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DRAFT REPORT

CONCEPTUAL MODEL REPORT: GROUNDWATER AVAILABILITY MODEL FOR NORTHERN PORTION OF THE QUEEN CITY, SPARTA, AND CARRIZO-WILCOX AQUIFERS

PREPARED FOR

TEXAS WATER DEVELOPMENT BOARD

PREPARED BY

STAFFAN SCHORR AND MEGAN ZIVIC
Montgomery & Associates

WILLIAM R. HUTCHISON
Independent Groundwater Consultant

SORAB PANDAY
GSI Environmental, Inc.

JAMES RUMBAUGH
Environmental Simulations, Inc.

Professional Seal

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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 previously developed 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 GAM was previously updated in 2004 when the Queen City and Sparta aquifers were added to the Carrizo-Wilcox GAM. This study provides an additional update to the GAM, 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 GAMs, except as necessary to describe the development of the updated GAM.

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 GAM 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 GAM 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 overly 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 extend of the Wilcox Group to the north. The southern model boundary is the up-dip limit 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-one minor aquifers in Texas (George and others, 2011). These aquifers are shown on **Figures 1.0.1 and 1.0.2**. 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 GAMs.

The Queen City and Sparta aquifers are classified as minor aquifers in Texas. These minor aquifers extend from the Frio River region in south Texas to east Texas. The Queen City Aquifer continues into Arkansas and the northwest area of Louisiana as part of the Cane River Formation of the Claiborne Group. The Sparta Aquifer continues into Louisiana where it is mapped as Sparta Sand and in Arkansas where it is included with the Claiborne Group. For groundwater modeling purposes, the TWDB divided the Queen City and Sparta 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 GAM for the northern portions of the Queen City, Sparta, and Carrizo-Wilcox Aquifers. The GAM is used to simulate impacts of groundwater pumping on groundwater resources in northeast Texas. The study area is shown on **Figure 1.0.3**. This model will build from two primary sources of data and information: (1) the existing GAMs for the Queen City and Sparta Aquifers (Kelley and others, 2004), and (2) the existing GAM 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 GAM will also be used to assist the groundwater conservation districts in Groundwater Management Area 11 to develop and/or revise their desired future conditions.

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 current and proposed 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 1.0.3**). The study area is essentially the same as the previous GAM 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 2.0.1**. Major and minor aquifers that occur in the study area are shown on **Figures 2.0.2 and 2.0.3**. 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 **Figures 2.0.4 through 2.0.6**. The boundaries for these areas were obtained from TWDB (2017b). The study area extends across portions of five Regional Water Planning Areas (**Figure 2.0.4**): 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 2.0.5**): 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 2.0.6**).

Figure 2.0.7 shows the major rivers and associated drainage basins in the study area, based on geospatial datasets obtained from Texas Natural Resources Information System (TNRIS) (TWDB, 2017g). 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 GAMs developed by Fryar and others (2003) and Kelley and others (2004).

2.1 Physiography and Climate

Digital elevation model (DEM) datasets (1 arc-second resolution, or 30 meters) were obtained for the study area from United States Geological Survey (USGS) National Elevation Datasets. Land surface elevation in the study area is shown on **Figure 2.1.1**. 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 (amsl) along isolated river basin divides to less than 100 feet amsl along major river valleys. The land surface is substantially dissected by streams and drainages.

The study area is located within the Interior Coastal Plain of the Gulf Coast Plains physiographic province. The Gulf Coast Plains 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 2.1.2**). 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, the dominant vegetation types in the valley are pine hardwood forest, oak forest, and grasslands. Vegetation types are shown on **Figure 2.1.3**. Similar vegetation maps for Louisiana and Arkansas were not discovered for this study.

The climate in the study area is subtropical humid. 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 (PRISM Climate Group, 2017). The thirty-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 2.1.4**.

The thirty-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 2.1.5**. 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 2.1.6**.

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 2.1.7**. 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 (NRCS, 2007) were classified from gridded SSURGO soils datasets downloaded from the U.S. Department of Agriculture (USDA) National Resources Conservation Service (NRCS) Web Soil Survey website (https://websoilsurvey.nrcs.usda.gov/app/). The NRCS 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 2.1.8**. 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.

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 an USGS integrated geologic database (Stoeser and others, 2007), is shown on **Figure 2.2.1** and major structural features are shown on **Figure 2.2.2**. 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 2.2.2**). 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 Enterprise Faults to the east. The Elkhart Graben consists of parallel, normal faults which define a graben approximately 25 miles long. The Mt. Enterprise Fault Zone is east-northeast of the Elkhart Graben and is composed of an array of parallel and en echelon 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).

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 GAMs for the northern portions of the Queen City, Sparta, and Carrizo-Wilcox aquifers.

Fryar and others (2003) developed the GAM 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 RWPGs and GCDs.

The Carrizo-Wilcox GAM 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 GAM. 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 GAM are the same as specified in the northern Carrizo-Wilcox GAM. Principal limitations of this GAM 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 hydrostratifgraphic framework constructed for this GAM 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 hydrostratigraphic 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 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 Queen City, Sparta, Carrizo, and Wilcox formations 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 (HSUs) are geologic sub-units with similar hydrogeologic properties or geologic units with distinct hydrogeologic properties.
The hydrostratigraphic framework of an aquifer system is the elevation surfaces of thetop and bottom of the hydrostratigraphic units in chronostratigraphic order. The stratigraphic column for the Sparta, Queen City, and Carrizo-Wilcox aquifer system is presented on **Figure 4.1.1**.

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 4.1.1**.

Table 4.1.1. Subsurface Data Sources for the Hydrostratigraphic Framework

HSU	Ayers and Lewis (1985)	Rusk County GCD[a]	Wilson & Hosman (1987) (USGS RASA)[b]	East Texas Model (TWDB, unpublished)	M&A and BRACs[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 RASA data from USGS Open-File Report 87-677
[c] BRACS electrical logs reviewed by Montgomery & Associates
[d] Data sources for the Central Carrizo-Wilcox GAM 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 4.1.1** and also utilized surficial geologic map information from the USGS integrated geologic database (Stoeser and others, 2007) available from the TNRIS.

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 thickness of this formation 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 USGS 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 GAM.

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 aquifer layering control points used for the previous GAMs. The principal data source for this analysis are electrical logs (elogs) provided by Brackish Resources Aquifer Characterization System (BRACS) in July 2017. These elogs were used to verify HSU 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 BRACS. Of the well locations reviewed, 453 wells with HSU contacts provided by a data source were confirmed with an elog. In some cases, the data source distinguished only a few HSUs necessary for their study, but other contacts were apparent in the elog. Where possible, Montgomery & Associates (M&A) identified additional HSU contacts for these locations. The remaining 261 elogs did not match the HSU contacts and suggests the data source may be different than the proximal BRACS elog. In addition to these verified locations, M&A identified and reviewed 107 additional locations to fill spatial gaps of available elogs in support of the geologic model. **Figure 4.1.2** shows elog locations in support of the geologic model.

The method for reviewing elogs involved the following steps:

1. Review available reports to determine the elog curve characteristics for each HSU 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) 569-A
   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 BRACS elog location to determine if the HSU contacts correlate with the elog. M&A added additional contacts not included in the data source if apparent on the elog.

3. After the HSU contacts were verified for each county, additional elogs were analyzed to fill in spatial gaps.

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

- Sparta Sand
  - South: High resistivity peak with fluctuations. Spontaneous potential (SP) 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. SP 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 SP 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. SP 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. SP is not a good indication for this HSU 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 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.

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 prepared 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 USGS geology map datasets.

The outcrop areas of the main aquifer units and the Quaternary river alluvium within the stream channels and tributaries in the study area are shown on **Figure 4.1.3**. Geologic cross-sections of this detailed framework are presented on **Figure 4.1.4**. 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 aquifer 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.

Quaternary Deposits (River Alluvium)

The Quaternary Deposits (river alluvium) were distinguished from other aquifer 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 TNRIS. 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 100 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 4.1.5**.

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 aquifer is easily distinguished from the younger Cook Mountain Formation and older Weches Formation, which are both marly marine transgressive units. **Figure 4.1.6** shows the top elevation of the Sparta Sand, which ranges from about 550 feet amsl in the northern portion of the study area to -6,300 feet amsl in the southern portion. The bottom (base) elevations and thickness of the Sparta Sand are shown on **Figures 4.1.7 and 4.1.8**, respectively. The bottom elevation of the Sparta Sand is 735 feet amsl in the north and decreases to about -6,750 feet below mean sea level (bmsl) in the south (**Figure 4.1.7**). The thickness of the Sparta Sand is up to 940 feet in the south and thins to zero in the north (**Figure 4.1.8**).

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 unit is considered a confining layer to the Queen City aquifer. **Figure 4.1.7** shows the top elevation of the Weches Formation (base of overlying Sparta Sand), which ranges from about 735 feet amsl in the northern portion of the study area to -6,750 feet bmsl in the southern portion. The bottom (base) elevations and thickness of the Weches Formation are shown on **Figures 4.1.9 and 4.1.10**, respectively. The bottom elevation of the Weches Formation is about 720 feet amsl in the north and decreases to about -6,900 feet bmsl in the south (**Figure 4.1.9**). The thickness of the Weches Formation is up to 565 feet in the south and thins to zero in the north (**Figure 4.1.10**).

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 4.1.9** shows the top elevations of the Queen City Sand (or base of overlying Weches Formation), which ranges from about 720 feet amsl in the northern portion of the study area to -6,900 feet bmsl in the southern portion. The bottom (base) elevations and thickness of the Queen City Sand are shown on **Figures 4.1.11 and 4.1.12**, respectively. The bottom elevation of the Queen City Sand is about 565 feet amsl in the north and decreases to about -7,000 feet bmsl in the south (**Figure 4.1.11**). The thickness of the Queen City Sand is up to 695 feet (**Figure 4.1.12**).

Reklaw Formation

The Reklaw Formation is composed of mud and sand is considered as a confining unit to the Carrizo-Wilcox aquifer. **Figure 4.1.11** shows the top elevation of the Reklaw Formation (or base of overlying Queen City Sand), which ranges from about 570 feet amsl in the northern portion of the study area to -7,000 feet bmsl in the southern portion. The bottom (base) elevations and thickness of the Reklaw Formation are shown on **Figures 4.1.13 and 4.1.14**, respectively. The bottom elevation of the Reklaw Formation is about 565 feet amsl in the north and decreases to about -7,130 feet bmsl in the south (**Figure 4.1.13**). The thickness of the Reklaw Formation is up to 490 feet (**Figure 4.1.14**).

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 4.1.13** shows the top elevation of the Carrizo Sand (or base of overlying Reklaw Formation), which ranges from about 565 feet amsl in the northern portion of the study area to -7,130 feet bmsl in the southern portion. The bottom (base) elevations and thickness of the Carrizo Sand are shown on **Figures 4.1.15 and 4.1.16**, respectively. The bottom elevation of the Carrizo Sand is about 640 feet amsl in the north and decreases to about -7,230 feet bmsl in the south (**Figure 4.1.15**). The thickness of the Carrizo Sand is up to 485 feet (**Figure 4.1.16**).

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, respectively (Kaiser, 1974). The top of the Upper Wilcox includes a thin regional marine-transgressive unit which separates the Wilcox Group from the Carrizo Sand. **Figure 4.1.15** shows the top elevation of the Upper Wilcox unit (or base of the overlying Carrizo Sand), which ranges from about 640 feet amsl to -7,230 feet bmsl. The bottom (base) elevations and thickness of the Upper Wilcox unit are shown on **Figures 4.1.17 and 4.1.18**, respectively. The bottom elevation of the Upper Wilcox unit is about 570 feet amsl in the north and decreases to about -9,550 feet bmsl in the south (**Figure 4.1.17**). The thickness of the Upper Wilcox unit is up to 2,680 feet (**Figure 4.1.18**).

Figure 4.1.17 shows the top elevation of the Middle Wilcox unit (or base of the overlying Upper Wilcox unit), which ranges from about 570 feet amsl to -9,550 feet bmsl. The bottom (base) elevations and thickness of the Middle Wilcox unit are shown on **Figures 4.1.19 and 4.1.20**, respectively. The bottom elevation of the Middle Wilcox unit is about 565 feet amsl in the north and decreases to about -10,430 feet bmsl in the south (**Figure 4.1.19**). The thickness of the Middle Wilcox unit is up to 1,560 feet (**Figure 4.1.20**).

Figure 4.1.15 shows the top elevation of the Lower Wilcox unit (or base of the overlying Middle Wilcox unit), which ranges from about 565 feet amsl to -10,430 feet bmsl. The bottom (base) elevations and thickness of the Lower Wilcox unit are shown on **Figures 4.1.21 and 4.1.22**, respectively. The bottom elevation of the Lower Wilcox unit is about 560 feet amsl in the north and decreases to about -11,700 feet bmsl in the south

(**Figure 4.1.21**). The thickness of the Lower Wilcox unit is up to 2,735 feet (**Figure 4.1.22**).

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 BRACS database (TWDB, 2017d), and monitoring locations from the USGS National Water Information System (NWIS) in Louisiana. For many wells, the BRACS 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 GAM, 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 GAM. 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 4.2.1**. 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 **Figures 4.2.2 and 4.2.3,** 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 4.2.1**).

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 GAMs 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’s Groundwater Database (September 2017) the BRACS database (TWDB, 2017a), and monitoring locations from the USGS NWIS 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 for winter 2014-2015 and 2 years prior and 1 year after 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 1 year then forward 1 year;
3. If no winter measurements were available for the 3-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 (**Figures 4.2.4 and 4.2.5**). Very few data are available for the Carrizo-Wilcox aquifer and therefore predevelopment groundwater level contours were not developed for the previous GAM. Locations of predevelopment groundwater level measurements compiled by Fryar and others (2003) are shown on **Figure 4.2.6**. 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 **Figures 4.2.7 through 4.2.12**, 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 2.2.2**), 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 **Figures 4.2.7 through 4.2.12** 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 (**Figures 4.2.9 through 4.2.11**). 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 GAMs 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 GAMs 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 **Figures 4.2.13 through 4.2.19**.

Groundwater levels have remained relatively stable in the Sparta Aquifer, with variations generally less than 10 feet at most wells (**Figure 4.2.13**). 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 (**Figures 4.2.14 and 4.2.15**). 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 (**Figures 4.2.16 and 4.2.17**). 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 4.2.17**). 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 (**Figures 4.2.18 and 4.2.19**). 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.

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 Texas Railroad Commission (RRC). 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 GAM. 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 GAM for the Queen City, Sparta, and Carrizo-Wilcox aquifers in the study area. **Figure 4.3.1** 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 4.3.1** (a)), which averaged about 2 in/yr in the study area (**Figure 4.3.2**(a)). Scanlon performed extensive unsaturated zone simulations using the widely used USDA NRCS State Soil Geographic (STATSGO) database and Soil Survey Geographic (SSURGO) 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.

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 4.3.1** (b)) and one excluding the highest point (**Figure 4.3.1** (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 (NADP). 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 4.3.2**). The Kelly 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.

Volumetric comparisons of all methods are presented in **Table 4.3.1**. 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 4.3.1**).

All the approaches presented above could be used as a starting point for calibration of recharge. Topology and geology can also be used to scale recharge as necessary in the model calibration phase similar to Kelley and others (2004). All methods use relationship with precipitation which will allow variation of recharge in time. 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.

The recharge distribution simulated for each layer in the previous calibrated GAM 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 GAM 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.

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 4.3.3**). These reservoirs provide potential areas of focused recharge to the underlying aquifers of interest. **Table 4.3.2** lists the names, owners, and year impounded for each reservoir. 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 4.3.4** includes historic lake stage (water level) elevations obtained from the U.S. Army Corp of Engineers. 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.

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 4.4.1**). Big Cypress Creek and Sulphur River are major tributaries to Red River. Angelina River is a major tributary to Neches River. Numerous other smaller river and streams are also included in the study area. Flows along the rivers are measured by the USGS at several streamflow gages in the study area. Daily streamflow data are available from the USGS for the period of 1903 through 2016. Annual streamflows are assessed for this study because annual stress periods will be simulated in the updated GAM. 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 **Figures 4.4.2 through 4.4.6**. 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/year. Streamflow measurements indicate a general increase in flow along its length (**Figure 4.4.2**). 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/year. Streamflow measurements indicate a general increase in flow along its length (**Figure 4.4.3**). 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/year. Streamflow measurements indicate a general increase in flow along its length (**Figure 4.4.4**). 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.

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 4.4.5**). 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 4.4.6**). The two downstream gages have relatively short periods of record; flows at these gages are more variable than the upstream gage.

4.4.2 Reservoirs, Lakes, and Springs

Reservoirs, lakes, and springs can be found throughout the study area (**Figure 4.4.1**). 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 4.3.3**. Daily discharge flows from reservoirs in the study area with available data are shown on **Figure 4.4.7**. 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 4.4.1**). 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.

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 Texas RRC 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 Natural Resources Conservation Commission. 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 (TCEQ) wells processed by Kelly and others (2004) and TWDB. A total of 445 TCEQ measurements and 44 TWDB measurements were added using data collected since the previous GAM 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 4.5.1**. Histograms for estimated hydraulic conductivity values for each aquifer unit are shown on **Figure 4.5.1**. 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 **Figures 4.5.2 and 4.5.3**, 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.

<u>River Alluvium</u>

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 GAM 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 4.5.1**). 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 4.5.2**).

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 4.5.2**). 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 4.5.2**). 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 4.5.1**).

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 4.5.2**). Hydraulic conductivity values in Reklaw Formation have a more log-normal distribution than other layers (**Figure 4.5.1**).

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 4.5.3**). Like the Reklaw Formation, the Carrizo Sand has a more log-normal distribution of hydraulic conductivity than other units (**Table 4.5.1**).

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 most number of measurements (1,136 points) mostly focused at the outcrop areas (**Figure 4.5.3**).

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 4.5.3**).

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 4.5.3**).

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 GAM 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 GAM 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.

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 GAM assumed a vertical hydraulic conductivity value of $1x10^{-4}$ ft/day, 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 GAM for the northern portions of the Queen City and Sparta aquifers indicate isotropic hydraulic conductivity properties, which means horizontal conductivity is equal to vertical conductivity.

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 GAM 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 3.0×10^{-6}, 4.5×10^{-6}, 4.0×10^{-6}, 5.5×10^{-6}, and 3.6×10^{-6} 1/ft, respectively. Storativity values specified for the three Wilcox layers in a previous GAM by Fryar and others (2003) were also specified in the GAM 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 4.5×10^{-6} 1/ft at all these layers.

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 GAMs 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 **Figures 4.5.4 through 4.5.6**. Net sand thicknesses in the Sparta and Queen City aquifers (**Figures 4.5.4 and 4.5.5**) 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 4.5.6**. 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 GAMs 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.

4.6 Potential for Subsidence

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 is currently being conducted by LRE, Inc. for the TWDB. The study will identify and characterize areas within the Texas major and minor aquifers that are susceptible to land subsidence resulting from groundwater pumping. The project report was not yet released at the time of this report.

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 componenets 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 USGS NWIS. In addition, pumping records were obtained from GCDs and the Texas RRC 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 2015 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 4.7.1**). 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 2015 and has followed a gradual declining trend since 2012.

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 4.7.1**). 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 2015 for the study area within Texas is shown on **Figure 4.7.2**. Annual pumping is summarized by water use and aquifer source in **Table 4.7.1**. 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 2015, peaking at 80 percent in 2005. Withdrawals for manufacturing decreased from 18 percent of total withdrawals in 1980 to 2 percent in 2015, 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 USGS, Rusk County GCD, and Texas RRC, 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 4.7.2**. 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 USGS 5-year water use reports for counties and parishes in Arkansas and Louisiana for the years 1960 through 2010 and are summarized on **Figure 4.7.3**. The USGS reports summarize groundwater pumping by water use sectors, including domestic, livestock, industrial, municipal, and irrigation. Based on the USGS 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 USGS annual groundwater pumping estimates for each county or parish included within the study area are summarized in **Tables 4.7.3 and 4.7.4**. Aquifer sources were not reported in the available data. It is assumed the USGS 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 USGS 5-year water use reports and were compared to the water use estimates obtained from TWDB (**Figure 4.7.4**). 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 USGS 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 USGS estimates of industrial pumping. Total pumping volumes shown on **Figure 4.7.4** are larger than those shown on **Figures 4.7.1 and 4.7.2** 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 USGS data compare reasonably well with the TWDB data. However, the USGS 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 USGS estimates. Groundwater pumping varies from year to year and has generally increased since the early 1990s. Pumping has gradually decreased since 2010, 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 4.7.5**). 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 USGS 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 has 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 USGS 5-year water use reports; however, they are not included in TWDB water use survey estimates. The USGS estimates for domestic pumping were used to estimate annual domestic pumping for each county using well records obtained from the TWDB GWDB. For example, an average production volume of 2.9 AF per well in Wood County in 1990 was calculated by dividing the USGS reported domestic pumping volume of 146 AF for that county by 50, the number of domestic wells reported in the TWDB GWDB 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 5-year report to generate an annual pumping estimate for each year. The TWDB GWDB 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 registered 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 USGS reported volumes.

Data requests were submitted to all GCDs in the study area for current and historical groundwater production information. Data were received from Rusk County GCD for 2001 through 2017 and from Mid-East Texas GCD for 2004 through 2017 for all monitored wells. All groundwater production data obtained from the districts were compiled together and summarized by water use sector in **Table 4.7.5.** Data provided by each GCD contain more detail than TWDB records with regards to pumping at individual well locations and for particular water uses.

Additional pumping data were acquired from the Texas RRC, which monitors groundwater production by mines. Annual groundwater production by mines in the study area is summarized in **Table 4.7.6**. The Texas RRC 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 2015, and Robertson County in years 2011 through 2014. Pumping records obtained from GCDs and the RRC will be incorporated into the pumping dataset for input into the groundwater model. These locally refined pumping estimates will improve model results in the respective areas. Pumping and well information from additional GCDs would help further improve the 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 for registered water wells (Louisiana DNR, 2018). In addition to well locations, the wells datasets included 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 registered groundwater production wells located in the study area are shown on **Figure 4.7.6**. 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. The coverage of registered 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 4.7.6**.

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. Fryar and others (2003) and Kelley and others (2004) provide a comprehensive summary of these studies. 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 the 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, 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 4.4.1**. 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 GAMs. For this study, the springs dataset from Kelley and others (2004) was updated with spring features listed in the USGS National Hydrography Dataset (NHD). 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 wells. Available measured flow rates range from less than 0.01 ft^3 per second (cfs) (<7 AF/year) to 3.4 cfs (2,462 AF/year) 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 (ET) is the loss of water from a vegetated surface through the combined processes of soil evaporation and plants transpiration (UACE, 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 ET, maximum ET rate, and ET extinction depth (or rooting depth). ET of groundwater occurs when groundwater levels are above the 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 2.1.3**). 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 USGS Gap Analysis Project (GAP) land cover dataset was obtained for a continuous and consistent coverage of vegetation and land cover. The USGS GAP land cover dataset for the study area is shown on **Figure 4.7.7**. Although the USGS 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 ET was simulated in the previous GAM developed by Kelley and others (2004) for the northern portions of the Queen City and Sparta aquifers. For that GAM, the USDA Soil Water Assessment Tool (SWAT) was used to estimate groundwater ET and ET extinction depth. SWAT was used because it is a physically-based method for estimating regional components of a groundwater system. Potential ET is converted to actual ET based on vegetation type and model-calculated soil water availability, using user-specified climate and vegetation information. For each stress period of the previous GAM, SWAT was used to calculate max ET rate and ET extinction depth for every model grid cell. The average maximum ET rate for each ET cell in the previous GAM is shown on **Figure 4.7.8**. Note that ET was not simulated south of the interface between the Sparta Sand and overlying younger units which are not a part of this study. Maximum ET rates specified in the model range from less than 0.001 ft/day to more than 0.0025 ft/day. ET rates are generally small in the northern portions of the study area. The largest ET rates occur in the central portions of the study area, just north of the interface with the younger units. ET 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) and 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 vs well depth analyses conducted for developing the previous GAMs, 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 **Figures 4.2.8 through 4.2.10** 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.

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 GAM.

4.8.1 Previous Studies

In the previous GAM 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 USGS, and the TCEQ 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 MCL exceedances include nitrate and lead and secondary MCL exceedances include total dissolved solids (TDS), iron, and manganese. For irrigation water quality, high specific conductance and sodium adsorption ratios (SAR) 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 GAM 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 USGS 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 TDS from north to south. A pattern of down-dip increase in TDS 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 TDS concentrations generally increase down-dip in each aquifer layer. Smaller TDS concentrations in outcrop areas indicate displacement of connate water with meteoric water (recharge of precipitation). TDS 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 GWDB for wells within the model boundary in Texas, and from the USGS NWIS 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 TDS was performed to evaluate salinity in the study area.

A detailed characterization of salinity (TDS) 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 an EPA designated primary or secondary MCL. Since 2010, there have been primary MCL exceedances in at least one well within the model boundary of lead and selenium, and secondary MCL exceedances of aluminum, chloride, fluoride, iron, manganese, pH, sulfate and TDS. 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 TDS (23 percent).

For irrigation use, salinity hazard was evaluated based on specific conductance and SAR. High specific conductance was found in 30 percent of wells, and high SAR in 44 percent of wells (very high in 35 percent). Boron, chloride, and TDS were other potential constituents of concern for irrigation purposes, but were not found in concentrations unsuitable for irrigation.

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.

Results for those constituents for which exceedances were found are summarized in **Table 4.8.1**.

4.8.4 Water Quality Evaluation Based on TDS Distribution

Figures 4.8.1 through 4.8.4 display the most recent TDS 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 TDS hydrographs for each aquifer are also shown on **Figures 4.8.1 through 4.8.4**, 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 TDS measurements indicate that groundwater in the outcrop areas of the Sparta Sand is mostly freshwater (**Figure 4.8.1**). In the Sparta Aquifer, a sample from one well in Rapides County, Louisiana reports a TDS concentration classified as brine (72,900 mg/L). The sample is from 1957 and is the only recorded TDS 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. A few of the selected hydrographs suggest that TDS 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, TDS measurements indicate that groundwater in the outcrop portions of the Queen City Sand is predominantly freshwater (**Figure 4.8.2**). 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. Based on available historical data, there are no obvious temporal trends throughout the aquifer. TDS has 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 4.8.3**). There were two instances of very saline TDS 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. Based on available historical data, TDS 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 4.8.4**). 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. Several examples of decreasing TDS trends are shown on **Figure 4.8.4;** 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 TDS 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 TDS concentration (Kelley and others, 2004) was verified, as seen in the concentrations in **Table 4.1.2**, with the exception of the Wilcox Aquifer where the mean concentrations are very similar.

Table 4.8.2. Geometric Mean of TDS 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

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 5.0.1**.

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 9-layer groundwater system is shown on **Figure 5.0.1**. 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 concept-tualization 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 GAMs, 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 GAMs 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.

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) ET. 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 ET will be initially based on average maximum ET rate and ET extinction depths described in **Chapter 4**. Components of ET 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 GAM; however, the information is used for qualitative interpretations for the conceptual model. TDS concentrations generally increase down-dip in each aquifer layer. Smaller TDS concentrations in outcrop areas indicate displacement of connate water with meteoric water (recharge of precipitation). TDS 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 GAM include groundwater recharge studies, ET 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 GAM 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 are likely reported in the surveys. This is evident by the substantial discrepancy between mining pumping reported by the TMDB 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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9 ACRONYMS & ABBREVIATIONS

AF ....acre-feet
AF/day...........acre-feet per day
AF/yr ....acre-feet per year
amsl ....above mean sea level
BRACS ....Brackish Resources Aquifer Characterization System
bmsl................below mean sea level
cfs...................cubic feet per second
DEM..............Digital Elevation Model
ET...................evapotranspiration
ft/day ....feet per day
ft/year ....feet per year
ft^2/day............square feet per day
GAM ....Groundwater Availability Model
GCD ....Groundwater Conservation District
GWDB ....Groundwater Database
HSU................hydrostratigraphic unit
HUC ....hydrologic unit code
in/yr ....inches per year
MCL ....maximum contaminant level
M&A ....Montgomery & Associates
mg/L ....milligrams per liter
NADP.............National Atmospheric Depositional Program
NHD ....National Hydrography Dataset
NRCS ....National Resources Conservation Service
NWIS ....National Water Information System (USGS)
ºF ....degrees Fahrenheit
PRISM............Parameter-elevation Regressions on Independent Slopes Model
QCSCW ....Queen City, Sparta, and Carrizo-Wilcox
RRC................Railroad Commission (Texas)
RWPA ....Regional Water Planning Area
SAR................sodium adsorption ratio
SP ....spontaneous potential
SWAT ....Soil Water Assessment Tool
TCEQ ....Texas Commission on Environmental Quality
TDS ....total dissolved solids
TNRIS ....Texas Natural Resources Information System

TWDB............Texas Water Development Board
UACE.............University of Arizona Cooperative Extension
USDA.............United States Department of Agriculture
USGS ....United States Geological Survey
3D...................three-dimensional

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 topograpy 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.

TABLE 4.3. 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
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

TABLE 4.4. SUMMARY OF AQUIFER TESTING RESULTS FROM WELLS IN NORTHERN PORTION 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

TABLE 4.7.1. 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
Municipal																
CARRIZO-WILCOX AQUIFER	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
QUEEN CITY AQUIFER	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
SPARTA AQUIFER	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
Manufacturing																
CARRIZO-WILCOX AQUIFER	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
GULF COAST AQUIFER	47,726	47,338	48,074	49,212	41,386	43,125	47,430	45,766	46,528	50,917	52,664	49,559	47,787	45,337	49,530	45,823
QUEEN CITY AQUIFER	52	65	56	53	0	0	0	0	0	0	1	0	0	1	3	3
SPARTA AQUIFER	0	40	72	73	70	69	70	70	69	69	74	74	148	181	156	136
Mining																
CARRIZO-WILCOX AQUIFER	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
QUEEN CITY AQUIFER	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
SPARTA AQUIFER	112	32	33	32	29	30	27	27	38	38	37	37	37	37	37	37
Electric Power																
CARRIZO-WILCOX AQUIFER	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
QUEEN CITY AQUIFER	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SPARTA AQUIFER	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Irrigation																
CARRIZO-WILCOX AQUIFER	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
QUEEN CITY AQUIFER	236	507	425	412	570	438	151	131	122	122	206	128	116	139	139	139
SPARTA AQUIFER	186	198	160	144	144	144	12	11	11	11	45	84	73	96	96	96
Livestock																
CARRIZO-WILCOX AQUIFER	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
QUEEN CITY AQUIFER	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
SPARTA AQUIFER	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

TABLE 4.7.1. ANNUAL ESTIMATED GROUNDWATER PUMPING BY WATER USE SECTOR AND AQUIFER SOURCE FOR TEXAS COUNTIES IN STUDY AREA

	Aquifer Source	1999	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Municipal																
	CARRIZO-WILCOX AQUIFER	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
	QUEEN CITY AQUIFER	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
	SPARTA AQUIFER	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
Manufacturing																
	CARRIZO-WILCOX AQUIFER	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
	GULF COAST AQUIFER	47,434	49,156	47,215	35,608	51,499	46,834	45,464	43,668	40,270	37,005	34,140	37,779	39,739	37,514	44,358
	QUEEN CITY AQUIFER	3	0	0	0	0	0	0	0	0	36	58	59	70	1,026	1,094
	SPARTA AQUIFER	217	185	188	191	204	216	197	192	212	0	0	0	0	0	0
Mining																
	CARRIZO-WILCOX AQUIFER	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
	QUEEN CITY AQUIFER	488	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	SPARTA AQUIFER	37	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Electric Power																
	CARRIZO-WILCOX AQUIFER	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
	QUEEN CITY AQUIFER	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	SPARTA AQUIFER	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Irrigation																
	CARRIZO-WILCOX AQUIFER	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
	QUEEN CITY AQUIFER	139	452	278	546	761	851	1,025	607	947	1,055	1,173	1,251	2,050	1,848	1,162
	SPARTA AQUIFER	96	595	292	384	555	601	590	492	529	587	790	680	902	645	418
Livestock																
	CARRIZO-WILCOX AQUIFER	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
	QUEEN CITY AQUIFER	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
	SPARTA AQUIFER	1,215	856	855	595	238	216	205	216	219	359	363	295	297	303	303

Units in acre-feet

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

TABLE 4.7.2. 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
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
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
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
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
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
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
FRANKLIN	305	265	302	318	331	450	456	383	282	275	162	310	125	178	92	122
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
GREGG	1,030	958	909	837	540	645	560	612	724	922	902	911	1,101	1,129	1,084	986
GRIMES	2	2	2	2	2	3	5	4	4	6	6	6	6	6	6	6
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
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
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
HOUSTON	810	837	879	823	945	978	803	648	455	432	576	1,052	1,096	1,156	1,122	1,139
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
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
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
MARION	879	823	850	783	749	775	801	761	780	678	804	777	756	741	751	839
MORRIS	1,249	984	1,010	861	784	859	852	805	811	772	788	730	752	740	826	849
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
NAVARRO	7	9	11	10	11	12	11	11	11	10	0	0	0	0	0	0
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
RAINS	166	68	0	0	0	0	0	0	0	0	0	0	0	0	0	0
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
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
SABINE	374	125	86	83	82	85	113	119	112	124	139	148	122	128	120	155
SAN AUGUSTINE	334	190	172	192	174	177	185	177	134	117	132	146	157	119	134	139
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
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
TITUS	422	486	409	436	448	423	446	407	405	410	430	446	487	500	527	541
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
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
WALKER	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

TABLE 4.7.2. ANNUAL ESTIMATED GROUNDWATER PUMPING FROM THE QUEEN CITY, SPARTA, AND CARRIZO-WILCOX AQUIFERS BY WATER USE SECTOR FOR TEXAS COUNTIES IN STUDY AREA

County	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Municipal																	
ANDERSON	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
ANGELINA	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
BOWIE	592	977	1,103	1,119	1,075	1,054	1,126	991	838	910	951	1,008	1,084	996	817	728	667
CAMP	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
CASS	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
CHEROKEE	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
FRANKLIN	289	198	176	64	70	41	51	52	42	45	34	22	22	18	16	22	27
FREESTONE	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
GREGG	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
GRIMES	6	5	5	4	4	3	4	0	0	0	0	0	0	0	0	0	0
HARRISON	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
HENDERSON	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
HOPKINS	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
HOUSTON	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
LEON	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
LIMESTONE	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
MADISON	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
MARION	639	795	807	776	761	771	859	847	723	745	645	400	562	474	403	369	398
MORRIS	652	662	653	644	602	591	646	654	574	611	675	725	716	652	626	476	378
NACOGDOCHES	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
NAVARRO	0	0	0	0	0	0	0	13	11	12	34	56	56	48	48	40	21
PANOLA	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
RAINS	0	248	265	274	288	269	296	315	261	299	276	819	544	465	373	360	284
ROBERTSON	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
RUSK	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
SABINE	84	248	253	295	378	355	392	122	235	214	566	233	384	336	382	377	580
SAN AUGUSTINE	142	270	319	325	407	301	386	404	376	414	465	528	574	545	495	484	400
SHELBY	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
SMITH	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
TITUS	535	91	92	91	92	97	102	118	100	111	115	120	141	155	144	111	121
UPSHUR	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
VAN ZANDT	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
WALKER	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
WOOD	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

TABLE 4.7.2. 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
Manufacturing																
ANDERSON	349	455	303	347	346	344	431	0	0	0	0	0	0	0	0	0
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
BOWIE	42	45	44	39	22	7	5	27	17	1	17	16	15	16	17	3
CAMP	0	198	199	201	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
CHEROKEE	0	0	0	0	0	0	0	0	0	0	4	0	0	2	0	0
FRANKLIN	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
GREGG	278	196	186	186	161	161	161	161	161	161	161	161	161	161	162	24
GRIMES	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
HENDERSON	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
HOPKINS	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
LEON	161	162	162	162	162	162	162	162	162	162	260	290	277	290	486	459
LIMESTONE	398	413	335	338	332	597	438	732	383	447	447	447	447	0	0	0
MADISON	0	34	69	70	70	69	70	70	69	69	74	74	148	181	156	136
MARION	9	14	25	25	18	33	34	26	35	0	0	0	0	1	3	3
MORRIS	221	15	7	6	6	0	6,412	6,412	6,412	40	32	31	34	31	30	30
NACOGDOCHES	21	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
PANOLA	0	0	15	16	20	20	19	59	14	20	20	20	20	0	0	0
RAINS	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
RUSK	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SABINE	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
SHELBY	23	2	4	4	0	0	0	52	66	63	49	57	45	50	57	62
SMITH	10	1,048	1,055	885	744	662	637	464	390	377	328	406	418	457	406	343
TITUS	316	235	290	74	145	57	242	209	115	122	112	300	120	295	223	176
UPSHUR	312	157	99	90	121	163	157	171	188	225	207	146	150	146	164	160
VAN ZANDT	684	343	191	268	422	396	415	159	156	190	339	139	255	574	178	258
WALKER	0	0	0	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

TABLE 4.7.2. ANNUAL ESTIMATED GROUNDWATER PUMPING FROM THE QUEEN CITY, SPARTA, AND CARRIZO-WILCOX AQUIFERS BY WATER USE SECTOR FOR TEXAS COUNTIES IN STUDY AREA

County	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Manufacturing																	
ANDERSON	0	340	340	445	445	0	0	0	0	0	0	0	0	0	0	0	724
ANGELINA	10,715	12,306	8,995	8,345	9,137	1,914	610	782	20	16	16	0	0	0	0	0	0
BOWIE	3	3	3	15	20	12	25	25	35	43	29	31	26	31	22	14	13
CAMP	0	0	0	430	36	0	0	0	0	0	0	0	0	0	0	0	0
CASS	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
CHEROKEE	0	7	9	5	6	23	23	10	9	10	5	5	0	0	0	0	0
FRANKLIN	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	19
GREGG	24	0	0	0	0	1	0	0	0	0	3	3	3	2	2	3	2
GRIMES	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
HARRISON	123	173	211	179	169	130	151	239	251	219	8,735	111	145	146	145	113	128
HENDERSON	0	0	0	0	0	0	187	180	169	124	124	122	122	122	122	124	128
HOPKINS	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
LEON	484	545	466	430	450	533	766	798	748	687	557	545	819	711	672	657	524
LIMESTONE	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MADISON	217	183	177	185	188	191	204	216	197	192	212	0	0	0	0	0	0
MARION	3	4	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MORRIS	32	88	25	21	76	79	196	72	77	20	23	23	23	19	9	9	9
NACOGDOCHES	0	0	20	31	20	11	32	27	110	31	24	30	36	25	31	24	22
NAVARRO	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PANOLA	0	0	921	473	513	424	498	185	338	523	408	1	1	1	1	1	1
RAINS	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ROBERTSON	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
RUSK	0	0	184	143	150	176	210	188	71	188	196	0	0	0	0	0	0
SABINE	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SAN AUGUSTINE	3	3	4	4	5	3	3	3	5	4	6	5	4	3	3	3	2
SHELBY	71	64	48	36	14	1	1	1	0	0	0	0	0	0	0	0	0
SMITH	387	0	0	0	263	310	289	361	453	361	196	179	154	156	146	103	110
TITUS	199	194	104	90	104	96	93	94	80	100	91	90	90	132	670	728	0
UPSHUR	129	153	183	134	100	31	35	47	38	46	36	41	32	35	23	24	16
VAN ZANDT	292	0	0	0	0	0	0	0	0	289	253	0	189	167	175	246	75
WALKER	0	0	0	2	1	0	0	0	0	0	0	0	0	0	0	0	0
WOOD	0	2	0	0	193	193	459	677	629	617	617	663	663	663	663	977	1,045

TABLE 4.7.2. 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
Mining																
ANDERSON	1,691	329	405	382	359	325	303	303	318	318	315	315	430	430	430	411
ANGELINA	0	0	0	0	0	0	0	0	22	22	22	22	22	22	22	22
BOWIE	0	0	0	18	18	17	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
CASS	1,218	567	629	756	689	792	767	767	819	819	819	819	822	822	822	481
CHEROKEE	81	117	120	111	89	80	53	53	81	81	81	81	81	81	81	81
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
FREESTONE	18	74	35	209	43	44	36	36	34	44	37	37	37	37	37	30
GREGG	305	3,984	129	156	66	61	29	29	11	0	0	0	0	0	0	0
GRIMES	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
HENDERSON	304	925	906	819	411	456	102	199	200	374	374	387	475	475	492	153
HOPKINS	73	0	67	138	127	133	187	120	147	143	144	145	145	145	143	78
HOUSTON	0	32	33	32	29	30	27	27	38	38	37	37	37	37	37	37
LEON	26	72	85	133	145	207	131	146	448	461	437	463	1,005	1,005	1,025	865
LIMESTONE	0	0	0	0	0	0	0	0	0	807	807	807	807	807	807	360
MADISON	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
MORRIS	0	0	0	0	0	0	0	0	32	32	32	32	32	32	32	32
NACOGDOCHES	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
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
RAINS	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
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
SABINE	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
SHELBY	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
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
UPSHUR	2	1	0	0	0	0	0	0	1	1	1	1	1	1	1	1
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
WALKER	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

TABLE 4.7.2. ANNUAL ESTIMATED GROUNDWATER PUMPING FROM THE QUEEN CITY, SPARTA, AND CARRIZO-WILCOX AQUIFERS BY WATER USE SECTOR FOR TEXAS COUNTIES IN STUDY AREA

County	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Mining																	
ANDERSON	430	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ANGELINA	22	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
CAMP	24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
CASS	741	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
CHEROKEE	81	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FRANKLIN	895	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FREESTONE	30	7	14	14	14	0	31	79	50	50	60	77	72	287	324	121	177
GREGG	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
GRIMES	0	0	0	0	0	0	0										
HARRISON	197	3	3	6	4	4	5	3	3	3	4	4	5	4	5	1	136
HENDERSON	474	2	0	2	2	2	2	2	2	2	2	2	2	2	0	0	0
HOPKINS	78	67	67	67	67	67	67	67	17	0	0	0	0	0	0	0	0
HOUSTON	37	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LEON	867	164	131	127	123	124	91	50	32	29	20	25	41	45	36	38	44
LIMESTONE	360	645	645	647	645	642	642	642	642	0	642	642	642	1,362	932	1,275	1,449
MADISON	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MARION	83	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MORRIS	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
NAVARRO	59	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PANOLA	1,947	7	7	7	7	7	8	7	7	1	1	482	562	518	571	532	453
RAINS	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ROBERTSON	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
RUSK	1,201	38	7	6	6	6	3	0	0	0	0	173	160	115	169	162	1,623
SABINE	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
SHELBY	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SMITH	257	0	0	0	0	0	0	0	0	0	0	0	0	263	69	126	110
TITUS	1,729	0	0	0	0	0	0	0	0	0	0	1	1	2	2	0	0
UPSHUR	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
VAN ZANDT	687	225	73	102	252	337	220	384	156	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	280	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

TABLE 4.7.2. 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
Electric Power																
ANDERSON	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
BOWIE	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
CASS	0	3	1	3	0	0	1	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
FRANKLIN	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
GREGG	1	1	1	1	1	1	1	1	1	1	1	1	19	64	113	1
GRIMES	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
HENDERSON	0	0	0	8	1	0	0	0	1	0	1	1	0	0	0	0
HOPKINS	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
LEON	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LIMESTONE	0	182	779	964	829	808	1,240	2,584	1,153	971	940	960	822	994	973	916
MADISON	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
MORRIS	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
NAVARRO	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
RAINS	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
RUSK	0	0	0	0	0	0	0	0	18	24	23	18	20	179	14	18
SABINE	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
SHELBY	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
TITUS	62	16	2	85	4	4	31	4	4	4	4	4	0	0	0	0
UPSHUR	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
WALKER	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

TABLE 4.7.2. ANNUAL ESTIMATED GROUNDWATER PUMPING FROM THE QUEEN CITY, SPARTA, AND CARRIZO-WILCOX AQUIFERS BY WATER USE SECTOR FOR TEXAS COUNTIES IN STUDY AREA

County	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Electric Power																	
ANDERSON	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	36	0
BOWIE	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
CASS	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
CHEROKEE	115	132	128	86	119	115	124	136	155	127	167	121	181	170	118	144	119
FRANKLIN	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FREESTONE	92	91	117	99	99	95	110	113	755	241	146	135	152	122	102	143	158
GREGG	101	42	258	25	267	194	242	242	242	243	242	242	242	243	242	242	242
GRIMES	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
HENDERSON	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
HOUSTON	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
LIMESTONE	966	1,014	877	829	853	726	649	666	0	671	677	711	681	592	637	639	572
MADISON	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MARION	100	99	96	0	82	60	82	79	73	74	81	91	75	82	76	70	57
MORRIS	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
NAVARRO	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PANOLA	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
ROBERTSON	3,549	0	0	1	0	0	0	1	1	10	183	0	4,806	3,401	4,359	4,709	5,018
RUSK	18	11	12	97	99	113	0	287	356	147	183	358	1,023	245	0	49	33
SABINE	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
SHELBY	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
TITUS	0	0	0	0	0	0	0	22	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
VAN ZANDT	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

TABLE 4.7.2. 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
Irrigation																
ANDERSON	0	113	125	60	60	60	28	23	26	26	172	78	180	265	254	632
ANGELINA	372	372	297	264	264	264	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
CAMP	0	145	142	96	96	96	60	78	78	79	23	17	17	23	23	23
CASS	0	0	0	0	0	0	0	0	0	0	12	9	8	11	11	11
CHEROKEE	50	117	72	90	90	90	96	100	82	82	12	28	29	29	29	29
FRANKLIN	0	0	0	0	0	0	0	0	0	0	3	2	2	3	3	3
FREESTONE	0	0	100	50	50	50	25	25	25	25	13	17	17	17	17	17
GREGG	0	0	0	0	0	0	0	0	0	0	20	25	25	25	25	25
GRIMES	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
HENDERSON	100	20	70	70	70	70	20	21	21	21	20	20	20	20	20	20
HOPKINS	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
HOUSTON	0	26	24	24	25	24	24	23	23	23	101	146	125	170	170	170
LEON	0	0	0	0	75	75	0	0	0	0	0	0	0	0	0	0
LIMESTONE	0	0	0	0	150	150	0	0	0	0	0	0	0	0	0	0
MADISON	0	0	0	0	0	0	0	0	0	0	18	18	18	18	18	18
MARION	0	0	0	0	0	0	0	0	0	0	55	63	59	55	55	55
MORRIS	0	255	225	225	225	125	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
NAVARRO	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PANOLA	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
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
RUSK	0	33	38	19	19	19	32	27	27	27	149	38	151	149	149	149
SABINE	0	0	0	0	0	50	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
SHELBY	0	5	12	13	13	39	11	12	12	12	29	32	29	29	29	29
SMITH	50	0	0	0	228	183	39	10	10	10	114	113	100	112	112	112
TITUS	0	0	0	0	0	50	0	0	0	0	0	0	0	0	0	0
UPSHUR	0	0	0	0	0	0	0	0	0	0	15	15	15	15	15	15
VAN ZANDT	0	0	0	0	0	0	0	0	0	0	19	30	19	112	91	623
WALKER	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

TABLE 4.7.2. ANNUAL ESTIMATED GROUNDWATER PUMPING FROM THE QUEEN CITY, SPARTA, AND CARRIZO-WILCOX AQUIFERS BY WATER USE SECTOR FOR TEXAS COUNTIES IN STUDY AREA

County	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Irrigation																	
ANDERSON	309	96	96	81	17	30	56	0	284	180	425	259	458	414	452	625	355
ANGELINA	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	1,246	762	1,382	916	1,094	346
CAMP	23	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0
CASS	11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
CHEROKEE	29	31	26	28	16	22	50	41	232	125	140	193	8	270	269	286	297
FRANKLIN	3	0	0	0	0	0	0	0	33	0	0	0	0	0	0	0	0
FREESTONE	17	0	0	0	0	0	0	38	0	43	76	216	613	680	598	550	314
GREGG	25	0	0	0	0	0	9	24	0	0	0	0	16	4	8	8	1
GRIMES	0	0	0	0	0	0	0										
HARRISON	34	39	37	42	29	125	112	95	124	0	708	626	642	411	422	405	177
HENDERSON	20	0	0	2	23	39	41	119	139	155	150	133	50	181	1,348	1,408	945
HOPKINS	0	0	0	0	0	0	0	241	201	16	210	2,317	315	880	913	50	116
HOUSTON	170	576	428	756	269	342	496	615	808	198	267	144	90	738	990	462	76
LEON	0	542	542	542	300	300	285	242	88	208	21	31	223	152	601	491	127
LIMESTONE	0	0	0	0	0	0	0	0	0	0	0	0	18	0	0	11	7
MADISON	18	0	0	0	0	0	0	0	5	7	7	211	370	318	299	312	336
MARION	55	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	0	0	0	0	0	0	0	0	0
NACOGDOCHES	1,016	186	419	187	395	281	206	248	143	145	226	141	298	31	0	106	106
NAVARRO	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PANOLA	0	0	0	0	0	0	0	18	31	64	31	346	383	137	322	1,630	1,122
RAINS	0	0	0	0	0	0	0	0	58	0	0	0	7	53	0	3	3
ROBERTSON	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
RUSK	149	18	49	49	73	92	92	100	25	29	0	0	172	69	201	93	78
SABINE	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SAN AUGUSTINE	77	112	82	82	50	50	50	63	0	0	0	0	14	0	0	0	0
SHELBY	29	26	20	24	22	20	23	27	20	25	0	0	13	8	10	7	6
SMITH	112	208	137	137	126	194	182	442	0	0	418	64	300	68	3	274	92
TITUS	0	0	0	0	0	0	0	0	0	0	46	0	109	46	171	147	91
UPSHUR	15	0	0	0	0	0	0	0	200	0	0	116	108	2	12	10	46
VAN ZANDT	146	33	33	33	0	0	0	80	0	0	33	87	143	1	20	37	27
WALKER	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
WOOD	103	149	112	112	117	119	110	4	80	0	0	306	232	155	352	285	190

MONTGOMERY & ASSOCIATES

TABLE 4.7.2. 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
Livestock																
ANDERSON	490	584	610	610	625	648	672	679	691	832	816	721	717	717	717	627
ANGELINA	47	97	94	84	88	98	88	88	90	126	124	102	102	92	90	102
BOWIE	286	301	258	298	274	275	283	319	321	262	280	311	296	395	258	267
CAMP	277	229	198	235	225	221	233	275	276	320	337	385	396	393	336	348
CASS	328	350	305	301	300	322	333	334	341	340	318	340	317	328	297	320
CHEROKEE	584	585	626	574	542	512	526	701	694	948	1,055	985	906	988	792	780
FRANKLIN	342	423	446	413	395	410	378	521	516	637	668	582	572	567	460	452
FREESTONE	501	1,142	456	381	381	404	356	350	356	499	468	487	524	650	487	546
GREGG	109	102	82	82	75	87	94	92	94	106	99	87	87	87	92	83
GRIMES	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
HENDERSON	651	793	780	1,067	641	1,004	1,027	1,037	1,056	800	762	785	777	954	735	846
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
HOUSTON	472	572	581	432	495	522	531	541	552	541	514	552	498	498	438	494
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
LIMESTONE	108	162	143	135	135	140	125	244	125	101	117	129	119	124	113	106
MADISON	245	323	318	266	290	279	237	238	243	301	282	246	261	388	240	204
MARION	62	88	68	54	61	66	65	65	66	73	79	73	59	66	79	58
MORRIS	157	144	139	140	150	159	165	166	169	250	235	187	207	196	157	168
NACOGDOCHES	738	650	473	496	478	479	498	596	596	597	614	667	600	805	561	503
NAVARRO	13	15	15	13	13	14	13	13	13	11	11	13	11	14	9	11
PANOLA	708	654	640	670	695	705	747	858	869	812	815	1,090	1,059	1,126	1,128	1,118
RAINS	149	211	197	183	200	192	202	252	251	223	217	233	233	229	227	211
ROBERTSON	569	631	691	676	622	861	567	558	571	599	617	616	777	621	677	570
RUSK	593	566	507	478	455	473	482	507	515	495	507	467	414	353	367	425
SABINE	100	98	88	93	113	115	117	129	132	114	118	43	34	31	71	149
SAN AUGUSTINE	129	110	98	111	121	124	126	139	142	151	151	50	54	47	86	167
SHELBY	748	584	561	588	664	684	721	785	801	779	781	1,107	1,137	1,161	1,201	1,231
SMITH	423	511	430	464	430	454	470	483	491	442	413	451	421	374	374	427
TITUS	356	426	362	358	376	389	400	416	424	304	322	387	375	395	356	362
UPSHUR	419	454	394	422	404	394	394	530	525	771	838	768	673	963	603	602
VAN ZANDT	728	899	771	873	786	813	837	881	893	950	914	953	985	921	980	910
WALKER	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
WOOD	545	565	533	546	569	541	567	726	722	1,025	1,008	1,014	1,021	1,091	901	839

TABLE 4.7.2. ANNUAL ESTIMATED GROUNDWATER PUMPING FROM THE QUEEN CITY, SPARTA, AND CARRIZO-WILCOX AQUIFERS BY WATER USE SECTOR FOR TEXAS COUNTIES IN STUDY AREA

County	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Livestock																	
ANDERSON	644	665	327	330	298	260	62	66	66	46	48	46	46	40	43	44	46
ANGELINA	118	155	152	144	134	66	14	14	14	16	16	38	36	34	32	32	32
BOWIE	287	293	173	163	160	0	0	0	0	0	0	0	0	0	0	0	0
CAMP	357	372	586	412	383	381	372	394	381	380	378	1,940	1,921	1,877	2,056	2,034	2,097
CASS	363	334	189	186	173	174	22	22	22	20	21	87	87	76	75	74	76
CHEROKEE	780	618	625	603	501	487	181	190	185	181	158	262	261	241	234	234	232
FRANKLIN	484	449	249	229	225	217	428	426	335	444	440	1,172	1,161	1,141	1,133	1,093	1,113
FREESTONE	569	571	475	471	530	565	187	216	229	140	156	134	134	113	110	112	116
GREGG	101	95	74	63	48	48	23	19	23	20	22	26	26	19	21	13	13
GRIMES	0	0	0	0	0	0	0										
HARRISON	96	87	48	43	41	40	77	65	66	55	62	50	50	43	49	62	49
HENDERSON	830	820	447	122	368	370	455	433	435	398	432	446	449	370	398	416	411
HOPKINS	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
HOUSTON	519	471	266	257	258	278	127	107	96	109	109	125	131	83	87	88	92
LEON	1,036	1,014	634	613	695	703	90	84	111	73	75	147	145	132	148	151	148
LIMESTONE	111	107	85	94	116	70	8	8	6	6	7	8	8	6	7	7	8
MADISON	216	286	208	200	223	227	90	88	87	82	89	120	118	109	112	119	114
MARION	65	434	56	51	51	50	6	6	6	4	4	12	12	7	7	10	10
MORRIS	188	194	95	118	138	141	63	68	68	52	58	173	173	149	155	152	157
NACOGDOCHES	546	568	546	547	474	464	113	126	105	112	115	929	915	899	911	889	917
NAVARRO	11	12	12	12	11	11	6	6	7	6	6	8	9	5	5	5	6
PANOLA	1,216	1,238	1,264	1,254	1,249	1,270	320	333	327	304	314	288	288	245	255	250	258
RAINS	220	216	200	182	190	218	28	27	24	24	24	21	21	19	22	23	23
ROBERTSON	578	531	520	540	635	596	432	387	316	404	385	857	881	645	627	626	642
RUSK	459	462	236	231	215	221	231	202	216	209	194	353	351	308	321	325	339
SABINE	142	179	154	155	166	112	60	61	60	82	85	10	10	8	10	15	10
SAN AUGUSTINE	159	208	159	161	159	290	89	89	94	109	111	180	178	176	177	178	176
SHELBY	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
SMITH	472	447	250	232	217	221	582	636	644	533	455	600	604	434	517	580	462
TITUS	383	358	184	176	154	173	183	201	157	190	198	616	608	592	576	554	571
UPSHUR	617	612	395	378	383	332	192	180	159	190	202	228	228	211	225	231	234
VAN ZANDT	973	970	342	336	352	296	501	512	332	514	543	469	471	430	378	407	403
WALKER	0	26	13	13	13	13	19	23	21	37	36	23	23	17	27	28	24
WOOD	904	825	681	717	720	658	107	84	67	84	89	156	155	151	150	153	153

Units in acre-feet

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TABLE 4.7.2. 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

TABLE 4.7.2. ANNUAL ESTIMATED GROUNDWATER PUMPING FROM THE QUEEN CITY, SPARTA, AND CARRIZO-WILCOX AQUIFERS BY WATER USE SECTOR FOR TEXAS COUNTIES IN STUDY AREA

County	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015

Source: Texas Water Development Board water use surveys (TWDB, 2016)

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TABLE 4.7.3. ANNUAL ESTIMATED GROUNDWATER PUMPING BY WATER USE SECTOR FOR LOUISIANA PARISHES IN STUDY AREA

	Parish	1960	1965	1970	1975	1980	1985	1990	1995	2000	2005	2010
Public Supply												
	Bossier Parish	269	381	482	1,110	1,087	1,345	1,480	1,939	2,219	1,939	2,410
	Caddo Parish	639	1,704	1,962	1,098	1,379	1,491	1,031	1,524	1,267	1,749	1,984
	De Soto Parish	785	897	841	1,244	1,782	1,020	1,367	1,390	1,435	1,502	1,580
	Grant Parish	191	280	269	717	1,020	2,141	1,412	2,006	1,693	1,749	2,219
	Natchitoches Parish	1,121	67	123	471	538	572	930	829	1,042	1,211	998
	Rapides Parish	7,207	8,754	11,904	28,583	35,420	33,066	36,205	31,755	32,808	30,454	28,997
	Red River Parish	191	202	258	482	527	852	616	886	729	807	740
	Sabine Parish	448	841	740	1,065	437	280	426	841	1,009	1,367	1,401
	Vernon Parish	673	1,199	1,390	4,697	6,288	280	426	841	1,009	1,367	1,401
Commercial												
	Bossier Parish	0	0	0	0	0	0	22	22	0	0	0
	Caddo Parish	0	0	0	0	0	0	78	123	0	0	0
	De Soto Parish	0	0	0	0	0	0	0	11	0	0	0
	Grant Parish	0	0	0	0	0	0	0	0	0	0	0
	Natchitoches Parish	0	0	0	0	0	0	0	0	0	0	0
	Rapides Parish	0	0	0	0	0	0	886	101	0	0	0
	Red River Parish	0	0	0	0	0	0	0	11	0	0	0
	Sabine Parish	0	0	0	0	0	0	78	45	0	0	0
	Vernon Parish	0	0	0	0	0	0	5,515	4,596	0	0	0
Industrial												
	Bossier Parish	168	471	1,412	1,659	493	549	471	404	773	471	370
	Caddo Parish	56	157	1,278	1,906	258	0	45	34	101	101	0
	De Soto Parish	67	224	146	146	22	0	0	0	381	112	325
	Grant Parish	168	168	168	168	67	22	90	146	235	78	78
	Natchitoches Parish	392	34	0	0	0	0	0	0	0	0	34
	Rapides Parish	673	1,782	16,230	2,163	1,693	0	56	45	22	729	740
	Red River Parish	22	34	11	527	303	67	0	0	11	0	0
	Sabine Parish	112	347	135	280	135	370	303	291	359	0	0
	Vernon Parish	336	2,623	3,677	0	0	0	0	0	0	0	11
Electric Power												
	Bossier Parish	0	0	0	0	0	0	0	0	0	0	0
	Caddo Parish	0	34	0	0	0	0	0	0	0	0	0
	De Soto Parish	0	0	0	0	0	0	0	0	0	0	0
	Grant Parish	0	0	0	0	0	0	0	0	0	0	0
	Natchitoches Parish	0	0	0	0	0	0	0	0	0	0	0
	Rapides Parish	0	0	0	404	247	0	135	135	135	135	135
	Red River Parish	0	0	0	0	0	0	0	0	0	0	0
	Sabine Parish	0	0	0	0	0	0	0	0	0	0	0
	Vernon Parish	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
	Caddo Parish	0	0	0	0	0	0	0	0	0	0	0
	De Soto Parish	0	0	0	0	0	101	0	0	370	1,390	2,500
	Grant Parish	0	0	0	0	0	0	0	0	0	0	0
	Natchitoches Parish	0	0	0	0	0	0	0	0	0	0	0
	Rapides Parish	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
	Sabine Parish	0	0	0	0	0	0	0	0	0	0	157
	Vernon Parish	0	0	0	0	0	0	0	0	0	0	0

TABLE 4.7.3. ANNUAL ESTIMATED GROUNDWATER PUMPING BY WATER USE SECTOR FOR LOUISIANA PARISHES IN STUDY AREA

	Parish	1960	1965	1970	1975	1980	1985	1990	1995	2000	2005	2010
Irrigation												
	Bossier Parish	34	224	224	0	605	404	22	101	247	460	235
	Caddo Parish	90	1,827	2,612	2,018	1,356	1,558	1,110	594	2,892	3,295	6,468
	De Soto Parish	0	0	0	2,107	0	0	0	11	11	22	22
	Grant Parish	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
	Rapides Parish	78	90	11	7,017	0	0	404	2,242	4,450	4,170	7,824
	Red River Parish	0	45	2,219	0	1,435	1,457	471	392	1,076	818	1,323
	Sabine Parish	0	0	0	123	0	0	0	0	11	0	0
	Vernon Parish	0	0	45	0	0	0	0	0	0	0	0
Livestock												
	Bossier Parish	168	168	235	11	202	123	303	213	135	78	179
	Caddo Parish	224	213	56	157	460	213	191	78	67	112	112
	De Soto Parish	224	247	213	258	325	191	22	22	224	202	191
	Grant Parish	45	56	112	101	45	112	22	22	34	22	22
	Natchitoches Parish	448	448	695	123	135	538	2,208	3,363	56	314	67
	Rapides Parish	560	538	460	504	235	269	4,517	2,006	45	34	34
	Red River Parish	224	247	280	45	22	22	67	101	90	56	67
	Sabine Parish	112	146	863	280	404	112	404	280	11	22	11
	Vernon Parish	112	112	269	135	628	280	34	11	22	22	22
Aquaculture												
	Bossier Parish	0	0	0	0	0	0	0	0	213	235	0
	Caddo Parish	0	0	0	0	0	0	0	0	269	1,558	1,446
	De Soto Parish	0	0	0	0	0	0	0	0	0	34	0
	Grant Parish	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
	Rapides Parish	0	0	0	0	0	0	0	0	3,004	1,614	3,643
	Red River Parish	0	0	0	0	0	0	0	0	45	0	0
	Sabine Parish	0	0	0	0	0	0	0	0	0	0	0
	Vernon Parish	0	0	0	0	0	0	0	0	56	34	56
Domestic												
	Bossier Parish	34	224	224	0	605	404	22	101	247	460	235
	Caddo Parish	90	1,827	2,612	2,018	1,356	1,558	1,110	594	2,892	3,295	6,468
	De Soto Parish	0	0	0	2,107	0	0	0	11	11	22	22
	Grant Parish	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
	Rapides Parish	78	90	11	7,017	0	0	404	2,242	4,450	4,170	7,824
	Red River Parish	0	45	2,219	0	1,435	1,457	471	392	1,076	818	1,323
	Sabine Parish	0	0	0	123	0	0	0	0	11	0	0
	Vernon Parish	0	0	45	0	0	0	0	0	0	0	0

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

TABLE 4.7.4. 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
Public Supply											
	Lafayette County	404	426	392	381	1,076	1,278	1,054	953	1,031	1,042
	Miller County	0	56	11	67	235	112	112	247	280	112
Industrial											
	Lafayette County	628	796	0	0	157	0	0	0	0	11
	Miller County	90	448	0	0	179	0	0	0	0	157
Electric Power											
	Lafayette County	2,018	1,289	0	0	1,188	1,345	1,255	1,009	560	392
	Miller County	0	0	0	0	0	0	0	0	0	0
Mining											
	Lafayette County	0	0	0	0	0	0	0	0	0	0
	Miller County	0	0	0	0	22	202	0	0	0	0
Irrigation											
	Lafayette County	4,338	3,609	0	0	16,443	0	23,113	10,222	37,034	21,398
	Miller County	1,681	874	0	0	19,907	7,689	10,402	7,151	16,533	6,367
Livestock											
	Lafayette County	135	235	0	0	1,031	572	1,962	280	291	247
	Miller County	235	336	0	0	986	448	751	258	235	202
Aquaculture											
	Lafayette County	695	1,031	0	0	0	0	0	22	5,033	3,677
	Miller County	0	325	0	0	0	0	0	0	392	0
Domestic											
	Lafayette County	258	392	224	0	381	392	347	247	213	179
	Miller County	482	583	235	258	1,177	1,435	11	146	807	841

Units in acre-feet

Source: USGS water use reports (USGS, 2017). Aquifer sources are not reported.

TABLE 4.7.5. ANNUAL ESTIMATED GROUNDWATER PUMPING BY WATER USE SECTOR FOR GROUNDWATER CONSERVATION DISTRICTS IN STUDY AREA

Groundwater Conservation District (GCD)	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
Municipal																	
MID-EAST TEXAS	---	---	---	5,879	6,621	6,448	6,265	6,651	6,706	7,205	8,072	6,902	7,180	6,985	7,253	6,773	6,452
RUSK COUNTY	---	---	---	---	---	---	---	---	---	---	---	---	---	---	5,395	4,965	---
Industrial																	
MID-EAST TEXAS	---	---	---	962	1,201	1,182	1,180	1,729	1,723	1,706	2,604	2,176	2,088	2,685	1,923	1,831	1,665
RUSK COUNTY	---	---	---	---	---	---	---	---	---	---	---	---	---	---	172	85	---
Mining																	
MID-EAST TEXAS	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
RUSK COUNTY	2,491	1,787	1,256	664	802	3,723	2,897	1,069	811	566	920	1,215	2,661	2,090	1,584	1,989	---
Electric Power																	
MID-EAST TEXAS	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
RUSK COUNTY	---	---	---	---	---	---	---	---	---	---	---	---	---	---	17	7	---
Irrigation																	
MID-EAST TEXAS	---	---	---	---	---	---	---	---	---	---	112	170	664	462	428	315	255
RUSK COUNTY	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
Livestock																	
MID-EAST TEXAS	---	---	---	---	---	---	---	---	5	86	120	119	134	266	251	427	211
RUSK COUNTY	---	---	---	---	---	---	---	---	---	---	---	---	---	---	9	29	---
Domestic																	
MID-EAST TEXAS	---	---	---	---	---	---	---	4	3	5	2	39	3	---	---	---	---
RUSK COUNTY	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---

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

TABLE 4.7.6. 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

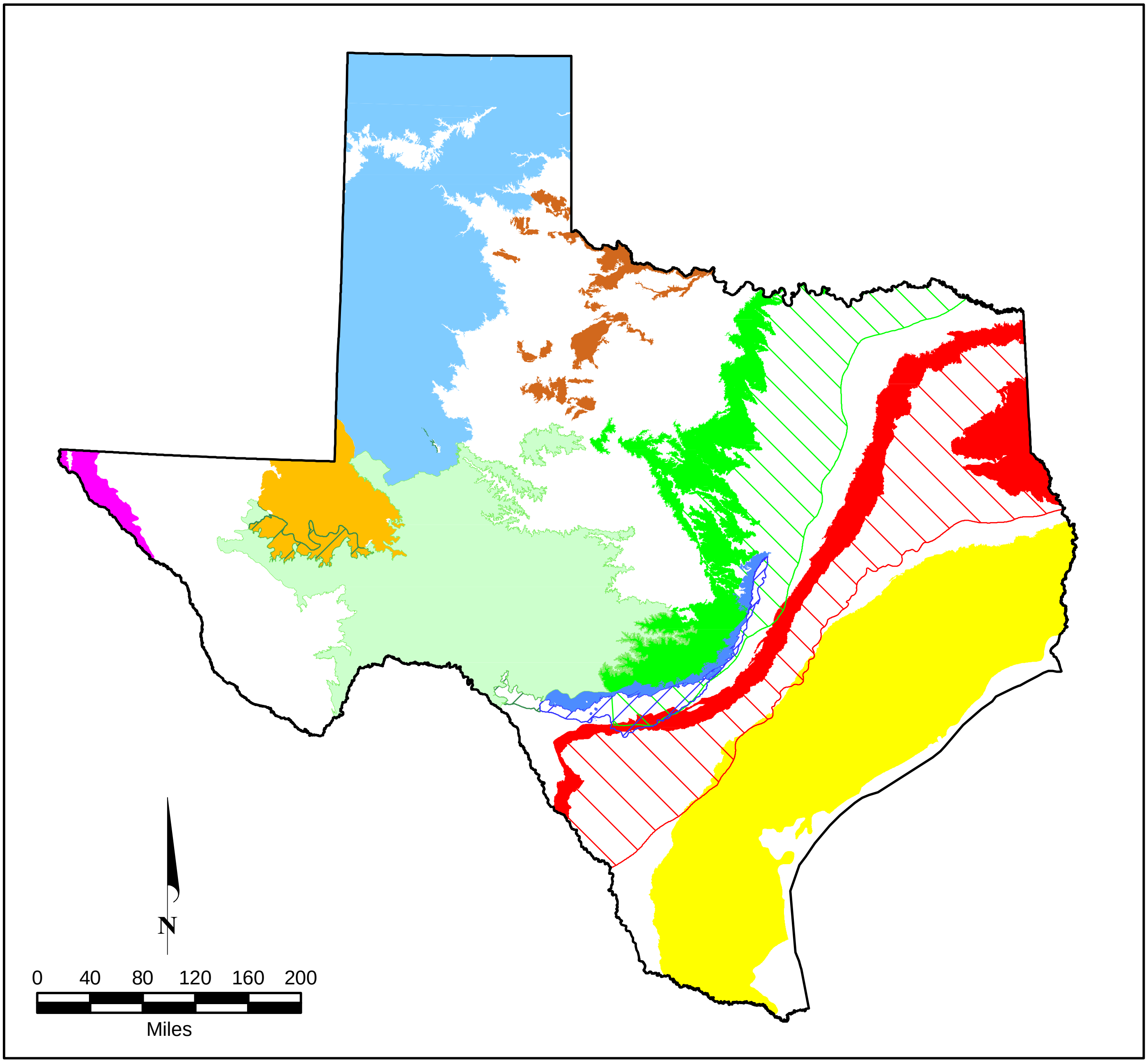
Source: Texas Railroad Commission (RRC), reported Texas lignite dewatering volumes. Aquifer sources are not reported.

--- = No data available

TABLE 4.8.1. SUMMARY OF EXCEEDANCES OF WATER QUALITY STANDARDS FOR SELECTED CONSTITUENTS

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]	262	3	1.1%
Selenium	50	Primary MCL	250	1	0.4%
Aluminum	0.2	Secondary MCL	250	1	0.4%
Chloride	250	Secondary MCL	290	5	1.7%
Fluoride	2	Secondary MCL	285	3	1.1%
Iron	0.3	Secondary MCL	287	47	16.4%
Manganese	0.05	Secondary MCL	288	49	17.0%
pH	<6.5 or >8.5	Secondary MCL	288	156	54.2%
Sulfate	250	Secondary MCL	250	1	0.4%
TDS	500	Secondary MCL	284	66	23.2%
Hardness	180	Industrial	288	10	3.5%
Silica	40	Industrial	284	42	14.8%
Boron	2	Irrigation	250	1	0.4%
SAR[c] (High)	18	Irrigation	284	125	44.0%
SAR (Very High)	26	Irrigation	284	99	34.9%
Specific Conductance (High)	750	Irrigation	285	85	30.2%

[a]mg/L = milligrams per liter
[b]MCL = Maximum contaminant level
[c]SAR = sodium adsorption ratios



EXPLANATION

Major Aquifers Defined by TWDB (updated 2006)

- Pecos Valley
- Seymour
- Gulf Coast
- Carrizo - Wilcox (outcrop)
- Carrizo - Wilcox (subcrop)
- Hueco - Mesilla Bolson
- Ogallala
- Edwards - Trinity Plateau (outcrop)
- Edwards - Trinity Plateau (subcrop)
- Edwards BFZ (outcrop)
- Edwards BFZ (subcrop)
- Trinity (outcrop)
- Trinity (subcrop)
- State Boundary

FIGURE 1.0.1. MAJOR AQUIFERS IN TEXAS

1480\REPORT_MAPS\MajorAquifers_State.mxd\25April2017

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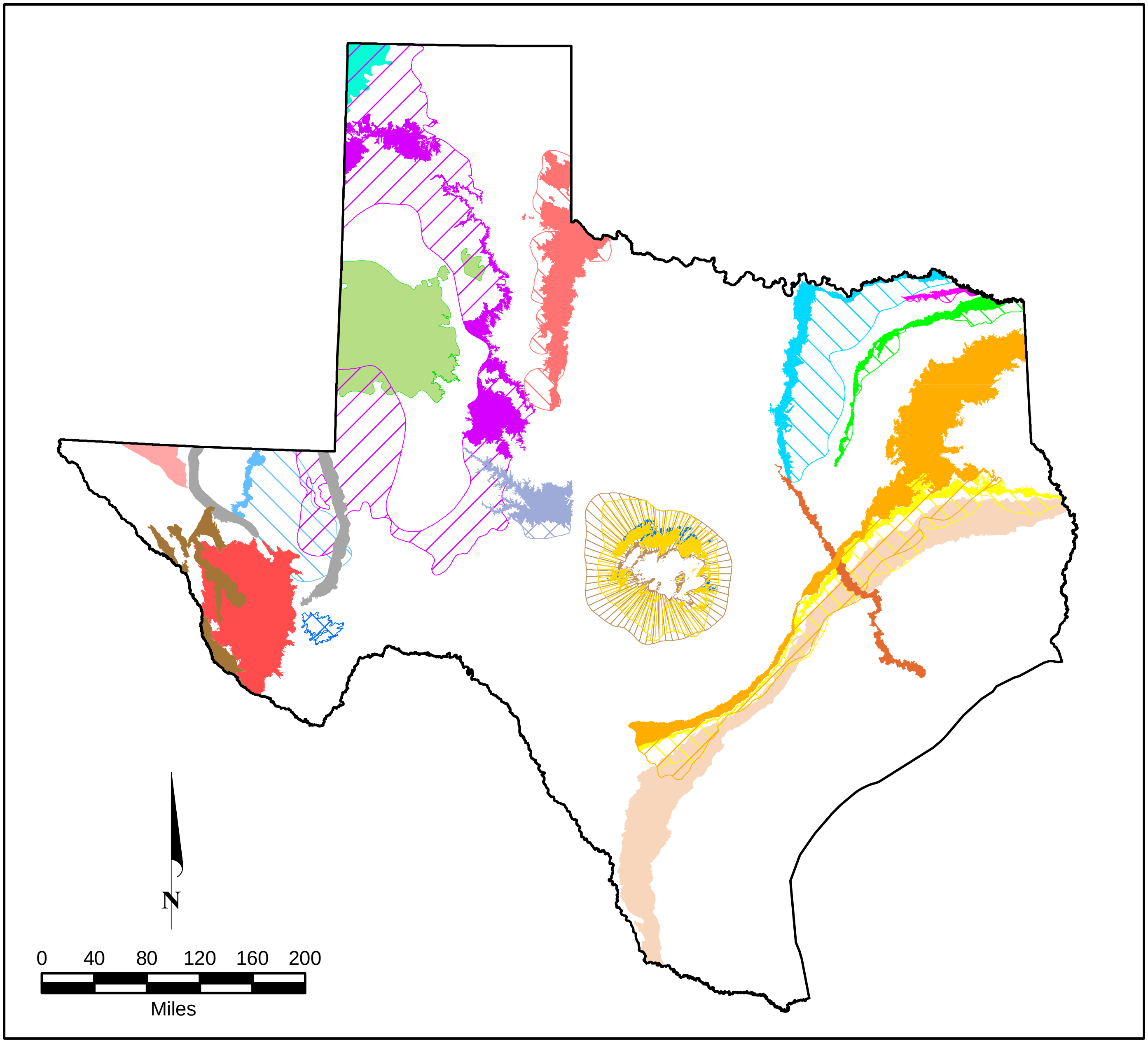

EXPLANATION

Minor Aquifers Defined by TWDB (updated 2017)

- Brazos River Alluvium
- West Texas Bolsons
- Lipan (outcrop)
- Lipan (subcrop)
- Yegua Jackson
- Igneous
- Sparta (outcrop)
- Sparta (subcrop)
- Queen City (outcrop)
- Queen City (subcrop)
- Nacatoch (outcrop)
- Nacatoch (subcrop)
- Blossom (outcrop)
- Blossom (subcrop)
- Woodbine (outcrop)
- Woodbine (subcrop)
- Rita Blanca
- Edwards -Trinity (High Plains)
- Dockum (outcrop)
- Dockum (subcrop)
- Rustler (outcrop)
- Rustler (subcrop)
- Capitan Reef Complex
- Blaine (outcrop)
- Blaine (subcrop)
- Bone Spring - Victorio Peak
- Marble Falls
- Marathon
- Ellenburger - San Saba (outcrop)
- Ellenburger - San Saba (subcrop)
- Hickory (outcrop)
- Hickory (subcrop)
- State Boundary

FIGURE 1.0.2. MINOR AQUIFERS IN TEXAS

1480\REPORT_MAPS\MinorAquifers_State.mxd\25April2018

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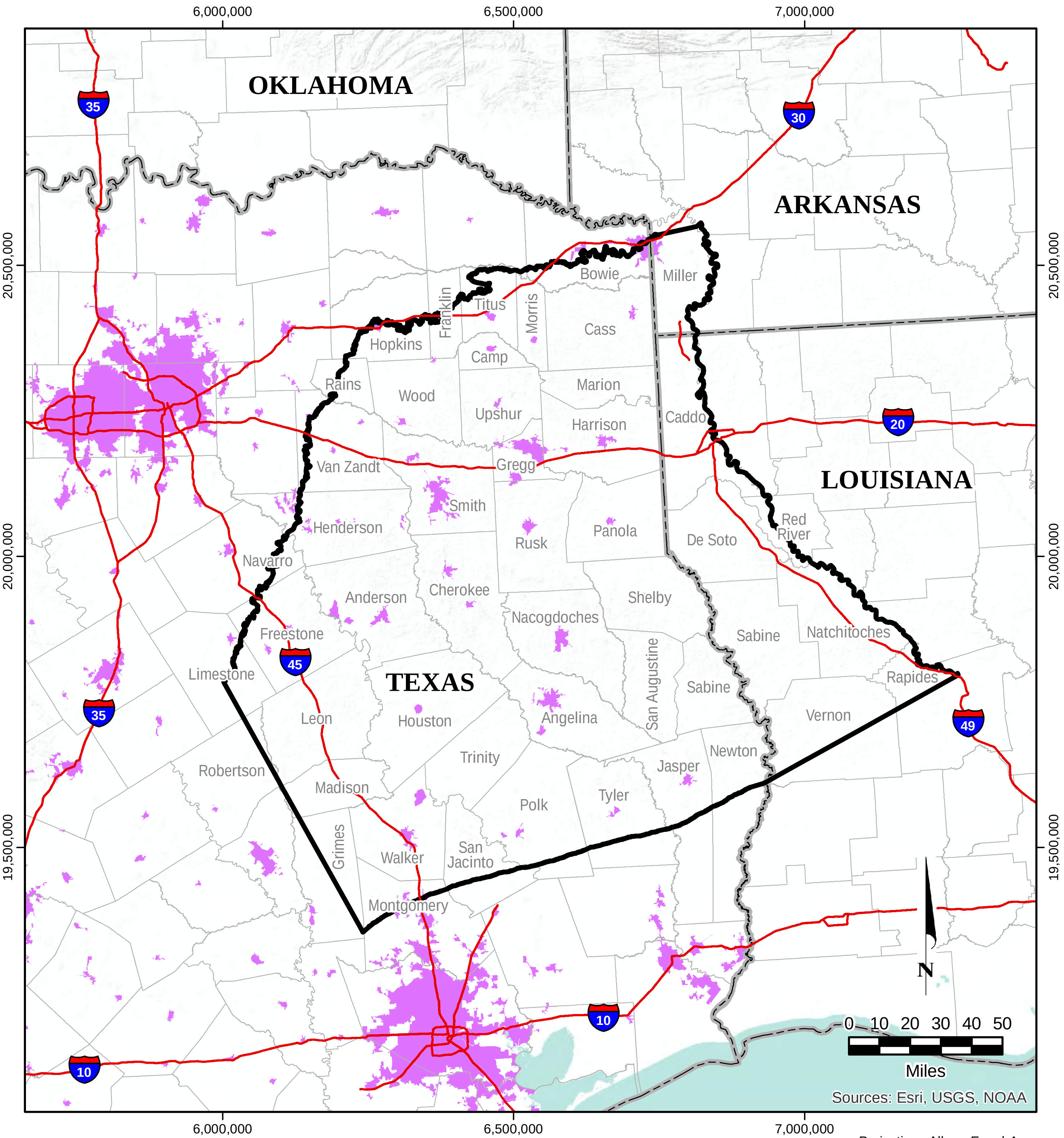

Projection: Albers Equal-Area
Datum: NAD 1983

EXPLANATION

Roadway

Urban Area, Texas (TNRIS, dated 2015)

Study Area

Polk County/Parish and Identifier

State

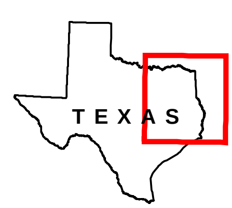

FIGURE 1.0.3. LOCATION OF STUDY AREA

MONTGOMERY & ASSOCIATES

1480\REPORT_MAPS\StudyAreaMap.mxd\30May2018

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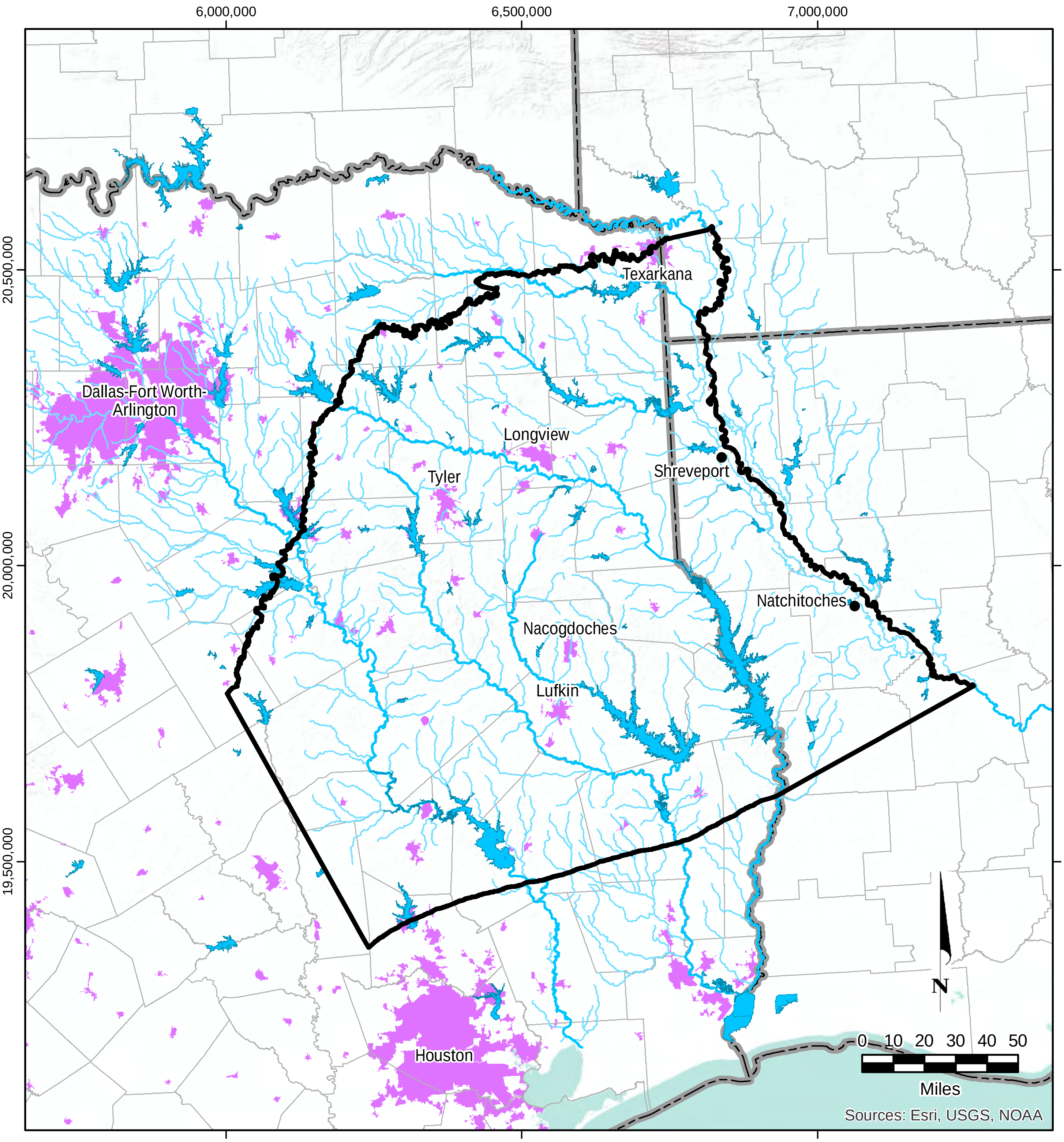

Projection: Albers Equal-Area
Datum: NAD 1983

EXPLANATION

Urban Area, Texas (TNRIS, dated 2015)	Major River
Study Area	Tributary
County/Parish	Reservoir or Lake
State	

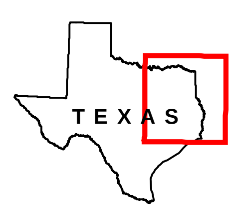

FIGURE 2.0.1. CITIES AND SURFACE WATER FEATURES IN STUDY AREA

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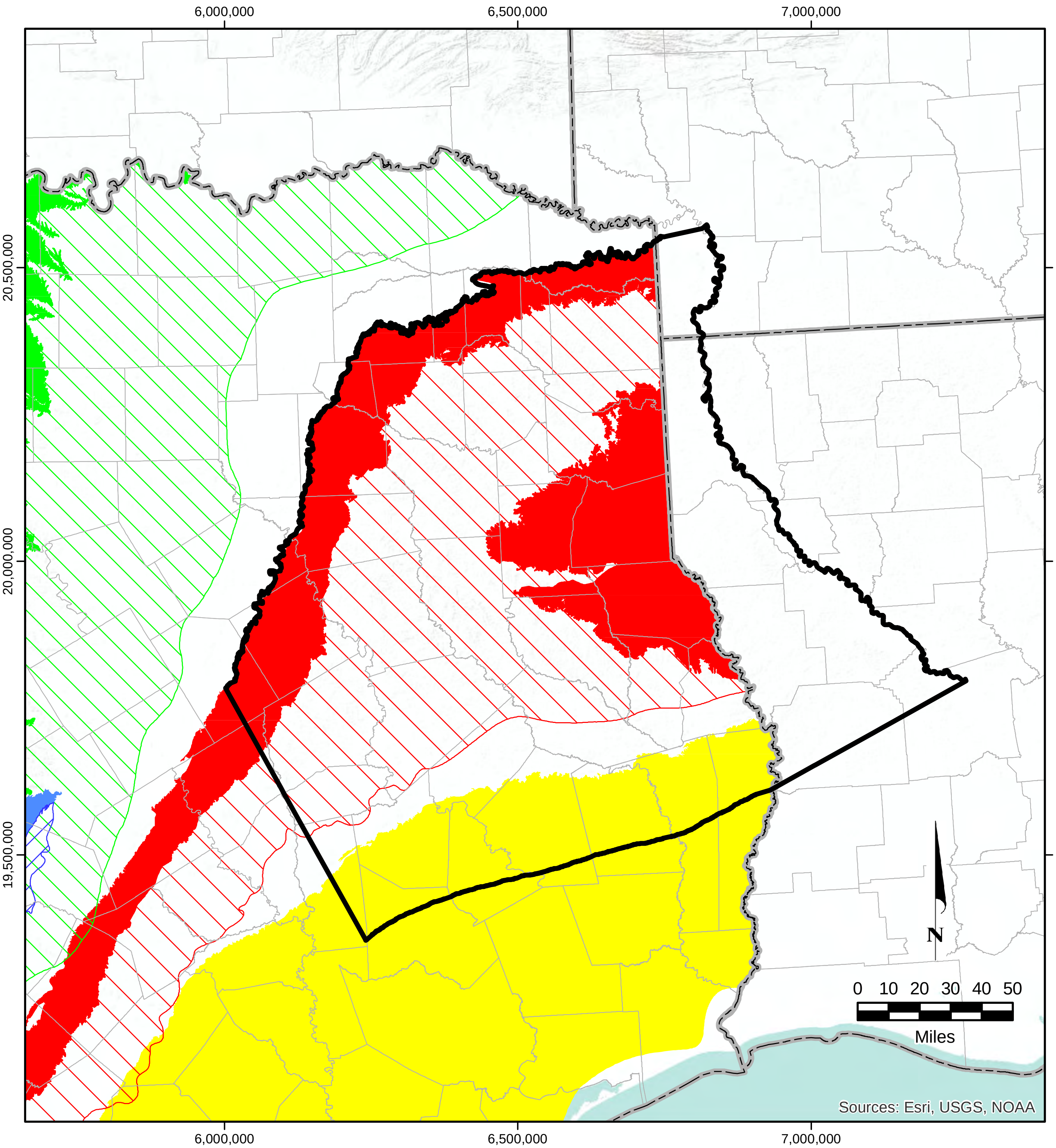
1480\REPORT_MAPS\Cities_SurfWater.mxd\26June2018

DRAFT



EXPLANATION

Projection: Albers Equal-Area
Datum: NAD 1983

Study Area
County
State

Major Aquifers Defined by TWDB (updated 2006)

Gulf Coast
Carrizo - Wilcox (outcrop)
Carrizo - Wilcox (subcrop)
Edwards - Trinity Plateau (subcrop)
Edwards BFZ (outcrop)
Edwards BFZ (subcrop)
Trinity (outcrop)

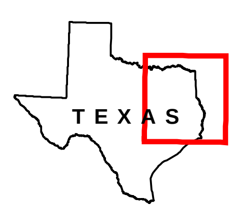


FIGURE 2.0.2. MAJOR AQUIFERS IN STUDY AREA

MONTGOMERY & ASSOCIATES

1480\REPORT_MAPS\Aquifers_major.mxd\11June2018

DRAFT

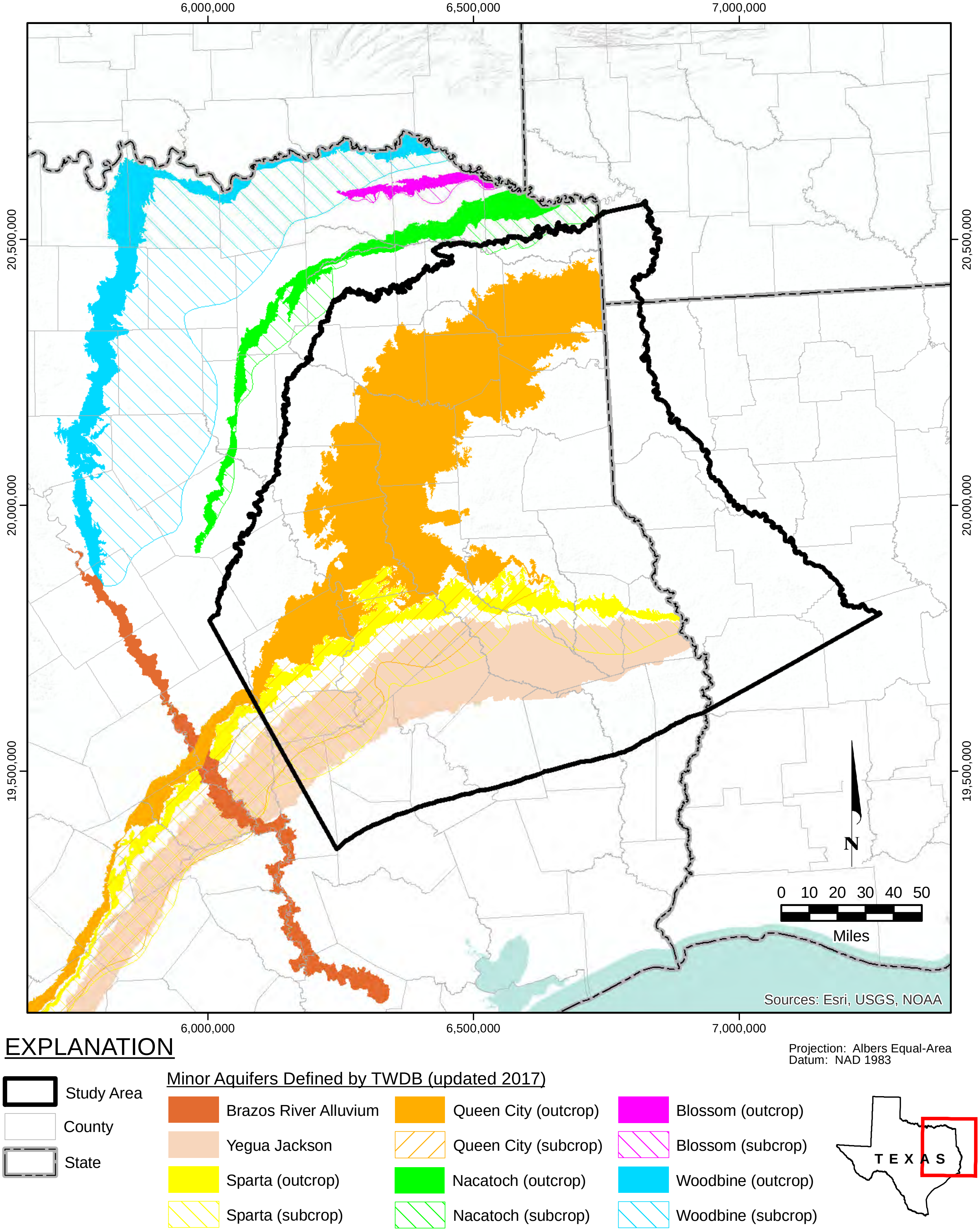
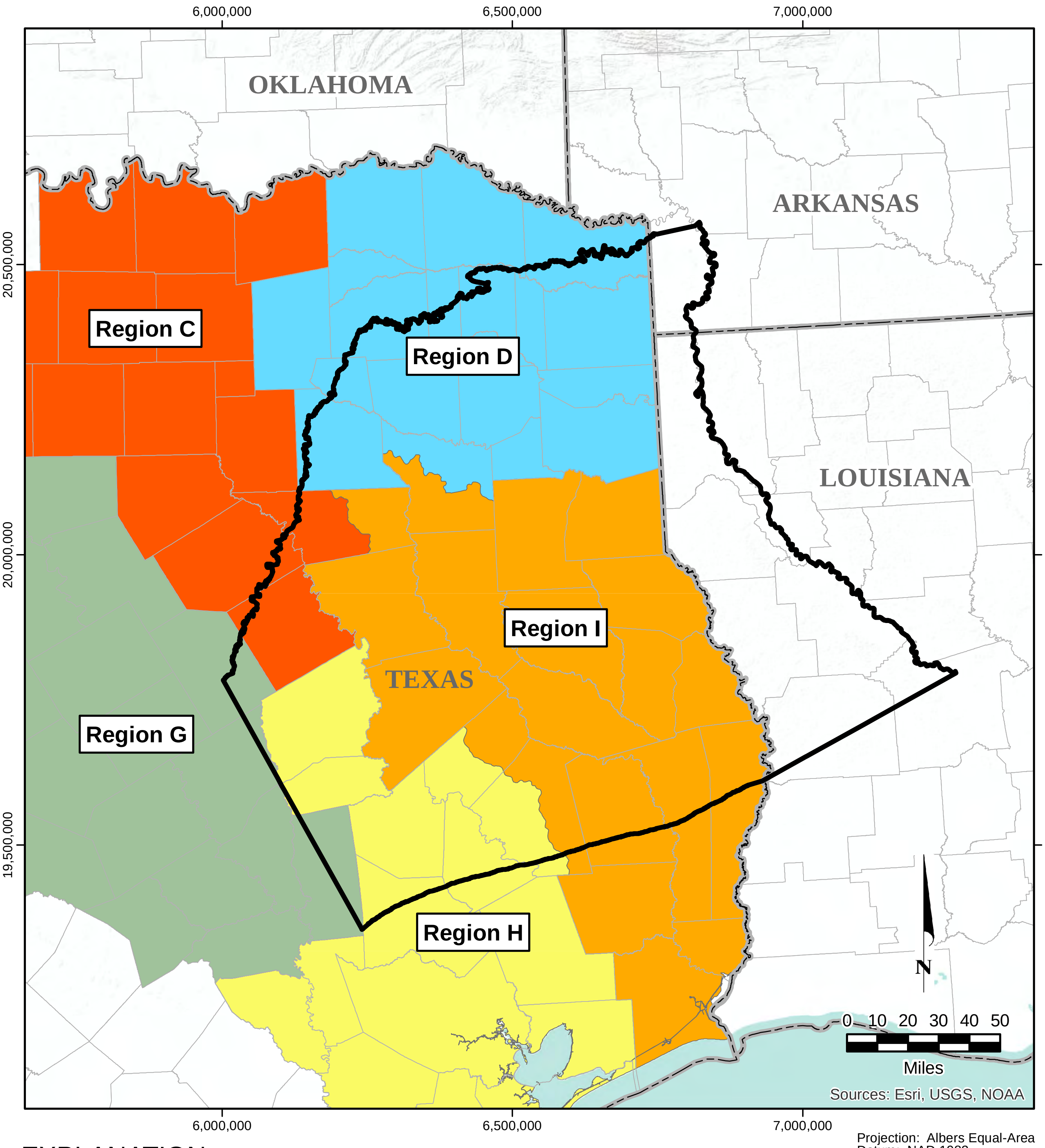


FIGURE 2.0.3. MINOR AQUIFERS IN STUDY AREA

MONTGOMERY & ASSOCIATES

1480\REPORT_MAPS\Aquifers_minor.mxd\11June2018

DRAFT



Projection: Albers Equal-Area
Datum: NAD 1983

EXPLANATION

Study Area

County/Parish

State

Regional Water Planning Area
Source: TWDB, updated Novemeber 2014

Region C
Region D
Region G
Region H
Region I

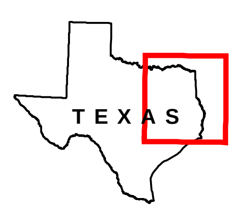
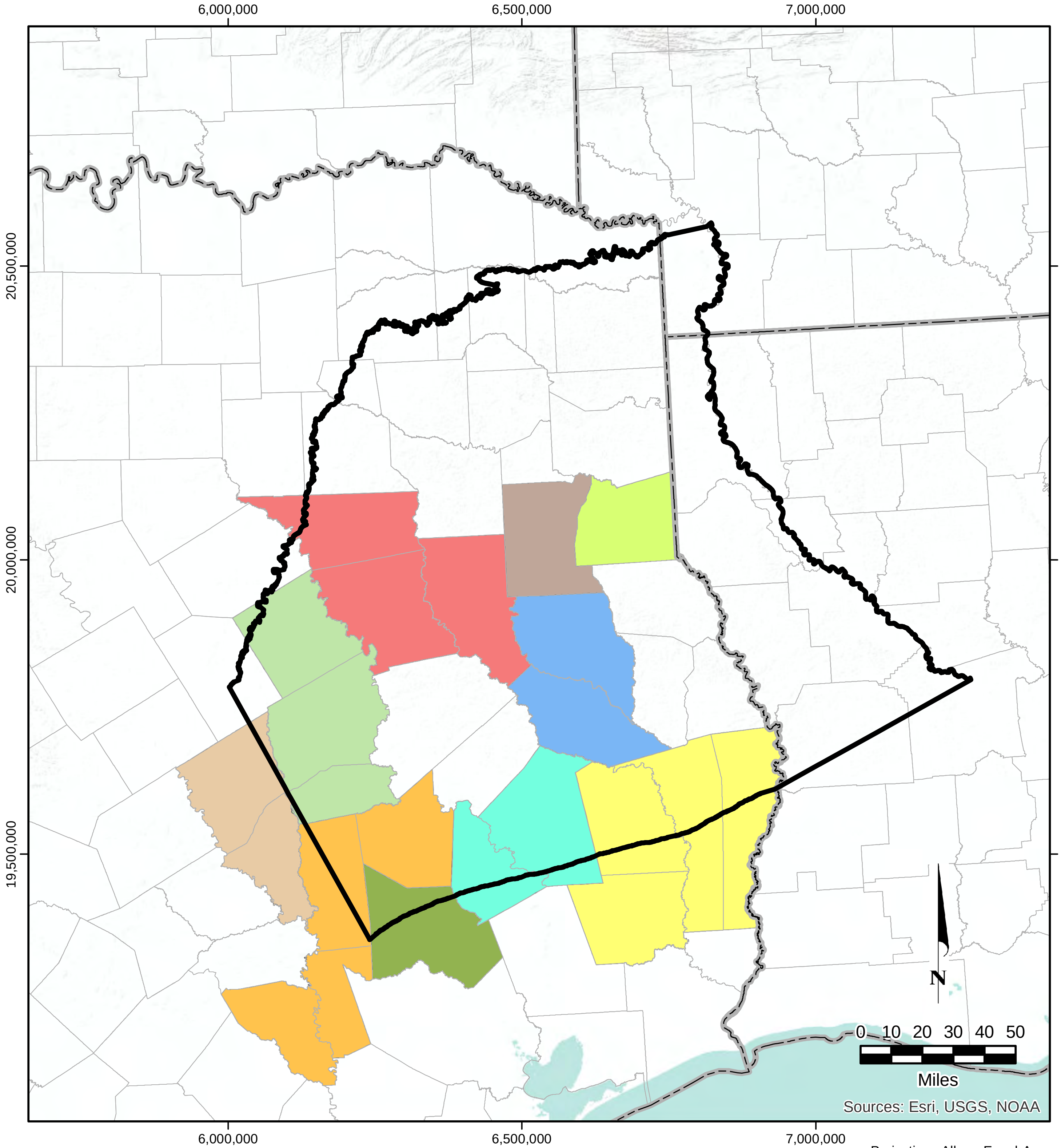


FIGURE 2.0.4. REGIONAL WATER PLANNING AREAS IN STUDY AREA

MONTGOMERY & ASSOCIATES

1480\REPORT_MAPS\Admin_RWPAs.mxd\01June2018

DRAFT



Projection: Albers Equal-Area
Datum: NAD 1983

EXPLANATION

- Study Area
- County/Parish
- State

Groundwater Conservation District
Source: TWDB, dated December 2017

- Bluebonnet GCD
- Brazos Valley GCD
- Lone Star GCD
- Lower Trinity GCD
- Mid-East Texas GCD
- Neches & Trinity Valleys GCD
- Panola County GCD
- Pineywoods GCD
- Rusk County GCD
- Southeast Texas GCD

TEXAS

FIGURE 2.0.5. GROUNDWATER CONSERVATION DISTRICTS IN STUDY AREA

1480\REPORT_MAPS\Admin_GCDs.mxd\01June2018

DRAFT

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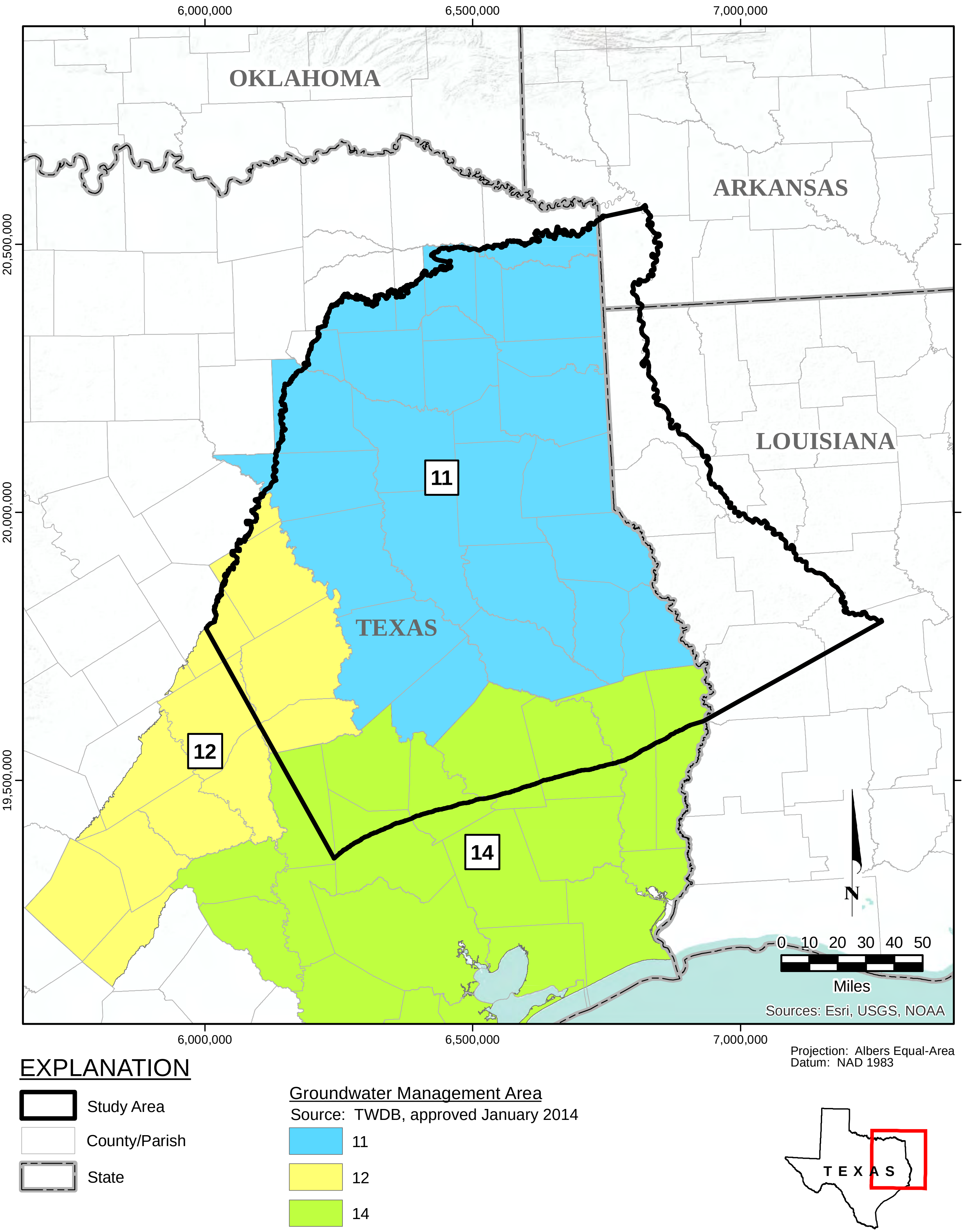

FIGURE 2.0.6. GROUNDWATER MANAGEMENT AREAS IN STUDY AREA

1480\REPORT_MAPS\Admin_GMAs.mxd\01June2018

DRAFT

MONTGOMERY & ASSOCIATES

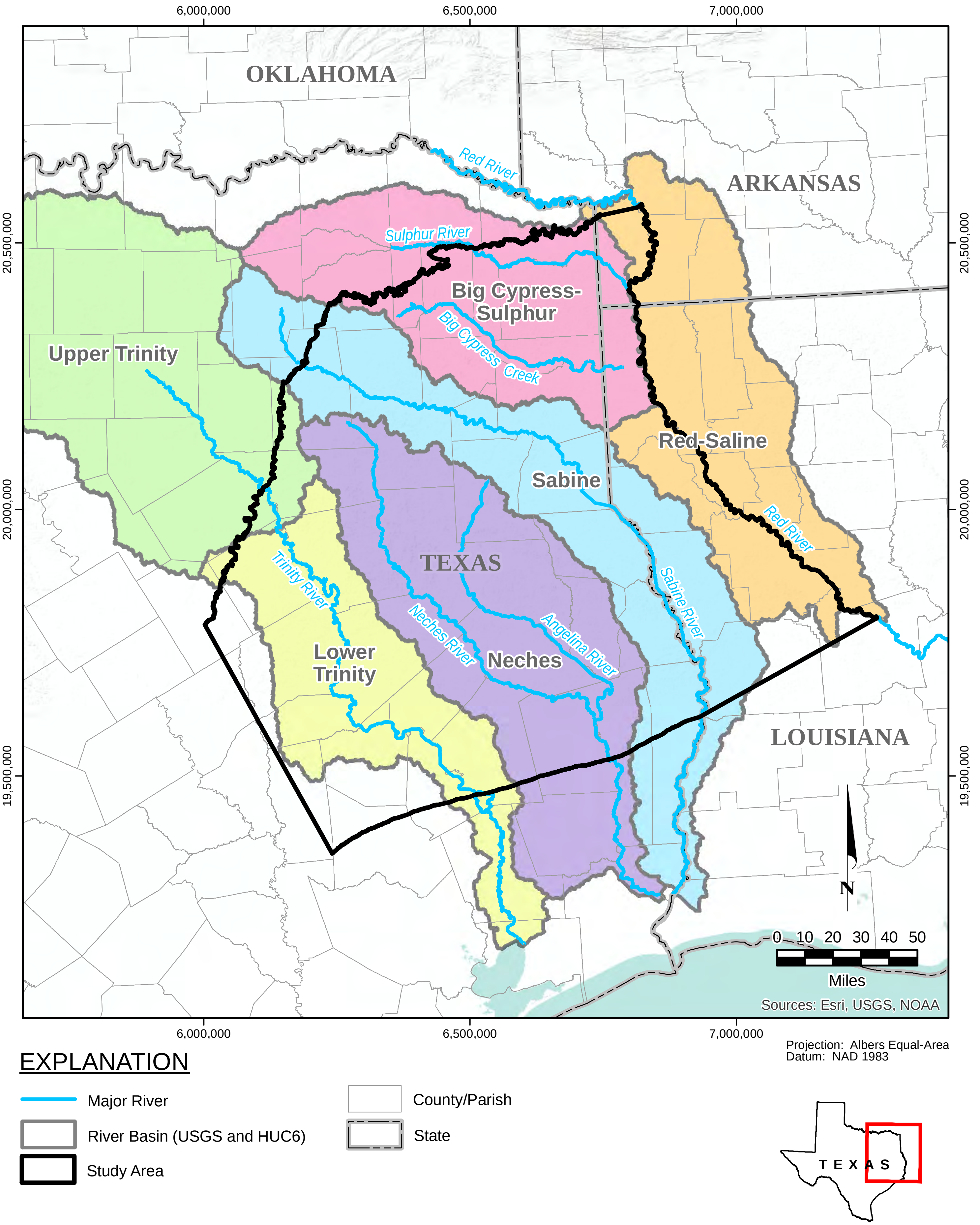

FIGURE 2.0.7. MAJOR RIVER BASINS IN STUDY AREA

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1480\REPORT_MAPS\RiverBasins.mxd\01June2018

DRAFT

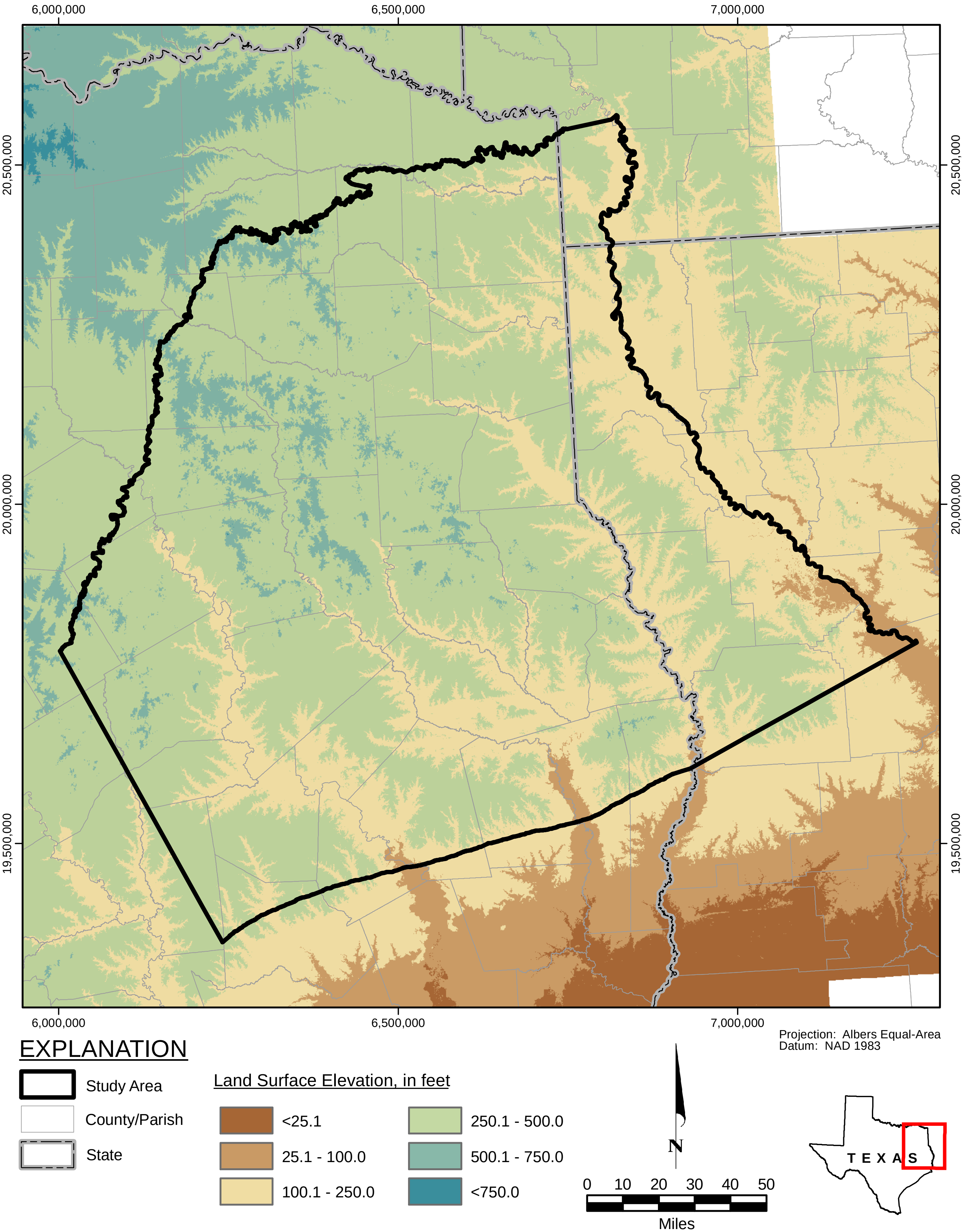

FIGURE 2.1.1 LAND SURFACE ELEVATION IN STUDY AREA

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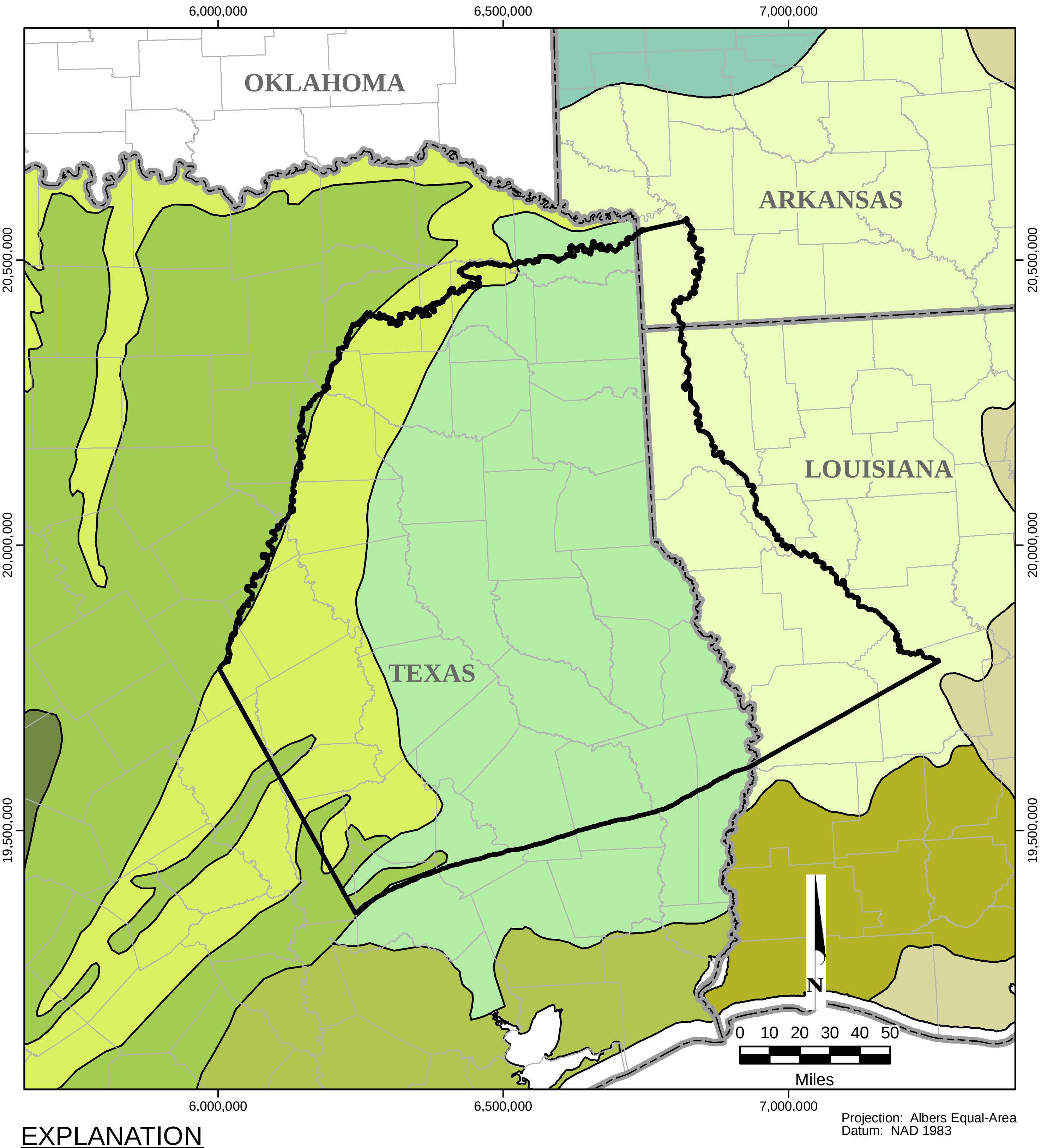
1480\REPORT_MAPS\LandSurf_Elev.mxd\31May2018

DRAFT



EXPLANATION

Study Area
County/Parish
State

Ecological Regions

- Blackland Prairie
- Edwards Plateau
- Gulf Coast Prairies and Marshes
- Oak Woods and Prairies
- Piney Woods
- Mississippi Alluvial Plain
- Ouachita Mountains
- South Central Plains
- Western Gulf Coastal Plain

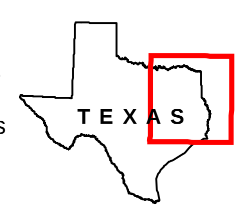


FIGURE 2.1.2. ECOLOGICAL REGIONS IN STUDY AREA

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1480\REPORT_MAPS\EcoRegions.mxd\26June2018

DRAFT

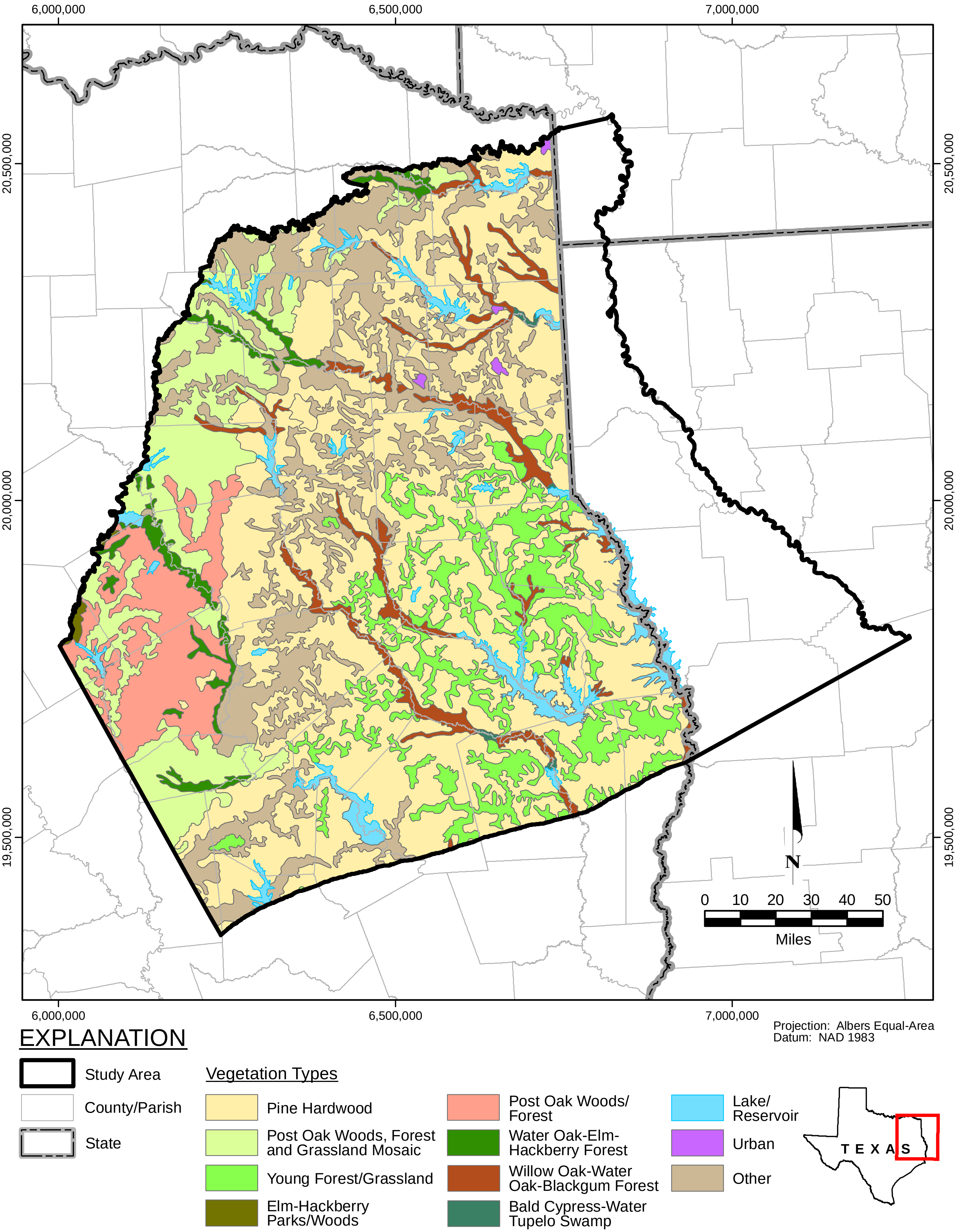

FIGURE 2.1.3. VEGETATION TYPES IN STUDY AREA

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1480\REPORT_MAPS\Veg_types.mxd\26June2018

DRAFT

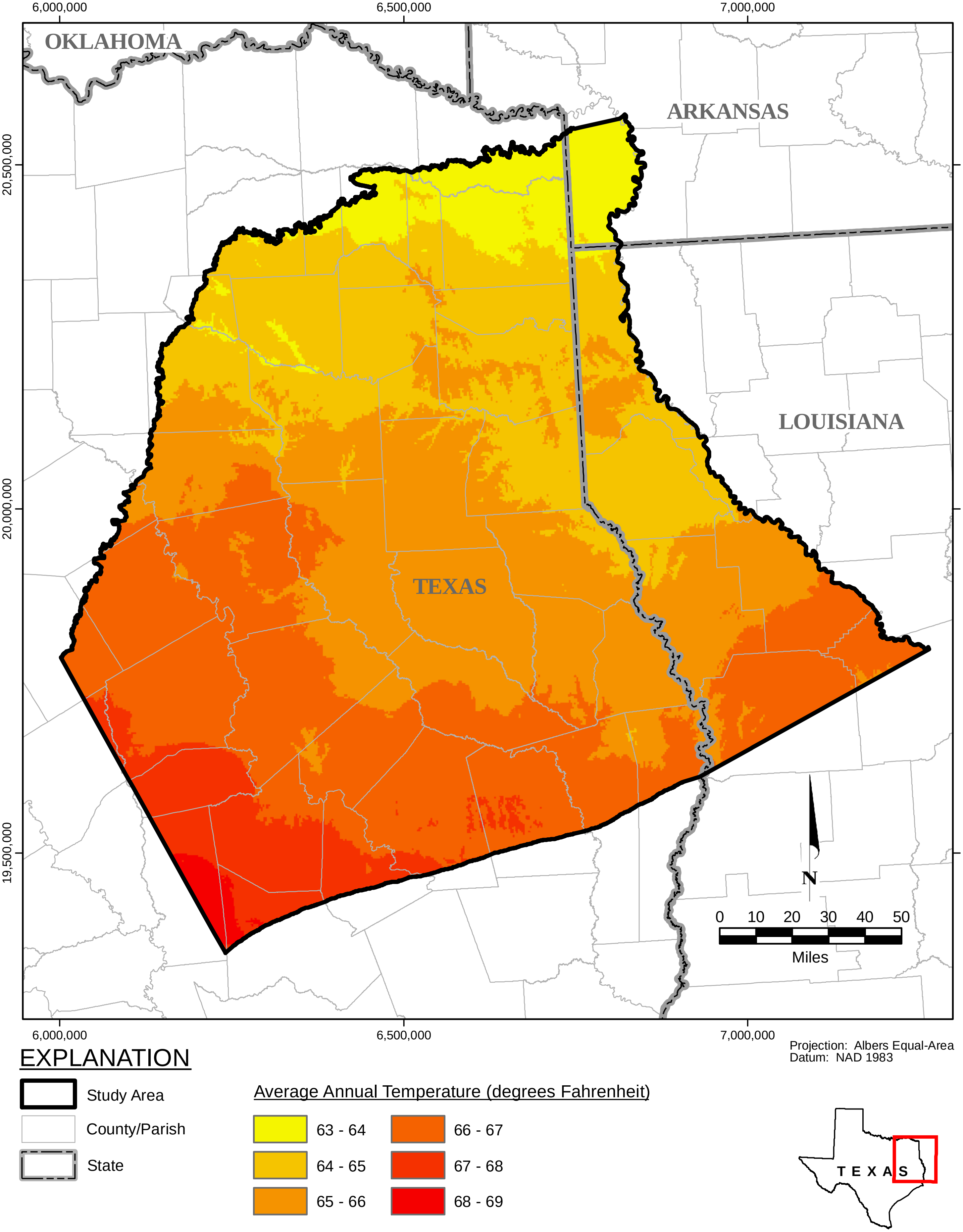

FIGURE 2.1.4. AVERAGE ANNUAL TEMPERATURE IN STUDY AREA

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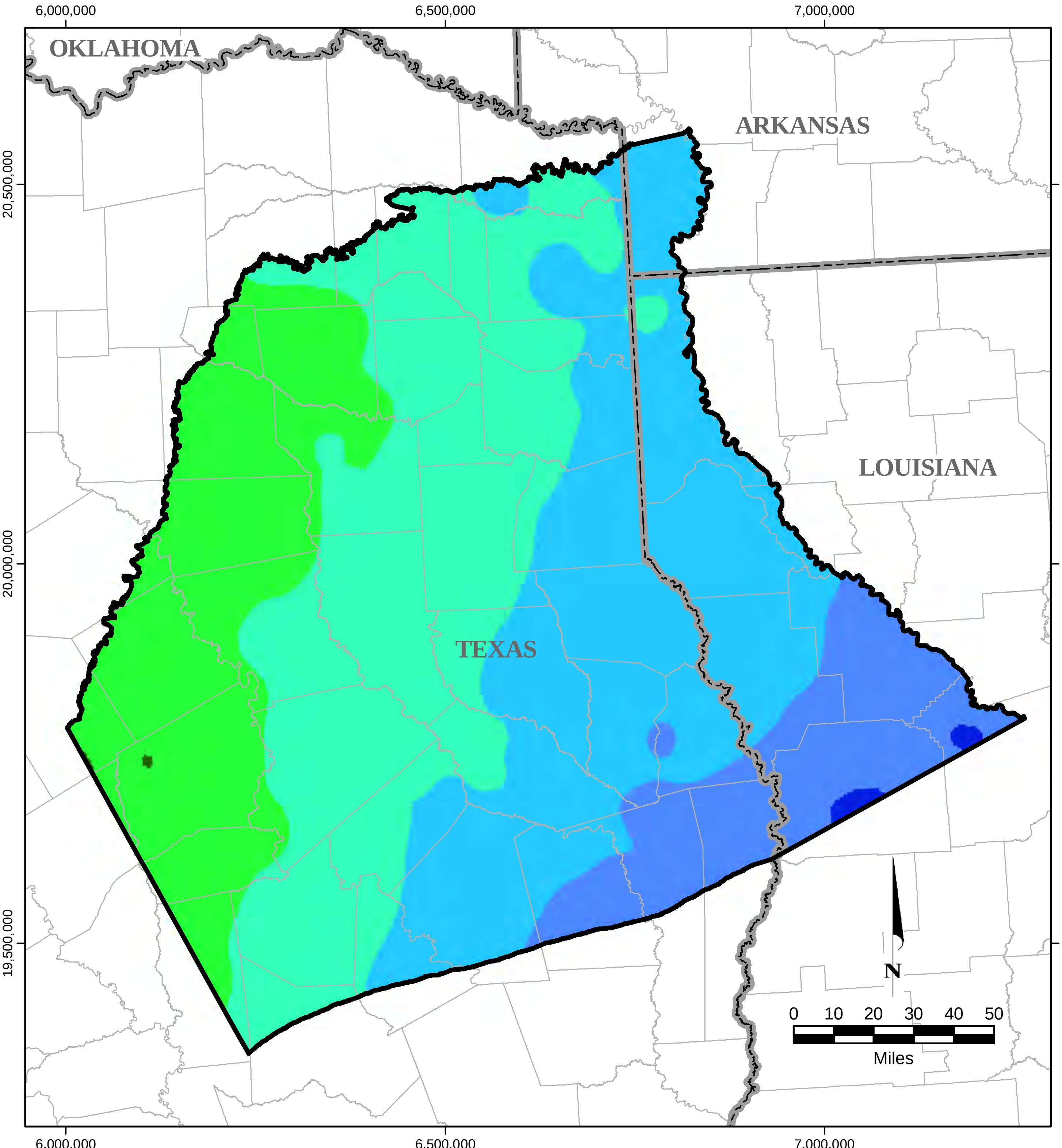


Projection: Albers Equal-Area
Datum: NAD 1983

EXPLANATION

Study Area

County/Parish

State

Average Annual Precipitation (inches)

39 - 40

40 - 45

45 - 50

50 - 55

55 - 60

60 - 61

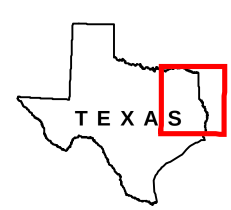
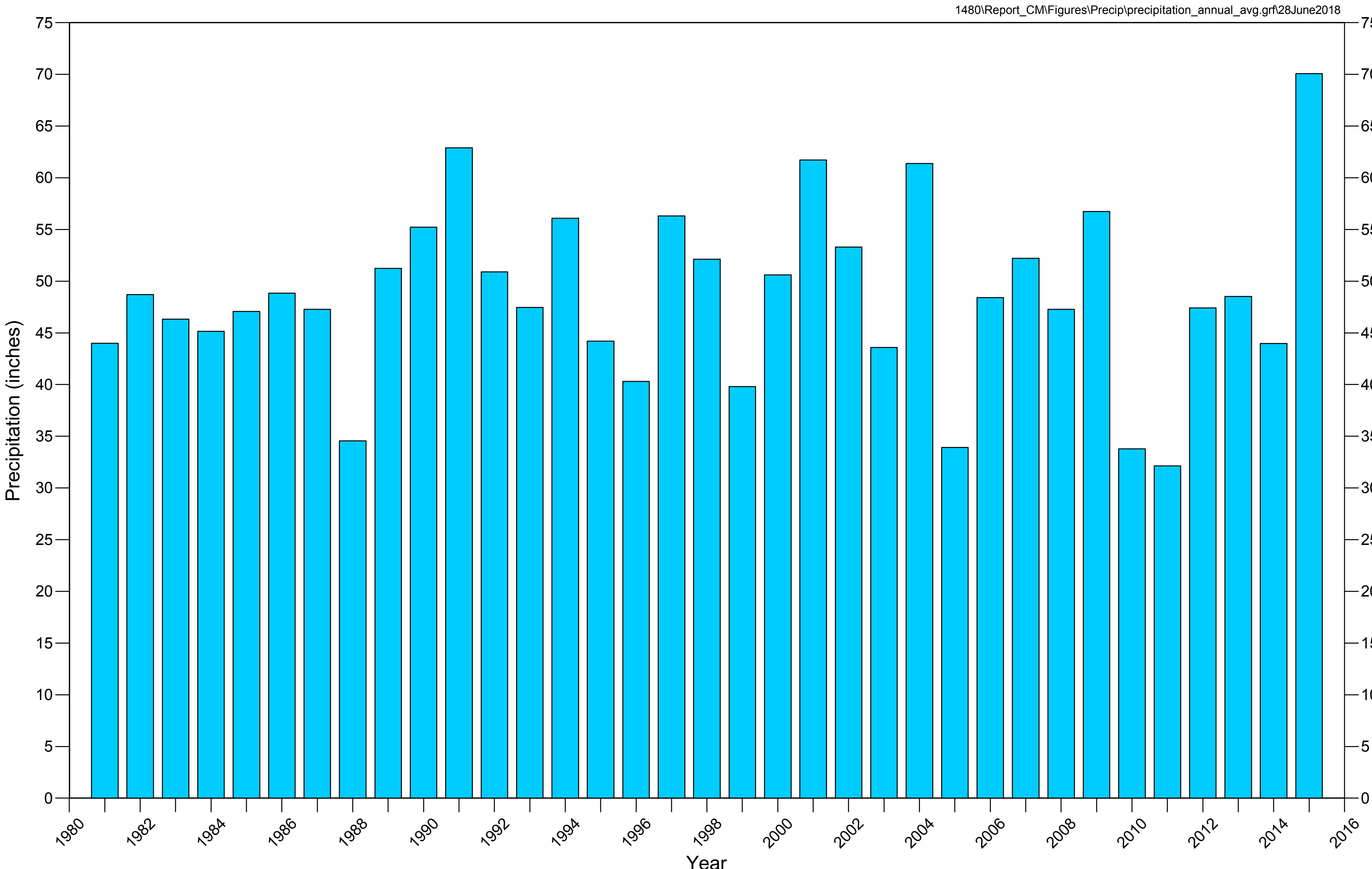


FIGURE 2.1.5. AVERAGE ANNUAL PRECIPITATION IN STUDY AREA

MONTGOMERY & ASSOCIATES

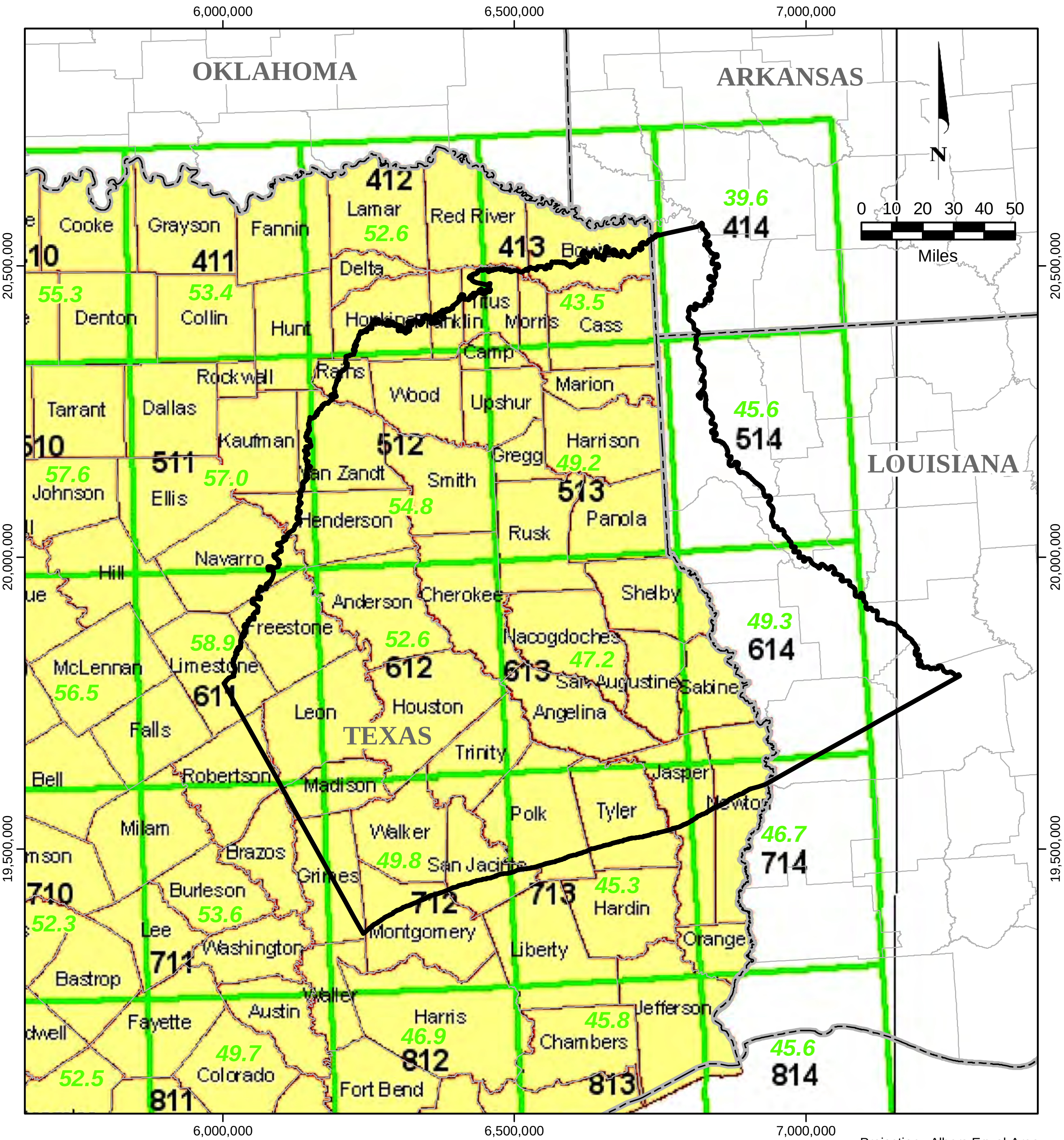


Source: PRISM Climate Group (2017)

FIGURE 2.1.6. ANNUAL PRECIPITATION IN STUDY AREA

MONTGOMERY & ASSOCIATES

DRAFT



Projection: Albers Equal-Area
Datum: NAD 1983

EXPLANATION

52.5	Quadrangle and Average Evaporation Rate (inches/year)
	Study Area
	County/Parish
	State

NOTE: Quadrangle map image saved from TWDB website for Precipitation and Lake Evaporation

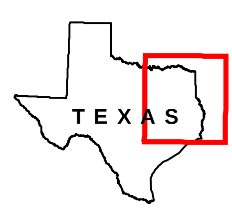


FIGURE 2.1.7. AVERAGE ANNUAL LAKE EVAPORATION

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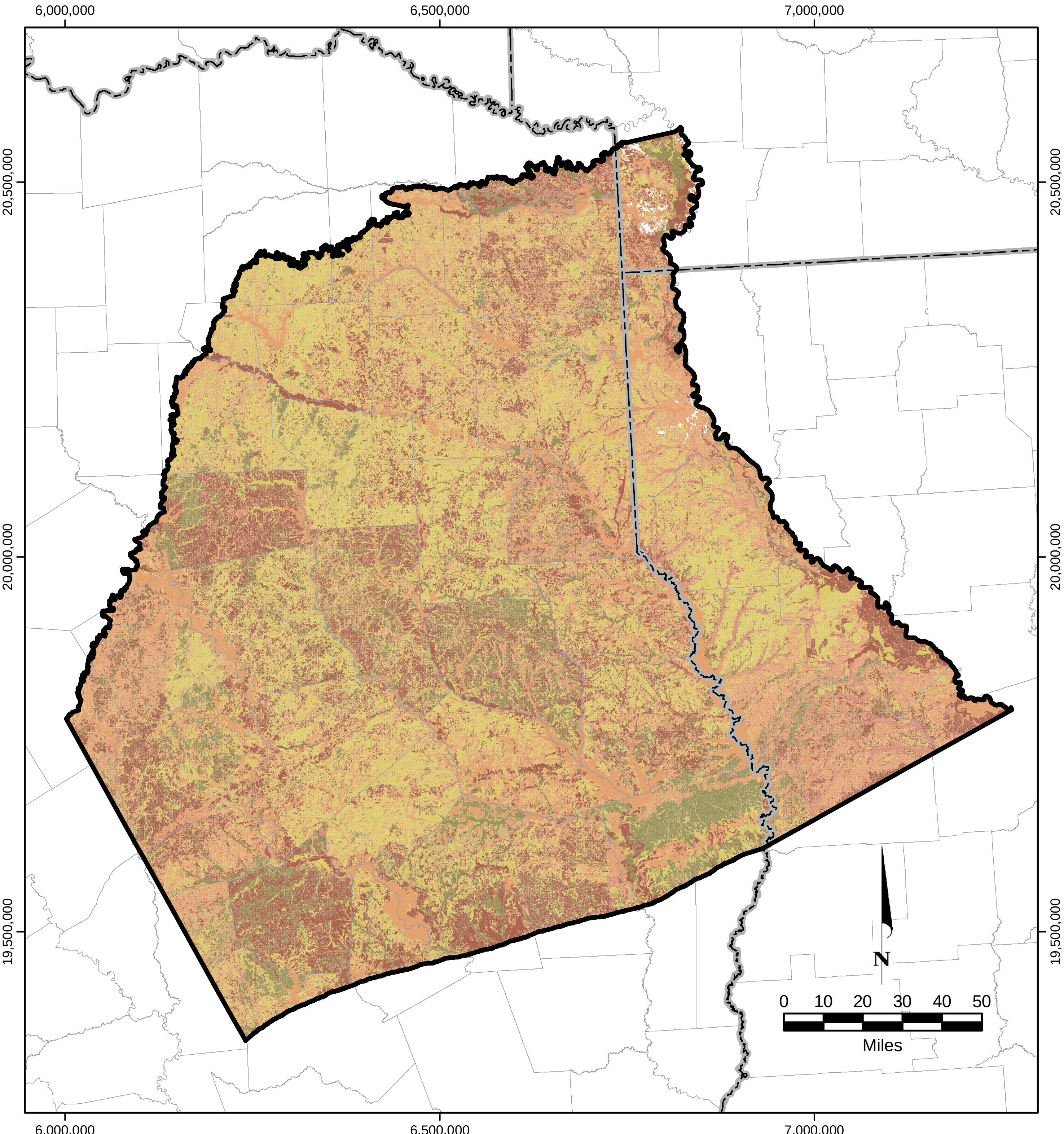
1480\REPORT_MAPS\EvapQuads.mxd\27June2018

DRAFT



Projection: Albers Equal-Area
Datum: NAD 1983

EXPLANATION

- Study Area
- County/Parish
- State

Hydrologic Soil Groups

- A - Well drained sand, gravels; high infiltration rate
- B - Moderately drained soils; moderate infiltration rate
- C - Fine soils; slow infiltration rate
- D - Clayey soils; very slow infiltration rate
- A/D - Group A where drained, Group D where undrained
- B/D - Group B where drained, Group D where undrained
- C/D - Group C where drained, Group D where undrained

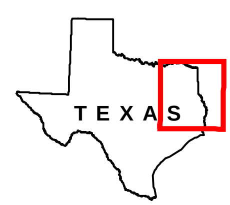


FIGURE 2.1.8. HYDROLOGIC SOIL GROUPS IN STUDY AREA

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1480\REPORT_MAPS\sOILS.mxd\05June2018

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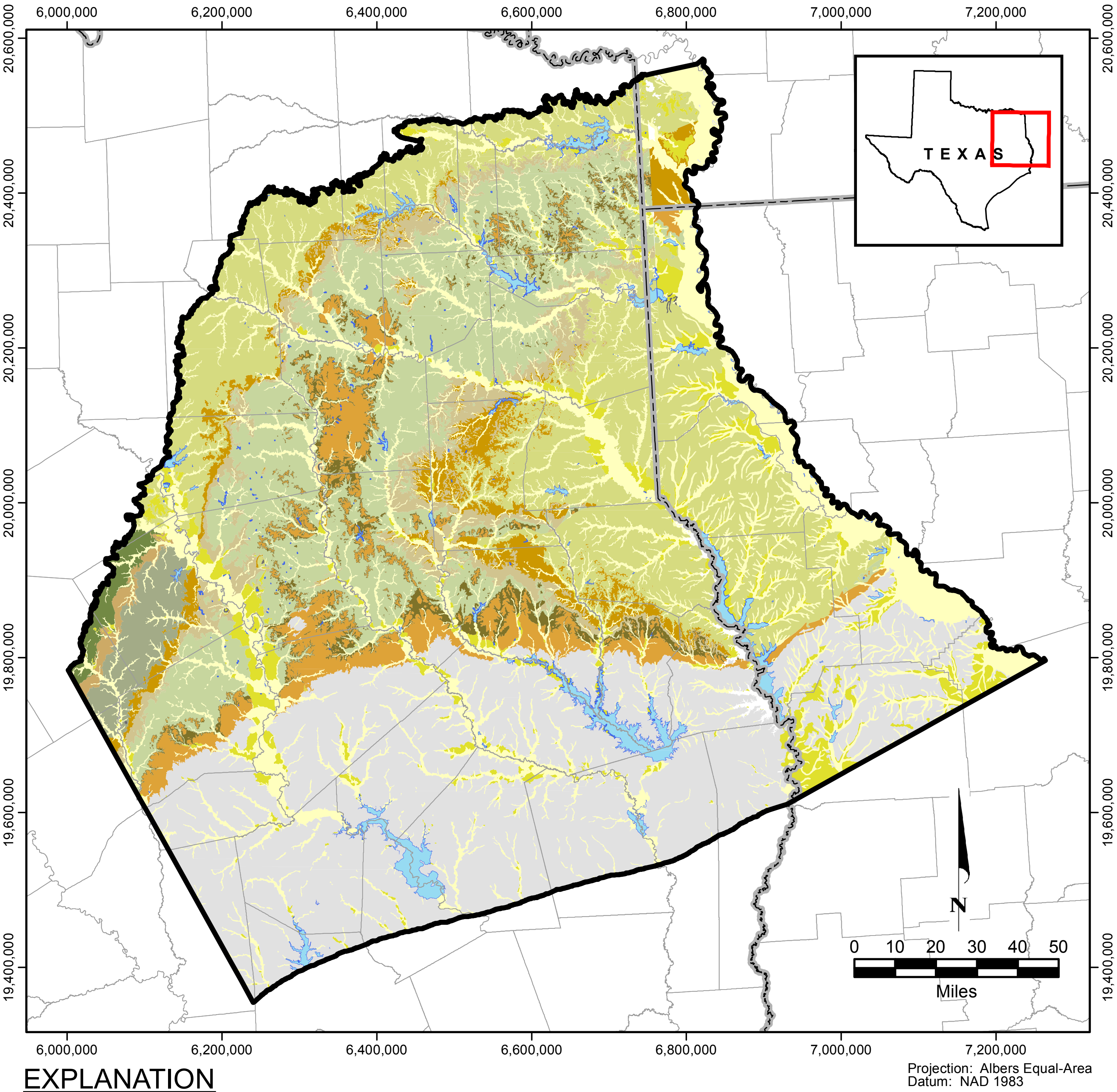

EXPLANATION

Study Area
County/Parish
State

Geologic Units

Water
Young Quaternary Deposits
Quaternary Deposits, Undivided
Younger Units
Sparta Sand
Weches Formation
Queen City Sand
Reklaw Formation
Carrizo Sand
Wilcox Group, Undivided
Wilcox Group (Upper)
Wilcox Group (Middle)
Wilcox Group (Lower)
Eocene Rocks, Undivided
Midway Group and Older Units

FIGURE 2.2.1. SURFACE GEOLOGY OF THE NORTHERN PORTION OF THE QUEEN CITY, SPARTA, AND CARRIZO-WILCOX AQUIFERS

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1480\REPORT_MAPS\Geology.mxd\01June2018

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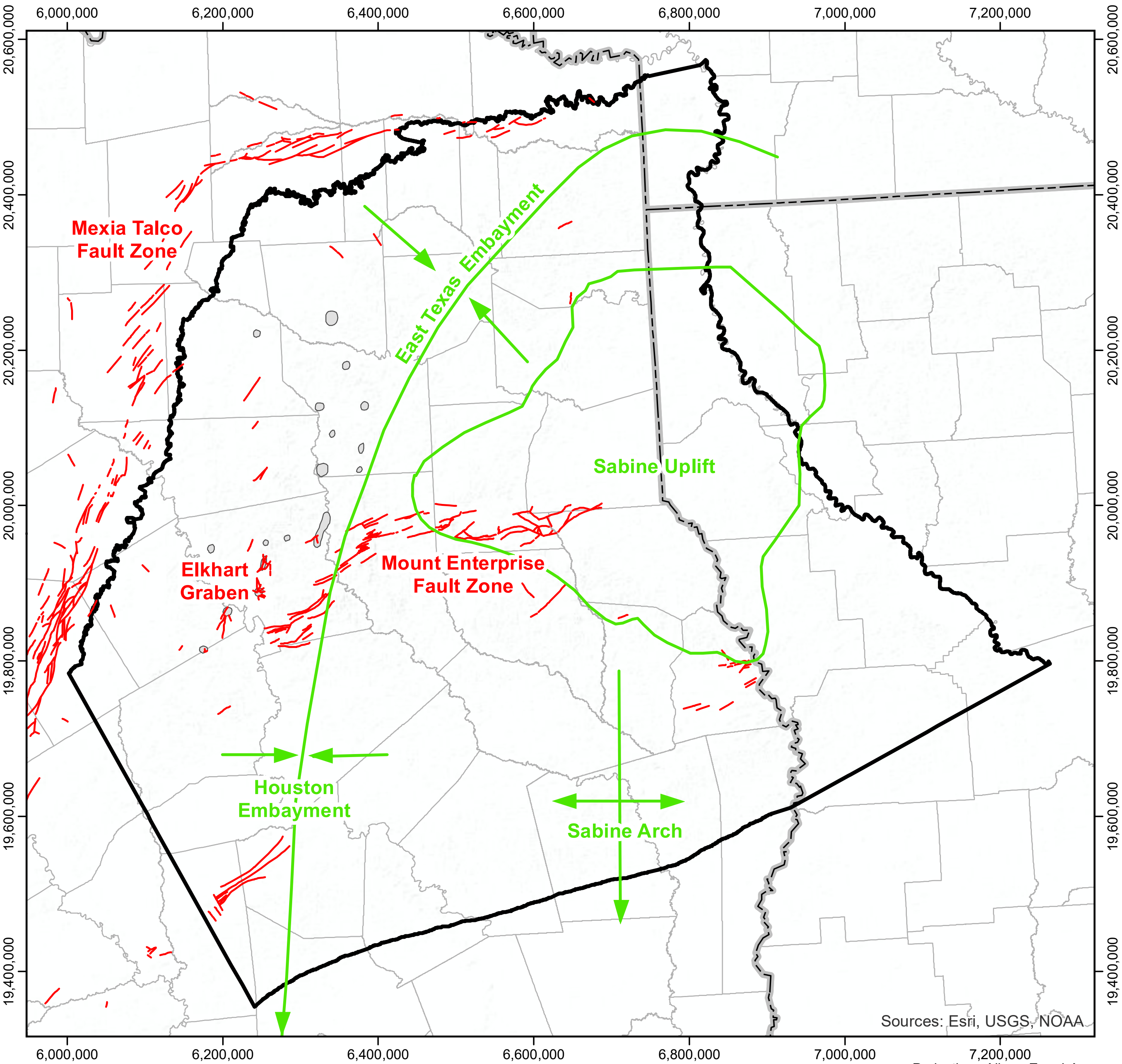
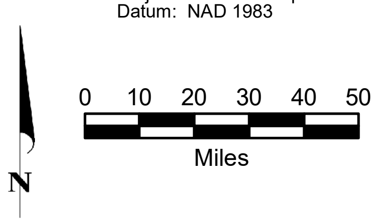


Projection: Albers Equal-Area
Datum: NAD 1983

EXPLANATION

- Normal Fault
- Salt Dome
- Anticline Showing Dip Direction
- Syncline Showing Dip Direction
- Study Area
- County
- State

Source: Structural axes digitized from Figure 4.2.1 by Fryar and others (2003).



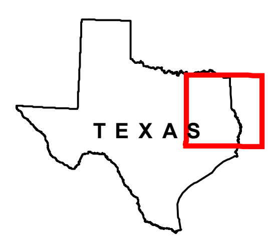


FIGURE 2.2.2. MAJOR FAULTS AND STRUCTURAL FEATURES

1480\REPORT_MAPS\MajFaults_Structure_v2.mxd\04June2018

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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

FIGURE 4.1.1. GENERALIZED STRATIGRAPHIC SECTION OF HYDROSTRATIGRAPHIC UNITS

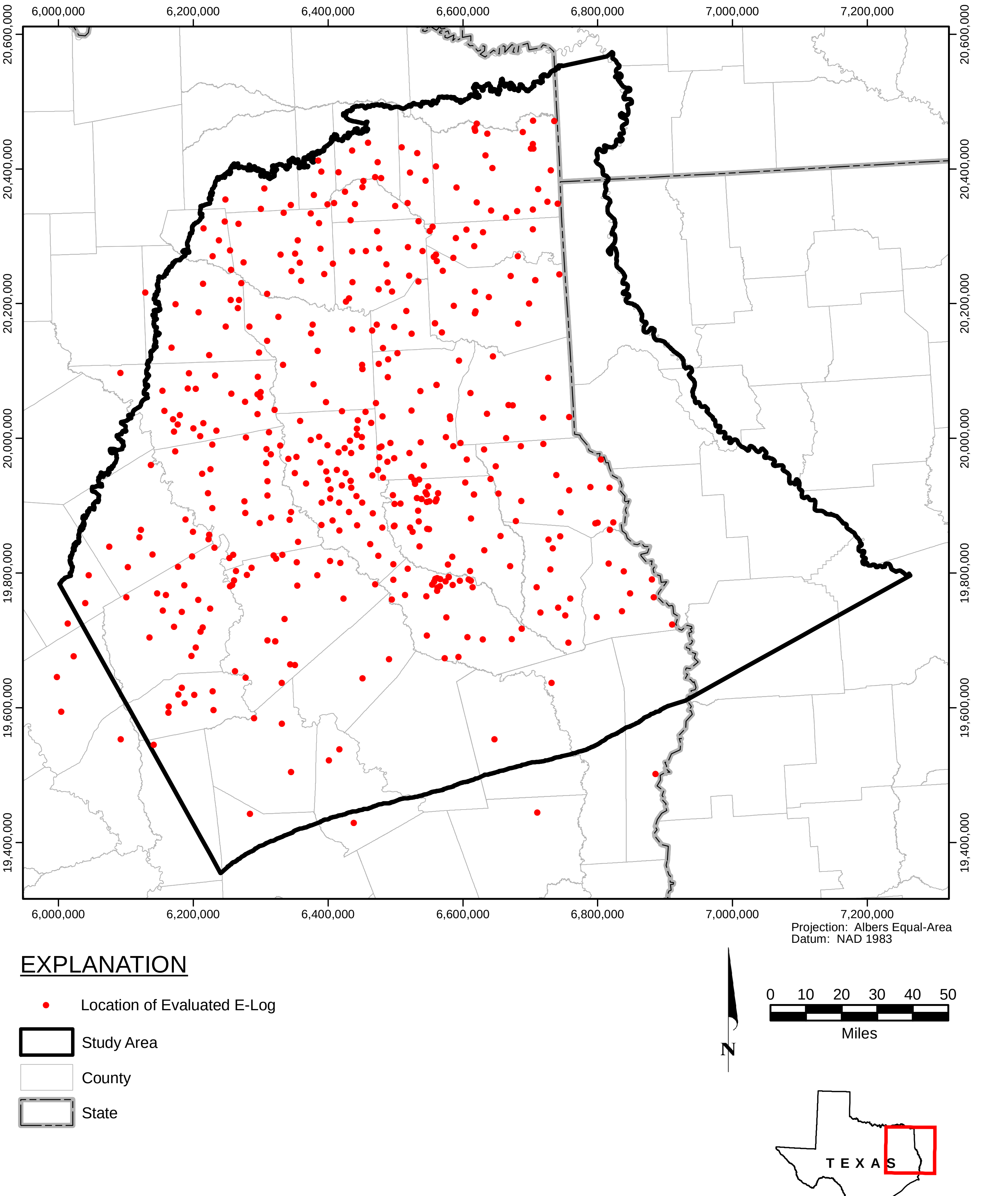

FIGURE 4.1.2. LOCATIONS OF EVALUATED BOREHOLE GEOPHYSICAL LOGS

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1480\REPORT_MAPS\GeoModel_ELogs.mxd\12June2018

DRAFT

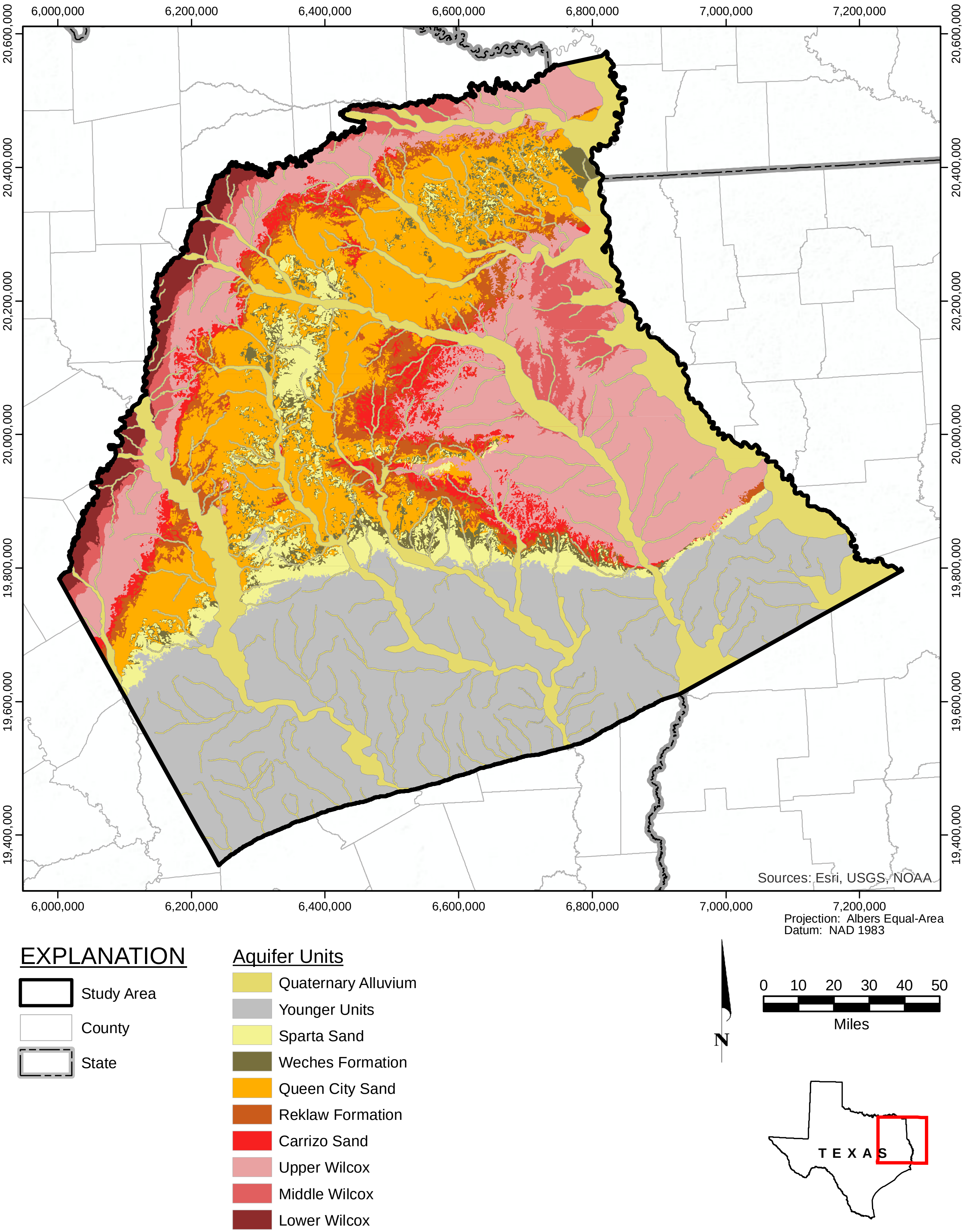

FIGURE 4.1.3. AQUIFER OUTCROPS FROM GEOLOGIC MODEL

1480\REPORT_MAPS\GeoModel_Outcrops.mxd\26June2018

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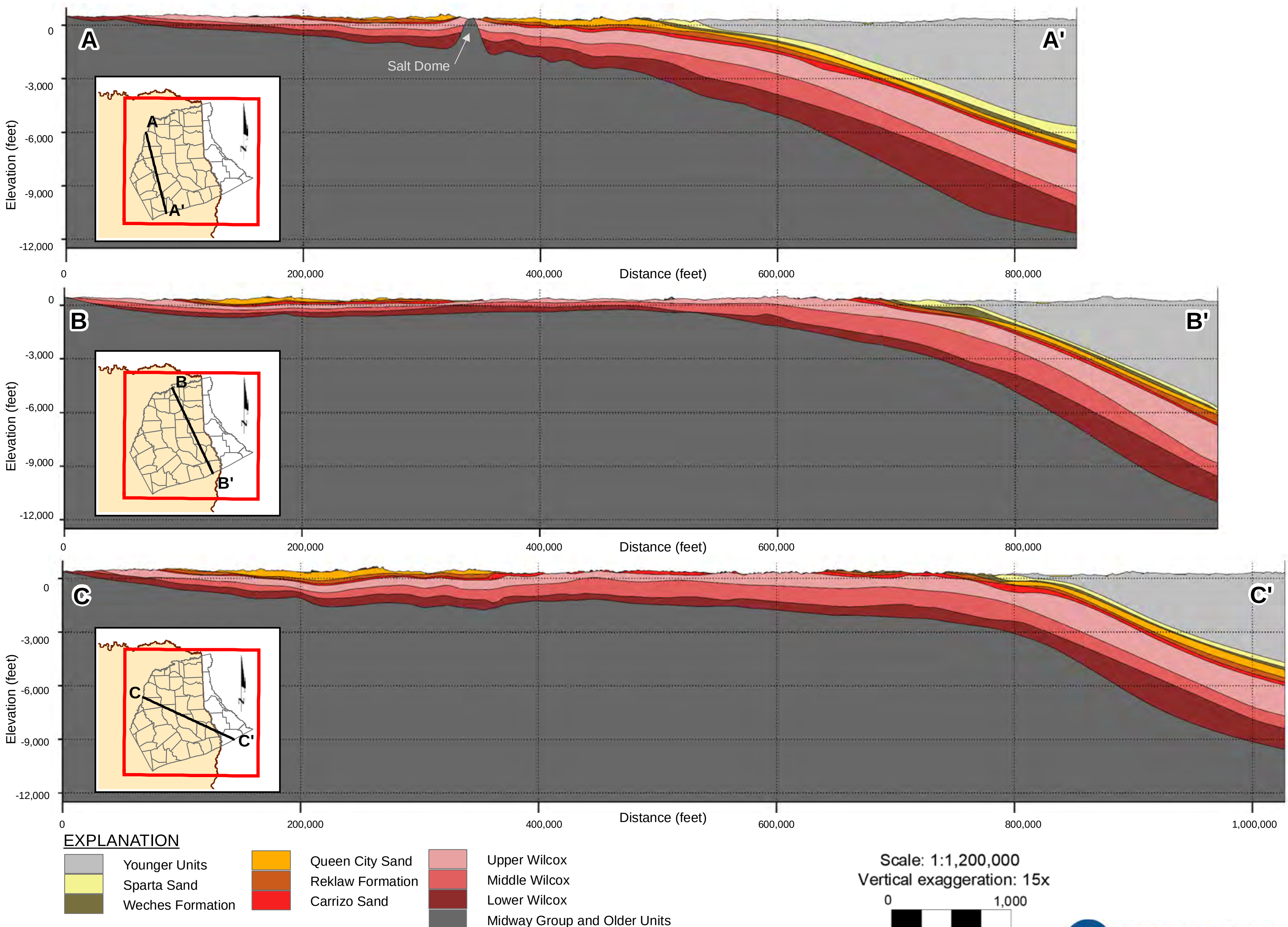

FIGURE 4.1.4. HYDROGEOLOGIC SECTIONS A-A', B-B', AND C-C'

1480\REPORT_MAPS\SectionABC.mxd\26June2018

DRAFT

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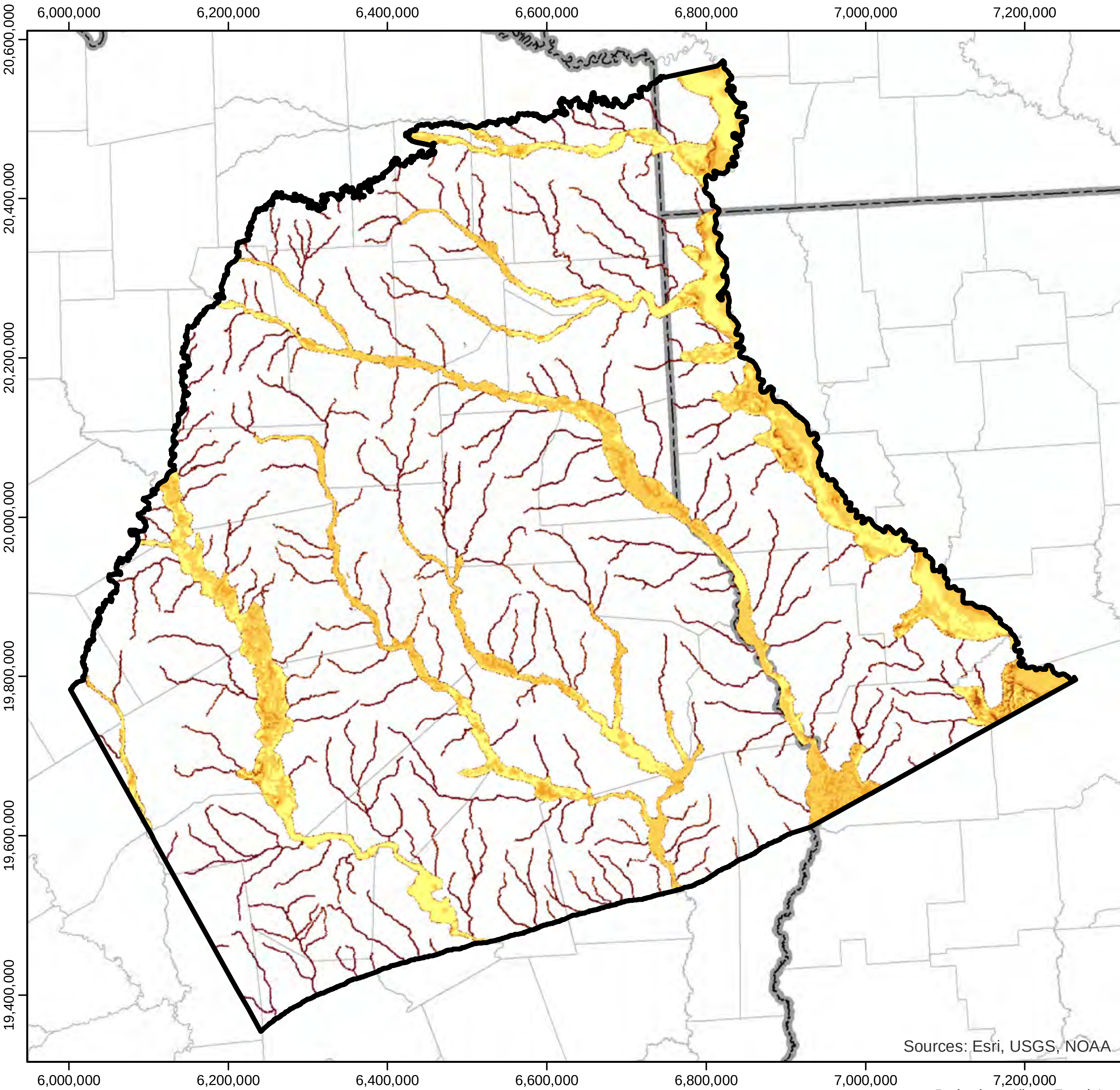


Projection: Albers Equal-Area
Datum: NAD 1983

500 - 600

EXPLANATION

Study Area

County Boundary

State Boundary

Thickness of Quaternary Deposits

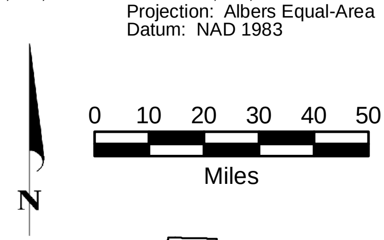
< 20

20 - 35

35 - 50

50 - 65

65 - 80



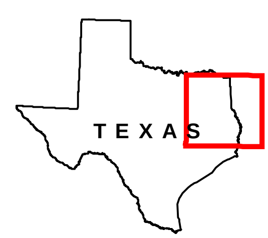


FIGURE 4.1.5. THICKNESS OF QUATERNARY DEPOSITS

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1480\REPORT_MAPS\Thickness_QuaternaryDeposits.mxd\27June2018

DRAFT

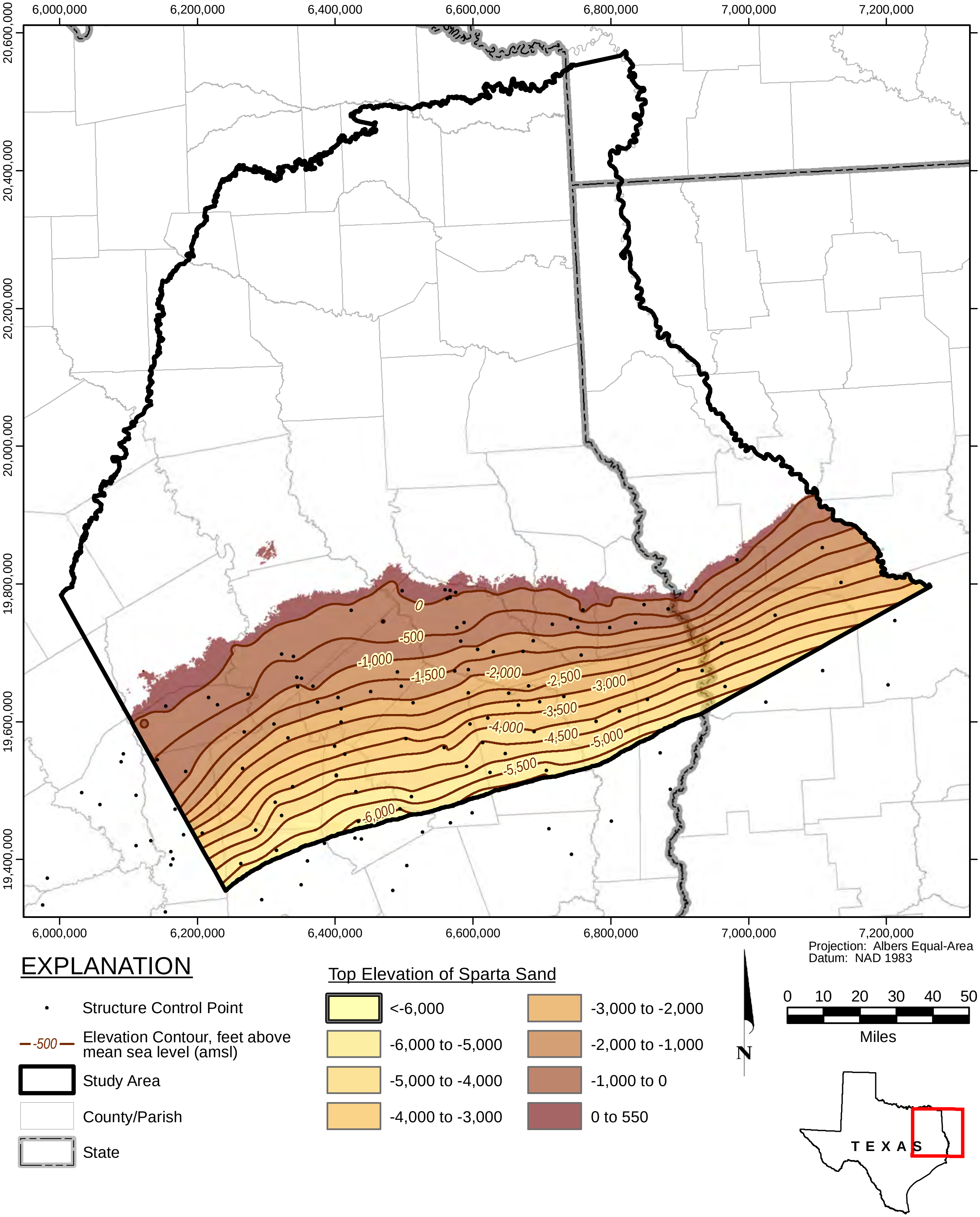

FIGURE 4.1.6. TOP ELEVATION CONTOURS FOR SPARTA SAND

1480\REPORT_MAPS\Structure_TopOfSpartaSand.mxd\25June2018

DRAFT

MONTGOMERY & ASSOCIATES

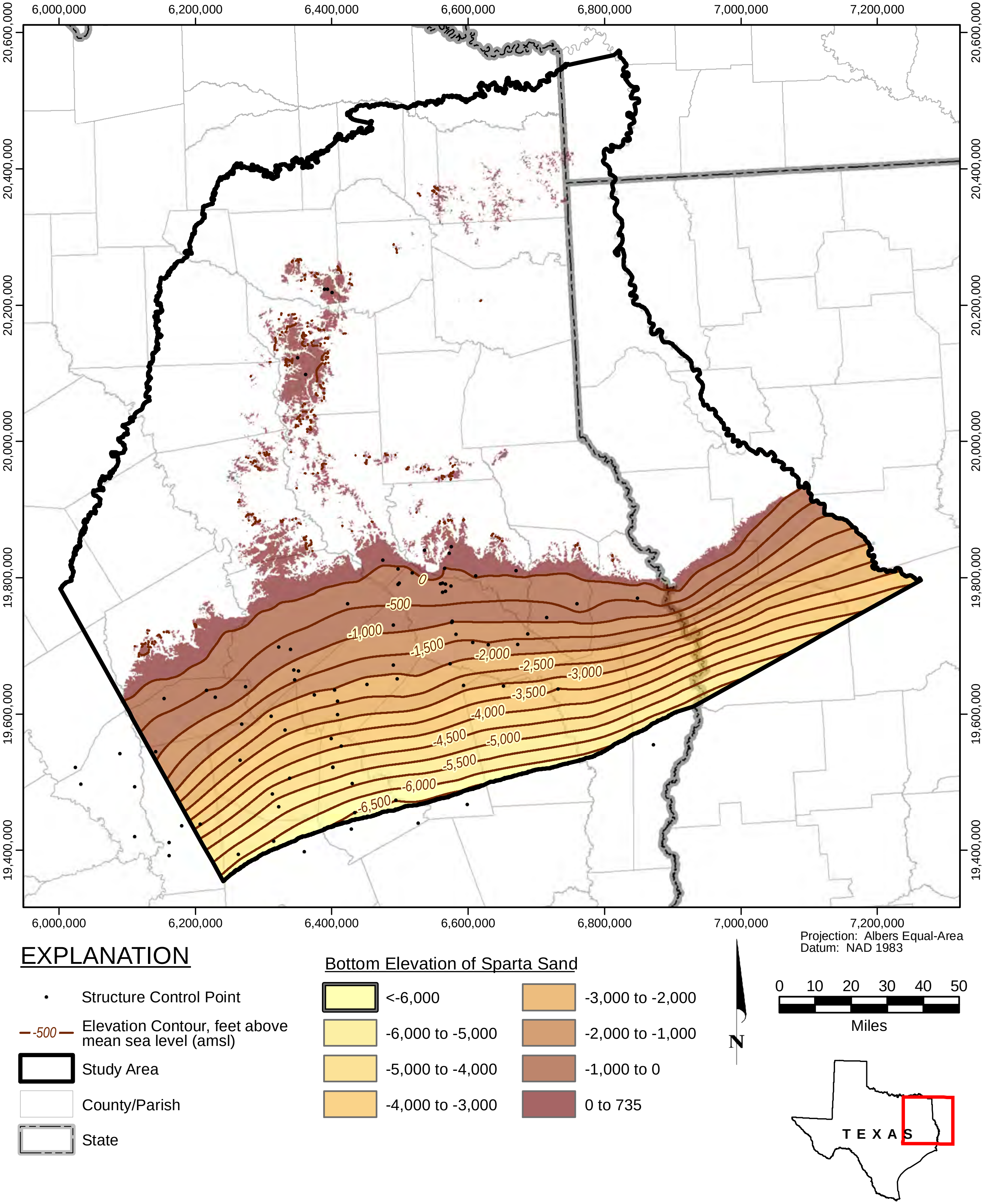

FIGURE 4.1.7. BOTTOM ELEVATION CONTOURS FOR SPARTA SAND

1480\REPORT_MAPS\Structure_BottomOfSpartaSand.mxd\25June2018

DRAFT

MONTGOMERY & ASSOCIATES

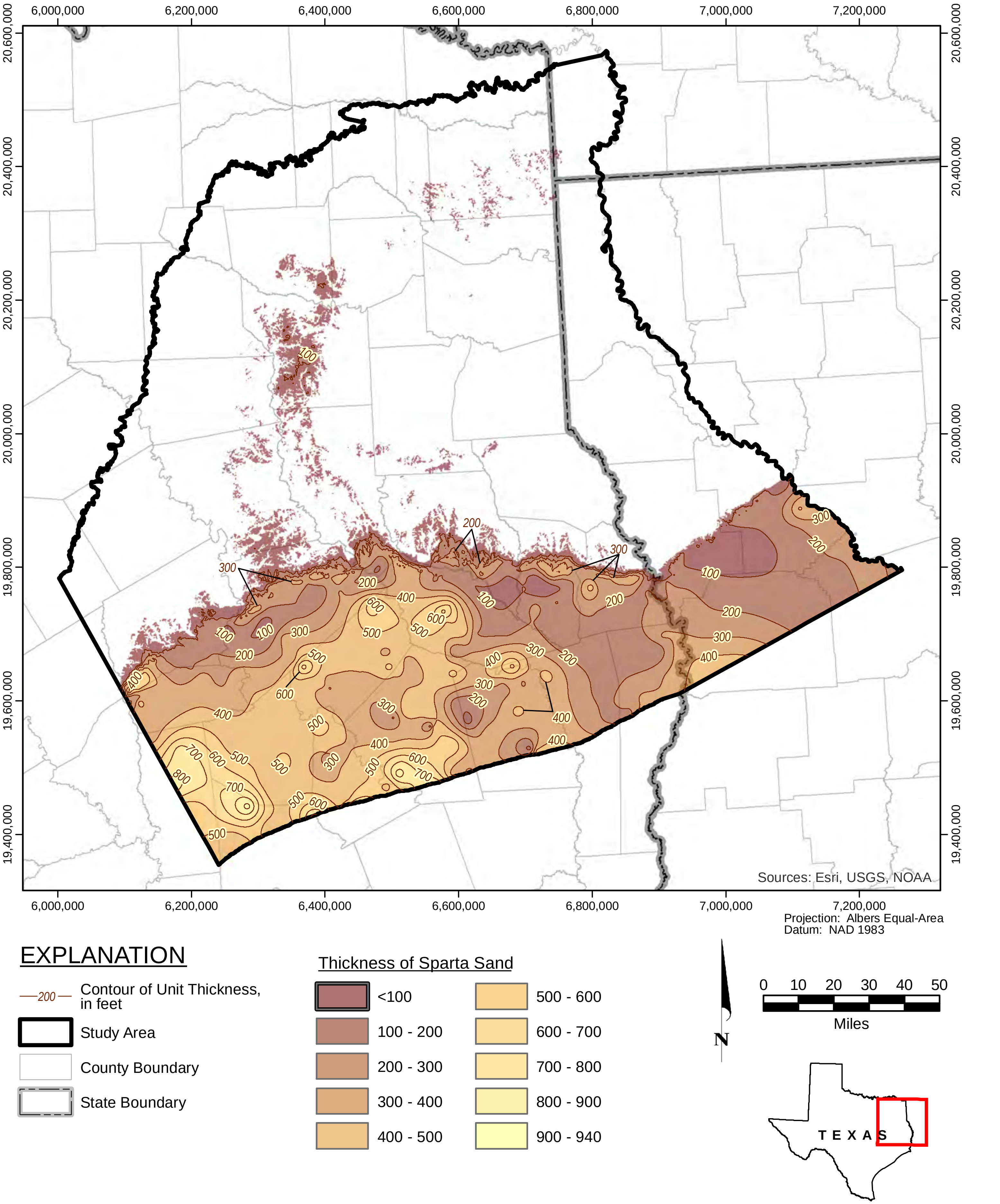

FIGURE 4.1.8. THICKNESS OF SPARTA SAND

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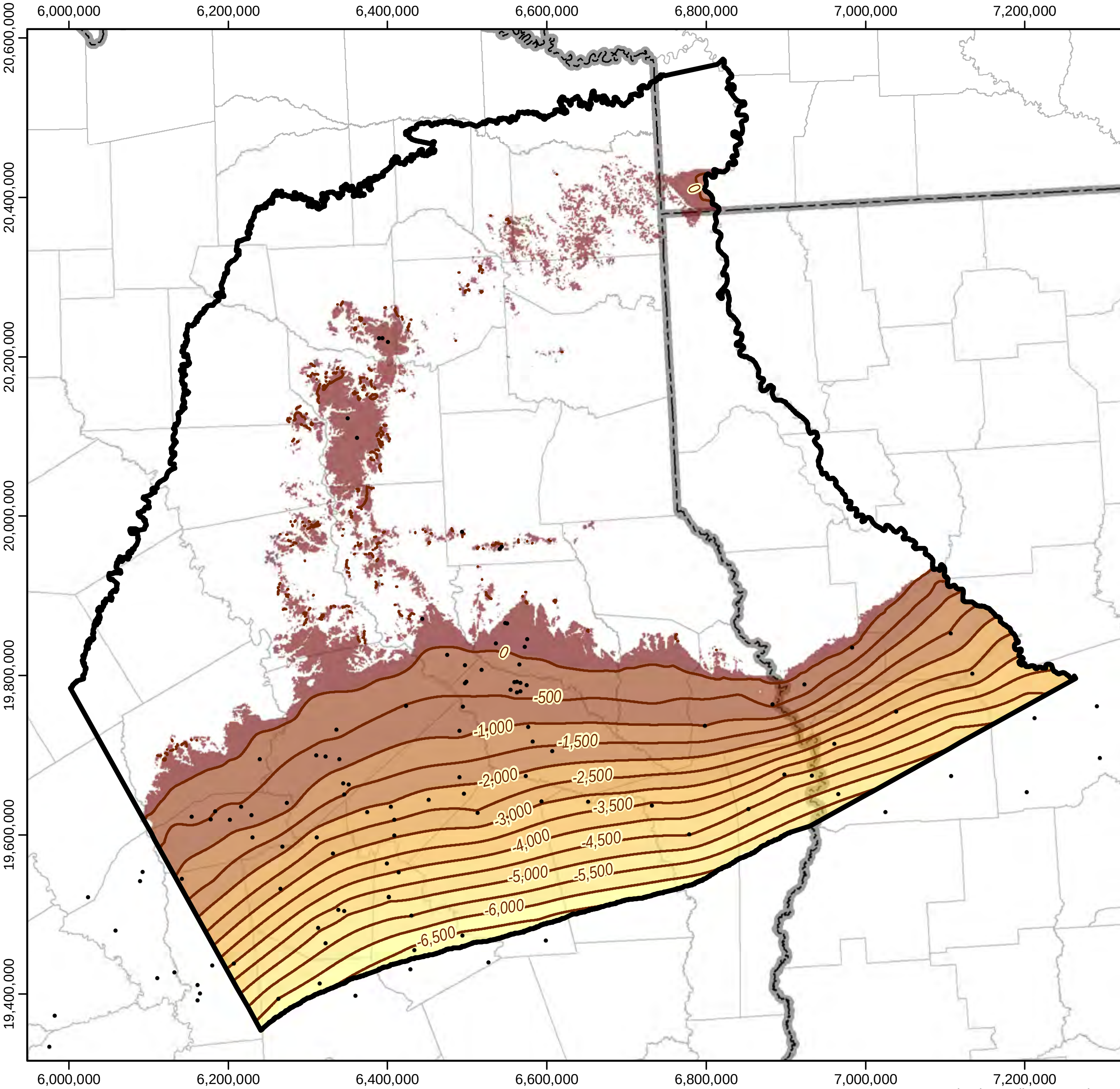
1480\REPORT_MAPS\Thickness_SpartaSand.mxd\25June2018

DRAFT



Projection: Albers Equal-Area
Datum: NAD 1983

EXPLANATION

- Structure Control Point
- -500 Elevation Contour, feet above mean sea level (amsl)
- Study Area
- County/Parish
- State

Bottom Elevation of Weches Formation

<-6,000	-3,000 to -2,000
-6,000 to -5,000	-2,000 to -1,000
-5,000 to -4,000	-1,000 to 0
-4,000 to -3,000	0 to 735

N

0 10 20 30 40 50
Miles

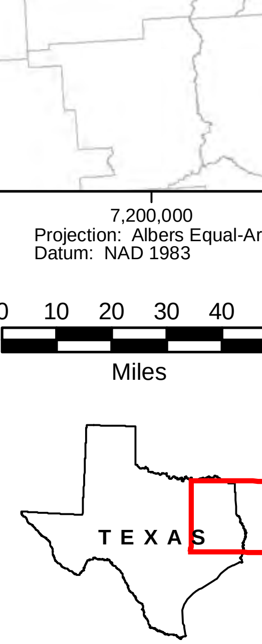
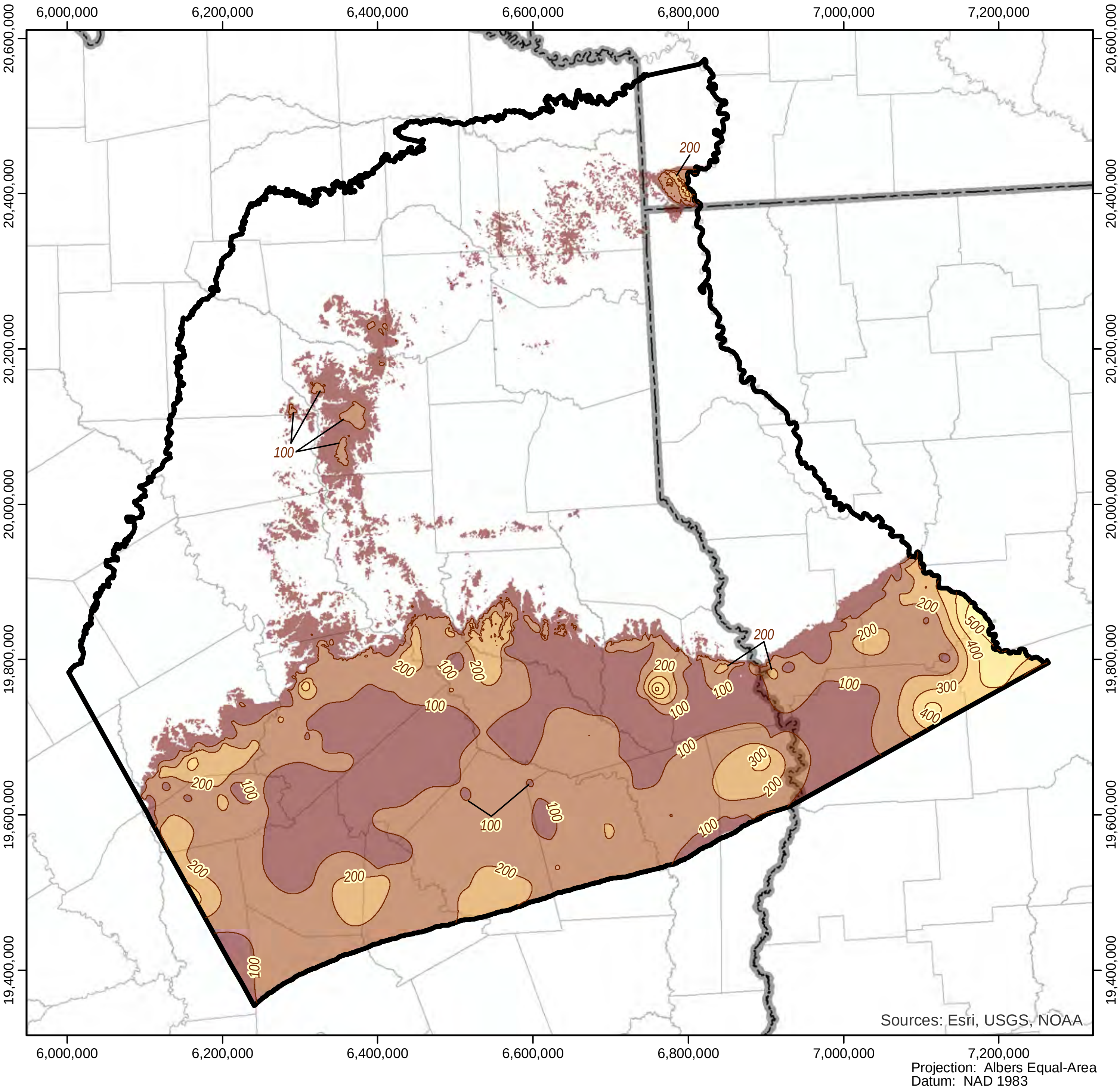


FIGURE 4.1.9. BOTTOM ELEVATION CONTOURS FOR WECHES FORMATION

MONTGOMERY & ASSOCIATES

1480\REPORT_MAPS\Structure_BottomOfWechesFormation.mxd\25June2018

DRAFT



EXPLANATION

- 200 — Contour of Unit Thickness, in feet
- Study Area
- County Boundary
- State Boundary

Thickness of Weches Formation

- <100
- 100 - 200
- 200 - 300
- 300 - 400
- 400 - 500
- 500 - 565

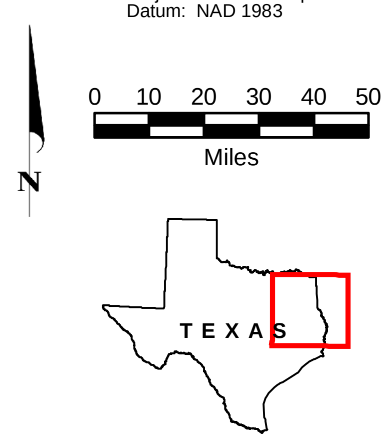
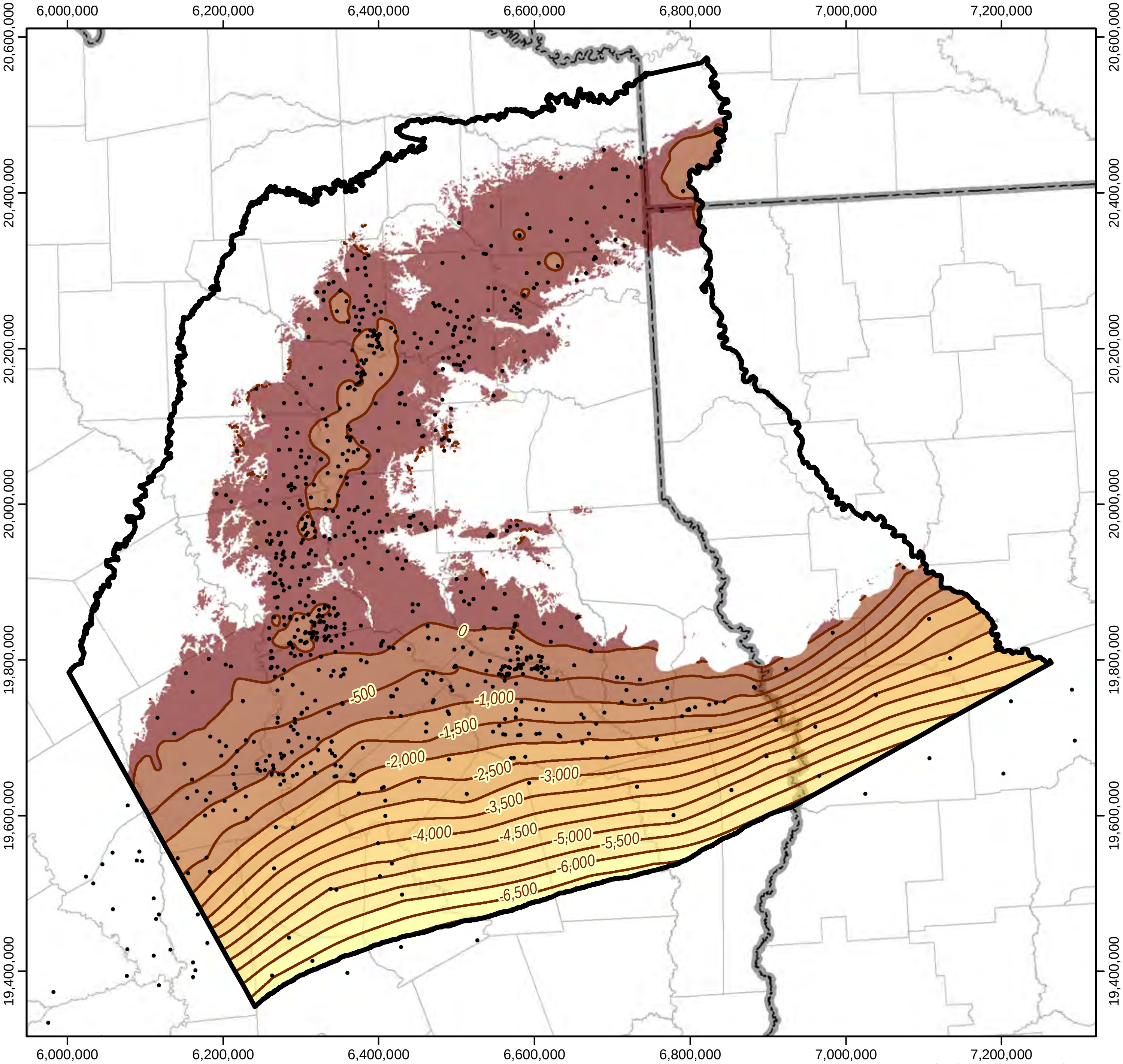


FIGURE 4.1.10. THICKNESS OF WECHES FORMATION

MONTGOMERY & ASSOCIATES

1480\REPORT_MAPS\Thickness_WechesFormation.mxd\25June2018

DRAFT



EXPLANATION

- Structure Control Point
- -500 Elevation Contour, feet above mean sea level (amsl)
- Study Area
- County/Parish
- State

Bottom Elevation of Queen City Sand

- <-6,000
- -6,000 to -5,000
- -5,000 to -4,000
- -4,000 to -3,000
- -3,000 to -2,000
- -2,000 to -1,000
- -1,000 to 0
- 0 to 735

N

0 10 20 30 40 50

Miles

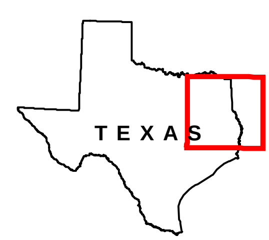
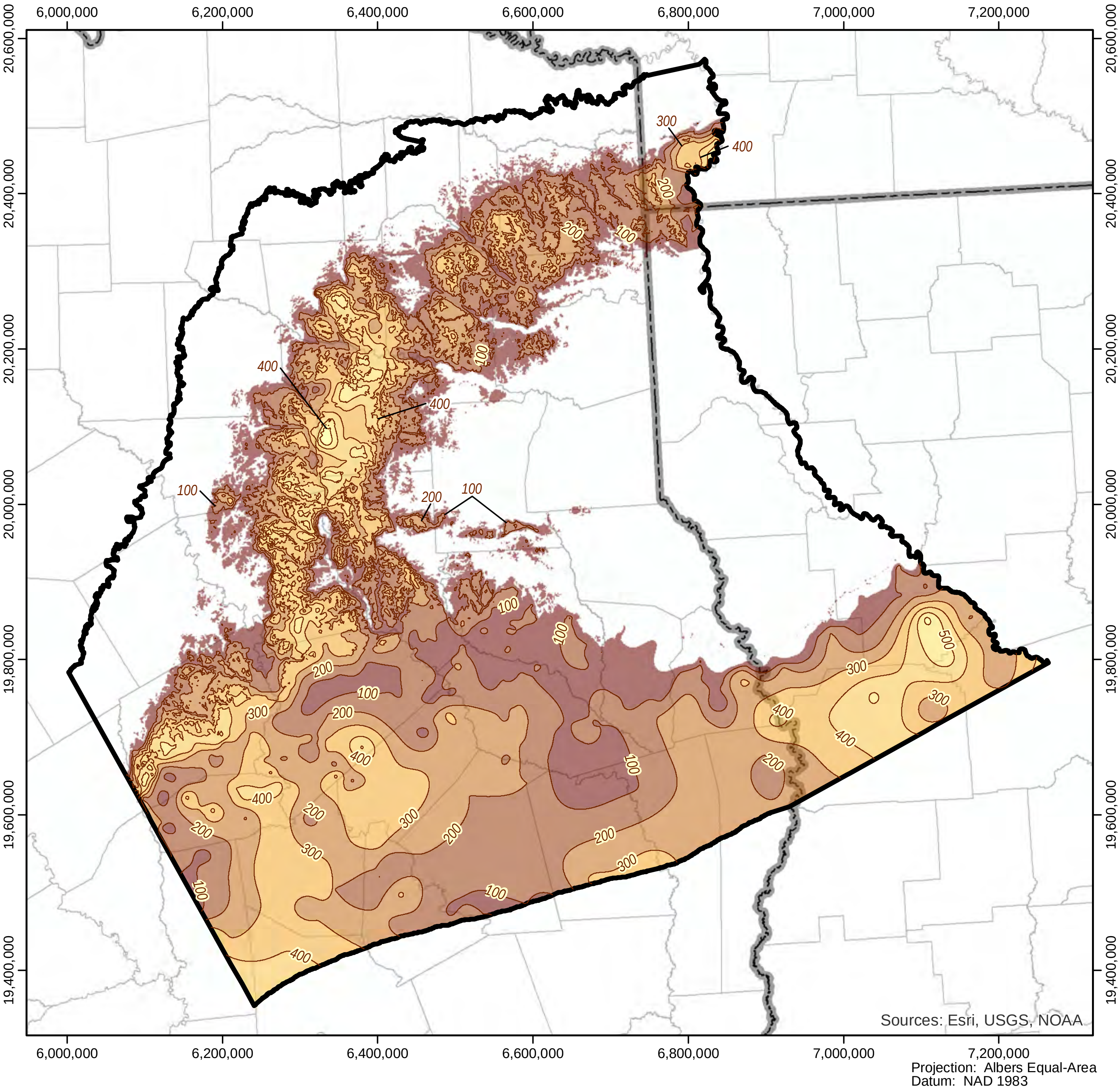


FIGURE 4.1.11. BOTTOM ELEVATION CONTOURS FOR QUEEN CITY SAND

MONTGOMERY & ASSOCIATES

1480\REPORT_MAPS\Structure_BottomOfQueenCitySand.mxd\25June2018

DRAFT



EXPLANATION

- 200 — Contour of Unit Thickness, in feet
- Study Area
- County Boundary
- State Boundary

Thickness of Queen City Sand

- <100
- 100 - 200
- 200 - 300
- 300 - 400
- 400 - 500
- 500 - 600
- 600 - 695

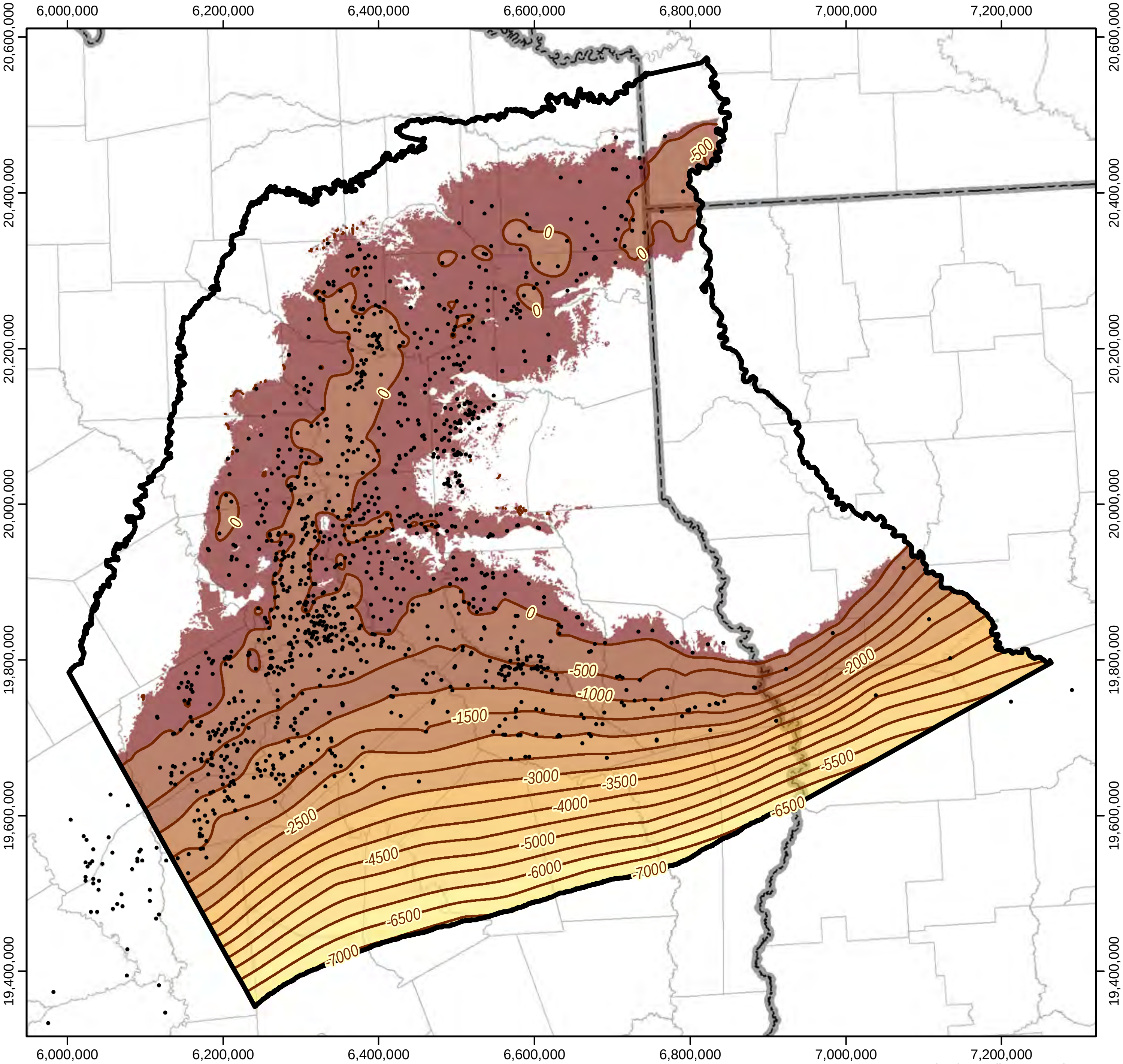
N

0 10 20 30 40 50
Miles

TEXAS

FIGURE 4.1.12. THICKNESS OF QUEEN CITY SAND

MONTGOMERY & ASSOCIATES



EXPLANATION

- Structure Control Point
- -500 Elevation Contour, feet above mean sea level (amsl)
- Study Area
- County/Parish
- State

Bottom Elevation of Reklaw Formation

- <-7,000
- -7,000 to -6,000
- -6,000 to -5,000
- -5,000 to -4,000
- -4,000 to -3,000
- -3,000 to -2,000
- -2,000 to -1,000
- -1,000 to 0
- 0 to 570

FIGURE 4.1.13. BOTTOM ELEVATION CONTOURS FOR REKLAW FORMATION

MONTGOMERY & ASSOCIATES

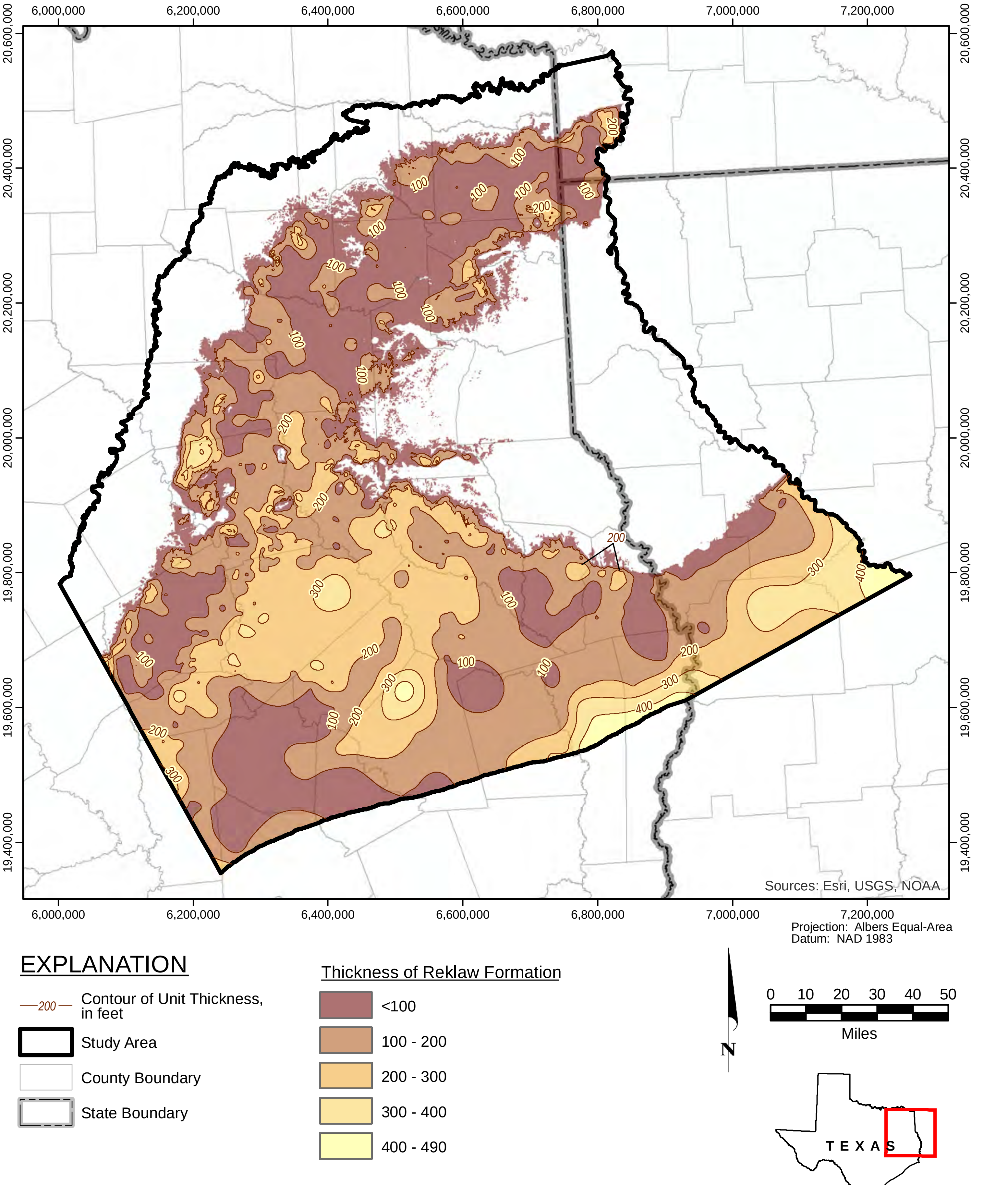
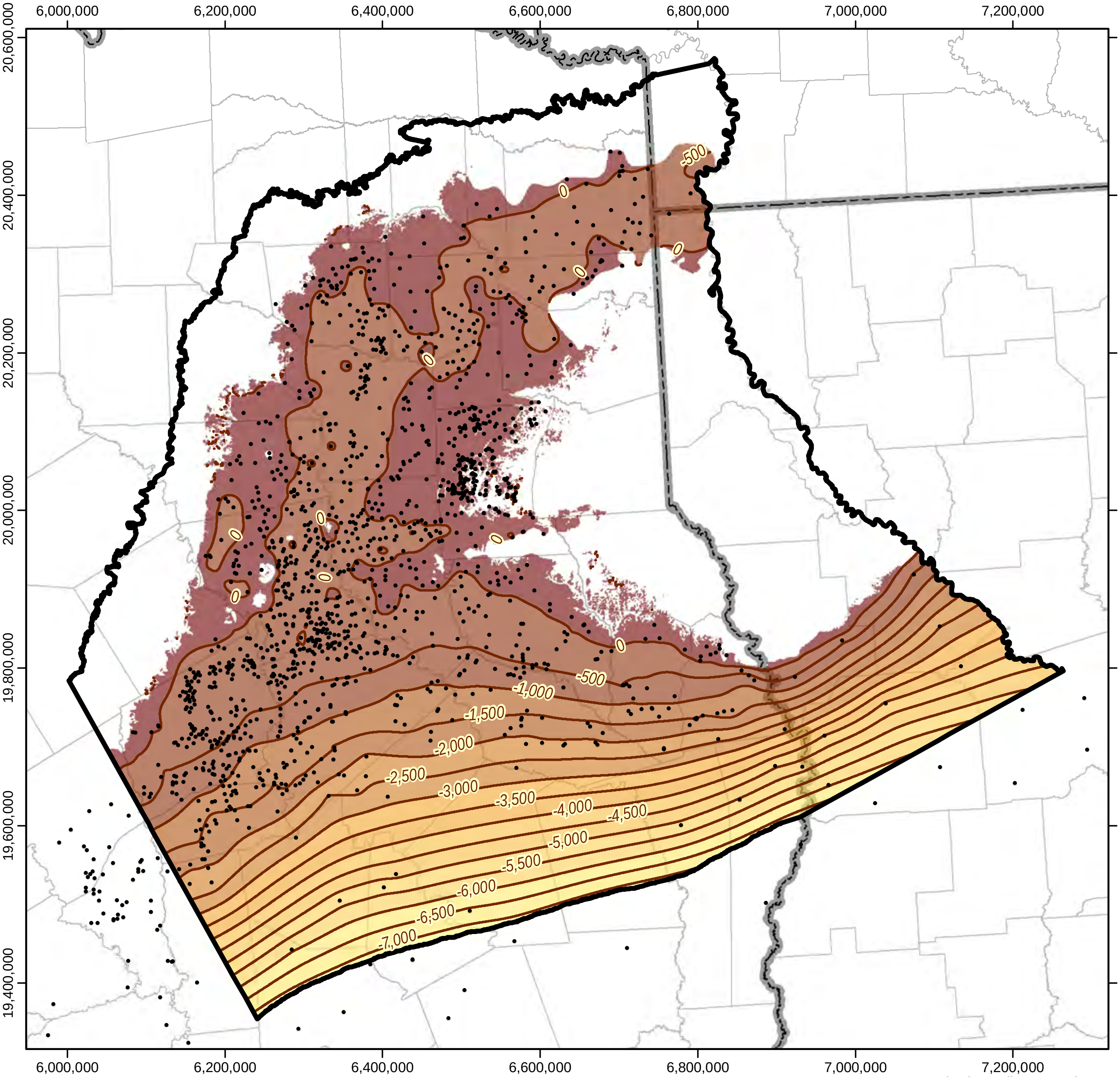


FIGURE 4.1.14. THICKNESS OF REKLAW FORMATION

MONTGOMERY & ASSOCIATES

1480\REPORT_MAPS\Thickness_ReklawFormation.mxd\25June2018

DRAFT

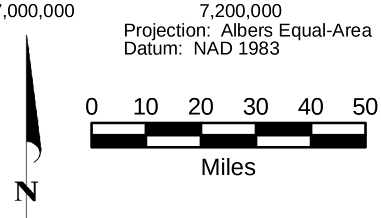


EXPLANATION

- Structure Control Point
- -500 Elevation Contour, feet above mean sea level (amsl)
- Study Area
- County/Parish
- State

Bottom Elevation of Carrizo Sand

- <-7,000
- -7,000 to -6,000
- -6,000 to -5,000
- -5,000 to -4,000
- -4,000 to -3,000
- -3,000 to -2,000
- -2,000 to -1,000
- -1,000 to 0
- 0 to 640



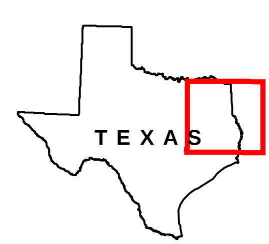
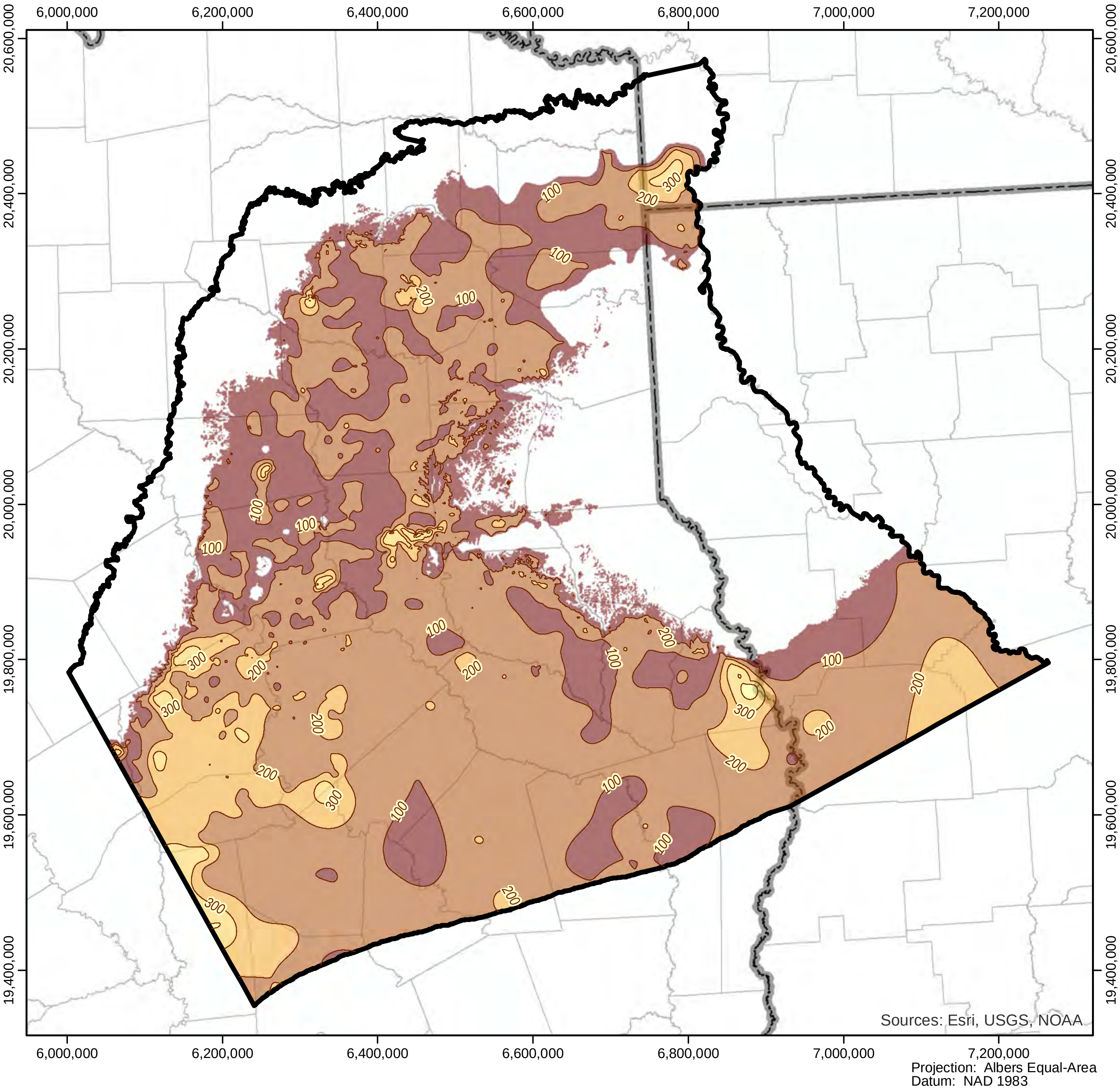


FIGURE 4.1.15. BOTTOM ELEVATION CONTOURS FOR CARRIZO SAND



EXPLANATION

—200— Contour of Unit Thickness, in feet

Study Area

County Boundary

State Boundary

Thickness of Carrizo Sand

<100

100 - 200

200 - 300

300 - 400

400 - 485

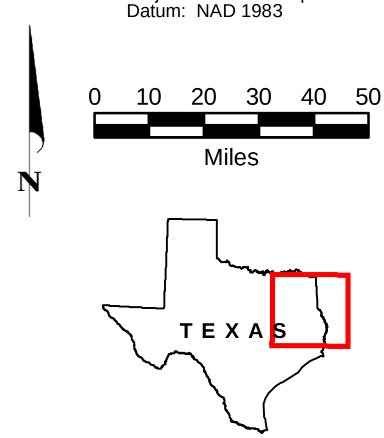


FIGURE 4.1.16. THICKNESS OF CARRIZO SAND

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1480\REPORT_MAPS\Thickness_CarrizoSand.mxd\25June2018

DRAFT

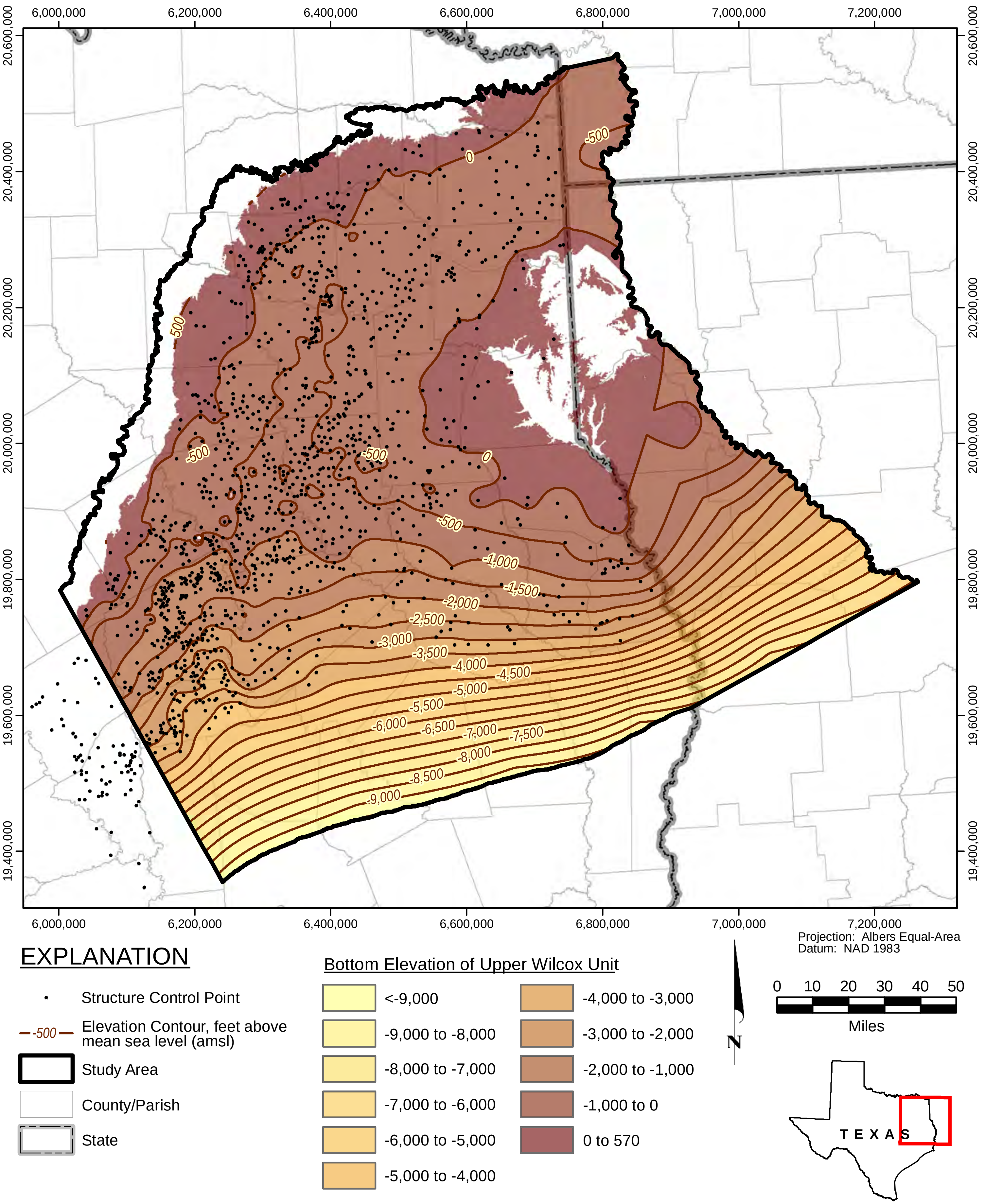

FIGURE 4.1.17. BOTTOM ELEVATION CONTOURS FOR UPPER WILCOX UNIT

1480\REPORT_MAPS\Structure_BottomOfUpperWilcox.mxd\27June2018

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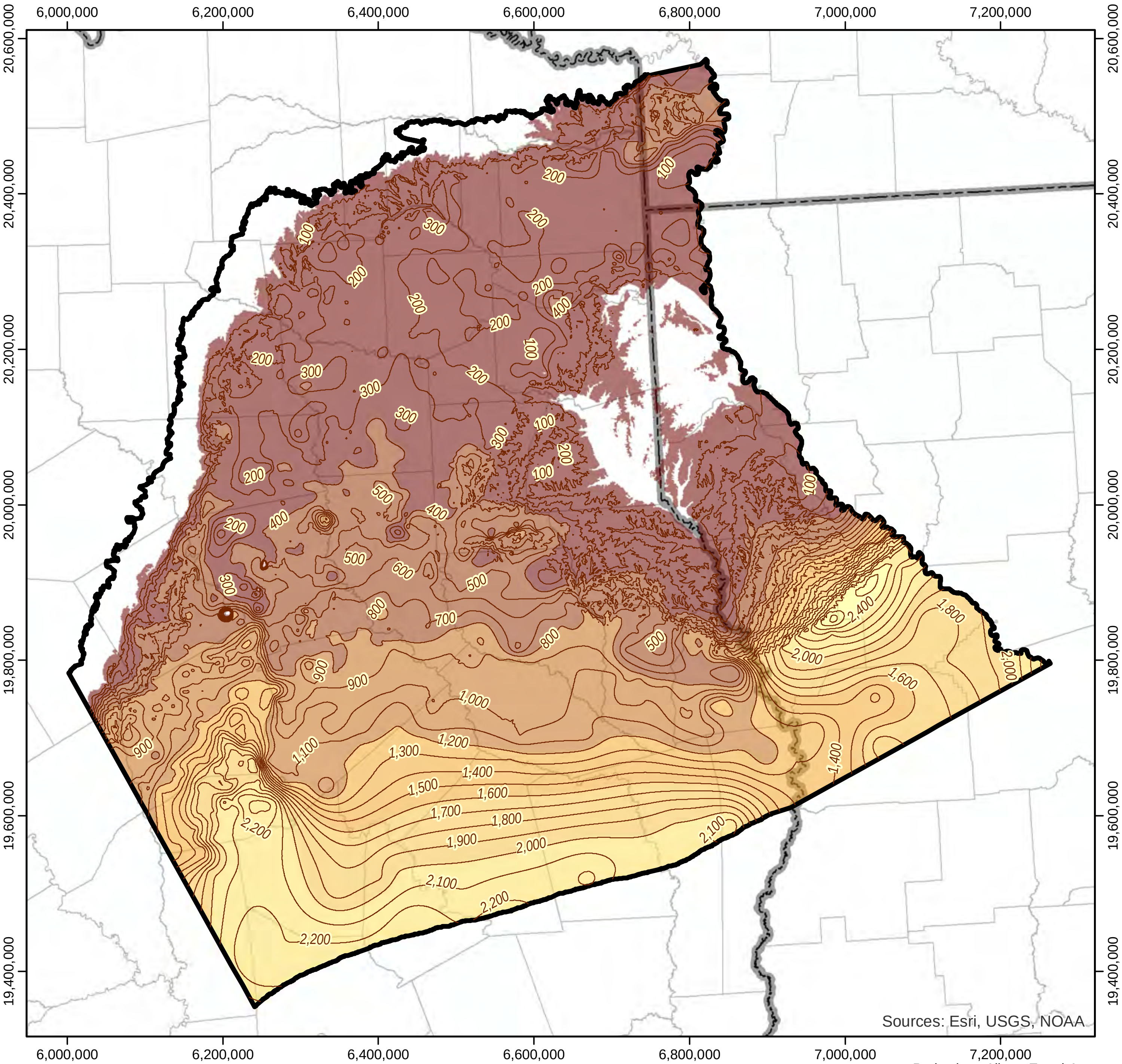
MONTGOMERY & ASSOCIATES



Projection: Albers Equal-Area
Datum: NAD 1983

EXPLANATION

—200—	Contour of Unit Thickness, in feet
	Study Area
	County Boundary
	State Boundary

Thickness of Upper Wilcox Unit

<400	1,600 - 2,000
400 - 800	2,000 - 2,400
800 - 1,200	2,400 - 2,680
1,200 - 1,600	

N

0 10 20 30 40 50
Miles

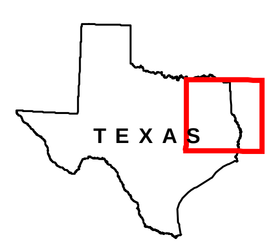


FIGURE 4.1.18. THICKNESS OF UPPER WILCOX UNIT

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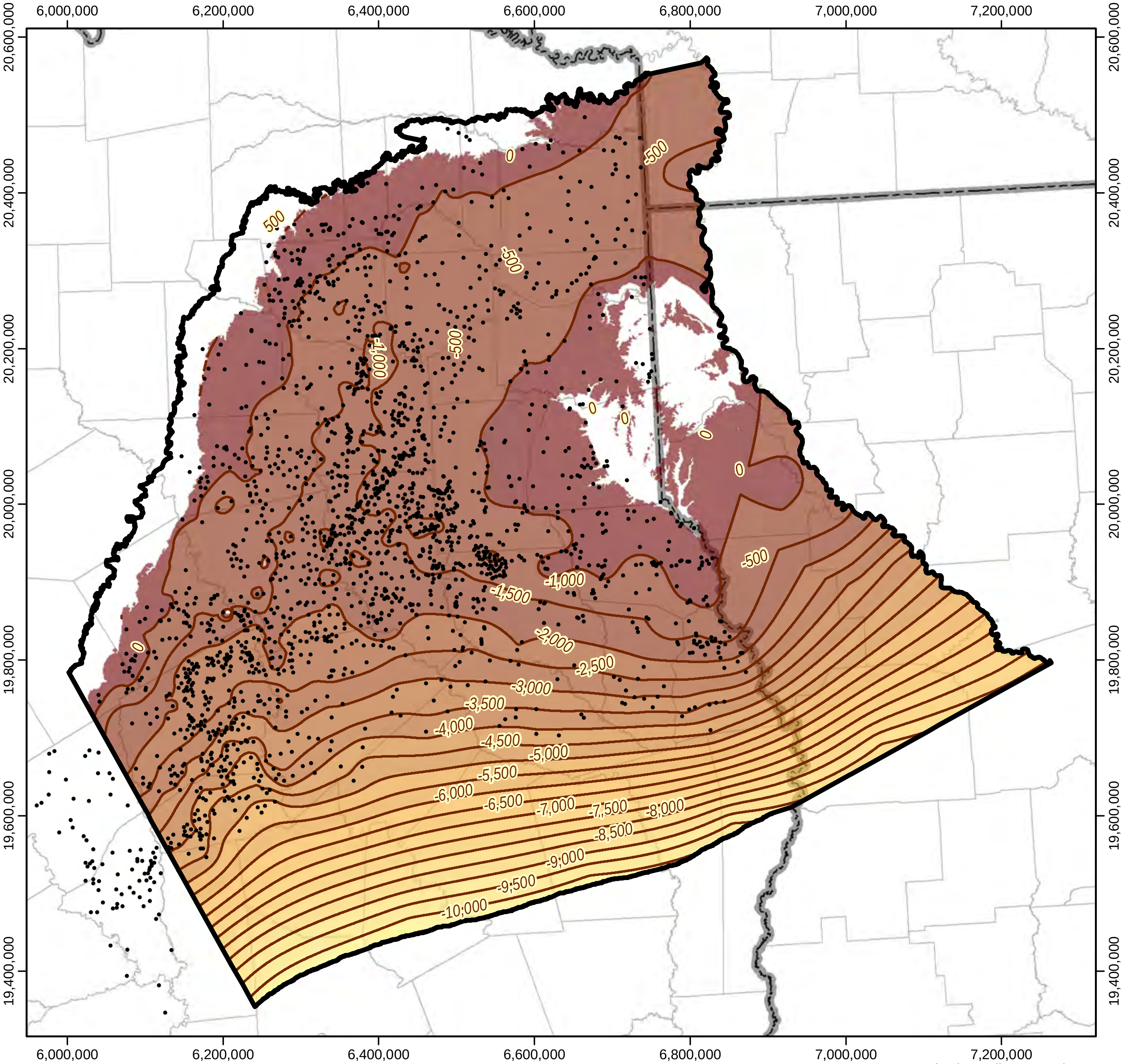
1480\REPORT_MAPS\Thickness_UpperWilcox.mxd\25June2018

DRAFT



EXPLANATION

- Structure Control Point
- -500 Elevation Contour, feet above mean sea level (amsl)
- Study Area
- County/Parish
- State

Bottom Elevation of Middle Wilcox Unit

<-10,000	-5,000 to -4,000
-10,000 to -9,000	-4,000 to -3,000
-9,000 to -8,000	-3,000 to -2,000
-8,000 to -7,000	-2,000 to -1,000
-7,000 to -6,000	-1,000 to 0
-6,000 to -5,000	0 to 565

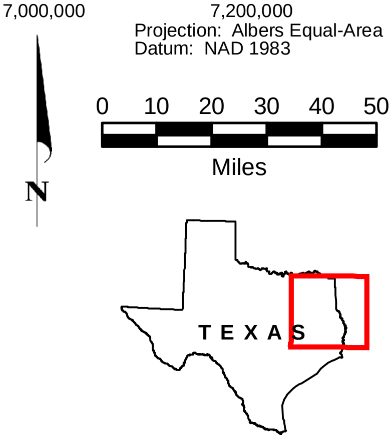


FIGURE 4.1.19. BOTTOM ELEVATION CONTOURS FOR MIDDLE WILCOX UNIT

1480\REPORT_MAPS\Structure_BottomOfMiddleWilcox.mxd\27June2018

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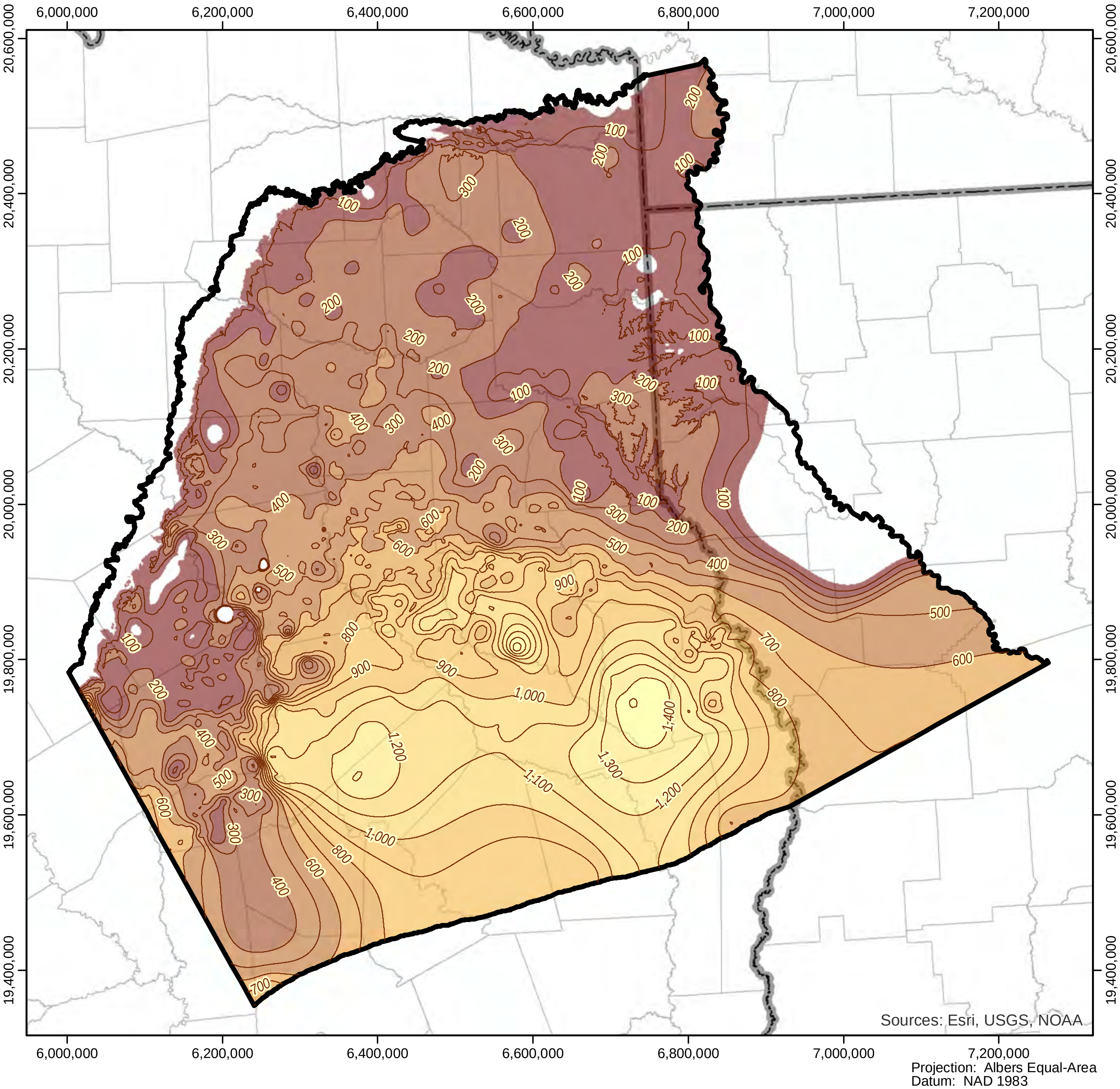
MONTGOMERY & ASSOCIATES



Projection: Albers Equal-Area
Datum: NAD 1983

EXPLANATION

200	Contour of Unit Thickness, in feet
	Study Area
	County Boundary
	State Boundary

Thickness of Middle Wilcox Unit

<200	800 - 1,000
200 - 400	1,000 - 1,200
400 - 600	1,200 - 1,400
600 - 800	1,400 - 1,560

N

0 10 20 30 40 50
Miles

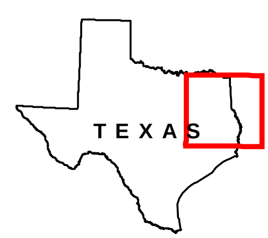


FIGURE 4.1.20. THICKNESS OF MIDDLE WILCOX UNIT

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1480\REPORT_MAPS\Thickness_MiddleWilcox.mxd\25June2018

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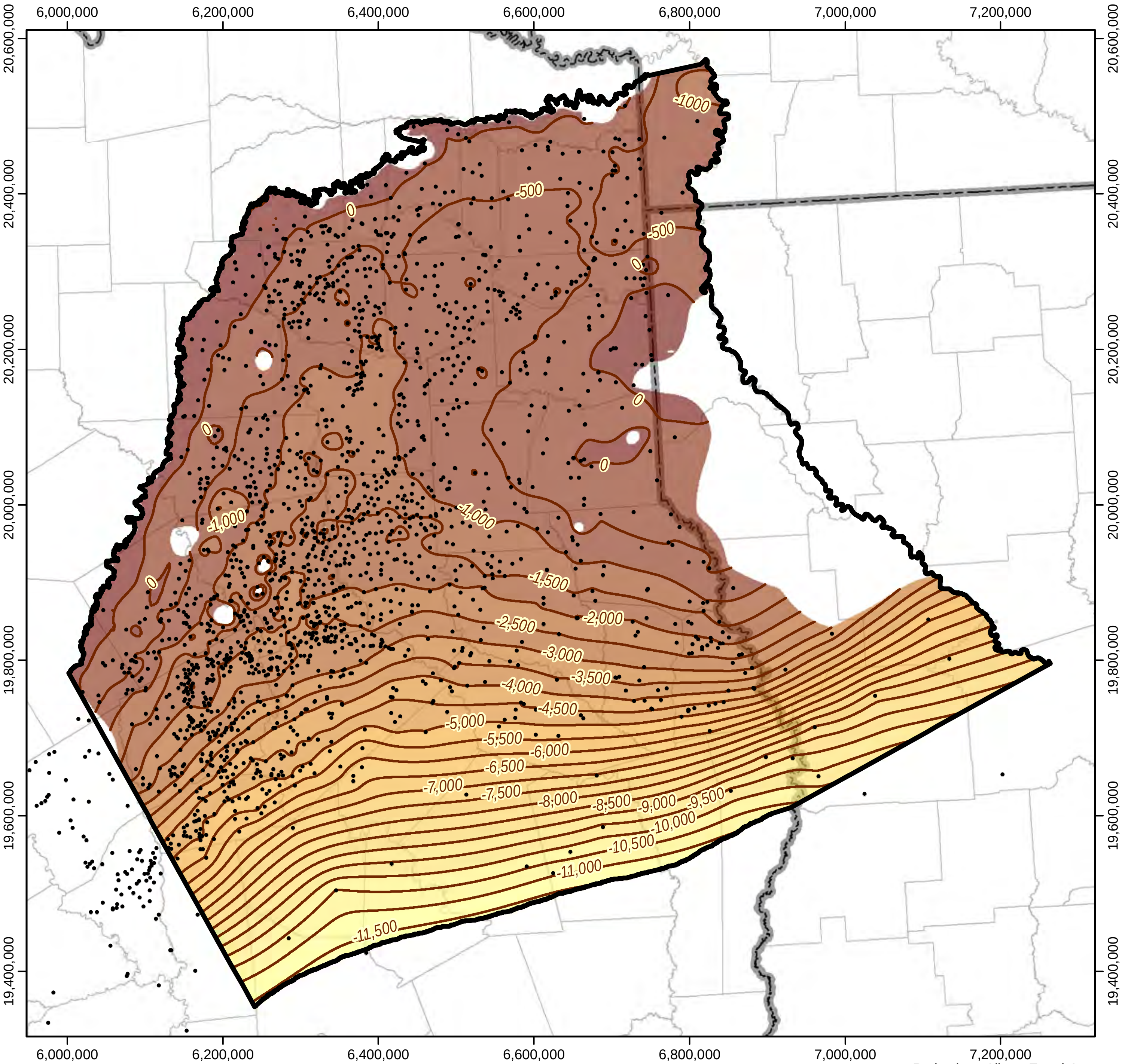

Projection: Albers Equal-Area
Datum: NAD 1983

EXPLANATION

- Structure Control Point
- -500 Elevation Contour, feet above mean sea level (amsl)
- Study Area
- County/Parish
- State

Bottom Elevation of Lower Wilcox Unit

<-11,000	-5,000 to -4,000
-11,000 to -10,000	-4,000 to -3,000
-10,000 to -9,000	-3,000 to -2,000
-9,000 to -8,000	-2,000 to -1,000
-8,000 to -7,000	-1,000 to 0
-7,000 to -6,000	0 to 565
-6,000 to -5,000	

N

0 10 20 30 40 50
Miles

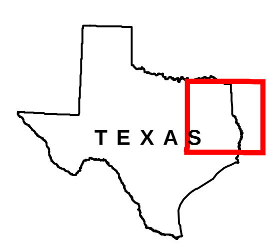

FIGURE 4.1.21. BOTTOM ELEVATION CONTOURS FOR LOWER WILCOX UNIT

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1480\REPORT_MAPS\Structure_BottomOfLowerWilcox.mxd\25June2018

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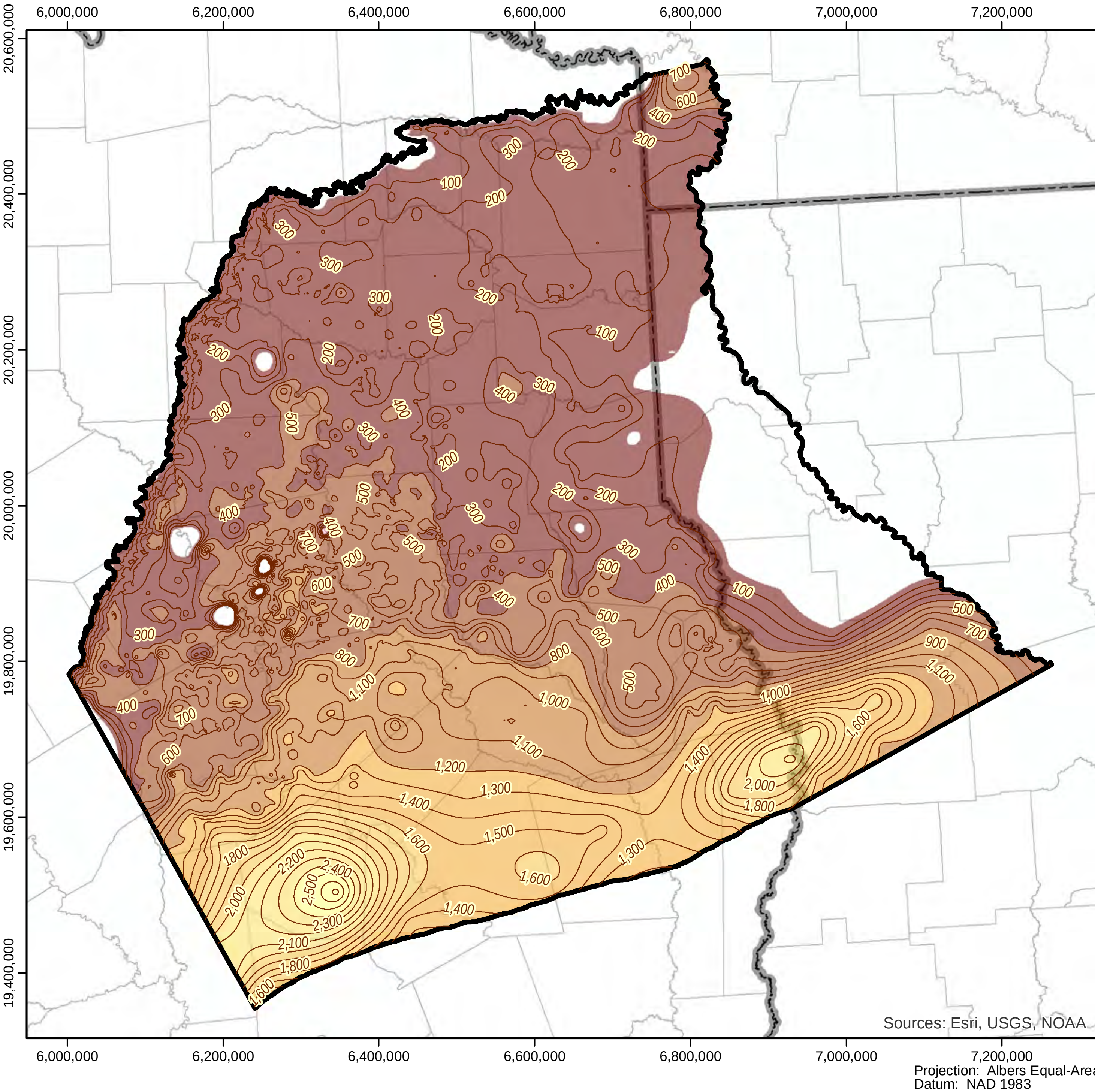
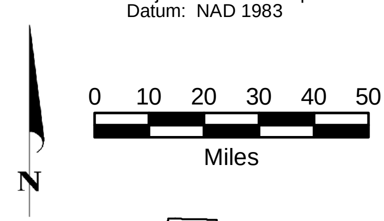


EXPLANATION

200	Contour of Unit Thickness, in feet
	Study Area
	County Boundary
	State Boundary

Thickness of Lower Wilcox Unit

<400	1,600 - 2,000
400 - 800	2,000 - 2,400
800 - 1,200	2,400 - 2,735
1,200 - 1,600	



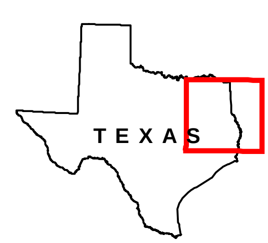


FIGURE 4.1.22. THICKNESS OF LOWER WILCOX UNIT

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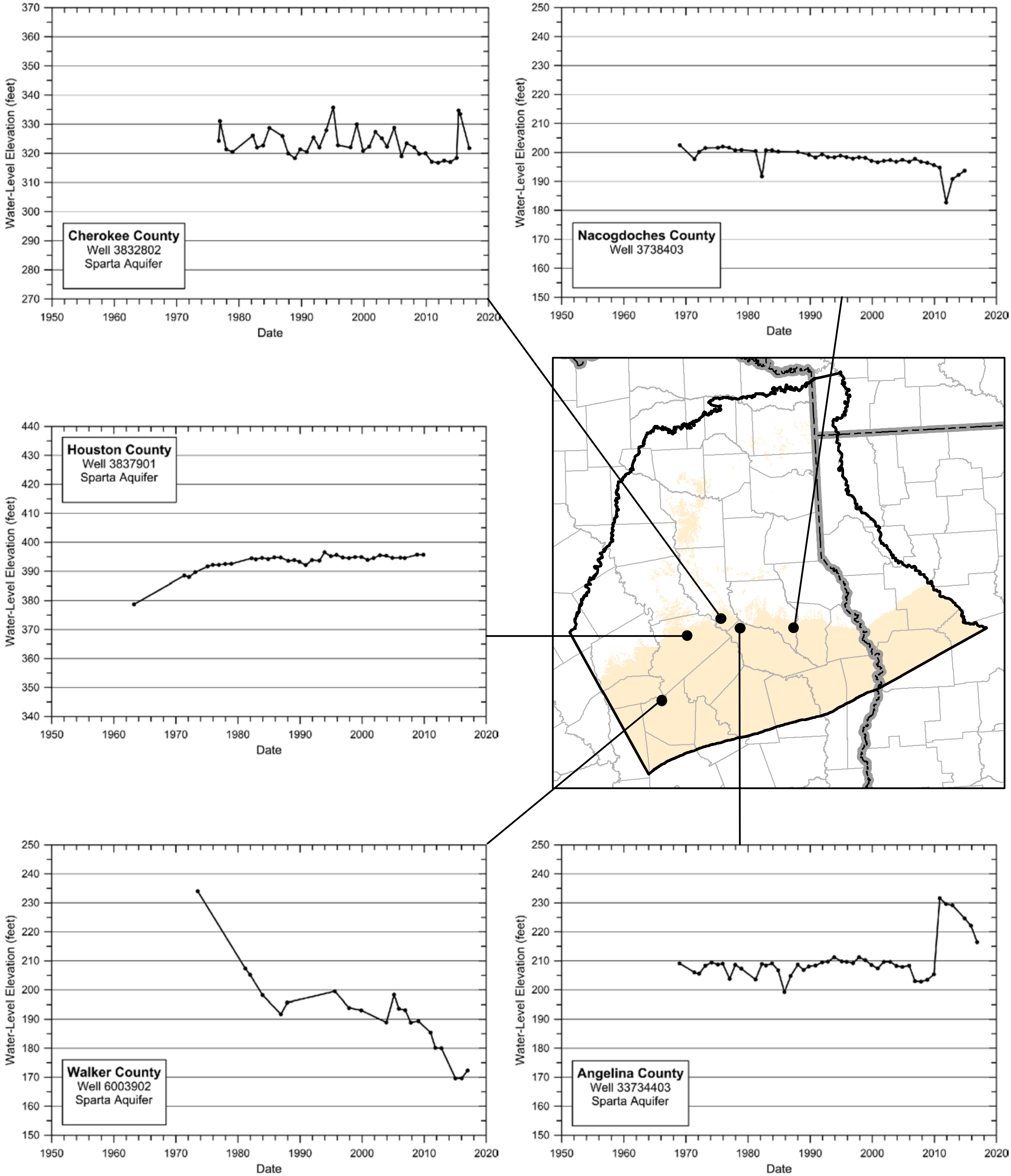

FIGURE 4.2.13. SELECTED GROUNDWATER LEVEL ELEVATION HYDROGRAPHS FOR SPARTA AQUIFER

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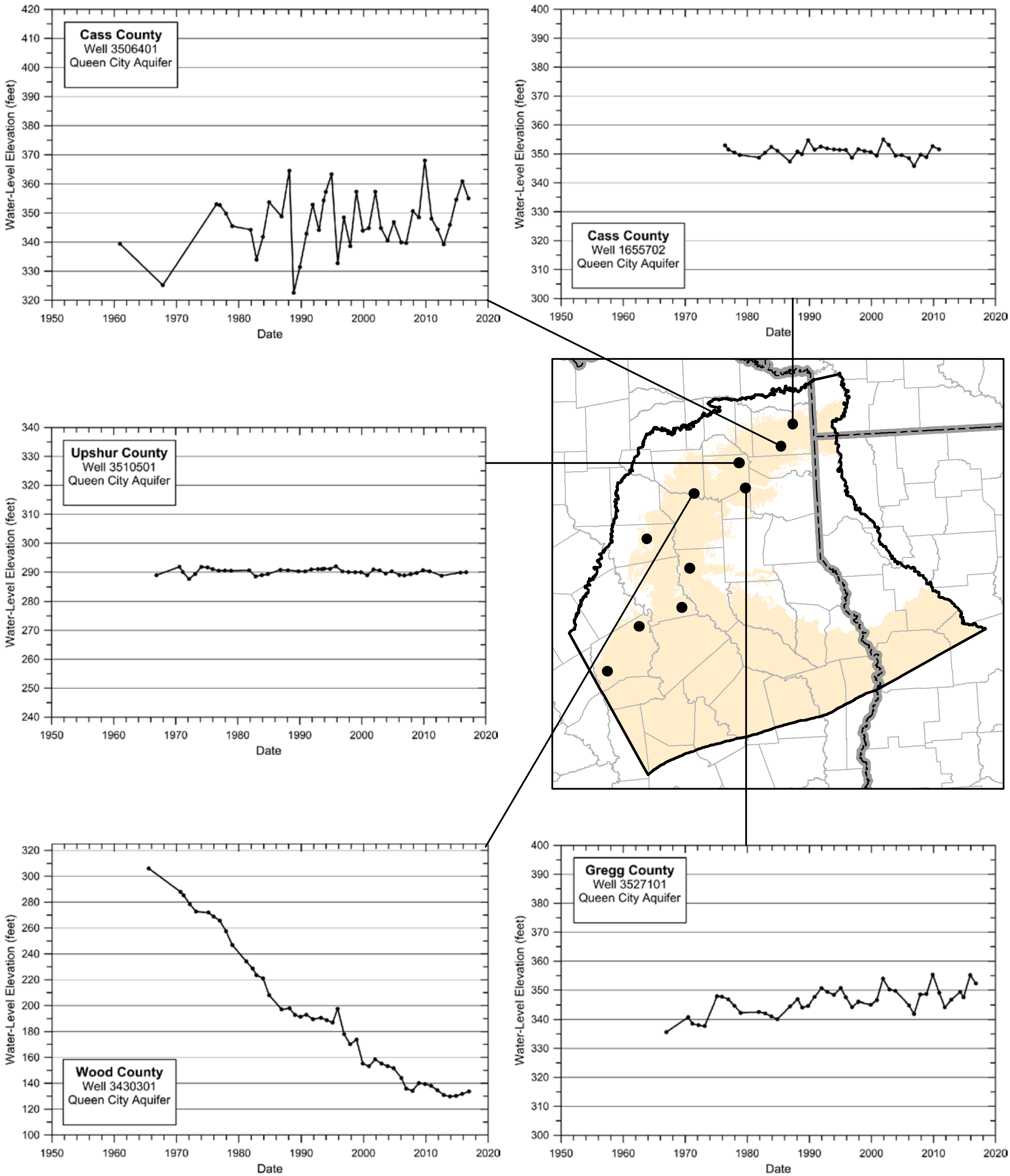

FIGURE 4.2.14. SELECTED GROUNDWATER LEVEL ELEVATION HYDROGRAPHS FOR QUEEN CITY AQUIFER IN NORTHERN PORTION OF STUDY AREA

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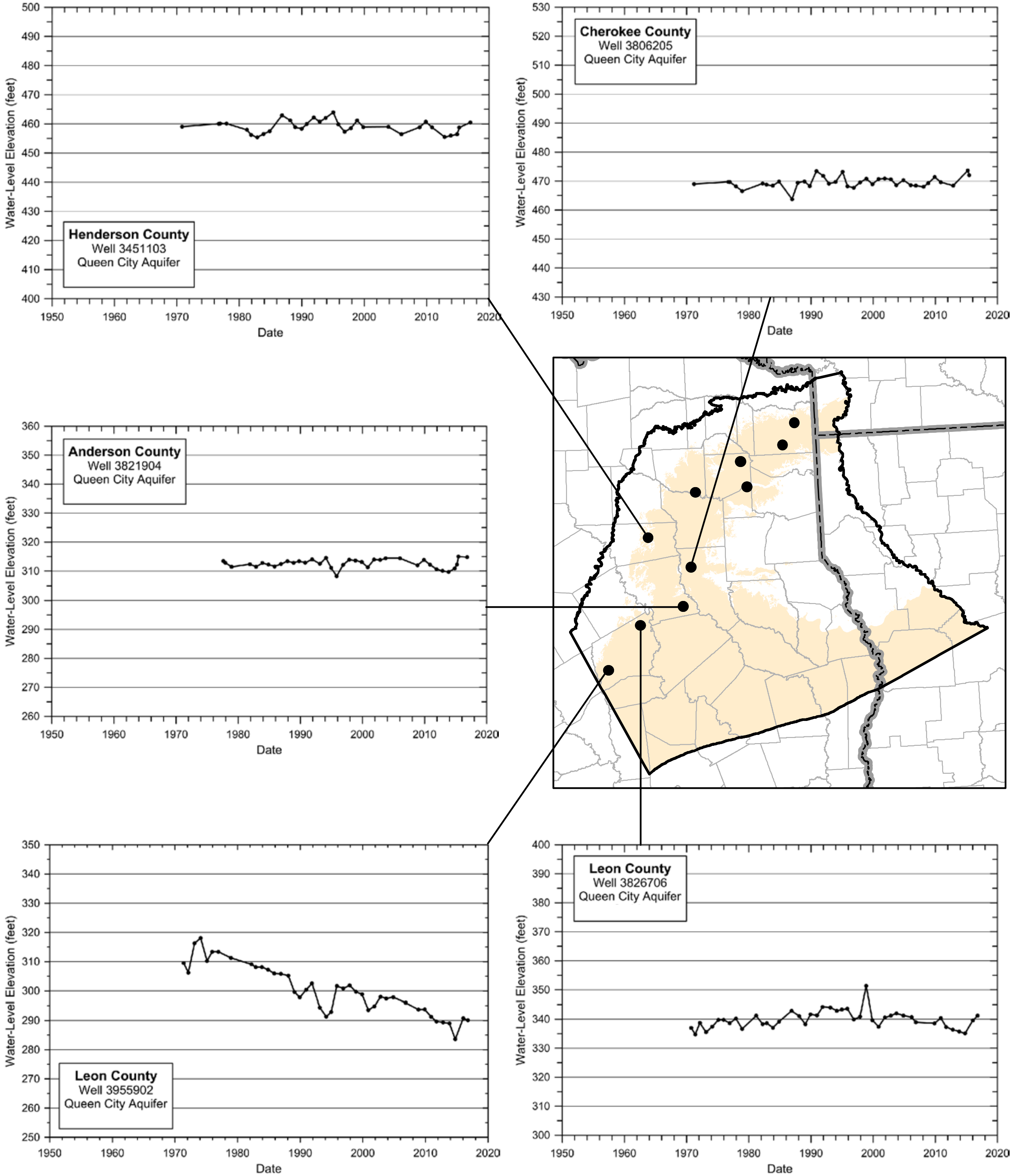

FIGURE 4.2.15. SELECTED GROUNDWATER LEVEL ELEVATION HYDROGRAPHS FOR QUEEN CITY AQUIFER IN SOUTHERN PORTION OF STUDY AREA

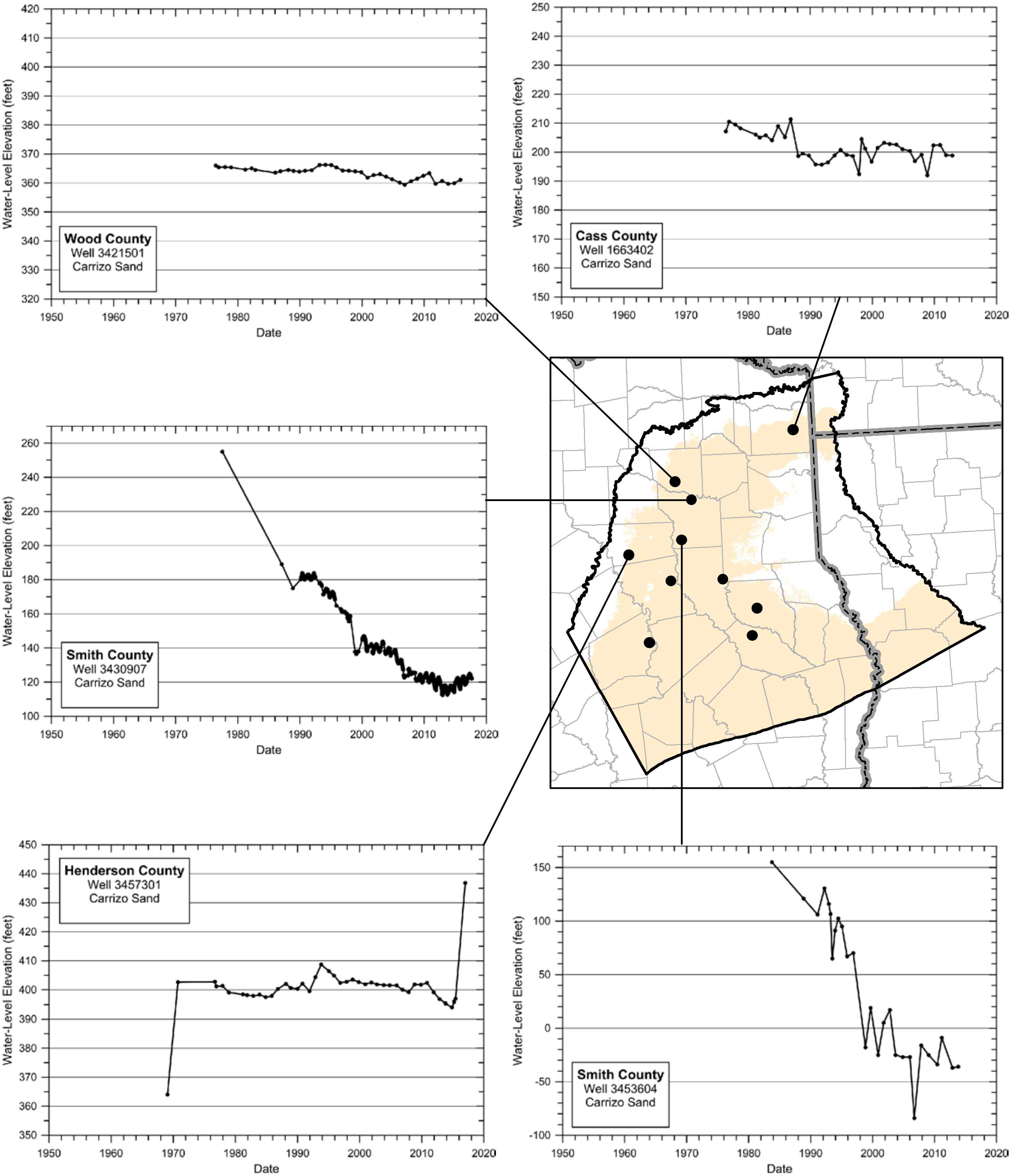

FIGURE 4.2.16. SELECTED GROUNDWATER LEVEL ELEVATION HYDROGRAPHS FOR CARRIZO AQUIFER IN NORTHERN PORTION OF STUDY AREA

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1480\REPORT_MAPS\Hydrographs_CarrizoNorth.mxd\25June2018

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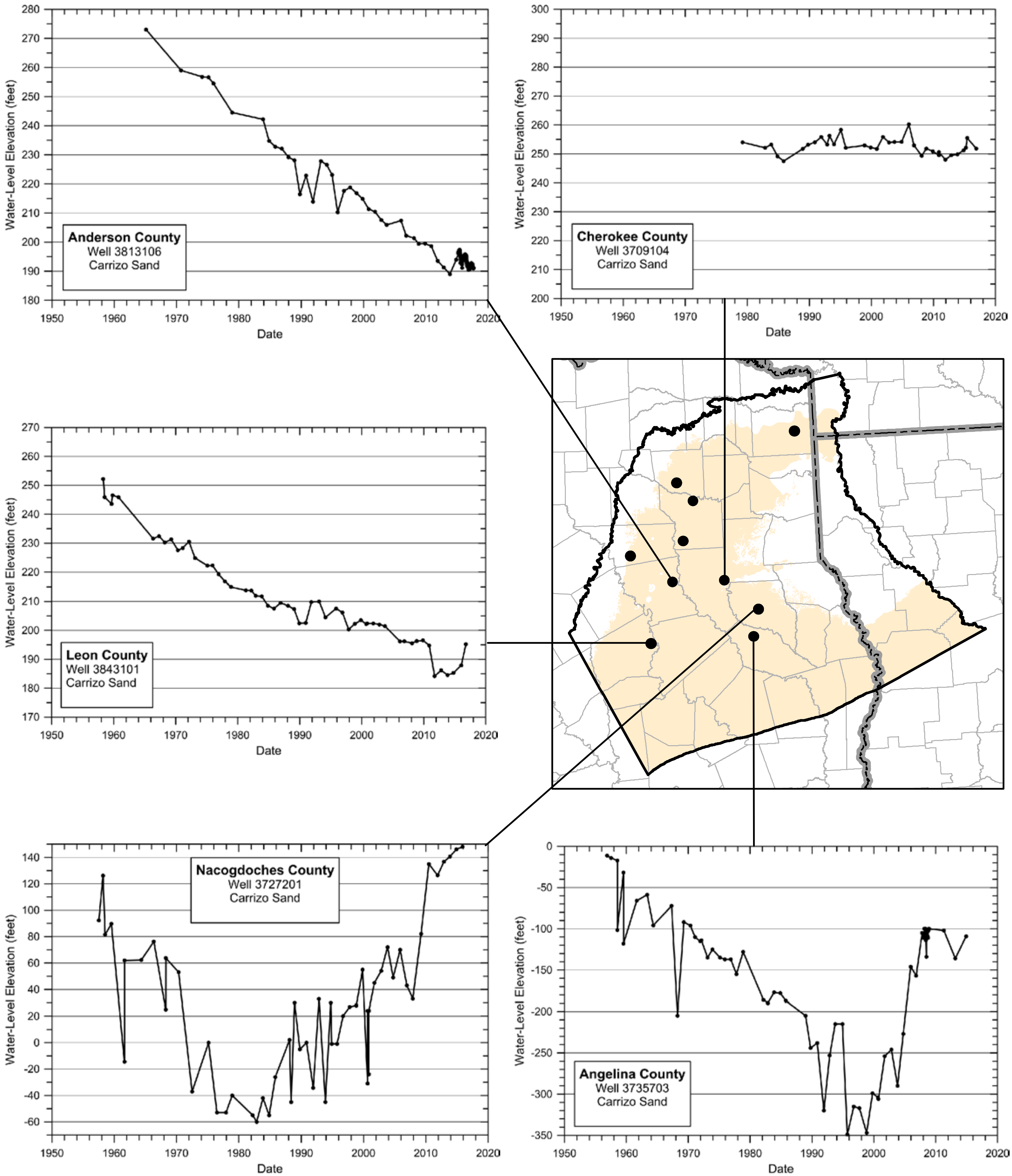

FIGURE 4.2.17. SELECTED GROUNDWATER LEVEL ELEVATION HYDROGRAPHS FOR CARRIZO AQUIFER IN SOUTHERN PORTION OF STUDY AREA

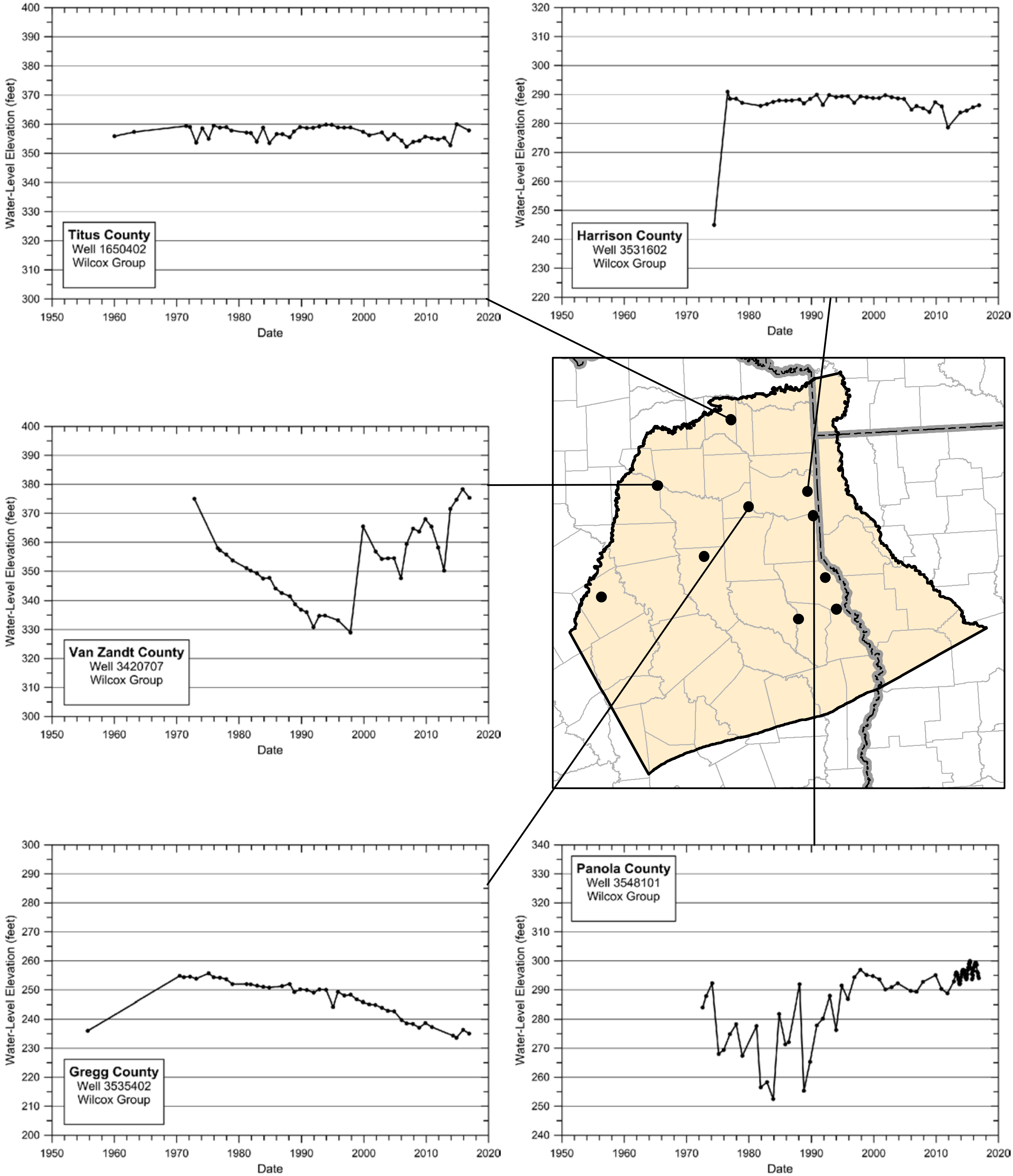

FIGURE 4.2.18. SELECTED GROUNDWATER LEVEL ELEVATION HYDROGRAPHS FOR WILCOX AQUIFER IN NORTHERN PORTION OF STUDY AREA

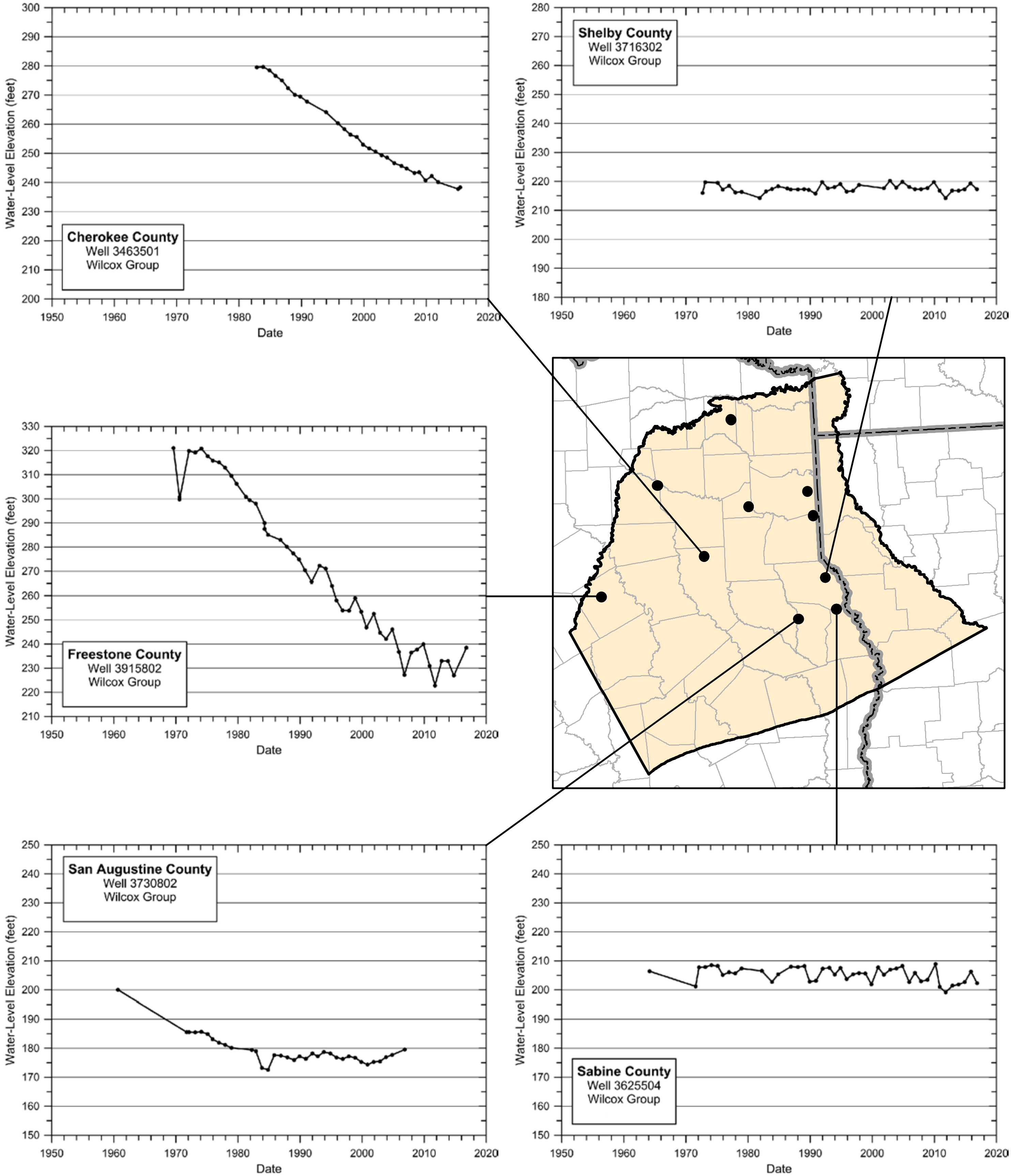

FIGURE 4.2.19. SELECTED GROUNDWATER LEVEL ELEVATIONS HYDROGRAPHS FOR WILCOX AQUIFER IN SOUTHERN PORTION OF STUDY AREA

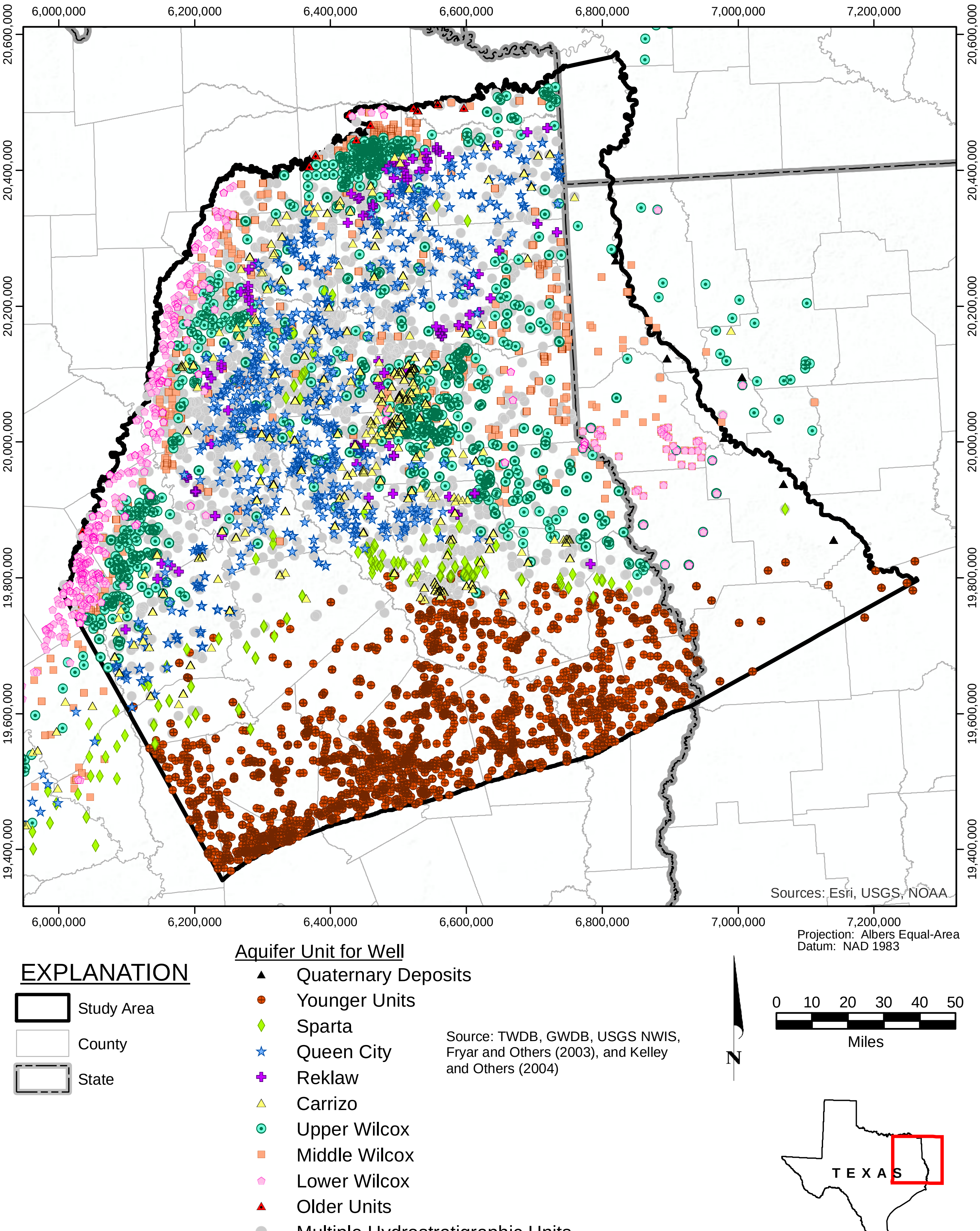

FIGURE 4.2.1. LOCATION OF WELLS WITH GROUNDWATER LEVEL MEASUREMENTS

1480\REPORT_MAPS\WL_Measurements_All.mxd\25June2018

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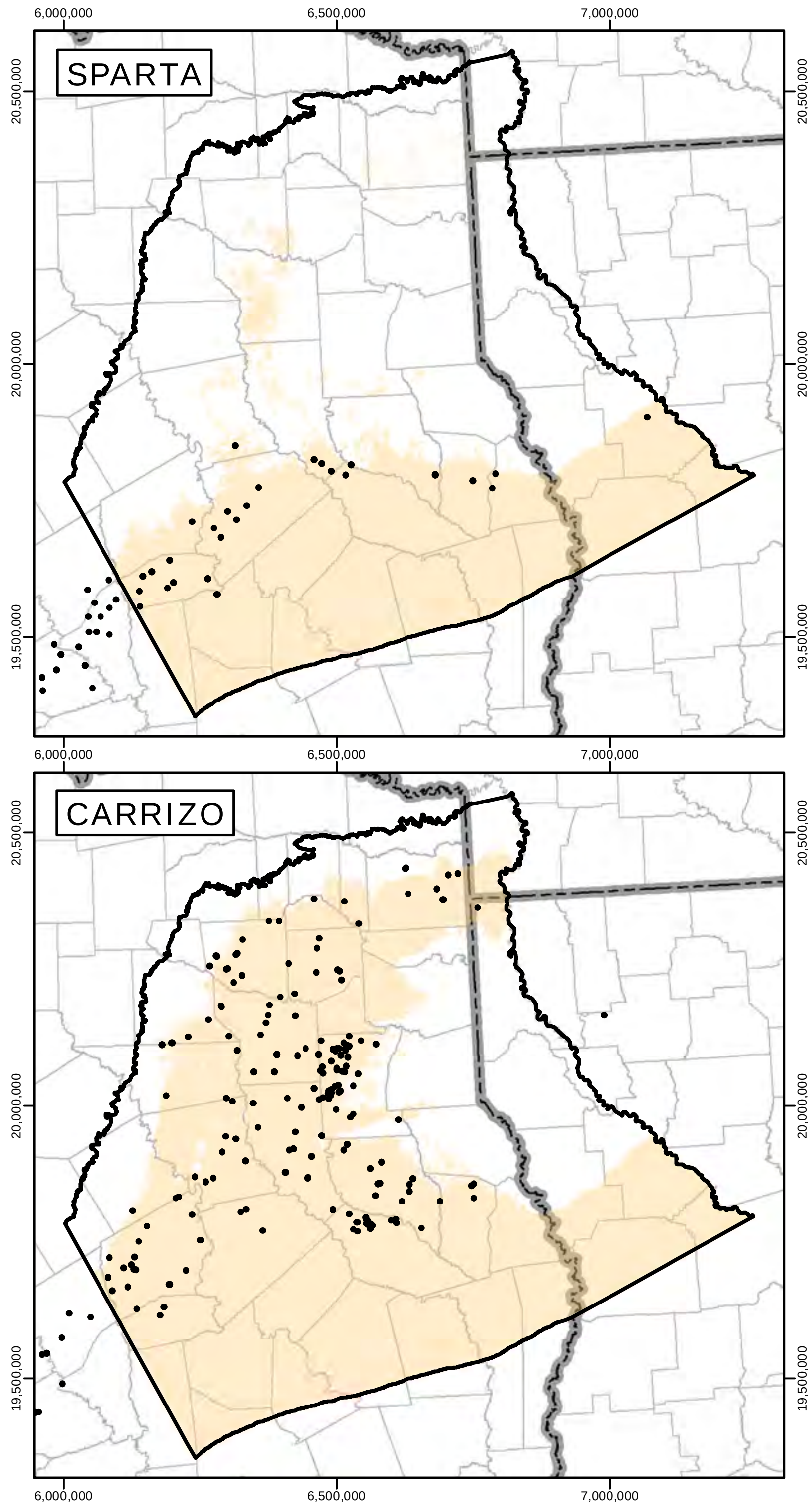

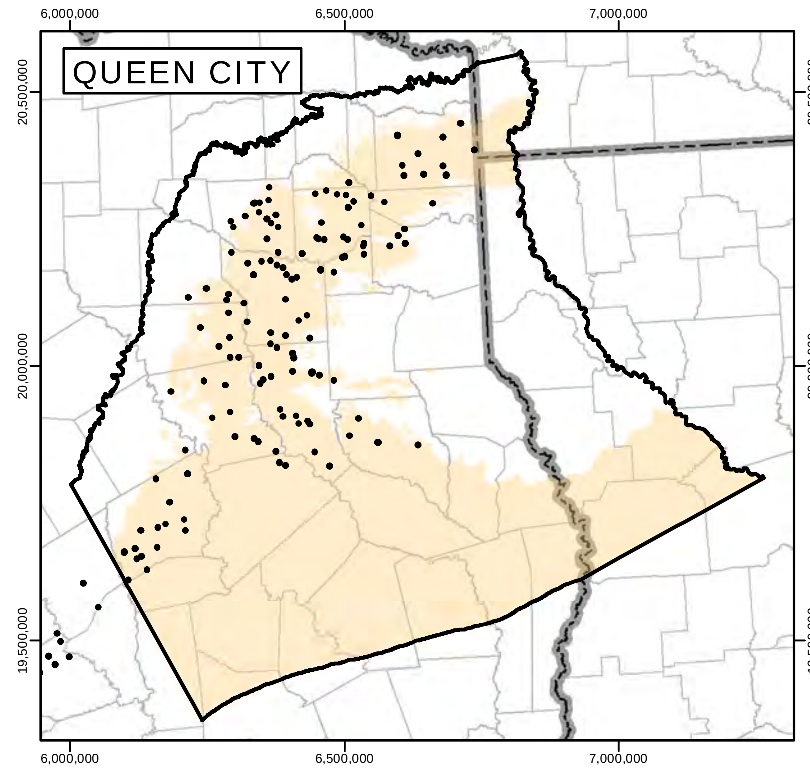

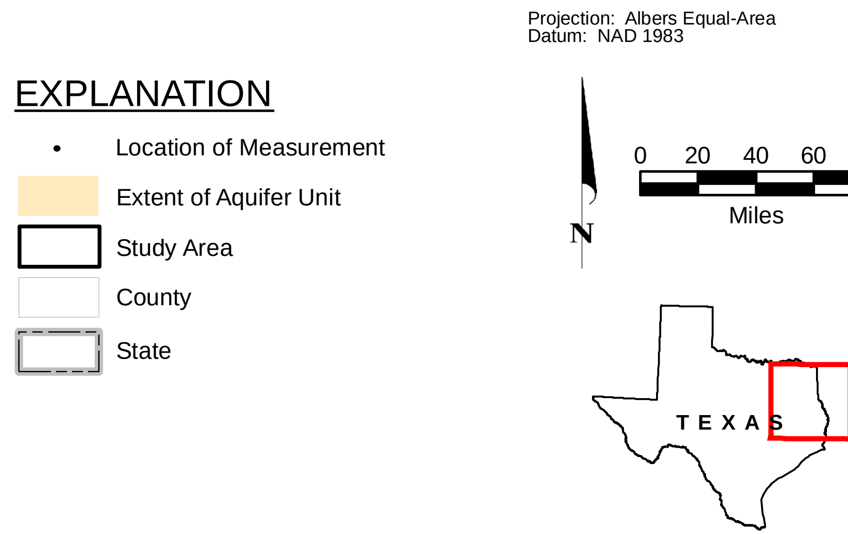

FIGURE 4.2.2. LOCATIONS OF SELECTED GROUNDWATER LEVEL MEASUREMENTS FOR SPARTA, QUEEN CITY, AND CARRIZO AQUIFERS

1480\REPORT_MAPS\WL_Measurements_Sparta_QueenCity_CarrizoSand.mxd\
26June2018

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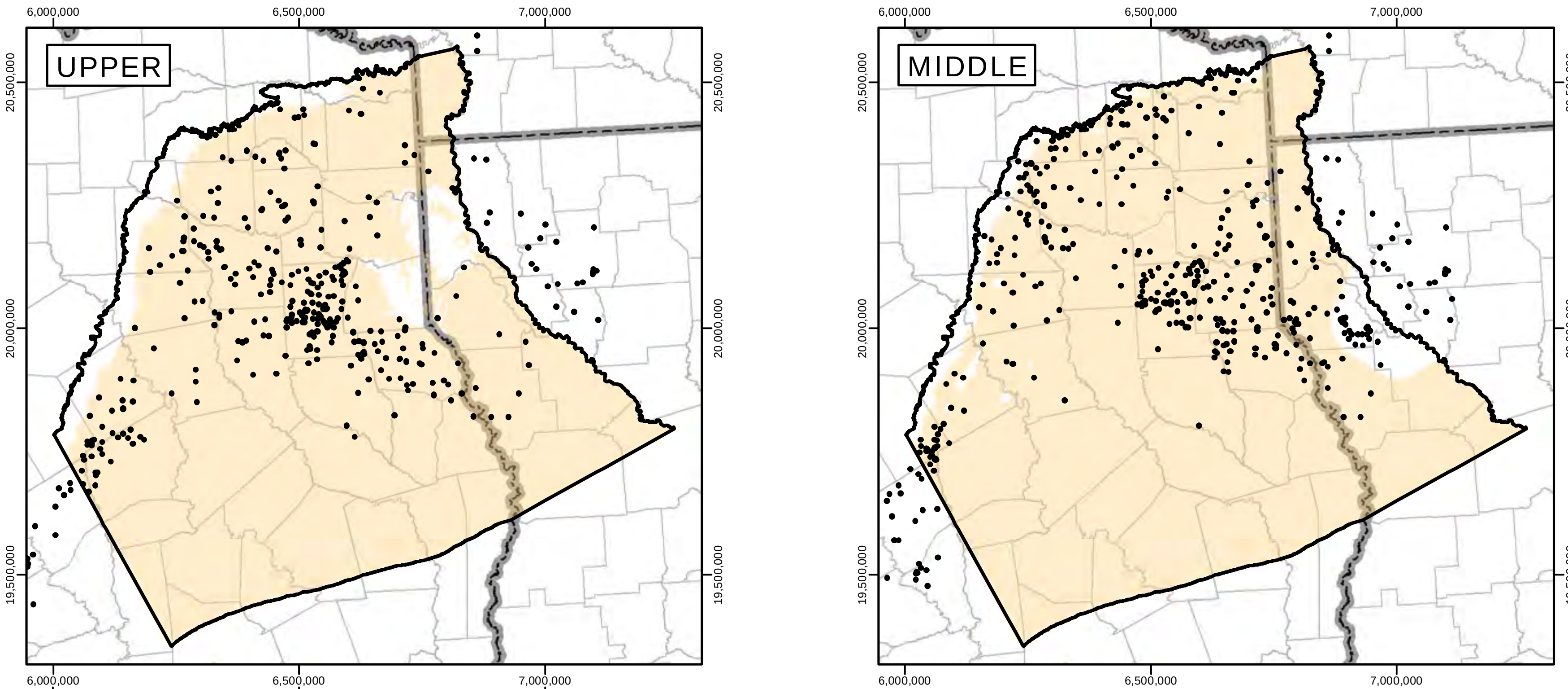

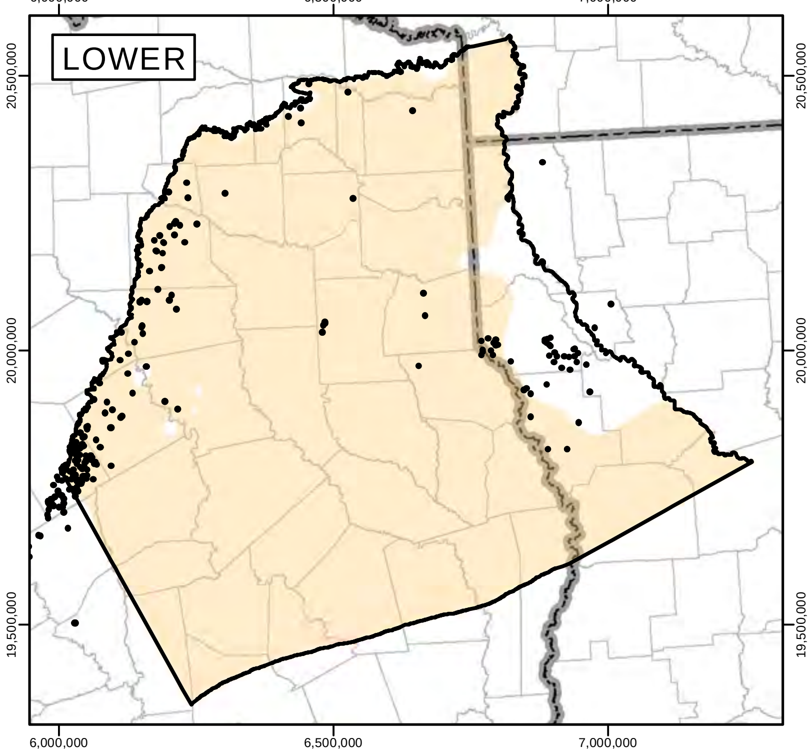

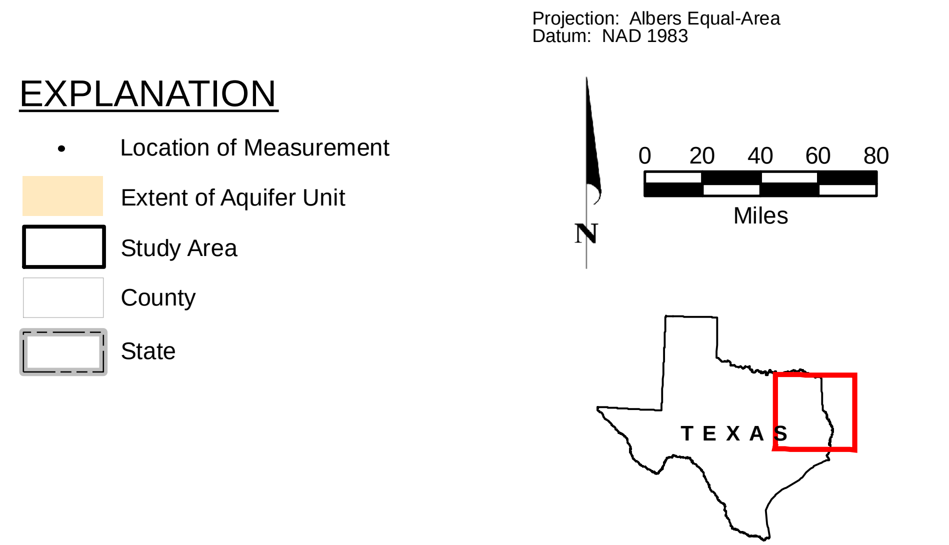

FIGURE 4.2.3. LOCATIONS OF SELECTED GROUNDWATER LEVEL MEASUREMENTS FOR UPPER, MIDDLE, AND LOWER WILCOX AQUIFERS

1480\REPORT_MAPS\WL_Measurements_Upper_Middle_LowerWilcox.mxd\ 26June2018

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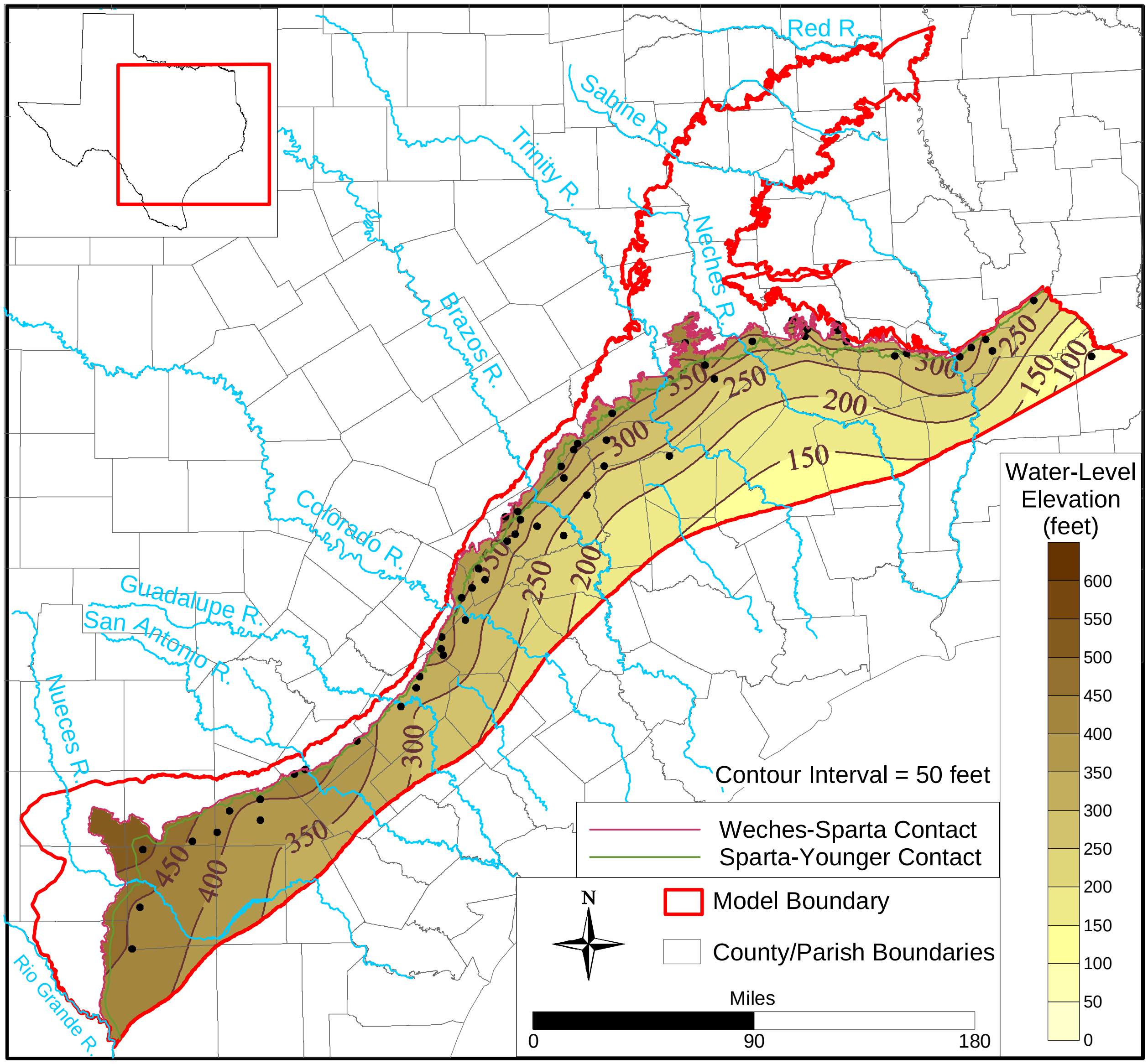

Source: Figure 4.4.8 from final report for Groundwater Availability Models for the Queen City and Sparta Aquifers (Kelley and others, 2004)

FIGURE 4.2.4. ESTIMATED GROUNDWATER LEVEL ELEVATION CONTOURS FOR PREDEVELOPMENT CONDITIONS IN THE ENTIRE SPARTA AQUIFER

GIS\1480\ReportMaps\QCSP_EstimatedGWelevContours_Predevelop_SpartaAquif.pdf\26June2018

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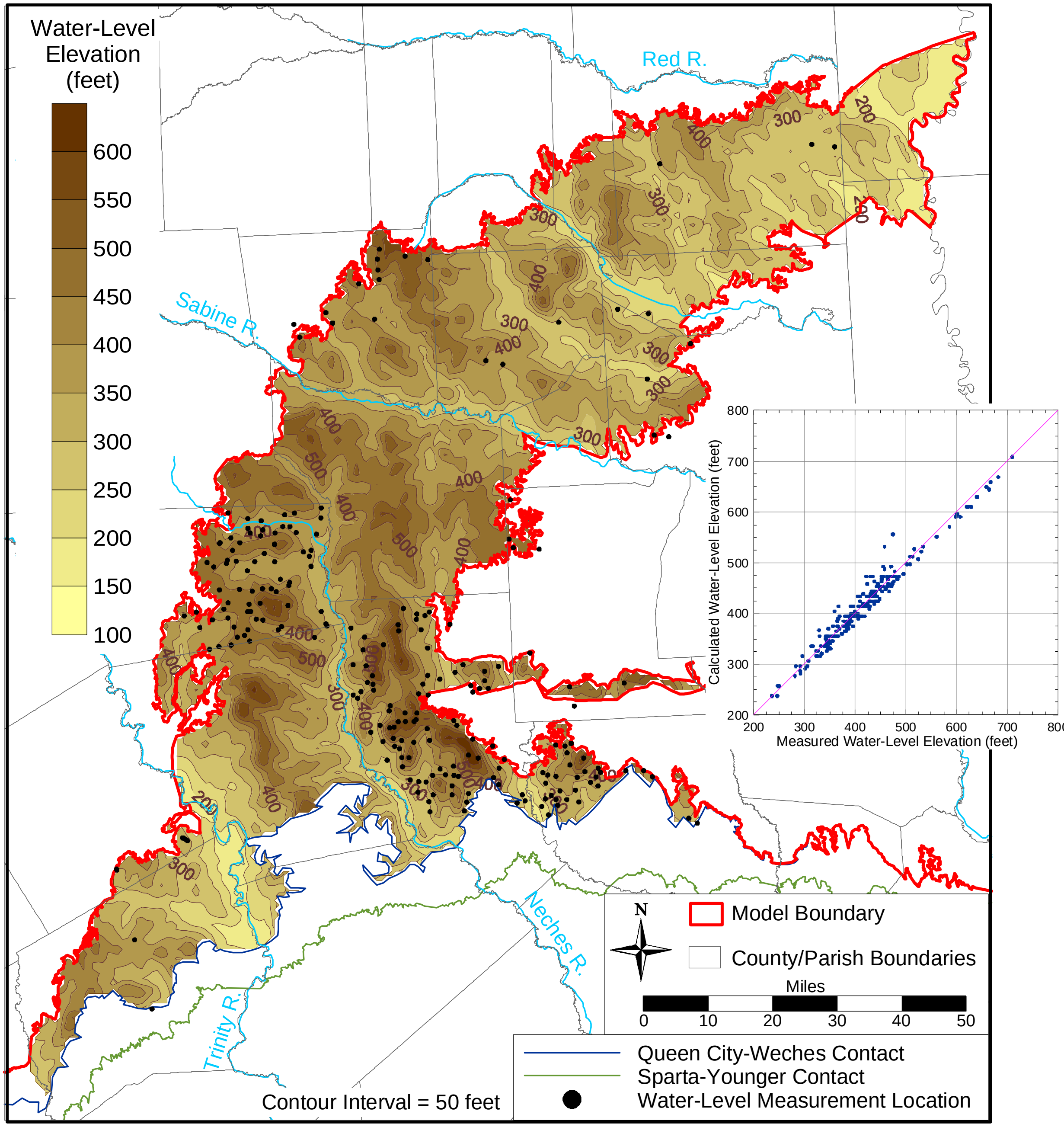
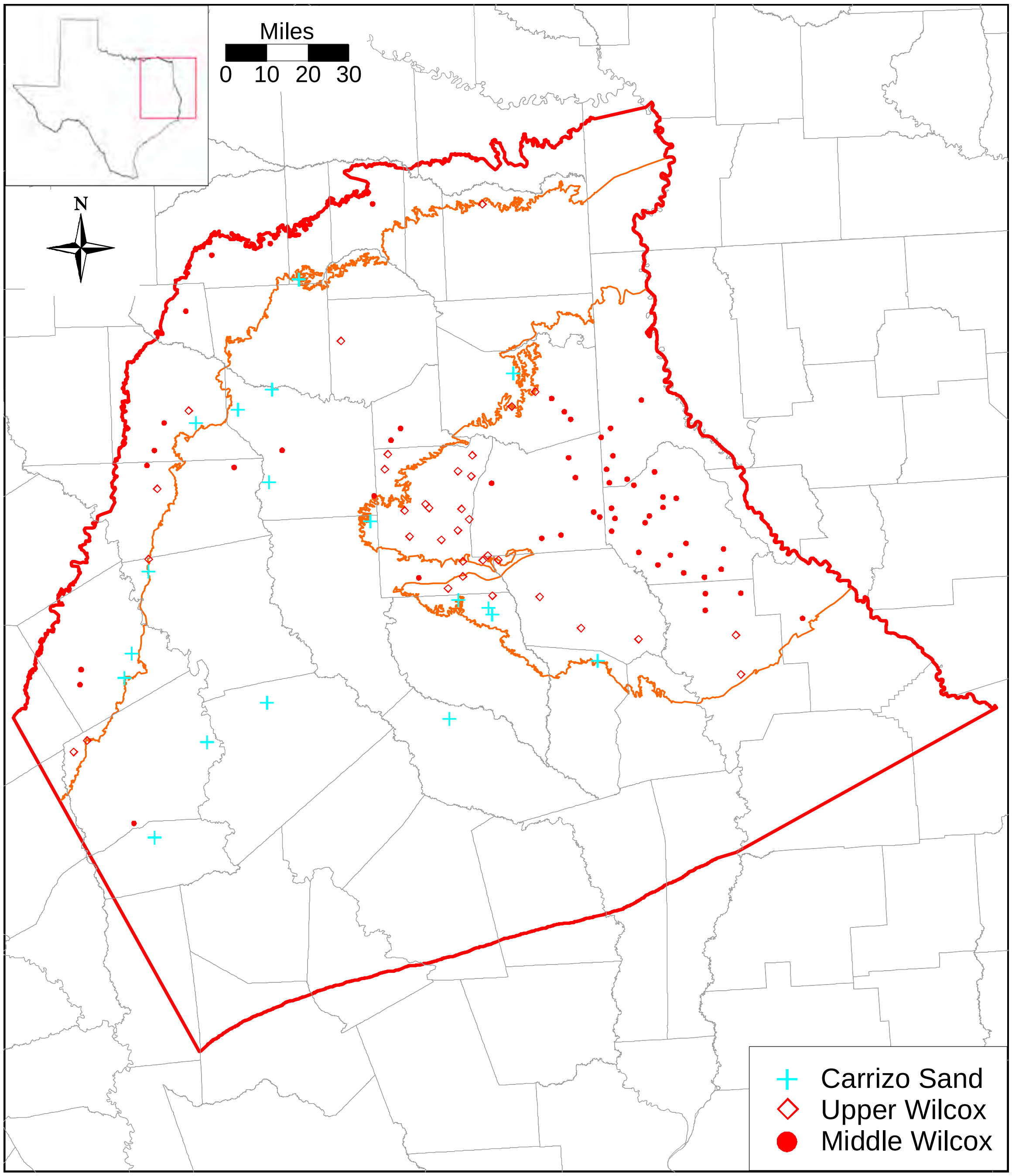


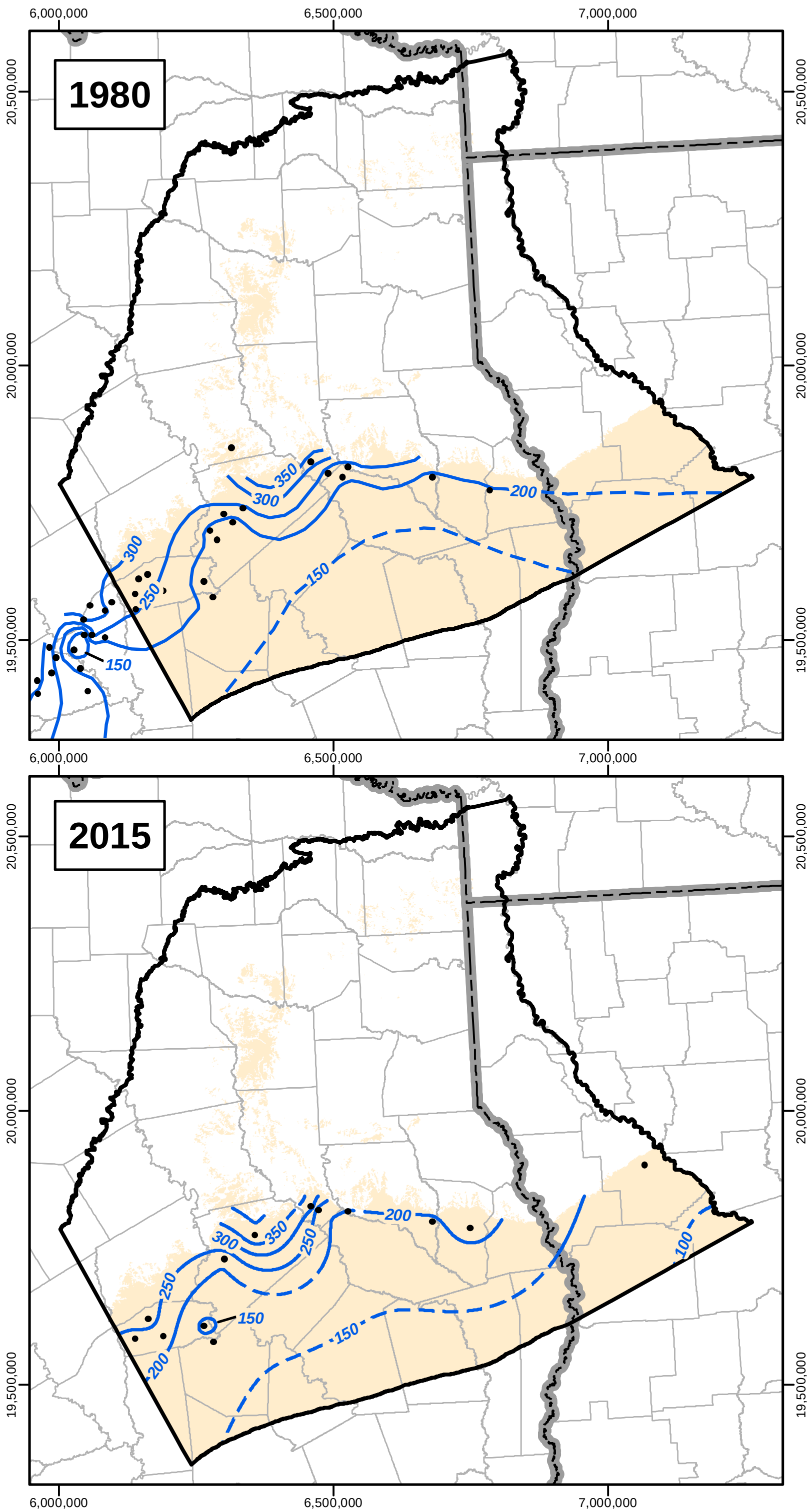
Source: Figure 4.4.5 from final report for Groundwater Availability Models for the Queen City and Sparta Aquifers (Kelley and others, 2004)

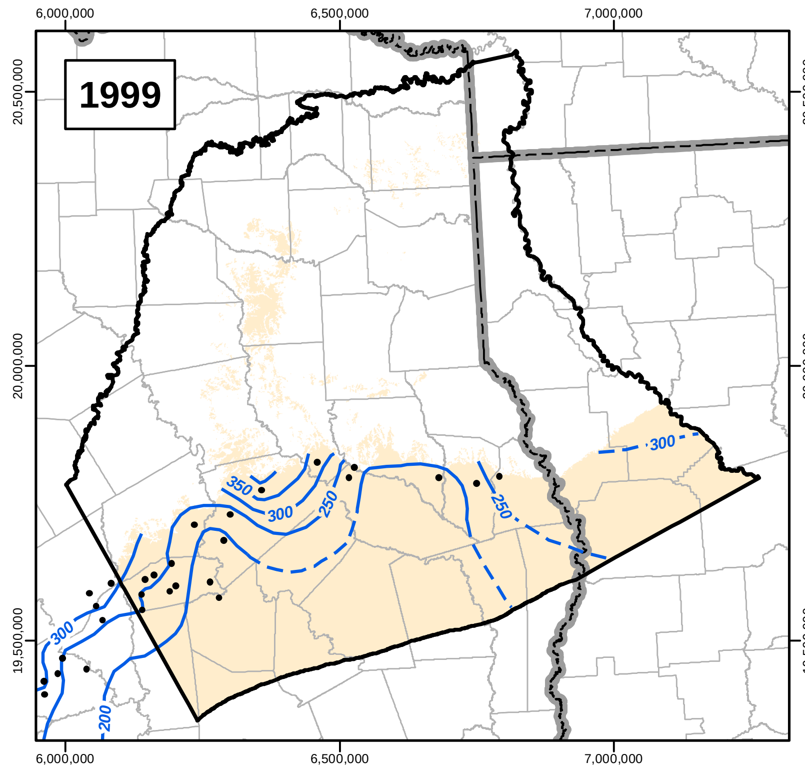
FIGURE 4.2.5. ESTIMATED GROUNDWATER LEVEL ELEVATION CONTOURS FOR PREDEVELOPMENT CONDITIONS IN THE NORTHERN PORTION OF THE QUEEN CITY AQUIFER



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

FIGURE 4.2.6. LOCATION AND AQUIFER UNIT FOR PREDEVELOPMENT GROUNDWATER LEVEL ELEVATION TARGETS IN CARRIZO-WILCOX AQUIFER





Projection: Albers Equal-Area
Datum: NAD 1983

EXPLANATION

- Location of Measurement
- × Approximated Value
- 50 Groundwater Level Elevation Contour, in feet amsl (dashed where approximate)
- Extent of Aquifer Unit
- Study Area
- County
- State

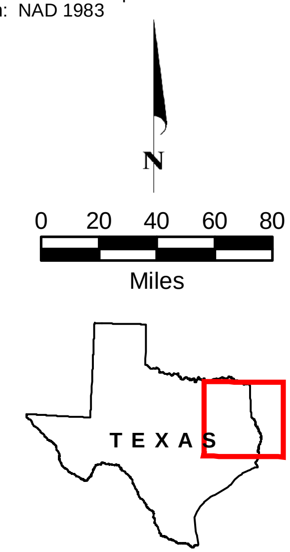
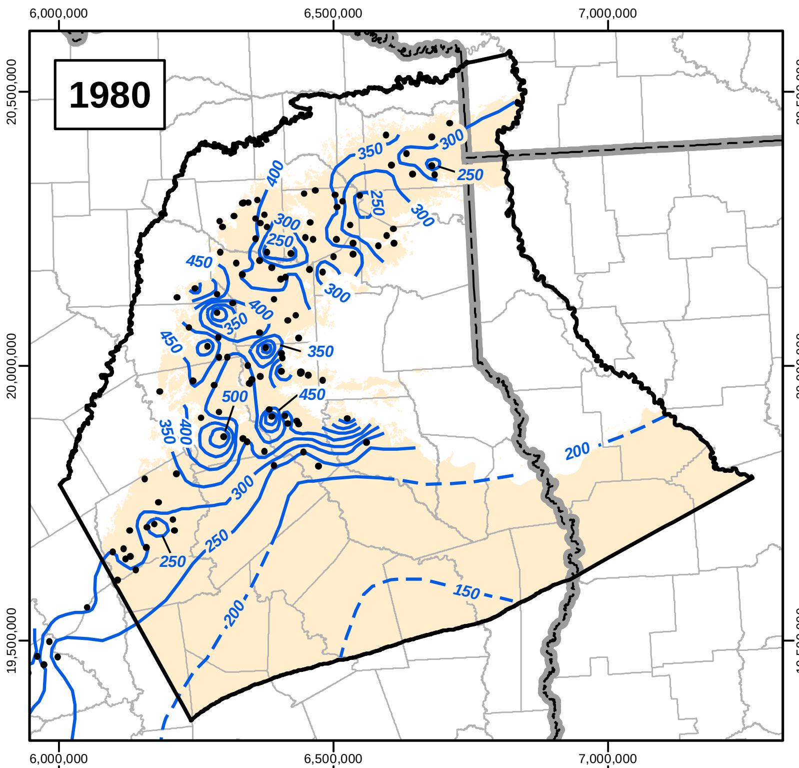
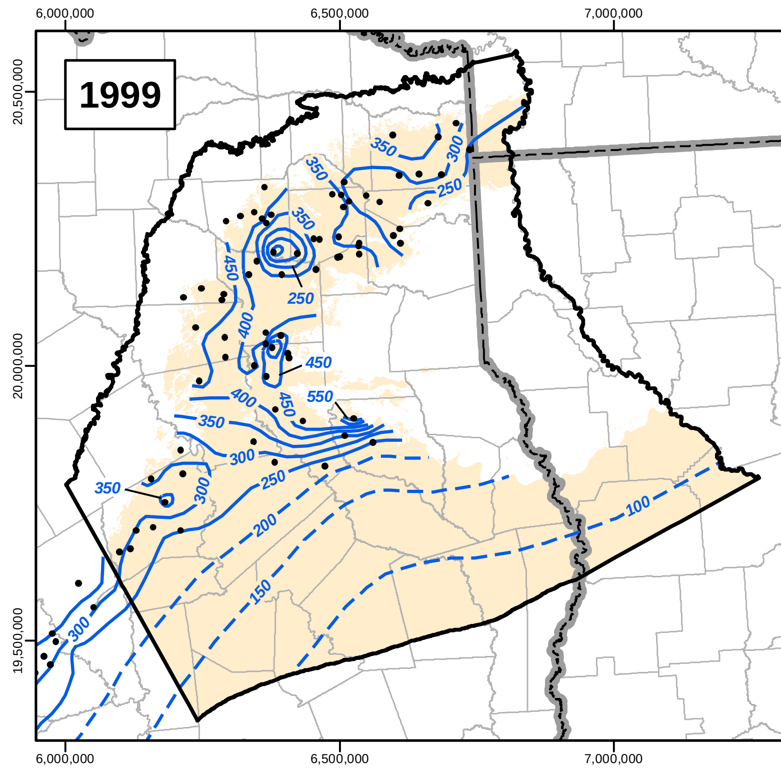
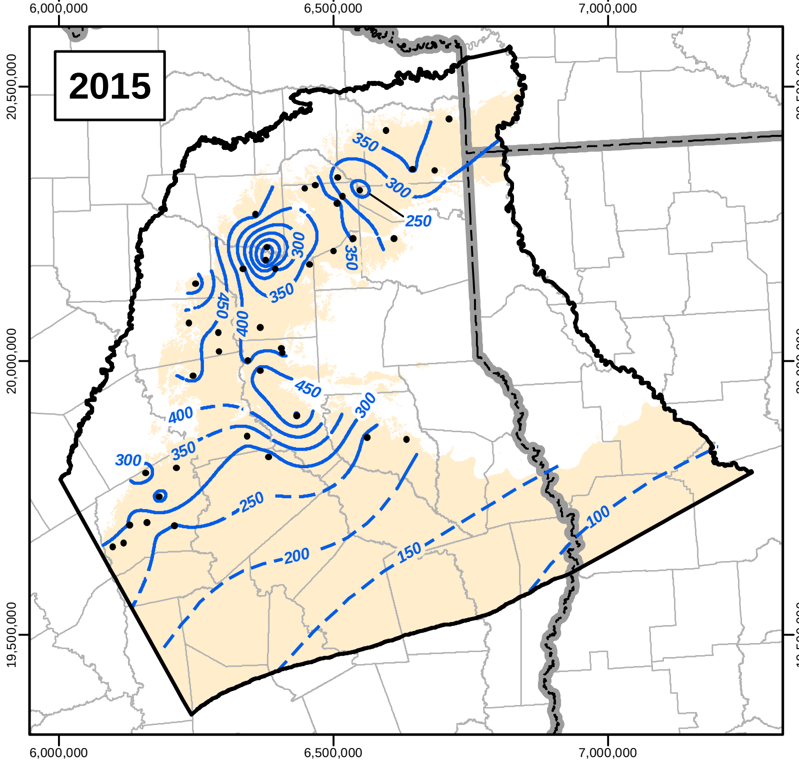


FIGURE 4.2.7. GROUNDWATER LEVEL ELEVATION CONTOURS FOR SPARTA AQUIFER







Projection: Albers Equal-Area
Datum: NAD 1983

EXPLANATION

- Location of Measurement
- × Approximated Value
- —50— Groundwater Level Elevation Contour, in feet amsl (dashed where approximate)
- Extent of Aquifer Unit
- Study Area
- County
- State

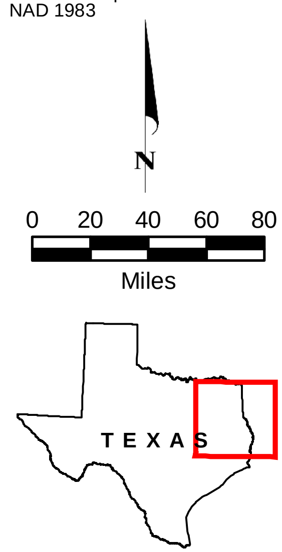


FIGURE 4.2.8. GROUNDWATER LEVEL ELEVATION CONTOURS FOR QUEEN CITY AQUIFER

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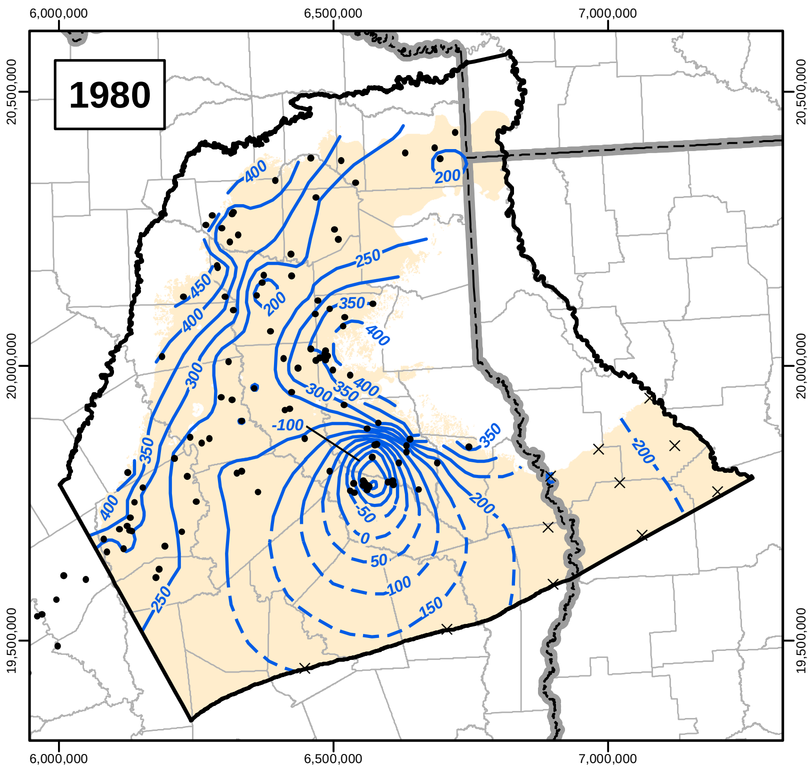
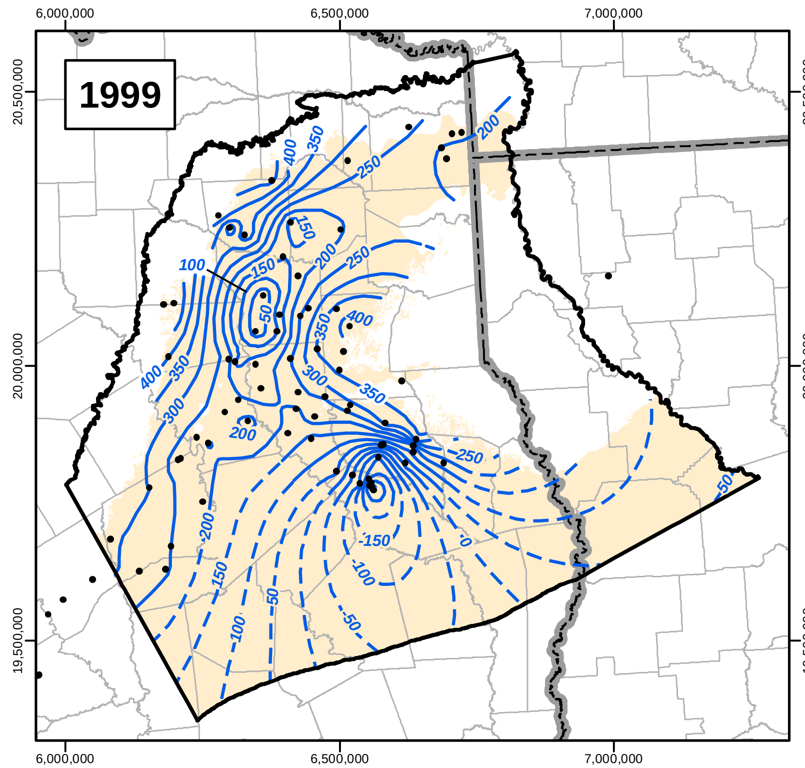
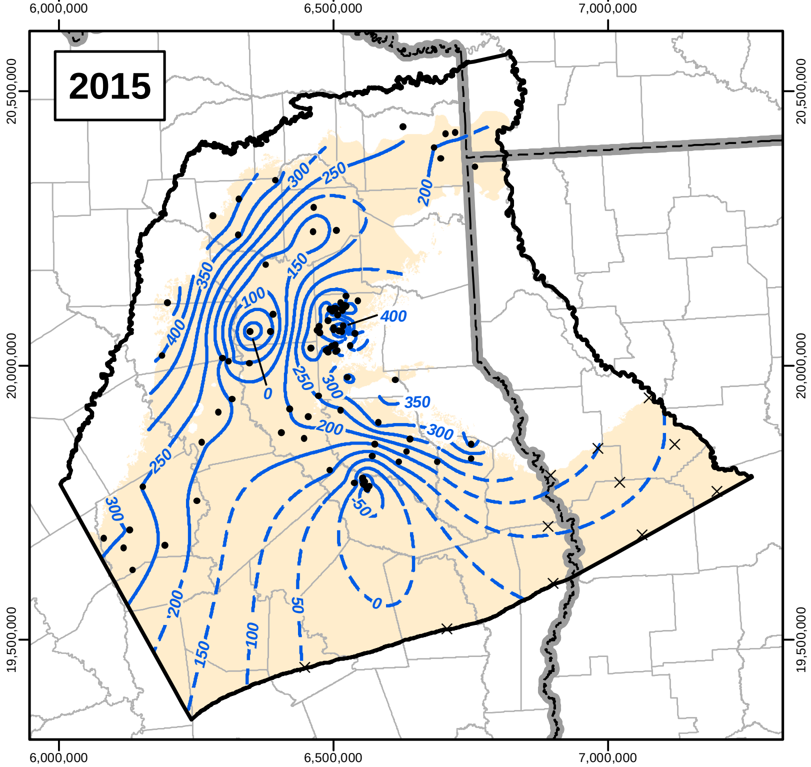
1480\REPORT_MAPS\WaterLevelMaps\QueenCity_WLE\25June2018







Projection: Albers Equal-Area
Datum: NAD 1983

EXPLANATION

- Location of Measurement
- × Approximated Value
- 50 Groundwater Level Elevation Contour, in feet amsl (dashed where approximate)
- Extent of Aquifer Unit
- Study Area
- County
- State

N

0 20 40 60 80
Miles

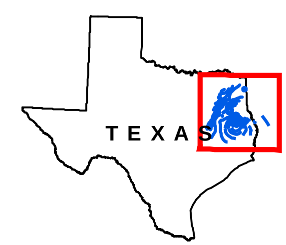


FIGURE 4.2.9. GROUNDWATER LEVEL ELEVATION CONTOURS FOR CARRIZO AQUIFER

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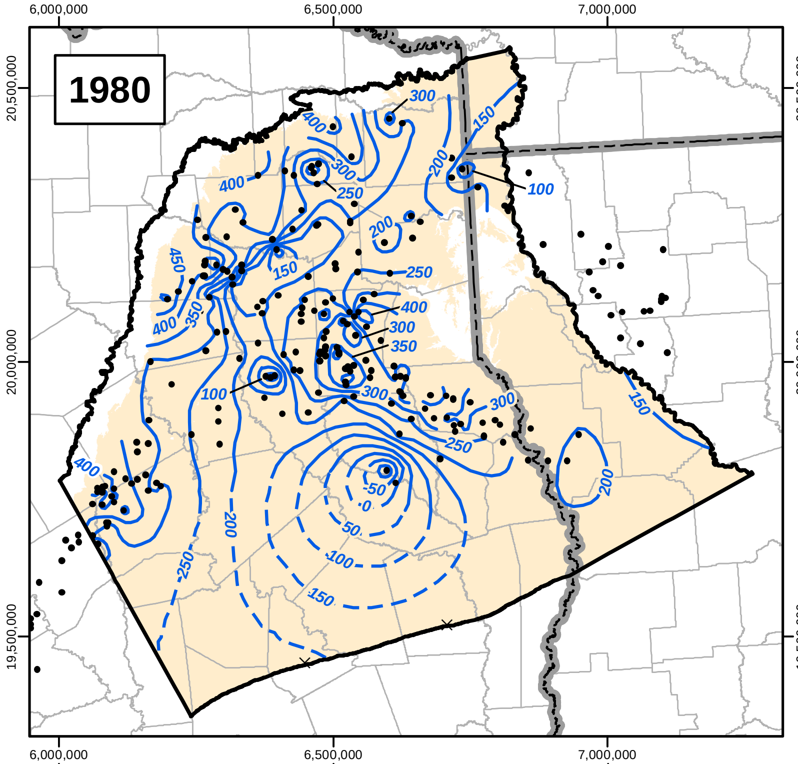
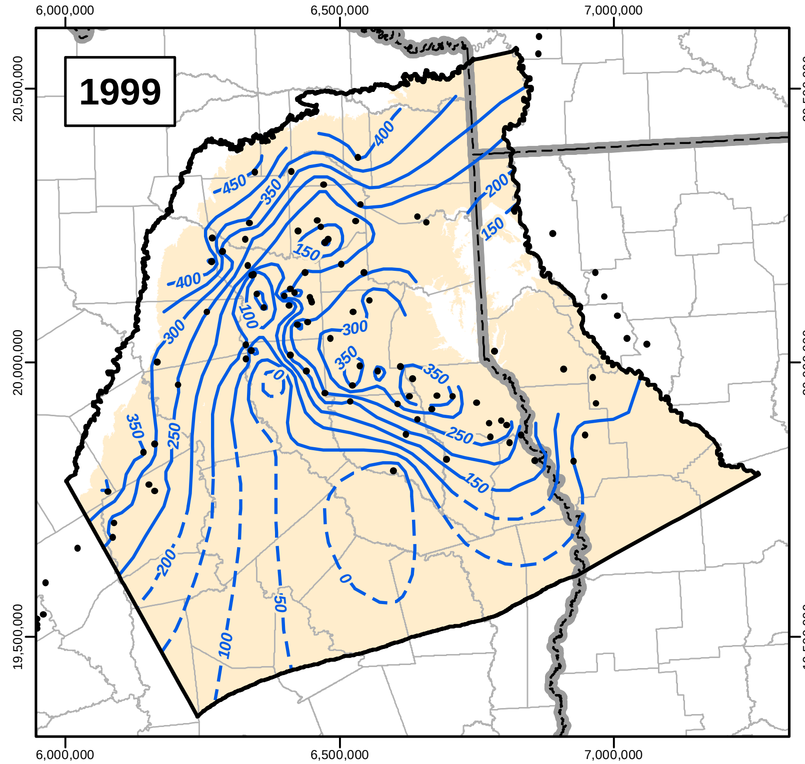
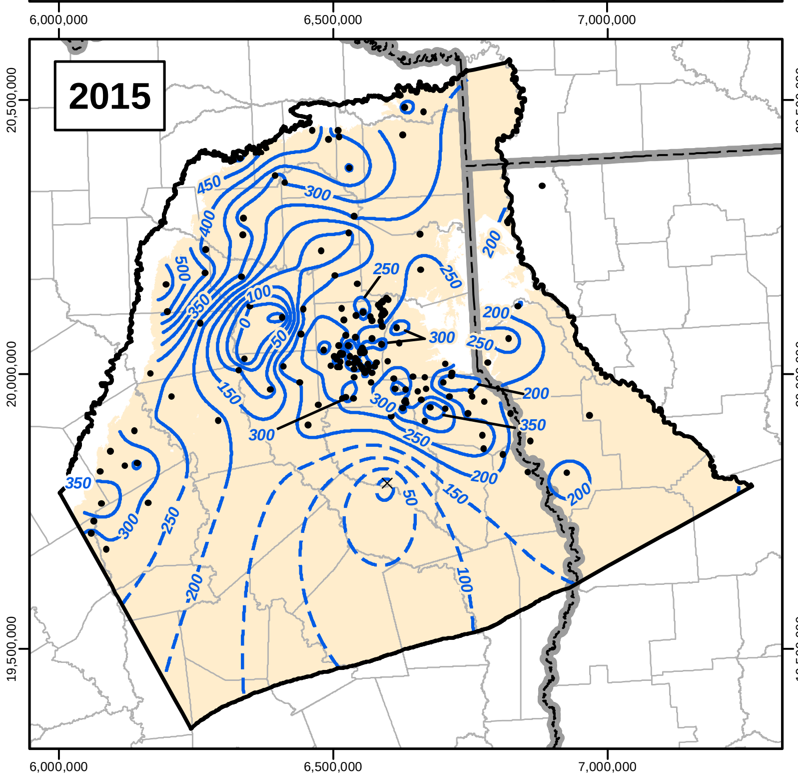
1480\REPORT_MAPS\WaterLevelMaps\Carrizo_WLE\25June2018







Projection: Albers Equal-Area
Datum: NAD 1983

EXPLANATION

- Location of Measurement
- × Approximated Value
- —50— Groundwater Level Elevation Contour, in feet amsl (dashed where approximate)
- Extent of Aquifer Unit
- Study Area
- County
- State

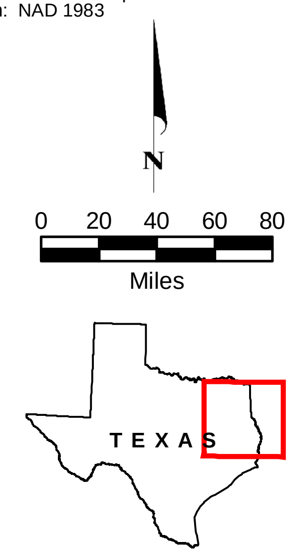


FIGURE 4.2.10. GROUNDWATER LEVEL ELEVATION CONTOURS FOR UPPER UNIT OF WILCOX AQUIFER

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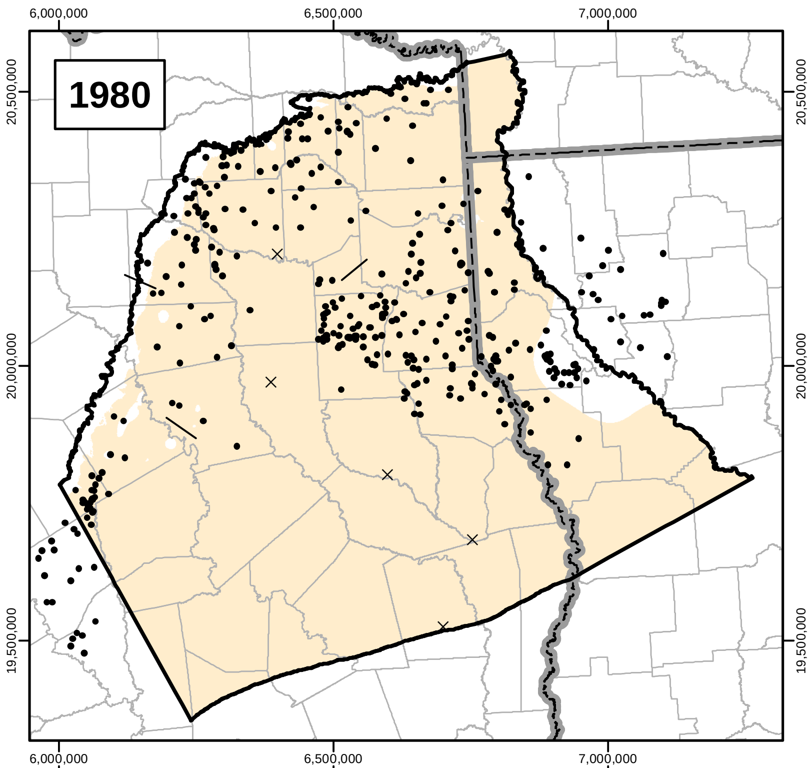
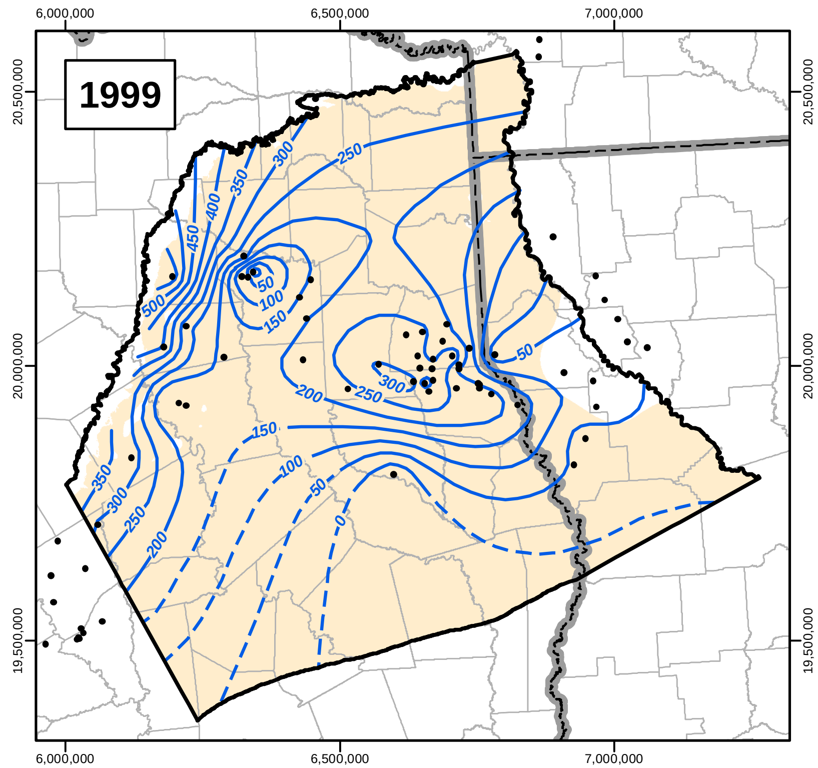
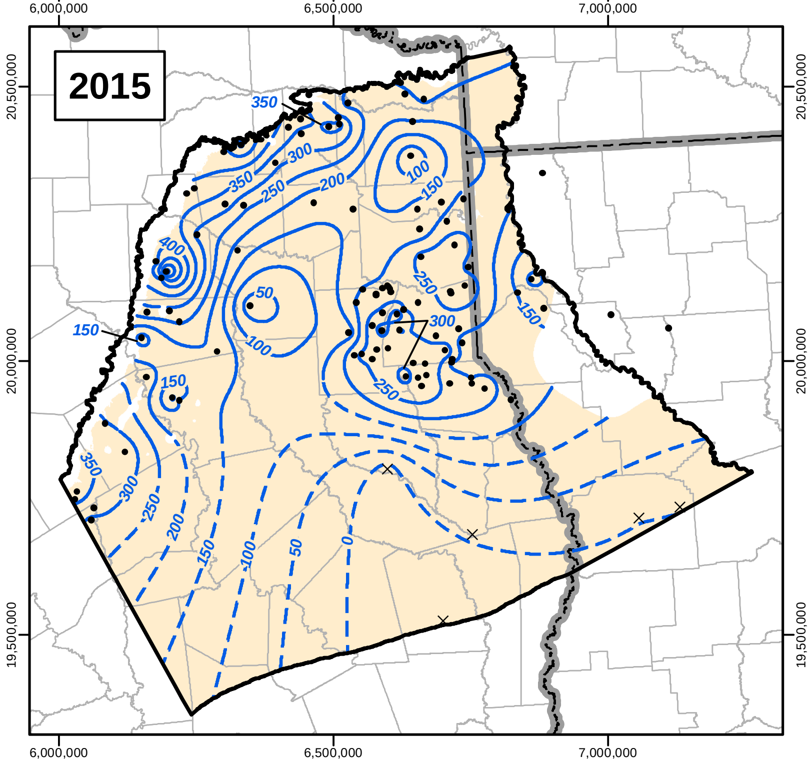
1480\REPORT_MAPS\UpperWilcox_WLE\26June2018







Projection: Albers Equal-Area
Datum: NAD 1983

EXPLANATION

- Location of Measurement
- Approximated Value
- 50 Groundwater Level Elevation Contour, in feet amsl (dashed where approximate)
- Extent of Aquifer Unit
- Study Area
- County
- State

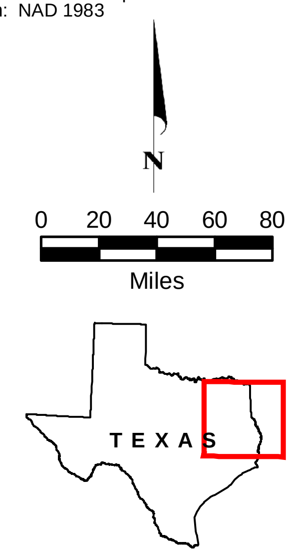
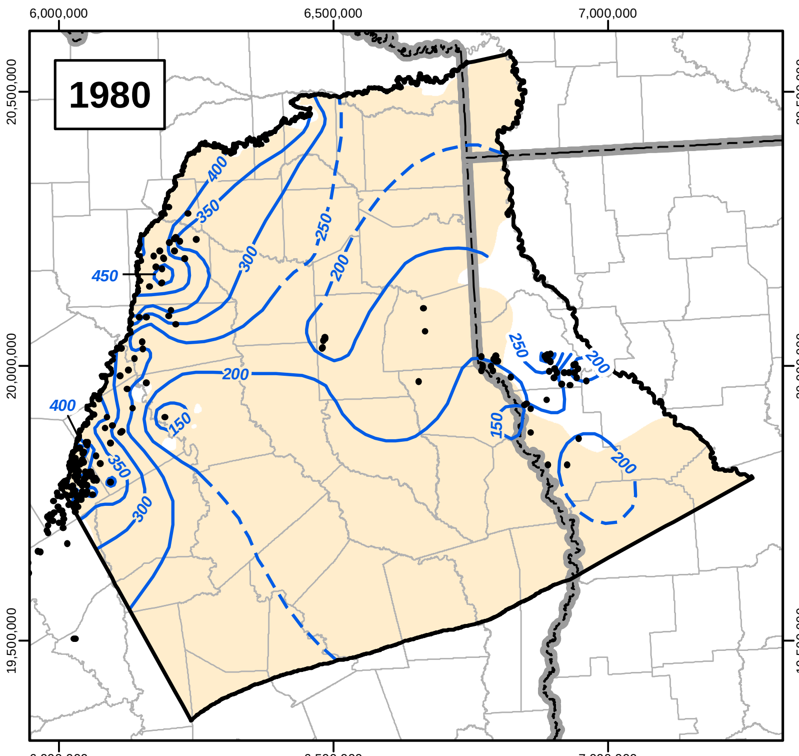


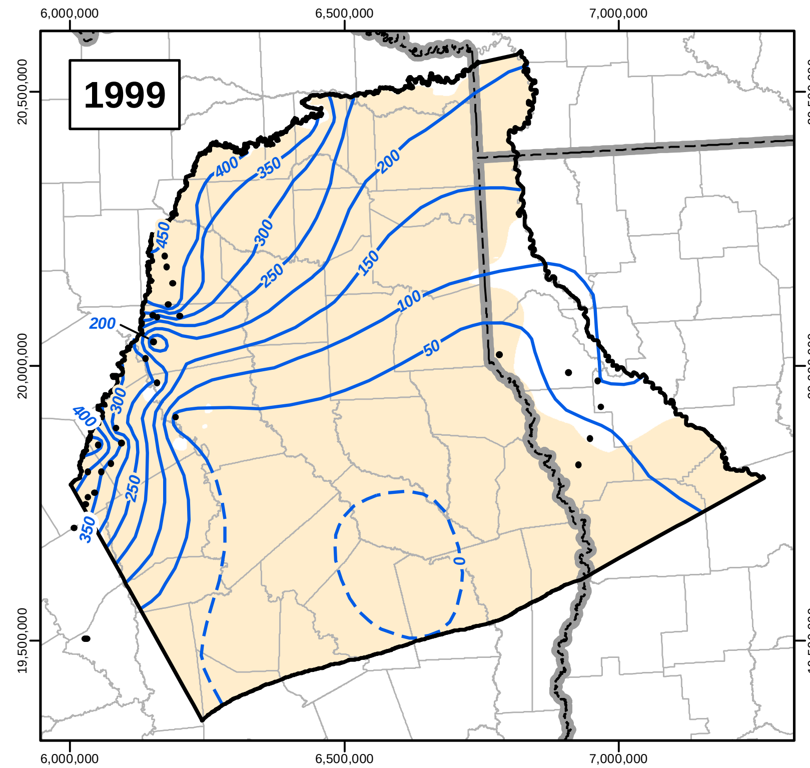
FIGURE 4.2.11. GROUNDWATER LEVEL ELEVATION CONTOURS FOR MIDDLE UNIT OF WILCOX AQUIFER

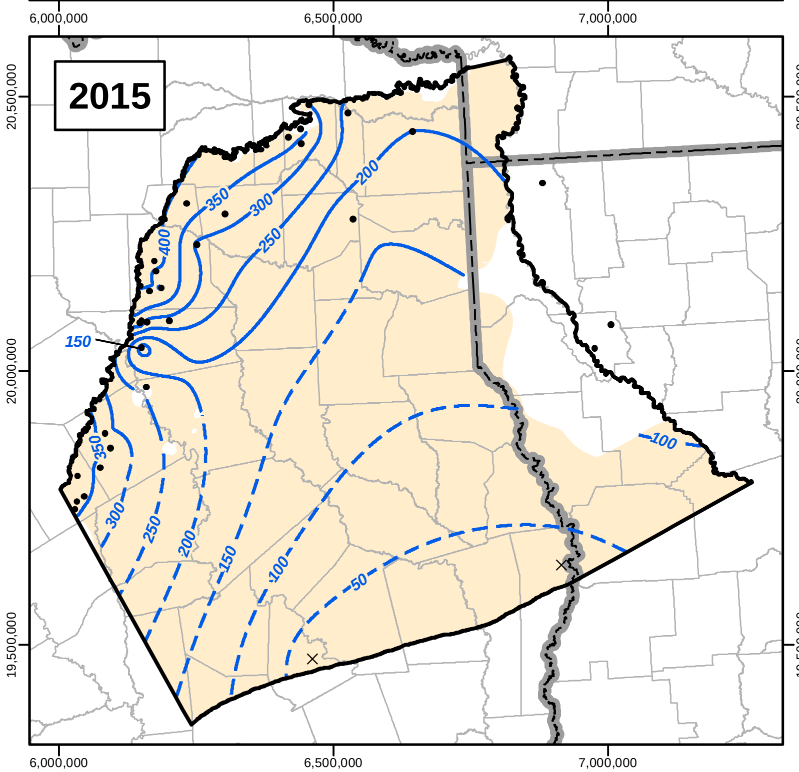
MONTGOMERY & ASSOCIATES

DRAFT

1480\REPORT_MAPS\MiddleWilcox_WLE\27June2018







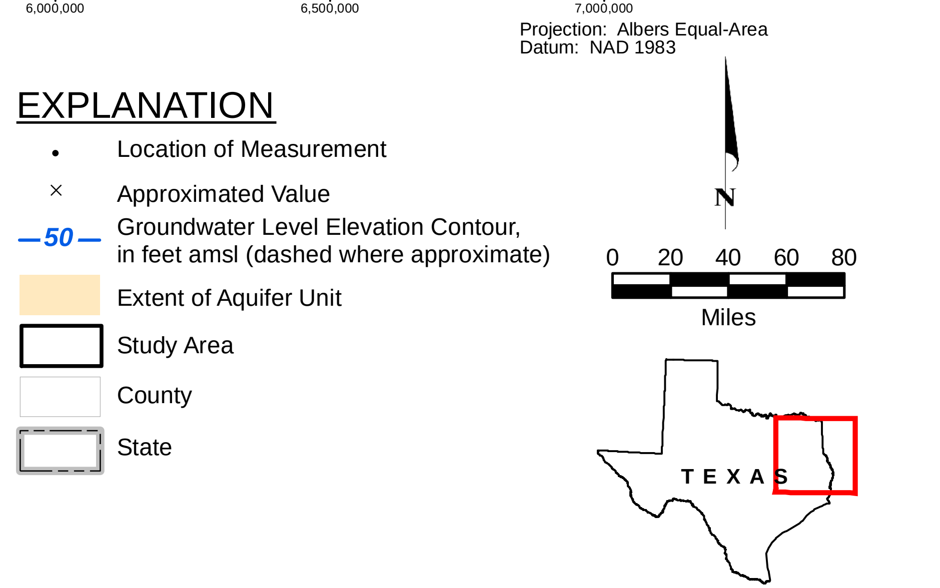


FIGURE 4.2.12. GROUNDWATER LEVEL ELEVATION CONTOURS FOR LOWER UNIT OF WILCOX AQUIFER

MONTGOMERY & ASSOCIATES

1480\REPORT_MAPS\LowerWilcox_WLE\26June2018

DRAFT

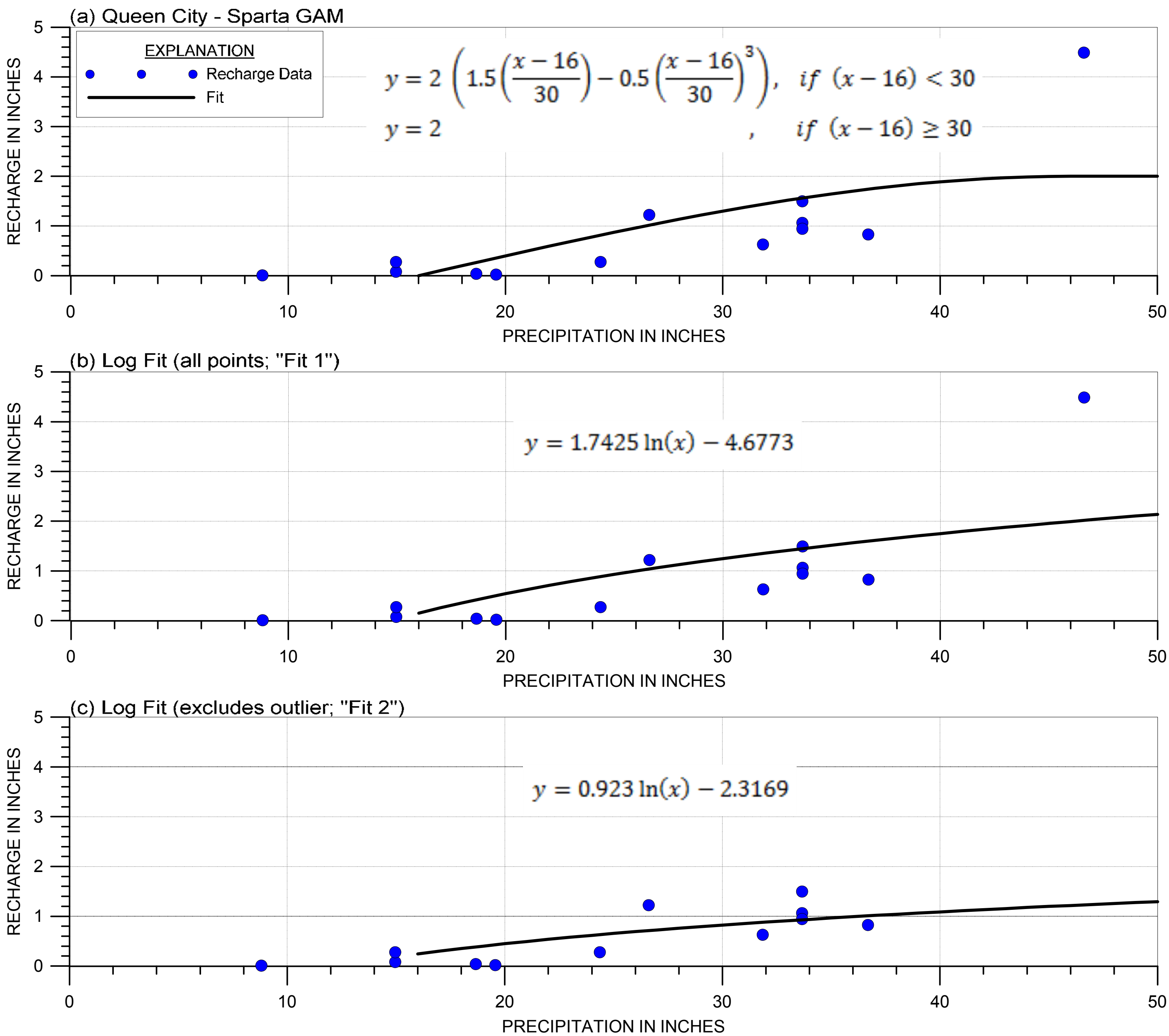


FIGURE 4.3.1 ESTIMATED RECHARGE AS A FUNCTION OF PRECIPITATION

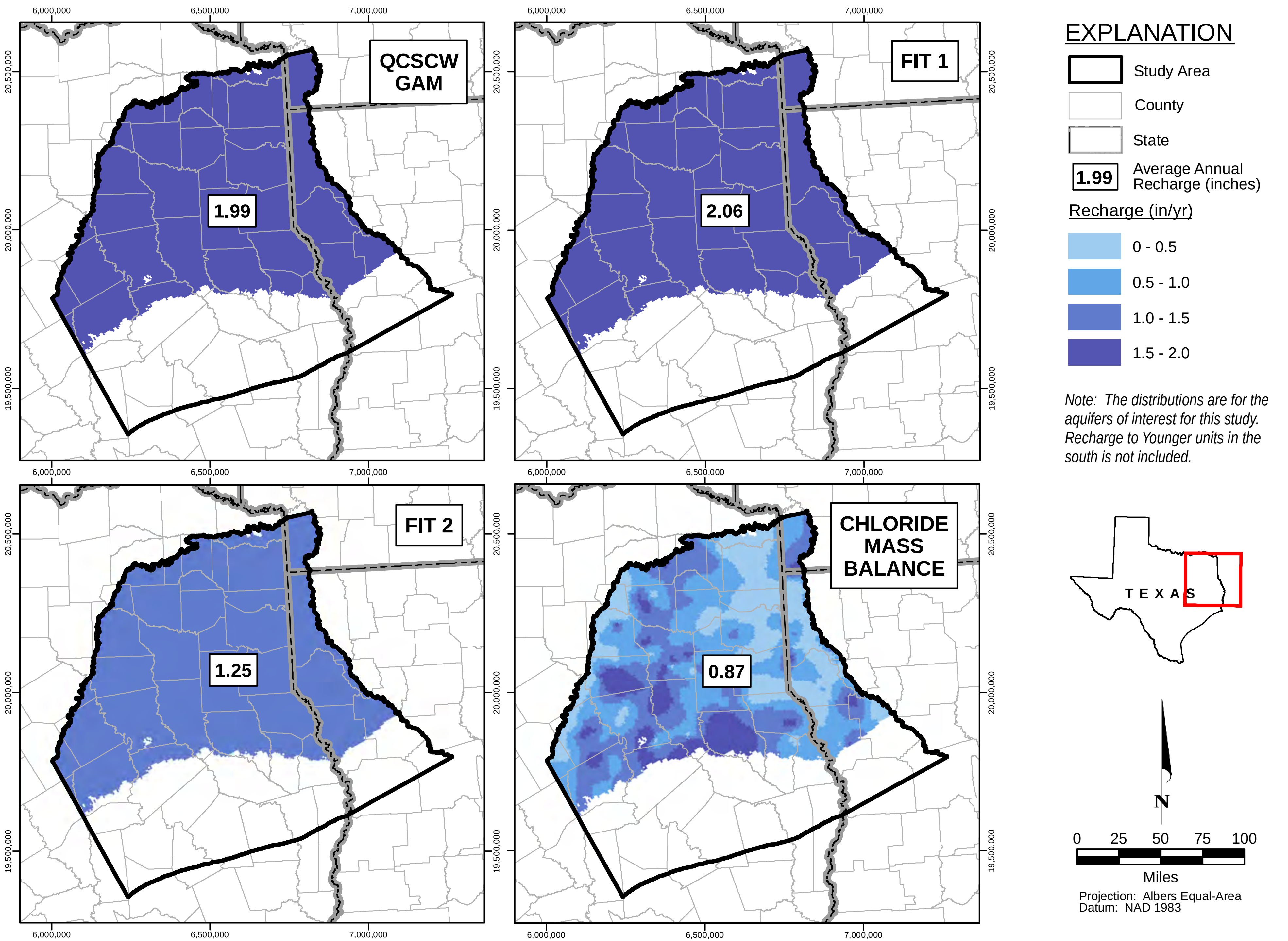


FIGURE 4.3.2. RECHARGE DISTRIBUTIONS FROM VARIOUS METHODS BASED ON 30-YEAR AVERAGE PRECIPITATION

1480\REPORT_MAPS\Recharge_Distribution_30yrAvPrecip.mxd\27June2018

DRAFT

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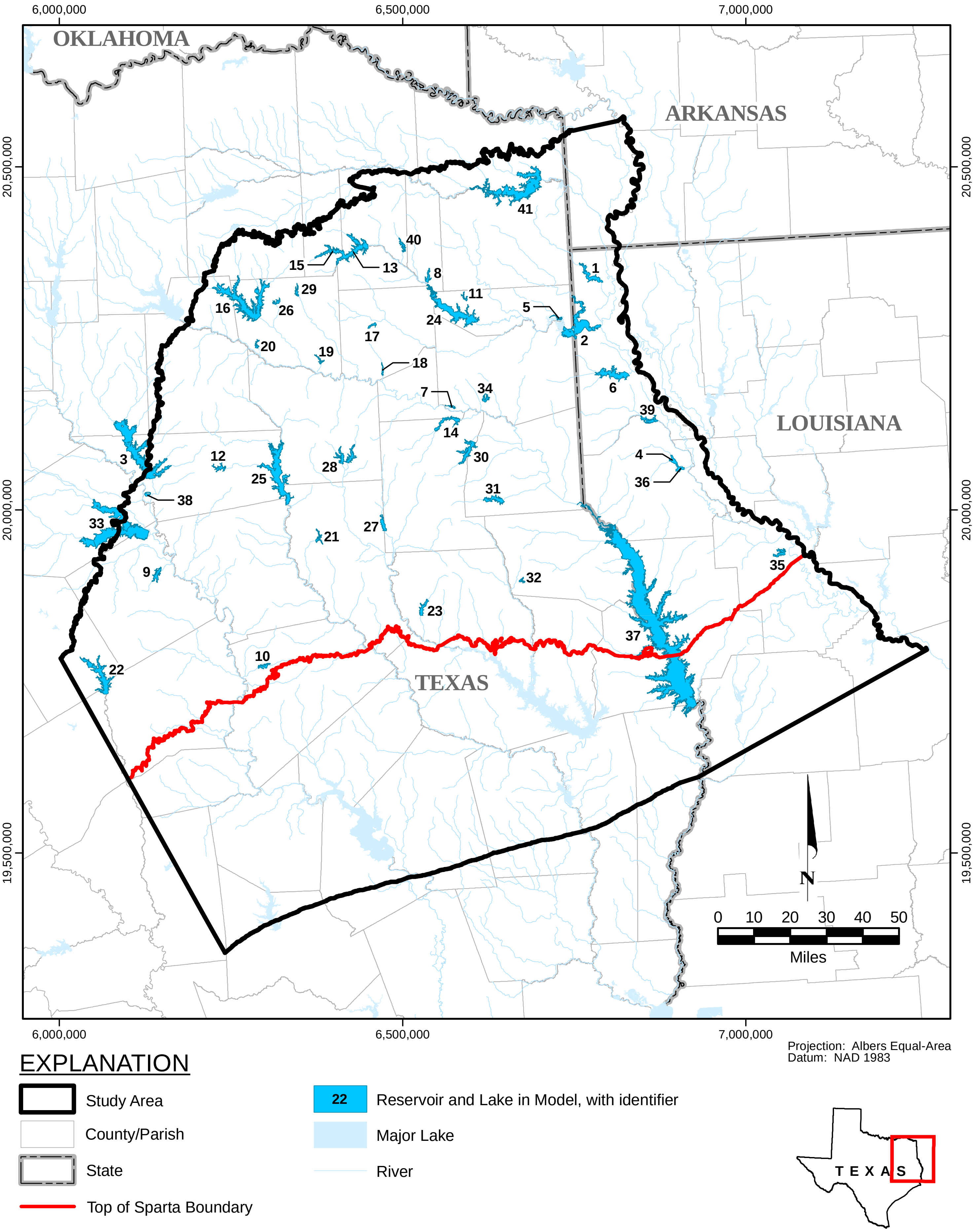

FIGURE 4.3.3. MAJOR RESERVOIRS IN STUDY AREA

MONTGOMERY & ASSOCIATES

1480\REPORT_MAPS\Reservoirs.mxd\11June2018

DRAFT

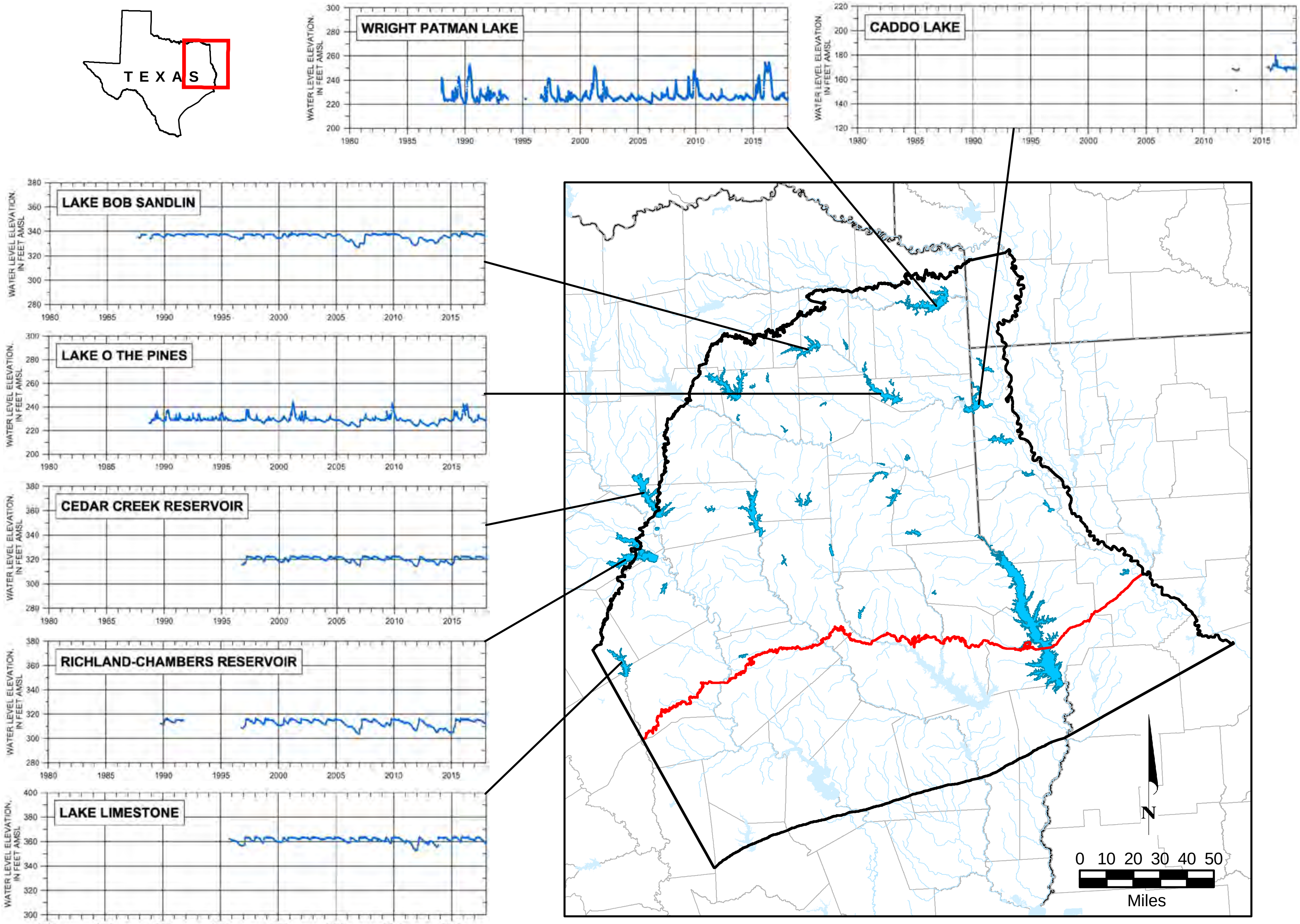

FIGURE 4.3.4. WATER LEVEL HYDROGRAPHS FOR SELECT RESERVOIRS IN STUDY AREA

1480\REPORT_MAPS\WLE_Reservoirs_Hydrographs.mxd\13June2018

EXPLANATION

- Top of Sparta Boundary
- Reservoir and Lake in Model
- River
- Major Lake

Projection: Albers Equal-Area
Datum: NAD 1983

DRAFT

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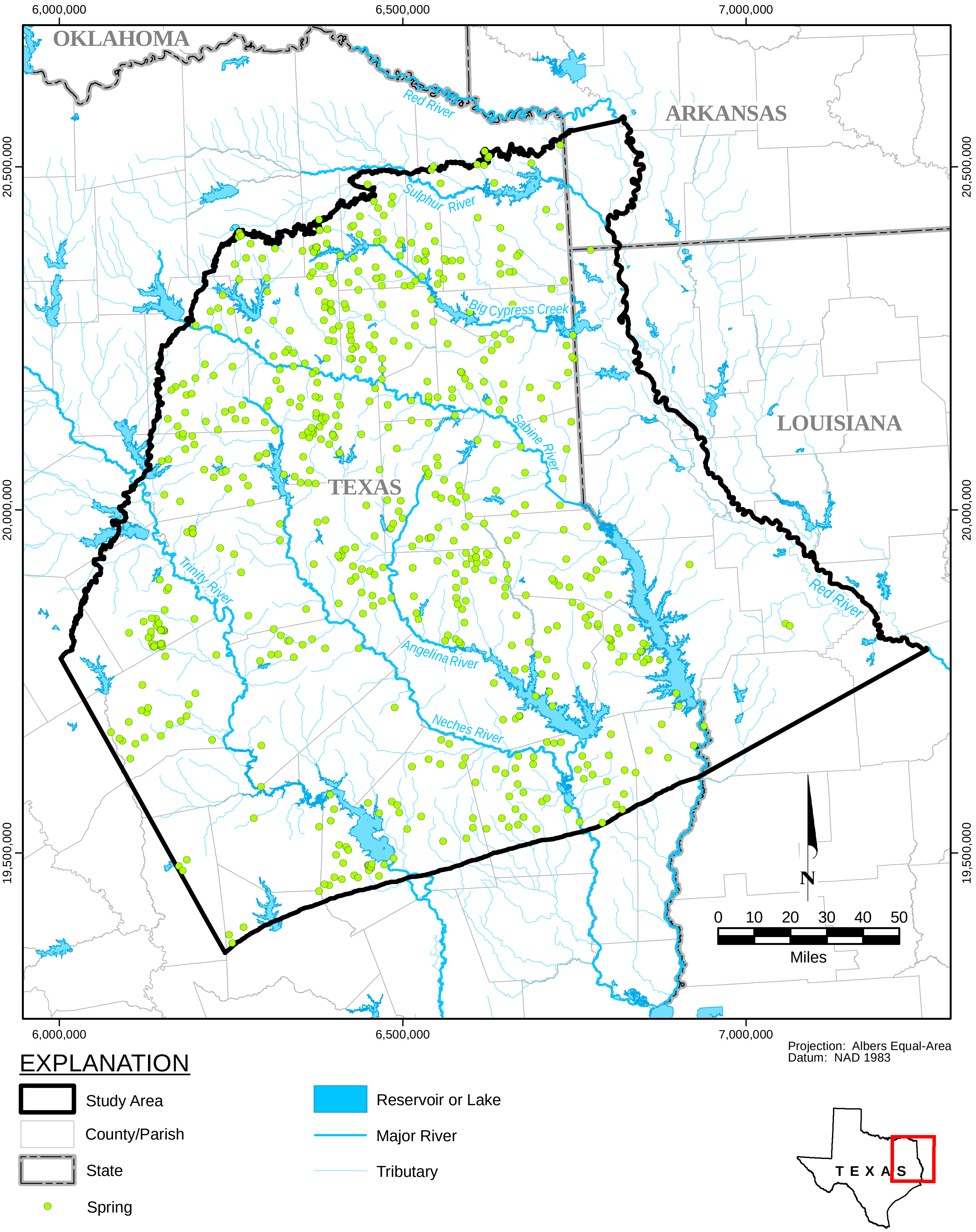

FIGURE 4.4.1. SURFACE WATER FEATURES IN STUDY AREA

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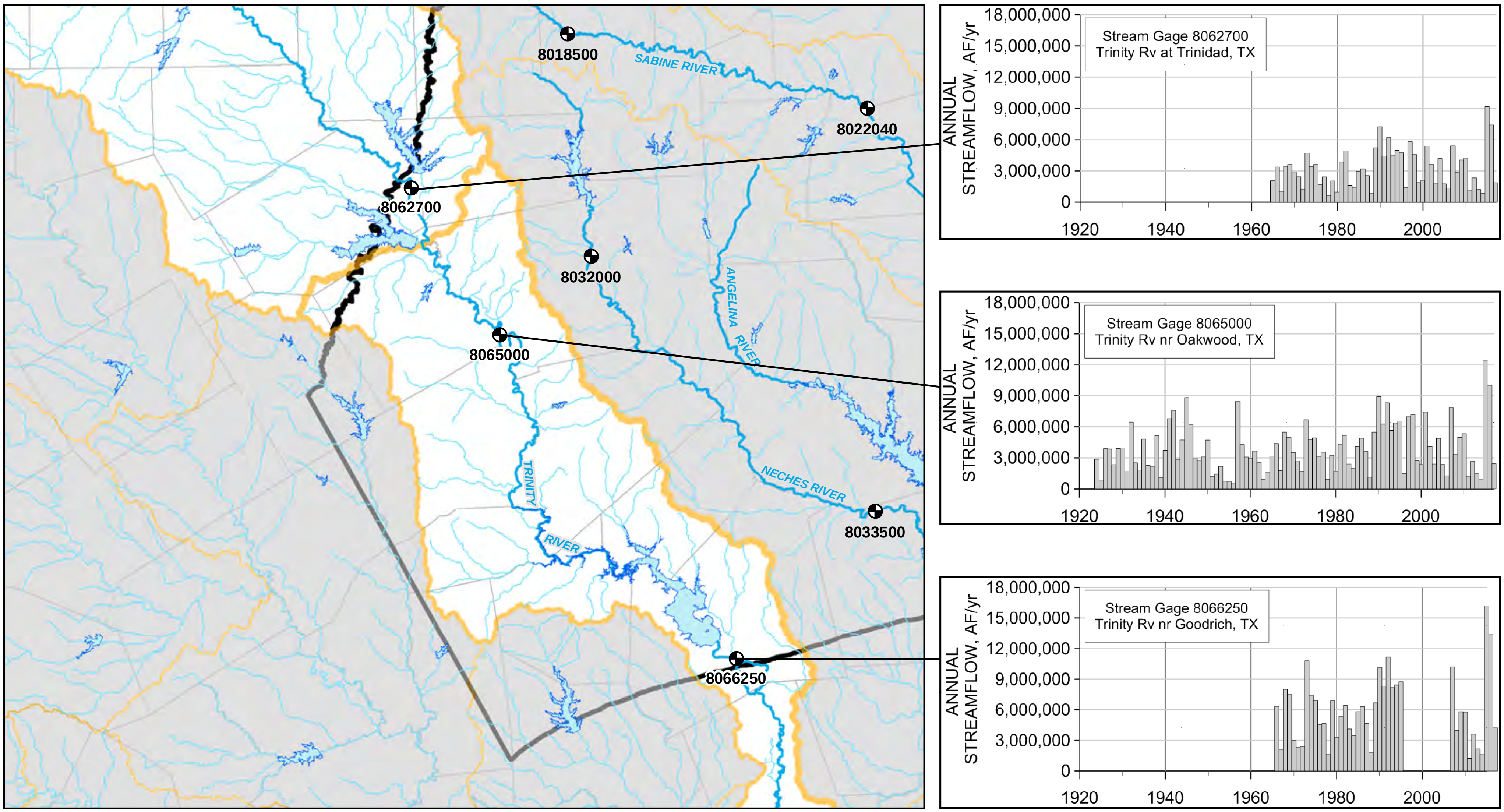
1480\REPORT_MAPS\SurfaceWater_Features.mxd\13June2018

DRAFT



Source: USGS, daily mean streamflow summarized to annual streamflow

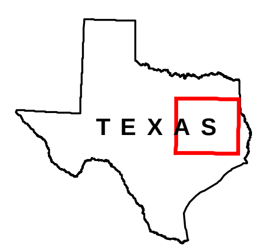
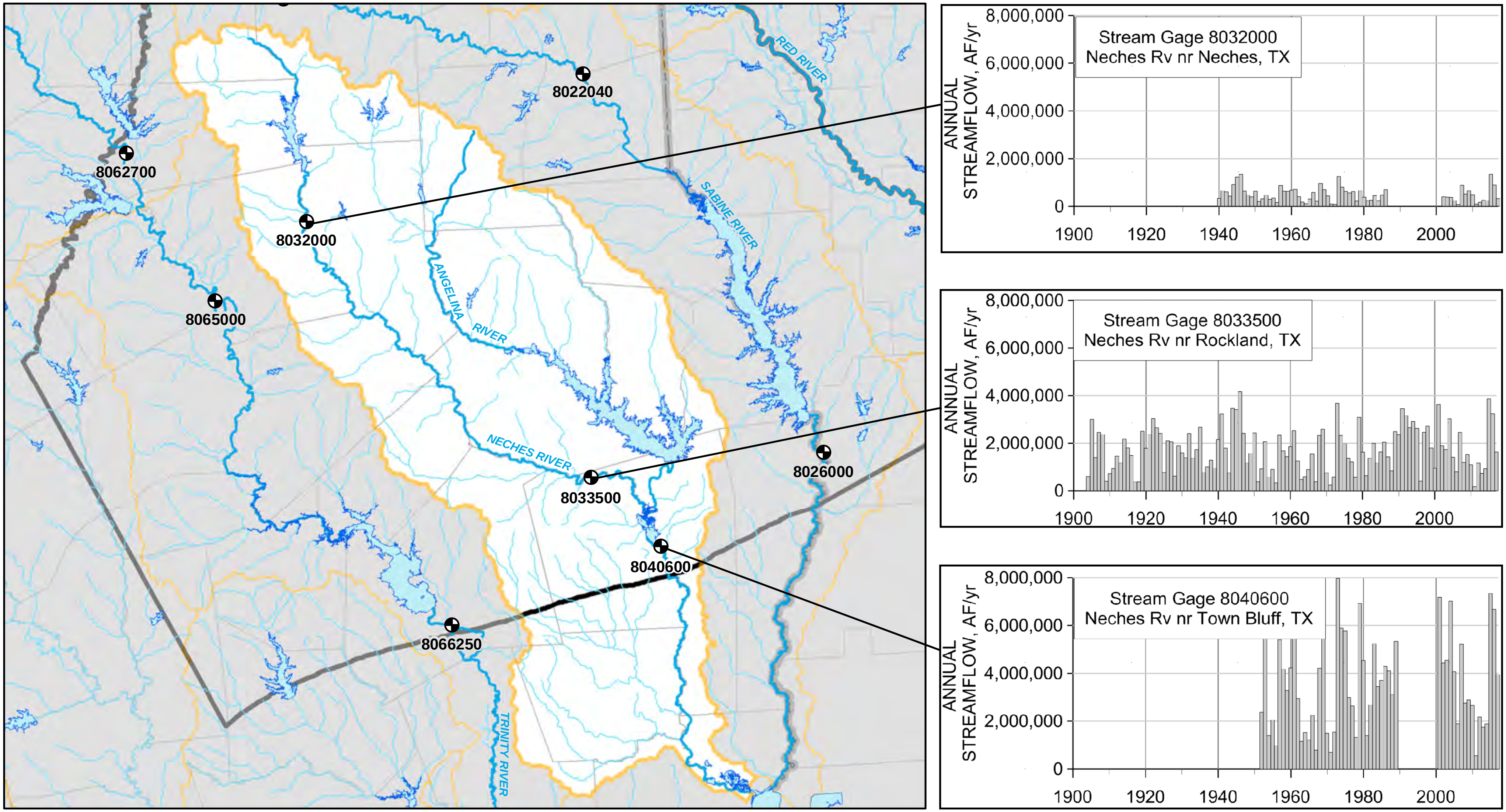


FIGURE 4.4.2. ANNUAL STREAMFLOWS ALONG TRINITY RIVER

GIS-Tuc\1480\StreamflowHydrograph_Trinity\25June2018

DRAFT



Source: USGS, daily mean streamflow summarized to annual streamflow

EXPLANATION

- 8066250 — USGS Stream Gage and Identifier
- State
- County
- Basin (WBD HU6)
- Major River
- Tributary
- Reservoir or Lake

N

0 10 20 30 40 50
Miles

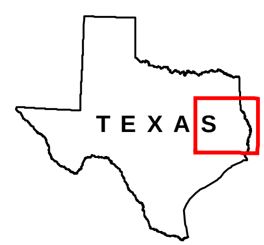


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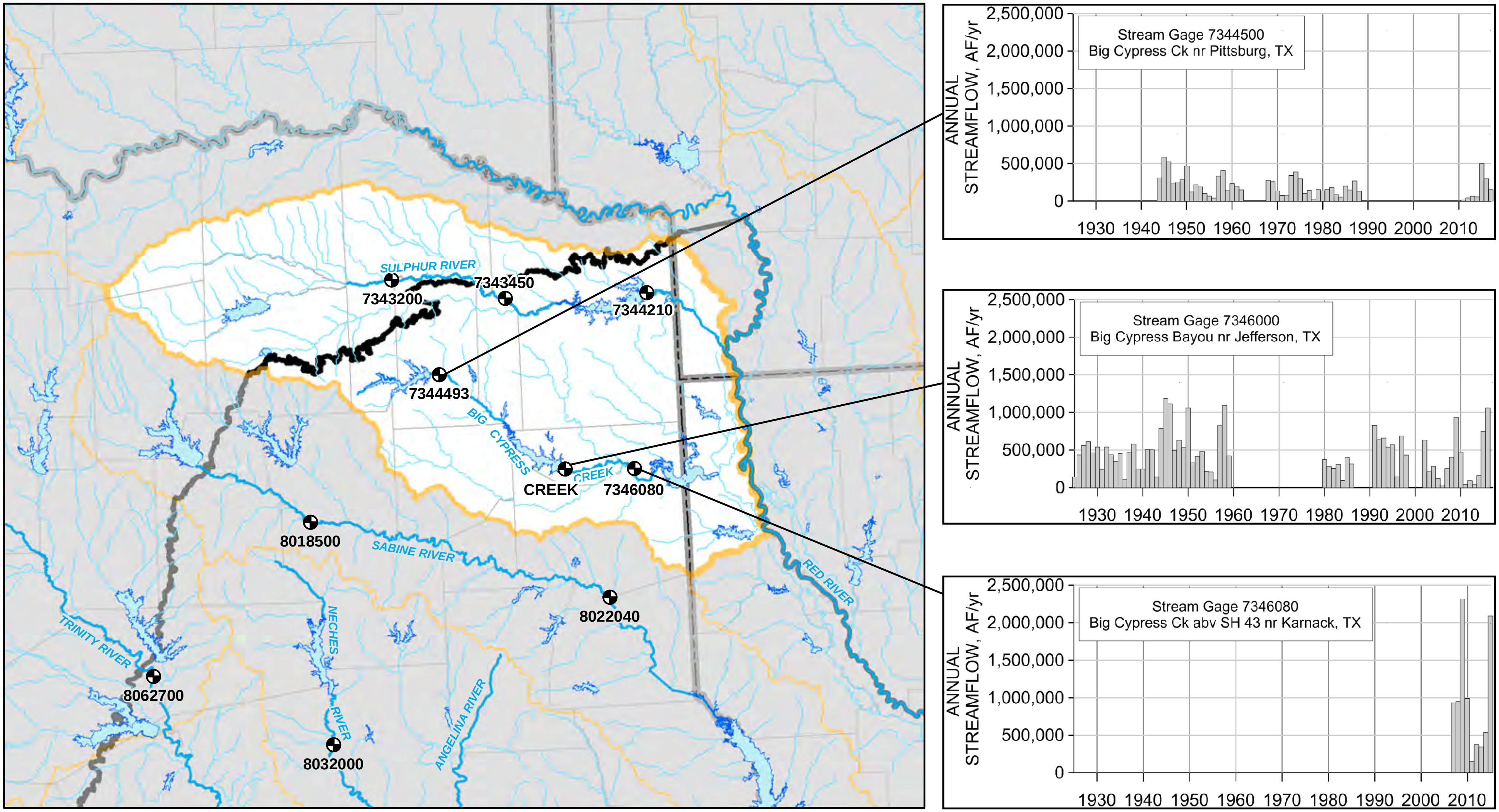
FIGURE 4.4.3. ANNUAL STREAMFLOWS ALONG NECHES RIVER

GIS-Tuc\1480\StreamflowHydrograph_Neches\25June2018

DRAFT



Source: *USGS, daily mean streamflow summarized to annual streamflow*

EXPLANATION

- 8032000 USGS Stream Gage and Identifier
- State
- County
- Basin (WBD HU6)
- Major River
- Tributary
- Reservoir or Lake

N

0 10 20 30 40 50
Miles

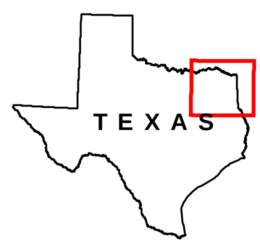


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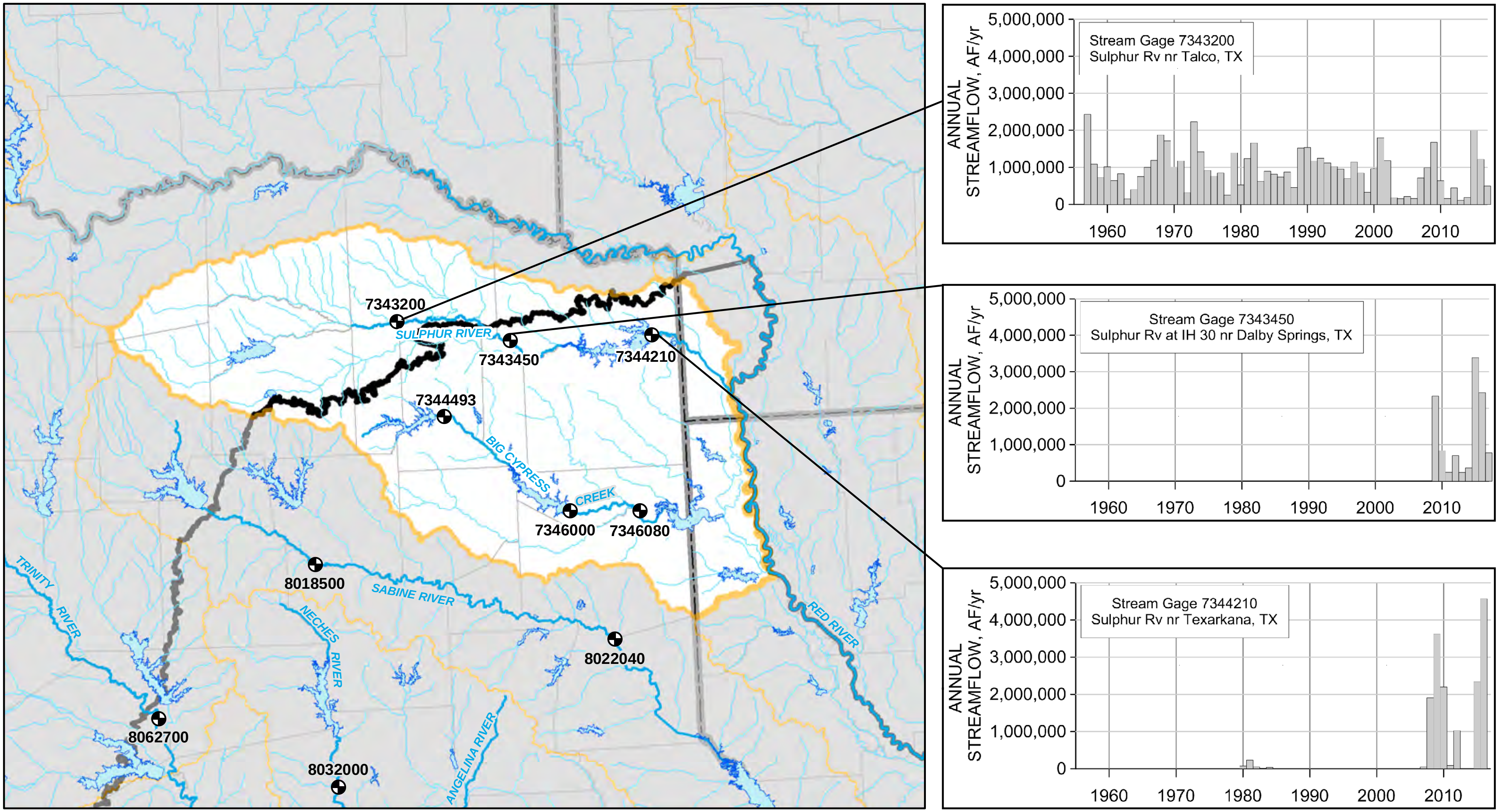
FIGURE 4.4.5. ANNUAL STREAMFLOWS ALONG BIG CYPRESS CREEK

GIS-Tuc\1480\StreamflowHydrograph_BigCyprus\25June2018

DRAFT



Source: USGS, daily mean streamflow summarized to annual streamflow

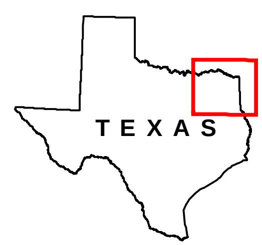
EXPLANATION

8062700	USGS Stream Gage and Identifier
	State
	County
	Basin (WBD HU6)
	Major River
	Tributary
	Reservoir or Lake

N

0 10 20 30 40 50

Miles

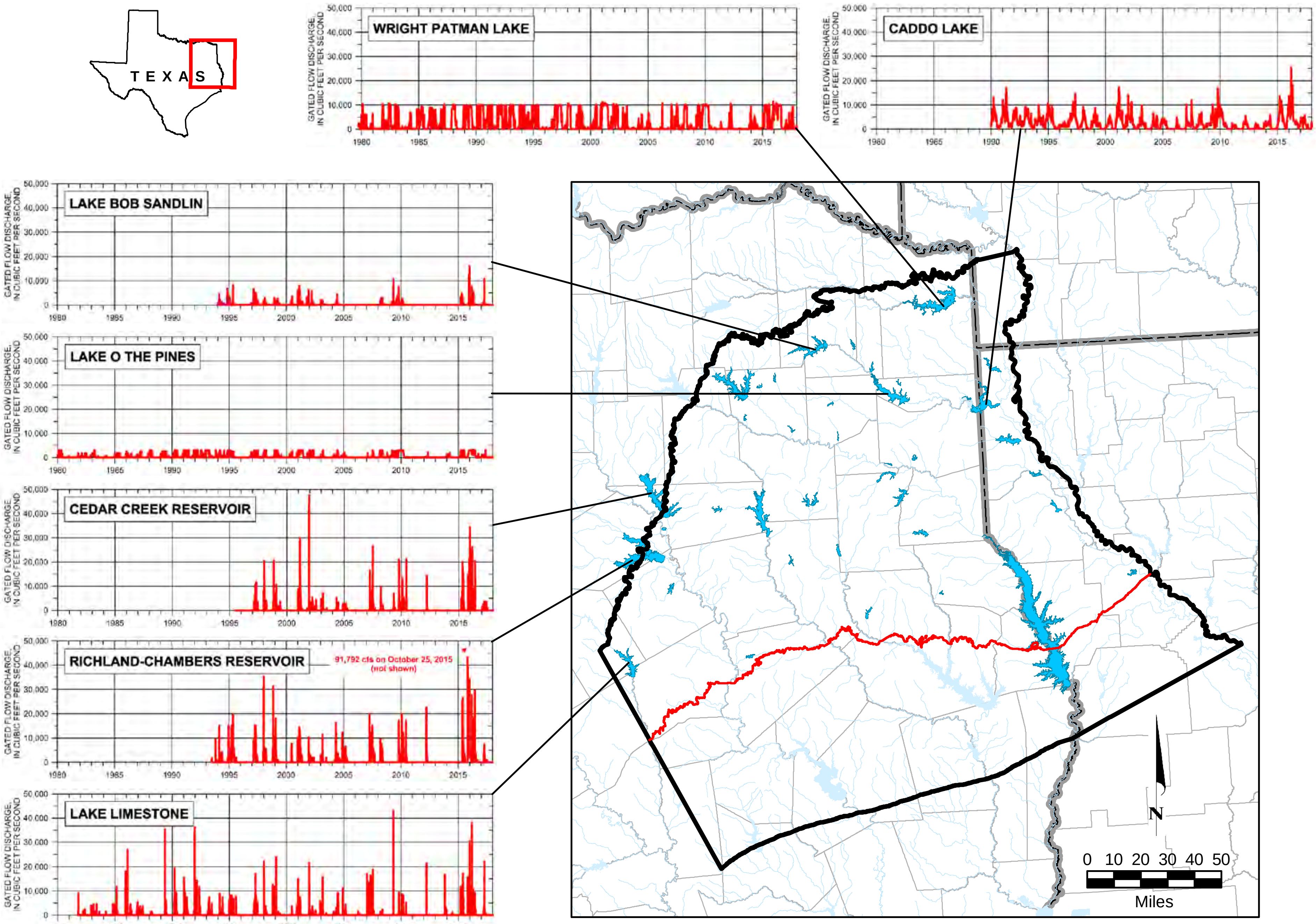


MONTGOMERY & ASSOCIATES

FIGURE 4.4.6. ANNUAL STREAMFLOWS ALONG SULPHUR RIVER

GIS-Tuc\1480\StreamflowHydrograph_Sulphur\25June2018

DRAFT



EXPLANATION

- Top of Sparta Boundary
- Reservoir and Lake in Model
- River
- Major Lake

Projection: Albers Equal-Area
Datum: NAD 1983

DRAFT

MONTGOMERY & ASSOCIATES

FIGURE 4.4.7. DAILY DISCHARGE FLOWS FOR SELECT RESERVOIRS IN STUDY AREA

1480\REPORT_MAPS\Reservoirs_Hydrographs.mxd\26June2018

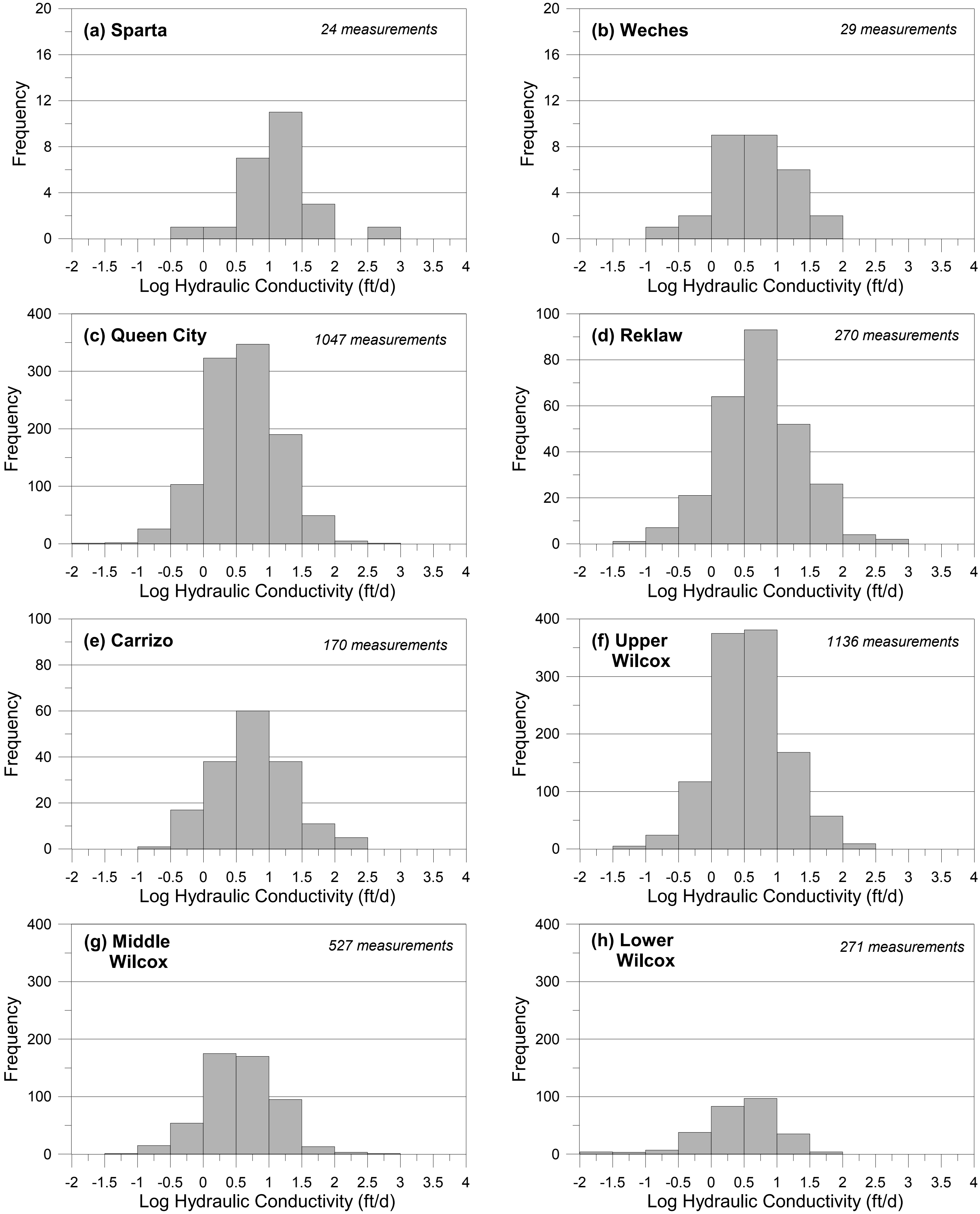


FIGURE 4.5.1. HISTOGRAMS OF MEASURED HYDRAULIC CONDUCTIVITY FOR THE NORTHERN QUEEN CITY, SPARTA, AND CARRIZO-WILCOX AQUIFERS

MONTGOMERY & ASSOCIATES

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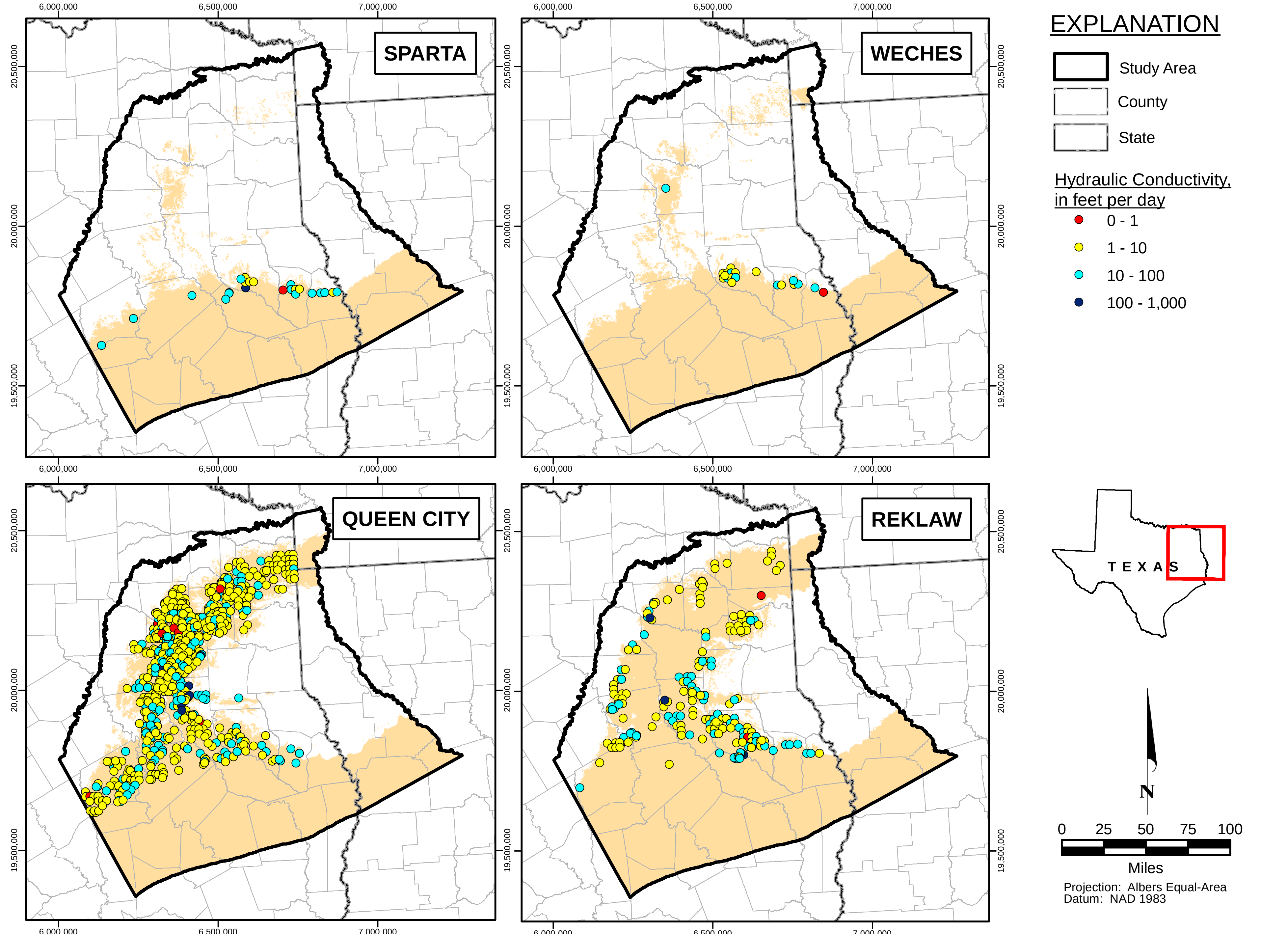


FIGURE 4.5.2. HYDRAULIC CONDUCTIVITY FOR UPPER AQUIFER UNITS

1480\REPORT_MAPS\HydraulicParameters\BaseMap_K-1_4.mxd\07June2018

DRAFT

MONTGOMERY & ASSOCIATES

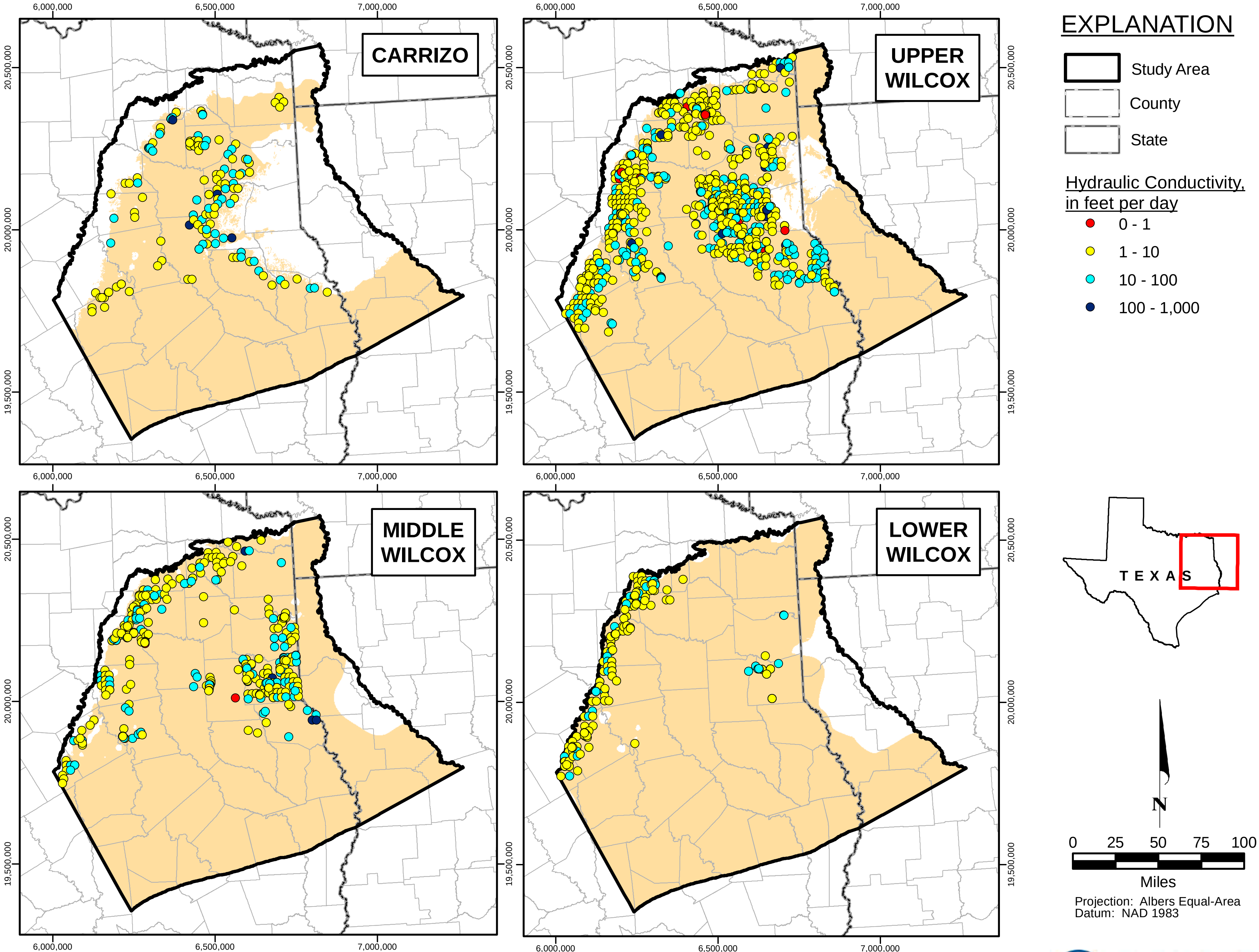
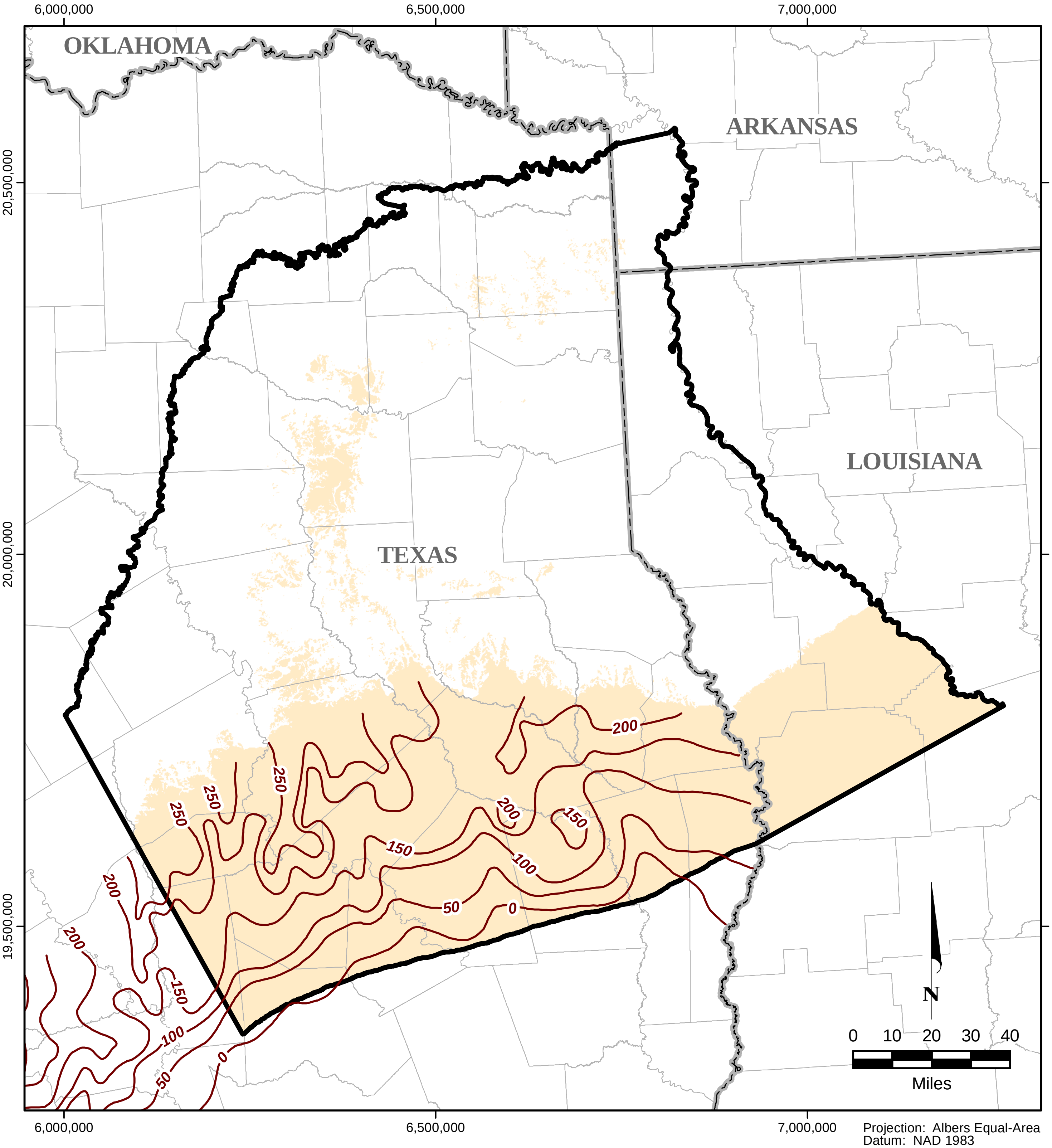


FIGURE 4.5.3. HYDRAULIC CONDUCTIVITY FOR LOWER AQUIFER UNITS

1480\REPORT_MAPS\HydraulicParameters\BaseMap_K-5_8.mxd\07June2018

DRAFT

MONTGOMERY & ASSOCIATES



EXPLANATION

Study Area

County/Parish

State

50 Contour of Net Sand Thickness, in feet (Kelley and others, 2004)

Extent of Aquifer Unit

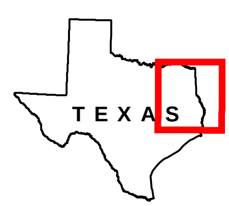
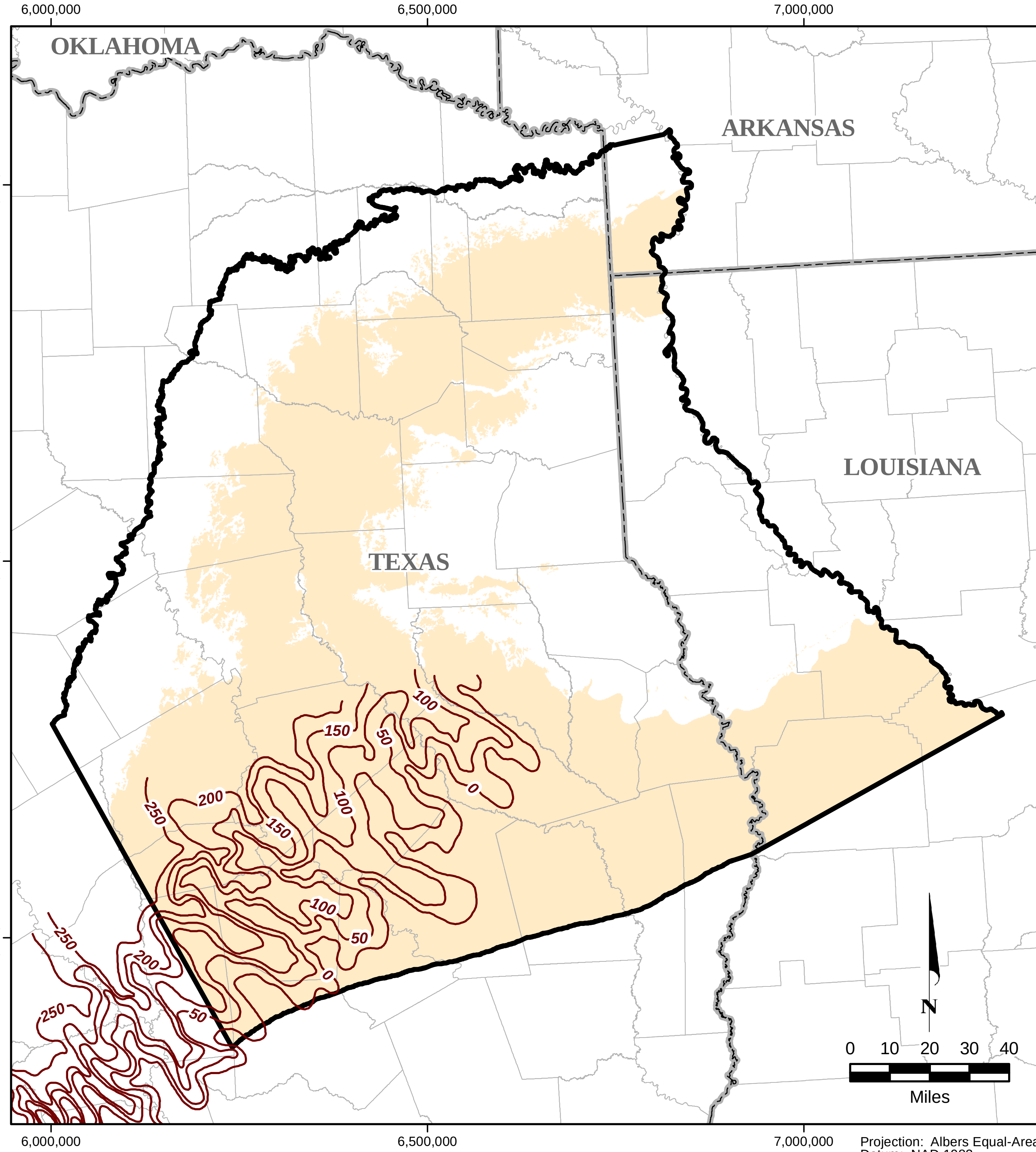


FIGURE 4.5.4. NET SAND THICKNESS CONTOURS FOR SPARTA AQUIFER

MONTGOMERY & ASSOCIATES

DRAFT



Projection: Albers Equal-Area
Datum: NAD 1983

EXPLANATION

Study Area

County/Parish

State

50 Contour of Net Sand Thickness, in feet (Kelley and others, 2004)

Extent of Aquifer Unit

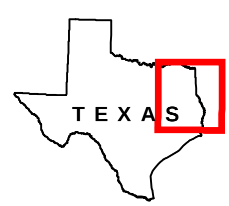
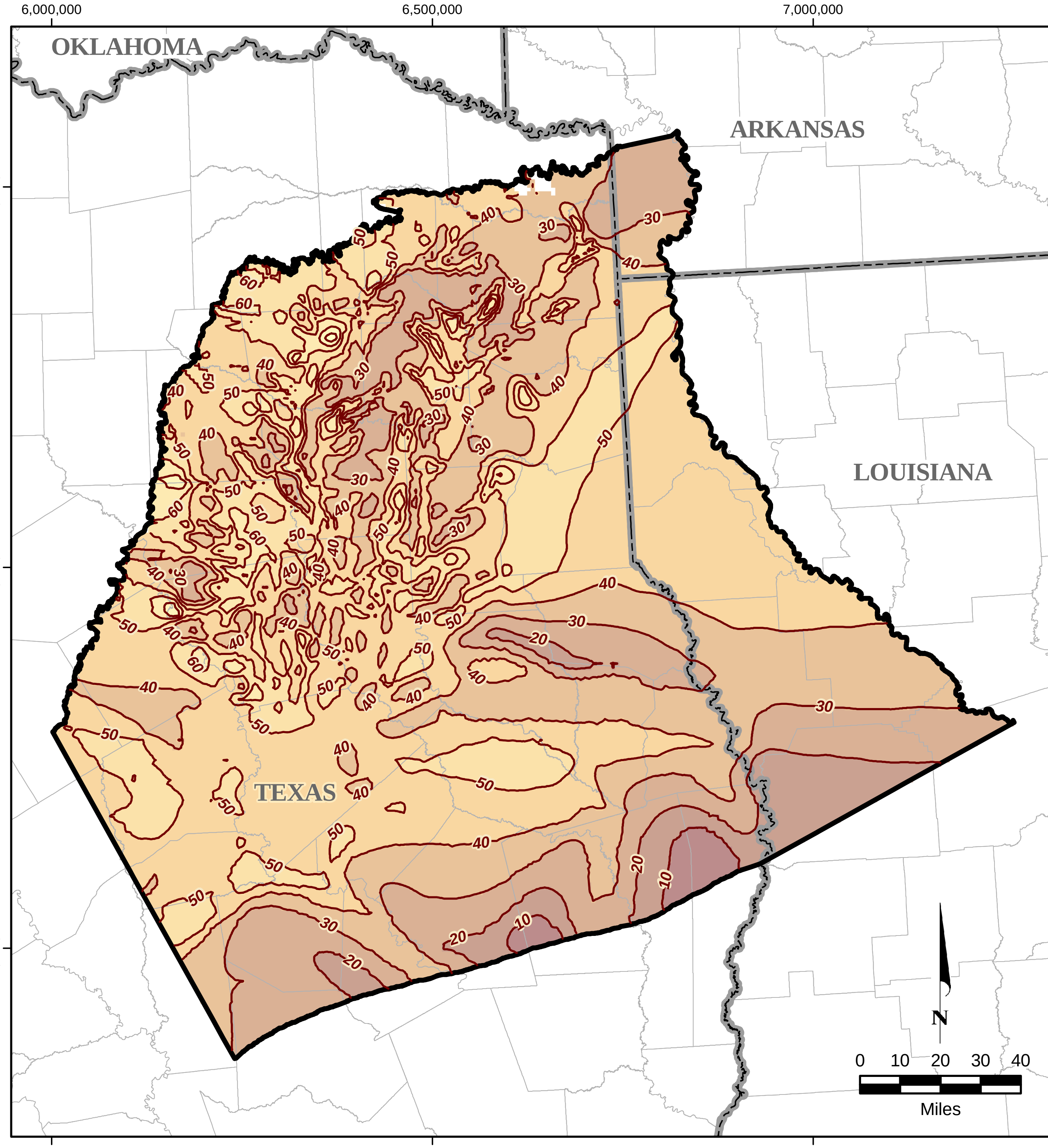


FIGURE 4.5.5. NET SAND THICKNESS CONTOURS FOR QUEEN CITY AQUIFER

1480\REPORT_MAPS\NetSand_QC.mxd\12June2018

DRAFT

MONTGOMERY & ASSOCIATES



EXPLANATION

Study Area

County/Parish

State

50 Contour of Percent Sand, in feet (Fryar and others, 2003)

Net Sand Thickness, in feet

<10.1	30.1 - 40.0	60.1 - 70.0
10.1 - 20.0	40.1 - 50.0	70.1 - 80.0
20.1 - 30.0	50.1 - 60.0	>80.0

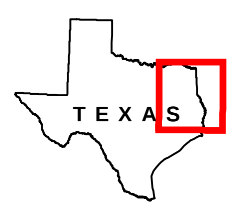
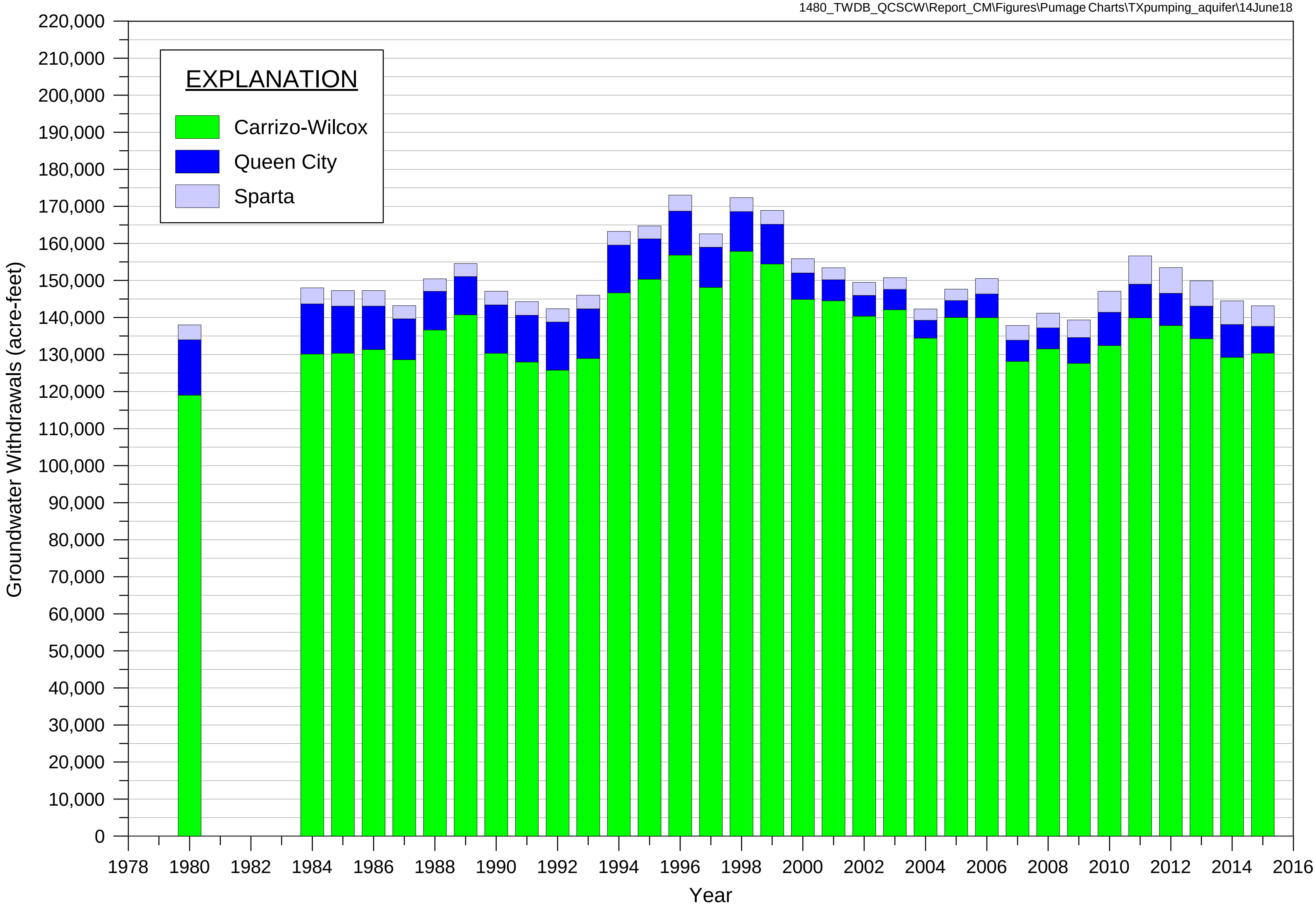


FIGURE 4.5.6. PERCENT SAND CONTOURS FOR WILCOX AQUIFER

1480\REPORT_MAPS\PercnetSand_Wilcox.mxd\19June2018

DRAFT

MONTGOMERY & ASSOCIATES



Source: TWDB annual water use surveys; does not include domestic pumping estimates

FIGURE 4.7.1. ESTIMATED ANNUAL GROUNDWATER PUMPING BY AQUIFER SOURCE IN TEXAS COUNTIES IN STUDY AREA: 1980 THROUGH 2015

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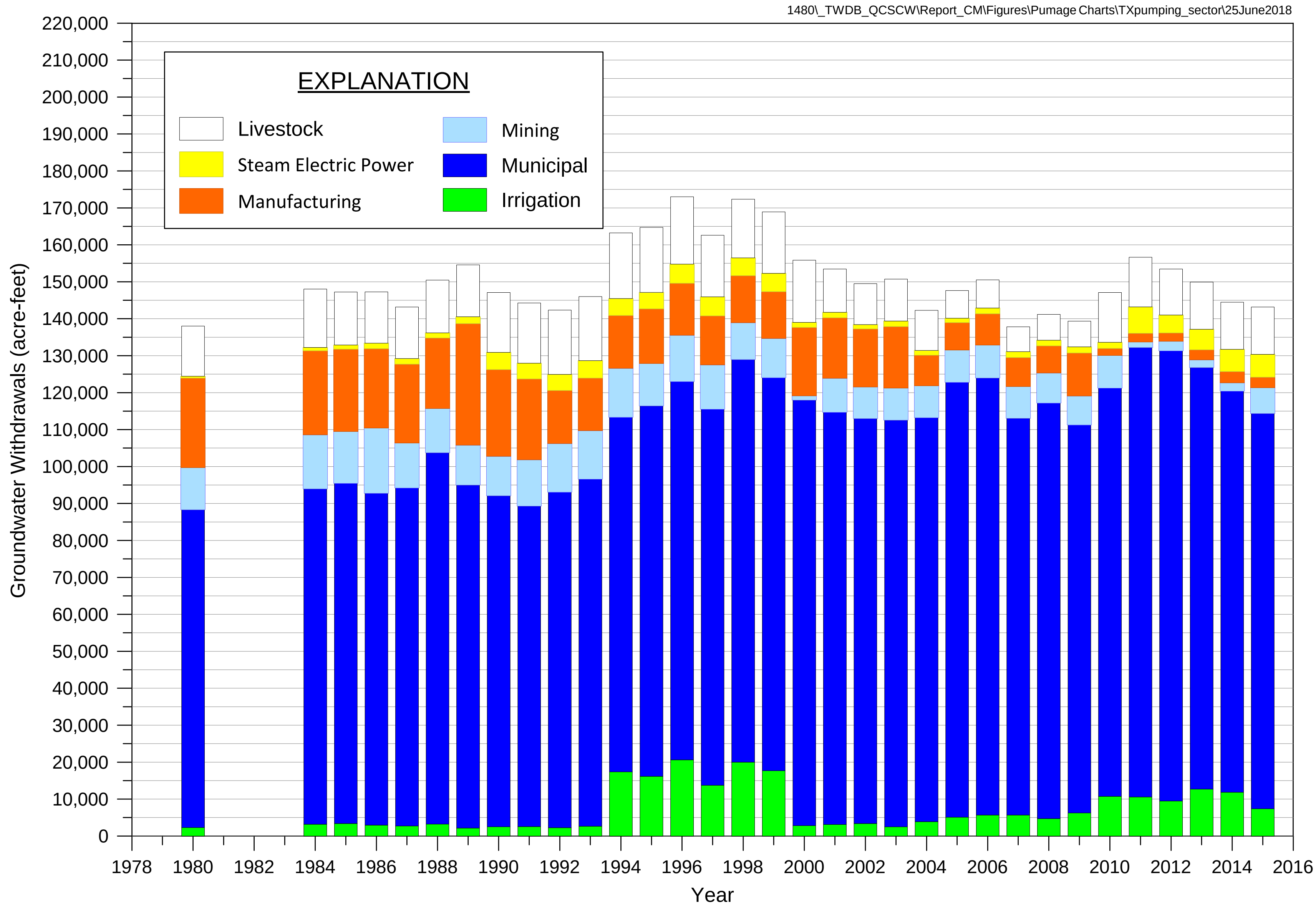
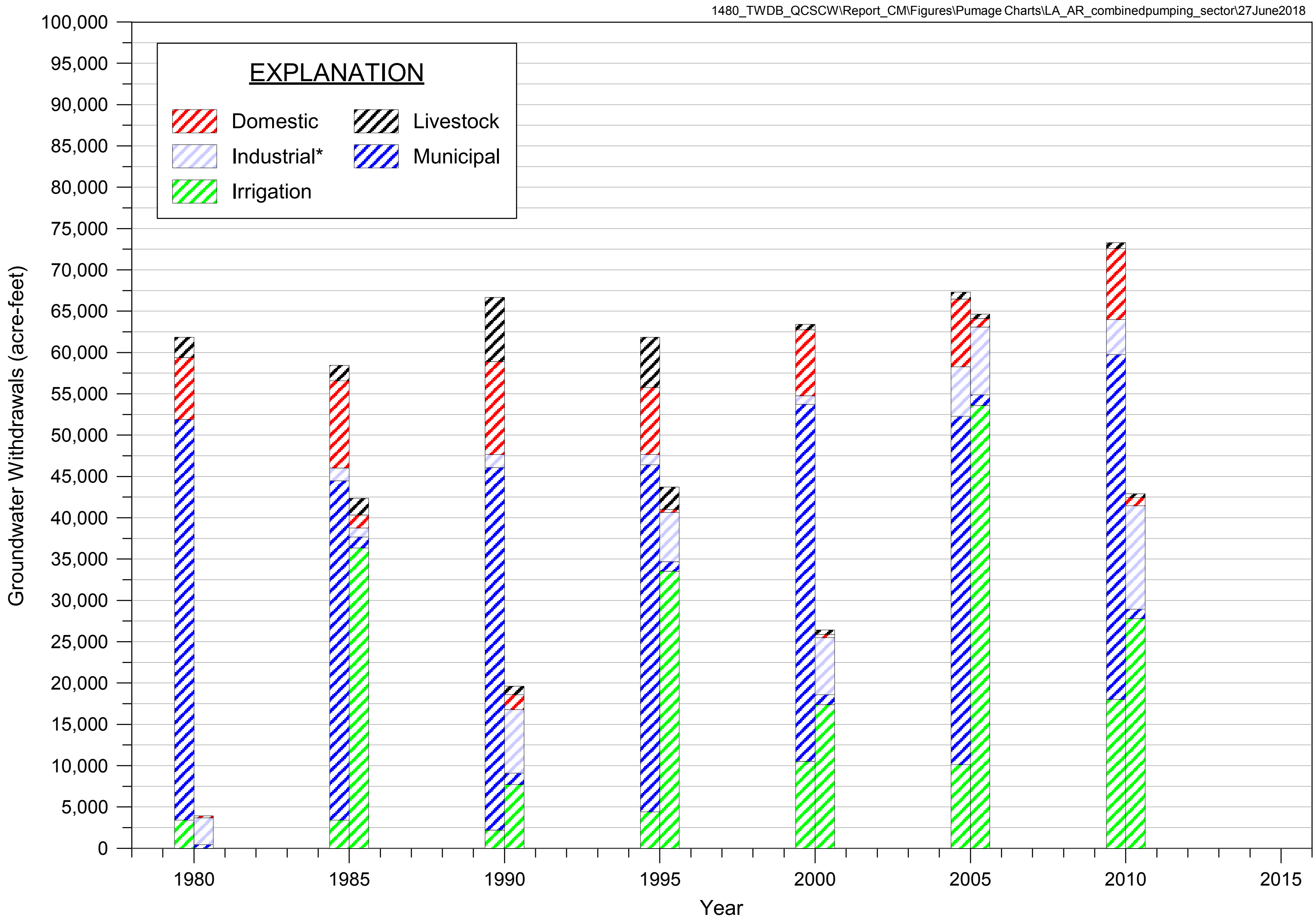
DRAFT



Source: TWDB annual water use surveys; totals include estimated pumpage from Queen City, Sparta, and Carrizo-Wilcox aquifers

FIGURE 4.7.2. ESTIMATED ANNUAL GROUNDWATER PUMPING BY WATER USE SECTOR IN TEXAS COUNTIES IN STUDY AREA: 1980 THROUGH 2015

MONTGOMERY & ASSOCIATES



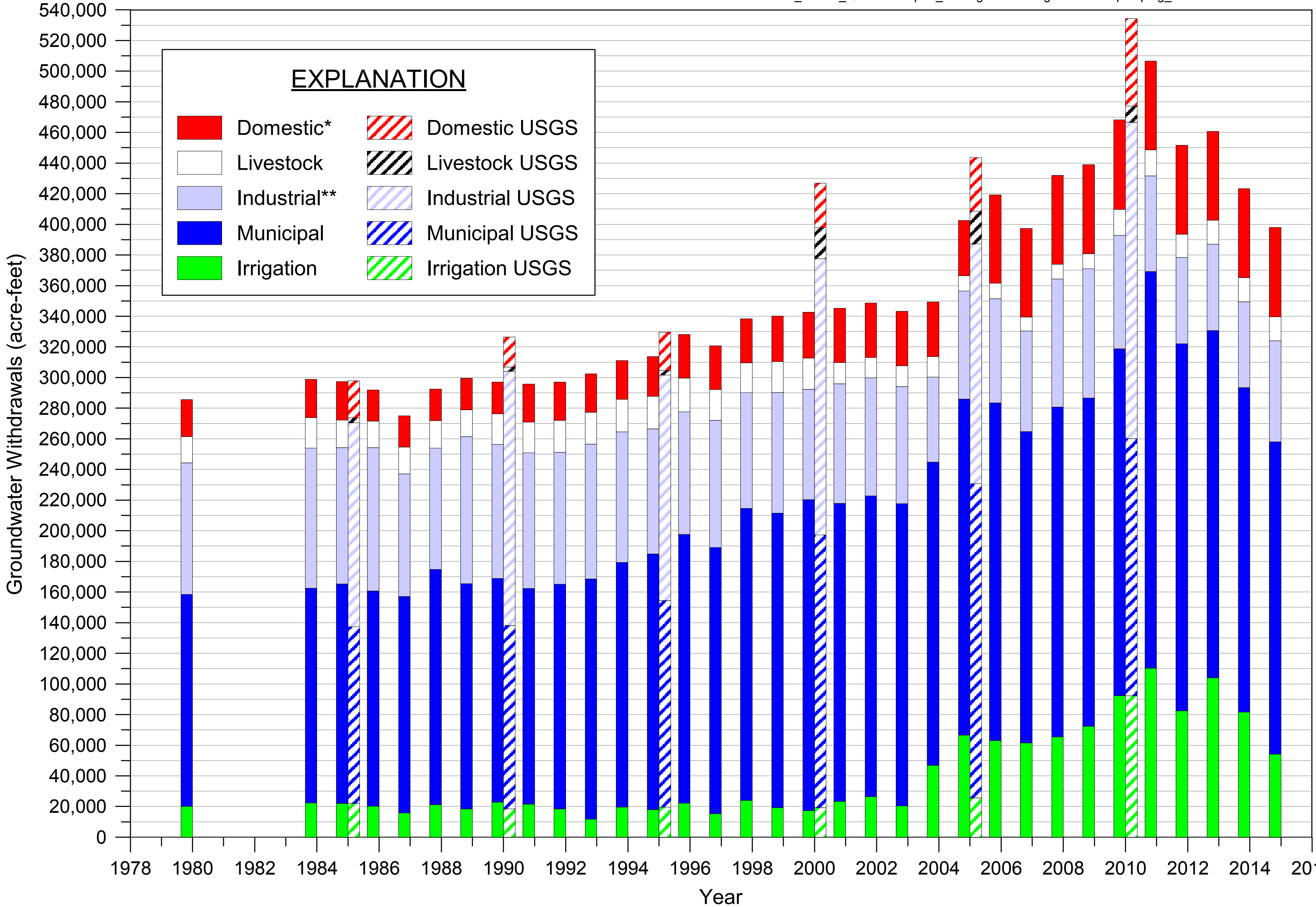
Source: USGS 5-year water use survey pumping estimates (Totals include pumping from all aquifer sources in a county or parish); bar totals on the left side of each pair are for Louisiana, and on the right are for Arkansas

**Industrial category includes the sum of the reported estimates for industrial, mining, electric power, and aquaculture sectors*

FIGURE 4.7.3. ESTIMATED ANNUAL GROUNDWATER PUMPING BY WATER USE SECTOR IN LOUISIANA PARISHES AND ARKANSAS COUNTIES IN STUDY AREA

MONTGOMERY & ASSOCIATES

DRAFT



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 4.7.4. COMPARISON OF TWDB AND USGS TOTAL ANNUAL GROUNDWATER PUMPING ESTIMATES BY WATER USE SECTOR IN TEXAS COUNTIES IN STUDY AREA: 1980 THROUGH 2015

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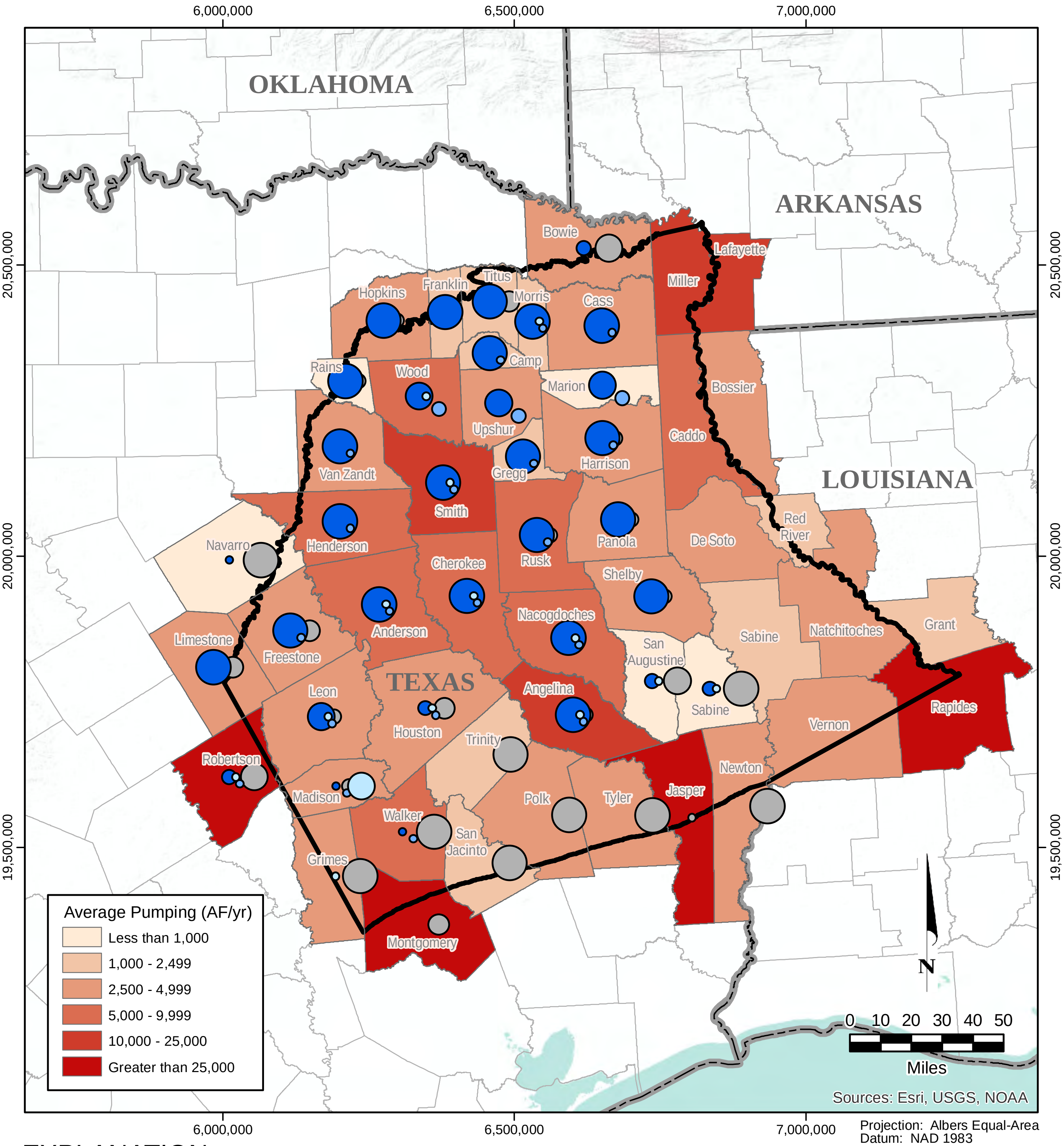
DRAFT



Projection: Albers Equal-Area
Datum: NAD 1983

EXPLANATION

Study Area

Polk — County/Parish and Identifier

State

Percent of Average Pumping by Aquifer Source

- <20%
- 21% - 40%
- 41% - 60%
- 61% - 80%
- 81% - 100%

Aquifer Source

- Sparta Aquifer
- Queen City Aquifer
- Carrizo-Wilcox Aquifer
- Other Aquifer

Data source for Arkansas counties and Louisiana parishes is USGS 5-year water use reports 1980 -2010; aquifer source data was not available.
Data source for Texas counties is TWDB water use surveys 1980-2015.

FIGURE 4.7.5. SUMMARY OF AVERAGE PUMPING FOR COUNTIES AND PARISHES IN STUDY AREA FROM 1980 THROUGH 2015

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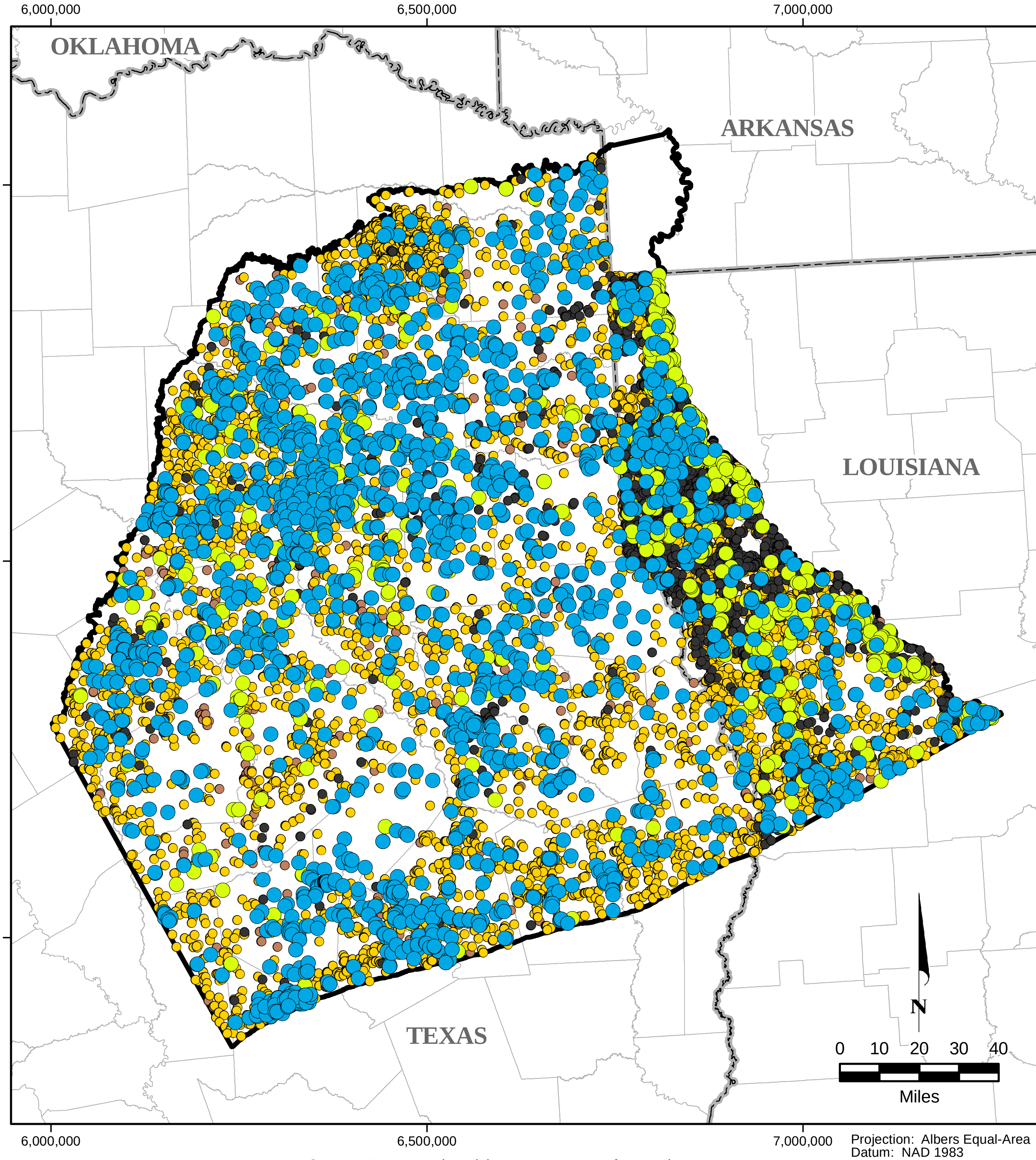
1480\REPORT_MAPS\Pumping_County.mxd\26June2018

DRAFT



Projection: Albers Equal-Area
Datum: NAD 1983

Source: TWDB and Louisiana Department of Natural Resources

EXPLANATION

Study Area
County/Parish
State

Water Use Sector

Municipal
Domestic
Irrigation
Stock
Industrial

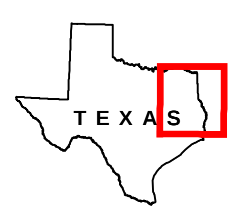


FIGURE 4.7.6. LOCATIONS OF REGISTERED GROUNDWATER PRODUCTION WELLS IN STUDY AREA

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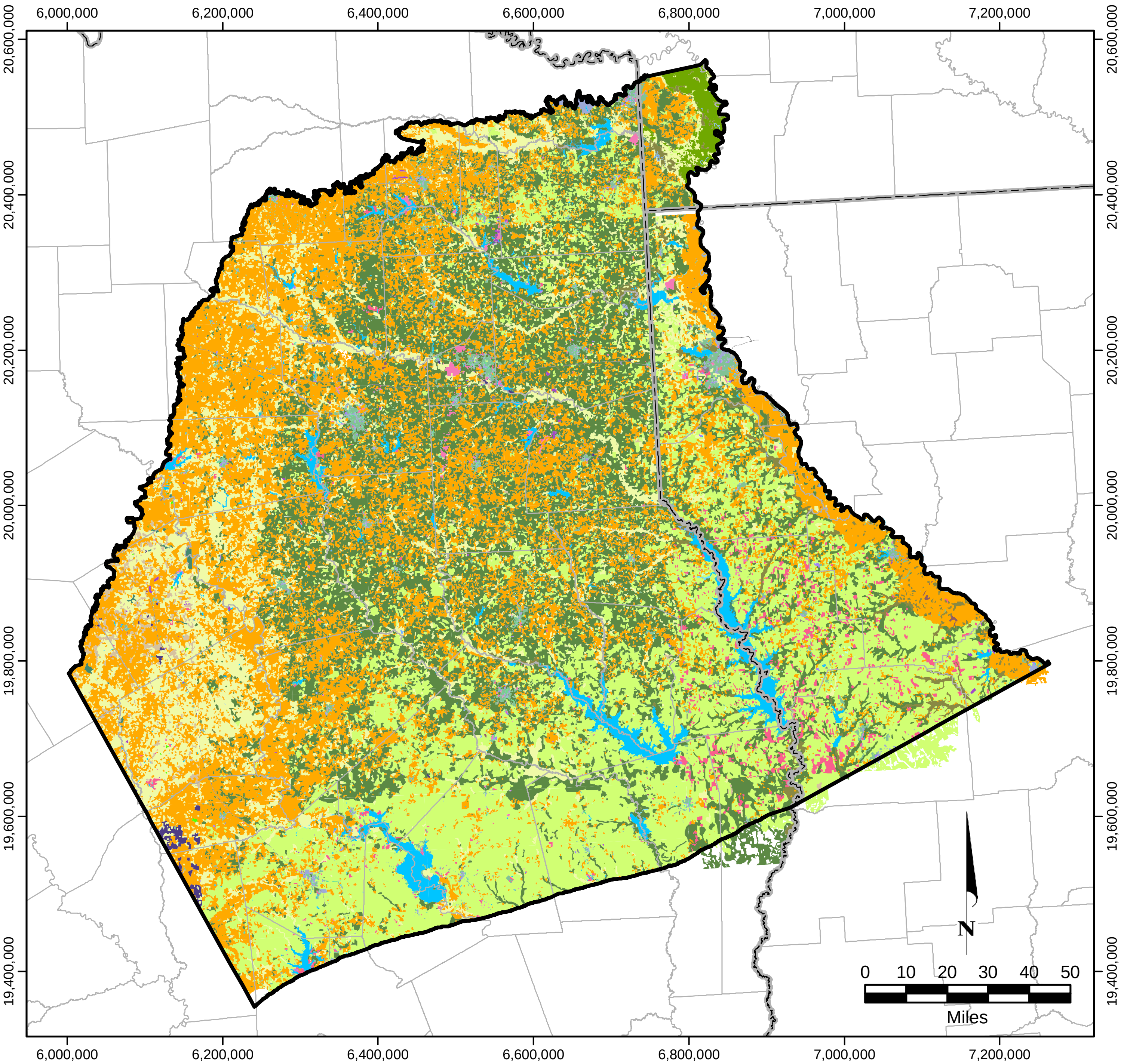
1480\REPORT_MAPS\PumpWells.mxd\14June2018

DRAFT



Projection: Albers Equal-Area
Datum: NAD 1983

EXPLANATION

Study Area

County/Parish

State

USGS GAP Land Cover Units

- Bare exposed rock
- Beaches
- Commercial and services
- Confined feeeding operations
- Cropland and pasture
- Deciduous forest land
- Evergreen forest land
- Forested wetland
- Herbaceous rangeland
- Industrial
- Industrial and commercial complexes
- Lakes
- Mixed forest land
- Mixed rangeland
- Mixed urban or built-up land
- Nonforested wetland
- Orchards, groves, vineyards, nurseries, and ornamentals
- Other agricultural land
- Other urban or built-up land
- Reservoirs
- Residental
- Sandy areas not beaches
- Shrub and brush rangeland
- Streams and canals
- Strip mines, quarries, gravel pits
- Transitional areas
- Transportation, communication, utilities

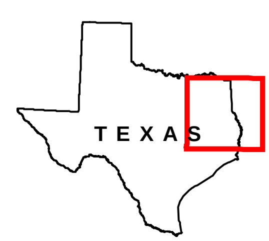


FIGURE 4.7.7. USGS GAP LAND COVER DISTRIBUTION IN STUDY AREA

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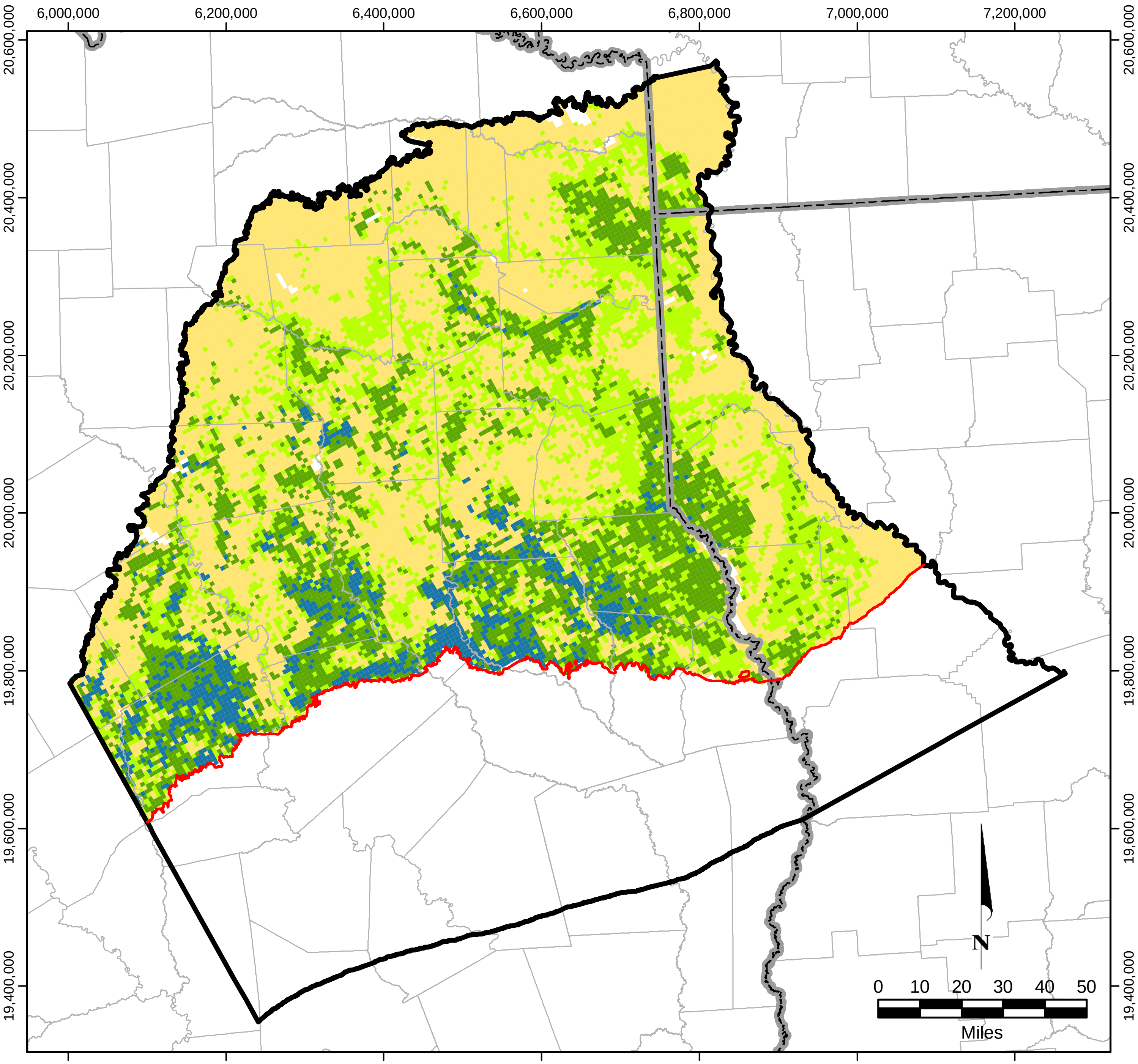
1480\REPORT_MAPS\Veg_gap.mxd\13June2018

DRAFT



Projection: Albers Equal-Area
Datum: NAD 1983

EXPLANATION

Study Area

County/Parish

State

Top of Sparta Boundary

Evapotranspiration Rate, in feet/day

<0.0010

>0.0010 - 0.0015

>0.0015 - 0.0025

>0.0025

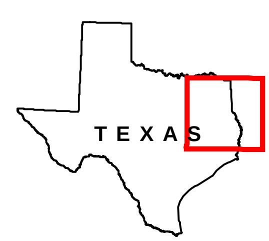


FIGURE 4.7.8. AVERAGE MAXIMUM EVAPOTRANSPIRATION RATE SPECIFIED IN PREVIOUS GAM FOR NORTHERN PORTIONS OF QUEEN CITY AND SPARTA AQUIFERS

MONTGOMERY & ASSOCIATES

1480\REPORT_MAPS\Veg_maxET_prevGAM.mxd\25June2018

DRAFT

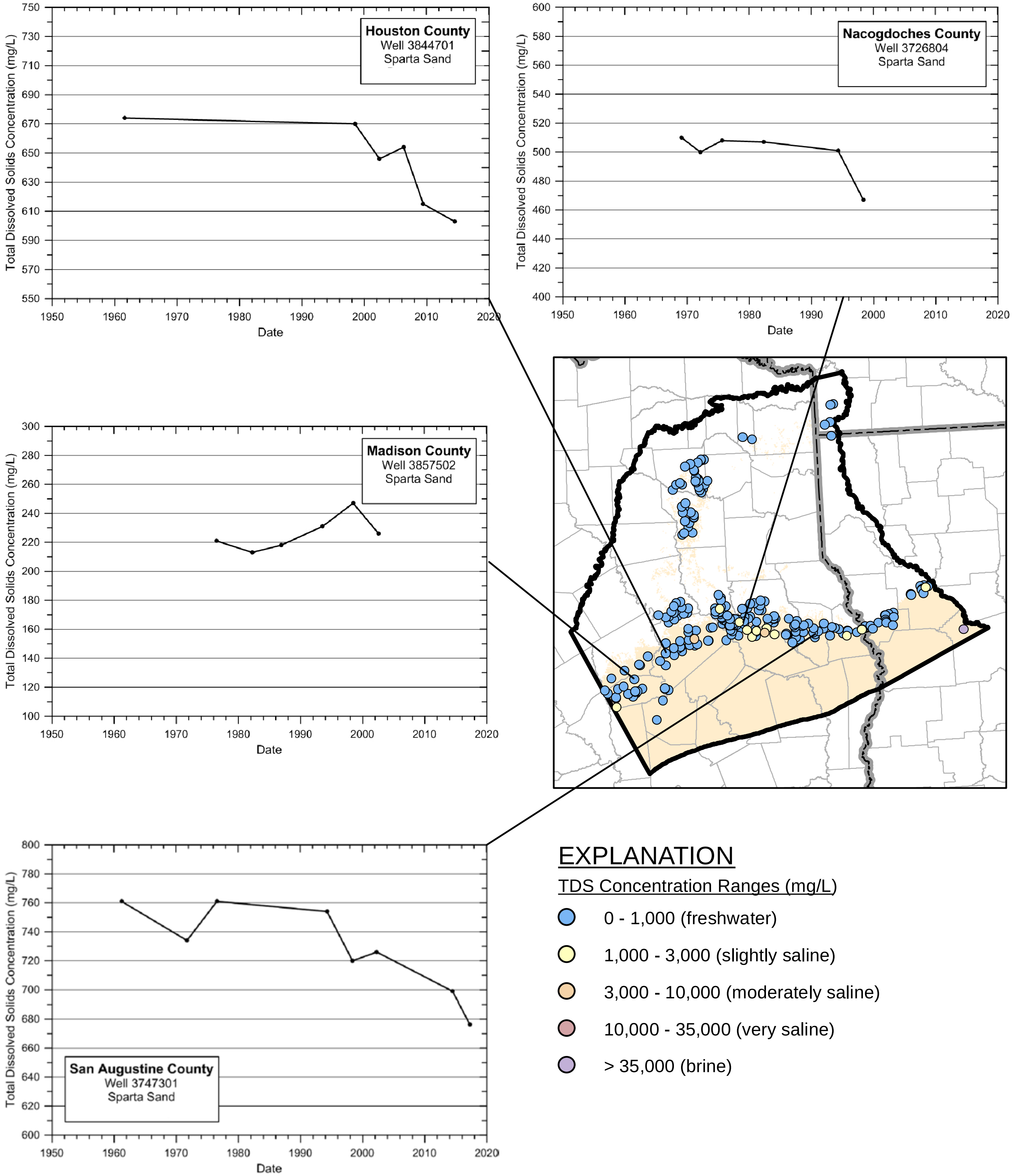


FIGURE 4.8.1. TDS DISTRIBUTION AND SELECTED HISTORIC CONCENTRATIONS FOR SPARTA WELLS IN STUDY AREA

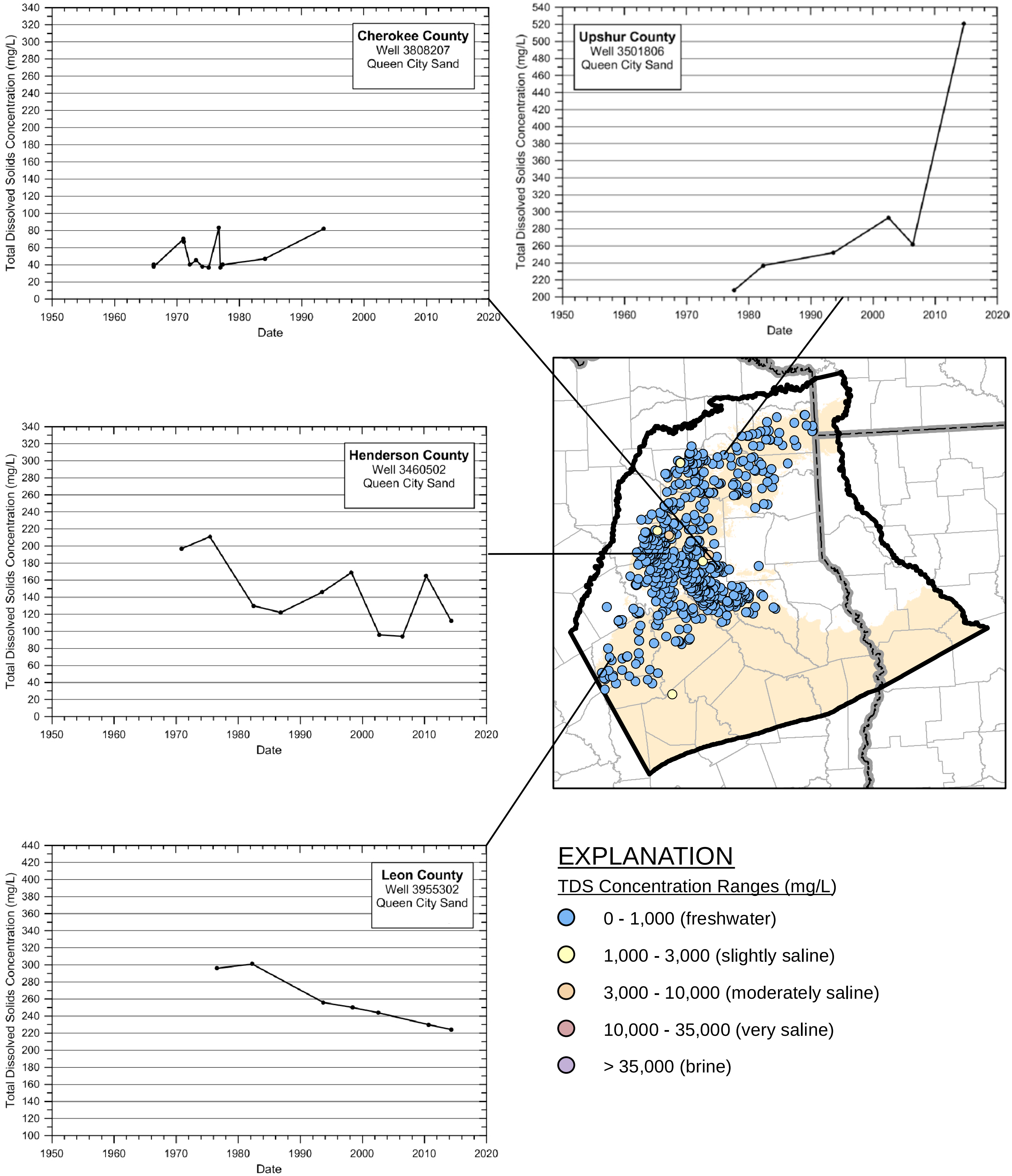


FIGURE 4.8.2. TDS DISTRIBUTION AND SELECTED HISTORIC CONCENTRATIONS FOR QUEEN CITY WELLS IN STUDY AREA

MONTGOMERY & ASSOCIATES

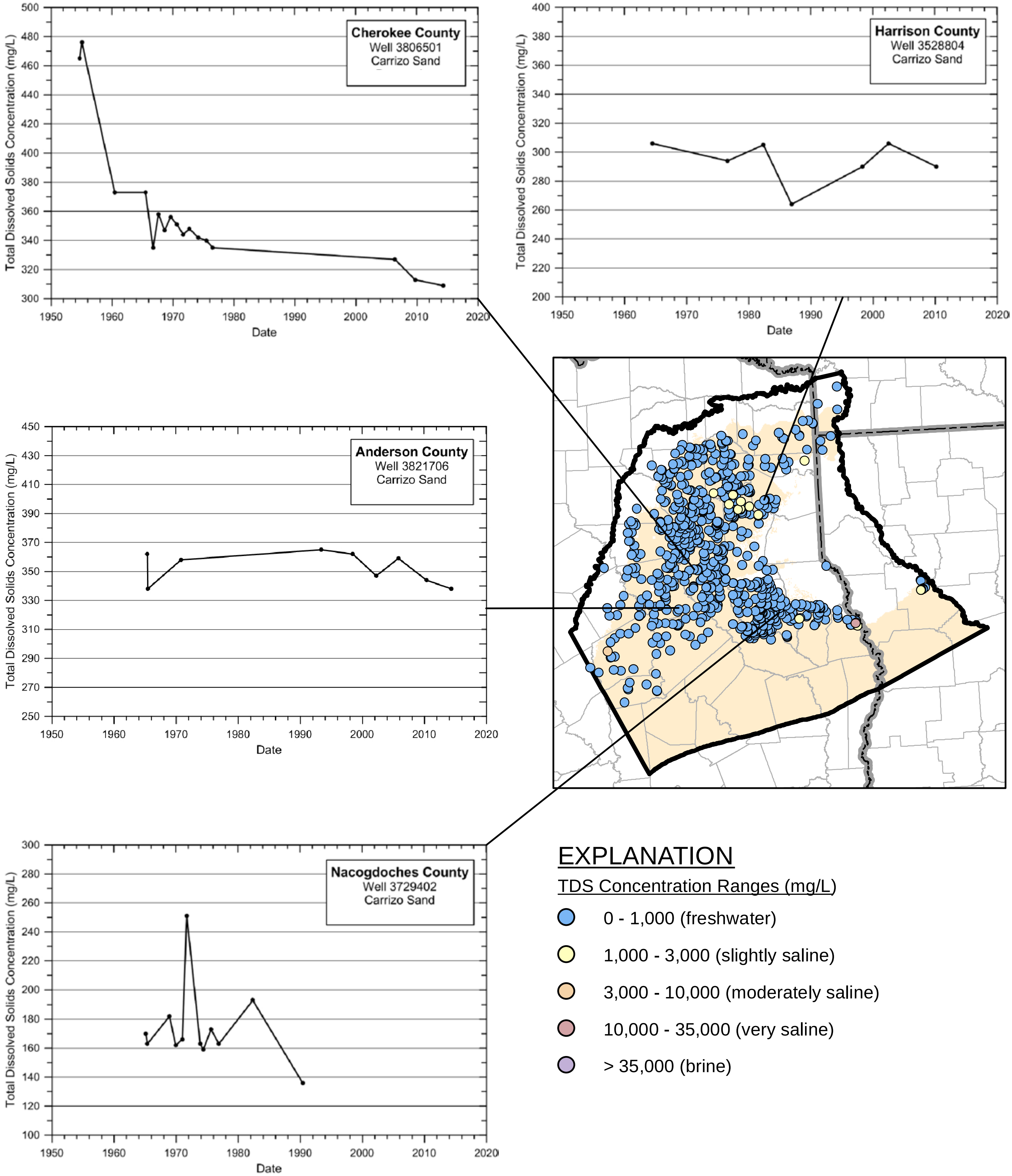


FIGURE 4.8.3. TDS DISTRIBUTION AND SELECTED HISTORIC CONCENTRATIONS FOR CARRIZO WELLS IN STUDY AREA

MONTGOMERY & ASSOCIATES

1480\REPORT_MAPS\TDS_graph_CarrizoSand.mxd\26June2018

DRAFT

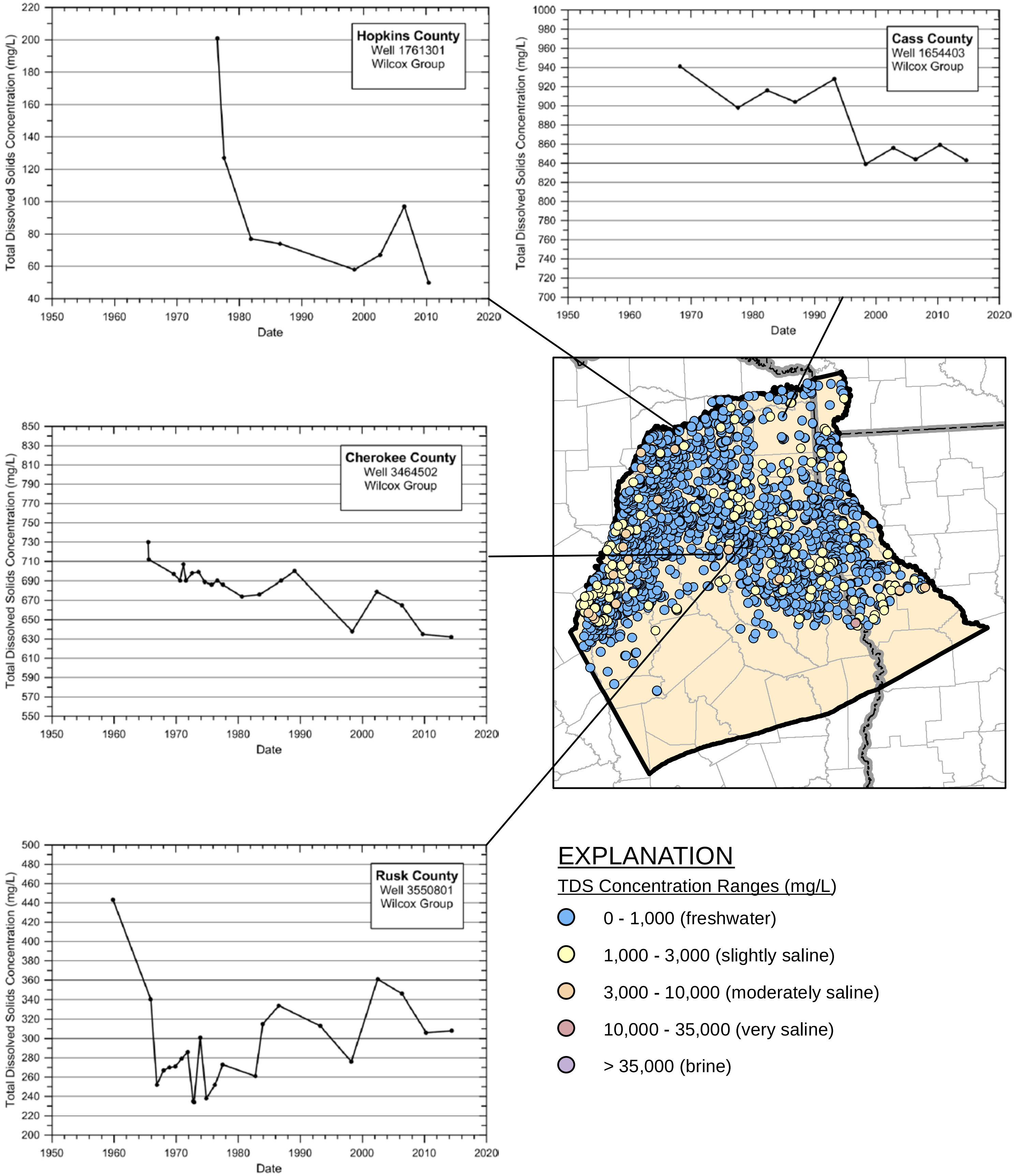


FIGURE 4.8.4. TDS DISTRIBUTION AND SELECTED HISTORIC CONCENTRATIONS FOR WILCOX GROUP WELLS IN STUDY AREA

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1480\REPORT_MAPS\TDSgraphs_Wilcox\26June2018

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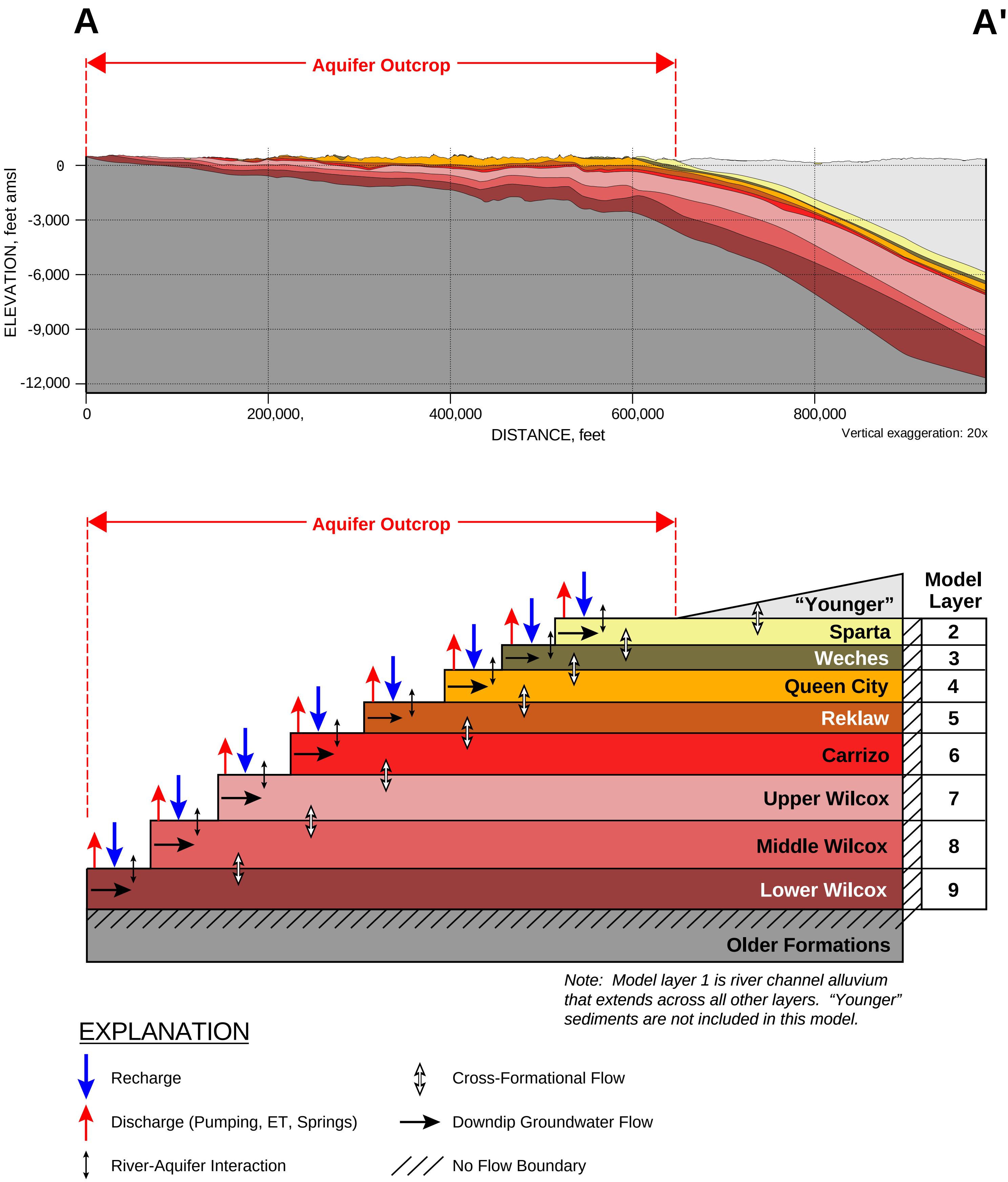

FIGURE 5.0.1. CONCEPTUAL GROUNDWATER FLOW MODEL FOR NORTHERN PORTIONS OF QUEEN CITY, SPARTA, AND CARRIZO-WILCOX GAM

G:\1480\ReportMaps\GWflowModel\26June2018

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