856	855	595	238	216	205	216	219	359	363	295	297	303	303	311

Units in acre-feet

Source: Texas Water Development Board water use surveys (TWDB, 2016). Surveys do not include pumping for domestic supplies.

Table 4.7. Annual Estimated Groundwater Pumping from the Queen City, Sparta, and Carrizo-Wilcox Aquifers by Water Use Sector for Texas Counties in Study Area

COUNTY	1980	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
Municipal																																		
Anderson	3,347	4,356	4,891	5,205	5,442	4,938	5,044	5,511	5,055	5,776	5,977	6,494	6,993	8,498	8,188	8,743	8,252	9,485	8,836	8,883	9,196	8,990	9,299	9,537	8,414	8,796	9,012	9,176	9,748	9,718	9,527	8,728	8,463	8,419
Angelina	8,544	8,417	8,596	8,227	7,883	7,764	8,293	8,622	8,487	9,197	8,966	9,157	9,194	10,313	10,823	12,332	12,402	13,118	12,442	12,003	11,801	11,848	12,992	12,467	11,714	11,848	11,451	10,954	12,024	10,780	10,338	10,658	10,982	10,709
Bowie	1,653	1,492	1,586	1,584	1,234	1,488	1,636	1,340	1,394	1,286	1,351	1,194	945	760	725	682	592	977	1,103	1,119	1,075	1,054	1,126	991	838	910	951	1,008	1,084	996	817	728	667	418
Camp	1,495	1,747	1,762	1,683	1,773	1,802	1,743	1,750	1,846	1,422	1,525	1,623	1,412	1,396	1,567	1,561	1,410	1,437	1,360	1,345	1,361	1,447	1,536	1,579	1,443	1,508	1,656	1,802	1,784	1,677	1,657	1,639	1,260	1,290
Cass	3,441	3,741	3,753	3,643	3,624	3,572	3,535	3,493	3,220	2,695	2,561	2,515	2,675	2,538	2,579	2,514	2,368	1,328	1,234	1,206	1,278	1,304	1,411	1,284	1,162	1,535	1,327	1,683	1,396	1,364	1,328	1,249	1,316	1,194
Cherokee	5,284	4,843	5,075	5,147	5,525	5,702	5,657	5,215	4,635	5,554	5,460	5,792	5,843	5,668	5,990	6,652	6,391	6,659	6,550	6,251	6,322	7,033	6,917	7,112	6,600	6,630	6,875	7,307	7,818	6,979	7,122	6,678	6,767	7,149
Franklin	305	265	302	318	331	450	456	383	282	275	162	310	125	178	92	122	289	198	176	64	70	41	51	52	42	45	34	22	22	18	16	22	27	29
Freestone	1,755	1,893	1,885	1,781	1,771	2,154	1,784	1,916	1,749	1,909	1,952	2,132	2,212	2,382	2,264	2,657	2,481	2,986	2,769	2,780	2,917	2,789	2,851	2,929	2,651	3,035	3,016	2,735	2,545	2,086	2,042	1,800	1,875	1,704
Gregg	1,030	958	909	837	540	645	560	612	724	922	902	911	1,101	1,129	1,084	986	1,105	1,220	1,189	1,202	1,274	1,299	3,600	3,276	1,677	1,820	1,957	3,288	2,584	1,924	1,734	1,590	1,346	1,094
Grimes	2	2	2	2	2	3	5	4	4	6	6	6	6	6	6	6	6	5	5	4	4	3	4											
Harrison	2,743	2,952	2,892	2,970	3,072	3,097	2,692	2,801	2,855	2,852	2,792	2,931	2,933	2,789	2,728	2,881	2,703	3,957	3,760	4,003	3,871	3,801	4,117	4,370	3,572	3,710	3,586	3,823	4,214	4,034	3,225	2,868	3,132	2,879
Henderson	2,926	3,849	3,872	3,602	3,845	4,028	3,882	3,569	3,456	3,470	3,964	3,990	4,081	4,117	4,058	4,439	4,435	5,345	5,217	5,193	4,929	4,969	5,411	5,270	4,943	5,233	5,843	6,042	6,783	6,188	5,853	5,419	5,299	4,255
Hopkins	583	908	1,023	1,016	1,072	1,052	1,038	962	909	1,128	1,494	1,579	1,729	1,692	1,609	1,792	1,604	1,619	1,601	1,873	1,897	1,859	1,605	1,745	1,564	1,493	1,579	1,412	1,776	1,652	1,527	1,235	1,208	1,110
Houston	810	837	879	823	945	978	803	648	455	432	576	1,052	1,096	1,156	1,122	1,139	1,207	1,072	1,205	1,184	1,390	1,181	1,215	978	1,291	1,893	1,862	2,077	3,684	3,338	3,162	3,203	3,160	3,191
Leon	1,386	1,763	1,816	1,765	1,757	1,820	1,814	1,976	1,701	1,764	1,863	1,753	1,788	1,851	1,804	1,951	1,798	2,470	2,352	2,342	2,417	2,582	2,785	2,728	2,503	2,553	2,671	2,784	3,088	2,776	2,524	2,370	2,376	2,300
Limestone	550	419	454	498	1,583	1,744	1,571	1,393	1,176	1,469	1,486	1,411	1,452	1,500	1,471	1,725	1,607	2,210	2,179	2,009	2,060	2,058	2,327	2,468	2,472	2,443	2,482	808	2,274	2,359	2,283	2,043	2,039	1,769
Madison	1,697	2,138	2,068	2,316	1,596	1,672	1,899	1,905	1,938	1,688	1,731	1,801	1,606	2,582	1,911	2,051	1,925	2,073	1,842	1,912	1,794	1,906	2,083	2,053	2,095	2,073	2,469	2,670	3,325	2,979	3,202	3,177	3,117	2,824
Marion	879	823	850	783	749	775	801	761	780	678	804	777	756	741	751	839	639	795	807	776	761	771	859	847	723	745	645	400	562	474	403	369	398	403
Morris	1,249	984	1,010	861	784	859	852	805	811	772	788	730	752	740	826	849	652	662	653	644	602	591	646	654	574	611	675	725	716	652	626	476	378	
Nacogdoches	6,762	6,833	6,972	7,273	7,413	7,932	8,058	7,573	7,323	7,825	8,329	7,912	8,663	7,347	7,381	7,182	7,142	7,805	7,682	7,292	6,669	7,144	7,465	7,195	6,135	6,406	5,560	6,230	6,571	5,628	5,964	5,551	5,759	5,575
Navarro	7	9	11	10	11	12	11	11	11	10	0	0	0	0	0	0	0	0	0	0	0	0	0	13	11	12	34	56	56	48	48	40	21	12
Panola	2,233	2,316	2,495	2,188	2,229	2,290	2,203	2,212	2,184	2,381	2,324	2,322	2,395	2,306	2,268	2,186	2,219	2,743	2,808	2,564	2,588	2,589	2,546	3,148	2,689	2,444	2,637	5,201	3,616	3,255	2,685	2,353	2,357	2,260
Rains	166	68	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	248	265	274	288	269	296	315	261	299	276	819	544	465	373	360	284	239
Robertson	3,008	2,512	2,474	2,280	2,444	2,678	2,685	2,730	2,564	2,881	2,734	2,840	2,766	3,010	2,932	3,085	2,882	3,138	2,949	3,020	2,918	2,846	3,025	3,014	2,718	2,937	2,841	2,692	2,195	1,888	2,054	2,456	2,176	2,015
Rusk	4,792	4,396	5,491	5,122	4,966	5,557	5,336	5,392	5,270	5,298	5,562	5,307	6,003	6,225	5,889	6,162	5,646	7,159	6,531	6,639	6,729	6,700	6,649	6,887	6,137	6,529	6,347	6,822	8,226	7,399	7,071	6,762	6,754	6,436
Sabine	374	125	86	83	82	85	113	119	112	124	139	148	122	128	120	155	84	248	253	295	378	355	392	122	235	214	566	233	384	336	382	377	580	520
San Augustine	334	190	172	192	174	177	185	177	134	117	132	146	157	119	134	139	142	270	319	325	407	301	386	404	376	414	465	528	574	545	495	484	400	412
Shelby	2,015	2,661	1,891	1,645	1,753	1,439	1,591	1,600	1,673	1,875	1,681	1,568	1,501	1,478	1,494	1,623	1,716	2,351	1,975	1,927	1,913	1,931	2,155	2,062	1,888	1,757	2,046	2,484	2,910	2,731	2,613	2,450	2,416	2,408
Smith	16,478	17,809	17,522	16,984	17,449	24,015	17,130	15,246	15,230	16,445	17,701	18,196	20,183	19,936	19,353	20,978	21,595	22,064	21,411	20,511	20,889	19,272	19,854	21,245	20,463	22,647	12,889	12,908	16,366	25,164	21,919	20,842	19,917	20,872
Titus	422	486	409	436	448	423	446	407	405	410	430	446	487	500	527	541	535	91	92	91	92	97	102	118	100	111	115	120	141	155	144	111	121	81
Upshur	3,191	3,771	3,790	3,318	3,485	3,520	3,484	3,643	3,632	3,329	3,483	3,671	3,757	3,696	3,890	4,273	4,267	3,781	3,723	3,675	3,729	3,655	4,034	4,180	3,555	3,468	3,543	3,836	4,104	3,678	3,480	3,427	3,865	3,735
Van Zandt	2,715	2,818	2,743	2,858	2,853	2,975	2,864	2,937	2,964	2,935	3,038	3,014	3,033	3,012	3,326	3,644	3,504	2,522	3,071	2,867	2,916	2,755	3,871	3,656	3,290	3,221	3,149	4,022	4,531	4,127	4,004	4,023	3,589	3,268
Walker																		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Wood	3,821	4,373	4,381	4,354	4,656	4,847	4,648	3,826	3,756	3,909	4,002	4,246	4,458	4,580	4,839	5,043	4,741	5,079	5,161	5,305	5,516	5,874	6,083	5,566	5,215	5,147	6,461	5,805	5,987	6,393	5,451	5,058	4,913	5,804
Manufacturing																																		
Anderson	349	455	303	347	346	344	431	0	0	0	0	0	0	0	0	0	0	340	340	445	445	0	0	0	0	0	0	0	0	0	0	0	724	1,537
Angelina	21,296	19,284	19,120	18,582	18,561	16,199	23,578	14,668	13,565	12,404	11,999	12,030	12,552	11,771	11,262	10,922	10,715	12,306	8,995	8,345	9,137	1,914	610	782	20	16	16	0	0	0	0	0	0	0
Bowie	42	45	44	39	22	7	5	27	17	1	17	16	15	16	17	3	3	3	3	15	20	12	25	25	35	43	29	31	26	31	22	14	13	9

COUNTY	1980	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
Camp	0	198	199	201	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	430	36	0	0	0	0	0	0	0	0	0	0	0	0	0
Cass	0	11	11	11	2	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Cherokee	0	0	0	0	0	0	0	0	0	0	4	0	0	2	0	0	0	7	9	5	6	23	23	10	9	10	5	5	0	0	0	0	0	0
Franklin	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Freestone	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	19	31
Gregg	278	196	186	186	161	161	161	161	161	161	161	161	161	161	162	24	24	0	0	0	0	1	0	0	0	0	3	3	3	2	2	3	2	1
Grimes	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0											
Harrison	80	116	136	144	125	131	122	102	110	57	155	142	104	102	110	123	123	173	211	179	169	130	151	239	251	219	8,735	111	145	146	145	113	128	139
Henderson	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	187	180	169	124	124	122	122	122	122	124	128	141
Hopkins	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Houston	0	7	4	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Leon	161	162	162	162	162	162	162	162	162	162	260	290	277	290	486	459	484	545	466	430	450	533	766	798	748	687	557	545	819	711	672	657	524	626
Limestone	398	413	335	338	332	597	438	732	383	447	447	447	447	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Madison	0	34	69	70	70	69	70	70	69	69	74	74	148	181	156	136	217	183	177	185	188	191	204	216	197	192	212	0	0	0	0	0	0	0
Marion	9	14	25	25	18	33	34	26	35	0	0	0	0	1	3	3	3	4	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	18
Morris	221	15	7	6	6	0	6,412	6,412	6,412	40	32	31	34	31	30	30	32	88	25	21	76	79	196	72	77	20	23	23	23	19	9	9	9	
Nacogdoches	21	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	20	31	20	11	32	27	110	31	24	30	36	25	31	24	22	35
Navarro	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Panola	0	0	15	16	20	20	19	59	14	20	20	20	20	0	0	0	0	0	921	473	513	424	498	185	338	523	408	1	1	1	1	1	1	1
Rains	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Robertson	27	16	13	27	27	27	25	24	24	20	20	19	18	17	13	12	12	4,465	4,682	4,790	4,757	4,135	3,645	4,610	4,616	3,882	88	51	43	39	43	45	40	35
Rusk	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	184	143	150	176	210	188	71	188	196	0	0	0	0	0	0	0
Sabine	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
San Augustine	0	0	0	0	0	0	0	0	0	0	0	3	3	3	2	2	3	3	4	4	5	3	3	3	5	4	6	5	4	3	3	3	2	3
Shelby	23	2	4	4	0	0	0	52	66	63	49	57	45	50	57	62	71	64	48	36	14	1	1	1	0	0	0	0	0	0	0	0	0	0
Smith	10	1,048	1,055	885	744	662	637	464	390	377	328	406	418	457	406	343	387	0	0	0	263	310	289	361	453	361	196	179	154	156	146	103	110	119
Titus	316	235	290	74	145	57	242	209	115	122	112	300	120	295	223	176	199	194	104	90	104	96	93	94	80	100	91	90	90	132	670	728	0	0
Upshur	312	157	99	90	121	163	157	171	188	225	207	146	150	146	164	160	129	153	183	134	100	31	35	47	38	46	36	41	32	35	23	24	16	14
Van Zandt	684	343	191	268	422	396	415	159	156	190	339	139	255	574	178	258	292	0	0	0	0	0	0	0	0	289	253	0	189	167	175	246	75	42
Walker																		0	0	2	1	0	0	0	0	0	0	0	0	0	0	0	0	0
Wood	22	3	3	3	41	38	8	2	4	2	0	0	0	0	0	0	0	2	0	0	193	193	459	677	629	617	617	663	663	663	663	977	1,045	876
Mining																																		
Anderson	1,691	329	405	382	359	325	303	303	318	318	315	315	430	430	430	411	430	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Angelina	0	0	0	0	0	0	0	0	22	22	22	22	22	22	22	22	22	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Bowie	0	0	0	18	18	17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Camp	156	82	84	79	75	76	71	71	15	15	15	15	24	24	24	24	24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Cass	1,218	567	629	756	689	792	767	767	819	819	819	819	822	822	822	481	741	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Cherokee	81	117	120	111	89	80	53	53	81	81	81	81	81	81	81	81	81	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Franklin	552	631	768	1,222	1,117	1,153	706	706	1,399	1,399	1,399	1,408	1,354	1,354	895	894	895	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Freestone	18	74	35	209	43	44	36	36	34	44	37	37	37	37	37	30	30	7	14	14	14	0	31	79	50	50	60	77	72	287	324	121	177	107
Gregg	305	3,984	129	156	66	61	29	29	11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

COUNTY	1980	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
Grimes	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0											
Harrison	777	378	261	248	211	182	181	195	195	167	198	196	207	207	208	197	197	3	3	6	4	4	5	3	3	3	4	4	5	4	5	1	136	4
Henderson	304	925	906	819	411	456	102	199	200	374	374	387	475	475	492	153	474	2	0	2	2	2	2	2	2	2	2	2	2	2	0	0	0	125
Hopkins	73	0	67	138	127	133	187	120	147	143	144	145	145	145	143	78	78	67	67	67	67	67	67	67	17	0	0	0	0	0	0	0	0	0
Houston	0	32	33	32	29	30	27	27	38	38	37	37	37	37	37	37	37	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Leon	26	72	85	133	145	207	131	146	448	461	437	463	1,005	1,005	1,025	865	867	164	131	127	123	124	91	50	32	29	20	25	41	45	36	38	44	29
Limestone	0	0	0	0	0	0	0	0	0	807	807	807	807	807	807	360	360	645	645	647	645	642	642	642	642	0	642	642	642	1,362	932	1,275	1,449	1,128
Madison	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Marion	13	0	69	65	61	60	56	56	53	53	53	53	83	83	83	83	83	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Morris	0	0	0	0	0	0	0	0	32	32	32	32	32	32	32	32	32	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
Nacogdoches	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Navarro	0	127	63	66	55	60	56	56	59	59	59	59	59	59	59	59	59	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Panola	244	358	426	3,305	989	1,047	1,078	1,078	1,044	1,051	1,064	1,064	1,045	1,944	1,947	1,947	1,947	7	7	7	7	7	8	7	7	1	1	482	562	518	571	532	453	244
Rains	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Robertson	0	24	24	25	20	21	20	20	40	40	40	40	40	94	94	94	94	0	8,286	7,549	7,580	7,472	7,672	7,672	7,731	8,027	7,114	7,443	15	6	0	0	2,983	3,200
Rusk	634	1,690	2,492	2,584	2,111	2,020	2,043	1,855	1,241	1,232	1,202	1,173	1,189	1,189	1,201	1,201	1,201	38	7	6	6	6	3	0	0	0	0	173	160	115	169	162	1,623	1,758
Sabine	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
San Augustine	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Shelby	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Smith	689	505	815	772	722	739	689	689	680	680	660	660	251	259	259	255	257	0	0	0	0	0	0	0	0	0	0	0	0	263	69	126	110	74
Titus	0	165	359	1,475	319	320	318	318	1,736	1,736	1,729	1,729	1,729	1,729	1,729	1,729	1,729	0	0	0	0	0	0	0	0	0	0	1	1	2	2	0	0	0
Upshur	2	1	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Van Zandt	1,795	946	1,530	1,043	950	927	781	781	1,085	1,068	1,068	1,091	1,098	1,117	1,117	684	687	225	73	102	252	337	220	384	156	0	0	0	0	0	0	0	0	8
Walker																		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Wood	2,846	3,619	4,729	4,006	3,577	3,238	3,161	3,161	2,841	2,488	2,535	2,626	560	560	488	280	280	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Electric Power																																		
Anderson	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Angelina	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	36	0	0
Bowie	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Camp	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Cass	0	3	1	3	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Cherokee	333	408	218	293	510	439	347	343	262	136	166	162	133	131	108	118	115	132	128	86	119	115	124	136	155	127	167	121	181	170	118	144	119	156
Franklin	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Freestone	101	156	144	135	147	145	144	163	155	149	141	125	105	99	95	110	92	91	117	99	99	95	110	113	755	241	146	135	152	122	102	143	158	137
Gregg	1	1	1	1	1	1	1	1	1	1	1	1	19	64	113	1	101	42	258	25	267	194	242	242	242	243	242	242	242	243	242	242	242	242
Grimes	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0											
Harrison	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Henderson	0	0	0	8	1	0	0	0	1	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Hopkins	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Houston	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Leon	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

COUNTY	1980	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
Limestone	0	182	779	964	829	808	1,240	2,584	1,153	971	940	960	822	994	973	916	966	1,014	877	829	853	726	649	666	0	671	677	711	681	592	637	639	572	629
Madison	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Marion	0	0	0	0	0	0	0	0	0	0	0	0	1	1	74	88	100	99	96	0	82	60	82	79	73	74	81	91	75	82	76	70	57	41
Morris	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
Nacogdoches	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Navarro	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Panola	2	125	11	20	24	16	17	17	155	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Rains	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Robertson	0	0	0	10	1	5	81	1,528	2,532	3,080	3,462	3,338	3,346	3,711	3,787	3,579	3,549	0	0	1	0	0	0	1	1	10	183	0	4,806	3,401	4,359	4,709	5,018	4,668
Rusk	0	0	0	0	0	0	0	0	18	24	23	18	20	179	14	18	18	11	12	97	99	113	0	287	356	147	183	358	1,023	245	0	49	33	16
Sabine	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
San Augustine	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Shelby	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Smith	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Titus	62	16	2	85	4	4	31	4	4	4	4	4	0	0	0	0	0	0	0	0	0	0	0	22	0	0	0	0	0	0	0	0	0	0
Upshur	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Van Zandt	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Walker																		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Wood	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Irrigation																																		
Anderson	0	113	125	60	60	60	28	23	26	26	172	78	180	265	254	632	309	96	96	81	17	30	56	0	284	180	425	259	458	414	452	625	355	368
Angelina	372	372	297	264	264	264	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Bowie	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1,246	762	1,382	916	1,094	346	471
Camp	0	145	142	96	96	96	60	78	78	79	23	17	17	23	23	23	23	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0
Cass	0	0	0	0	0	0	0	0	0	0	12	9	8	11	11	11	11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Cherokee	50	117	72	90	90	90	96	100	82	82	12	28	29	29	29	29	29	31	26	28	16	22	50	41	232	125	140	193	8	270	269	286	297	218
Franklin	0	0	0	0	0	0	0	0	0	0	3	2	2	3	3	3	3	0	0	0	0	0	0	0	33	0	0	0	0	0	0	0	0	0
Freestone	0	0	100	50	50	50	25	25	25	25	13	17	17	17	17	17	17	0	0	0	0	0	0	38	0	43	76	216	613	680	598	550	314	341
Gregg	0	0	0	0	0	0	0	0	0	0	20	25	25	25	25	25	25	0	0	0	0	0	9	24	0	0	0	0	16	4	8	8	1	2
Grimes	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0											
Harrison	0	20	95	95	95	95	32	50	50	50	39	34	34	39	39	34	34	39	37	42	29	125	112	95	124	0	708	626	642	411	422	405	177	305
Henderson	100	20	70	70	70	70	20	21	21	21	20	20	20	20	20	20	20	0	0	2	23	39	41	119	139	155	150	133	50	181	1,348	1,408	945	770
Hopkins	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	241	201	16	210	2,317	315	880	913	50	116	576
Houston	0	26	24	24	25	24	24	23	23	23	101	146	125	170	170	170	170	576	428	756	269	342	496	615	808	198	267	144	90	738	990	462	76	224
Leon	0	0	0	0	75	75	0	0	0	0	0	0	0	0	0	0	0	542	542	542	300	300	285	242	88	208	21	31	223	152	601	491	127	321
Limestone	0	0	0	0	150	150	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	18	0	0	11	7	0
Madison	0	0	0	0	0	0	0	0	0	0	18	18	18	18	18	18	18	0	0	0	0	0	0	0	5	7	7	211	370	318	299	312	336	368
Marion	0	0	0	0	0	0	0	0	0	0	55	63	59	55	55	55	55	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Morris	0	255	225	225	225	125	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
Nacogdoches	0	19	39	40	40	40	138	140	140	140	980	1,117	1,016	1,016	1,016	1,016	1,016	186	419	187	395	281	206	248	143	145	226	141	298	31	0	106	106	102
Navarro	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

COUNTY	1980	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
Panola	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	18	31	64	31	346	383	137	322	1,630	1,122	1,102
Rains	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	58	0	0	0	7	53	0	3	3	5
Robertson	1,700	1,605	1,638	1,370	969	1,547	1,390	1,807	1,847	1,539	697	15,338	14,089	18,331	11,472	16,837	15,345	816	1,153	1,325	1,034	2,267	3,380	3,276	3,195	3,513	3,480	4,311	5,232	3,479	4,792	3,544	2,510	3,544
Rusk	0	33	38	19	19	19	32	27	27	27	149	38	151	149	149	149	149	18	49	49	73	92	92	100	25	29	0	0	172	69	201	93	78	83
Sabine	0	0	0	0	0	50	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
San Augustine	0	0	0	0	0	100	0	0	0	0	78	75	77	77	77	77	77	112	82	82	50	50	50	63	0	0	0	0	14	0	0	0	0	0
Shelby	0	5	12	13	13	39	11	12	12	12	29	32	29	29	29	29	29	26	20	24	22	20	23	27	20	25	0	0	13	8	10	7	6	7
Smith	50	0	0	0	228	183	39	10	10	10	114	113	100	112	112	112	112	208	137	137	126	194	182	442	0	0	418	64	300	68	3	274	92	126
Titus	0	0	0	0	0	50	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	46	0	109	46	171	147	91	124
Upshur	0	0	0	0	0	0	0	0	0	0	15	15	15	15	15	15	15	0	0	0	0	0	0	0	200	0	0	116	108	2	12	10	46	40
Van Zandt	0	0	0	0	0	0	0	0	0	0	19	30	19	112	91	623	146	33	33	33	0	0	0	80	0	0	33	87	143	1	20	37	27	47
Walker																		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Wood	0	465	510	533	250	102	260	219	219	219	94	135	131	103	103	103	103	149	112	112	117	119	110	4	80	0	0	306	232	155	352	285	190	214
Livestock																																		
Anderson	490	584	610	610	625	648	672	679	691	832	816	721	717	717	717	627	644	665	327	330	298	260	62	66	66	46	48	46	46	40	43	44	46	46
Angelina	47	97	94	84	88	98	88	88	90	126	124	102	102	92	90	102	118	155	152	144	134	66	14	14	14	16	16	38	36	34	32	32	32	34
Bowie	286	301	258	298	274	275	283	319	321	262	280	311	296	395	258	267	287	293	173	163	160	0	0	0	0	0	0	0	0	0	0	0	0	0
Camp	277	229	198	235	225	221	233	275	276	320	337	385	396	393	336	348	357	372	586	412	383	381	372	394	381	380	378	1,940	1,921	1,877	2,056	2,034	2,097	2,187
Cass	328	350	305	301	300	322	333	334	341	340	318	340	317	328	297	320	363	334	189	186	173	174	22	22	22	20	21	87	87	76	75	74	76	79
Cherokee	584	585	626	574	542	512	526	701	694	948	1,055	985	906	988	792	780	780	618	625	603	501	487	181	190	185	181	158	262	261	241	234	234	232	238
Franklin	342	423	446	413	395	410	378	521	516	637	668	582	572	567	460	452	484	449	249	229	225	217	428	426	335	444	440	1,172	1,161	1,141	1,133	1,093	1,113	1,149
Freestone	501	1,142	456	381	381	404	356	350	356	499	468	487	524	650	487	546	569	571	475	471	530	565	187	216	229	140	156	134	134	113	110	112	116	117
Gregg	109	102	82	82	75	87	94	92	94	106	99	87	87	87	92	83	101	95	74	63	48	48	23	19	23	20	22	26	26	19	21	13	13	14
Grimes	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0											
Harrison	324	404	331	82	359	97	99	99	101	77	78	80	81	71	79	89	96	87	48	43	41	40	77	65	66	55	62	50	50	43	49	62	49	50
Henderson	651	793	780	1,067	641	1,004	1,027	1,037	1,056	800	762	785	777	954	735	846	830	820	447	122	368	370	455	433	435	398	432	446	449	370	398	416	411	420
Hopkins	1,496	1,670	1,666	1,485	1,517	1,246	1,322	2,253	2,297	2,670	2,569	2,800	2,605	2,536	2,417	1,873	1,849	1,825	1,009	997	995	810	1,849	1,960	1,509	1,636	1,544	2,132	2,147	2,120	2,119	2,091	2,096	2,167
Houston	472	572	581	432	495	522	531	541	552	541	514	552	498	498	438	494	519	471	266	257	258	278	127	107	96	109	109	125	131	83	87	88	92	93
Leon	864	1,453	1,473	1,269	1,473	1,537	1,353	1,332	1,359	1,261	1,212	1,053	1,273	1,061	1,313	1,000	1,036	1,014	634	613	695	703	90	84	111	73	75	147	145	132	148	151	148	152
Limestone	108	162	143	135	135	140	125	244	125	101	117	129	119	124	113	106	111	107	85	94	116	70	8	8	6	6	7	8	8	6	7	7	8	8
Madison	245	323	318	266	290	279	237	238	243	301	282	246	261	388	240	204	216	286	208	200	223	227	90	88	87	82	89	120	118	109	112	119	114	118
Marion	62	88	68	54	61	66	65	65	66	73	79	73	59	66	79	58	65	434	56	51	51	50	6	6	6	4	4	12	12	7	7	10	10	9
Morris	157	144	139	140	150	159	165	166	169	250	235	187	207	196	157	168	188	194	95	118	138	141	63	68	68	52	58	173	173	149	155	152	157	
Nacogdoches	738	650	473	496	478	479	498	596	596	597	614	667	600	805	561	503	546	568	546	547	474	464	113	126	105	112	115	929	915	899	911	889	917	948
Navarro	13	15	15	13	13	14	13	13	13	11	11	13	11	14	9	11	11	12	12	12	11	11	6	6	7	6	6	8	9	5	5	5	6	6
Panola	708	654	640	670	695	705	747	858	869	812	815	1,090	1,059	1,126	1,128	1,118	1,216	1,238	1,264	1,254	1,249	1,270	320	333	327	304	314	288	288	245	255	250	258	267
Rains	149	211	197	183	200	192	202	252	251	223	217	233	233	229	227	211	220	216	200	182	190	218	28	27	24	24	24	21	21	19	22	23	23	23
Robertson	569	631	691	676	622	861	567	558	571	599	617	616	777	621	677	570	578	531	520	540	635	596	432	387	316	404	385	857	881	645	627	626	642	659
Rusk	593	566	507	478	455	473	482	507	515	495	507	467	414	353	367	425	459	462	236	231	215	221	231	202	216	209	194	353	351	308	321	325	339	353
Sabine	100	98	88	93	113	115	117	129	132	114	118	43	34	31	71	149	142	179	154	155	166	112	60	61	60	82	85	10	10	8	10	15	10	10
San Augustine	129	110	98	111	121	124	126	139	142	151	151	50	54	47	86	167	159	208	159	161	159	290	89	89	94	109	111	180	178	176	177	178	176	183

COUNTY	1980	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
Shelby	748	584	561	588	664	684	721	785	801	779	781	1,107	1,137	1,161	1,201	1,231	1,329	1,393	1,048	1,051	1,074	1,099	562	588	579	530	571	1,812	1,785	1,769	1,787	1,739	1,788	1,848
Smith	423	511	430	464	430	454	470	483	491	442	413	451	421	374	374	427	472	447	250	232	217	221	582	636	644	533	455	600	604	434	517	580	462	468
Titus	356	426	362	358	376	389	400	416	424	304	322	387	375	395	356	362	383	358	184	176	154	173	183	201	157	190	198	616	608	592	576	554	571	587
Upshur	419	454	394	422	404	394	394	530	525	771	838	768	673	963	603	602	617	612	395	378	383	332	192	180	159	190	202	228	228	211	225	231	234	238
Van Zandt	728	899	771	873	786	813	837	881	893	950	914	953	985	921	980	910	973	970	342	336	352	296	501	512	332	514	543	469	471	430	378	407	403	413
Walker																		26	13	13	13	13	19	23	21	37	36	23	23	17	27	28	24	24
Wood	545	565	533	546	569	541	567	726	722	1,025	1,008	1,014	1,021	1,091	901	839	904	825	681	717	720	658	107	84	67	84	89	156	155	151	150	153	153	158

Units in acre-feet
Source: Texas Water Development Board water use surveys (TWDB, 2016)

Table 4.8. Annual Estimated Groundwater Pumping by Water Use Sector for Louisiana Parishes in Study Area

COUNTY	1960	1965	1970	1975	1980	1985	1990	1995	2000	2005	2010	2015
Public Supply												
Bossier Parish	269	381	482	1,110	1,087	1,345	1,480	1,939	2,219	1,939	2,410	2,724
Caddo Parish	639	1,704	1,962	1,098	1,379	1,491	1,031	1,524	1,267	1,749	1,984	1,480
De Soto Parish	785	897	841	1,244	1,782	1,020	1,367	1,390	1,435	1,502	1,580	1,390
Grant Parish	191	280	269	717	1,020	2,141	1,412	2,006	1,693	1,749	2,219	3,262
Natchitoches Parish	1,121	67	123	471	538	572	930	829	1,042	1,211	998	1,401
Rapides Parish	7,207	8,754	11,904	28,583	35,420	33,066	36,205	31,755	32,808	30,454	28,997	21,196
Red River Parish	191	202	258	482	527	852	616	886	729	807	740	661
Sabine Parish	448	841	740	1,065	437	280	426	841	1,009	1,367	1,401	1,211
Vernon Parish	673	1,199	1,390	4,697	6,288	280	426	841	1,009	1,367	1,401	4,876
Commercial												
Bossier Parish	0	0	0	0	0	0	22	22	0	0	0	0
Caddo Parish	0	0	0	0	0	0	78	123	0	0	0	0
De Soto Parish	0	0	0	0	0	0	0	11	0	0	0	0
Grant Parish	0	0	0	0	0	0	0	0	0	0	0	0
Natchitoches Parish	0	0	0	0	0	0	0	0	0	0	0	0
Rapides Parish	0	0	0	0	0	0	886	101	0	0	0	0
Red River Parish	0	0	0	0	0	0	0	11	0	0	0	0
Sabine Parish	0	0	0	0	0	0	78	45	0	0	0	0
Vernon Parish	0	0	0	0	0	0	5,515	4,596	0	0	0	0
Industrial												
Bossier Parish	168	471	1,412	1,659	493	549	471	404	773	471	370	0
Caddo Parish	56	157	1,278	1,906	258	0	45	34	101	101	0	0
De Soto Parish	67	224	146	146	22	0	0	0	381	112	325	639
Grant Parish	168	168	168	168	67	22	90	146	235	78	78	90
Natchitoches Parish	392	34	0	0	0	0	0	0	0	0	34	0
Rapides Parish	673	1,782	16,230	2,163	1,693	0	56	45	22	729	740	0
Red River Parish	22	34	11	527	303	67	0	0	11	0	0	0
Sabine Parish	112	347	135	280	135	370	303	291	359	0	0	0
Vernon Parish	336	2,623	3,677	0	0	0	0	0	0	0	11	0
Electric Power												
Bossier Parish	0	0	0	0	0	0	0	0	0	0	0	0
Caddo Parish	0	34	0	0	0	0	0	0	0	0	0	0
De Soto Parish	0	0	0	0	0	0	0	0	0	0	0	0
Grant Parish	0	0	0	0	0	0	0	0	0	0	0	0
Natchitoches Parish	0	0	0	0	0	0	0	0	0	0	0	0
Rapides Parish	0	0	0	404	247	0	135	135	135	135	135	370
Red River Parish	0	0	0	0	0	0	0	0	0	0	0	0
Sabine Parish	0	0	0	0	0	0	0	0	0	0	0	0
Vernon Parish	0	0	0	0	0	0	0	0	0	0	0	0
Mining												
Bossier Parish	0	0	0	0	0	0	0	0	0	0	0	34
Caddo Parish	0	0	0	0	0	0	0	0	0	0	0	34
De Soto Parish	0	0	0	0	0	101	0	0	370	1,390	2,500	213
Grant Parish	0	0	0	0	0	0	0	0	0	0	0	0
Natchitoches Parish	0	0	0	0	0	0	0	0	0	0	0	0
Rapides Parish	0	0	0	0	0	0	0	0	0	0	0	0
Red River Parish	0	0	0	0	0	0	0	0	0	0	661	415
Sabine Parish	0	0	0	0	0	0	0	0	0	0	157	90
Vernon Parish	0	0	0	0	0	0	0	0	0	0	0	0
Irrigation												
Bossier Parish	34	224	224	0	605	404	22	101	247	460	235	135
Caddo Parish	90	1,827	2,612	2,018	1,356	1,558	1,110	594	2,892	3,295	6,468	5,122
De Soto Parish	0	0	0	2,107	0	0	0	11	11	22	22	11
Grant Parish	0	0	0	0	0	0	0	0	0	0	0	0
Natchitoches Parish	112	0	67	347	0	0	191	1,054	1,827	1,356	2,152	1,558
Rapides Parish	78	90	11	7,017	0	0	404	2,242	4,450	4,170	7,824	5,335
Red River Parish	0	45	2,219	0	1,435	1,457	471	392	1,076	818	1,323	2,320
Sabine Parish	0	0	0	123	0	0	0	0	11	0	0	0
Vernon Parish	0	0	45	0	0	0	0	0	0	0	0	0
Livestock												
Bossier Parish	168	168	235	11	202	123	303	213	135	78	179	123
Caddo Parish	224	213	56	157	460	213	191	78	67	112	112	45
De Soto Parish	224	247	213	258	325	191	22	22	224	202	191	157
Grant Parish	45	56	112	101	45	112	22	22	34	22	22	22
Natchitoches Parish	448	448	695	123	135	538	2,208	3,363	56	314	67	56
Rapides Parish	560	538	460	504	235	269	4,517	2,006	45	34	34	45
Red River Parish	224	247	280	45	22	22	67	101	90	56	67	90
Sabine Parish	112	146	863	280	404	112	404	280	11	22	11	11
Vernon Parish	112	112	269	135	628	280	34	11	22	22	22	11

COUNTY	1960	1965	1970	1975	1980	1985	1990	1995	2000	2005	2010	2015
Aquaculture												
Bossier Parish	0	0	0	0	0	0	0	0	213	235	0	78
Caddo Parish	0	0	0	0	0	0	0	0	269	1,558	1,446	112
De Soto Parish	0	0	0	0	0	0	0	0	0	34	0	0
Grant Parish	0	0	0	0	0	0	0	0	0	0	0	0
Natchitoches Parish	0	0	0	0	0	0	0	0	930	1,715	2,365	3,273
Rapides Parish	0	0	0	0	0	0	0	0	3,004	1,614	3,643	3,161
Red River Parish	0	0	0	0	0	0	0	0	45	0	0	0
Sabine Parish	0	0	0	0	0	0	0	0	0	0	0	0
Vernon Parish	0	0	0	0	0	0	0	0	56	34	56	34
Domestic												
Bossier Parish	426	785	785	471	2,107	1,166	1,356	1,233	1,289	1,457	1,614	1,244
Caddo Parish	1,950	1,569	1,726	437	1,244	2,130	2,096	1,793	1,749	1,827	1,849	1,648
De Soto Parish	560	549	370	235	370	673	829	661	661	695	706	673
Grant Parish	359	303	493	112	291	516	605	235	247	258	291	247
Natchitoches Parish	673	583	437	370	493	942	998	538	549	560	583	572
Rapides Parish	897	807	863	22	258	1,323	1,233	549	560	560	583	504
Red River Parish	269	280	258	146	280	325	392	235	247	247	235	224
Sabine Parish	392	392	359	370	1,076	1,603	1,412	1,098	1,110	1,110	1,132	1,121
Vernon Parish	448	168	673	695	1,390	1,883	2,354	1,737	1,569	1,491	1,592	1,401

Units in acre-feet
Source: USGS water use reports (USGS, 2011a, b, c, 2014, 2017b). Aquifer sources are not reported.

Table 4.9. Annual Estimated Groundwater Pumping by Water Use Sector for Arkansas Counties in Study Area

COUNTY	1965	1970	1975	1980	1985	1990	1995	2000	2005	2010	2015
Public Supply											
Lafayette County	404	426	392	381	1,076	1,278	1,054	953	1,031	1,042	415
Miller County	0	56	11	67	235	112	112	247	280	112	101
Industrial											
Lafayette County	628	796	0	0	157	0	0	0	0	11	0
Miller County	90	448	0	0	179	0	0	0	0	157	0
Electric Power											
Lafayette County	2,018	1,289	0	0	1,188	1,345	1,255	1,009	560	392	0
Miller County	0	0	0	0	0	0	0	0	0	0	0
Mining											
Lafayette County	0	0	0	0	0	0	0	0	0	0	0
Miller County	0	0	0	0	22	202	0	0	0	0	0
Irrigation											
Lafayette County	4,338	3,609	0	0	16,443	0	23,113	10,222	37,034	21,398	15,244
Miller County	1,681	874	0	0	19,907	7,689	10,402	7,151	16,533	6,367	0
Livestock											
Lafayette County	135	235	0	0	1,031	572	1,962	280	291	247	269
Miller County	235	336	0	0	986	448	751	258	235	202	202
Aquaculture											
Lafayette County	695	1,031	0	0	0	0	0	22	5,033	3,677	2,623
Miller County	0	325	0	0	0	0	0	0	392	0	0
Domestic											
Lafayette County	258	392	224	0	381	392	347	247	213	179	56
Miller County	482	583	235	258	1,177	1,435	11	146	807	841	695

Units in acre-feet
Source: USGS water use reports (USGS, 2011a, b, c, 2014, 2017b). Aquifer sources are not reported.

Table 4.10. Annual Reported Groundwater Pumping by Water Use Sector for Groundwater Conservation Districts in Study Area

Groundwater Conservation District	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
Municipal																	
Mid-East Texas	--	--	--	5879	6621	6448	6265	6651	6706	7205	8072	6902	7180	6985	7253	6773	6452
Netches & Trinity Valley	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Panola County	--	--	--	--	--	--	--	--	--	362	1163	1579	1271	1151	1278	1265	--
Pineywoods	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Rusk County	--	--	--	--	--	--	--	--	--	--	--	--	--	--	5395	4965	--
Industrial																	
Mid-East Texas	--	--	--	962	1201	1182	1180	1729	1723	1706	2360	2090	1850	2148	1789	1751	1573
Netches & Trinity Valley	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Panola County	--	--	--	--	--	--	--	--	--	0	937	1373	3864	2992	1811	--	--
Pineywoods	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Rusk County	--	--	--	--	--	--	--	--	--	--	--	--	--	--	143	85	--
Municipal & Industrial/Commercial																	
Mid-East Texas	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Netches & Trinity Valley	829	4211	7377	19320	17780	18695	17009	19153	17664	18522	21978	19859	19863	18290	19240	21245	20672
Panola County	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Pineywoods	--	22517	29933	23222	23214	23731	20993	21205	19882	19631	22898	19605	19389	18389	18907	17952	17952
Rusk County	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Mining																	
Mid-East Texas	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Netches & Trinity Valley	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Panola County	--	--	--	--	--	--	--	367	1297	1010	561	579	589	514	414	244	--
Pineywoods	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Rusk County	2491	1787	1256	664	802	3723	2897	1069	811	566	920	1215	2661	2090	1584	1989	--
Electric Power																	
Mid-East Texas	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Netches & Trinity Valley	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Panola County	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Pineywoods	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Rusk County	--	--	--	--	--	--	--	--	--	--	--	--	--	--	17	7	--
Hydraulic Fracturing																	
Mid-East Texas	--	--	--	--	--	--	--	--	--	--	244	87	238	538	135	79	92
Netches & Trinity Valley	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	131	0
Panola County	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Pineywoods	--	--	--	--	--	--	--	--	--	454	1294	274	0	0	58	58	152
Rusk County	--	--	--	--	--	--	--	--	--	--	--	--	--	--	29	--	--
Irrigation																	
Mid-East Texas	--	--	--	--	--	--	--	--	--	--	112	170	664	462	428	315	255
Netches & Trinity Valley	--	--	--	--	--	0	0	0	0	0	12	92	157	98	59	56	63
Panola County	--	--	--	--	--	--	--	--	--	--	0	102	75	89	113	69	--
Pineywoods	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Rusk County	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Livestock																	
Mid-East Texas	--	--	--	--	--	--	--	--	5	86	120	119	134	266	251	427	211
Netches & Trinity Valley	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Panola County	--	--	--	--	--	--	--	--	--	--	0	8	--	0	0	12	--
Pineywoods	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Rusk County	--	--	--	--	--	--	--	--	--	--	--	--	--	--	9	29	--
Domestic																	
Mid-East Texas	--	--	--	--	--	--	--	4	3	5	2	39	3	--	--	--	--
Netches & Trinity Valley	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Panola County	--	--	--	--	--	--	--	--	--	--	1	24	--	--	--	1	--
Pineywoods	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Rusk County	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Frac Ponds																	
Mid-East Texas	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Netches & Trinity Valley	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Panola County	--	--	--	--	--	--	--	--	--	--	165	1125	--	--	--	108	--
Pineywoods	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Rusk County	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--

Units in acre-feet
Source: GCD data requests
--- = No data reported

Table 4.11. Reported Annual Groundwater Pumping Volumes for Mine Dewatering in Texas Study Area

Company	Mine	County	2008	2009	2010	2011	2012	2013	2014	2015	2016
Luminant Mining Co.	Big Brown	Freestone	1,224	2,349	1,651	1,133	1,045	528	121	75	0
Luminant Mining Co.	Turlington	Freestone	0	0	0	327	453	551	1,377	1,260	506
Northwestern Resources Co.	Jewett (47A)	Freestone	395	489	323	1,389	608	796	301	591	0
Northwestern Resources Co.	Jewett (32F)	Freestone, Leon, Limestone	2,115	1,071	812	2,066	2,583	2,023	2,980	3,775	3,684
Luminant Mining Co.	Monticello Thermo	Hopkins	1,037	715	565	291	365	41	0	0	0
Luminant Mining Co.	Martin Lake	Panola, Rusk	523	127	0	0	0	0	0	0	0
Walnut Creek Mining Co.	Calvert	Robertson	7,997	7,102	7,424	7,089	6,398	3,845	3,050	2,983	3,218
Luminant Mining Co.	Liberty	Rusk	---	---	---	---	---	---	13	8	30
Luminant Mining Co.	Oak Hill	Rusk	546	684	566	920	1,215	2,661	2,051	1,419	1,548
Sabine Mining Co.	Rusk Mine	Rusk	---	---	---	---	---	---	26	132	385
Luminant Mining Co.	Monticello Winfield	Titus, Franklin	16	0	21	117	65	72	0	0	0

Units in acre-feet
Source: Railroad Commission of Texas, reported Texas lignite dewatering volumes. Aquifer sources are not reported.
--- = No data available

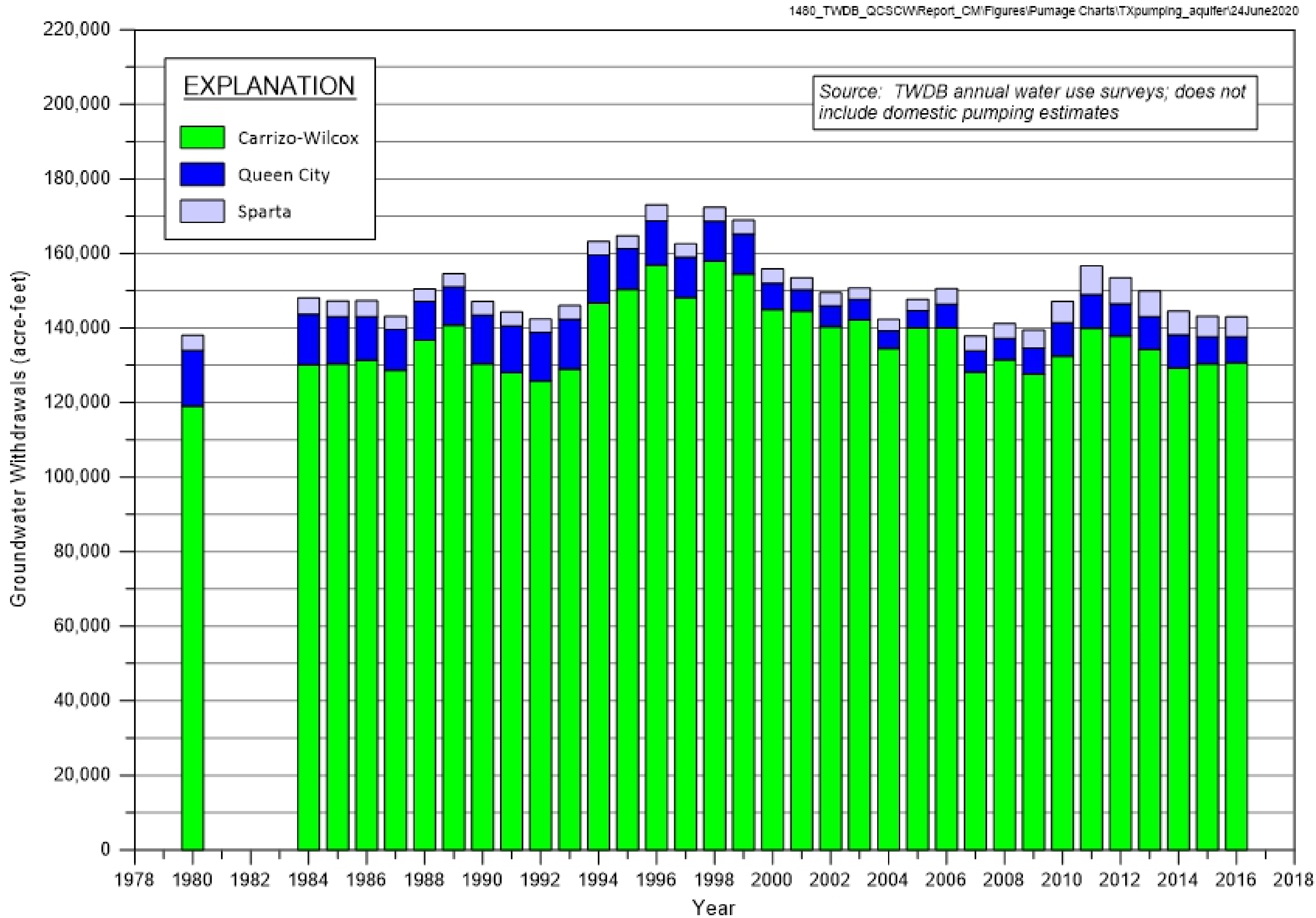


Figure 4-62. Estimated Annual Groundwater Pumping by Aquifer Source in Texas Counties in Study Area: 1980 through 2016

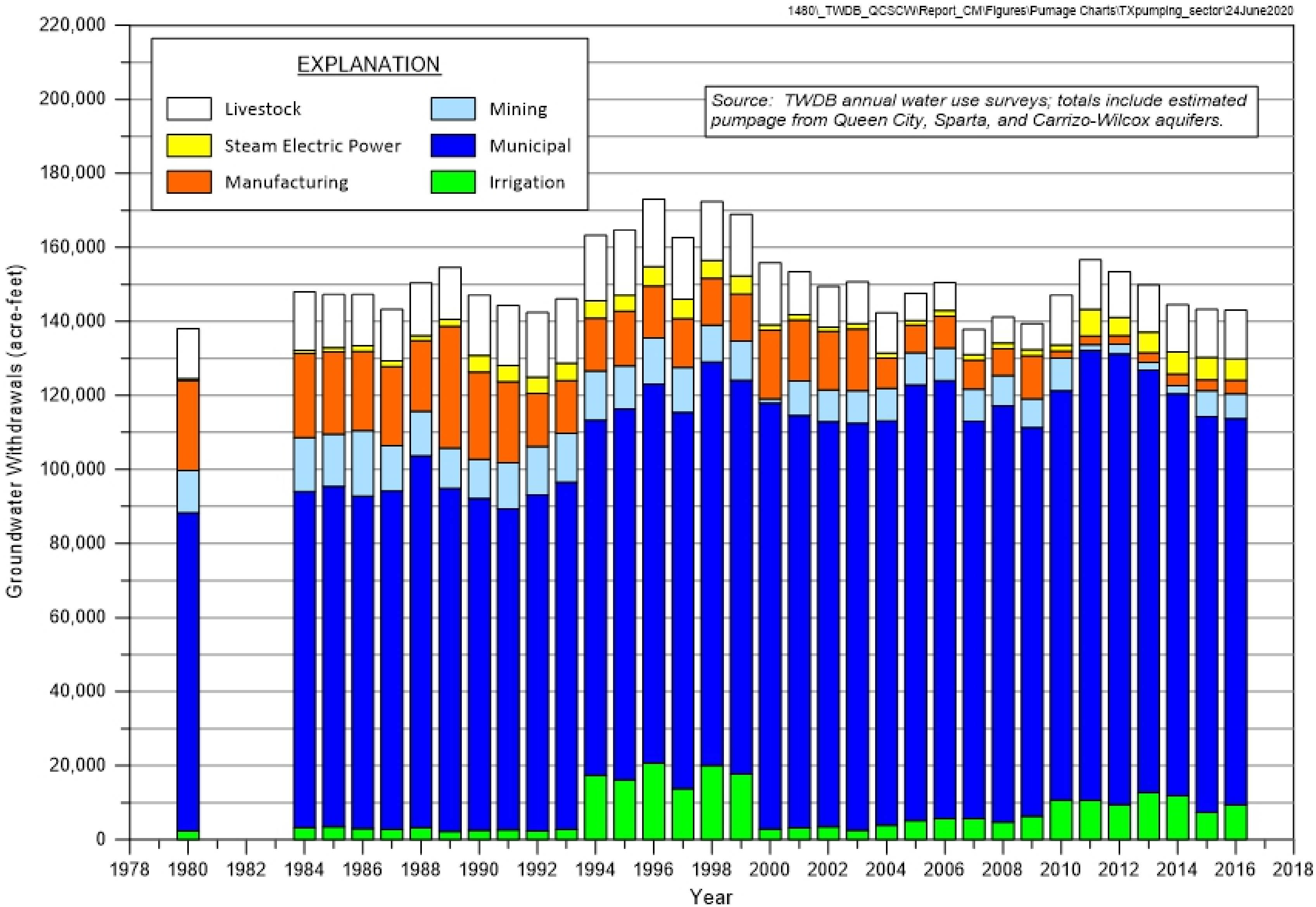
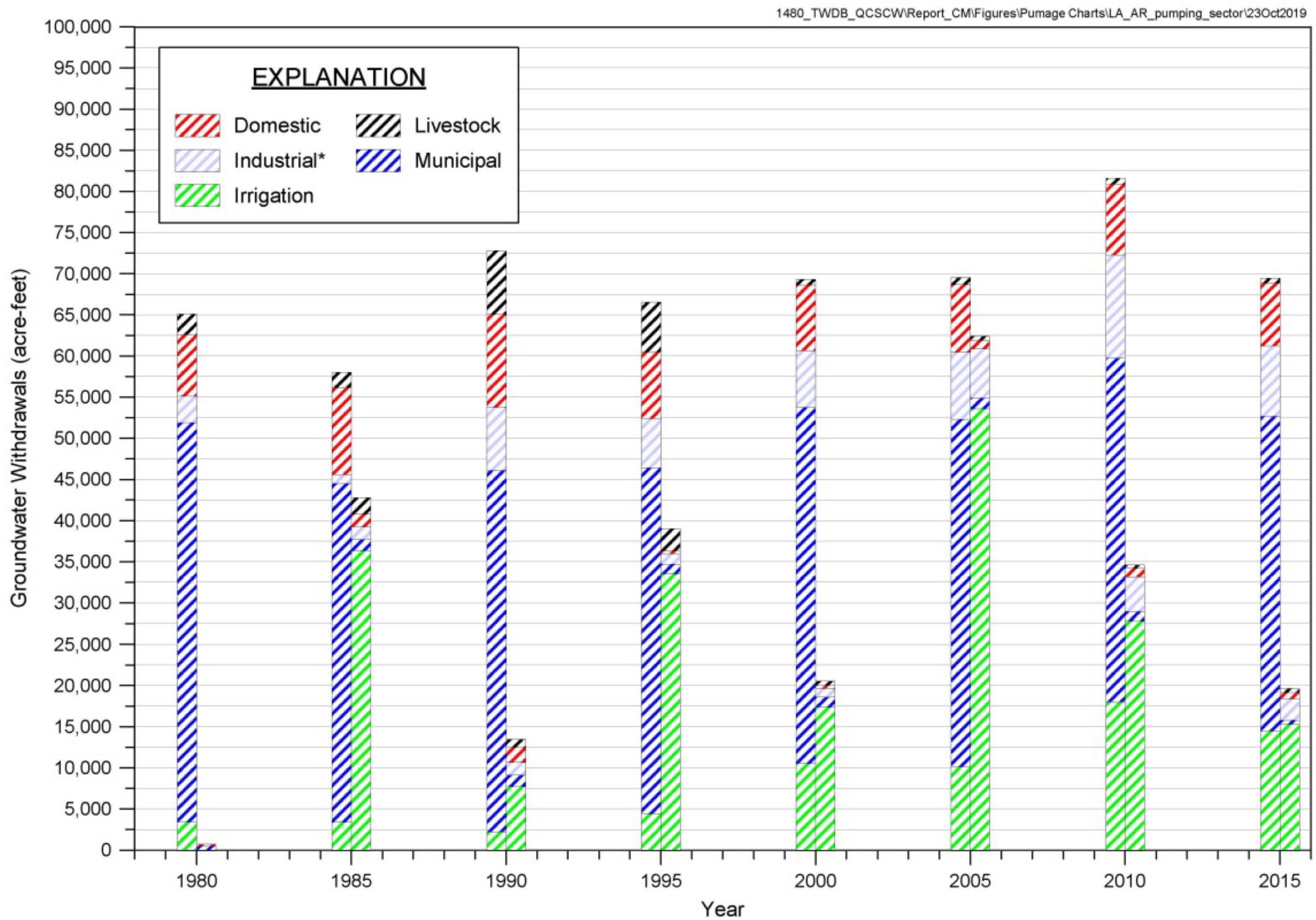
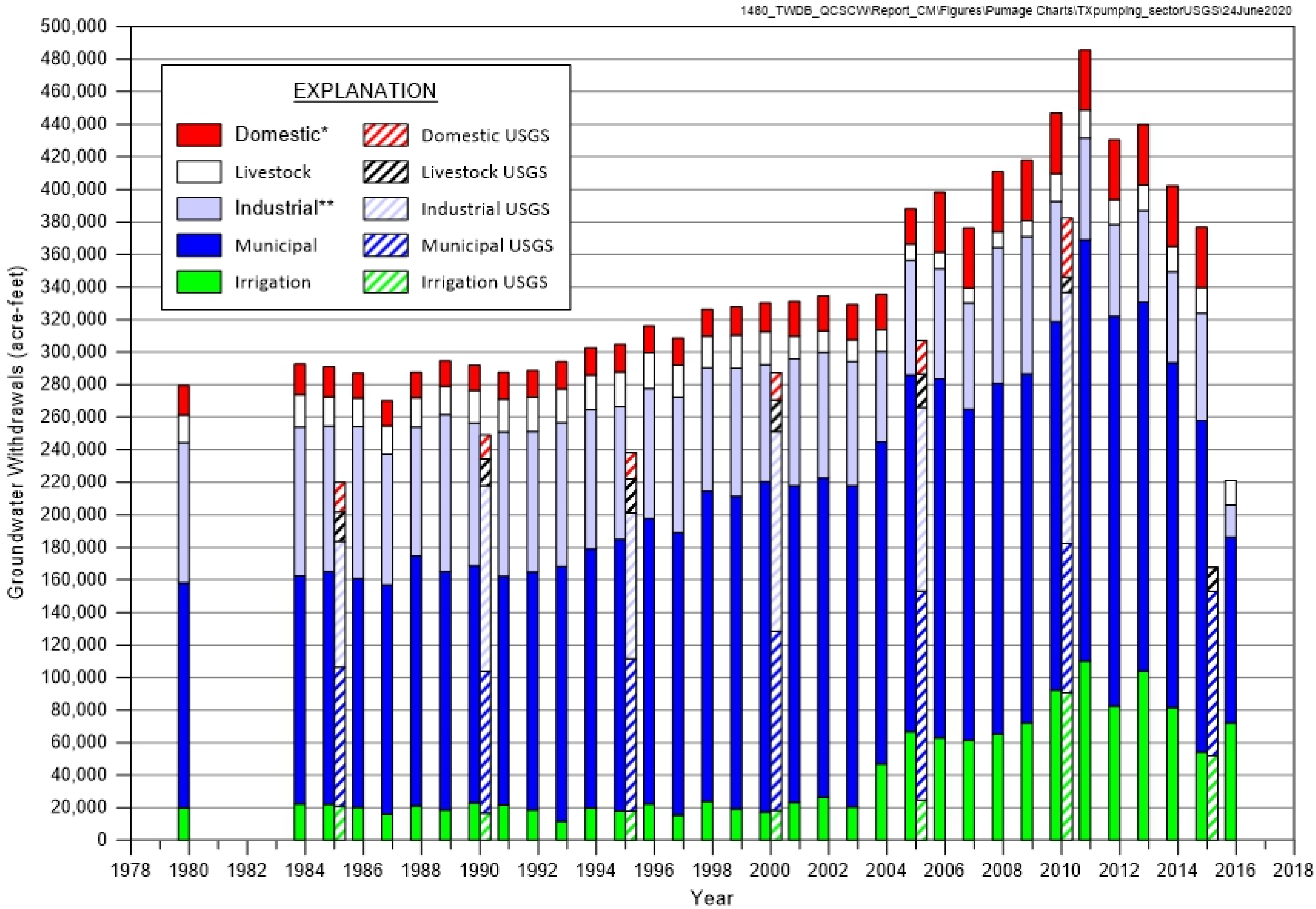


Figure 4-63. Estimated Annual Groundwater Pumping by Water Use Sector in Texas Counties in Study Area: 1980 through 2016



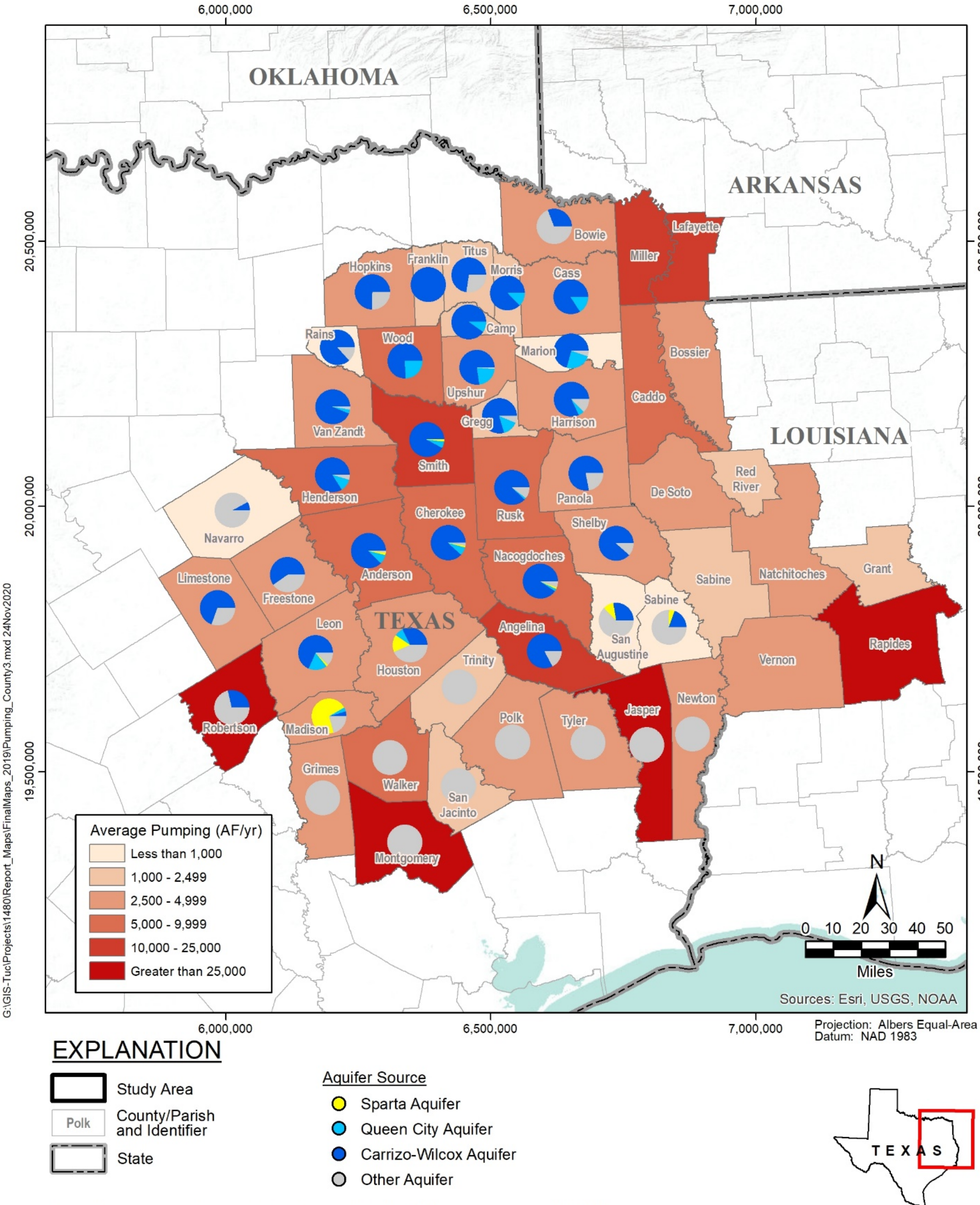
Source: USGS 5-year water use survey pumping estimates (Totals include pumping from all aquifer sources in a county or parish); bar totals on the left side of each pair are for Louisiana, and on the right are for Arkansas
**Industrial category includes the sum of the reported estimates for industrial, mining, electric power, and aquaculture sectors*

Figure 4-64. Estimated Annual Groundwater Pumping by Water Use Sector in Louisiana Parishes and Arkansas Counties in Study Area



Source: *TWDB annual water use survey and USGS 5-year water use reports pumping estimates; data are for all aquifers, including units not included in this GAM.*
**Domestic values were estimated based on the USGS data applied to the number of TWDB listed domestic wells for a given year*
***Industrial category includes the sum of manufacturing, mining, and electric power sectors*

Figure 4-65. Comparison of TWDB and USGS Total Annual Groundwater Pumping Estimates by Water Use Sector in Texas Counties in Study Area: 1980 through 2015



Source: Pumping and aquifer source data for Texas counties from TWDB water use surveys 1980-2016.
Pumping data for Arkansas counties and Louisiana parishes from USGS 5-year water use reports 1980 -2015; aquifer source data not available.

Pie charts show relative proportions of average annual pumping by aquifer source for the county.

Figure 4-66. Summary of Average Pumping for Counties and Parishes in Study Area: 1980 through 2015

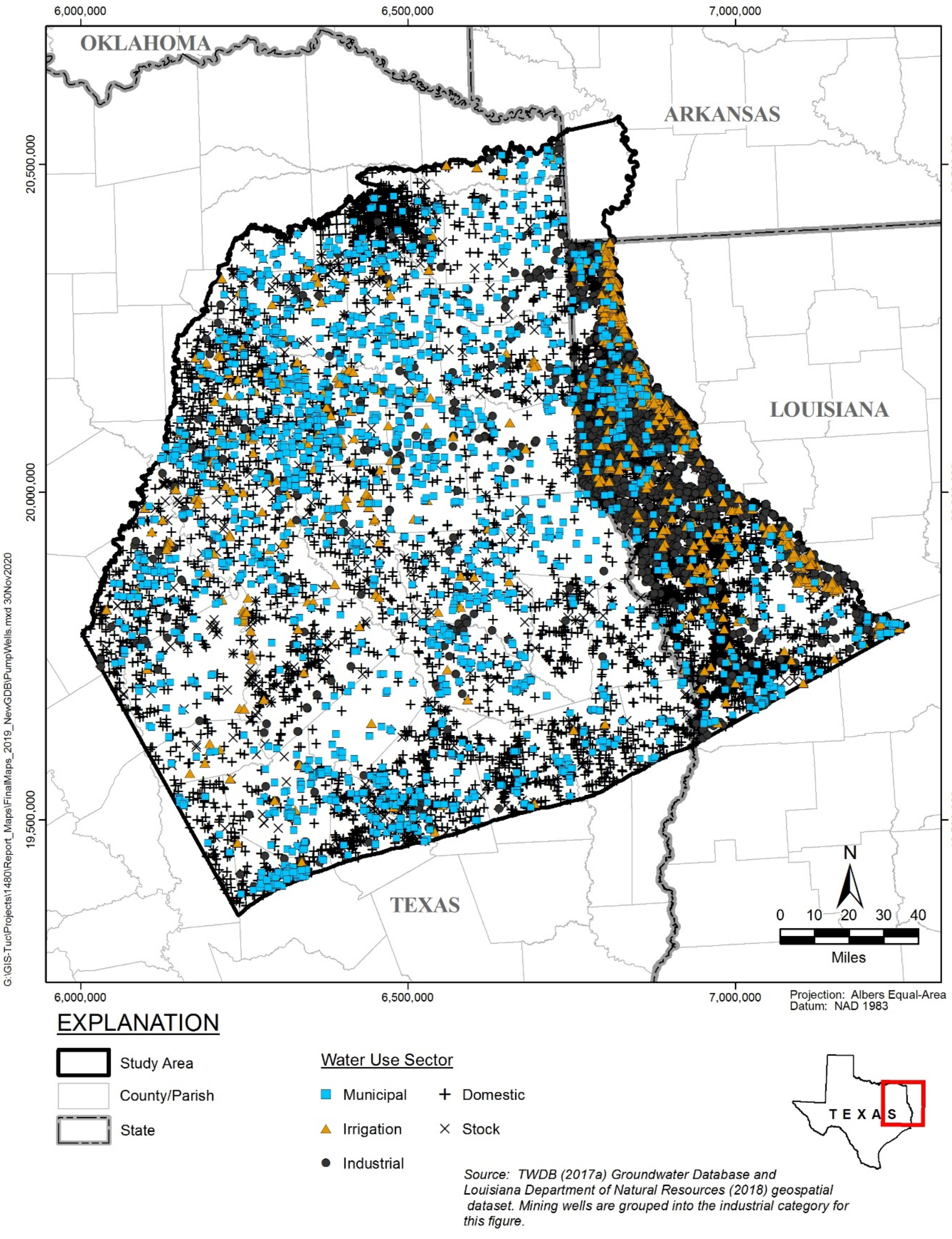


Figure 4-67. Locations of Reported Groundwater Production Wells in Study Area

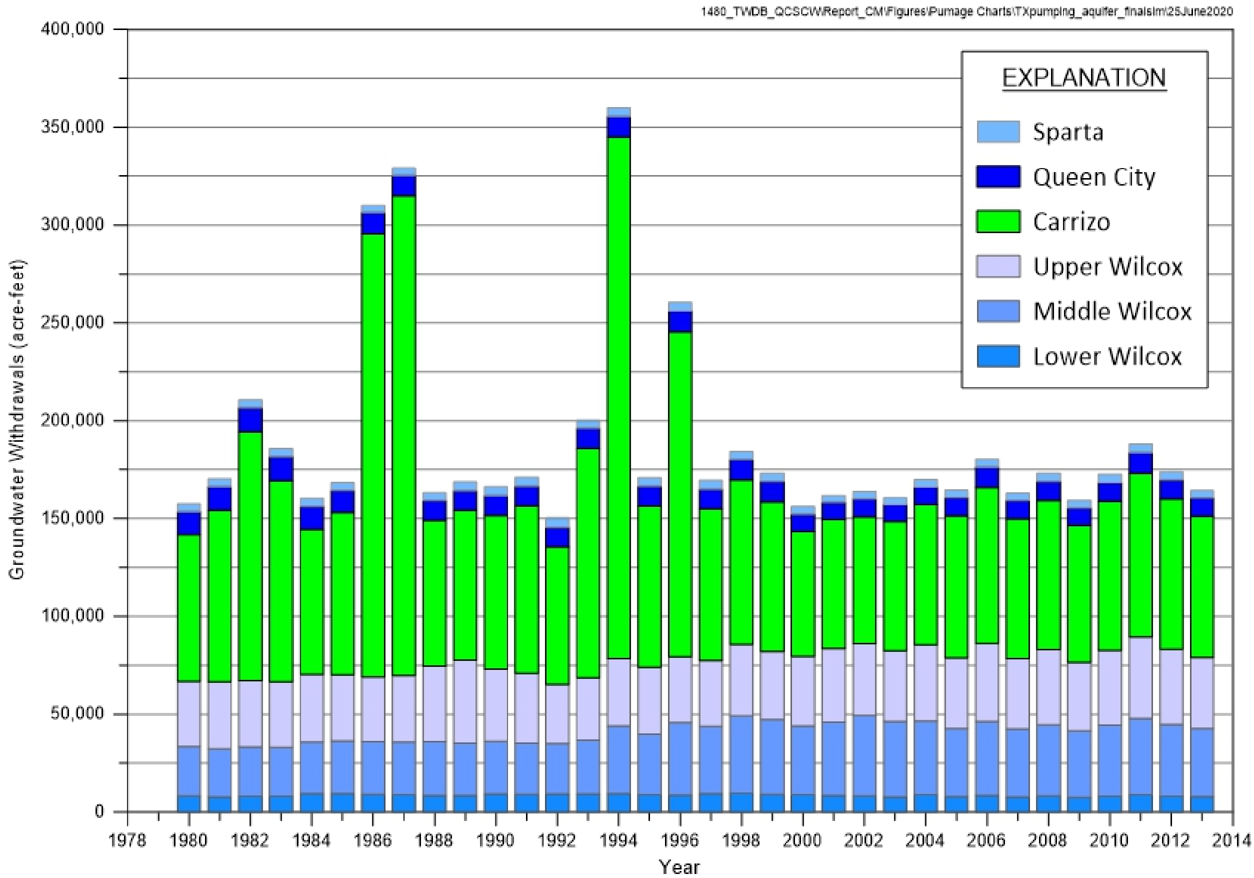


Figure 4-68. Adjusted Annual Groundwater Pumping Used to Calibrate Groundwater Model.

4.7.2 DISCHARGE TO RIVERS AND SPRINGS

Base streamflow is the contribution of groundwater to gaining reaches along a stream. Numerous stream gain/loss studies have been conducted for rivers and tributaries in the study area, particularly for the Carrizo-Wilcox Aquifer. The results of these gain/loss surveys indicate that most major rivers and tributaries have gaining streamflows, which is consistent with streamflow characteristics previously summarized in Section 4.4.1 of this report.

Groundwater discharge also occurs at springs and seeps where the water table intersects the land surface. Springs generally occur in low lying areas along river valleys and in outcrop areas where hydrogeologic conditions preferentially reject recharge (Kelley and others, 2004). Locations of springs in the study area are shown on Figure 4-46. Fryar and others (2003) and Kelley and others (2004) conducted a literature survey of springs in the outcrop areas in the study area for the previous groundwater availability models. For this study, the springs dataset from Kelley and others (2004) was updated with spring features listed in the United States Geological Survey National Hydrography Dataset. Information for 633 springs was compiled from these sources. The number of springs in the area is a result of humid climate, gently dipping aquifer layers, and a dissected topography, all of which contribute to rejected recharge and runoff in the region. Thousands of smaller springs in the study area are likely undocumented, particularly in the northeast (Kelley and others, 2004). Flow data are missing for most springs in the study area. Available measured flow rates range from less than 0.01 ft^3 per second (cfs) (<7 AF/yr) to 3.4 cfs (2,462 AF/yr) measured at Elkhart Creek Springs, which originate from the Sparta Sand (Brune, 1975; Kelley and others, 2004).

Spring flows in the study area have generally declined though time. Brune (1981) reported that groundwater level declines due to pumping and flowing wells have caused thousands of smaller springs to dry up and reduced flows in larger springs. Although pumping in the study area has resulted in a decline and drying of spring flows, numerous springs still discharge to the surface (Kelley and others, 2004).

4.7.3 EVAPOTRANSPIRATION

Evapotranspiration is the loss of water from a vegetated surface through the combined processes of soil evaporation and plants transpiration (University of Arizona Cooperative Extension, 2000). Evapotranspiration rates depend on plant density, plant age, depth to groundwater, and available soil moisture from infiltration of precipitation. This study is principally interested in the interaction of plants with groundwater. Inputs to the groundwater model include location of evapotranspiration, maximum evapotranspiration rate, and evapotranspiration extinction depth (or rooting depth). Evapotranspiration of groundwater occurs when groundwater levels are above the maximum rooting depth of the vegetation.

Limited information exists regarding groundwater use by native vegetation and crops within the study area. Vegetation present in the Texas portions of the study area includes pine hardwood, oak woodlands, elm and hackberry forest, and grasslands (Figure 2-10). The dominant vegetation type is pine hardwood. Many of these plants have deep root depths and are likely sustained in part by groundwater consumption. Similar vegetation maps are not readily available for this study for Louisiana and Arkansas.

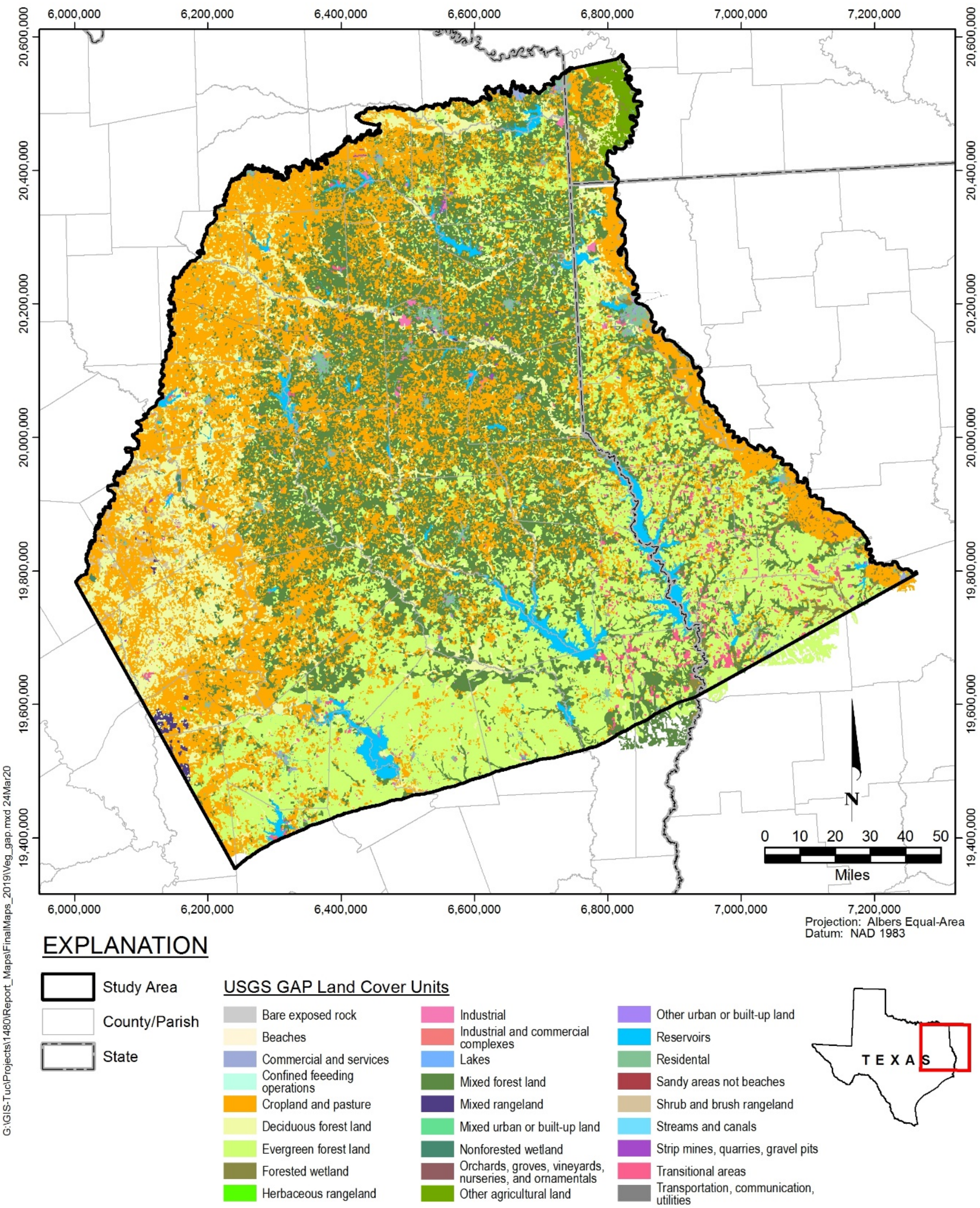
The Unites States Geological Survey's Gap Analysis Project (USGS, 2011) land cover dataset was obtained for a continuous and consistent coverage of vegetation and land cover. The Unites States Geological Survey's Gap Analysis Project land cover dataset for the study area is shown on Figure 4-69. Although the United States Geological Survey dataset lacks the details vegetation species provided by the Texas vegetation dataset, it can be useful for understanding the complex distributions of vegetation across the entire study area.

Potential evapotranspiration was simulated in the previous Groundwater Availability Model developed by Kelley and others (2004) for the northern portions of the Queen City and Sparta aquifers. For that Groundwater Availability Model, the United States Department of Agriculture's Soil Water Assessment Tool was used to estimate groundwater evapotranspiration and evapotranspiration extinction depth. The United States Department of Agriculture's Soil Water Assessment Tool was used because it is a physically based method for estimating regional components of a groundwater system. Potential evapotranspiration is converted to actual evapotranspiration based on vegetation type and model-calculated soil water availability, using user-specified climate and vegetation information. For each stress period of the previous groundwater availability model, the United States Department of Agriculture's Soil Water Assessment Tool was used to calculate max evapotranspiration rate and evapotranspiration extinction depth for every model grid cell. The average maximum evapotranspiration rate for each evapotranspiration cell in the previous groundwater availability model is shown on Figure 4-70. Note that evapotranspiration was not simulated south of the interface between the Sparta Sand and overlying younger units which are not a part of this study. Maximum evapotranspiration rates specified in the model range from less than 0.001 ft/day to more than 0.0025 ft/day. Evapotranspiration rates are generally small in the northern portions of the study area. The largest evapotranspiration rates occur in the central portions of the study area, just north of the interface with the younger units. Evapotranspiration extinction depths were also estimated for each grid cell and remained constant through the simulation period. Extinction depths ranged from less than 1 foot to 7.6 feet. Canadell and others (1996) report a range for maximum rooting depths for temperate terrestrial biomes of up to 5 meters (16 feet) with an average of 2 to 3 meters (7 to 10 feet).

4.7.4 CROSS-FORMATIONAL FLOWS

Groundwater discharge also occurs as cross-formational groundwater flows from one aquifer unit to an adjacent unit. Flow across the Reklaw Formation, which is a confining unit, is generally downward from the Queen City Aquifer to the Carrizo Aquifer (Fogg and Kreitler, 1982; Fogg and others, 1983). However, hydraulic gradients are reversed in the vicinity of the Trinity and Sabine rivers with groundwater from the Carrizo-Wilcox Aquifer discharging through upward leakage across the Reklaw. Fogg and others (1983) concluded that such leakage across the Reklaw must be substantial because effects of topography can be seen in large portions of the confined Carrizo Aquifer.

Cross-formational flows are also indicated by the pressure versus well depth analyses conducted for developing the previous groundwater availability models, as summarized in Section 4.2.1 of this report. Results of those analyses indicate that upward groundwater movement occurs in the southern and central portions of the study area, and downward movement occurs in the northern portions. Furthermore, these previous studies found evidence suggesting a decrease in upward flows through time in the central portions of the study area and an increase in downward flows through time in the northern portions. Groundwater level elevation contours shown on Figure 4-31, Figure 4-32 and Figure 4-33 also suggest that groundwater movement is upward from the Middle Wilcox into the overlying Upper Wilcox and Carrizo Sand in the down-dip central-south portions of the aquifer system.



Source: United States Geological Survey Gap Analysis Project (GAP) (2011)

Figure 4-69. Land Cover Distribution in Study Area

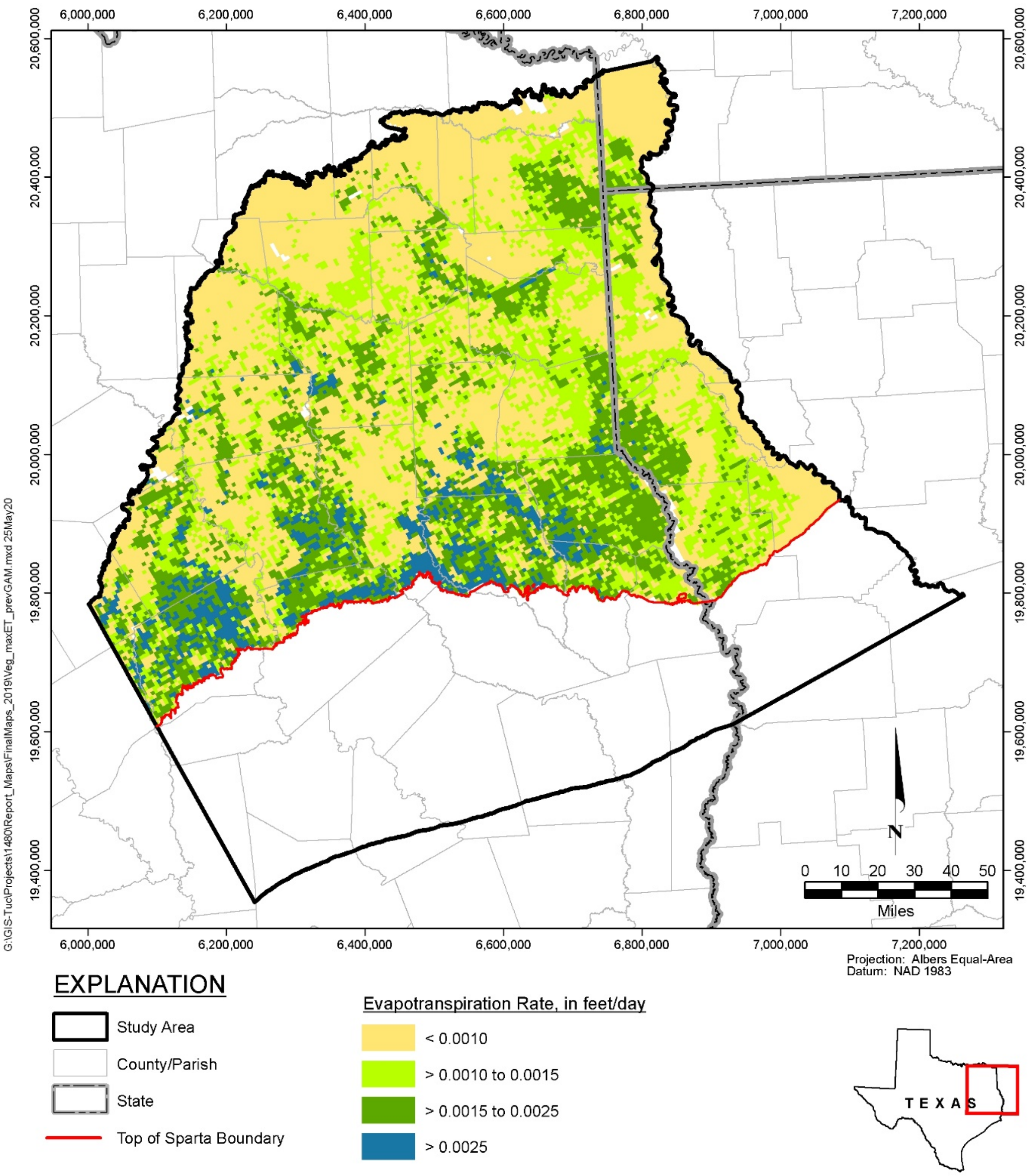


Figure 4-70. Average Maximum Evapotranspiration Rate Specified in Previous Groundwater Availability Model for Northern Portions of Queen City and Sparta Aquifers

4.8 WATER QUALITY

Water quality of the aquifer system is considered herein for completeness and qualitative interpretations for the conceptual model. Changes in water quality in the study area will not be simulated in the groundwater availability model.

4.8.1 PREVIOUS STUDIES

In the previous groundwater availability model for the Northern Carrizo-Wilcox Aquifer, Fryar, and others (2003) evaluated water quality in terms of drinking water quality, irrigation water quality, and industrial water quality. Screening levels were set for each category based on maximum contaminant levels (MCL) or by setting limits on constituents of concern for suitability of crop irrigation and industrial purposes. All available historical data, from about 1920 to 2001, were compiled from TWDB, the United States Geological Survey, and the Texas Commission on Environmental Quality Public Water System and compared to screening levels to find the percentage of wells in the model area that have an exceedance at any time in the historical record. Notable primary maximum contaminant level exceedances include nitrate and lead and secondary maximum contaminant level exceedances include total dissolved solids, iron, and manganese. For irrigation water quality, high specific conductance and sodium adsorption ratios were found and considered to be an indication for salinity hazard. For industrial water use, pH, hardness, and silica were found to exceed screening levels and indicate increased potential for corrosion, scaling, and sediment buildup. For percentage of wells with exceedances, see Appendix F of the model report (Fryar and others, 2003).

In the previous groundwater availability model for the northern Queen City and Sparta aquifers, Kelley, and others (2004) performed an analysis of hydrochemical facies. Data were compiled from TWDB and the United States Geological Survey for oil and gas wells near the southern boundary of the Queen City and Sparta aquifers. Using the most recent sample for each well, hydrochemical facies were calculated to describe the major dissolved cations and anions; the cation name reflected the one which made up more than 50 percent of the total cationic charge, and the same calculation was done for anions. The dominant facies in the Queen City and Sparta aquifers were calcium-bicarbonate type, sodium-bicarbonate type, and sodium-mixed anion type. Samples with a calcium-bicarbonate type water dominate in the unconfined Queen City aquifer and are more prevalent in the northern part of the aquifer than in the southern part. In the Sparta Aquifer, sodium-bicarbonate type water dominates in the north and sodium-mixed anion type water is dominant in the south. Generally, the Queen City and Sparta aquifers have similar chemical compositions and trends, with a regional increase in total dissolved solids from north to south. A pattern of down-dip increase in total dissolved solids was found, with an average of 305 and 287 milligrams per liter (mg/L) in the unconfined area versus 759 and 784 mg/L in the confined area, in the Queen City and Sparta aquifers, respectively (Kelley and others, 2004). The study concluded that total dissolved solids concentrations generally increase down-dip in each aquifer layer. Smaller total dissolved solids concentrations in outcrop areas indicate displacement of connate water with meteoric water (recharge of precipitation). Total dissolved solids concentrations are larger in deeper, down-dip portions of the aquifer layers, indicating less displacement of connate water by meteoric water. Displacement of connate water by meteoric water is controlled by the recharge rate, extent of recharge area, and aquifer hydraulic properties.

4.8.2 DATA SOURCES

In this report, groundwater quality data was compiled from the TWDB Groundwater Database for wells within the model boundary in Texas, and from the United States Geological Survey National Water Information System for wells within the study area in Arkansas and Louisiana. General water quality was evaluated in terms of drinking, irrigation, and industrial water quality based on screening levels developed by Fryar and others (2003), using only samples taken since 2010. A more detailed analysis of the spatial and temporal distribution of total dissolved solids was performed to evaluate salinity in the study area.

A detailed characterization of salinity (represented as total dissolved solids) is not required for the current groundwater flow model. However, an attempt was made to assess salinity using the borehole geophysical logs evaluated for developing the hydrostratigraphic framework for this study. Although not apparent in most logs, a muted signal in the geophysical log often indicated influence by brackish water. This was evident in some logs in deep, down-dip portions of the aquifer units and in logs for Wilcox units in the northern portion of the study area.

4.8.3 WATER QUALITY EVALUATION BASED ON WATER USE

To evaluate drinking water quality, samples since 2010 were analyzed to find exceedances of any constituent with a United States Environmental Protection Agency designated primary or secondary maximum contaminant levels. Since 2010, there have been primary maximum contaminant level exceedances in at least one well within the model boundary of lead and selenium, and secondary maximum contaminant level exceedances of aluminum, chloride, fluoride, iron, manganese, pH, sulfate, and total dissolved solids. Consistent with the findings of Fryar and others (2003), constituents with the largest percentage of wells showing exceedances are iron (16 percent), manganese (17 percent), pH (54 percent) and total dissolved solids (23 percent). Primary maximum contaminant level exceedances occurred solely at Carrizo-Wilcox wells. Locations of the exceedances are shown on Figure 4-71. Secondary maximum contaminant level exceedances occurred in multiple aquifer units, as shown on Figure 4-72, Figure 4-73, and Figure 4-74.

For irrigation use, salinity hazard was evaluated based on specific conductance and sodium adsorption ratio. High specific conductance was found in 30 percent of wells, and high sodium adsorption ratio in 44 percent of wells (very high in 35 percent). Boron, chloride, and total dissolved solids were other potential constituents of concern for irrigation purposes but were not found in concentrations unsuitable for irrigation. Locations of irrigation water quality exceedances are shown on Figure 4-75, Figure 4-76, and Figure 4-77.

Constituents associated with scaling, corrosion, and sediment buildup were evaluated to assess the quality of groundwater for industrial purposes. Notable exceedances include high silica concentration in 15 percent of wells, and pH out of the 6.5-8.5 range in 54 percent of wells. Locations of industrial water quality exceedances are shown on Figure 4-78 and Figure 4-79. Results for those constituents for which exceedances were found are summarized in Table 4.12.

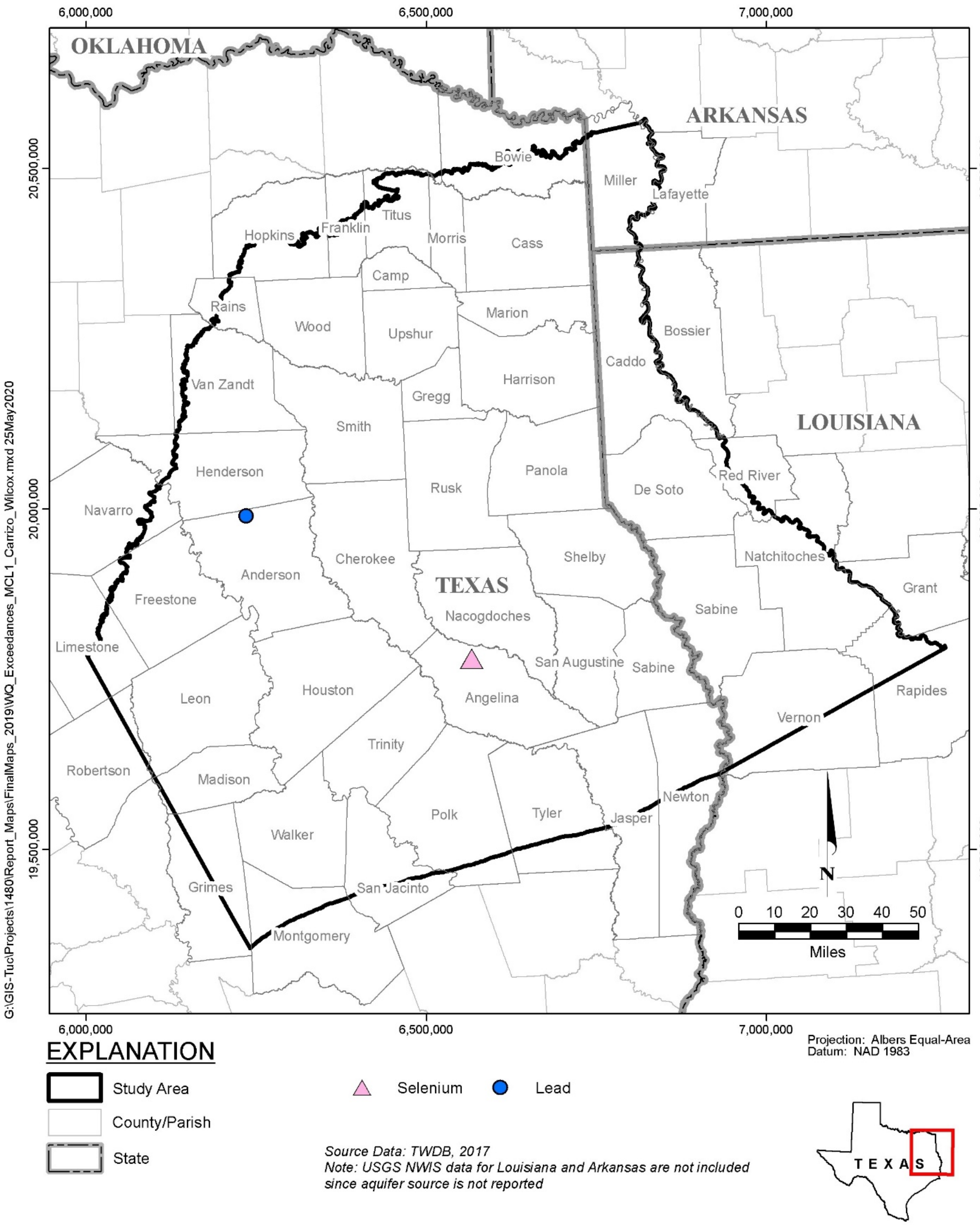


Figure 4-71. Locations of Primary Maximum Contaminant Level Exceedances in Well Completed in Carrizo-Wilcox Aquifer Since 2010

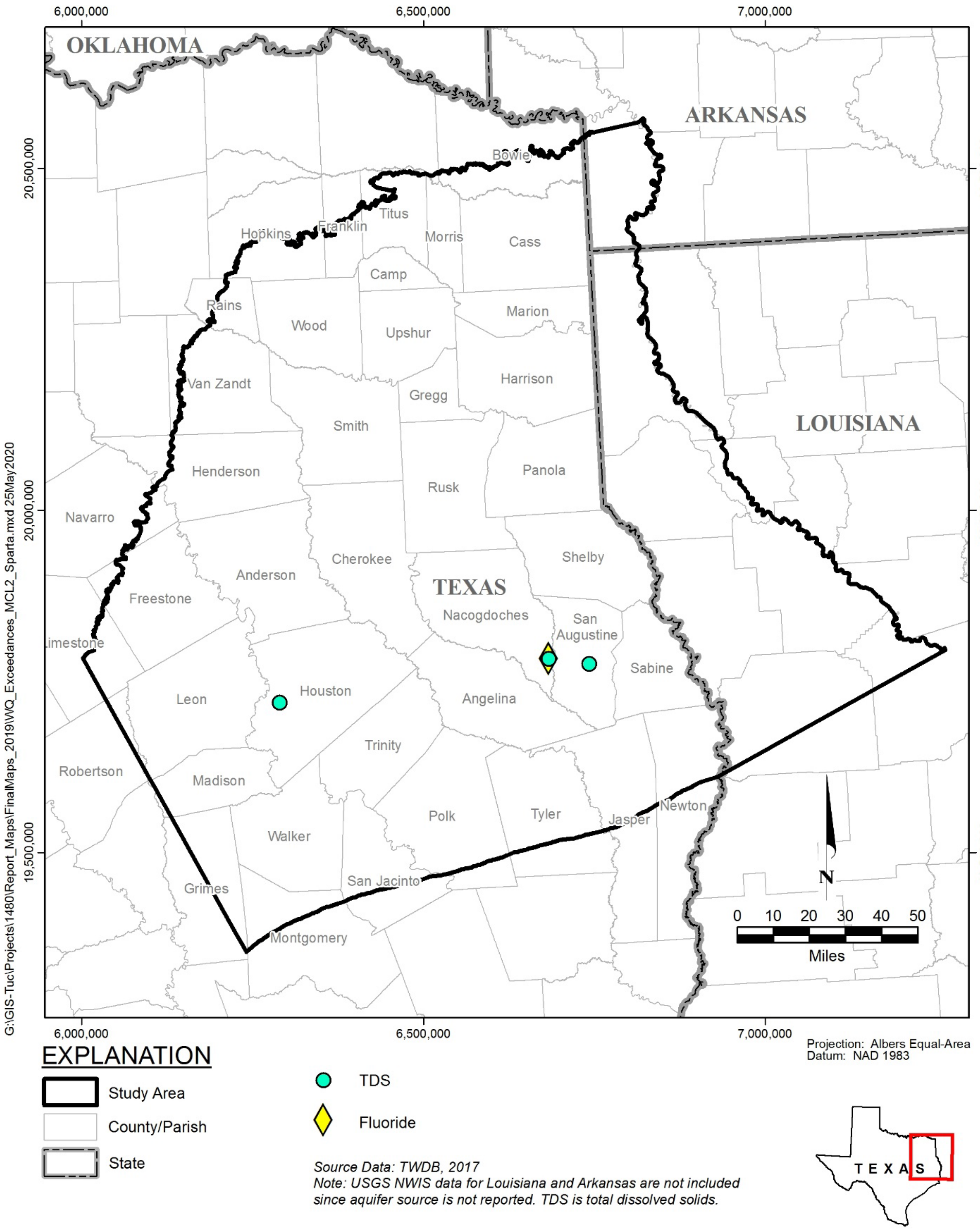


Figure 4-72. Locations of Secondary Maximum Contaminant Level Exceedances in Well Completed in Sparta Aquifer Since 2010

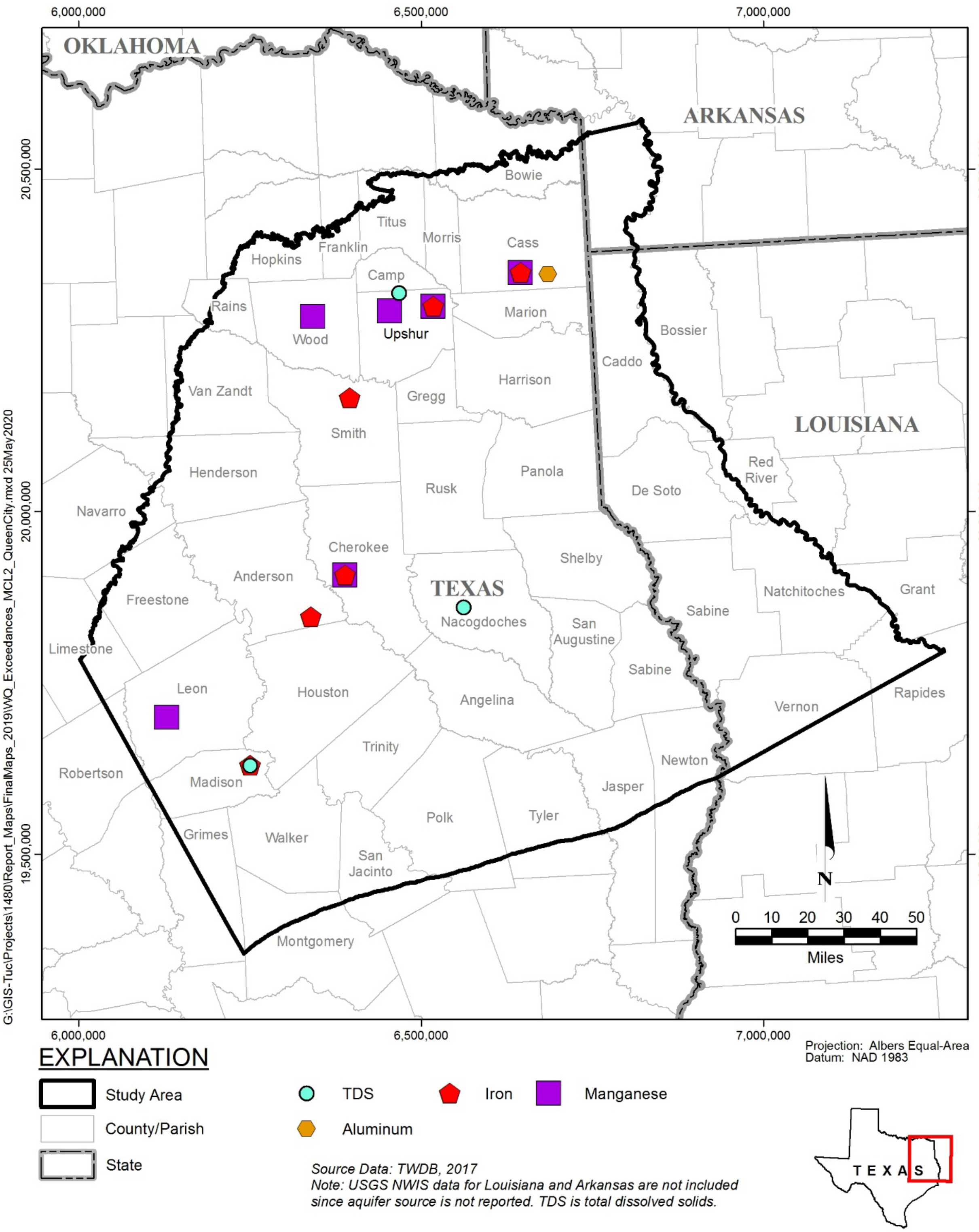


Figure 4-73. Locations of Secondary Maximum Contaminant Level Exceedances in Well Completed in Queen City Aquifer Since 2010

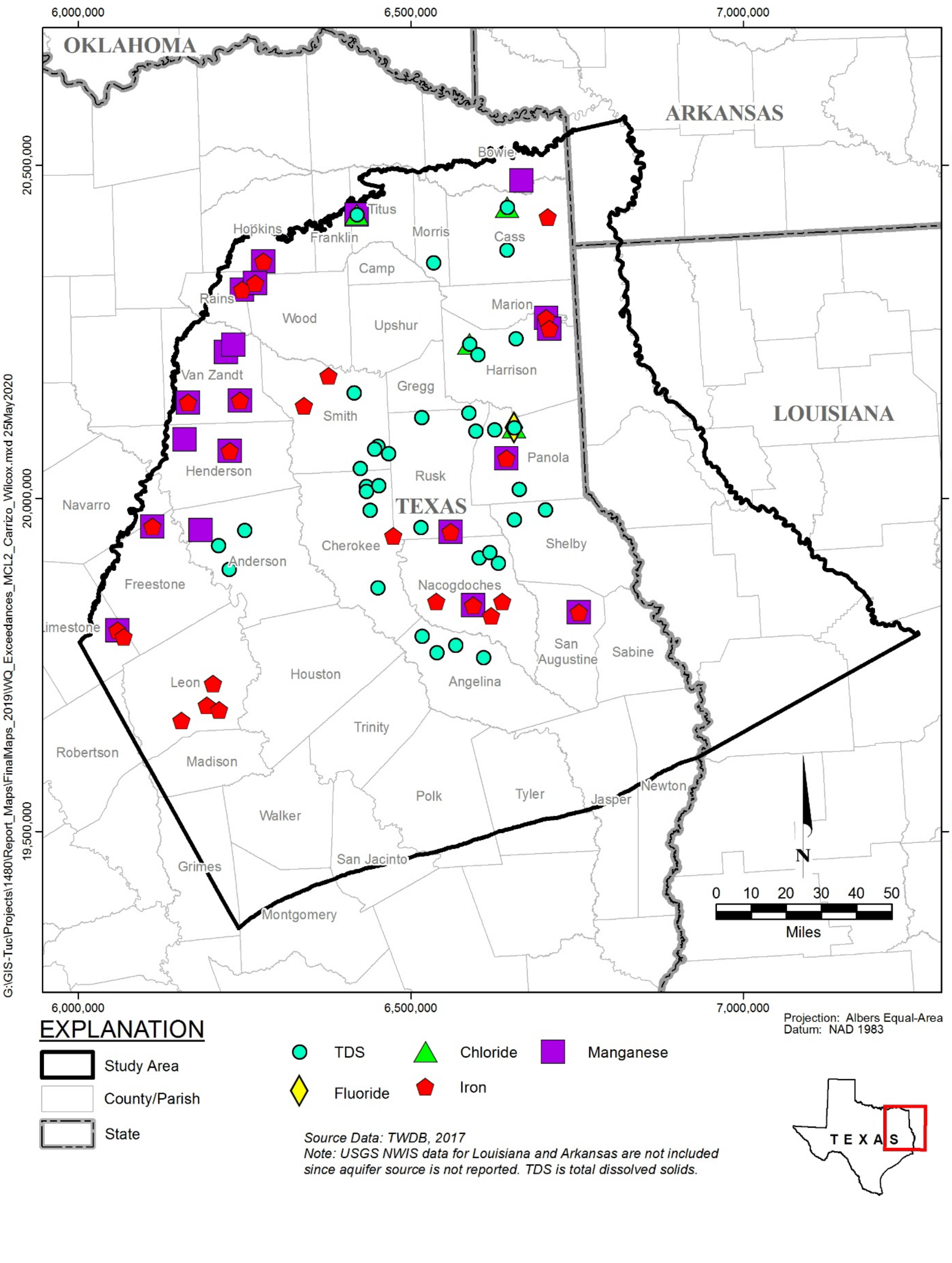


Figure 4-74. Locations of Secondary Maximum Contaminant Level Exceedances in Well Completed in Carrizo-Wilcox Aquifer Since 2010

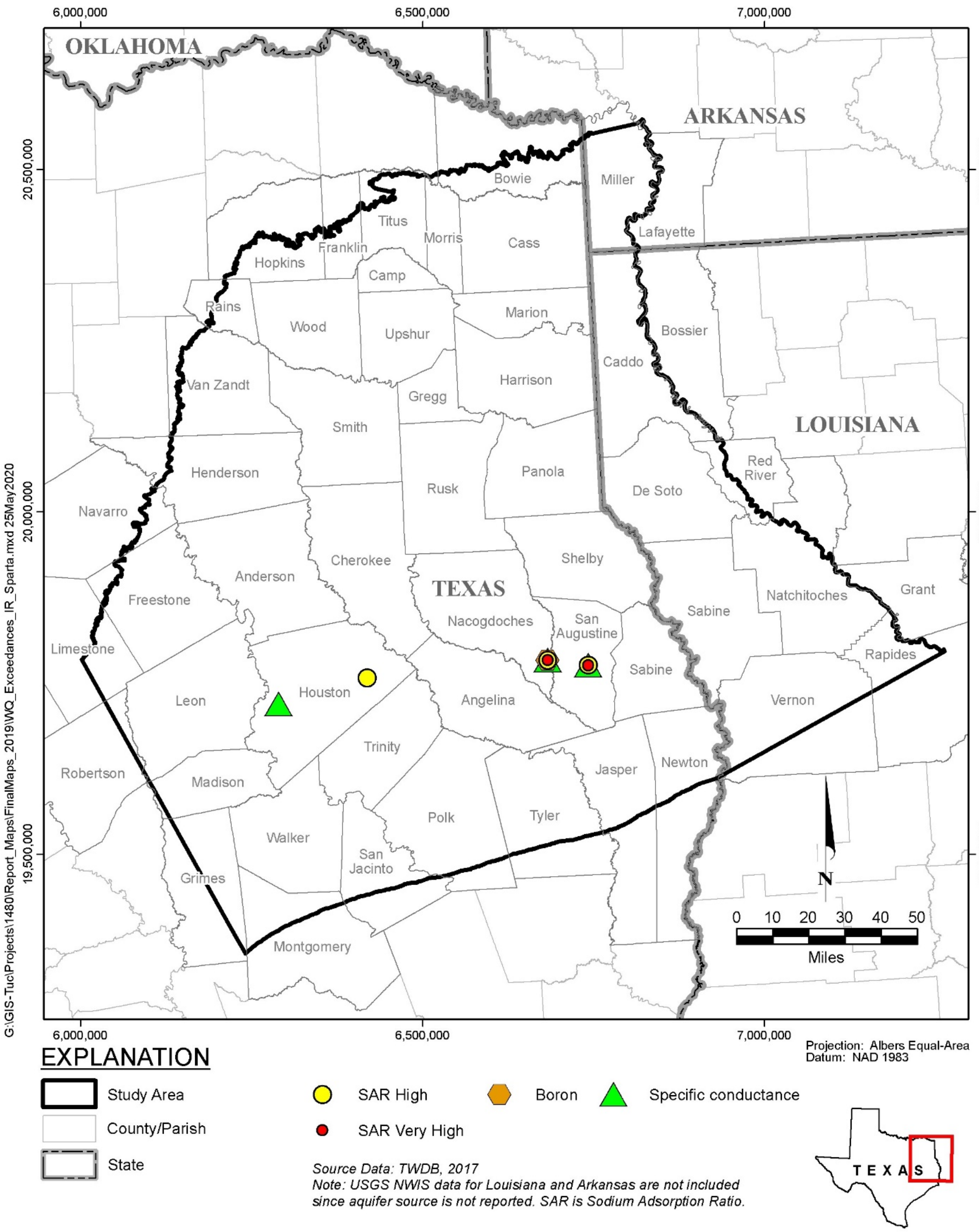


Figure 4-75. Locations of Irrigation Water Quality Exceedances in Well Completed in Sparta Aquifer Since 2010

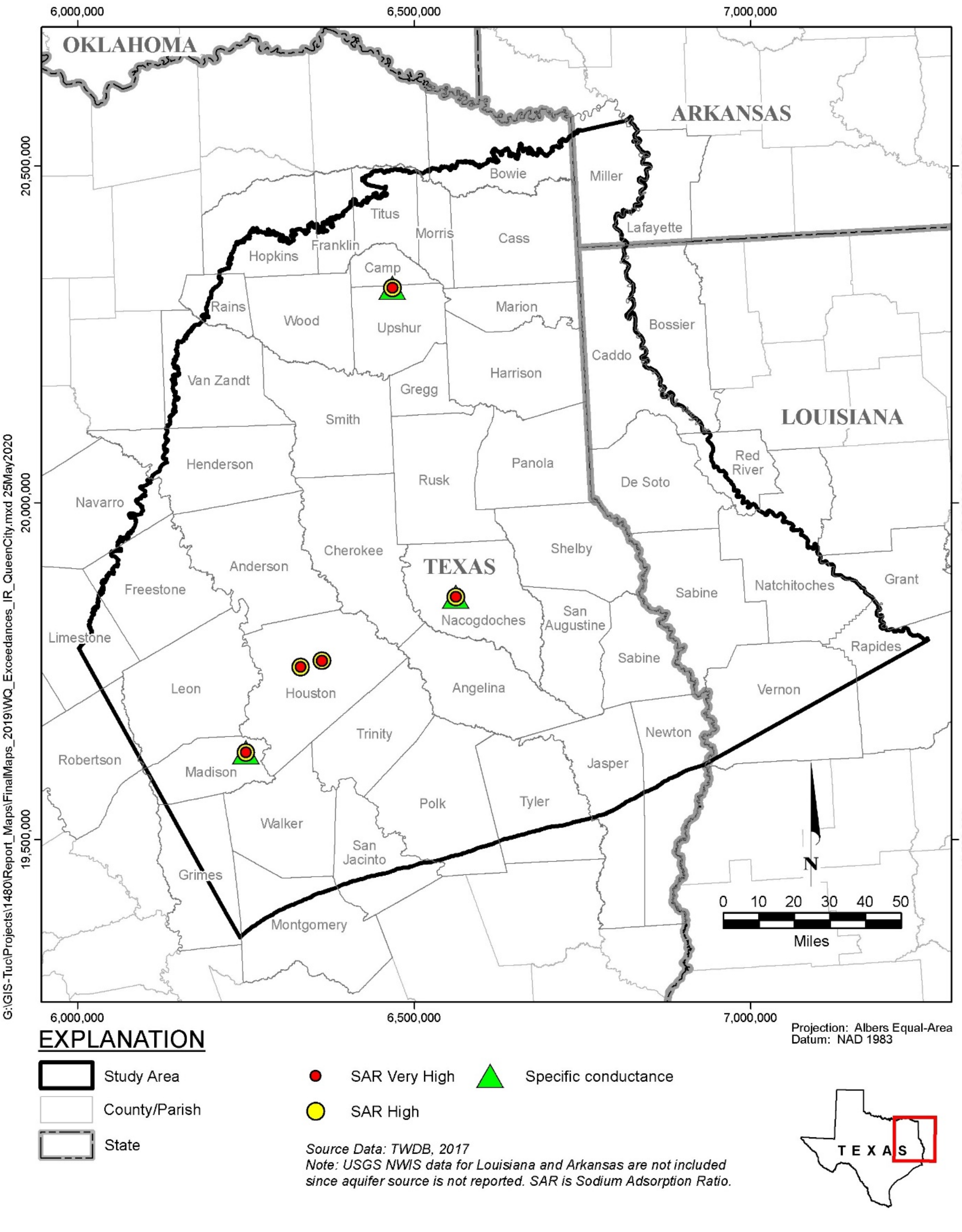


Figure 4-76. Locations of Irrigation Water Quality Exceedances in Well Completed in Queen City Aquifer Since 2010

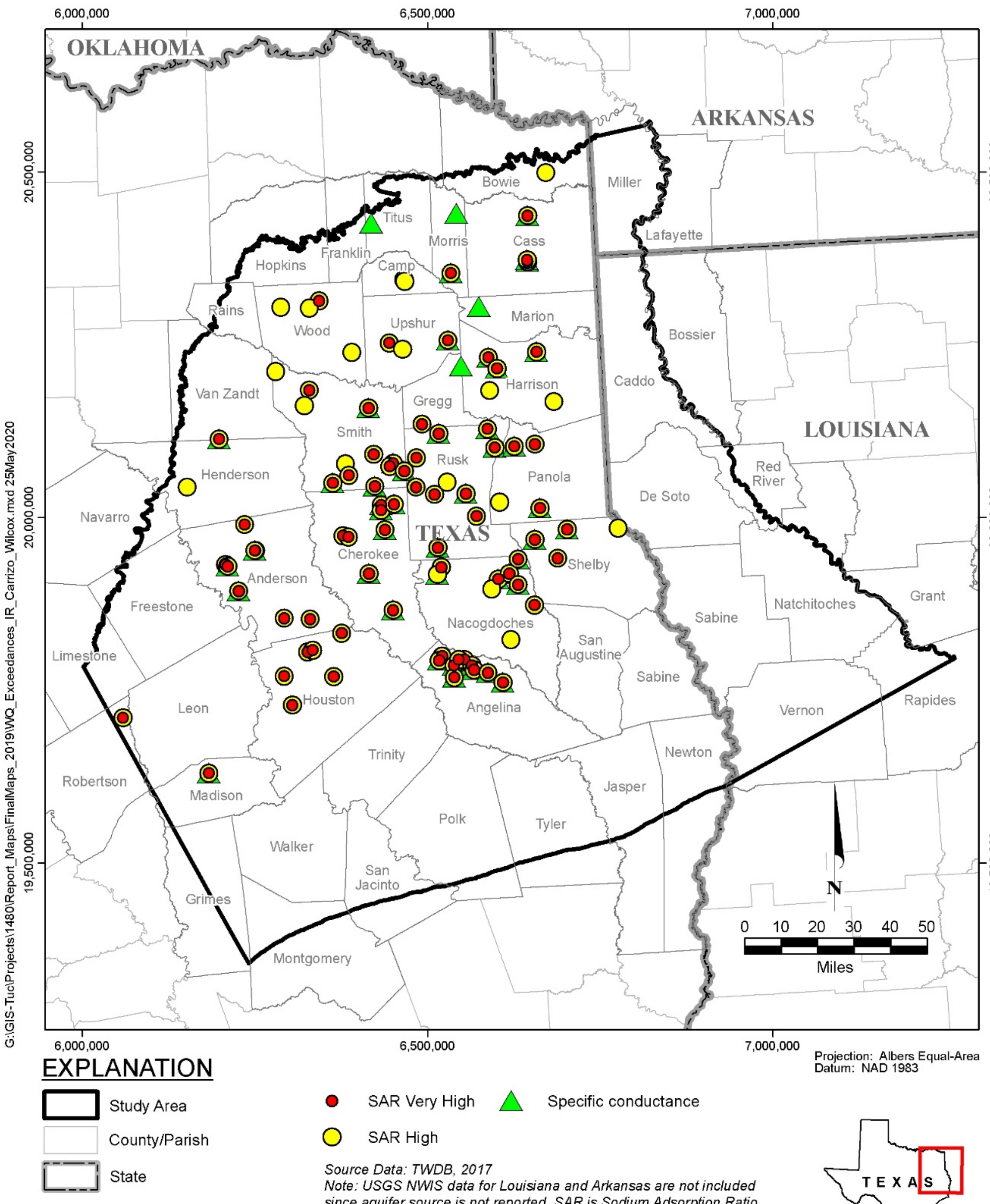


Figure 4-77. Locations of Irrigation Water Quality Exceedances in Well Completed in Carrizo-Wilcox Aquifer Since 2010

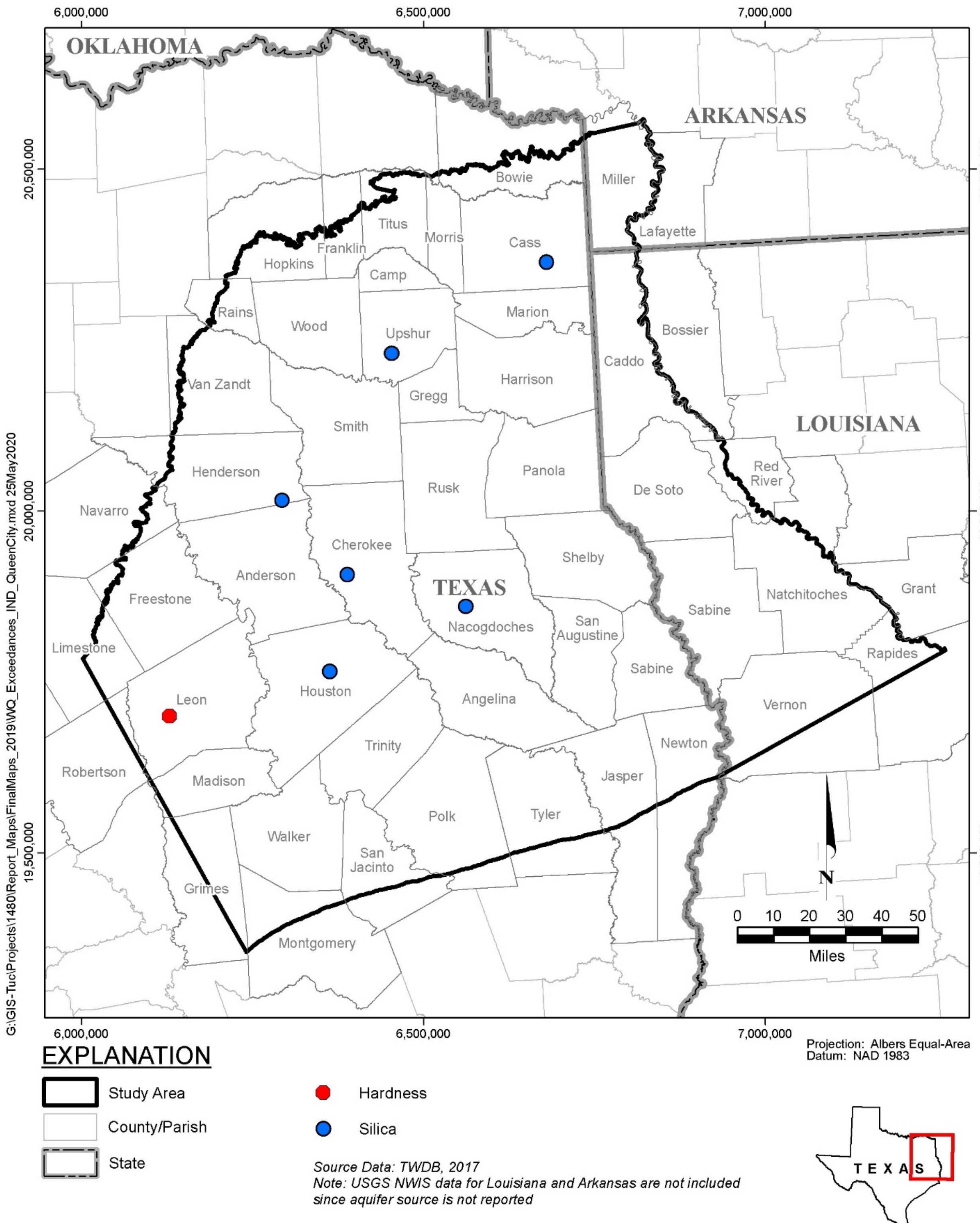


Figure 4-78. Locations of Industrial Water Quality Exceedances in Well Completed in Queen City Aquifer Since 2010

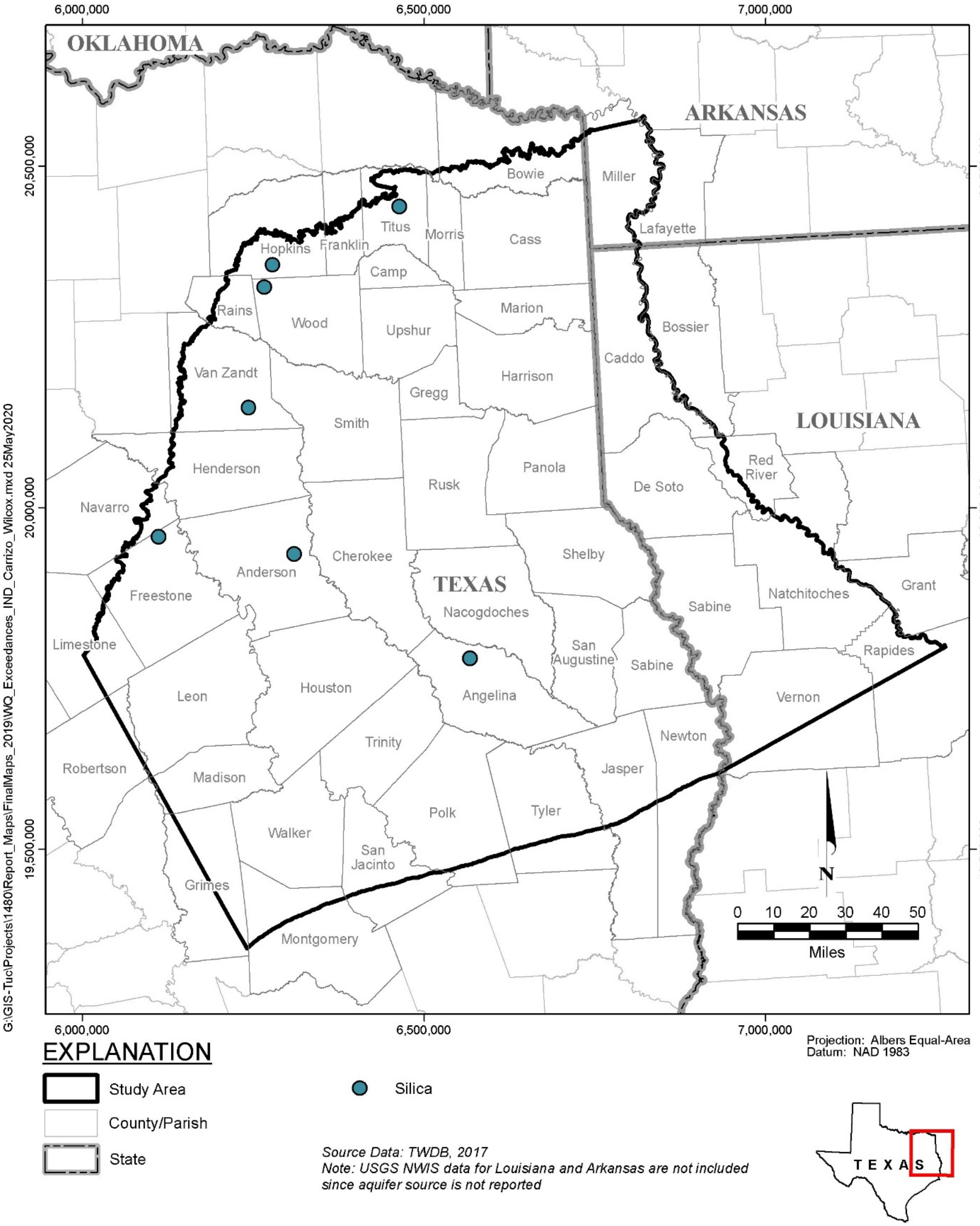


Figure 4-79. Locations of Industrial Water Quality Exceedances in Well Completed in Carrizo-Wilcox Aquifer Since 2010

Table 4.12. Summary of Exceedances of Water Quality Standards for Selected Constituents at Wells in Study Area

Constituent	Screening Level (mg/L)[a]	Type of Exceedance	Number of Wells Sampled Since 2010	Number of Wells with Exceedance Since 2010	Percent of Wells with Exceedance Since 2010
Lead	15	Primary MCL[b]	215	1	0.5%
Selenium	50	Primary MCL	215	1	0.5%
Aluminum	0.2	Secondary MCL	215	1	0.5%
Chloride	250	Secondary MCL	215	4	1.9%
Fluoride	2	Secondary MCL	215	2	0.9%
Iron	0.3	Secondary MCL	215	40	18.6%
Manganese	0.05	Secondary MCL	215	40	18.6%
pH	<6.5 or >8.5	Secondary MCL	215	135	62.8%
Sulfate	250	Secondary MCL	215	1	0.5%
Total Dissolved Solids	500	Secondary MCL	215	52	24.2%
Hardness	180	Industrial	215	6	2.8%
Silica	40	Industrial	215	35	16.3%
Boron	2	Irrigation	215	1	0.5%
Sodium Adsorption Ratio (High)	18	Irrigation	215	110	51.2%
Sodium Adsorption Ratio (Very High)	26	Irrigation	215	90	41.9%
Specific Conductance (High)	750	Irrigation	213	68	31.9%

[a] mg/L = milligrams per liter
[b] MCL = Maximum contaminant level

4.8.4 WATER QUALITY EVALUATION BASED ON TOTAL DISSOLVED SOLIDS DISTRIBUTION

Figure 4-80 through Figure 4-83 display the most recent total dissolved solids concentration for each well with available data. Concentrations are classified into the following salinity ranges: freshwater (0 to 1,000 mg/L), slightly saline groundwater

(1,000 to 3,000 mg/L), moderately saline groundwater (3,000 to 10,000 mg/L), very saline groundwater (10,000 to 35,000 mg/L), and brine (greater than 35,000 mg/L). Each well measurement was assigned to an aquifer using well construction information and the elevations of aquifers in the hydrostratigraphic framework. If a well is designated to intersect more than one aquifer unit, then the measurement value is displayed on the map for both aquifers. Selected total dissolved solids hydrographs for each aquifer are also shown on Figure 4-80 through Figure 4-83, with wells selected based on data availability. Due to lack of sampling frequency in many areas, temporal trends throughout several of the aquifer units could not be confidently established.

Sparta Sand

Available total dissolved solids measurements indicate that groundwater in the outcrop areas of the Sparta Sand is mostly freshwater (Figure 4-80). In the Sparta Aquifer, a sample from one well in Rapides County, Louisiana reports a total dissolved solids concentration classified as brine (72,900 mg/L). The sample is from 1957 and is the only recorded total dissolved solids value at this location. Two instances of slightly saline concentrations occur in Angelina and Houston counties in 1961 and 1957 samples, respectively. Slightly saline concentrations occur in Angelina, Cherokee, Madison, Natchitoches, and Sabine counties in sample dates ranging from 1935 through 1986. No salt domes are known to exist in these areas (Figure 2-19). A few of the selected hydrographs suggest that total dissolved solids concentrations have decreased slightly over time in some areas of the aquifer. No data exist for the deep, down-dip portions of the aquifer unit.

Queen City Sand

Similar to the Sparta Sand, total dissolved solids measurements indicate that groundwater in the outcrop portions of the Queen City Sand is predominantly freshwater (Figure 4-81). There are two instances of moderately saline concentrations in Henderson and Cherokee counties from 1936 samples. Slightly saline concentrations occur in Cherokee, Henderson, Walker, and Wood counties in sample dates ranging from 1936 through 1977. All instances of saline concentrations occur south of Van Zandt County. Salt domes are known to exist near the measured saline concentrations near Cherokee and Henderson Counties (Figure 2-19); however, there is no obvious correlation between the saline groundwater and the salt domes. Based on available historical data, there are no obvious temporal trends throughout the aquifer. Total dissolved solids have remained relatively stable through time in some areas and has either slightly increased or slightly decreased in other areas. No data exist for the deep, down-dip portions of the aquifer unit.

Carrizo Sand

In the Carrizo Aquifer, groundwater is mostly freshwater in the outcrop areas, with some areas with brackish water (Figure 4-82). There were two instances of very saline total dissolved solids values in Sabine County, both from 1942 samples, and both wells are designated as being in the Carrizo Sand and Wilcox Group, undifferentiated. There was one occurrence of a moderately saline concentration in Leon County from a 1962 sample, and slightly saline concentrations in Sabine, Gregg, Upshur, Marion, and San Augustine counties. Sample dates range from 1936 through 2006. No salt domes are known to exist in these areas (Figure 2-19). Based on available historical data, total dissolved solids concentrations have remained relatively stable through time in the northern areas of the study area. No data exist for the deep, down-dip portions of the aquifer unit.

Wilcox Group

Similar to the Carrizo Sand, groundwater in the Wilcox Group is mostly freshwater in the relatively shallow portions of the unit in the north (Figure 4-83). The same instances of very saline concentrations are present in this unit as was previously described for the Carrizo Aquifer. Moderately saline concentrations occur in the counties Freestone, Henderson, Nacogdoches, Rains, Rusk, Van Zandt, and Wood and parish Natchitoches with sample dates ranging from 1936 through 1998. Slightly saline concentrations are scattered throughout the study area in sample dates ranging from 1936 through 1998. No salt domes are known to exist near these measured saline concentrations (Figure 2-19). Several examples of decreasing total dissolved solids trends are shown on Figure 4-83**;** however, this trend is not consistently seen throughout the aquifer. No data exist for the deep, down-dip portions of the aquifer unit.

The geometric mean of the total dissolved solids concentration in each aquifer unit was calculated using the most recent concentration at each sampling location. The previously noted trend of down-dip increase in total dissolved solids concentration (Kelley and others, 2004) was verified, as seen in the concentrations in Table 4.13, with the exception of the Wilcox Aquifer where the mean concentrations are very similar.

Table 4.13. Geometric Mean of Total Dissolved Solids Concentrations in each Aquifer

Aquifer	Overall Mean (mg/L)	Outcrop (Unconfined) Mean (mg/L)	Downdip (Confined) Mean (mg/L)
Sparta	202.0	105.2	390.1
Queen City	131.0	126.5	148.9
Carrizo	222.9	96.8	252
Wilcox	366.8	378.9	346.6

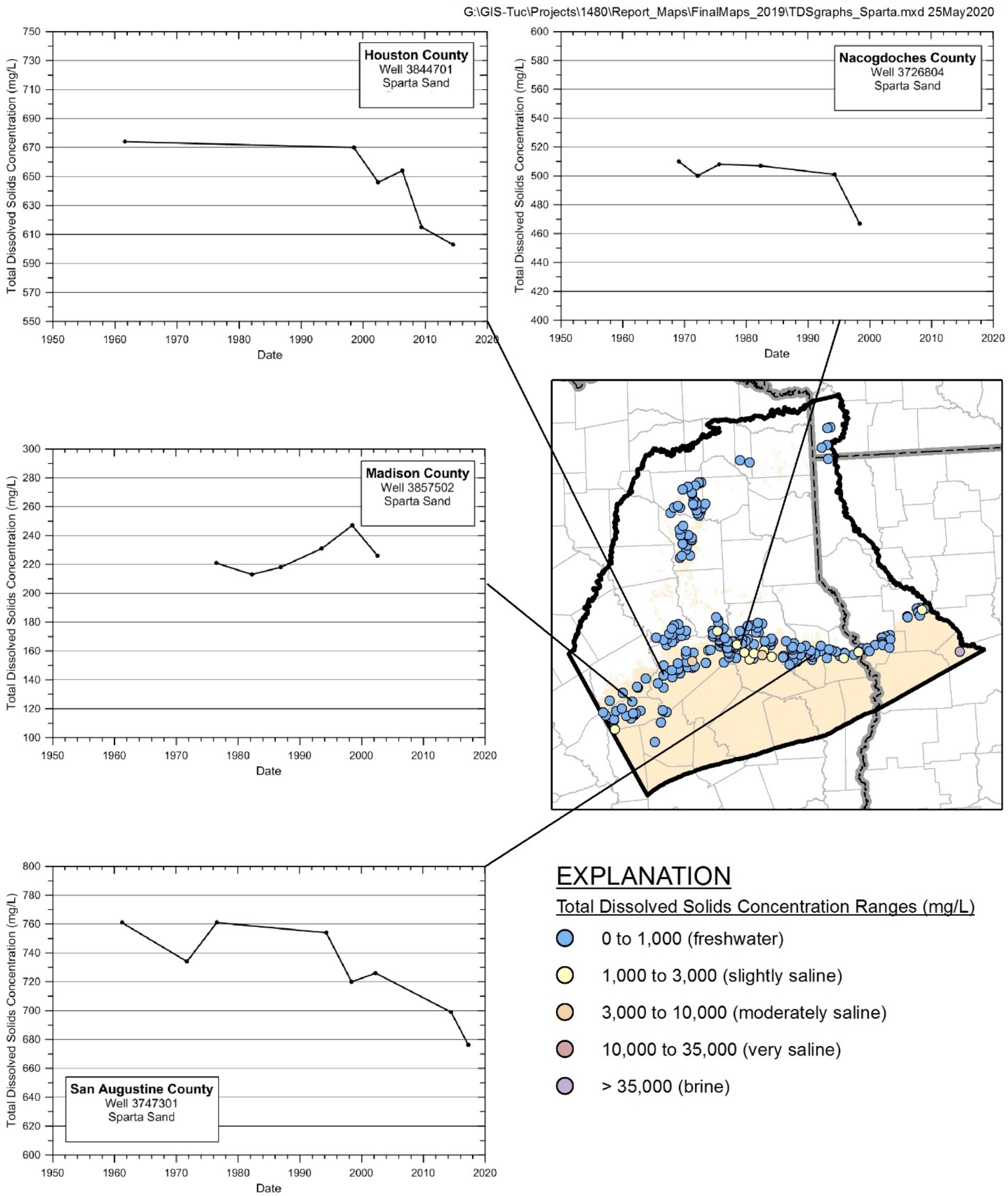


Figure 4-80. Total Dissolved Solids Distribution and Selected Historic Concentration for Sparta Aquifer Wells in Study Area

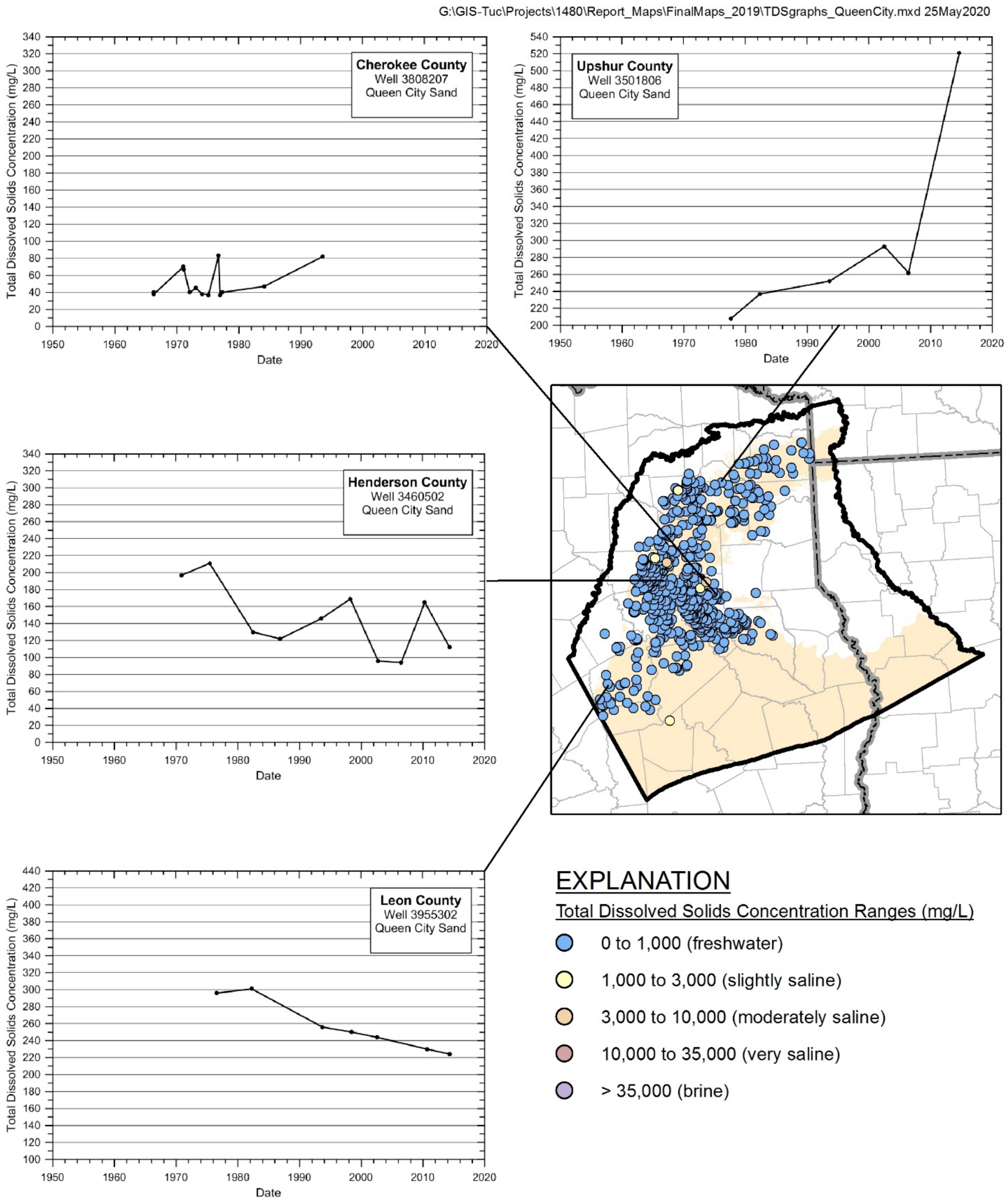


Figure 4-81. Total Dissolved Solids Distribution and Selected Historic Concentration for Queen City Aquifer Wells in Study Area

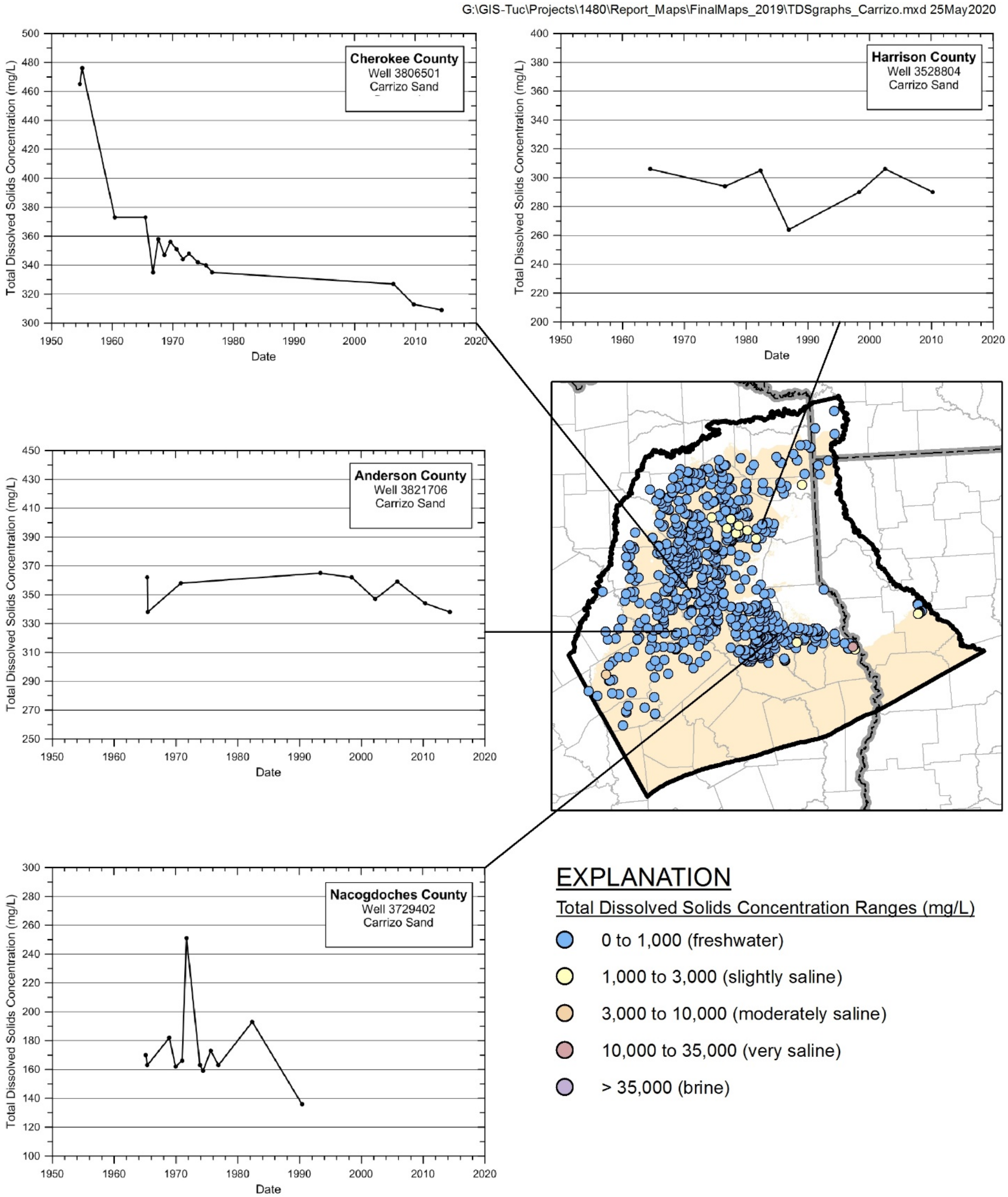


Figure 4-82. Total Dissolved Solids Distribution and Selected Historic Concentration for Carrizo Aquifer Wells in Study Area

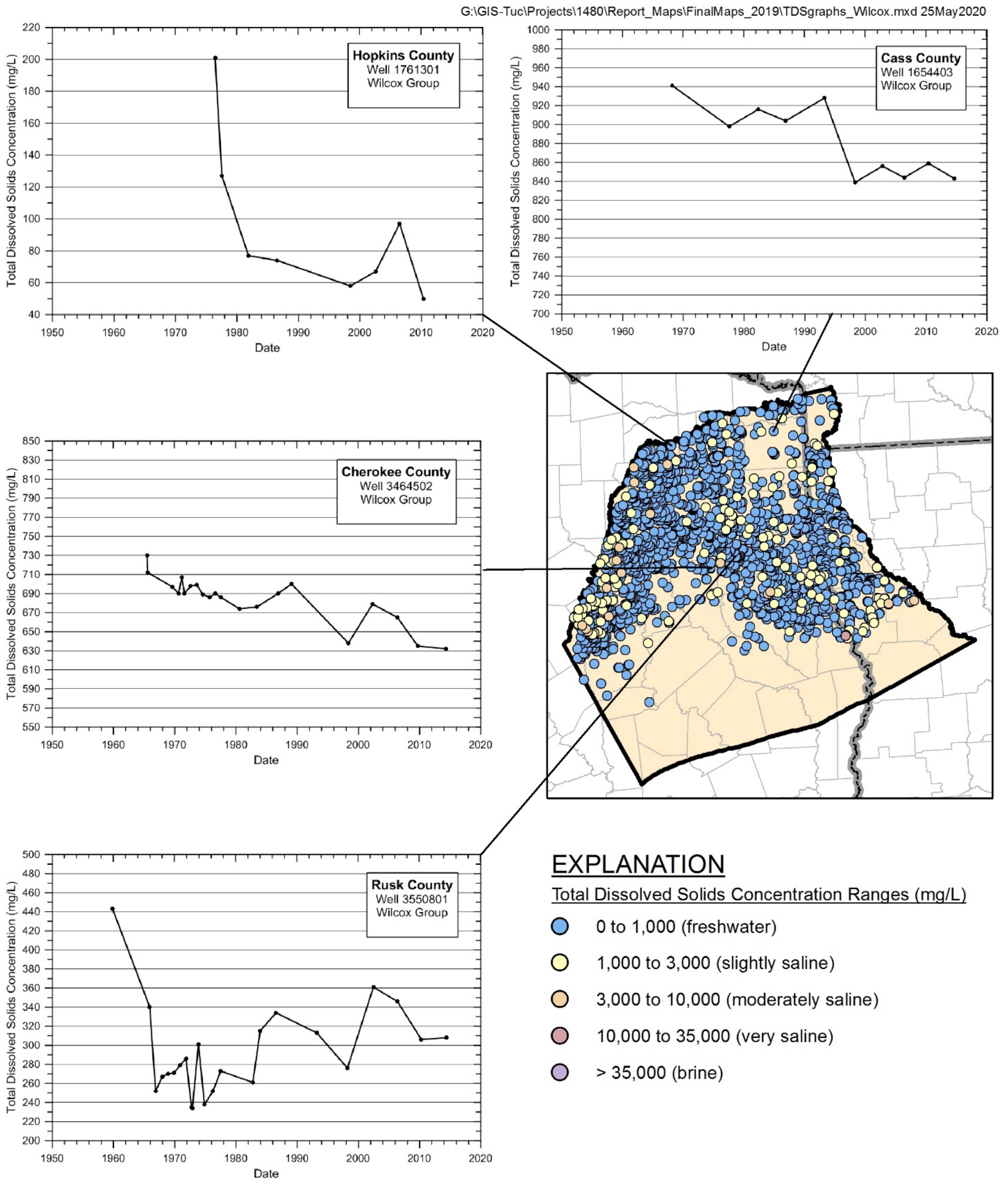


Figure 4-83. Total Dissolved Solids Distribution and Selected Historic Concentration for Wilcox Aquifer Wells in Study Area

5 SUMMARY OF CONCEPTUAL MODEL

The conceptual hydrogeologic model for this study is based on the hydrogeologic setting described in Chapter 4. A hydrogeologic conceptual model is a simplified representation of the important hydrogeologic features that govern groundwater movement in an aquifer system. Important hydrogeologic features include the hydrostratigraphic framework, hydraulic properties, aquifer recharge, natural and anthropogenic discharges from the aquifer, hydraulic boundaries, and groundwater occurrence and movement. The conceptual model provides the foundation for a numerical groundwater flow model. A simplified schematic of the conceptual hydrogeologic model for the northern portions of the Sparta, Queen City, and Carrizo-Wilcox aquifer system is shown on Figure 5-1.

The groundwater system in this conceptual model is a nine-layer system. Each model layer represents an individual hydrostratigraphic unit within the groundwater system. The nine layers represented in the model include the following, from top to bottom: river alluvium, Sparta Sand, Weches Formation, Queen City Sand, Reklaw Formation, Carrizo Sand, and the upper, middle, and lower units of the Wilcox Group. The Sparta, Queen City, Carrizo, and the three Wilcox units are capable of producing adequate volumes of groundwater for use. These aquifer units are separated by two confining aquitards. The Weches Formation separates the Sparta Aquifer from the underlying Queen City Aquifer, and the Reklaw Formation separates the Queen City Aquifer from the Carrizo-Wilcox Aquifer. A representative hydrogeologic cross-section of the nine-layer groundwater system is shown on Figure 5-1. The aquifer units in this model dip southward into the subsurface towards the Gulf Coast Basin and are overlain by a wedge of younger sediments (including the Gulf Coast Aquifer System), which are not included in this model.

Groundwater in the northern portions of the Queen City, Sparta, and Carrizo-Wilcox aquifer system occurs under unconfined (or water-table) conditions in the outcrop areas and confined conditions in down-dip areas. Confined conditions also occur in the north parts of the Queen City Sand where it is overlain by the Weches Formation and Sparta Sand. Regional groundwater movement is generally from the north-northwest in upland areas to the south towards the Gulf of Mexico, following the dip of the aquifer units. The sands of the Wilcox, Carrizo, and Queen City units are generally hydraulically connected and behave as a single aquifer in the northern-most margins of the study area. The sands of the Wilcox and Carrizo units are hydraulically connected and behave as a single aquifer in counties throughout the northwest and southeast portions of the study area. The Carrizo and Wilcox units behave as separate aquifers in the remaining portions of the study area. Groundwater movement from one aquifer unit to another (cross-formational flow) occurs when groundwater level elevations are different in the adjacent aquifers. Cross-formational flow is observed to occur through the confining units in the study area.

Groundwater levels in the northern portions of the study area are relatively shallow and contribute to gaining stream flows along the major rivers, creeks, and tributaries, as well as flows to numerous springs. The number of flowing springs and gaining stream reaches is a result of humid climate, shallow groundwater levels, and gently dipping and dissected topography. These factors contribute to rejected recharge and runoff in the study area and greater East Texas area.

Groundwater movement in the aquifers in controlled by topography, the hydro-stratigraphic framework, and variations in permeability within the aquifer layers. Groundwater movement in the confined, down-dip portions of the aquifer system are believed to be controlled by high-permeability sand intervals relative to lower permeability intervals.

The groundwater potentiometric surface in the deep, down-dip portions of the aquifer system are assumed to increase with depth, which produces upward cross-formational flows. Groundwater elevation contours developed for this study for each model layer will be used as initial conditions and guides for historical calibration. This conceptualization will be tested with the numerical model and a sensitivity analysis will be conducted to evaluate any impacts from uncertainty.

This conceptual model encompasses the northern portions of the Sparta, Queen City, and Carrizo-Wilcox aquifer systems in northeastern Texas, with portions in western Louisiana and southwest-most Arkansas. The model boundaries are defined based on surface and groundwater features. The northern boundary is the northern-most extent of the Lower Wilcox aquifer layer. The southern boundary is the same as defined for the previous groundwater availability models, which is the up-dip limit of the Wilcox growth fault zone as defined by Bebout and others (1982). The eastern boundary is the Red River in Louisiana. The western boundary is the approximate watershed drainage divide between the Trinity and Brazos river basins. The upper boundary is land surface in the outcrop area extending south to the extent of the Sparta outcrop. South of the Sparta outcrop, the upper model boundary is the contact between the Sparta and the overlying wedge of younger sediments. The bottom boundary of the model is the top of the underlying older geologic formations.

Hydraulic properties of the model layers will be evaluated and determined during model calibration. Measured hydraulic property data and the simulated properties specified in the previous groundwater availability models will be considered for model calibration. Additional adjustments may be required to vary properties within a layer, such as for outcrop and down-dip portions. Layer properties in the model will be described in detail in the Model Calibration Report.

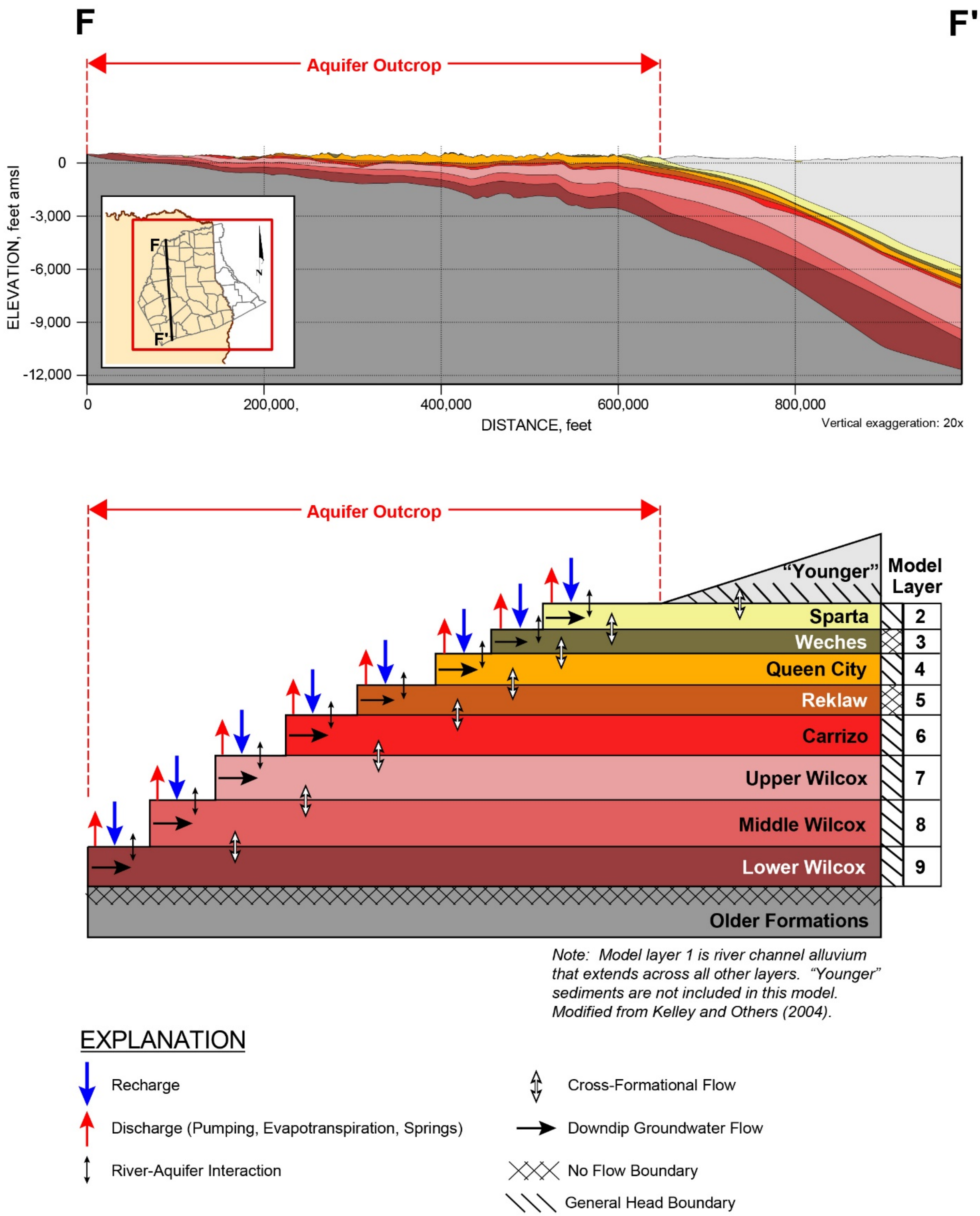


Figure 5-1. Conceptual Groundwater Flow Model Diagram for Northern Portions of Queen City, Sparta, and Carrizo-Wilcox Aquifers Groundwater Availability Model

5.1 HISTORICAL TRANSIENT CONDITIONS

The transient model period represents historical hydrogeologic conditions from 1984 through 2015. This time period was selected principally based on pumping data availability. Initial conditions for the transient model will represent conditions prior to 1984. Hydrogeologic conditions in the study area varied during the transient model period due to changes in groundwater pumping and climate. The groundwater model will be calibrated to match measured groundwater levels, streamflows, and the conceptualized groundwater flow regime in the study area.

Groundwater inflow components to the groundwater flow model for the northern portions of the Queen City, Sparta, and Carrizo-Wilcox aquifers include: (1) recharge from infiltration of precipitation and (2) recharge from deep percolation of impounded reservoir water. Inputs for recharge from infiltration of precipitation will be initially developed by applying a recharge-precipitation relationship, based on the interpolation methods described in Chapter 4. This input will be scaled, if needed, both spatially and temporally during model calibration to improve the match between measured and simulated groundwater levels. Spatial adjustments to recharge could be based on geology and/or topography. Recharge from reservoirs will be simulated using recorded reservoir water level data.

Groundwater outflow components to the groundwater flow model for the northern portions of the Queen City, Sparta, and Carrizo-Wilcox aquifers include: (1) groundwater withdrawals by pumping, (2) discharge to surface waters such as rivers, creeks, and springs, and (3) evapotranspiration. Annual groundwater pumping will be distributed to individual wells based on county location and well use classification. Pumping will be assigned to aquifer units based on the hydrostratigraphic framework and reported well construction information for each pumping well. The distribution of evapotranspiration will be initially based on average maximum evapotranspiration rate and evapotranspiration extinction depths described in Chapter 4. Components of evapotranspiration outputs could be scaled, if necessary, based on climatic factors and/or distributions of land cover.

Streamflows in major rivers that flow into the model domain will be specified at the model boundary. The water will be routed through the river system and infiltration will be dependent on the stage in the river, groundwater elevations in the model aquifer layers adjacent to the river channel, and channel conductance properties specified in the model. The initial flow rate for a river will be based on nearby streamflow measurements and could be adjusted during model calibration to match downstream measurements.

Changes in groundwater levels have varied through time and among the aquifer layers. Measurements at wells indicate rising, declining, or stable groundwater levels depending on location, with no overall regional trend. Declining levels are likely a result of groundwater pumping; this is especially evident near the pumping centers in Nacogdoches and Angelina counties.

The water quality within the aquifer layers varies throughout the study area. Changes in water quality will not be simulated in the groundwater availability model; however, the information is used for qualitative interpretations for the conceptual model. Total dissolved solids concentrations generally increase down-dip in each aquifer layer. Smaller total dissolved solids concentrations in outcrop areas indicate displacement of connate water with meteoric water (recharge of precipitation). Total dissolved solids concentrations are larger in deeper, down-dip portions of the aquifer layers, indicating less displacement of connate water by meteoric water. Displacement of connate water by meteoric water is controlled by the recharge rate, extent of recharge area, and aquifer hydraulic properties.

6 FUTURE IMPROVEMENTS

The conceptual model for the northern Queen City, Sparta, and Carrizo-Wilcox aquifers would improve with additional data. This is often the case for regional-scale groundwater modeling studies. Additional data that could be collected to better support the development of the groundwater availability model include groundwater recharge studies, evapotranspiration studies, groundwater pumping studies, and additional groundwater level monitoring and aquifer testing in the confined portions of the groundwater system in the southern portion of the study area.

Recharge is an important component to the groundwater availability model because it can be used to constrain hydraulic properties during model calibration. Although regional-scale relationships were determined to be reasonable for this study, the accuracy of future predictions of groundwater conditions would improve with additional recharge studies conducted in the study area. Groundwater evapotranspiration by vegetation in the study area consumes water that previously recharged the aquifer. Very limited data are available for evapotranspiration and rooting depths of the vegetation types in the area. Studies on groundwater evapotranspiration should be conducted in the study area to improve the understanding of the groundwater system.

Uncertainties regarding groundwater pumping in the study area exist due to limited reported information. The best available pumping information for the area is provided in the annual TWDB water use surveys. However, inconsistent or inaccurate information is likely reported in the surveys. This is evident by the substantial discrepancy between mining pumping reported by the TWDB and mining pumping reported by the Railroad Commission. Furthermore, the distribution of pumping within the valley is uncertain because pumping volumes for individual wells are not reported in the surveys. More reliable information on pumping locations and rates would improve the accuracy of the groundwater model.

This conceptual model will be updated, as needed, by additional information acquired through the stakeholder process and the development of the numerical groundwater model. The impact of uncertainties described herein will be evaluated via a sensitivity analysis to determine if further data collection is necessary.

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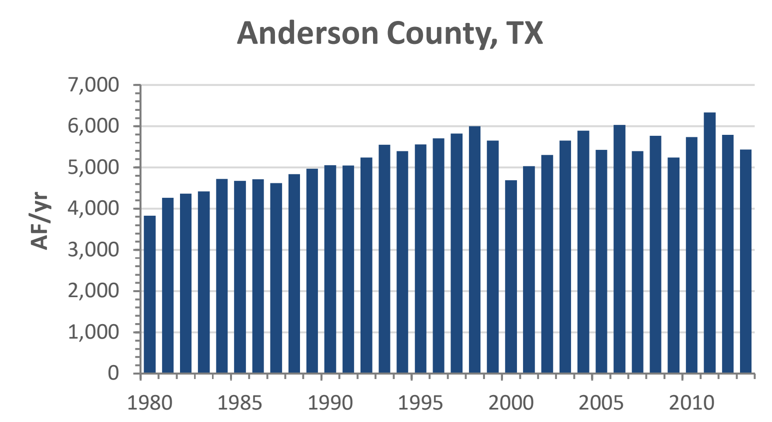
Appendix A

Estimated Groundwater Pumping by County for Northern Portions of the Queen City, Sparta, and Carrizo-Wilcox Aquifers Groundwater Availability Model


Anderson County, TX
AF/yr
7,000
6,000
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3,000
2,000
1,000
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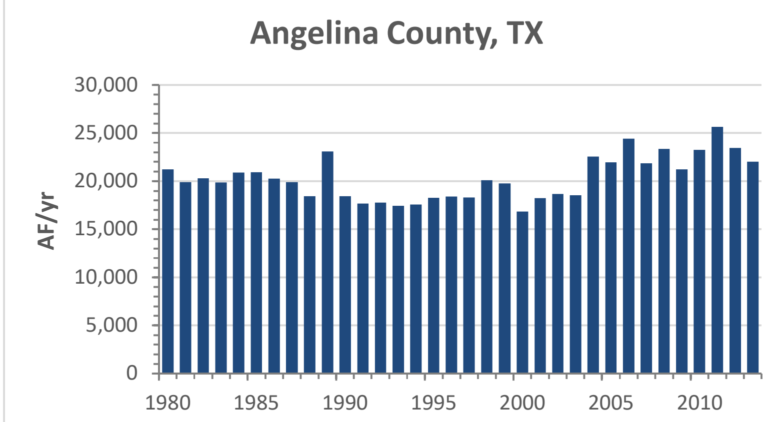
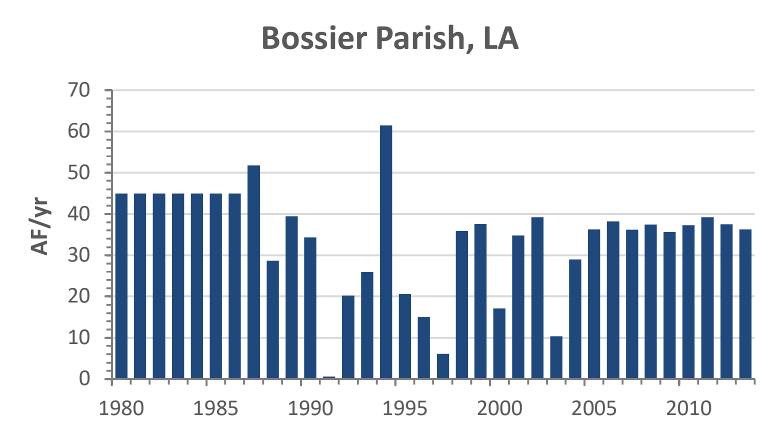
1980
1985
1990
1995
2000
2005
2010


Angelina County, TX
AF/yr
30,000
25,000
20,000
15,000
10,000
5,000
0
1980
1985
1990
1995
2000
2005
2010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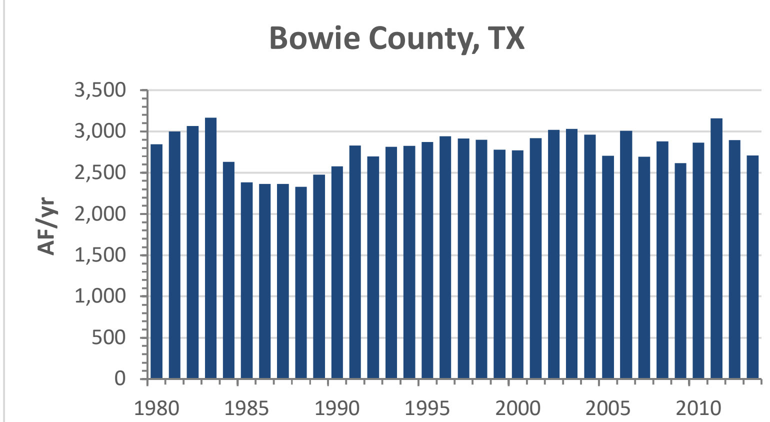
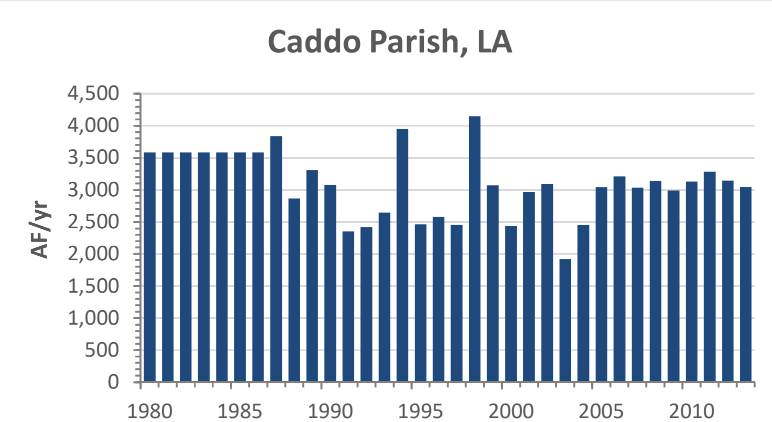
AF/yr
70
60
50
40
30
20
10
0
1980
1985
1990
1995
2000
2005
2010


Bowie County, TX
AF/yr
3,500
3,000
2,500
2,000
1,500
1,000
500
0
1980
1985
1990
1995
2000
2005
2010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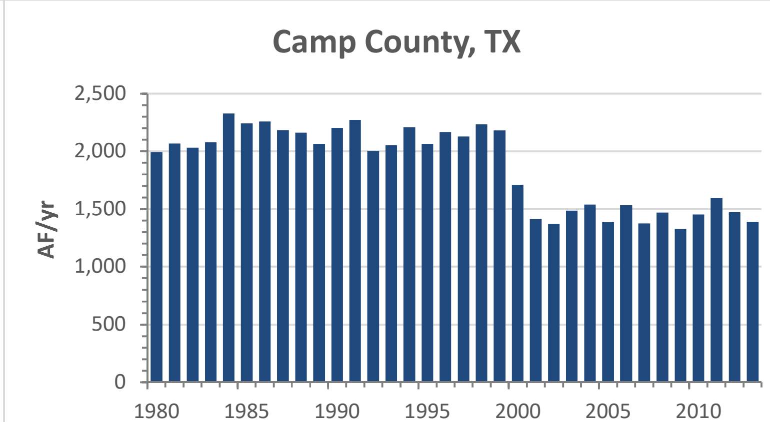
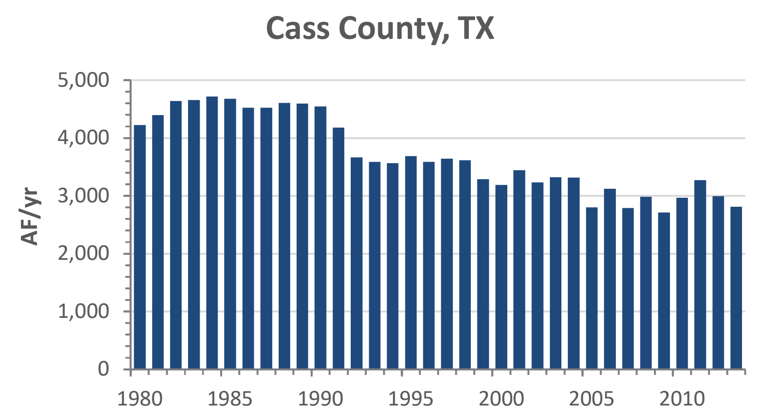
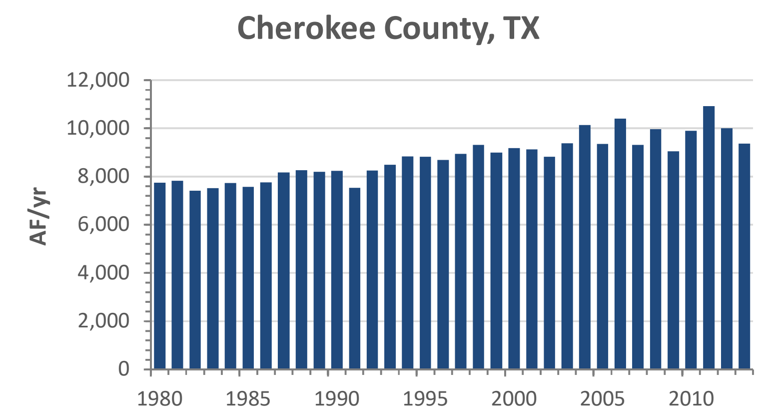
AF/yr
4,500
4,000
3,500
3,000
2,500
2,000
1,500
1,000
500
0
1980
1985
1990
1995
2000
2005
2010


Camp County, TX
AF/yr
2,500
2,000
1,500
1,000
500
0
1980
1985
1990
1995
2000
2005
2010


Cass County, TX
AF/yr
0
1,000
2,000
3,000
4,000
5,000
1980
1985
1990
1995
2000
2005
2010


Cherokee County, TX
AF/yr
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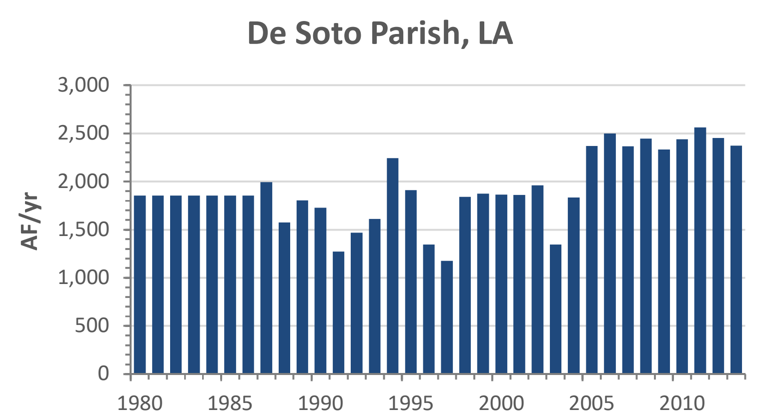
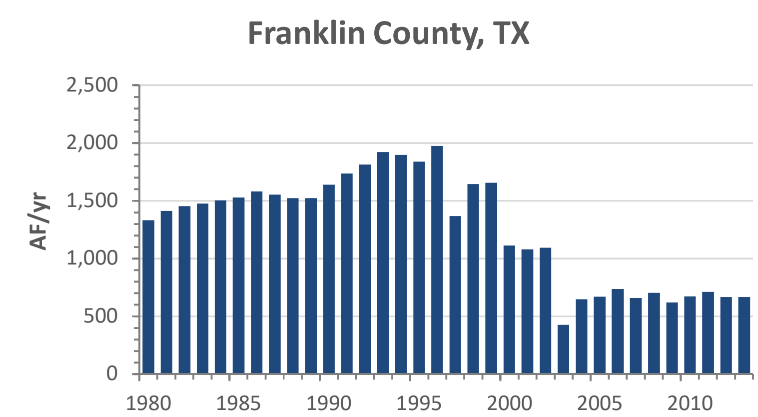
2,000
4,000
6,000
8,000
10,000
12,000
1980
1985
1990
1995
2000
2005
2010


De Soto Parish, LA
AF/yr
0
500
1,000
1,500
2,000
2,500
3,000
1980
1985
1990
1995
2000
2005
2010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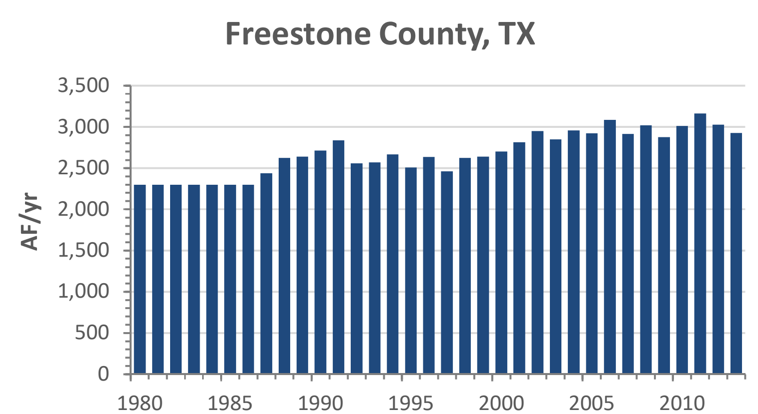
AF/yr
0
500
1,000
1,500
2,000
2,500
1980
1985
1990
1995
2000
2005
2010


Freestone County, TX
AF/yr
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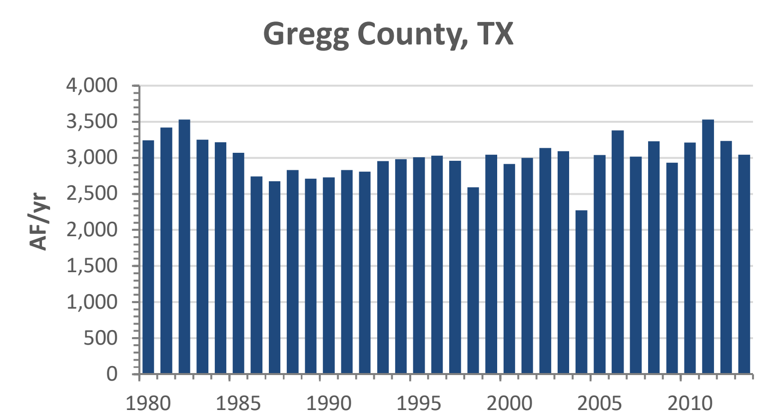
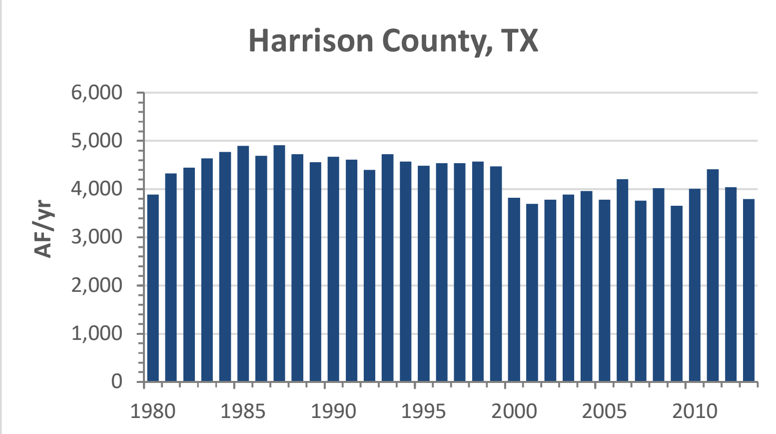
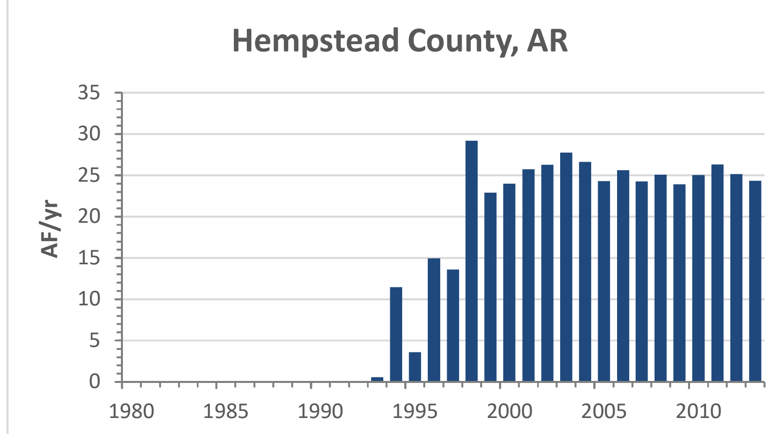
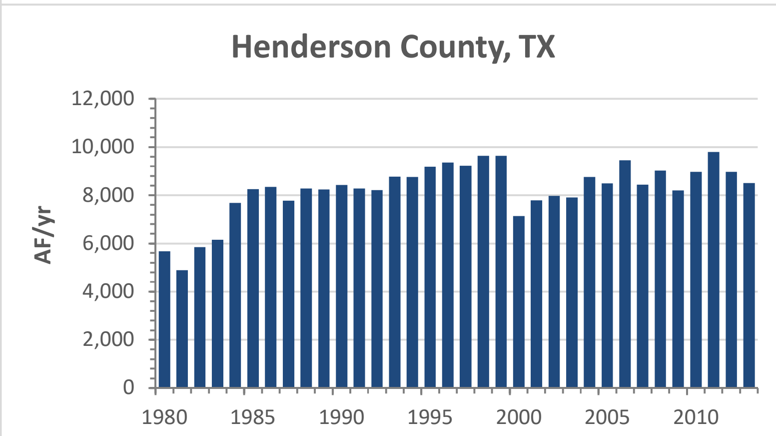
500
1,000
1,500
2,000
2,500
3,000
3,500
1980
1985
1990
1995
2000
2005
2010

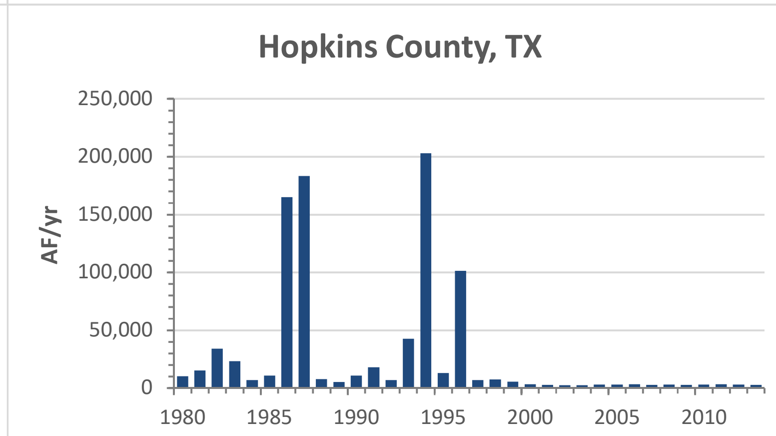

Gregg County, TX
AF/yr
0
500
1,000
1,500
2,000
2,500
3,000
3,500
4,000
1980
1985
1990
1995
2000
2005
2010

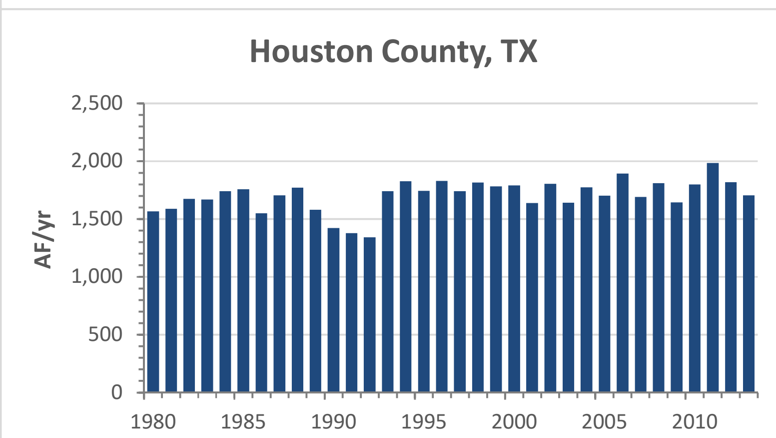
APPENDIX A. ESTIMATED GROUNDWATER PUMPING BY COUNTY FOR NORTHERN PORTIONS OF QUEEN CITY, SPARTA, AND CARRIZO-WILCOX AQUIFERS GROUNDWATER AVAILABILITY MODEL

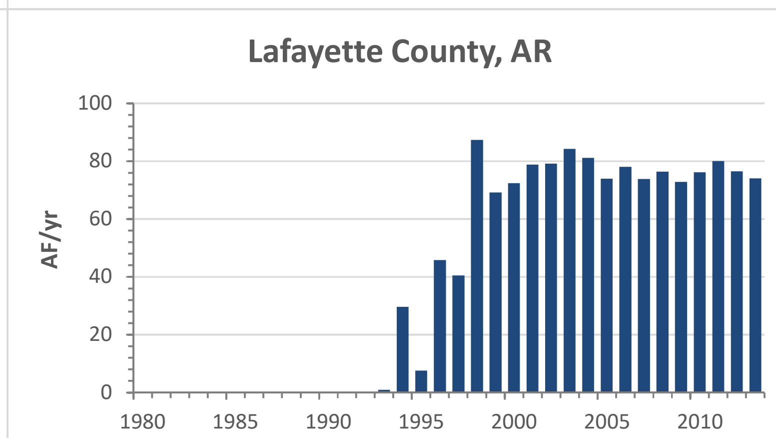


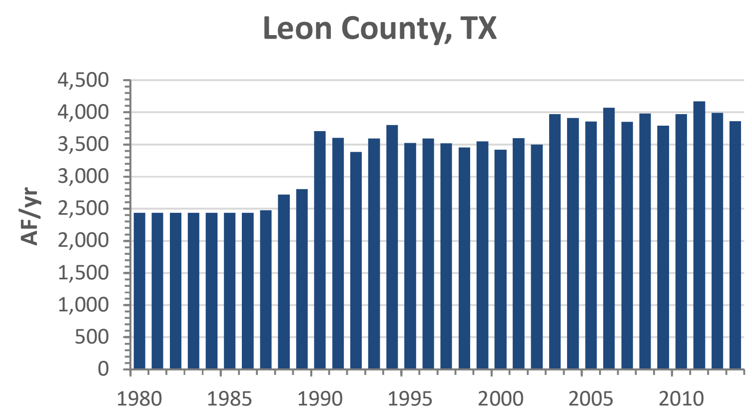


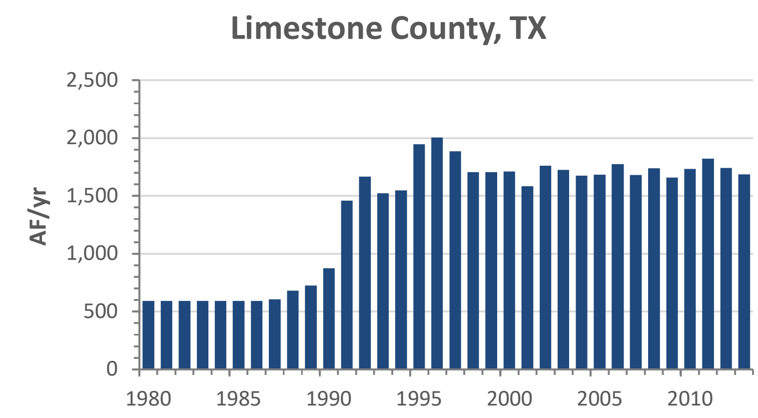









Leon County, TX
AF/yr
4,500
4,000
3,500
3,000
2,500
2,000
1,500
1,000
500
0
1980
1985
1990
1995
2000
2005
2010


Limestone County, TX
AF/yr
2,500
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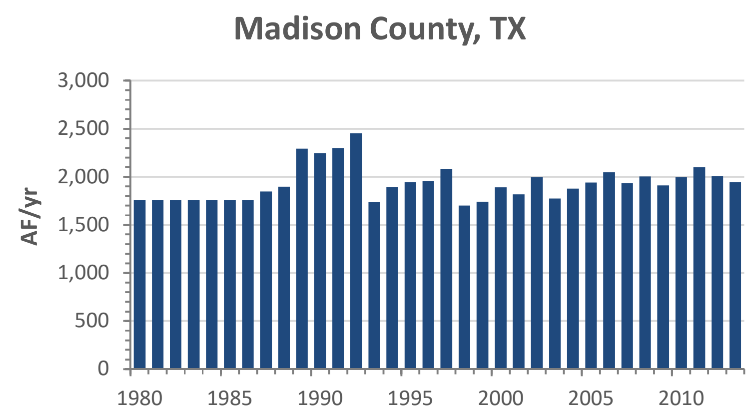
1,500
1,000
500
0
1980
1985
1990
1995
2000
2005
2010


Madison County, TX
AF/yr
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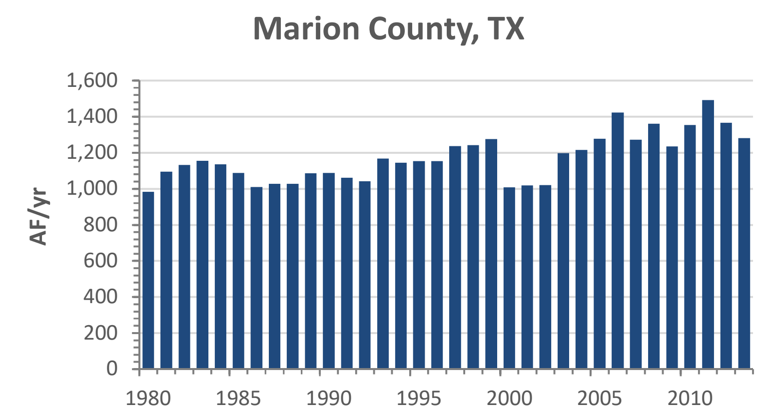
2,000
1,500
1,000
500
0
1980
1985
1990
1995
2000
2005
2010


Marion County, TX
AF/yr
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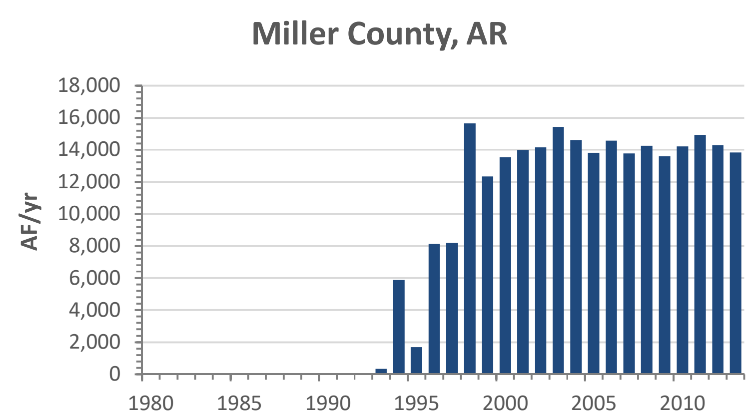
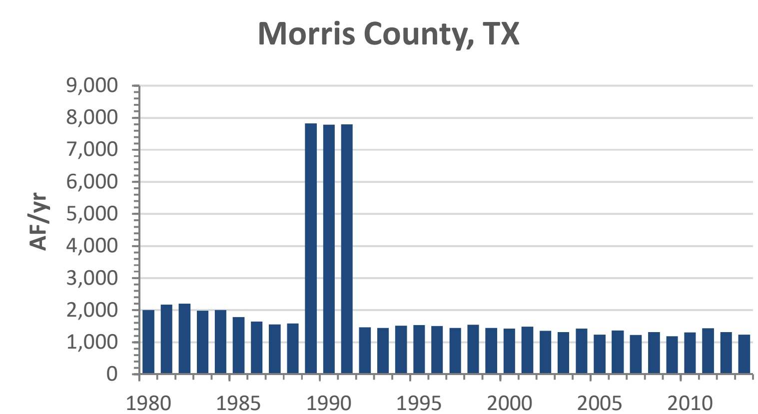
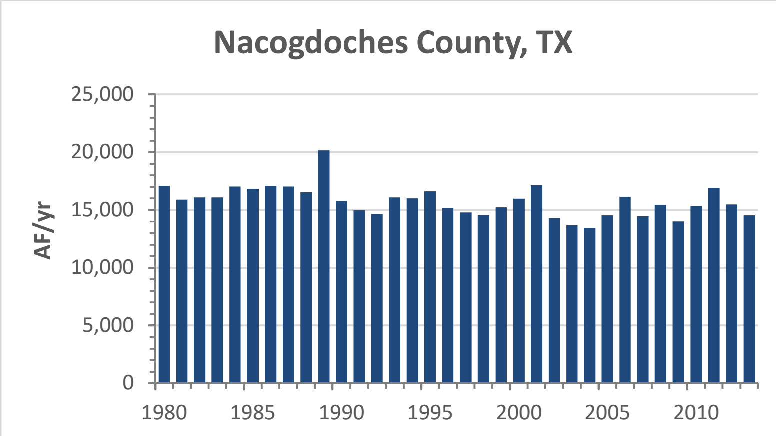
1,200
1,000
800
600
400
200
0
1980
1985
1990
1995
2000
2005
2010


Miller County, AR
AF/yr
18,000
16,000
14,000
12,000
10,000
8,000
6,000
4,000
2,000
0
1980
1985
1990
1995
2000
2005
2010


Morris County, TX
AF/yr
9,000
8,000
7,000
6,000
5,000
4,000
3,000
2,000
1,000
0
1980
1985
1990
1995
2000
2005
2010


Nacogdoches County, TX
AF/yr
25,000
20,000
15,000
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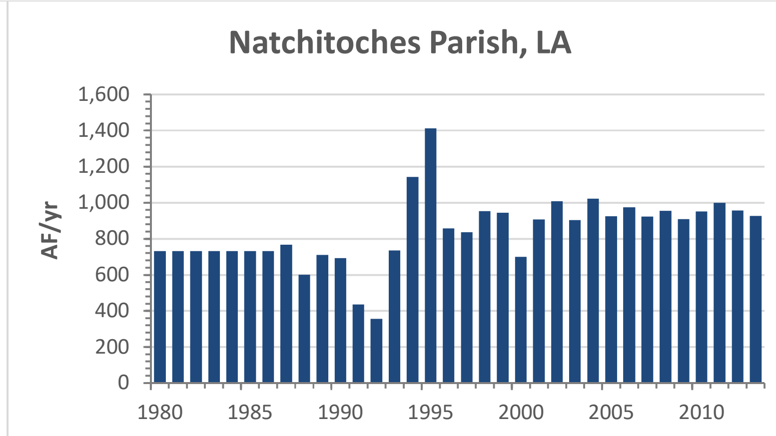
0
1980
1985
1990
1995
2000
2005
2010


Natchitoches Parish, LA
AF/yr
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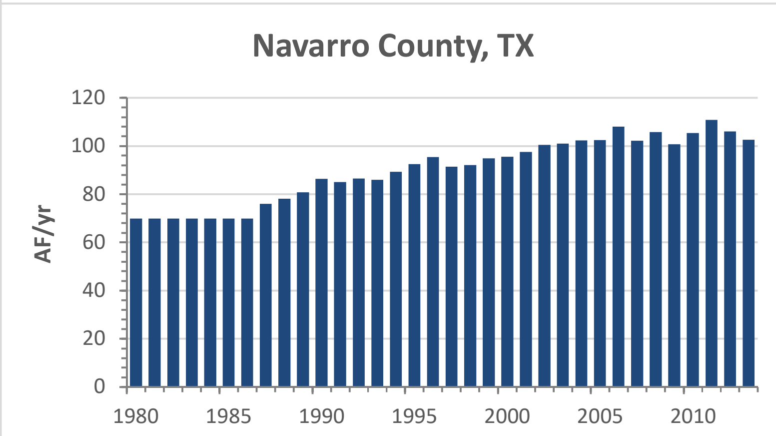
1,400
1,200
1,000
800
600
400
200
0
1980
1985
1990
1995
2000
2005
2010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AF/yr
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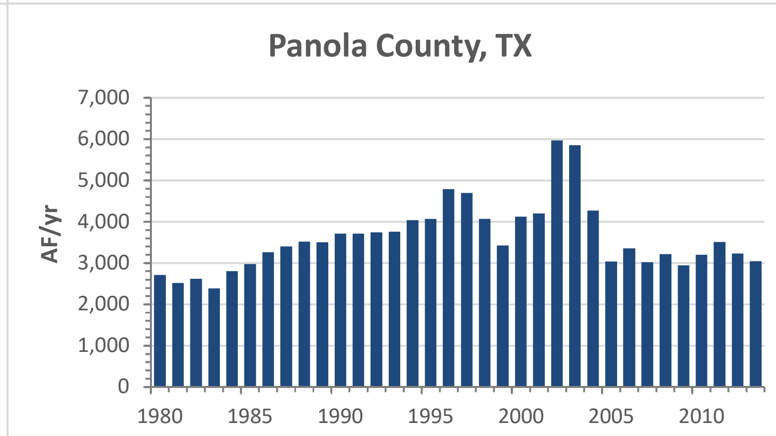
100
80
60
40
20
0
1980
1985
1990
1995
2000
2005
2010


Panola County, TX
AF/yr
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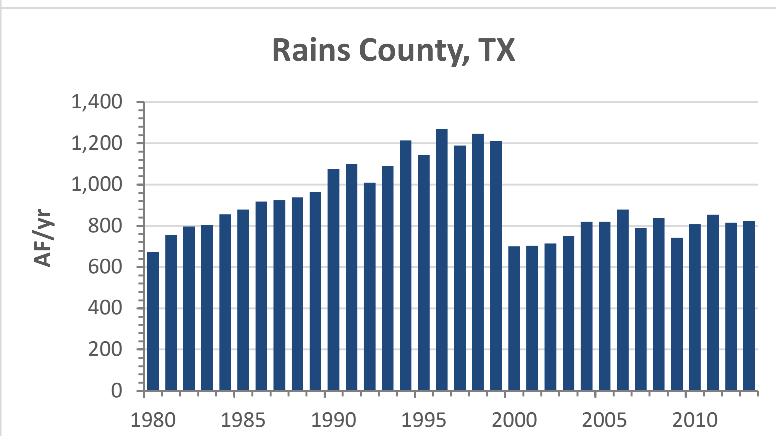
6,000
5,000
4,000
3,000
2,000
1,000
0
1980
1985
1990
1995
2000
2005
2010


Rains County, TX
AF/yr
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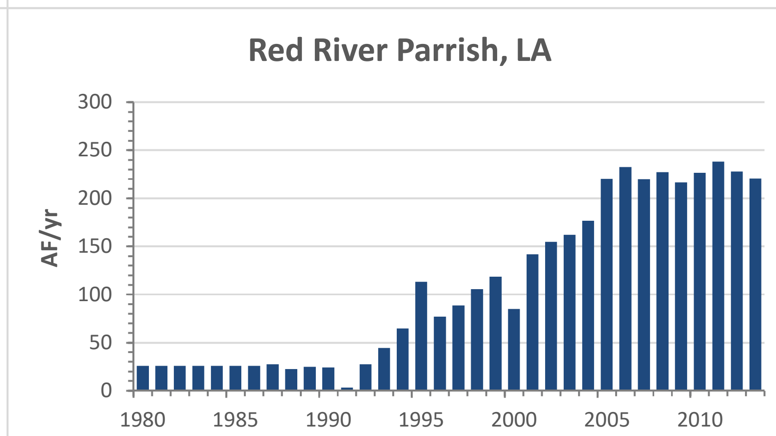
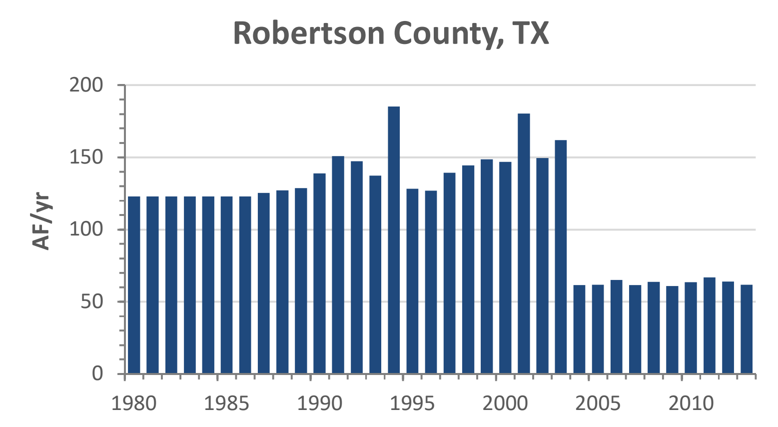
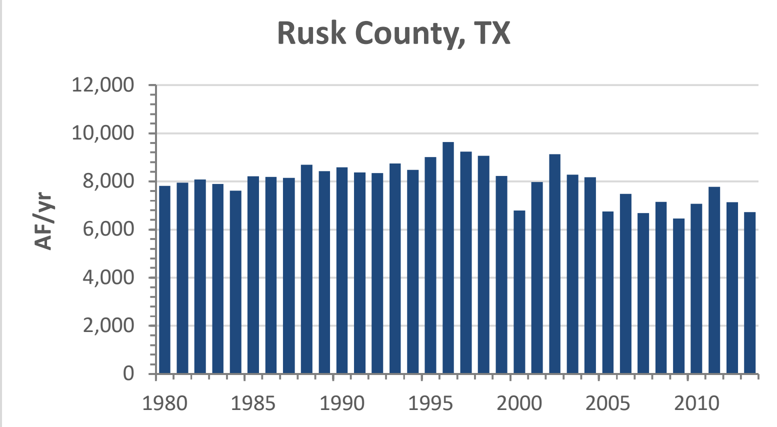
1,200
1,000
800
600
400
200
0
1980
1985
1990
1995
2000
2005
2010


Red River Parrish, LA
AF/yr
300
250
200
150
100
50
0
1980
1985
1990
1995
2000
2005
2010


Robertson County, TX
AF/yr
0
50
100
150
200
1980
1985
1990
1995
2000
2005
2010


Rusk County, TX
AF/yr
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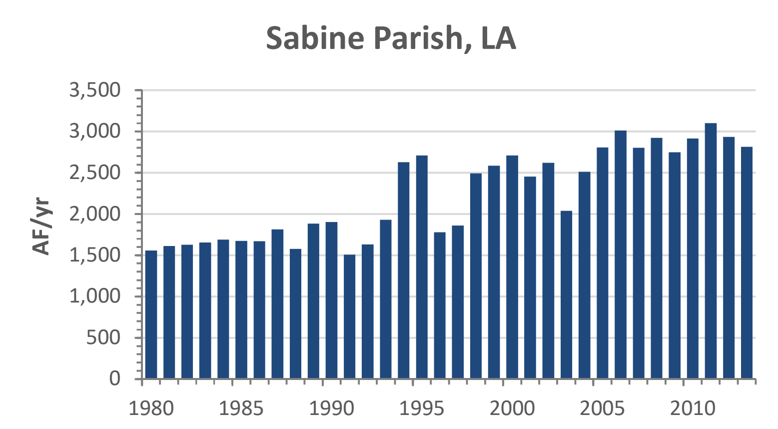
2,000
4,000
6,000
8,000
10,000
12,000
1980
1985
1990
1995
2000
2005
2010


Sabine Parish, LA
AF/yr
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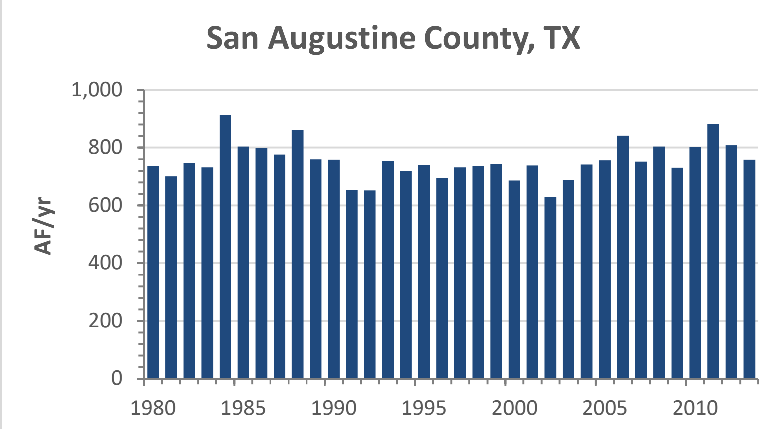
1985
1990
1995
2000
2005
2010


San Augustine County, TX
AF/yr
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200
400
600
800
1,000
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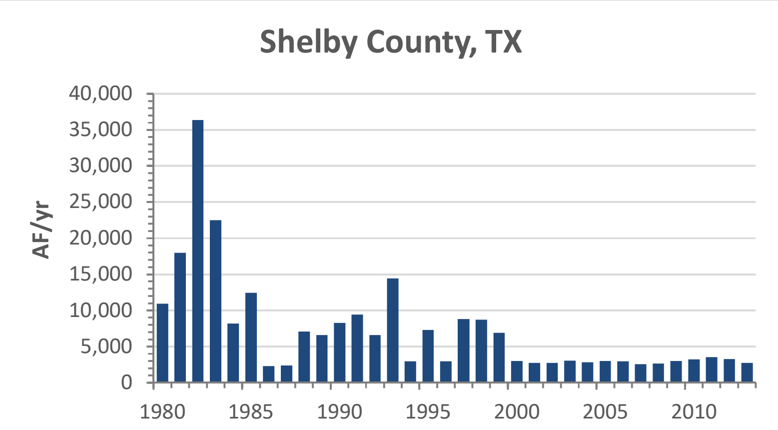
1985
1990
1995
2000
2005
2010


Shelby County, TX
AF/yr
0
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10,000
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20,000
25,000
30,000
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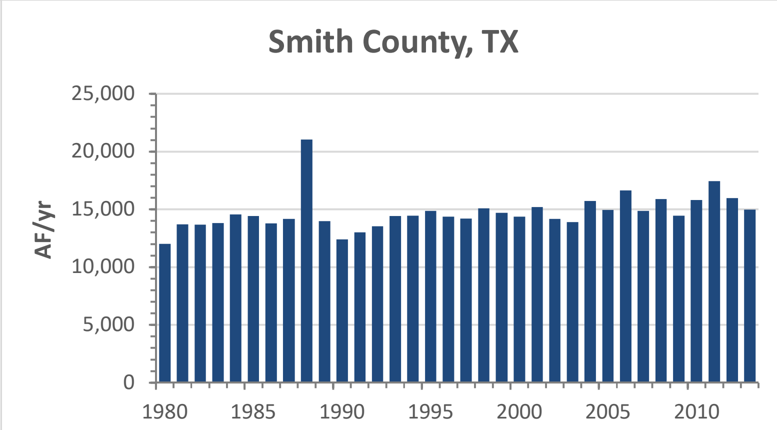
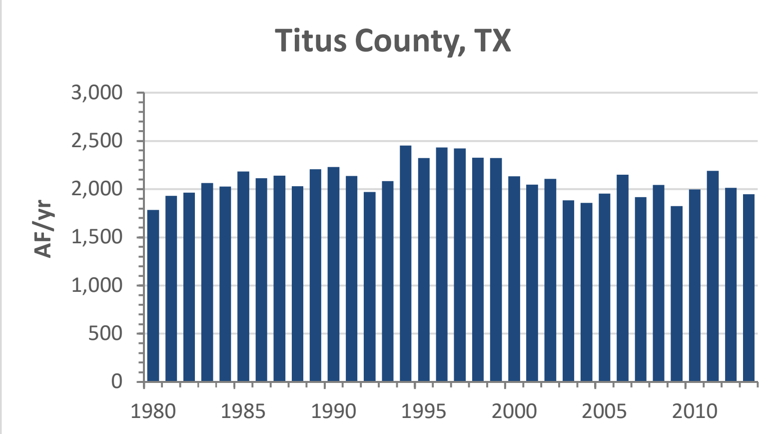
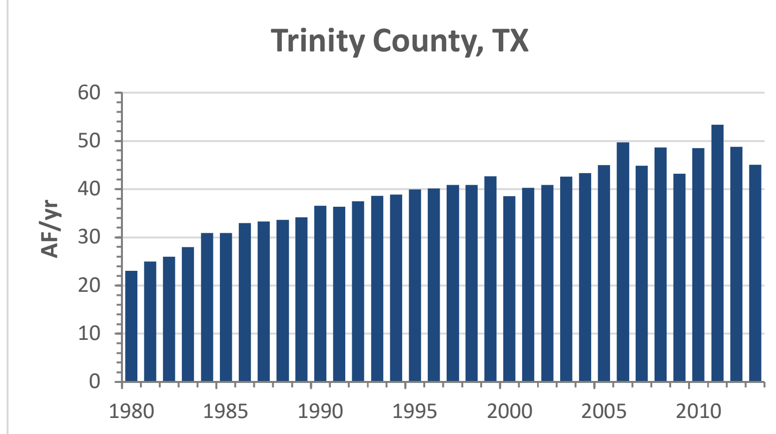
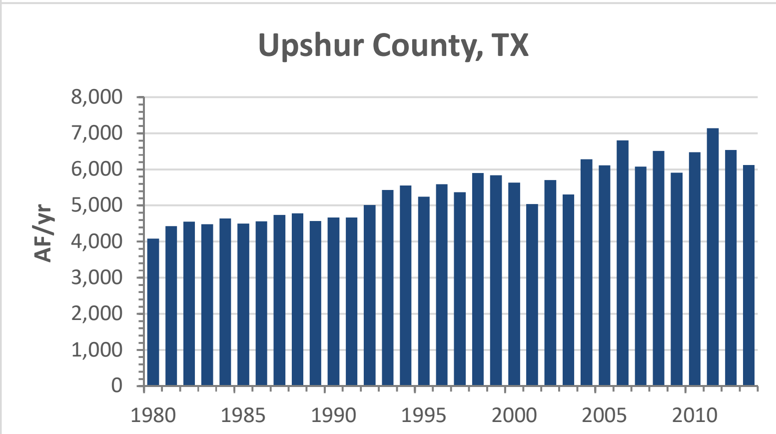
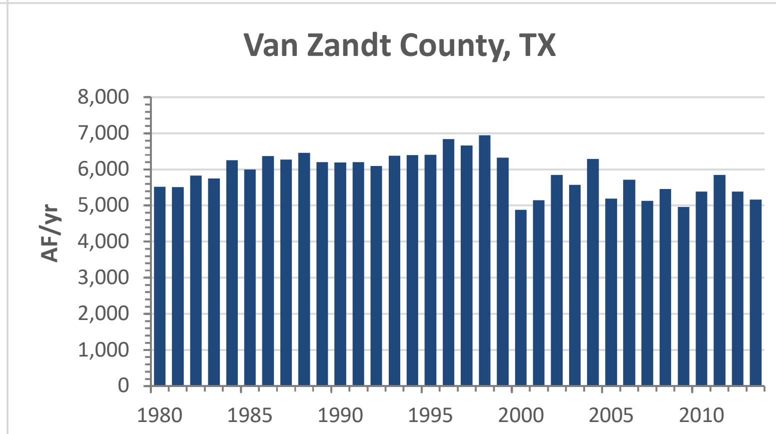
40,000
1980
1985
1990
1995
2000
2005
2010

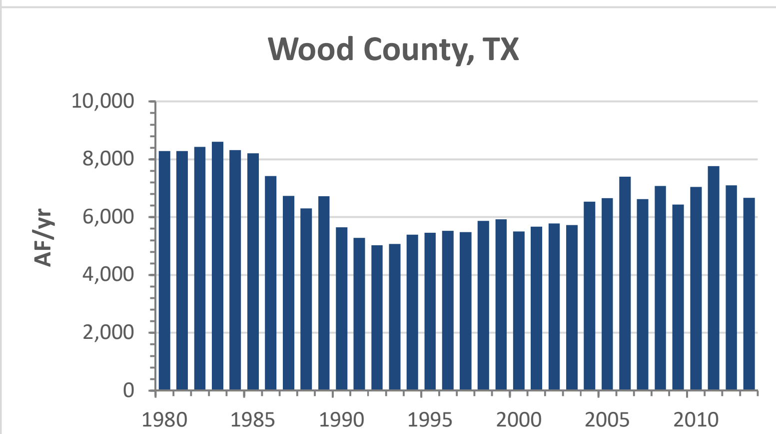

Smith County, TX
AF/yr
0
5,000
10,000
15,000
20,000
25,000
1980
1985
1990
1995
2000
2005
2010


Titus County, TX
AF/yr
3,000
2,500
2,000
1,500
1,000
500
0
1980
1985
1990
1995
2000
2005
2010


Trinity County, TX
AF/yr
60
50
40
30
20
10
0
1980
1985
1990
1995
2000
2005
2010


Upshur County, TX
AF/yr
8,000
7,000
6,000
5,000
4,000
3,000
2,000
1,000
0
1980
1985
1990
1995
2000
2005
2010


Van Zandt County, TX
AF/yr
8,000
7,000
6,000
5,000
4,000
3,000
2,000
1,000
0
1980
1985
1990
1995
2000
2005
2010


Wood County, TX
AF/yr
10,000
8,000
6,000
4,000
2,000
0
1980
1985
1990
1995
2000
2005
2010

MONTGOMERY & ASSOCIATES

Appendix B

Responses to Draft Review Comments

Attachment 1

The following report and data review comments shall be addressed and included in the final draft deliverables by no later than June 27, 2019. Please note that the items listed under 'Suggestions' are editorial in context and are not contractually required; however, the suggested adjustments noted may improve the readability of the report and/or the usability of the data deliverables.

Note: Responses to comments are shown in italics font.

Conceptual model report comments:

General comments to be addressed

1. Per Contract Exhibit B, Attachment 3, Guidelines for Authors Submitting Contract Reports: Please follow the report format specifications in the author guidelines. For example, graphics should be within 1-inch margins and figures should be embedded within the text after being called out in the report. The figure caption should be part of the Word document and should not be part of the figure image.

   Modified report format accordingly, including embedding figures and tables within the text with captions.

2. Per Contract Section II Article III number 5, please ensure that the final report is in compliance with Texas Administrative Code Chapters 206 and 213 (related to Accessibility and Usability of State Web Sites).

   Checked accessibility compliance prior to submittal.

Specific comments to be addressed

3. Page 3, Section 1 Introduction, paragraph 1: The TWDB now recognizes twenty-two minor aquifers. Please update the text accordingly.

   Modified text.

4. Page 6, Section 2.1 Physiography and Climate, paragraphs 1 and 2: Please include references in the text and associated figures for land surface elevation, ecoregions, and vegetation. United States Geological Survey and Texas Parks and Wildlife Department are considered incomplete references.

   Clarified source references in text and figures.

5. Section 2.1 Physiography and Climate: Per Contract, Exhibit B, Attachment 1, page 20 of 33, please include a map of climate divisions as delineated by the National Climate Data Center.

   New figure was added to show climate divisions.

6. Section 2.1 Physiography and Climate: Per Contract, Exhibit B, Attachment 1, page 20 of 33: Please include several plots of average monthly precipitation measured at rain gauges in the study area.

   A new figure was added to show plots of average monthly precipitation were added for several counties.

7. Pages 12 to 19, Section 4.1 Hydrostratigraphy and Layering Framework: Please compare the 'layers' to the TWDB aquifer footprints in the study area to determine if updates to the extent of the aquifers are needed and justified per this study. In addition, please compare the 'layers' in this study to the pre-existing layers from the previous model. This study suggests a different configuration of the Wilcox group when compared to Fryar and others (2003) and Kelley and others (2004).

   Addressed comment in Section 4.1.3. paragraph 2, sentence 2 and in Section 4.1.3 paragraph 2 and 3 under Wilcox Group

8. Page 13, Table 4.1.1 Subsurface Data Sources: Please include a reference in-text and in the References Cited section for USGS Open-File Report 87-677.

   Modified text to reference Wilson and Hosman (1987).

9. Page 13, Table 4.1.1 Subsurface Data Sources: Please include (TWDB, unpublished) in the references section.

   Modified text.

10. Page 16, Section 4.1.2 Review of Borehole Geophysical Logs, last bullet of Wilcox Group and Page 19, Section 4.1.3 Hydrostratigraphic Framework Wilcox Group: In the original model for the Carrizo-Wilcox Aquifer (Fryar and others, 2003) the model assumed the Lower Wilcox was missing in the northeastern portion of the model area (see Section 6.2 of the original model report). In the updated model (Kelley and others, 2004), Layer 8 is of nominal thickness and does not represent the Lower Wilcox unit in the Sabine Uplift area of the model. The Middle Wilcox is missing and Layers 6 and 7 represent the Upper and Lower Wilcox units, respectively. Please update the text to explain why the Wilcox Group was not subdivided when discussing elog characteristics (page 16) yet was subdivided when discussing the hydrostratigraphic framework (page 19). Please discuss if the Wilcox Group should be subdivided in the western part of the model where the Simsboro/Middle Wilcox is prolific and lumped into 2 units or 1 unit in the Sabine Uplift area of the model where the Middle Wilcox thins.

Modified text to include subunits of the Wilcox Group in the elog characteristics (see Section 4.1.2., Wilcox Group, bullets 3,4,5, and 6).

Modified text to address the subgroups of the Wilcox Group (see under Section 4.1.3., Wilcox Group, paragraphs 2 and 3).

11. Page 17, Section 4.1.3 Hydrostratigraphic Framework, Quaternary Deposits (River Alluvium) paragraph 1, last sentence: The text states that Quaternary Deposits were assigned a thickness of 100 feet. However, Figure 4.1.5 shows various thicknesses in the major rivers (from <20 to 80 feet). Please adjust the text or the figure so they agree.

    Modified text to "up to 80 feet".

12. Page 17, Section 4.1.3 Hydrostratigraphic Framework, Sparta Sand and Figure 4.1.6 Top Elevation contours for the Sparta Sand: The top elevation of the Sparta Sand does not correlate with the aquifer outcrops as shown in Figure 4.1.3. Please explain or include the correct raster to show the top elevation of the Sparta Sand. If the top is at land surface elevation, please include the top of Sparta at land surface in the map.

    Adjusted text in Figure to say "bottom of the Younger Unit". Added "(or base of overlying Younger Units" to Section 4.1.3, Sparta Sand

13. Page 17, Section 4.1.3 Hydrostratigraphic Framework, Sparta Sand and Figure 4.1.7 Bottom Elevation Contours for Sparta Sand: Please clarify if the updip extent of the Sparta Sand matches the TWDB boundary of the Sparta Aquifer. Please discuss any differences or adjust as needed. Please discuss in the appropriate section if the footprint of an aquifer differs from the TWDB extent. This will form the basis for future updates to the aquifers.

    Modified text in Section 4.1.3, paragraph 2, sentence 2.

    "The footprints of the hydrostratigraphic units may differ from the aquifer footprints due to the incorporation of small, discontinuous outcrops and due to the footprint including the downdip portion of the layer to the model boundary."

    Modified text to refer to units in Section 4.1.3. as hydrostratigraphic units instead of aquifers.

14. Pages 17-19, Section 4.1.3 Hydrostratigraphic Framework, subsections Sparta Sand, Weches Formation, Queen City Sand, Reklaw Formation, Carrizo Sand, and Wilcox Group: In the Sparta Sand subsection, an elevation of '-6,300 feet amsl' is noted. The negative indicates the measurement is below mean sea level. In the other subsections, a negative is included when the units are 'below mean sea level', which would indicate the elevation is actually above mean sea level. Please consistently use a negative number with amsl to indicate elevations below mean sea level.

    Modified text by removing the negative sign for all instances.

15. Page 21, Section 4.2.2 Distribution of Groundwater Level Measurements, paragraph 1, sentence 1: Please include a reference to the United States Geological Survey National Water Information System since references are also included for the TWDB databases.

    Modified text.

16. Page 22, Section 4.2.3 Groundwater Levels and Flow through Time, paragraph 3, sentence 1: Please correct the references to the TWDB Groundwater Database and BRACS database and include a reference to the United States Geological Survey National Water Information System.

    Modified text.

17. Page 23, Section 4.2.3 Groundwater Levels and Flow through Time, first partial paragraph, last sentence: The text states that data for winter 2014 to 2015, 2 years prior, and 1 year after were used. In number 2 of the list following this sentence, the text says data going back 1 year then forward 1 year were used; number 3 of this list indicates a 3-year window. For clarity, please correct the text accordingly to accurately reflect how many years prior to winter 2014 were used for data selection.

    Modified text.

18. Page 26, Section 4.3.1 Recharge from Precipitation, paragraph 1: The text states that recharge over younger units are not accounted for in this study and that no values are shown for the younger units in Figure 4.3.1. Please consider summarizing recharge from the Yegua Jackson Aquifer model to account for the younger units in this study.

    Younger units are not included in this study; only shown for reference due to dipping structure of aquifer system of interest.

19. Page 27, Section 4.3.1 Recharge from Precipitation: This section discusses and compares several methods for estimating recharge in the study area. However, this section does not state which method is preferred for the updated model. As noted in the Previous Studies Section (Section 3) the previous groundwater availability model was not able to accommodate increased recharge rates. Per contract Exhibit A page 42 of 48, the link between steady-state and transient recharge needs further review as part of the update to the groundwater availability model. Exhibit A on the same page also states that 'information on precipitation, irrigation application estimates, and differences in flow between stream gages will be established to note baseflow or stream losses for further use in model calibration'. Please clarify whether these analyses were completed and document them if they were. If these analyses were not completed, please document why they were not required. Additionally, please document which approach will be used to improve recharge in the model update, given the issues with recharge in the previous model.

    Modified text to state the approach used to improve recharge in the model. Improvements to simulated recharge are summarized in the model calibration report.

20. Pages 28 to 30, Section 4.4 Surface Water Network: Per contract Exhibit A, Page 40 of 48, 'a literature review will be conducted [of groundwater/surface-water interactions] for this project to compile and summarize results of any relevant studies completed in recent years'. Please discuss the findings of the literature review in this section.

    Clarified in text that no new relevant studies were found during online literature search.

21. Page 34, Section 4.5.1 Transmissivity and Hydraulic Conductivity, last paragraph, sentence 4: The text states that the previous groundwater availability model assumed a vertical hydraulic conductivity of $1x10^{-4}$ feet per day. Please revise this sentence to state 'the previous groundwater availability model assumed a vertical hydraulic conductivity of $1x10^{-4}$ feet per day for confining units'. Also, please add a sentence explaining that the vertical hydraulic conductivity for aquifers in the previous groundwater availability model was estimated based on sand and clay fractions and assumed a hydraulic conductivity of $1x10^{-4}$ feet per day for the clay.

    Modified text accordingly.

22. Page 35, Section 4.5.1 Transmissivity and Hydraulic Conductivity, paragraph 1, sentence 2: The text states that 'model input data sets for the previous groundwater availability model indicate isotropic hydraulic conductivity properties, which means horizontal hydraulic conductivity is equal to vertical conductivity'. The previous groundwater availability model used *horizontal* isotropy, so that horizontal hydraulic conductivity along rows was equal to horizontal hydraulic conductivity along columns. Please revise the text to indicate *horizontal* isotropy. The model input data sets used leakance, which incorporated vertical anisotropy.

    Modified text accordingly.

23. Page 31, Section 4.5 Hydraulic Properties, paragraph 1: Please update the reference from Texas Natural Resources Conservation Commission to Texas Commission on Environmental Quality as the agency has changed its name in 2002.

    Modified text.

24. Page 37, Section 4.6, Potential for Subsidence: The report and tool associated with the vulnerability of Texas aquifers to pumping-induced subsidence is now available for you to include in the report.
    www.twdb.texas.gov/groundwater/models/research/subsidence/subsidence.asp

    Updated text with brief summary of the study results.

25. Page 37, Section 4.7.1 Groundwater Withdrawals by Pumping: Groundwater pumpage estimates and water use survey data is available for 2016 from the TWDB. Please include 2016 data for groundwater withdrawals.

TWDB pumping data for 2016 were not available during the data compilation task for this project. These data were added to the project dataset.

26. Page 39, Section 4.7.1 Groundwater Withdrawals by Pumping: The United States Geological Survey has water use data available for 2015. Please update this section of the report and the associated tables and figures to include 2015 data.

    USGS pumping data for 2015 were not available during the data compilation task for this project. These data were added to the project dataset.

27. Page 38, Section 4.7.1 Groundwater Withdrawals by Pumping, paragraph 2, last sentence: The text states pumping has followed a gradual declining trend since 2012, but Figures 4.7.1 and 4.7.2 indicate pumping has decreased since 2011. Please update the text accordingly.

    Modified text.

28. Page 39, Section 4.7.1 Groundwater Withdrawals by Pumping, paragraph 2, last sentence: The text states pumping has gradually decreased since 2010, but Figures 4.7.1 and 4.7.2 indicate pumping has decreased since 2011. Please update the text accordingly.

    Modified text.

29. Page 41, Section 4.7.1 Groundwater Withdrawals by Pumping and Figure 4.7.6 Locations of Registered Groundwater Production Wells in Study Area: Wells in the TWDB Groundwater Database are not necessarily registered wells. The TWDB Groundwater Database contains information on selected water wells, springs, oil/gas tests, water levels, and water quality to gain representative information about aquifers in Texas. The TWDB Groundwater Database is a monitoring network; it is not a registration database. Please update the text and figure caption to more accurately characterize the well network in Texas.

    Modified text and figure accordingly.

30. Page 43, Section 4.7.3 Evapotranspiration, paragraph 3: Please include a reference to the USGS Gap Analysis Project.

    Reference added.

31. Page 46, Section 4.8.3 Water Quality Evaluation Based on Water Use and Table 4.8.1 Summary of Exceedances: For a greater spatial understanding, please include a map showing where the exceedance samples were collected and which aquifer they are from.

    Additional maps added.

32. Pages 47 to 48, Section 4.8.4 Water Quality Evaluation on TDS Distribution: Please clarify in the text if there are known salt domes in the vicinity where high total dissolved solids concentrations are discussed. Note: since there are no county labels in

Figure 2.2.2, it is difficult to see if there is any correlation. Please also consider spelling out 'total dissolved solids' in all instances for increase readability, rather than using 'TDS'.

Modified text to mention salt domes. County labels were added to the figure for reference. "TDS" was changed to "total dissolved solids" for the entire document.

33. Page 49, Section 5.0 Summary of Conceptual Model and Figure 5.0.1 Conceptual Groundwater Flow Model: Please provide an original conceptual model diagram that shows all the layers in the model for comparison to the updated conceptual model diagram. If the diagram is based mainly on the diagram from Kelley and others (2004), please note that in the figure caption (for example, 'modified from Kelley and others (2004)'). Also, please provide a location map showing where the cross-section is located.

    Modified figure to include the section location. Modified figure title to be Section F-F' since this section is not the same as a Section A-A' presented earlier.

    Added text to figure to show it is modified from Kelley and others (2004).

34. Page 55, Section 8 References Cited: Please remove the Ashworth reference or include an in-text reference to Ashworth and Hopkins, 1995.

    Reference removed because not cited in report.

35. Page 58, Section 8 References Cited: Please remove the 2012 Scanlon reference or include an in-text reference to Scanlon and others, 2012.

    Verified that in-text reference already exists.

36. Page 59, Section 8 References Cited: Please remove the 2007 USGS reference or include an in-text reference to USGS, 2007.

    Reference removed because not cited in report. Cited and used Stoeser and others 2007 instead.

37. Table 4.3 Reservoirs in the Study Area and page 28, Section 4.3.2 Recharge from Reservoirs: Please change this table number to Table 4.3.2 to match the reference to the information in the text, and please include a source for the information in this table.

    Table number corrected.

38. Table 4.4 Summary of Aquifer Testing Results and page 31, Section 4.5.1 Transmissivity and Hydraulic Conductivity: Please change this table number to Table 4.5.1 to match the reference to the information in the text, and please include a source for the information in this table.

    Figure number corrected and source information included in table.

39. Table 4.7.1 Annual Estimated Groundwater Pumping (by aquifer): Groundwater pumpage estimates and water use survey data is available for 2016 from the TWDB.

Please add 2016 data to this table and update the source reference to match the reference in the text.

TWDB pumping data for 2016 were not available during the data compilation task for this project. These data were added to the project dataset.

40. Table 4.7.1 Annual Estimated Groundwater Pumping (by county): Groundwater pumpage estimates and water use survey data is available for 2016 from the TWDB. Please add 2016 data to this table and update the source reference to match the reference in the text.

    TWDB pumping data for 2016 were not available during the data compilation task for this project. These data were added to the project dataset.

41. Table 4.7.3 Annual Estimated Groundwater Pumping (Louisiana Parishes): The United States Geological Survey has water use data available for 2015. Please add 2015 data to this table.

    USGS pumping data for 2015 were not available during the data compilation task for this project. These data were added to the project dataset.

42. Figure 1.0.2 Minor Aquifers: Please update the minor aquifers map using the latest TWDB Minor Aquifer shapefile that includes the Cross Timbers Aquifer, which can be found here: www.twdb.texas.gov/mapping/gisdata.asp.

    Dataset updated with most recent version from TWDB.

43. Figure 2.1.6 Annual Precipitation in the Study Area: Please include the data used to make this figure as a table in the geodatabase.

    Table added to geodatabase.

44. Figure 2.1.7 Average Annual Lake Evaporation: Please indicate the averaging period for the lake evaporation data (for example, 1981 to 2010), and please include the average evaporation rate (inches per year) for each quadrangle in the geodatabase.

    Modified figure and updated geodatabase.

45. Figure 4.1.5 Thickness of Quaternary Deposits: Please include units for thickness, and address or remove the '500-600' listed between the legend and north arrow.

    Modified figure.

46. Figure 4.1.6 Top Elevation contours for the Sparta Sand and Page 17, Section 4.1.3 Hydrostratigraphic Framework, Sparta Sand: The top elevation of the Sparta Sand does not correlate with the aquifer outcrops as shown in Figure 4.1.3. Please explain and include the correct raster to show the top elevation of the Sparta Sand. If the top is at land surface elevation, please include the top of the Sparta at land surface in the map.

    Adjusted text in Figure to state "bottom of the Younger Unit". Added "(or base of overlying Younger Units" to Section 4.1.3, Sparta Sand.

47. Figure 4.1.19 Bottom Elevation Contours for the Middle Wilcox Unit: In comparison with feature classes in the geodatabase, it appears that the contours used in this figure are for the Upper Wilcox, not the Middle Wilcox. Please ensure that the correct raster and contour shapefile is used to represent the base elevation of the Middle Wilcox.

    Geodatabase updated with correct datasets.

48. Figure 4.2.9 Groundwater Level Elevation Contours for Carrizo Aquifer: In comparison with feature classes in the geodatabase, it appears that the 1980 figure is missing the contours. Please add the WLEContour_Carrizo_1980 feature class to this figure.

    Figure 4.2.9 includes groundwater level elevation contours that are linked to a feature class in the geodatabase. No change needed.

49. Figure 4.2.11 Groundwater Level Elevation Contours for Middle Unit of Wilcox Aquifer: In comparison with feature classes in the geodatabase, it appears that the 1980 figure is missing the contours. Please add the WLEContour_Middle_1980 feature class to this figure.

    Modified figure to include contours.

50. Figure 4.5.6 Percent Sand: Please update the legend to reflect percent sand rather than net sand thickness and please update the legend symbol for the elevation contour to a 10-foot contour interval

    Modified figure.

51. Figure 4.7.1 Groundwater Pumping (by aquifer): Groundwater pumpage estimates and water use survey data is available for 2016 from the TWDB. Please add 2016 data to this figure and update the source reference to match the reference in the text.

    TWDB pumping data for 2016 were not available during the data compilation task for this project. These data were added to the project dataset.

52. Figure 4.7.2 Groundwater Pumping (by water use sector): Groundwater pumpage estimates and water use survey data is available for 2016 from the TWDB. Please add 2016 data to this figure and update the source reference to match the reference in the text.

    TWDB pumping data for 2016 were not available during the data compilation task for this project. These data were added to the project dataset.

53. Figure 4.7.3 Groundwater Pumping (in Louisiana): The United States Geological Survey has water use data available for 2015. Please add 2015 data to this table.

    USGS pumping data for 2015 were not available during the data compilation task for this project. These data were added to the project dataset.

54. Figure 4.7.4 Comparison of Groundwater Pumping Estimates: Groundwater pumpage estimates and water use survey data is available for 2016 from the TWDB, and the

United States Geological Survey has water use data available for 2015. Please add 2015 and 2016 data to this table.

Tables updated accordingly.

55. Figure 4.7.5 Summary of Average Pumping: Groundwater pumpage estimates and water use survey data is available for 2016 from the TWDB, and the United States Geological Survey has water use data available for 2015. Please update this figure to reflect 2015 and 2016 data, including the caption and data source explanation. This is a good figure; however, it could be improved by rearranging some of the circles representing aquifer source and percent pumping. There are some cases where symbols are almost completely hidden by larger symbols and some cases where it's difficult to tell which county the symbol belongs to.

    TWDB pumping data for 2016 and USGS pumping data for 2015 were added to the datasets and figures updated accordingly. Changed county plots to pie chart format.

56. Figure 5.0.1 Conceptual Groundwater Flow Model: Please spell out 'evapotranspiration' in the legend. Please provide a location map showing where the cross-section A-A' is located. Please provide an original conceptual model diagram that shows all the layers in the model for comparison to the updated conceptual model diagram. If the diagram is based mainly on the diagram from Kelley and others (2004), please note that in the figure caption (for example, 'modified from Kelley and others (2004)').

    Modified figure. See comment 33.

Public comments:

Comments received by Panola County Groundwater Conservation District and Rusk County Groundwater Conservation District are summarized below.

57. The previous groundwater availability model indicated that Panola County covers mainly the upper and lower Wilcox layers or the middle and lower Wilcox units. Please clarify whether a clear delineation exists between the upper, middle and lower units of the Wilcox Group. Please identify and document this issue in the report, including whether distinction between Wilcox Group units is needed and/or warranted for Panola County, and how the distinction will affect the model in Panola County.

    See response to comment 10.

58. There is a large discrepancy between TWDB estimates of mining production volume and field data from the Railroad Commission. In Rusk County, there are some years where there may be a 1,000- to 3,000-acre-foot difference between the TWDB estimates and Railroad Commission field data. Please consider using values from the Railroad Commission in place of the estimates from the TWDB.

Mining pumping data from Railroad Commission and GCDs are used when available. TWDB mining estimates used only when other data are not available.

Suggestions for the conceptual model report:

59. Please add the TWDB contract number to the cover of the report and remove the TWDB logo from the cover of the report.

    Modified cover.

60. For improved readability, please limit the use of acronyms and abbreviations to units and the TWDB; please spell out all other acronyms in the text.

    Modified text accordingly.

61. Please make table number references in text consistent with actual table numbers in the Tables section.

    References to figures and tables were corrected.

62. Please add county and parish names, at a minimum, to Figures 2.0.2 through 2.0.6 so the reader can better visually orient themselves in the map.

    County labels were added to the listed figures and others for reference.

63. Please consider incorporating all tables into the text.

    All tables and figures were inserted into the text.

64. Please consistently refer to the TWDB Groundwater Database as 'the TWDB Groundwater Database' instead of 'TWDB's Groundwater Database' or 'TWDB GWDB'.

    Modified text.

65. Please consistently refer to the USGS National Water Information System as 'the USGS National Water Information System' instead of 'USGS NWIS'.

    Modified text.

66. Please consistently refer to sodium adsorption ratio as 'sodium adsorption ratio' instead of using 'SAR'.

    Modified text.

67. Please consistently refer to evapotranspiration as 'evapotranspiration' rather than 'ET'.

    Modified text.

68. Please spell out 'Soil Survey Geographic Database' instead of writing 'SSURGO'.

    Modified text.

69. Please consistently list geological units in either ascending or descending stratigraphic order.

Text modified or clarified, where appropriate.

70. Page 2, Executive Summary, paragraph 1: Please check sentence for grammar and clarity; for example, please consider replacing "extend" with "up-dip extent".

    Modified text.

71. Page 3, Section 1 Introduction, paragraph 2, sentence 1: Please capitalize 'aquifer' after 'Carrizo-Wilcox'.

    Modified text.

72. Page 4, Section 1 Introduction, paragraph 2, sentence 2: Please clarify what is meant by "proposed extractions of interest in the region."

    Modified text to clarify.

73. Page 6, Section 2.1 Physiography and Climate, paragraph 3, last sentence: Please add a degree symbol between '68' and 'F'.

    Modified text.

74. Page 9, Section 2.2 Geologic Setting, paragraph 1: For clarity, please consistently use 'Mount Enterprise', 'Enterprise', or 'Mt. Enterprise' to describe this fault zone.

    Modified text.

75. Page 12, Section 4.1 Hydrostratigraphy and Layering Framework, paragraph 1, sentence 3: Please revise the part of the sentence that discusses tops and bottoms of units.

    Modified text.

76. Page 12, Section 4 Hydrogeologic Setting, paragraph 2, sentence 1: Three aquifers are listed as an aquifer system that extends to a described area, but then it is a 'major aquifer that extends…'. Please update the text to reflect that either the aquifer system extends or that the Carrizo-Wilcox Aquifer extends.

    Modified text to be "major aquifer system that extends…".

77. Page 13, Table 4.1.1 Subsurface Data Sources, footnote (b): Please spell out Regional Aquifer-System Analysis instead of using the RASA acronym.

    Modified text.

78. Page 13, Table 4.1.1 Subsurface Data Sources: Please capitalize the 's' in 'BRACs'.

    Modified text to eliminate abbreviation as per comment.

79. Page 14, Section 4.1.2 Review of Borehole Geophysical Logs, list item 1(d): Please remove '569-A' after the Payne (1968) reference.

    Modified text accordingly.

80. Page 16, Section 4.1.3 Hydrostratigraphic Framework, paragraph 1, last sentence: Please change the table reference to '4.1.1' to match the table number.

Table number corrected.

81. Page 28, Section 4.4.1 River Flows, sentence 3: Please add an 's' to 'river'.

    Modified text.

82. Page 42, Section 4.7.2 Discharge to Rivers and Springs, paragraph 2: The text discusses springs and the second to last sentence states that 'flow data are missing for most wells'. Please clarify if this should state that flow data are missing for most springs and update as needed.

    Modified text. Replaced "wells" with "springs".

83. Page 42, Section 4.7.2 Discharge to Rivers and Springs, paragraph 2, sentence 5: Please remove '(NHD)' because the acronym is not used after this mention in the report.

    Modified text.

84. Page 43, Section 4.7.3 Evapotranspiration, paragraph 3: Please refer to the USGS Gap Analysis Project as the 'USGS Gap Analysis Project' and remove all 'GAP' acronyms.

    Modified text.

85. Page 43, Section 4.7.3 Evapotranspiration, paragraph 4: Please refer to the USDA Soil Water Assessment Tool as the 'USDA Soil Water Assessment Tool' and remove all 'SWAT' acronyms.

    Modified text.

86. Page 44, Section 4.7.4 Cross-Formational Flows, paragraph 2, sentence 1: Please spell out 'versus' instead of using 'vs'.

    Modified text.

87. Page 44, Section 4.7.4 Cross-Formational Flows, paragraph 1, sentence 2: Please add a closing parenthesis after the references.

    Modified text.

88. Page 48, Section 4.8.4 Water Quality Evaluation: The text refers to Table 4.1.2 to indicate water quality in the outcrop versus downdip. The table appears to be Table 4.8.2. Please update the table number in the text.

    Table number reference corrected.

89. Page 49, Section 5 Summary of Conceptual Model, paragraph 2, sentence 7: Please change '9-layer' to 'nine-layer' to be consistent with the first sentence of this paragraph.

    Modified text.

90. Page 53, Section 6 Future Improvements, paragraph 3, sentence 4: Please spell out the acronym 'TMDB' or replace with 'TWDB', if TWDB was the intention.

    Text modified with "TWDB".

91. Page 57, Section 8 References Cited: Please alphabetize the L and M references.

    Reference list modified accordingly.

92. Page 58, Section 8 References Cited: Please correct the Stoeser reference; it appears an additional reference was added on to the end.

    Reference list modified accordingly.

93. Page 61, Section 9 Acronyms & Abbreviations: Please limit the use of acronyms and abbreviations to units and governmental agencies; spell out all other acronyms in the text.

    All acronyms removed except units and TWDB per other comments.

94. Page 60, Section 8 References Cited: Please revise the USGS Gap Analysis Project reference format to match the other references.

    Modified text.

95. Figure 2.0.7 Major River Basins: Please spell out the acronyms for USGS and HUC6.

    Acronyms removed on figure.

96. Table 4.2 Summary of Annual Recharge and page 27, Section 4.3.1 Recharge from Precipitation: Please change this table number to Table 4.3.1 to match the reference to the information in the text.

    Figure number reference corrected.

97. Figure 4.1.2 Locations of Evaluated Borehole Geophysical Logs: Please change 'E-log' to 'elog' to match the text in Section 4.1.2.

    Figure text modified.

98. Figures 4.1.6 through 4.1.22: Please include units for elevation/thickness in the legend for each of these figures.

    Added units to figure explanations.

99. Figure 4.1.8 Thickness of Sparta Sand, Figure 4.1.10 Thickness of Weches Formation, Figure 4.1.12 Thickness of Queen City Sand, Figure 4.1.14 Thickness of Reklaw Formation, Figure 4.1.16 Thickness of Carrizo Sand, Figure 4.1.18 Thickness of Upper Wilcox Unit, Figure 4.1.20 Thickness of Middle Wilcox Unit, and Figure 4.1.22 Thickness of Lower Wilcox Unit: The legend symbol for the elevation contour indicates a 200-foot contour interval. However, the figures and the color ramp legend symbols suggest a 100-foot contour interval. Please update all legends in the thickness figures.

    The contour line symbol in the Explanation shows an example contour label. Contour intervals are indicated by symbology in the Explanation. No changes made.

100. Figures 4.2.7 through 4.2.12: The text mentions counties in describing the water level maps, but the counties are not labeled on the maps. Please label the counties to help the reader follow the discussion.

Figures modified.

101. Figures 4.4.2 through 4.4.6: Please spell out the acronyms WBD and HUC6.

Figure text modified.

102. Figure 4.7.6 Locations of Registered Groundwater Production Wells in Study Area: Due to the density of points, this image could be improved by increasing the transparency of the symbols. Please either note in the figure that mining is not represented here, or update with wells classified with mining use.

Due to the number and density of the data, some wells will not be visible. Transparency does not improve the display of this number of points. Figure text modified to state mining wells are grouped into industrial category.

103. Figure 4.7.7 USGS Gap Analysis Project: Please spell out all instances of GAP as Gap Analysis Project.

Modified text.

104. Figure 4.8.1 through 4.8.4: Please spell out all instances of 'TDS' as 'total dissolved solids'.

Modified text.

Draft geodatabase and data deliverables comments:

General comments to be addressed

105. Per contract Exhibit B Attachment 1 Section 4.2, all tabular data and geographic information system raster and feature datasets shall be delivered to the TWDB within the groundwater availability modeling source geodatabase schema(s) provided to each project manager. The empty file geodatabase schema provided contains several feature classes that are not included in the draft geodatabase. If a feature class in the groundwater availability modeling empty geodatabase schema was not used in model development, please note this in the metadata for that feature class. Please also reorganize the existing geodatabase schema to follow the organization of the groundwater availability modeling empty geodatabase schema.

An empty geodatabase schema was obtained by TWDB after the draft report submittal. All data were moved to the schema for final submittal.

106. Please ensure that all spatial data has been projected into the groundwater availability modeling coordinate system (per contract Exhibit B Attachment 1 Section 4.2, spatial

information shall be projected into the groundwater availability modeling coordinate system with units of measure in feet prior to and during any spatial analysis).

All geospatial data is projected in the appropriate coordinate system, including the files that were submitted with the draft conceptual model report.

107. Please ensure that all data in tables in the report is included as a table in the geodatabase if it is source or derived data (per contract Exhibit B Attachment 1 Sections 4.0 and 4.2, source and derived information from the development of the conceptual model shall be documented in geodatabase format).

    All source data are now stored in the geodatabase.

Specific comments to be addressed

108. Geology feature dataset > ELog_Locations feature class: In the metadata, please include explanations for N, P, R, and U for the Elog_Code attribute

    Code descriptions were added to the metadata.

109. SubsurfaceHydro feature dataset > Compiled_WLEs_All_Measurements feature class: In the metadata, please explain all shorthand used for attributes, such as MULTI in USE_HGU or N in OlderUnit.

    Code descriptions were added to the metadata.

110. SubsurfaceHydro feature dataset > Minor_Aquifers_TX feature class: Please update the minor aquifers shapefile. The latest TWDB Minor Aquifer shapefile includes the Cross Timbers Aquifer, and can be found here: www.twdb.texas.gov/mapping/gisdata.asp.

    Dataset replaced with correct version.

111. SubsurfaceHydro feature dataset > Recharge_30_yr_avg feature class: Please include explanations in the metadata to describe which recharge estimate attributes correspond to which estimation method.

    Added field descriptions to the metadata.

112. SubsurfaceHydro feature dataset: Please include the pumping data used to generate figures 4.7.1 through 4.7.4 as a table(s) in the geodatabase.

    Table included in geodatabase.

113. SurfaceHydro feature dataset > WBDHU6 feature class: Please remove this feature class since a version is also included for river basins only in the study area.

    The river basin feature class was removed instead.

114. SurfaceHydro feature dataset: Please include water level elevation data for reservoirs, as shown in Figure 4.3.4, as a table in the geodatabase.

    Table included in geodatabase.

115. SurfaceHydro feature dataset: Please include annual streamflow data, as shown in figures 4.4.2 through 4.4.6, as a table in the geodatabase.

    Table included in geodatabase.

116. SurfaceHydro feature dataset: Please include daily discharge flow data, as shown in Figure 4.4.7, as a table in the geodatabase.

    Table included in geodatabase.

117. HGUBaseElev_01YoungerUnits: It appears that the base elevation of the younger units raster was used in Figure 4.1.6 to show the top elevation of the Sparta Sand, however, the top elevation of the Sparta Sand shown in that figure does not correlate with the aquifer outcrops as shown in Figure 4.1.3. Please include the correct raster to show the top elevation of the Sparta Sand.

    The raster for top elevation of Sparta Sand was modified to include outcrop areas for display on the report figure.

118. Base Elevation Rasters and Salt_Domes feature class: There are negative spaces (no base elevations) in several of the downdip portions of rasters which are assumed to represent locations of salt domes; however, the Salt_Domes feature class does not completely correlate with the negative spaces. Please explain what the negative spaces in the elevation surfaces represent and/or explain why these negative spaces do not correspond with the locations of the salt domes.

    In general, the blank or null portions of the base elevation rasters indicate locations where the unit is pinched out. Some of these areas are associated with salt domes. For other areas, the base elevation of river alluvium truncates (erodes into) the underlying layers, resulting in the removal of small areas of thin intervals of the underlying layers in the framework particularly along the major rivers.

Suggestions for the draft geodatabase and data deliverables:

119. Please consider creating Leapfrog scenes for Leapfrog Viewer (free to download) so that the geological model can be viewed without a Leapfrog Geo license (not free to download).

    This was an oversight. A Viewer file was mistakenly excluded from the submittal. A Viewer file will be submitted to TWDB with this final report.

Draft BRACS database and data deliverables comments:

120. BRACS Database table bracs_tblWell_Location is missing information for the majority of the new well controls (wells with a well_id greater than 150,000) for the following fields. Please populate these fields with the required data.

a. Depth_total
b. Depth_well
c. Drill_date
d. Kelly_Bushing
e. Owner
f. Well_Type
g. Location_method
h. Location_Date
i. Location_Agency
j. Initials (note: fill with value MA)

Populating the BRACS database with location details is beyond the scope provided by the TWDB which states "Any additional interpretation of new geophysical logs or adjustments to existing analysis of geophysical logs shall be provided in a format compatible with the BRACS database". This scope did not include determining all attributes associated with the locations. All of the locations appended on to the BRACS database were from datasets used from the previous GAM for this GAM update.

121. BRACS Database table Bracs_tblWell_Location contains values in the field depth_total that are incorrect. For example, the record with a well_id of 153334 and ma-uniqueid of 3668 has a depth_total value of 9,640. This well was in the BRACS Database before the project initiated and has a well_id of 24819 with a depth_total value of 12,946. Please verify the source of the depth_total values and update the table with correct information.

There were 19 appended locations where the Foreign Key table indicated a BRACS Elog ID. These locations should have been correctly linked with the BRACS ID and not included as an appended location. These locations were linked to the BRACS ID and their appended location ID was removed.

122. BRACS Database table Bracs_tblWell_Location contains many records with a data source of "other" that have a foreign key id_name of "TWDB_UnpublishedReport_ID" that are wells in the TWDB Groundwater Database. For example, the record with a well_id of 151759 has a state well number of 3740302. Please identify these records and update the data source of these records to "TWDB Groundwater Database" and update the foreign key table to "State_Well_Number".

Updated the data source to "TWDB Groundwater Database" and where the Foreign Key was seven digits, the foreign key table was changed to "State_Well_Number".

In addition to the record corrections, it is noted that the majority of these records have a latitude and longitude value that is different than that in the TWDB Groundwater

Database. Unless these wells have been re-located to a better location, please update the locations to be consistent with the Groundwater Database coordinates. If the well locations have been re-located, please update the table Bracs_tblWell_Location fields location_method, location_date, agency with new values to reflect that Montgomery and Associates has modified the coordinates.

The coordinates were sourced from the original GAM dataset. As this was an update to the GAM, the points were not relocated except where the location was verified with an elog.

123. BRACS Database table Bracs-tblBracs_ForeignKey contains the following errors that will need to be corrected. This information is critical for BRACS staff and other stakeholders to correctly determine the identity of a well and perform queries based on the foreign keys.

   a. Wells identified as having a state_well_number do not have the required 7 digits. Please investigate this and correct records as needed. An example of this is the record with a well_id of 153105 and a "state well number" of 369490. Some of these records may be Texas Department of Licensing and Regulation (TDLR), Submitted Driller Reports (SDR) track numbers instead of state well numbers.

      These records were sourced from the Rusk County GCD which identified these identifiers as "State of TX Well Report Tracking Number". The Foreign Key was updated for these records to reflect the Agency as "RCGCD" and the ID_Name as "RCGCD State of TX Well Report Tracking Number".

   b. Wells that are oil and gas should have the lease and well number appended to the foreign key table. An example of this is the record with a well_id of 150887 where the owner well number should be M.W. Armstrong 1

      Additional information for the purpose of developing a BRACS database was beyond the scope of this work.

   c. Please correct the format of each record with a Q-number by adding a dash after the letter Q, for example, Q-139. An example of this is record with a well_id of 150887.

      This formatting was from the original GAM dataset. The Q-number records have been updated to properly include a dash.

   d. All new and existing well control where the well was used on a published or unpublished cross-section needs to have a corresponding record in the foreign key table. This is critical for BRACS staff and stakeholders to be able to compare the stratigraphy shown on cross-sections to BRACS Database wells and to geological formation raster surfaces. These records should have an agency code (source of the cross-section), an id_name equal to cross_section well, and a for_key_txt value with the format of XS AAA, B-B, and ## where AAA is an abbreviation of the report, B-B refers to the cross-section line, and ## refers to the well name or number on the cross-section. An example of this is record with a well_id of 152772 where the agency is TWDB and the for_key_txt would be XS R150 B-B', 3801402.

This task is beyond the scope of work for the GAM update.

e. Wells with a record from the TDLR SDR database should have a corresponding record in the foreign key table.

No new records were identified from the TDLR SDR.

f. Please change the agency code from "UT-A" to "BEG" for all records where the id_name is "Ayers_Lewis_ID". This work was published by the Bureau of Economic Geology.

The agency code was updated to "BEG".

124. Please populate the BRACS Database table tblGeophysicalLog_Header with records for all new well control that has a digital geophysical well log. The second key field for these records may also start with the value of 150000.

Metadata_nQCSCW_geologs.docx in the Database for BRACS folder: The response to comment 3 states, "Note: Montgomery & Associates did not verify any geophysical logs not already in the BRACS database. Therefore, edits to the BRACS tblGeophysicalLog_Header and tblGeophysicalLog_Suite were not necessary." However, it was determined that a number of new wells appended to the BRACS Database from the Rusk GCD log collection (well_id from 152989 to 153333) do have digital geophysical well logs and stratigraphic data was appended to the table BRACS_tblWell_Geology.

This comment pertains to the Elogs provided by Rusk County GCD. The PDFs provided by the Rusk County GCD will be provided. The table GeophysicalLog_Header was updated to show the proper GL_Folder for these elogs and the GL_Digital_File_Name was assigned the RCGCD Well Number which is also the file name.

There are other new wells where stratigraphic information was verified with a Q-log, however the Q log was not added to the table. GIS file elog_locations.shp contains many new wells where stratigraphy was reviewed digital geophysical logs are available but were not submitted (for example, record with well_id 151876). Therefore, these geophysical well logs need to be appended to the table tblGeophysicalLog_Header.

Stratigraphic information was available from the previous GAM. The GAM update scope of work did not include the verification of elogs for the previous GAM. As part of the GAM update, M&A attempted to verify these stratigraphic contacts with available elogs from BRACS. The methodology for this verification process was included in the *report text. For the example, the GIS shapefile elog_locations.shp includes all locations and in the attribute table, the ELog_Code field should be queried to confirm which locations were verified with an elog. As specified in the shapefile metadata, where ELog_Code is "Y" the location has a verified elog.*

For example, record with a well_id of 152989 is Rusk GCD well 3536814 with a TDLR SDR tracking number of 164737. This well was used for stratigraphy and does have a digital geophysical well log with a filename of 3536814.pdf

This comment pertains to the Elogs provided by Rusk County GCD. The PDFs provided by the Rusk County GCD will be provided. The table GeophysicalLog_Header was updated to show the proper GL_Folder for these elogs and the GL_Digital_File_Name was assigned the RCGCD Well Number which is also the file name.

125. Please populate BRACS Database table tblGeophysicalLog_Suite with records for all new well controls that have a digital geophysical well log. The first and second key fields must be synchronized with table tblGeophysicalLog_Header. The third key field represents the tool name; please add all tools on the geophysical log to this table with top and bottom depths representing the section logged in the well.

    This task is beyond the scope of work for the GAM update.

126. Please provide copies of all digital geophysical well logs. The filename of the log should correspond to the filename in the table tblGeophysicalLog_Header. The logs should be organized in a folder system based on state_county codes.

    The PDFs provided by the Rusk County GCD will be provided.

127. The database provided (nQCSCW_geologs.accdb) contains the table tblWell_Geology$_ImportErrors with 5972 records. This table is created automatically by MS Access and lists records that failed to import properly. It appears that the fields thickness and depth_bottom did not import correctly. Since we were not provided the source table, we cannot determine why the errors occurred. Please investigate this issue and provide an updated copy of table BRACS_tblWell_Geology.

    This error was addressed in the BRACS_tblWell_Geology submitted, but the error log was not deleted. This has been fixed.

128. The table BRACS_tblWell_Geology has, for some records with a well_id value > 150000, a value in the remarks field indicating the geophysical well log used to determine the stratigraphic values. For example, the record with a well id of 153358 has a value of "BRACS Elog 42_225 HOUSTON 144" listed in the remarks field. It is not possible, based on the data supplied in the database, to determine which log this is. This

represents an example of why the data in the BRACS Database tables must be complete.

Another example, the record with a well_id 153346 has a value of "BRACS Elog 42_199 4240530002" listed in the remarks field. In this case, the API number 4240530002 refers to an existing record in the BRACS Database with a well _id of 33489. Since one of the objectives of the BRACS Database is to have only one record per well, please determine if any of the new well controls (wells with a well_id of 150000 or more) are duplicated and please modify the well id field to the correct BRACS Database well_id for all applicable tables.

This was addressed in comment 121. This was not a part of the GAM update scope of work, but an attempt was made to remove apparent duplicate wells where they are spatially correlated during the elog verification.

129. Additional duplicate wells are in the table BRACS_tblWell_Location. For example, record with a well_id of 151960 has a foreign key value of 3739502 which is the same well as record with a well_id of 153339 with a foreign key value of Q-34.

This was not a part of the GAM update scope of work, but an attempt was made to remove apparent duplicate wells where they are spatially correlated during the elog verification.

130. Please verify there are no duplicate wells in the database and consolidate any duplicate wells into one record per well. The table BRACS_tblBracs_ForeignKey should contain all applicable records to ensure the user understands one well may have multiple names or numbers.

This was not a part of the GAM update scope of work, but an attempt was made to remove apparent duplicate wells where they are spatially correlated during the elog verification.

131. The table BRACS_tblWell_Geology contains 268 records that contain a negative thickness due to an incorrect top or bottom depth value. For example, record with a well_id of 153358 has a negative thickness for the Carrizo – upper wilcox subgroup. Since there are many more records with missing bottom depth and thickness values, the number of additional errors may be greater. Other records indicate a negative top depth (for example, record with well_id of 151624) and/or negative bottom depth (for example, record with well id of 151831). Please provide correct values for depth_top, depth_bottom, and thickness.

The original BRACS database provided included a negative thickness for 95 entries and a few negative depth top and bottoms. M&A reviewed only locations added or modified (as indicated where the MA_UniqueID is greater than 0) and corrected the calculations to provide only positive values.

132. All new records in the BRACS Database should have the initials field populated with the value of MA. This applies to at least the tables BRACS_tblWell_Location, BRACS_tblWell_Geology, and tblGeophysicalLog_Header.

The initials field in the BRACS tables is populated with the value of MA where there are new records. The BRACS_tblWell_Location was modified to ensure the initials are shown for new records. The tables BRACS_tblWell_Geology and tblGeophysicalLog_Header already had the initials populated for new entries. The other tables originally included were for reference and not intended to be imported into the BRACS database. To simplify the submittal, the database is being limited to the BRACS database tables.

133. There are several records in the table tblWell_ElogComments with an Elog_Code of null, indicating that a digital geophysical well log was more than 1500 feet from a data source location. However, TWDB provided a copy of not only our digital geophysical well log collection that has records within the BRACS Database but also a collection of digital geophysical well logs from east Texas, primarily Q-logs, organized into county folders for use in verifying stratigraphy. For example, record with a well_id of 153339 has a state well number of 3739502 and a Q-log value of Q-34 for San Augustine County. This well was used for verifying stratigraphy but was not added to the table tblGeophysicalLog_header.

A preliminary review of the submitted digital (PDF) geophysical well log collection suggested most of these logs were already entered in the BRACS database. The example shows there were some cases where the BRACS database was not up to date with the available BRACS digital (PDF) geophysical well log collection which was not apparent during the GAM update. Modifications to the BRACS database were not a part of the scope of the GAM update and the BRACS data submittal was a best effort to provide some elog verification of the stratigraphy from the previous GAM. To simplify the submittal, the database is being limited to the BRACS database tables.

Another example is record with a well_id of 151733 that has a state well number of 3739501 and a Q log number of Q-10. This log was made available, but the Elog_code is null, meaning that the contractor did not have a digital geophysical well log. Although it is understandable that not all logs would be used to verify stratigraphy, some of these codes are completely misleading when logs are available.

Please append the geophysical well logs as referenced in previous comments.

The Elog_Code is only indicative of the elog verification process and is not intended to signify if an elog is available or not. This description was included in the lookup table tblLK_ElogCode. The null simply signifies that this location was not reviewed as it did not qualify for the spatial correlation. The example provided is another instance where *the BRACS database was not up to date with the digital (PDF) geophysical well log collection making it difficult to check for duplicates. To simplify the submittal, the database is being limited to the BRACS database tables.*

134. Draft report page 31, section 4.5.1 refers to table 4.5.1 that is not in the report. Please incorporate this table in the report.

    This was an inadvertent error. Table added to report.

Suggestions for the numerical model report:

135. Page 7, Section 2.1 Physiography and Climate and Figure 2.1.6: It will be important to note in the Numerical Model Report that the end of the transient calibration appears to be an above average climatic year. This may have a bearing on predictive drawdown results.

    Refer to model calibration report.

136. Page 51, Section 5.1 Historical Transient Conditions: Please consider starting the transient calibration in at least 1980 and determine a method of estimating pumping from 1980 to 1984. Also, please discuss the transition from pre-development in 1936 to the beginning of the transient calibration period. Model calibration should include both steady-state and transient calibration per contract Exhibit B, Attachment 1, page 27 of 33.

    Numerical model methods are described in the model calibration report. Transient simulations begin in 1980 and pumping was estimated for 1981 through 1983 using linear interpolation between 1980 and 1984 data.

Appendix C

Responses to Draft Final Review Comments

Attachment 1

The following report and data review comments shall be addressed and included in the final deliverables by no later than December 11, 2020. Please note that the items listed under ‘Suggestions’ are editorial in context and are not contractually required; however, the suggested adjustments noted may improve the readability of the report and/or the usability of the data deliverables. No public comments were received by the TWDB.

Note: Responses to comments related to the draft final conceptual model report are shown below in italic font.

Draft final conceptual model report comments:

General comments to be addressed

81. Per Contract Section II, Article III, number 5, please include draft conceptual model report comments in the final conceptual model report as an appendix and please also consider noting how and where the comments were addressed.

    The draft conceptual model comments are included in the following section of this appendix. Clarification on how and where comments were addressed are added for responses where needed.

82. Per Contract Section II, Article III, number 5, please ensure that the final conceptual model report is accessible: The alternate text for figures required to make the document accessible is not meaningful text. It is just a string of characters. Please provide alternate text for the figures to make the document accessible.

    Appropriate alternative text was added to each figure. Final report preparations will ensure proper accessibility.

Specific comments to be addressed

83. Per Contract Exhibit A, item H, page 42, ‘information on precipitation, irrigation application estimates, and differences in flow between stream gages will be established to note baseflow or stream losses for further use in model calibration’. Please clarify whether these analyses were completed and

document them in the conceptual model report if they were. If these analyses were not completed, please document why they were not required.

Differences in annual streamflows were indeed assessed for this study. A summary of the results was added to Section 4.4.1, page 99. And the annual differences are summarized in a new table, Table 4.4.

84. ***Page 5, Section 1, Figure 1-2***: Please update the minor aquifers map using the latest TWDB Minor Aquifer shapefile that includes the Cross Timbers Aquifer, which can be found here: www.twdb.texas.gov/mapping/gisdata.asp. It appears that the updated feature class is in the model geodatabase, but the figure has not been updated to include it. *(Not addressed after first round of comments)*

    Figure 1.2 was updated to show Cross Timbers Aquifer.

85. ***Page 66, Section 4.2.2, paragraph 1, sentence 1***: Please include a reference to the United States Geological Survey National Water Information System since references are also included for the TWDB databases. *(Not addressed after first round of comments)*

    Reference added to this sentence.

86. ***Page 67, Section 4.2.3, paragraph 3, sentence 1***: Please correct the references to the TWDB Groundwater Database and BRACS database and include a reference to the United States Geological Survey National Water Information System. *(Not addressed after first round of comments)*

    References corrected and added accordingly in this sentence.

87. ***Sections 4.2 and 4.3***: Please add reference and year to citations of the United States Geological Survey National Water Information System in Louisiana.

    This comment was addressed by responses to Comments 85 and 86. No other instances of this citation was found in the report.

88. ***Pages 98, Section 4.4 Surface Water Network***: Per contract Exhibit A, item G, page 40, 'a literature review will be conducted [of groundwater/surface-water interactions] for this project to compile and summarize results of any relevant studies completed in recent years'. Please discuss the findings of the literature review in this section.

A literature review was indeed conducted for this investigation and presented in the draft final report. However, the results were erroneously summarized in Section 4.7.2 Discharge to Rivers and Springs instead of in Section 4.4. The summary was moved from Section 4.7.2 to Section 4.4.1, 2nd paragraph, page 99.

89. ***Page 108, Section 4.5.1, Table 4.4***: The table footnote has a citation for Kekky and others (2004). Please change this to Kelley and others (2004). Please also add a year for the Texas Water Development Board groundwater database citation and change Texas Natural Resource Conservation Commission to Texas Commission on Environmental Quality in the same footnote and add a year.

    Footnotes for Table 4.4 were updated accordingly. Reference to Texas Commission on Environmental Quality in the footnote was an error, and it was removed from the footnote. Please note, with the addition of a new table to address comment 83, this is now Table 4.5.

90. ***Page 108, Table 4.4, Source***: Please update the reference from Texas Natural Resources Conservation Commission to Texas Commission on Environmental Quality as the agency has changed its name in 2002 and please ensure the table source includes a year that matches the reference in the references section. *(Partially addressed after first round of comments)*

    This comment was address by response to Comment 89. Please note, with the addition of a new table to address comment 83, this is now Table 4.5.

91. ***Page 120, Section 4.6, last paragraph***: Please change the font for this paragraph to 12-point Cambria.

    The style for this paragraph was updated to the correct Body style, including the appropriate font. Please note, with the addition of a new table to address comment 83, this is now page 125.

92. ***Page 122, Section 4.7.1***: Please spell out Texas ‘RRC’ as ‘Railroad Commission of Texas throughout this section and the rest of the report.

    Please note, with the addition of a new table to address comment 83, this is now page 127. This acronym was corrected in the two instances where it occurred in this section: page 127 and page 131. This correction was also made in the footnote for Table 4.11.

93. ***Page 123, Section 4.7.1***: Thank you for including 2016 data for groundwater withdrawals. Please indicate throughout this section that TWDB Water Use Survey data through 2016 was used and ensure that the years in the text (up to 2015) match the years presented in the tables, figures, and captions (up to 2016).

    Please note, with the addition of a new table to address comment 83, this is now page 128. Section 4.7.1 was updated with statistics through 2016 in paragraphs 2, 3, 5 for TWDB estimates, and through 2015 in paragraph 6 for USGS estimates.

94. ***Page 126, Section 4.7.1, paragraph 2, sentence 6***: Wells in the TWDB Groundwater Database are not necessarily registered wells. The TWDB Groundwater Database contains information on selected water wells, springs, oil/gas tests, water levels, and water quality to gain representative information about aquifers in Texas. The TWDB Groundwater Database is a monitoring network; it is not a registration database. Please update the text to more accurately characterize the well network in Texas. A mention of 'registered well locations' also occurs on page 125. *(Partially addressed in Figure 4-67 after first round of comments, but the text needs to be updated)*

    Please note, with the addition of a new table to address comment 83, this is now page 131. This paragraph was updated by replacing "registered" with "reported"; same for page 130.

95. ***Page 143, Figure 4-66***: Please update the source information on the figure to indicate that the 2015 USGS water use report was used for the figure, if this figure was updated with 2015 USGS data as the other figures for groundwater pumping were.

    The footnote on Figure 4-66 was updated accordingly. Please note, with the addition of a new table to address comment 83, this is now page 148.

96. ***Page 176, Section 8, References Cited***: Please remove the Ashworth reference or include an in-text reference to Ashworth and Hopkins, 1995. *(Not addressed after first round of comments)*

    The Ashworth reference was deleted from Reference Cited (Chapter 8).

97. ***Page 182, Section 8, References Cited***: Please remove the 2007 USGS reference or include an in-text reference to USGS, 2007. *(Not addressed after first round of comments)*

    The USGS 2007 reference was deleted from Reference Cited (Chapter 8).

98. ***Page 143, Figure 4-66***: The source text on this figure states that USGS data through 2010 were used while the geodatabase includes data from 2015. Further, the source text states that TWDB data through 2016 were used, while the figure caption indicates the data only go through 2015. Please correct the figure caption and source text to show the correct date ranges for the data used in the figure.

    The comment is addressed by responses to Comments 93 and 95. Please note, with the addition of a new table to address comment 83, this is now page 148.

99. ***Page 144, Figure 4-67***: The point symbols on this map vary in size for no clear reason, which causes unnecessary overlap between symbols and inhibits readability. Please consider using smaller, uniformly sized point symbols to improve the readability of this figure and to avoid confusion.

    Figure 4-67 was updated with revised symbology to improve clarity. However, overlapping symbols are unavoidable when displaying such a large number of wells. Please note, with the addition of a new table to address comment 83, this is now page 149.

Draft geodatabase and data deliverables comments:

General comments to be addressed

102. Per Contract Exhibit B, Attachment 1, Sections 4.0 and 4.2, source and derived information from the development of the conceptual model shall be documented in geodatabase format. Please ensure that all data in tables in the report is included as a table in the geodatabase if it is source or derived data.

     Tables used as source data for hydrograph displays within figures were missing from the draft final geodatabase. Tables for these data were added to the final geodatabase.

103. Per Contract Exhibit B, Attachment 1, Section 4.2, all tabular data and geographic information system raster and feature datasets shall be delivered to the TWDB within the groundwater availability modeling source geodatabase schema(s).

The empty file geodatabase schema provided contains several feature classes that are not included in the draft geodatabase. If a feature class in the groundwater availability modeling empty geodatabase schema was not used in model development, please include that feature class and note in the metadata that it was not used in model development. Several feature classes that are included in the Boundary feature dataset of the empty geodatabase were not included in the draft geodatabase.

We were instructed by TWDB to disregard this comment.

104. Per contract, Exhibit B, Attachment 2, Page 3 of 4, Section 1.1.4, "A model grid feature dataset shall be located within the Source and derivative geodatabase and consist of a polygon feature class of model grid cells and a point feature class of model cell grid nodes." The source geodatabase does not contain the model grid. Please provide polygon and point grid feature class files attributed with grid cell node numbers and parent grid row, column, and layer numbers. Please include the active only grid node numbers from 1 through 637,536 where the nodes are in the order listed in the MODFLOW 6 discretization file so that the ArcGIS feature dataset can be used to designate zone numbers to use with Zonebudget for MODFLOW 6. This file is particularly critical for the TWDB to be able to use the model to produce water budgets for groundwater conservation districts and to be able to provide modeled available groundwater values for groundwater management areas.

Polygon and point feature classes for each layer of the model grid were added to the geodatabase. Given the unstructured grid of the model, each layer has an unique grid and each layer grid dataset represents the active grid cells in that layer. Model grid node identifier is also provided.

Specific comments to be addressed

105. Please include data used to construct charts in Conceptual Model Report; for example, Figure 2-15 (Average Monthly Precipitation at Selected Rain Gauges) in table format in the geodatabase.

Two new tables containing source data for these charts were added to the geodatabase. The table Fig2_15_MonthlyPrecipAvg contains the average monthly values shown on the figure, while the table Fig2_15_MonthlyPrecip contains the source historical monthly values used to calculate the average monthly.

106. Please include data used to construct charts in Conceptual Model Report; for example, Figure 4-45 (Water Level Hydrographs for Selected Reservoirs in Study Area) in table format in the geodatabase.

    A new table (Fig4_45_ Reservoir_WLE) containing source data for these charts was added to the geodatabase.

107. Please include data used to construct charts in Conceptual Model Report; for example, Figures 4-47 through 4-51 (Annual Streamflows) in table format in the geodatabase.

    A new table (Figs4_47_to_51_Streamflow_Annual) containing source data for these charts was added to the geodatabase.

108. Please include data used to construct hydrographs in Conceptual Model Report; for example, Figure 4-52 (Daily Discharge Flows for Selected Reservoirs in Study Area) in table format in the geodatabase.

    A new table (Fig4_52_ Reservoir_Discharge) containing source data for these hydrographs was added to the geodatabase.

109. Subsidence risk data used in Conceptual Model Report Figures 4-59 through 4-61 do not appear to be included in the geodatabase. Please include these data in feature class or table format in the geodatabase.

    These figures are based on figures extracted from the report by Furnans and others (2017). JPG image files were provided with the electronic figure datasets for the final draft report submittal, and also with this final report submittal. The raster images were also added to the geodatabase in the parent directory.

110. Water quality data used in Conceptual Model Report Figures 4-71 through 4-79 do not appear to be included in the geodatabase. Please include these data in feature class or table format in the geodatabase.

    These datasets were added to the geodatabase in the \SubSurfHydro feature dataset with "WQ_" prefix in file names.

111. Total Dissolved Solids data used to construct maps and charts in Conceptual Model Report Figures 4-80 through 4-83 do not appear to be included in the geodatabase. Please include these data in feature class or table format in the geodatabase.

All total dissolved solids measurements are included in a feature class called “TDS_recent” in the \SubSurfHydro feature dataset submitted with the draft final report, including the data shown in the selected hydrographs on Figures 4-80 through 4-83. These data submitted again for the final geodatabase in the renamed feature class “WQ_TDS_recent”.

112. SurfaceHydro feature dataset > WBDHU6 feature class: Please remove this feature class since a version is also included for river basins only in the study area.

    This feature class was removed from the geodatabase.

113. Base Elevation Rasters and Salt_Domes feature class: There are negative spaces (no base elevations) in several of the downdip portions of rasters which are assumed to represent locations of salt domes; however, the Salt_Domes feature class does not completely correlate with the negative spaces. Please explain what the negative spaces in the elevation surfaces represent and/or explain why these negative spaces do not correspond with the locations of the salt domes.

    In general, the blank or null portions of the base elevation rasters indicate locations where the interpolation of the unit resulted in a pinch out. Some of these areas are associated with salt domes. For other areas, the base elevation of river alluvium truncates (erodes into) the underlying layers, resulting in the removal of small areas of thin intervals of the underlying layers in the framework particularly along the major rivers. There is an instance in the northern part of the model area where the Wilcox Group outcrops in Reklaw, indicating a pinchout of the Carrizo. This framework was converted into the unstructured grid for the numerical groundwater availability model, which allows for groundwater flows between adjacent cells regardless of layer assignment. The geodatabase metadata and report text (Section 4.1.3, page 40, first paragraph) was updated to reflect this clarification.

Suggestions for the draft geodatabase and data deliverables:

114. Please consider changing the name of feature class “NetSand_Wilcox” (in the Geology feature dataset) to something like “NetSand_Percent_Wilcox” to make it immediately clear that the contour values in the feature class do not use comparable units to those in the other net sand contour feature classes.

    The name of this feature class was renamed to “NetSand_percent_Wilcox”.

Draft Leapfrog deliverables comments:

General comments to be addressed

115. It appears the metadata explaining what information is contained in each layer in the project is missing for several input data layers. Please resubmit Leapfrog® with these metadata.

    The metadata for those input layers was added and a revised Leapfrog model will be included with the final deliverable.

116. The spatial extent of the Upper, Middle, and Lower Wilcox do not match the illustrated extents in Figures 4.1.17 (Upper), 4.1.19 (Middle), and 4.1.21 (Lower) of the conceptual model report. Please provide an explanation for this discrepancy.

    The spatial extents of the polygon areas, base elevation rasters, and thickness rasters for these three units were reviewed. The files provided are consistent with the illustrations provided in the draft final report. The figure numbering of the submitted draft final report does not conform to the figure numbers referenced in this comment. It appears that this comment might relate to the draft report which did show this discrepancy.

Specific comments to be addressed

117. Item 119 of the Draft Conceptual Review Comments suggested providing the geologic model created using Leapfrog in a Leapfrog Viewer file that can be viewed by the public at no cost. Please export the geologic model to a Leapfrog Viewer file.

    The Leapfrog Viewer file was provided on the FTP as part of the deliverable submitted for the draft final report. These were available on the GSI FTP under GAM_DratFinal_ConceptualModelReport/LeapfrogFiles. These files will be submitted again for the final submittal, both on a FTP site for download and on a portable data storage device.

Draft BRACS database and data deliverables comments:

118. BRACS Database table Bracs_tblWell_Location contains many records that have a latitude and longitude value that is different than that in the TWDB Groundwater Database. Unless these wells have been re-located to a better location, please update the locations to be consistent with the Groundwater Database

coordinates. If the well locations have been re-located, please update the table Bracs_tblWell_Location fields location_method, location_date, agency with new values to reflect that Montgomery and Associates has modified the coordinates. This comment applies to records that are in both the Bracs_tblWell_Location and the TWDB Groundwater Database *(Not addressed after first round of comments)*

This part of the original comment was missed in the first round of comments. The latitude and longitude values in the table Bracs_tblWell_Location provided in the submittal are consistent with the public BRACS database table "tblWell_Location" obtained for the project on December 13, 2016. None of the wells were relocated from this source file. The latitude and longitudes from the public BRACS database differed from the TWDB GWDB.