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

Texas Water Development Board Contract 1948312321

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Texas Water Development Board

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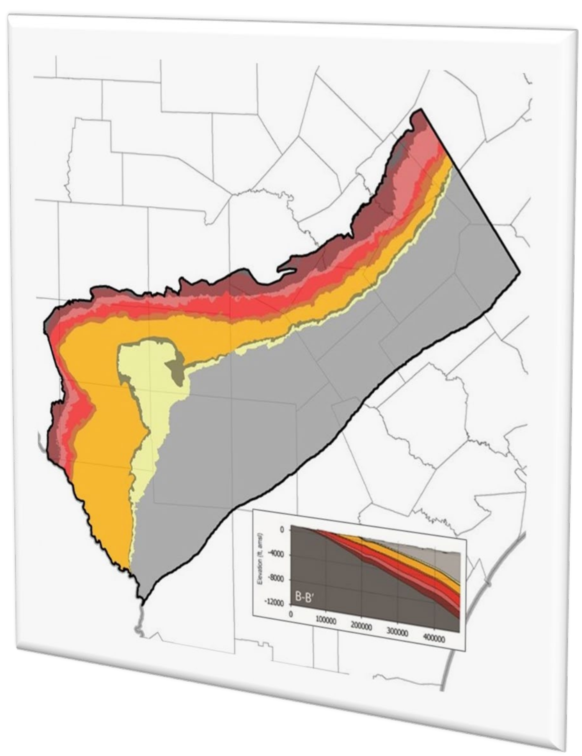

January 2021

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This report documents the work of the following Licensed Texas Geoscientists and Engineers:

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Table of Contents

List of Figures

List of Tables

List of Appendices

Executive Summary

The southern portion of the Carrizo-Wilcox, Queen City, and Sparta aquifer system is an important groundwater resource in south central 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 groundwater availability model was previously updated in 2004 when the Queen City and Sparta aquifers were added to the Carrizo-Wilcox groundwater availability model developed in 2003. This study provides an additional update to the groundwater availability model, with particular focus on improving the hydrostratigraphic framework to improve consistency with the adjacent groundwater availability model for the central portions of the aquifer system. This report summarizes the conceptual hydrogeologic model for the aquifer system, which will provide the foundation for construction of the updated groundwater model. This report does not reproduce documentation available on the construction of the previous groundwater availability models, except as necessary to describe the development of the updated groundwater availability model.

The conceptual model described herein provides the hydrogeologic framework and characterization of the aquifer of interest in the study area. This investigation involved evaluation of information regarding physiography, climate, hydrogeology, groundwater levels and groundwater movement, surface water features, recharge, hydraulic properties for the aquifer units, discharge (including well pumping), and groundwater quality.
The conceptual model relies on the results of previous groundwater availability model studies by Deeds 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 toward verifying and updating the hydrostratigraphic framework of the aquifer system for input to the updated groundwater model.

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

The flow system is bounded by the Rio Grande to the south, by the boundary between the Guadalupe and Colorado river basins to the north, and by the updip extent of the Wilcox Group to the west. The eastern model boundary is the downdip extent of the Wilcox growth

fault zone. Model boundary locations are the same as the previous groundwater availability model for this aquifer system.

The conceptual model includes two hydrogeologic conditions: initial conditions and transient conditions. The transient model period represents historical hydrogeologic conditions from 1980 through 2017. This time period was selected principally based on pumping data availability. Initial conditions for the transient model represent conditions prior to 1980.

Regional groundwater movement in the study area is generally from the upland areas in the west to the east toward the Gulf of Mexico. Groundwater withdrawals since the early 1980s have occurred predominantly for irrigation uses and, to a lesser degree, municipal and rural domestic supplies. Total annual groundwater withdrawals have generally remained larger than 240,000 acre-feet per year since 1980, with peak withdrawals of about 300,000 acre-feet per year during the 1990s. Pumping in recent years has been on the order of 275,000 acre-feet per year. Groundwater levels in the aquifers have declined and rebounded in areas in response to local pumping and recharge. Groundwater levels have been relatively stable in outcrop areas, with some areas of decline; while groundwater levels in down-dip portions of the aquifers have generally declined since the 1980s. Aquifer recharge occurs from percolation of precipitation and infiltration of impounded water in reservoirs and lakes. Shallow groundwater levels contribute to streamflows and a few flowing springs along the major drainages in the area. The major rivers have gaining streamflow conditions along their lengths within the study area.

Information from the conceptual model described herein will be incorporated in the numerical groundwater availability model. This report will be updated in the future with details about the construction and calibration of the groundwater model.

1 Introduction

The Texas Water Development Board (TWDB) recognizes nine major aquifers and twenty-two minor aquifers in Texas. These aquifers are shown on Figure 1-1 and Figure 1-2. Major aquifers produce large quantities of groundwater over large areas, while minor aquifers produce small quantities of groundwater over large areas or large quantities of groundwater over small areas. Groundwater models developed in Texas through the Groundwater Availability Model (GAM) program have been used in numerous ways to advance groundwater planning and management of the aquifers in the state. When the program began almost 20 years ago, one of the objectives was that the models were to be used as living tools that would be updated as data and modeling technology improved.

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

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

The primary objective of this project is to update the existing groundwater availability model for the southern portions of the Carrizo-Wilcox, Queen City, and Sparta aquifers. The groundwater availability model is used to simulate impacts of groundwater pumping on groundwater resources in southern Texas. The study area is shown on Figure 1-3. This model will build from two primary sources of data and information: (1) the existing groundwater availability models for the Queen City and Sparta Aquifers (Kelley and others, 2004), and (2) the existing groundwater availability model for the southern Carrizo-Wilcox Aquifer (Deeds and others, 2003). The resulting numerical model developed for this project will provide the means to assess future impacts on groundwater conditions from current pumping and projected increases in pumping. Model results will be used for evaluating groundwater impacts, surface water impacts, and the potential for ground subsidence that may occur in the area due to long-term withdrawal of groundwater. The groundwater availability model will also be used to assist the groundwater conservation districts in Groundwater Management Area 13 to develop and/or revise their desired future conditions.

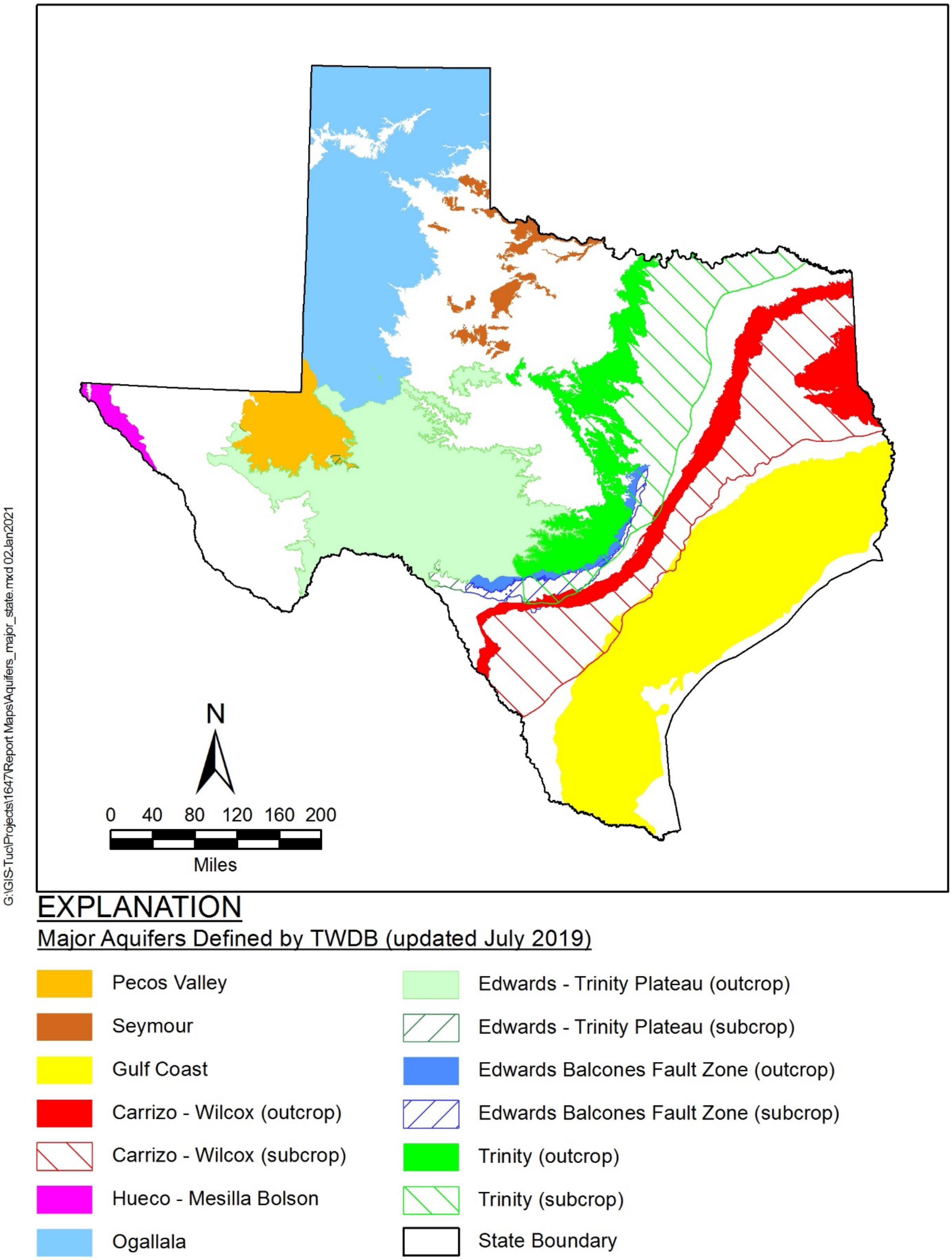

Figure 1-1. Major aquifers in Texas.

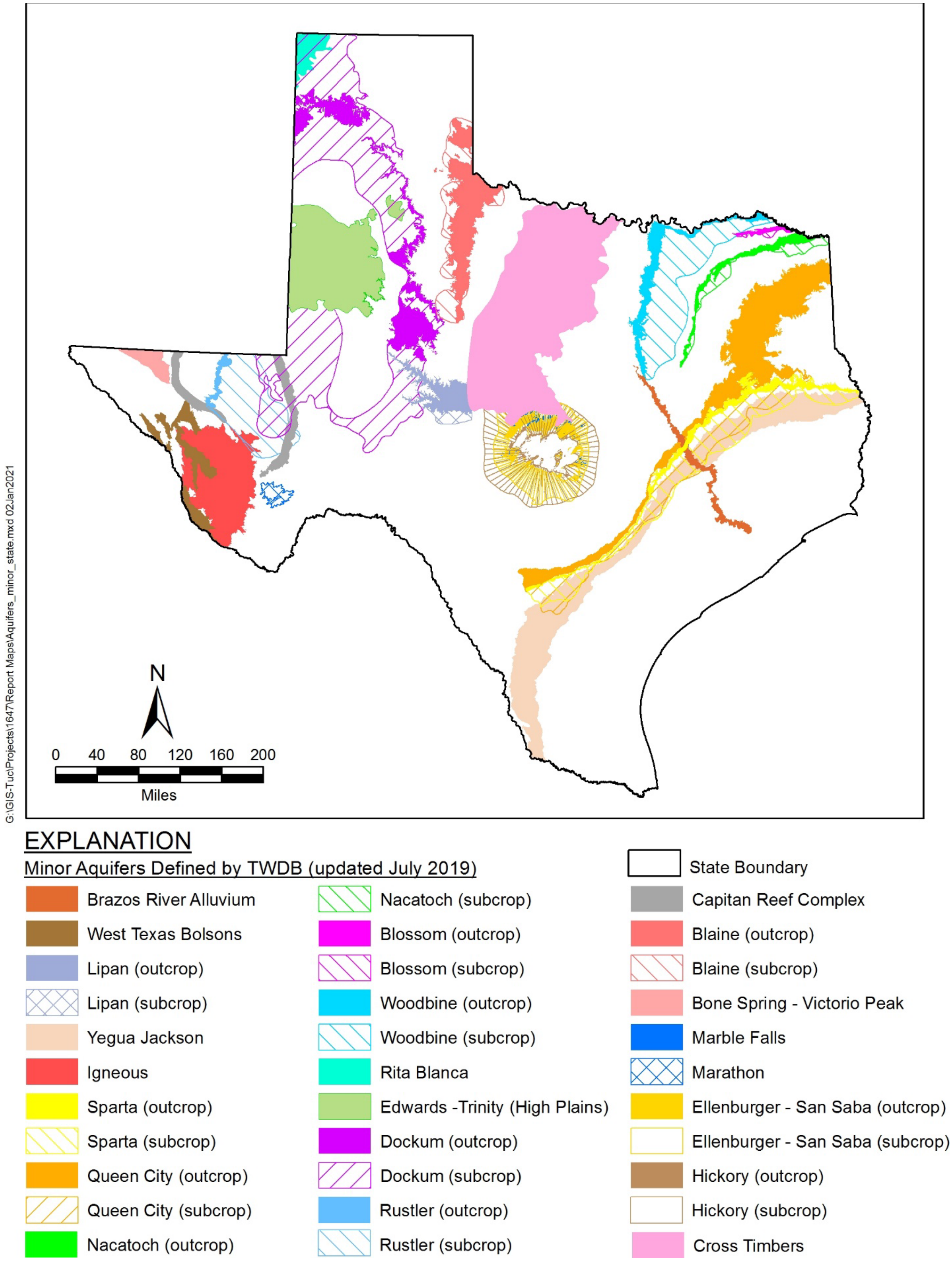

Figure 1-2. Minor aquifers in Texas.

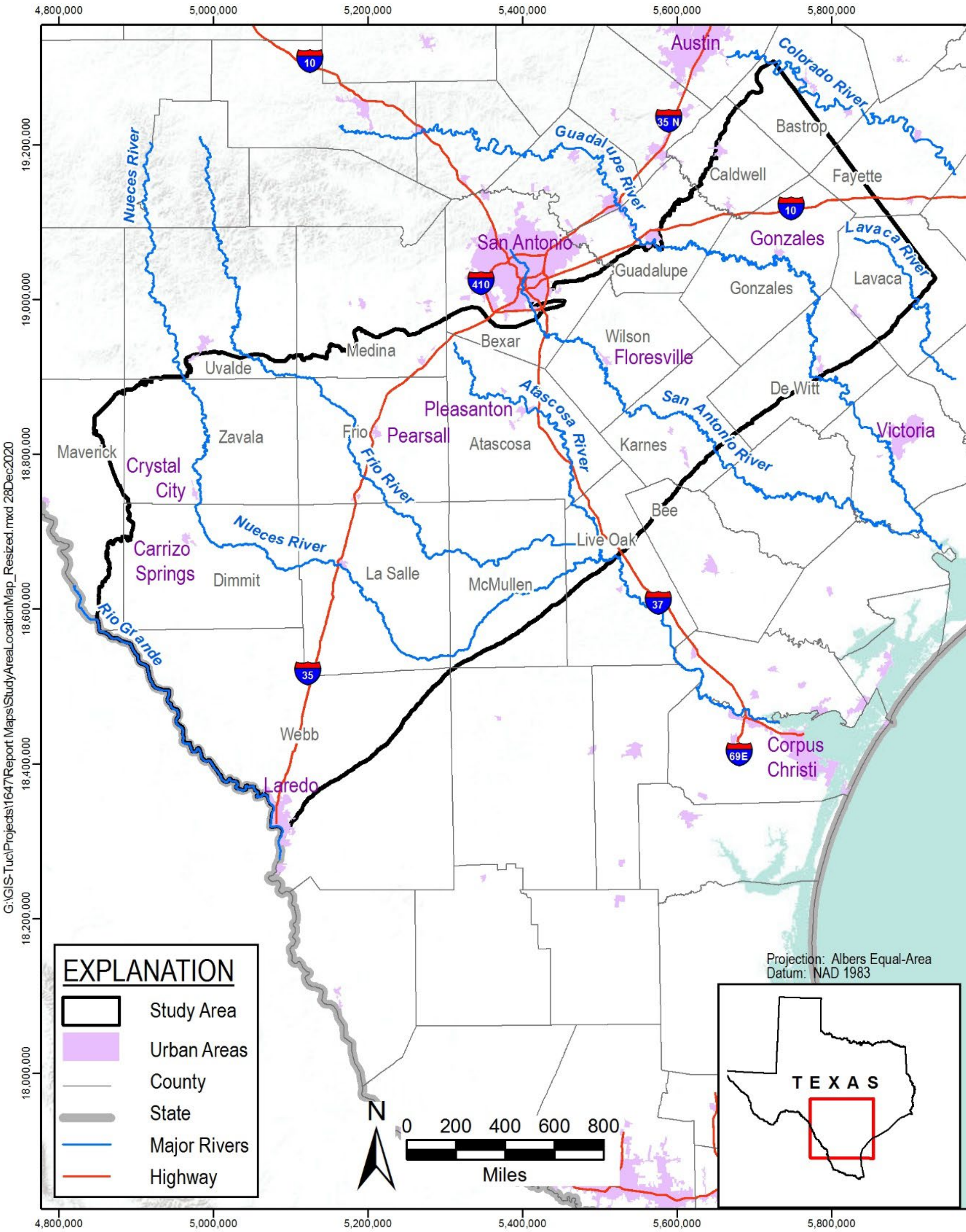

Figure 1-3. Location of study area.

The model for this study will be developed specifically to address the objectives summarized above. The model domain extent and actively simulated aquifers were selected to encompass the water extractions of interest in the region. The model will be calibrated to observed annual conditions (groundwater levels and flows) from 1980 through 2017. 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 subsequent chapters of this report.

This project is conducted in two phases. Phase 1 is the update of the conceptual hydrogeologic model for the southern portion of the Carrizo-Wilcox, Queen City, and Sparta 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 and the numerical groundwater model developed for the southern portion of the Carrizo-Wilcox, Queen City, and Sparta aquifers. An overview of the study area and summaries of previous studies are provided in Chapter 1. The hydrostratigraphy of the aquifer system, aquifer properties, groundwater recharge and discharge, surface water system, and water quality are described in detail in Chapter 2. The general conceptual model for development of the groundwater model is also summarized in Chapter 2. The information provided in this report will be used to update the numerical groundwater model in Phase 2 of this project, which will be described in detail in subsequent chapters. Phase 2 will begin in 2021.

1.1 Study Area

The study area for this investigation is located predominantly in south-central Texas (Figure 1-3). The study area is the same as the previous groundwater availability models by Deeds and others (2003) and Kelley and others (2004). The area includes all or portions of Atascosa, Bastrop, Bee, Bexar, Caldwell, De Witt, Dimmit, Fayette, Frio, Gonzales, Guadalupe, Karnes, La Salle, Lavaca, Live Oak, Maverick, McMullen, Medina, Uvalde, Webb, Wilson, and Zavala counties. Cities and major surface water drainages are shown on Figure 1-3. Major and minor aquifers that occur in the study area are shown on Figure 1-4 and Figure 1-5. The Yegua-Jackson Aquifer (minor) and Gulf Coast Aquifer System (major) overly the aquifers of interest for this study and are not explicitly included in this study.

Groundwater administrative areas located in Texas within the study area are shown on Figure 1-6, Figure 1-7, and Figure 1-8. The boundaries for these areas were obtained from TWDB (2019a). The study area extends across portions of five Regional Water Planning Areas (Figure 1-6): Region K (Lower Colorado), Region L (South Central Texas), Regional M (Rio Grande), Region N (Coastal Bend), and Region P (Lavaca). Region L extends across the majority of the study area. Fifteen Groundwater Conservation Districts are located within the study area (Figure 1-7): Bee, Duval County, Edwards Aquifer, Evergreen Underground Water Conservation District, Fayette County, Lost Pines, McMullen, Medina, Pecan Valley, Plum Creek, Gonzales Under Ground Water District, Guadalupe County, Live Oak Under Ground Water District, Uvalde Under Ground Water District, and Wintergarden. In addition, the study area encompasses Groundwater Management Area 13, and also extends across portions of Groundwater Management Areas 10, 12, 15, and 16 (Figure 1-8).

Figure 1-9 shows the major rivers and associated drainage basins in the study area. Major rivers basins present in the study area include Rio Grande, Nueces, San Antonio, and Guadalupe basins, with small portions of the Colorado and Lavaca basins. Basin boundaries represent TWDB-designated major river basins (TWDB, 2019a). The Nueces River basin includes the Frio and Atascosa rivers, which are considered major rivers for this study.

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 Rio Grande in the south, and the approximate surface water basin divide between the Guadalupe and Colorado rivers in the northeast. The western boundary is the western extent of the Wilcox Aquifer outcrop. The eastern boundary is the same as defined for the previous groundwater availability models, which is the updip limit of the Wilcox growth fault zone as defined by Bebout and others (1982). The top or upper boundary of the model is defined as the land surface and the bottom boundary is defined as the bottom of the Wilcox Group (top of Midway Formation). This study area is the same as the boundaries in the previous groundwater availability models developed by Deeds and others (2003) and Kelley and others (2004).

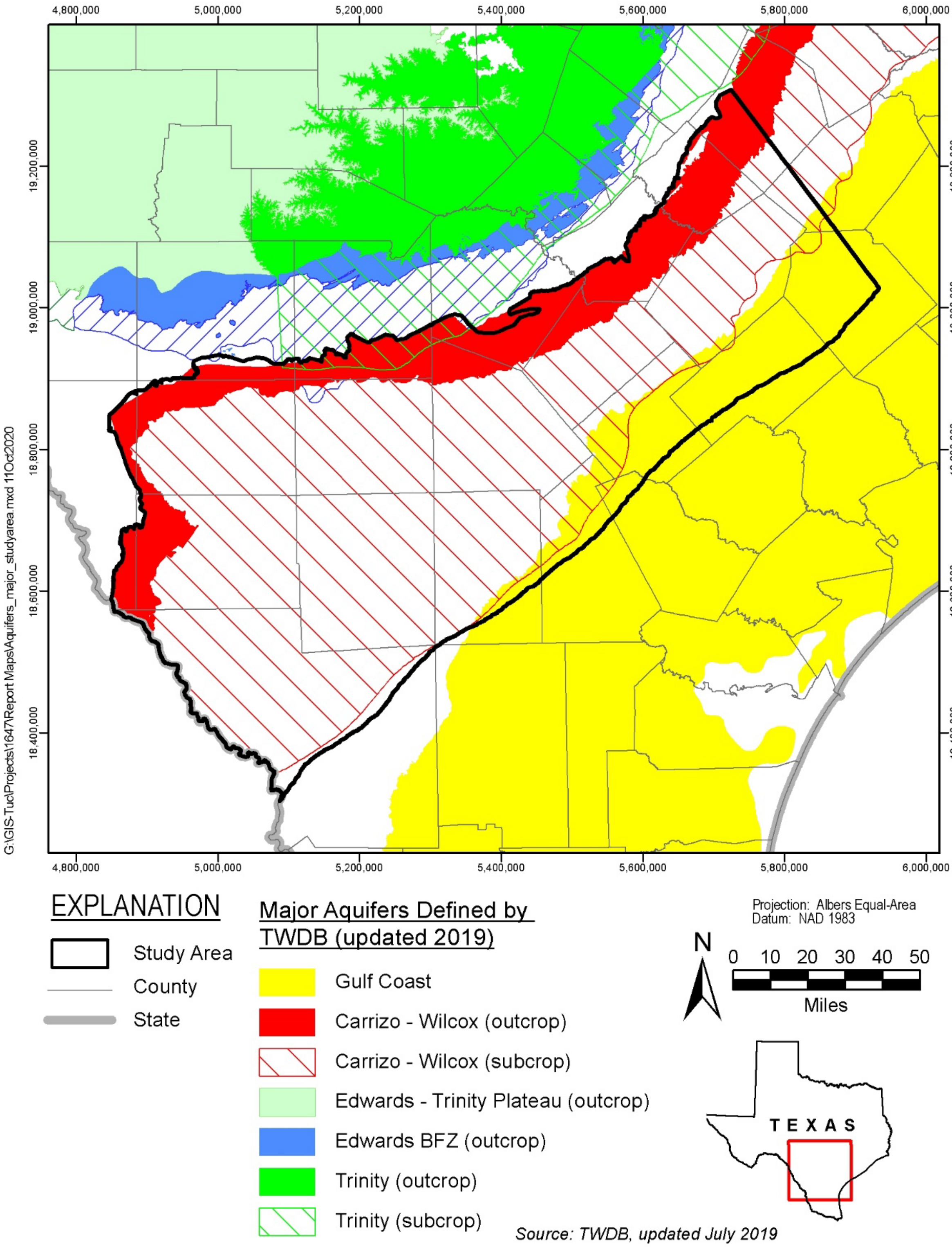

Figure 1-4. Major aquifers in study area.

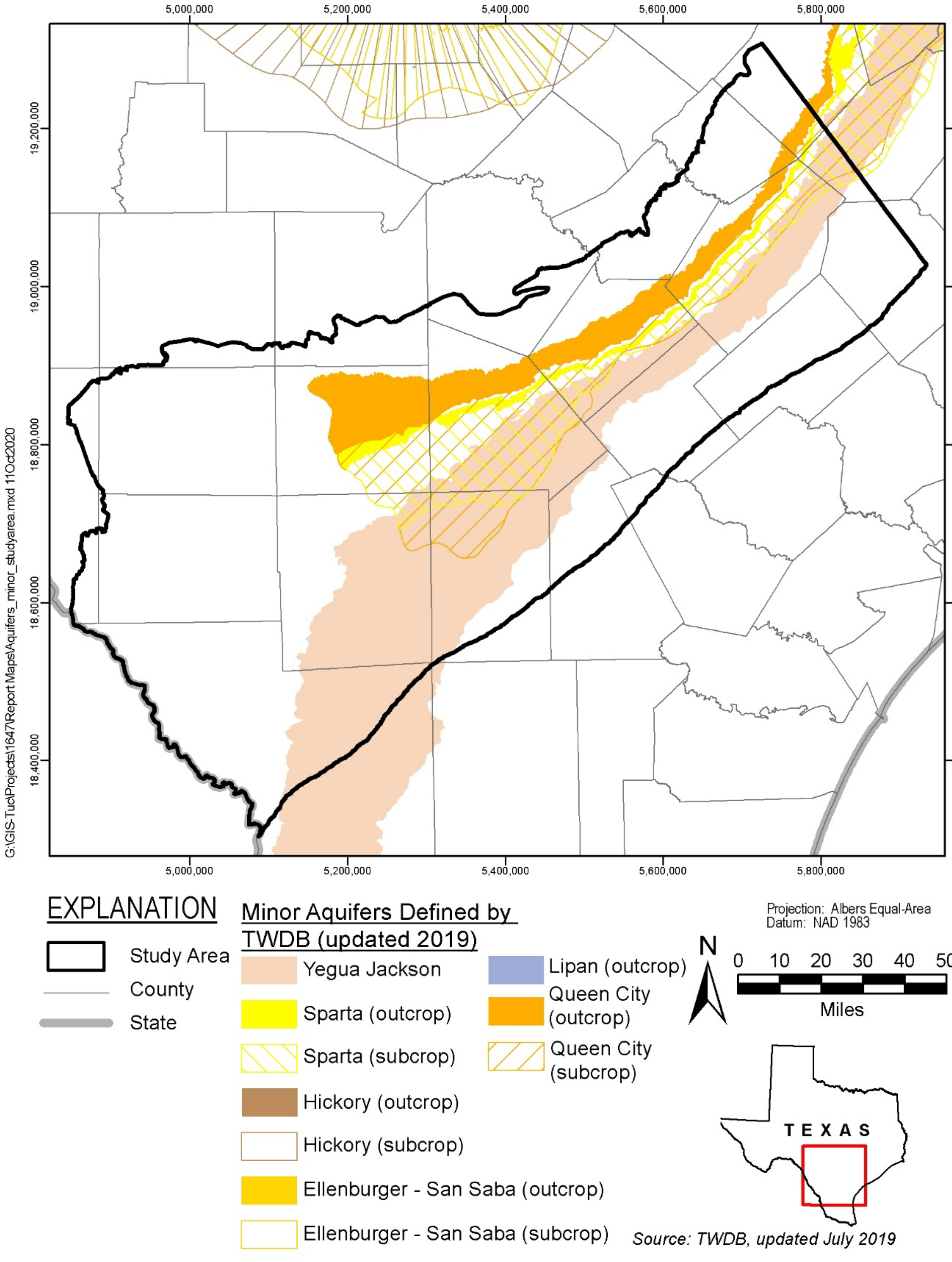

Figure 1-5. Minor aquifers in study area.

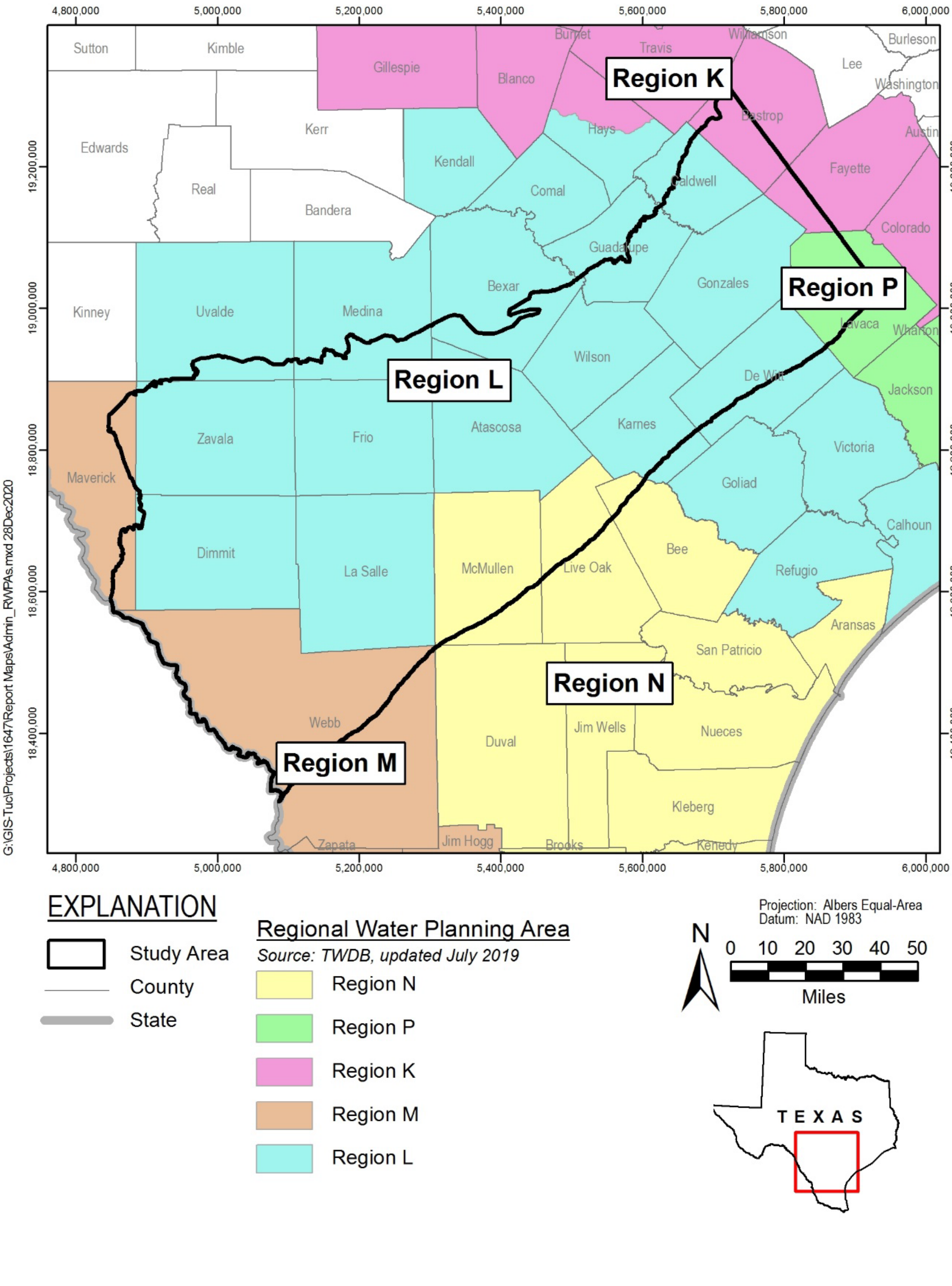

Figure 1-6. Regional planning areas in study area.

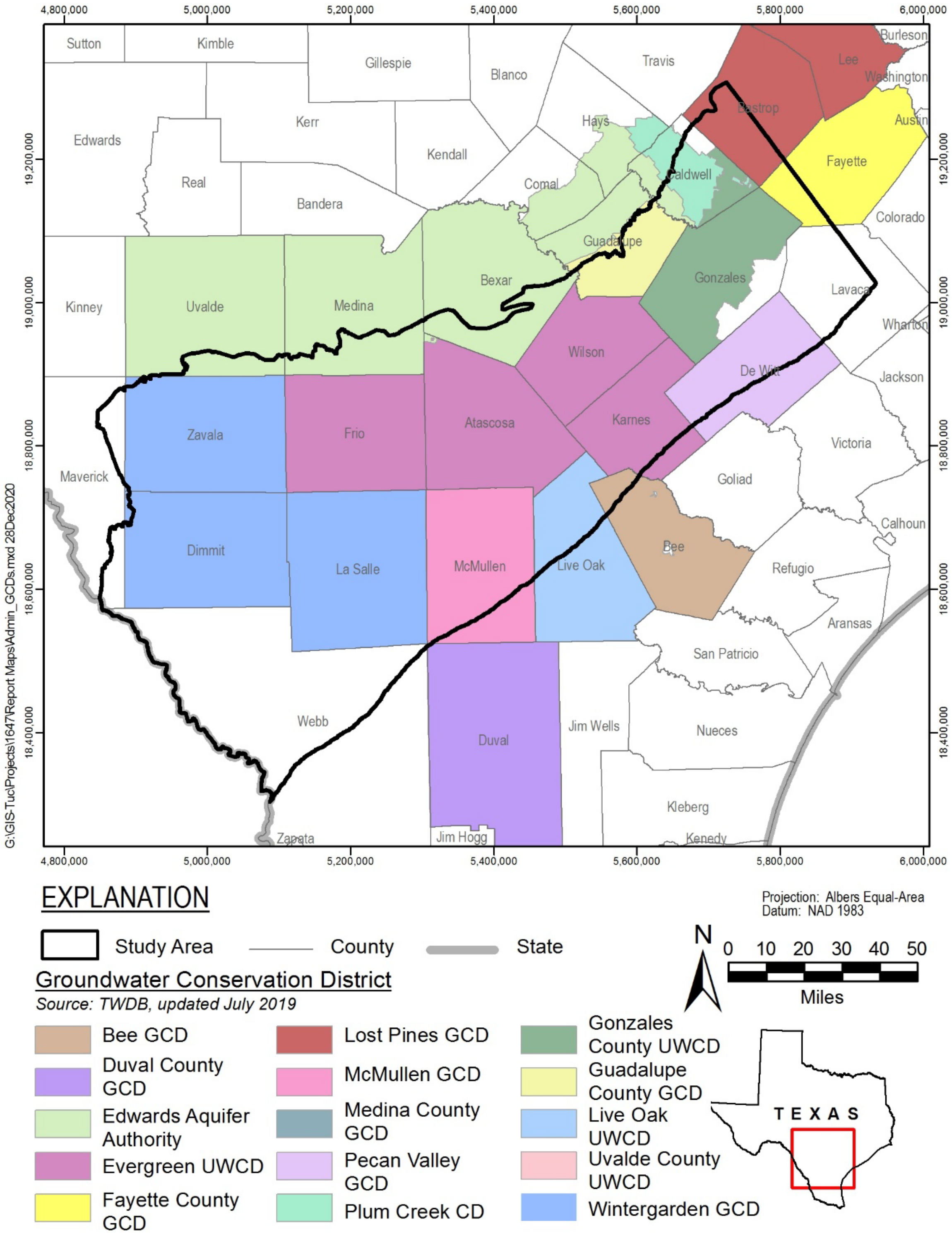

Figure 1-7. Groundwater conservation districts in study area.

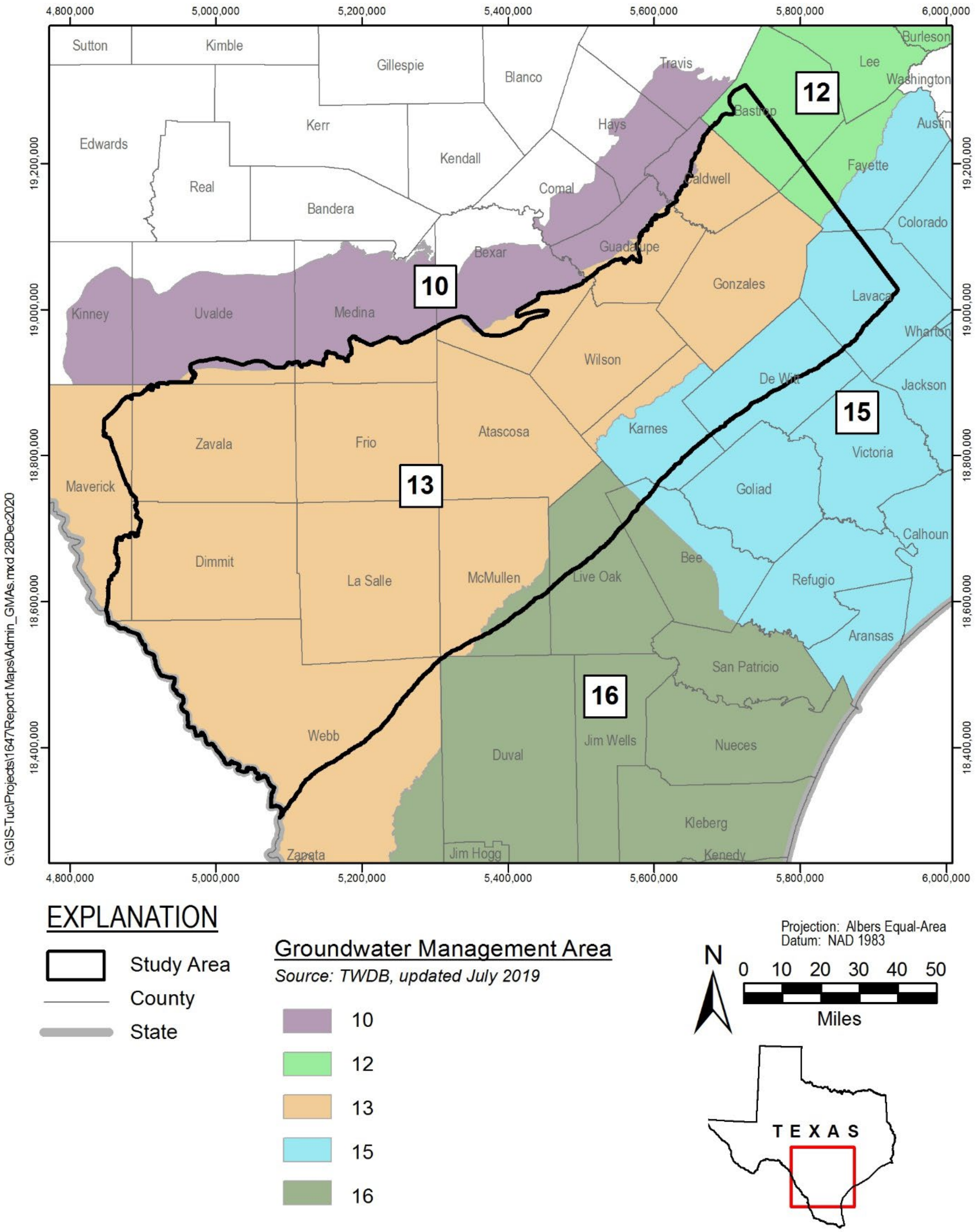

Figure 1-8. Groundwater management areas in study area.

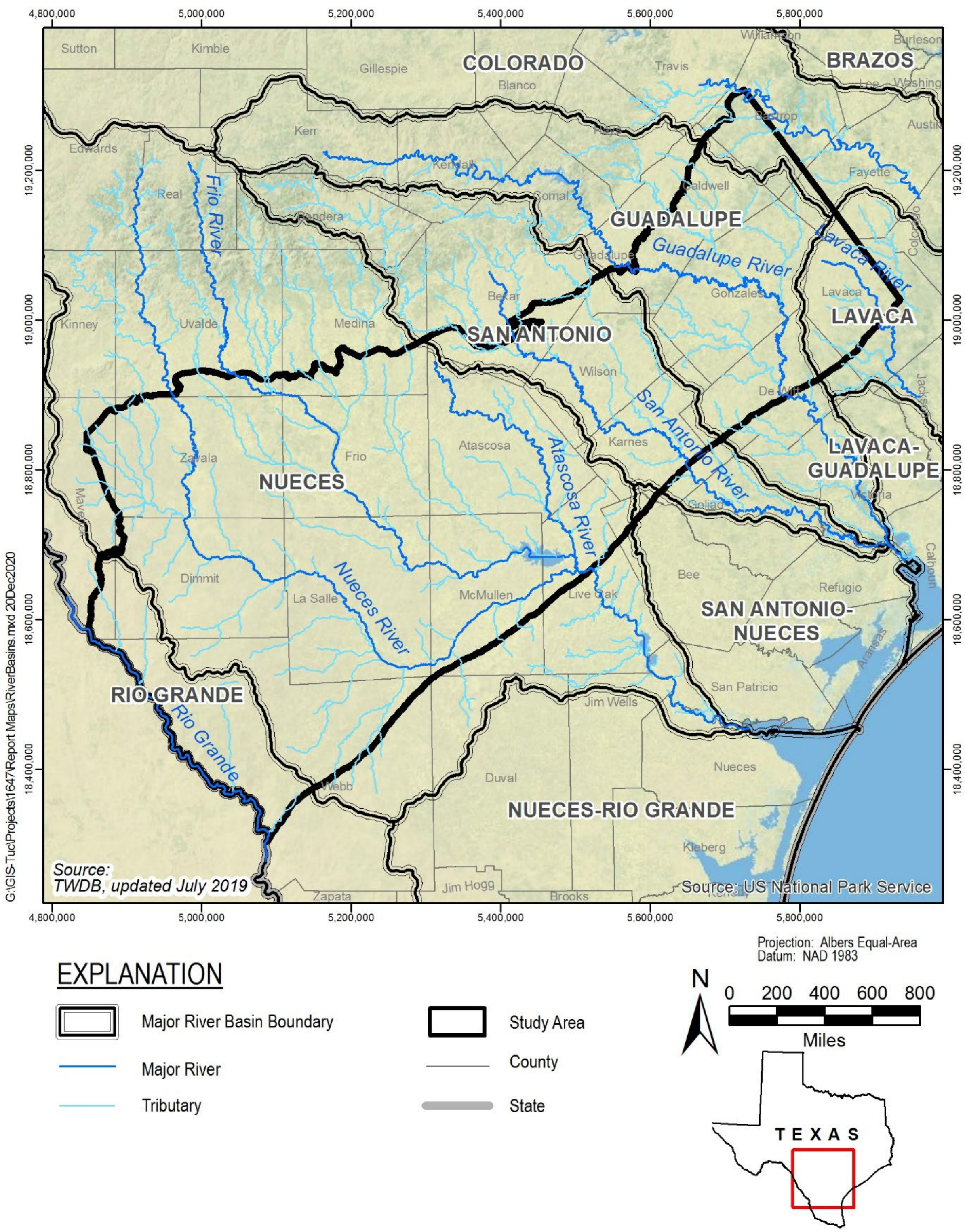

Figure 1-9. Major river basins in study area.

1.1.1 *Physiography and Climate*

Digital elevation model datasets (1 arc-second resolution, or 30 meters) were obtained for the study area from United States Geological Survey (USGS, 2019) National Elevation Datasets. Land surface elevation in the study area is shown on Figure 1-10. In general, land surface elevation in the study area decreases from the northwest to the southeast. Land surface elevations range from about 800 feet above mean sea level along the western boundary to about 200 feet above mean sea level along major river valleys along the eastern boundary. The land surface is substantially dissected by streams and drainages (Figure 1-10).

The study area is located within the Interior Coastal Plain physiographic province in Texas (Texas Bureau of Economic Geology, 1996). The province can be divided into different ecoregions based on topography and vegetation. Ecoregions in the study area include South Texas Brush County, Oak Woods and Prairies, and Blackland Prairie (Figure 1-11) (United States Environmental Protection Agency, 1998). South Texas Brush Country is the dominant ecoregion in the study area. According to the Texas Parks & Wildlife Department (2020) website for Texas Ecoregions, South Texas Brush County is characterized by plains of thorny shrubs and trees (mostly mesquite, acacia, and prickly pear) mixed with grasslands, and scattered patches of palms and subtropical woodlands in the Rio Grande Valley. Vegetation types mapped by McMahan and others (1984) are shown on Figure 1-12.

The study area lies within the Southern and South-Central climate divisions delineated by the National Oceanic and Atmospheric Administration (2018), as shown on Figure 1-13. Thirty-year averages (1981 through 2010) for precipitation and temperature were computed using climate data obtained from the PRISM Climate Group (2020). The 30-year average annual temperatures range slightly over the study area from about 68°F in the northeast to about 74°F in the southwest, as shown on Figure 1-14.

The nearly 40-year average (1981-2019) annual precipitation in the study area increases from about 19 inches in the southwest to about 40 inches in the northeast, as shown on Figure 1-15. Total average annual precipitation between 1981 and 2019 for the study area is based on precipitation data from the PRISM Climate Group (2020) and is shown on Figure 1-16. Monthly precipitation data for individual weather stations in the study area were downloaded from the National Oceanic and Atmospheric Administration's (2020) National Centers for Environmental Information. Average monthly precipitation measured at selected rain stations in the study area is shown on Figure 1-17. A bimodal rainfall pattern is apparent with majority of rainfall occurring in late spring (May and June) and early fall (September and October).

Information on net lake evaporation was obtained from the TWDB (2020a) for 1-degree quadrangles in the study area. Average lake evaporation across the valley is shown on Figure 1-18. Average annual net lake evaporation ranges from less than 18 inches in the northeastern portions of the study area to more than 40 inches in the southwestern portions.

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

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

The dominant hydrologic soil groups in the study area are shown on Figure 1-19. Moderate to fine-grained soils with moderate to slow infiltration rates occur throughout the majority of the study area. Areas with sands and gravels with high infiltration rates are present in the northwest portions of the study area.

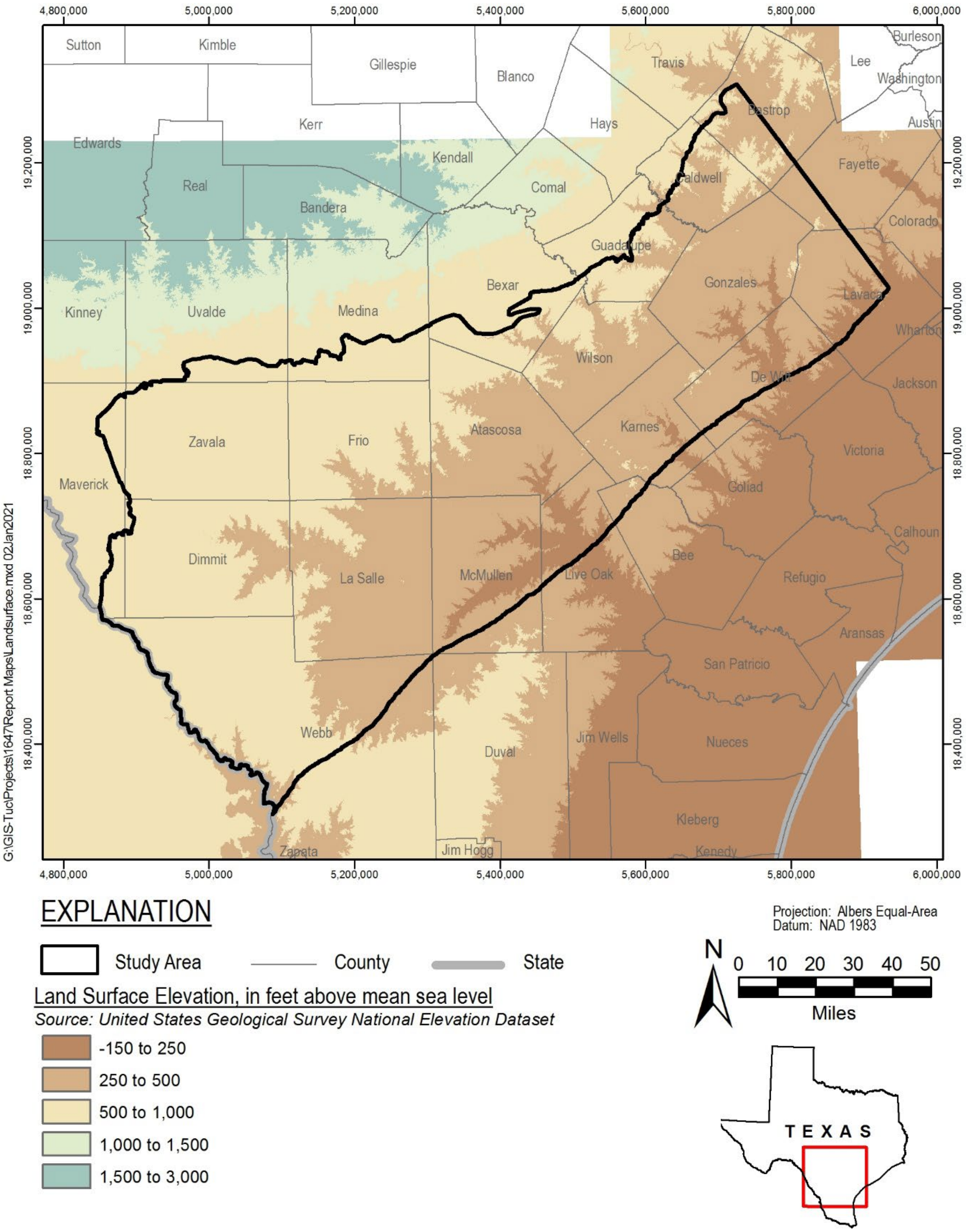

Figure 1-10. Land surface elevation in study area.

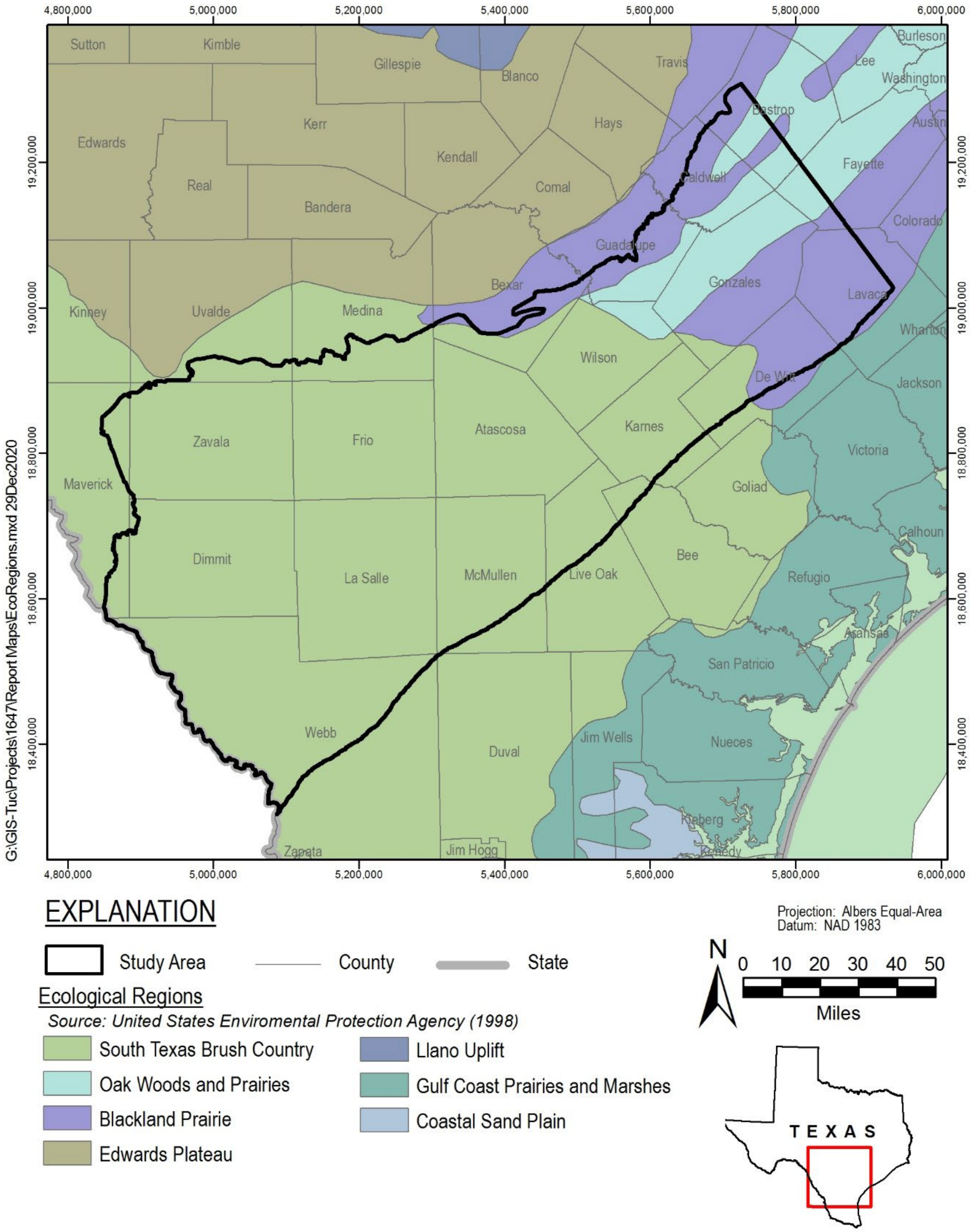

Figure 1-11. Ecological regions in study area.

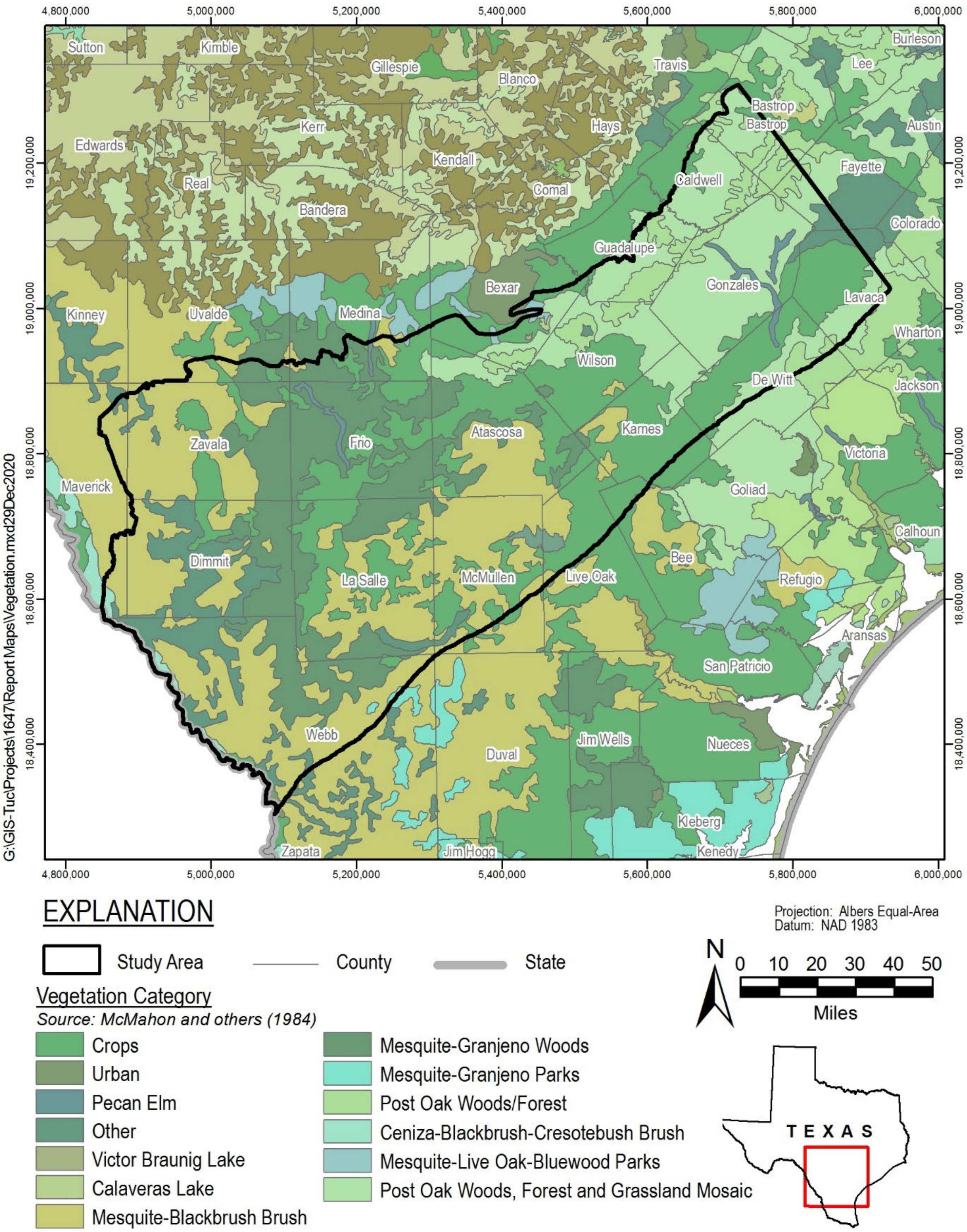

Figure 1-12. Vegetation types in study area.

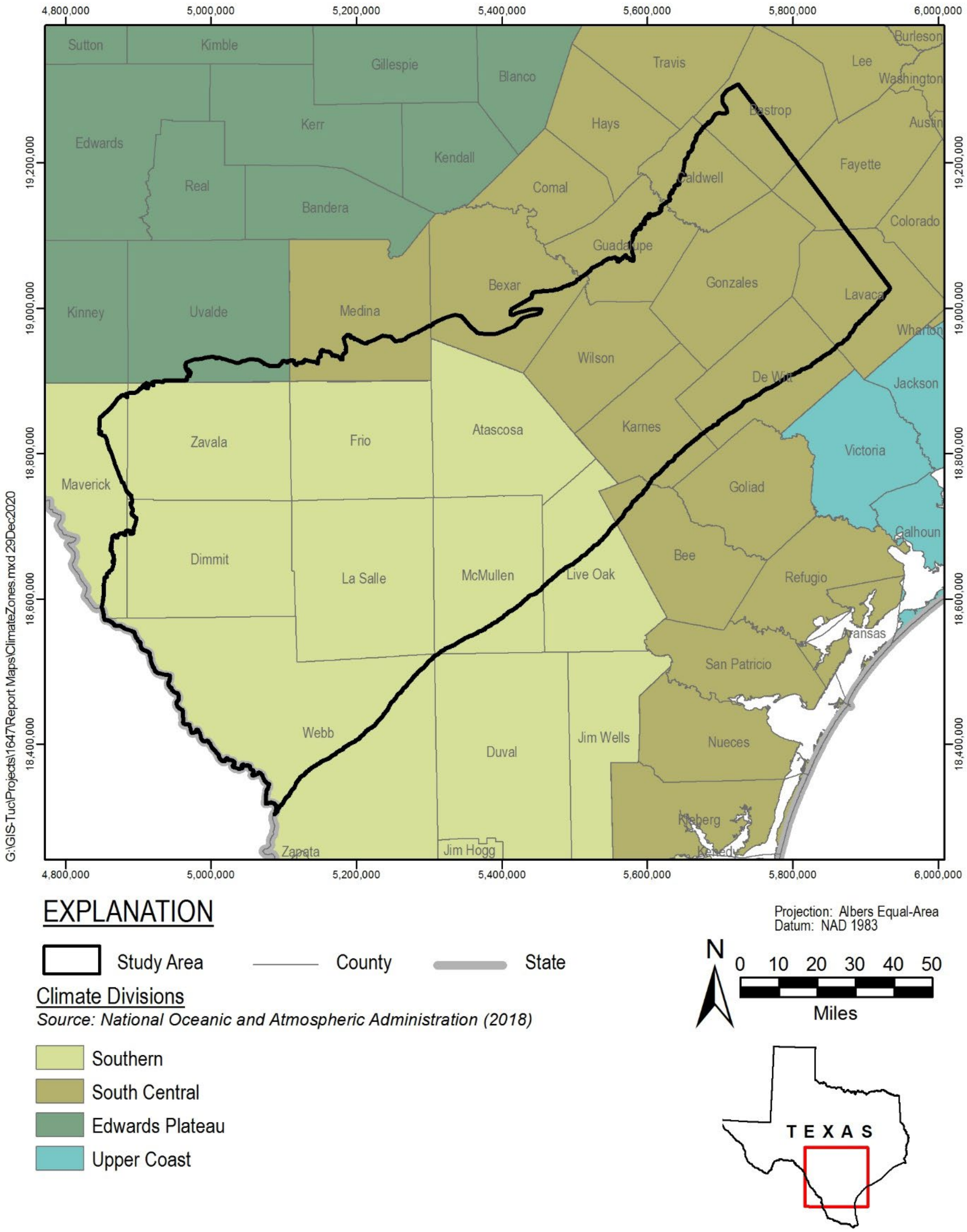

Figure 1-13. Climate divisions in study area.

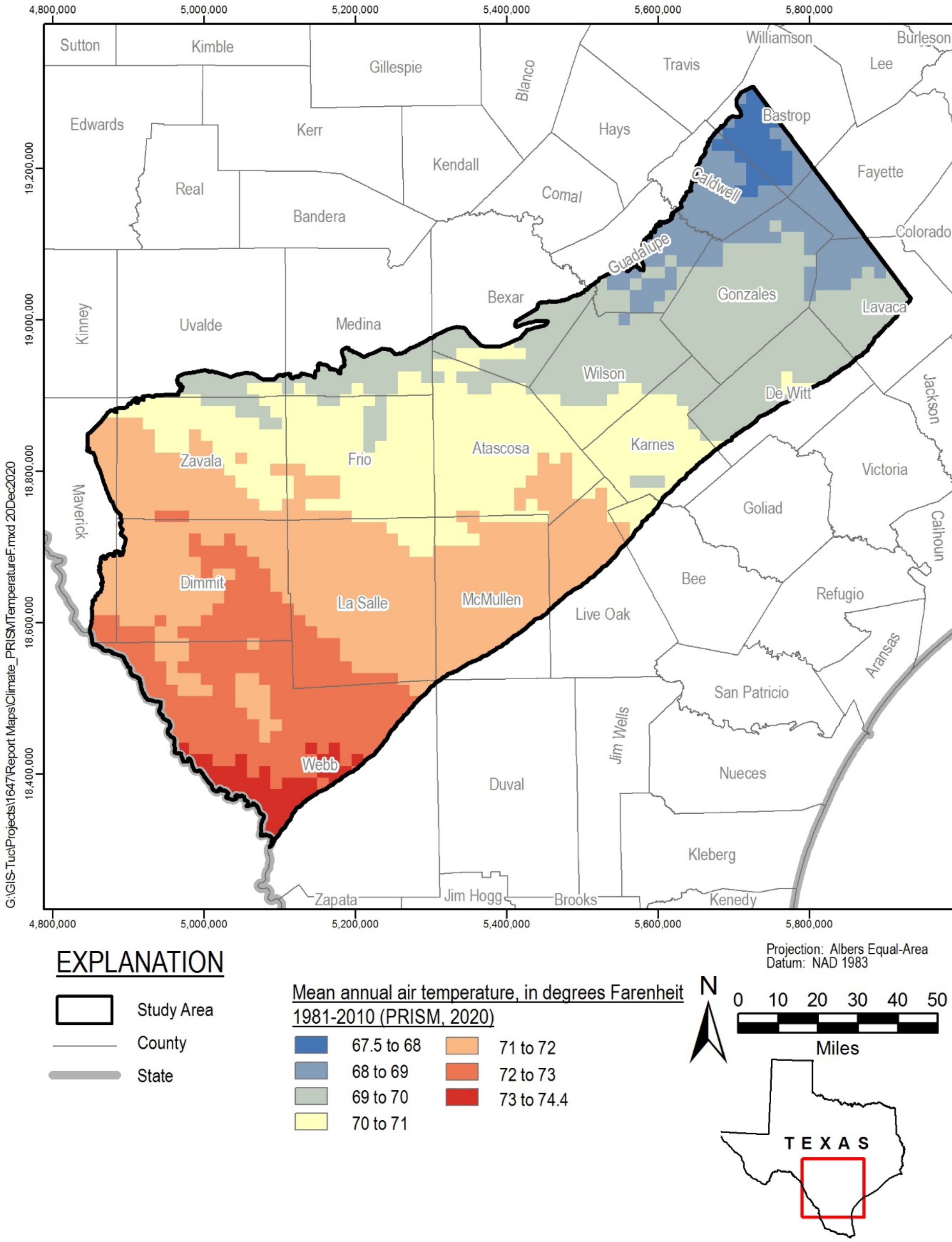

Figure 1-14. Average annual temperature in study area.

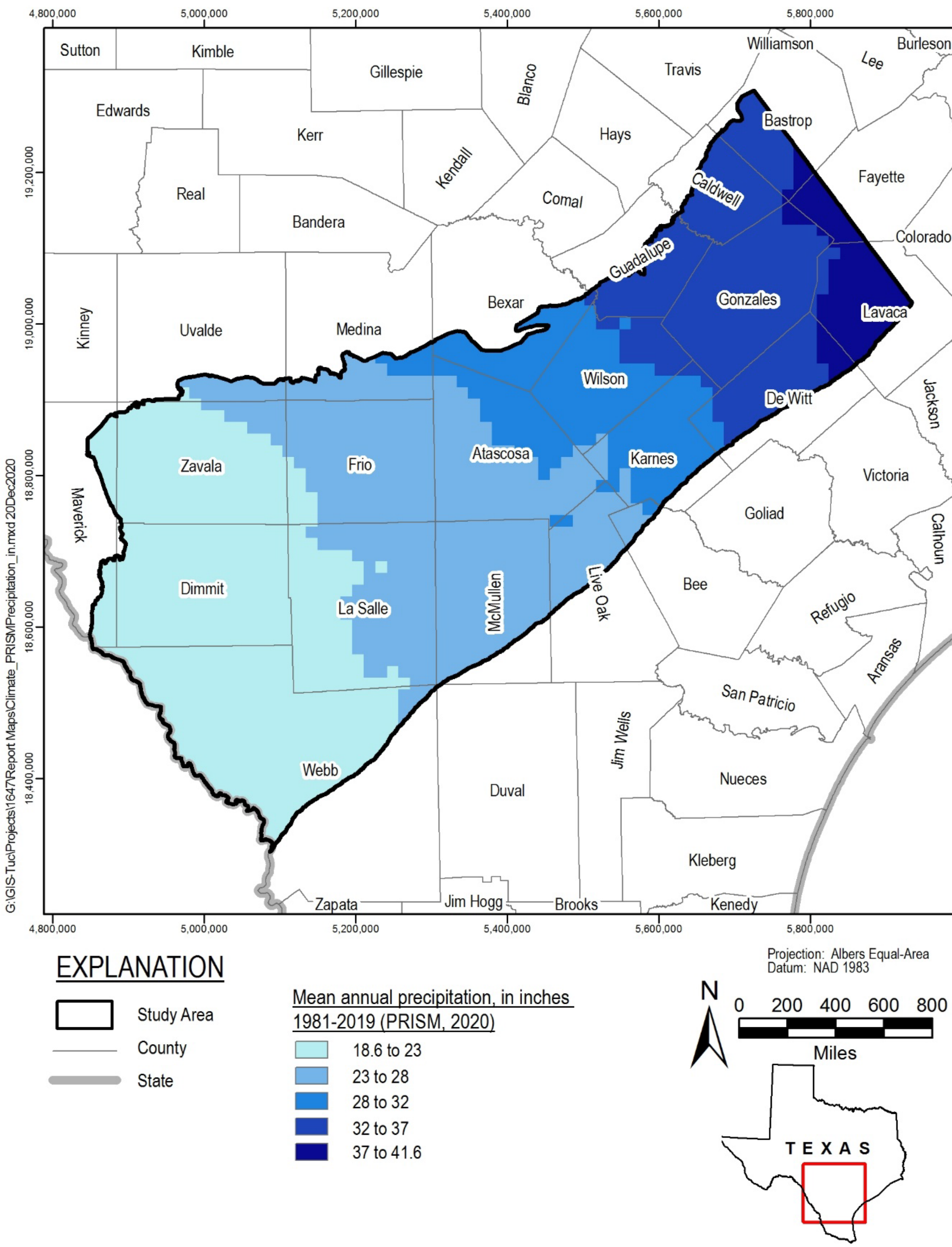

Figure 1-15. Average annual precipitation in study area.

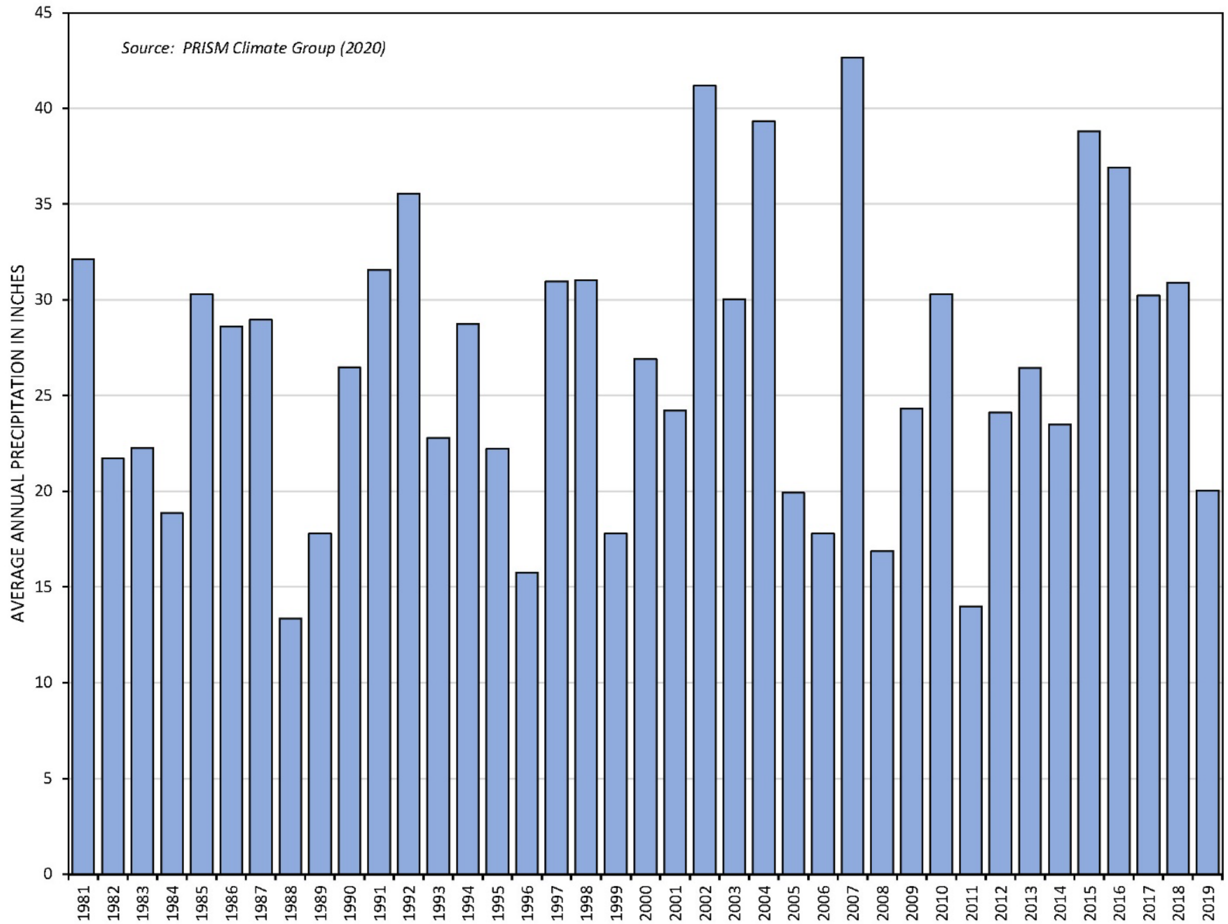

Figure 1-16. Annual precipitation in study area.

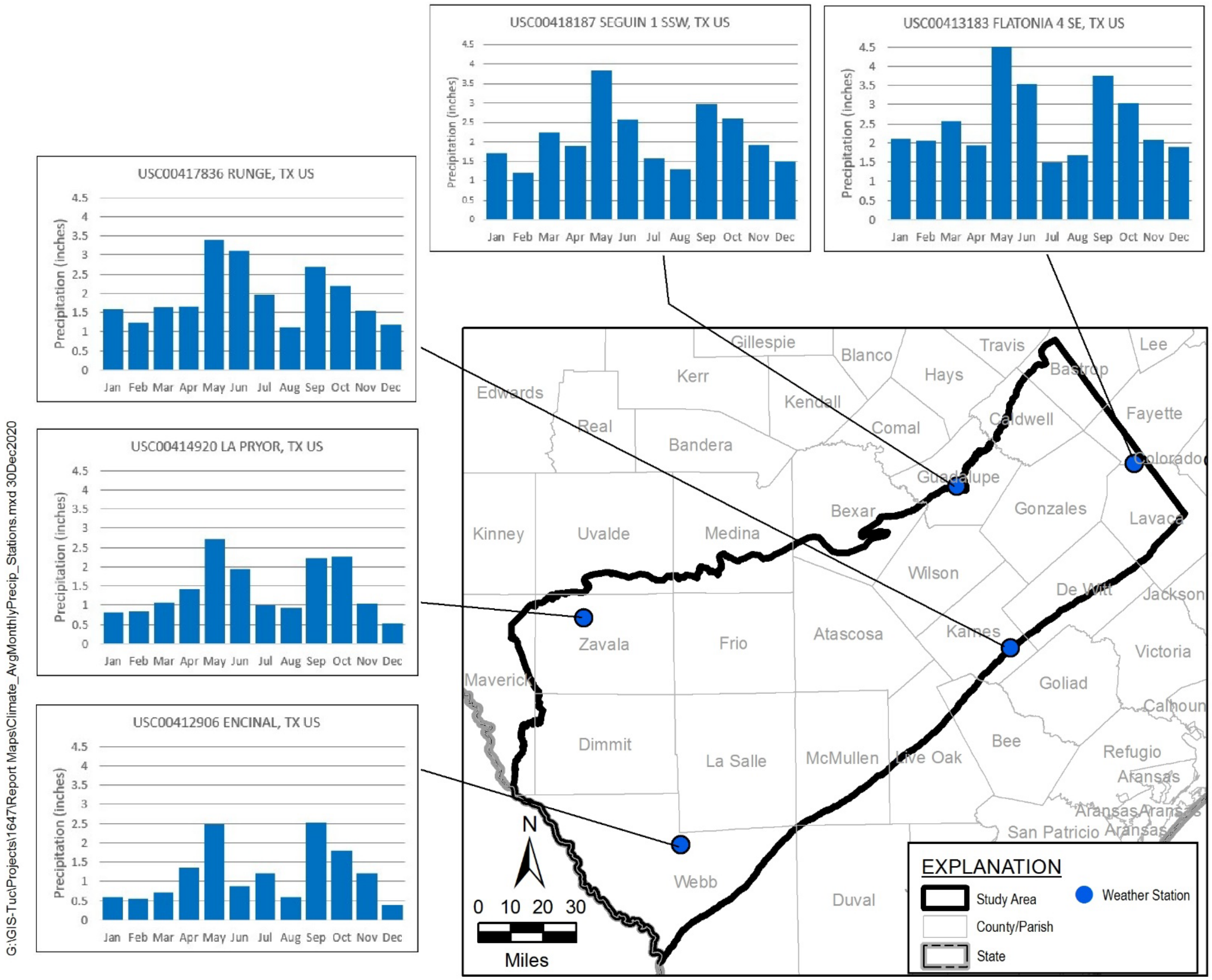

Figure 1-17. Average monthly precipitation at selected weather stations.

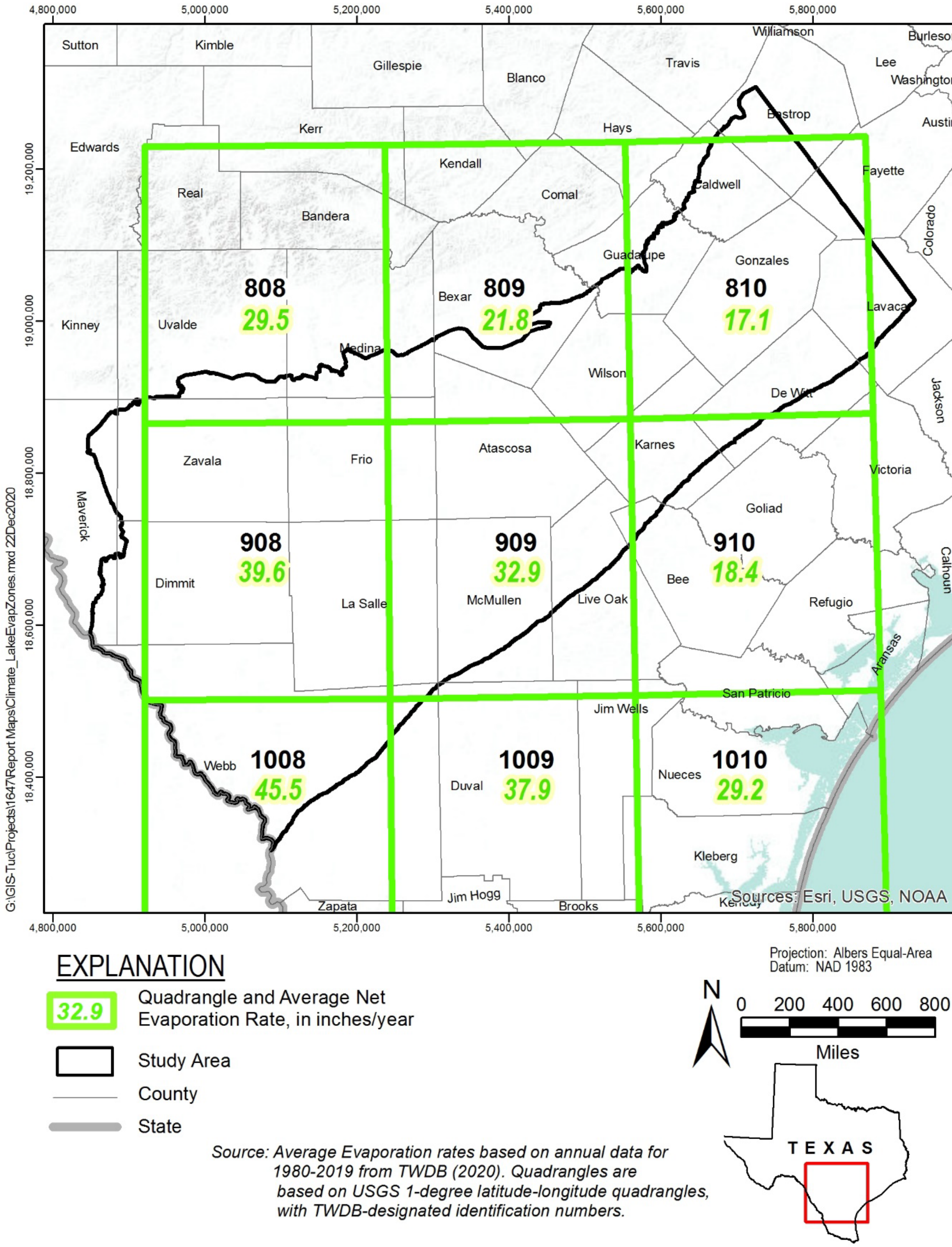

Figure 1-18. Average annual net lake evaporation.

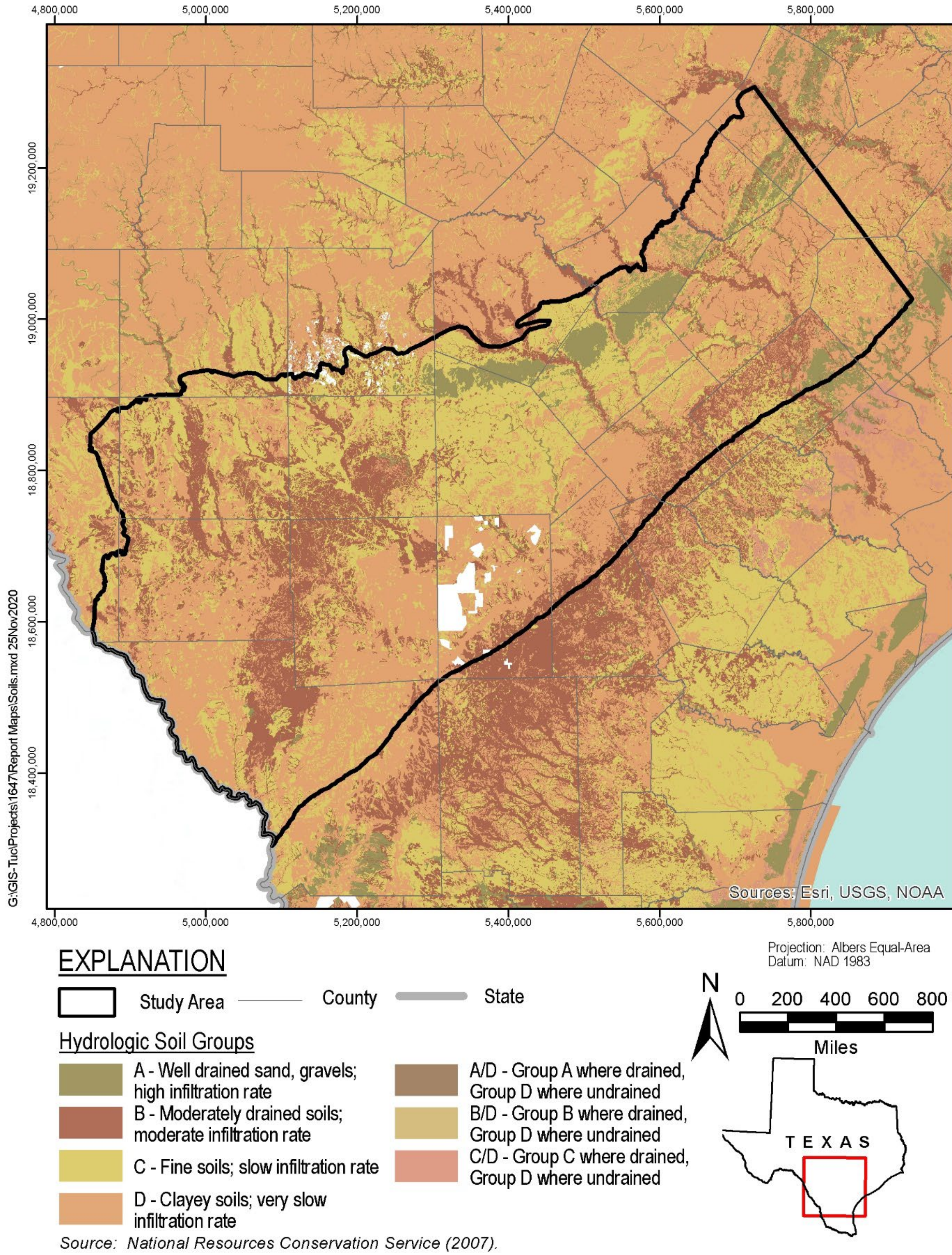

Figure 1-19. Hydrologic soil groups in study area.

1.2 Geologic Setting

Deeds 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. Regional subsidence, episodes of sediment inflow from outside the Gulf Coast Plain, and eustatic sea level change have influenced the deposition of sediments in the study area (Grubb, 1997). According to Galloway and others (1994), deposition of Cenozoic sequences is characterized by an off-lapping progression of successive, gulfward thickening wedges. Deposition occurred principally along continental margin deltaic depocenters within the Rio Grande Embayment and to a lesser extent on the stable San Marcos Arch which separates the Rio Grande Embayment from the Houston Embayment outside the study area.

In ascending stratigraphic order, the principal depositional sequences are the Wilcox group, Carrizo Sand, Queen City Sand, Sparta Sand, Yegua-Cockfield, Jackson, and Vicksburg-Frio formations (Galloway and others, 1994). Southwest of the Frio River, the Bigford Formation is equivalent to the Reklaw Formation and base of the Queen City Sand, the El Pico Clay is equivalent to the Queen City Sand and Weches Formation, and the Laredo Formation is equivalent to the Sparta Sand and Cook Mountain Formation (Deeds and others, 2003). These depositional sequences are bounded by marine shales and finer-grained sediments deposited by marine transgressions. The sequences of interest for this study, shown on Figure 1-20, 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 overlay the Carrizo Sand and Queen City Sand, respectively.

Surficial geology in the study area, obtained from a United States Geological Survey integrated geologic database (Stoeser and others, 2007) available from the Texas Natural Resources Information System, is shown on Figure 1-21. Major structural features are shown on Figure 1-22. Each unit outcrops along the northwestern extent of the study area and are generally oriented southwest to northeast. This outcrop orientation is coincident with depositional strike, the Balcones Fault Zone, and normal to basin subsidence (Deeds and others, 2003).

The dominant structural features in the model area include the Rio Grande Embayment in the southwest, San Marcos Arch to the northeast, and growth faults in the downdip area (Figure 1-22). The embayment focuses sediment input and is a central area of deposition. The axis of the Rio Grande Embayment coincides with the Frio River and a change in lithologic character of the aquifer units across the embayment axis (Deeds and others, 2003). The change in lithologic character is evidenced in borehole electrical logs and change in outcrop formations across this axis.

GIS-Tuc\1647\ReportMaps\Stratigrpahic_sections.ai\30Jan2020

Period	Epoch	Stratigraphic Units: Northeast of Frio River	Stratigraphic Units: Southwest of Frio River	Dominant Lithology	TWDB Aquifer/Aquitard	Hydrostratigraphic Unit
Quaternary	Post-Eocene	Alluvium		sand	---	Quaternary Deposits
Tertiary		---		---	---	Younger Units
	Eocene	Sparta	Laredo	sand	Queen City-Sparta aquifer	Sparta aquifer
		Weches	El Pico Clay	mud		Weches aquitard
		Queen City		sand and mud		Queen City aquifer
		Reklaw	Bigford	mud	aquitard	Reklaw aquitard
		Carrizo	Carrizo	sand	Carrizo-Wilcox aquifer	Carrizo - Upper Wilcox interval
		Wilcox Group	Wilcox Group	mud		Middle Wilcox interval
	Paleocene			sand and mud		Lower Wilcox interval
	Post-Paleocene	---	---	---	---	Midway Group and Older Units

Figure 1-20. Generalized stratigraphic section of hydrostratigraphic units; modified from Hamlin and others (2019).

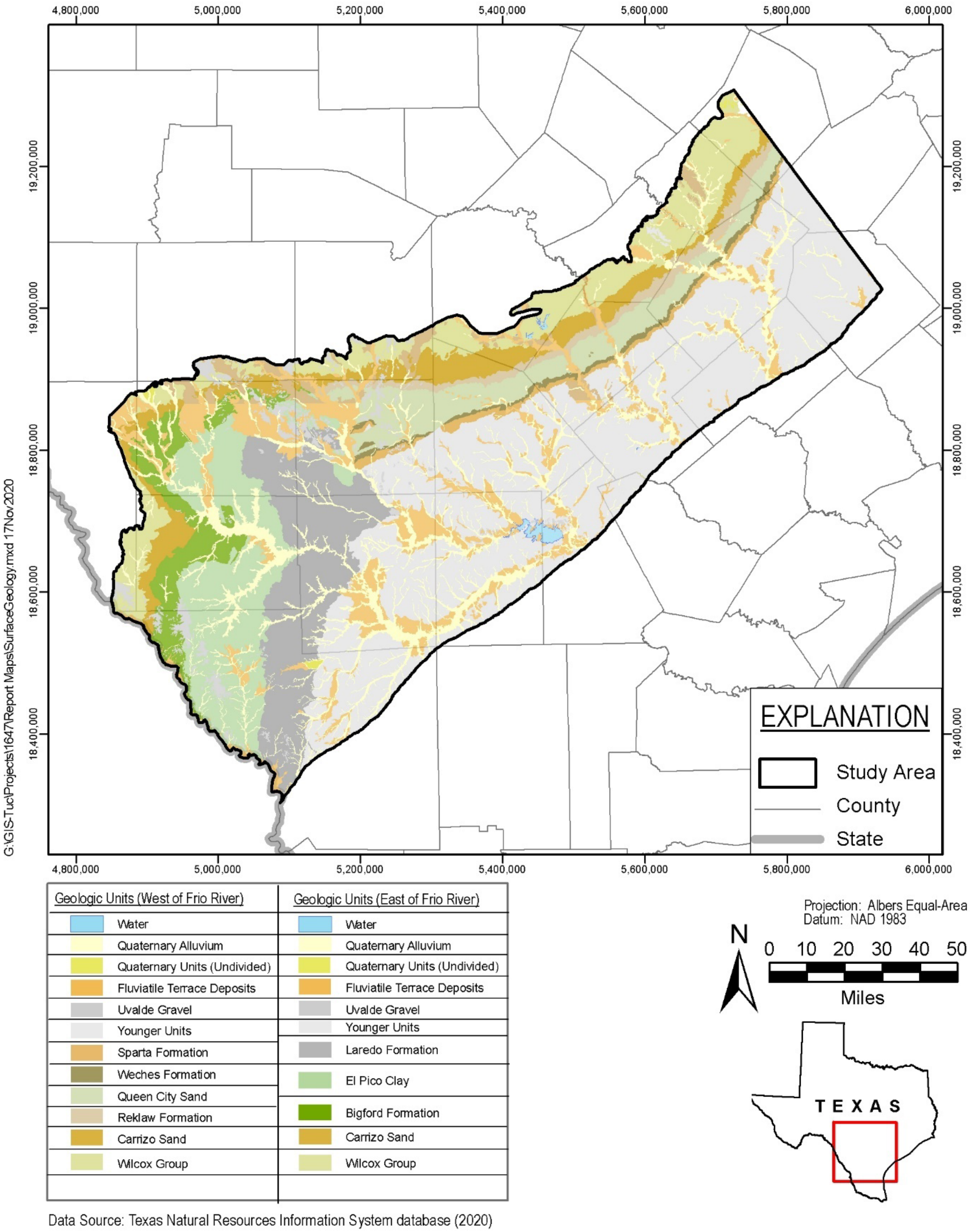

Figure 1-21. Surface geology of the northern portions of the Carrizo-Wilcox, Queen City, and Sparta aquifers.

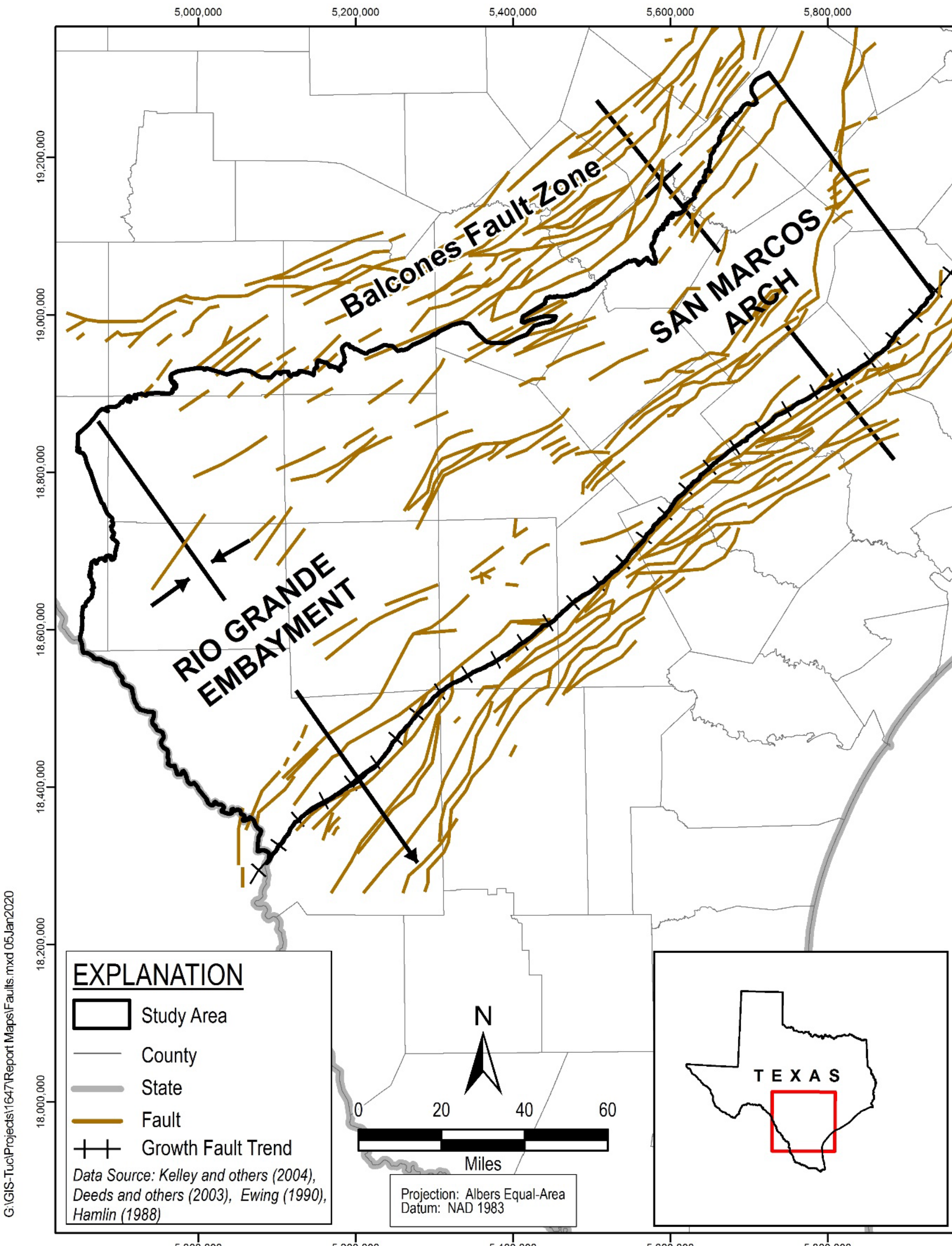

Figure 1-22. Major fault and structural features in study area.

1.3 Previous Studies

The southern portions of the Carrizo-Wilcox, Queen City, and Sparta 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 Deeds and others (2003) and Kelley and others (2004) for the previous groundwater availability models for these aquifers.

Deeds and others (2003) developed the groundwater availability model for the southern 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. The associated model report contains detailed information about the analysis that are not included in this report. The model is comprised of six layers, including, from top to bottom, Queen City, Reklaw, Carrizo, upper Wilcox, middle Wilcox, and lower Wilcox. Grid cells have uniform dimensions of 1-mile by 1-mile. The steady-state model was calibrated to predevelopment conditions. The transient model was calibrated to conditions from 1980 through 1989, with a subsequent model verification period from 1990 through 1999. The verified model was used to predict changes to groundwater conditions to the year 2050 based on future groundwater demands developed by Regional Water Planning Groups and Groundwater Conservation Districts.

The Carrizo-Wilcox groundwater availability model was updated in 2004 when the Queen City and Sparta aquifers were added to the model by Kelley and others (2004). The model included eight layers and was calibrated to the same period as the Carrizo-Wilcox groundwater availability model. The Sparta Sand and Weches Formation were added to the model as new layers. The Weches Formation layer is between the underlying Queen City Sand and the overlying Sparta Sand. The model grid, boundary conditions, and simulation periods of this groundwater availability model are the same as specified in the southern Carrizo-Wilcox groundwater availability model. The current study described herein relies on many aspects of the conceptual model developed by Kelley and others (2004).

2 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 principally in terms of salinity.

2.1 Hydrostratigraphy and Layering Framework

Hydrostratigraphic units are geologic units grouped by similar lithologies which influence the storage or movement of groundwater to determine aquifers or aquitards. Hydrostratigraphy refers to the layering of aquifers and associated confining units of a study area. The hydrostratigraphic chart for the Sparta, Queen City, and Carrizo-Wilcox aquifer system is presented on Figure 2-1. These units were deposited in altering progradation and transgressive sequences resulting in wedges of sand and shale, respectively, that dip and thicken toward the coast (Galloway and others, 2000). The thickest, most laterally extensive sand-rich wedges compose the major Carrizo-Wilcox aquifer system while the minor Sparta and Queen City aquifers are comparatively thinner, limited in lateral extent, and less sandy (George and others, 2011).

Across the Frio River, there is a change in formation names and contacts for units younger than the Carrizo Formation. Northeast of the Frio River, these formations are known as the following: Sparta Formation, Weches Formation, Queen City Formation, and Reklaw Formation. Southwest of the Frio River, in the Rio Grande Embayment area, the same stratigraphic interval is mapped and distinguished as the Laredo Formation, El Pico Clay, and Bigford Formation. Although the surface outcrops do not coincide across the Frio River, the aquifer units are continuous in the subsurface (Guevara and Garcia, 1972; Ricoy and Brown, 1977; Hamlin, 1988; Hamlin and others, 2019). The general relationship between the change in geologic formation across the Frio River is shown on Figure 2-1. The description for each unit's lithofacies is included in the hydrostratigraphic framework section (Section 2.1.4) of this report.

The Carrizo-Wilcox Aquifer is divided in southern Texas based on notable facies or system changes which influence the storage or movement of groundwater into the following intervals: the Carrizo-upper Wilcox, middle Wilcox, and lower Wilcox. The inclusion of the upper Wilcox with the Carrizo for this study is consistent with recent studies by Hamlin and others (2019) and Meyers and others (2019, unpublished). These studies based their stratigraphic interpretations on both Bebout and others (1982) and Hargis (1985, 1986, 2009), who described the Carrizo Formation as the updip equivalent of the upper Wilcox, and Hamlin (1988) who related the fluvial systems of the Carrizo Formation to the deltaic systems of the upper Wilcox. The middle and lower Wilcox are generally less sandy due to their deposition in coastal plain and marine environments with the middle Wilcox being generally more shale-dominated (Hamlin and others, 2019). The inclusion of upper Wilcox with Carrizo is described in further detail in Section 2.1.4 of this report.

Therefore, the hydrostratigraphy evaluated for the groundwater model comprises the following distinct hydrostratigraphic units, from youngest to oldest: Sparta aquifer, Weches aquitard, Queen City aquifer, Reklaw aquitard, Carrizo-upper Wilcox interval, middle Wilcox interval, and lower Wilcox interval (Figure 2-1). Although not considered a substantial aquifer in the study area, Quaternary Deposits (river alluvium) are also incorporated into the aquifer framework for this study.

2.1.1 *Overview of Stratigraphic Interpretation*

The stratigraphic interpretations for this study relied heavily upon the methodology and available interpretations in the TWDB Brackish Resources Aquifer Characterization System Database (TWDB, 2019b) from Meyers and others (2019, unpublished), Wise (2014), and Hamlin and others (2019). Figure 2-2 shows the spatial extent of stratigraphic interpretations for each of these studies compared to this report's study area. Notable differences in the data available between these studies are summarized as follows:

- Meyers and others (2019, unpublished) distinguished Calvert Bluff (middle Wilcox) and Hooper and Simsboro Formations (lower Wilcox) in Bastrop and Lee counties, otherwise these intervals are grouped as the Wilcox Group.
- Hamlin and others (2019) distinguished contacts for the middle and lower Wilcox throughout the study area.
- Wise (2014) distinguished contacts for the top of Sparta Formation to the bottom of the Reklaw Formation in Atascosa and McMullen counties. The bottom of Reklaw Formation contacts were later revised by Meyers and others (2019, unpublished) based on Reklaw interpretations from Bulling and Breyer (1989) and Sams (1991).

In June 2019, the Brackish Resources Aquifer Characterization System Group provided the stratigraphic interpretations available in their Database (TWDB, 2019b) from each of these studies, geophysical log images, and depth-calibrated geophysical logs, where available. The stratigraphic interpretations from these studies were first reviewed in Petra software (IHS, Inc.) to compare the distinguishing lithofacies for a given unit and correlation of lithofacies to adjacent logs.

The methodology used by Meyers and others (2019, unpublished) to distinguish each unit contact using geophysical logs was thoroughly documented, the dataset was spatially dense, and all geological formations present on a log were represented in the interpretations as required of this study. After confirmation with the TWDB, the decision was made to use the methodology developed by the Brackish Resources Aquifer Characterization System Group for the hydrostratigraphic unit contacts and to ensure interpretations by Hamlin and other (2019) were consistent with this methodology or provide new interpretations to ensure consistency. This study reviewed geophysical logs to 1) provide new stratigraphic interpretations from geophysical logs, as needed, to expand supporting structure control datasets, 2) revise other interpretations, if needed, to ensure they were consistent with the Brackish Resources Aquifer Characterization System Group methodology, and 3) subdivide the Wilcox Group into the middle and lower Wilcox for a subset of existing interpretations. Digital logs were analyzed from the Brackish Resources Aquifer Characterization System Group Database and logs provided by stakeholders, which were interpreted and submitted to the TWDB as part of this study.

Figure 2-3 shows the location of evaluated geophysical or water well logs used for this study. Stratigraphic interpretations for the hydrostratigraphic units are provided in detail in the hydrostratigraphic framework section (Section 2.4.1) of this report.

2.1.2 *Outcrop Analysis*

The studies conducted by Meyers and others (2019, unpublished) and Wise (2014) provided over 100 individual well sites with stratigraphic interpretations in outcrop areas from water well logs by a geologist or driller. The counties in their study area included Atascosa, Bastrop, Bexar, Caldwell, Gonzales, Guadalupe, and Wilson. Additionally, geophysical logs for outcrop monitoring wells were provided by the Gonzales Groundwater Conservation District in Gonzales County. Due to the complexity of the lithofacies correlation across the Frio River in the geophysical logs and based on adequate sites with logs near the outcrops, water well log data was not added for Frio, Zavala, and Dimmit counties. The extent of the outcrop area for each hydrostratigraphic surface is based on the surface geology as mapped by the United States Geological Survey (Stoeser and others, 2007) (Figure 2-21). Furthermore, outcrop extents were compared to stratigraphic interpretations in nearby downdip wells to ensure consistency with subsurface data.

2.1.3 *Major Updates from the Previous Groundwater Availability Model*

2.1.3.1 Carrizo-upper Wilcox

As part of the update to the southern portion of the Carrizo-Wilcox, Queen City, and Sparta aquifers groundwater availability model, the aquifer framework was evaluated using two recent, independent studies within the GMA 13 area (Figure 2-2): Meyers and others (2019, unpublished) and Hamlin and others (2019). Both studies interpreted formation contacts based on a review of borehole geophysical logs for the Sparta, Weches, Queen City, Reklaw, Carrizo, and Wilcox Group, which comprises the middle and lower Wilcox intervals. Importantly, both studies made the decisions to (1) group the upper Wilcox interval with the Carrizo Formation and therefore (2) classify the Wilcox Group as solely the equivalent of the middle and lower Wilcox intervals. This differs from the aquifer framework developed for the previous groundwater availability model by Deeds and others (2003), which specified a separate model layer for the upper Wilcox interval primarily in the downdip area and southwest of the Frio River.

The Brackish Resources Aquifer Characterization System Group defined the Carrizo Formation as a massive sand complex with some areas including interbedded sand and shale units in the lowermost part of the unit (Meyers and others, 2019, unpublished). The described interbedded sand and shale units are the equivalent of the upper Wilcox interval. They further note the contact is often difficult to distinguish between the Carrizo Formation from the interbedded upper Wilcox interval. Their method, which is the same as used by Hamlin and others (2019), opted to group the Carrizo Formation and upper Wilcox interval together with the base distinguished by the distinct, laterally extensive underlying shale marker of the middle Wilcox interval.

The Brackish Resources Aquifer Characterization System Group primarily provided stratigraphic interpretation entries for the Carrizo Formation and the Wilcox Group while Hamlin and others (2019) provided stratigraphic interpretation entries for the Carrizo-upper Wilcox, middle Wilcox, and lower Wilcox. A review of the stratigraphic interpretations from these studies shows that the Carrizo Formation, as it is distinguished by the Brackish Resources Aquifer Characterization System Group, has similar lithofacies as the Carrizo-upper Wilcox interval distinguished by Hamlin and others (2019).

This study reviewed stratigraphic interpretations from these recent studies to compare the respective lithofacies signatures used for the unit contacts. Particular attention was paid to understand the lithologic difference between the Carrizo Formation and the upper Wilcox interval. Overall, the upper Wilcox interval is composed of thick sand packages with relatively thin and variable shale beds, comprises considerably more sand than shale, and does not have a distinct marker to consistently distinguish it from the Carrizo Formation. The upper Wilcox interval as a whole is (1) comparatively thin, (2) not present in a large portion of the updip area, and (3) provides a more consistent overall unit thickness throughout the domain when grouped with the Carrizo Formation. Based on these observations, this study understands the merit of combining the upper Wilcox interval with the Carrizo Formation to be consistent with recent framework studies by both Meyers and others (unpublished) and Hamlin and others (2019).

Deeds and others (2003) did not provide a strong justification that the upper Wilcox interval was distinct from the Carrizo Formation. For the previous groundwater availability model, the upper Wilcox interval was determined by combining two different data sources with somewhat different interpretations of the Carrizo Formation. The upper Wilcox interval was determined by subtracting one study’s Carrizo-upper Wilcox interpretation from another study’s thickness of the Carrizo massive sand. Deeds and others (2003) note the updip limit of the upper Wilcox interval is somewhat artificial due to using two different interpretations. While reviewing geophysical logs located in the vicinity of the updip limit delineated by the previous groundwater availability model, this study noted that the presence of the upper Wilcox interval unit was not consistent and, therefore, would also result in a somewhat artificial limit if implemented in the groundwater availability model update.

On September 19, 2019, the project team for this study met with the TWDB and Brackish Resources Aquifer Characterization System Group regarding this matter. During the meeting, both options were discussed and the TWDB opted to group the upper Wilcox interval with the Carrizo Formation for the groundwater availability model update. This grouping will be called the “Carrizo-upper Wilcox” interval for this study. This decision will allow the update to the groundwater availability model to be consistent with recent studies and stratigraphic interpretations.

2.1.3.2 Yoakum Canyon

The Yoakum canyon is a massive submarine channel which eroded into the lower Wilcox interval and filled with shale late in the Wilcox stratigraphic sequence in Bastrop, Caldwell, Gonzales, Lavaca, and Dewitt counties (Hoyt, 1959; Dingus and Galloway, 1990). The canyon trends northwest to southeast for approximately 67 miles from the shallow subsurface near outcrop to the early Eocene shelf edge with widths exceeding 10 miles and depths greater than 3,500 feet (Dingus and Galloway, 1990). Dingus and Galloway (1990) distinguish the Yoakum shale in this channel from the overlying fluvial-deltaic sand-rich deposits and the underlying middle Wilcox interval described as a dominantly aggradational shale sequence capped by a progradational (coarsening upwards sequence) sand sequence. The lower Wilcox interval predates the incision of the Yoakum canyon and is described as a thick sand-rich, progradational sequence (Dingus and Galloway, 1990).

The Yoakum shale was not previously distinguished by Deeds and others (2003) in the hydrostratigraphic framework, based on the thickness of the middle Wilcox interval in the previous groundwater availability model, but was captured in adjusted hydraulic conductivities for the lower Wilcox interval. During the stakeholder advisory forum held on August 2, 2019, the concern was brought up by a stakeholder that the Yoakum shale was not represented in the previous groundwater availability model hydrostratigraphic framework. Recent framework studies have confirmed the importance of the Yoakum shale. Although the Brackish Resources Aquifer Characterization System Group did not subdivide the Wilcox Group during their stratigraphic interpretation, the Yoakum shale thickness was provided as a remark in the database. Hamlin and others (2019) distinguished and included the Yoakum shale as part of the middle Wilcox interval which similarly resulted in a thicker middle Wilcox interval in the Yoakum canyon.

Due to its deposition late in the Wilcox stratigraphic sequence and dominant shale lithofacies, this study included the Yoakum shale as part of the middle Wilcox interval which is considered to be more fine-grained than the underlying lower Wilcox interval and overlying Carrizo-upper Wilcox interval. As a result, the middle Wilcox interval substantially thickens in the Yoakum canyon to better represent the shaley lithofacies, similar to the results of Hamlin and others (2019).

2.1.4 *Hydrostratigraphic Framework*

The hydrostratigraphic framework of an aquifer system is composed of the elevation surfaces of the hydrostratigraphic units in stratigraphic order. The hydrostratigraphic framework for the groundwater model is principally based on geophysical well logs, selected water well controls primarily along outcrop, and surficial geologic map information from the United States Geological Survey integrated geologic database (Stoeser and others, 2007) available from the Texas Natural Resources Information System.

A continuous three-dimensional, volumetric representation of the hydrostratigraphic framework for the study area was prepared using the geologic modeling software Leapfrog® Geo, developed by Seequent. The Leapfrog geologic model was developed using contacts determined from the 1) review and analysis of geophysical logs from the Brackish

Resources Aquifer Characterization System Group, Bureau of Economic Geology, and Montgomery & Associates, 2) review and analysis of driller's logs, and 3) outcrop extent polylines from the digital United States Geological Survey geology map dataset. Layer elevation surfaces were then exported from Leapfrog and slightly adjusted to better match surface geology contacts using ESRI's ArcGIS tools. After the development of the hydrostratigraphic framework elevation surfaces in Leapfrog Geo, these surfaces were exported to ESRI's ArcGIS for post-processing to incorporate the river alluvium model layer.

The outcrop areas of the main hydrostratigraphic units in the study area are shown on Figure 2-4. The extents of the hydrostratigraphic units differ slightly from the TWDB-designated aquifer extents due to the incorporation of small, discontinuous outcrops, and the downdip portion of the layers being cutoff at the groundwater availability model study area boundary.

Geologic cross sections of this detailed framework are presented on Figure 2-5. The sections were intentionally oriented in a manner to illustrate the stacking of the generally wedge-shaped aquifer units. The relatively thin river alluvium layer is too thin to be visible in regional-scale cross section view.

Each hydrostratigraphic unit and the Quaternary Deposits are described from youngest to oldest in the following sections. The geologic model also includes volumes for the units younger than the Sparta Formation ("younger unit") and units older than the Wilcox Group ("older unit"); these volumes define the upper and lower limits of the aquifer system in the groundwater availability model.

2.1.5 *Quaternary Deposits (River Alluvium)*

The Quaternary Deposits (river alluvium) were distinguished from other hydrostratigraphic units for the groundwater model. An extent (width) and a thickness were assigned to these deposits along three categories of rivers and streams in the study area: Rio Grande, all other major rivers, and tributaries. Extents and thicknesses of Quaternary Deposits represented in the hydrostratigraphic framework are shown on Figure 2-6.

The extent (width) of the Quaternary Deposits along the major river channels was simplified from the mapped Quaternary units. Major rivers in the study area include Rio Grande, Nueces River, Frio River, Atascosa River, San Antonio River, Guadalupe River, and Lavaca River. For simplicity, the widths of Quaternary deposits along portions of major rivers with no mapped Quaternary units were defined by a buffered extent of 1,000 feet from the stream. The Rio Grande deposits were defined by a buffered extent of 2,000 feet from the river.

Only 28 available lithologic or geophysical log data for boreholes provided contacts for the Quaternary Deposits primarily in Bastrop and Caldwell counties, so a literature review was conducted to provide a basis for the unit thickness. According to the United States Geological Survey Groundwater Atlas of the United States (Ryder, 1996), Rio Grande river alluvium, located along the western boundary of the study area, may have a thickness of up to 200 feet. In a previous United States Geological Survey reconnaissance study with the Texas Water Commission, recent alluvium associated with the Guadalupe, San Antonio, and Nueces Rivers were estimated to have thicknesses of up to 30 feet (Alexander and others, 1964). Alluvial deposits of Frio River are estimated to be less than 100 feet thick (United States Department of Agriculture, 1992). Other Quaternary alluvium deposits associated with the Brazos River as well as other major streams in the state of Texas not in the study area are estimated to have a maximum thickness of about 100 feet (Ewing and others, 2016; Shah and others, 2007; Ryder, 1996). For the hydrostratigraphic framework, the Quaternary Deposits were assigned a thickness of 30 feet along all the major river channels, except Rio Grande. Rio Grande was assigned a thickness of 200 feet.

To aid with groundwater modeling, major tributary drainages were also included in the model framework as Quaternary Deposits. These areas had no subsurface contacts from borehole data and no specific documentation for unit thickness found in literature. Delineation of the stream network represented in the groundwater availability model is described in subsequent sections of this report. For simplicity, the width of Quaternary deposits along the tributaries with no mapped Quaternary units is defined by a buffered extent of 500 feet from the stream. A thickness of 15 feet was assigned to the deposits along the tributaries.

2.1.6 *Sparta Aquifer*

The Sparta Aquifer wholly comprises the Sparta Formation (George and others, 2011) which unconformably underlies the Cook Mountain Formation and conformably overlies the Weches Formation (Meyers and others, 2019, unpublished). The Sparta Aquifer is a distinct sand rich unit identified as a high-destructive wave dominated deltaic facies in south Texas (Ricoy and Brown, 1977). Northeast of the Frio River, this hydrostratigraphic unit is easily distinguished from the younger Cook Mountain Formation and older Weches Formation, which are both marly marine transgressive units. Southwest of the Frio River, the mapped outcrops of the Sparta Formation and Cook Mountain Formation grade into the equivalent Laredo Formation; however, the lithofacies of the Sparta Aquifer are still distinct in the subsurface geophysical logs. Although the outcrop delineations change across the Frio River, several regional studies have shown the aquifers in the subsurface are continuous across the entire study area (Ricoy and Brown, 1977; Kelley and others, 2004; Hamlin and others, 2019).

2.1.6.1 Stratigraphic Analysis

Stratigraphic interpretations for the Sparta Aquifer were based on the methodology used by Meyers and others (2019, unpublished). According to Meyers and others (2019, unpublished), the top of the Sparta Aquifer is defined as the “top of the fining upwards sequence subjacent to the shale of the Cook Mountain Formation” while the bottom contact is the “base of the first significant progradational of the Sparta Formation”. Meyers and others (2019, unpublished) noted the bottom contact can be difficult to distinguish in areas where there is more than one upward coarsening sequence below the major Sparta Aquifer sand. West of the Frio River, the bottom contact is also difficult to ascertain due to significant thinning of the underlying Weches aquitard.

2.1.6.2 Well Control and Formation Top, Bottom, Thickness

Top and bottom (base) elevation maps for the Sparta Aquifer are shown on Figure 2-7 and were prepared using 884 and 877 stratigraphic contacts, respectively, from wells within the study area as well as some wells immediately outside of the study area to control surface edge effects. The top elevation of the Sparta Aquifer ranges from about 861 feet from vertical datum in the northwest portion of the study area to -5,637 feet from vertical datum in the southeast portion. The vertical datum used for this framework and groundwater availability model is North American Vertical Datum 1988 (NAVD88). The bottom elevation of the Sparta Aquifer ranges from about 854 feet from vertical datum in the northwest and decreases to about -5,815 feet from vertical datum in the southeast. The thickness of the Sparta Aquifer (also shown on Figure 2-7) was prepared from subtracting the bottom elevation from the top elevation. A total of 822 wells had both a top and bottom stratigraphic contact to provide thickness control. The Sparta Aquifer thickness ranges from 0 at the updip outcrop edge to 396 feet.

2.1.7 *Weches Aquitard*

The Weches aquitard wholly comprises the Weches Formation (George and others, 2011) which conformably underlies the Sparta Formation and unconformably overlies the Queen City Formation (Meyers and others, 2019, unpublished). The Weches aquitard is composed of glauconitic muds and represents a marine transgression between the overlying Sparta Aquifer and underlying Queen City Aquifer (Ricoy and Brown, 1977).

This hydrostratigraphic unit is considered an aquitard to the Queen City Aquifer east of the Frio River. West of the Frio River, the Weches thins considerably and is difficult to discern from the underlying Queen City Aquifer; as a result, these units are traditionally known collectively as the El Pico Clay. Although the outcrop delineations change across the Frio River and the unit thins considerably in the outcrop area, several regional studies have shown the Weches aquitard as continuous in the subsurface across the entire study area (Ricoy and Brown, 1977; Guevara and Garcia, 1972; Kelley and others, 2004; Hamlin and others, 2019).

2.1.7.1 Stratigraphic Analysis

Stratigraphic interpretations for the Weches aquitard were based on the methodology used by Meyers and others (2019, unpublished). According to Meyers and others (2019, unpublished), the top of the Weches aquitard is defined as the “top of the shale subjacent to the base of the first significant progradational of the Sparta Formation” while the bottom contact is the “base of the shale marker above the uppermost sand signature of the Queen City Formation”. Meyers and others (2019, unpublished) noted the top contact can be difficult to distinguish in areas where there is more than one upward coarsening sequence below the major Sparta Aquifer sand. West of the Frio River, the Weches aquitard bottom is also difficult to ascertain due to significant thinning in the updip area combined with the top intervals of the underlying Queen City Aquifer becoming more shale dominated with thin sand intervals.

2.1.7.2 Well Control and Formation Top, Bottom, Thickness

Top and bottom elevation maps for the Weches aquitard are shown on Figure 2-8 and were prepared using 910 and 908 stratigraphic contacts, respectively, from wells within the study area as well as some wells immediately outside of the study area to control surface edge effects. The top elevation of the Weches aquitard ranges from about 858 feet from vertical datum in the northwest portion of the study area to -5,816 feet from vertical datum in the southeast portion. The bottom elevation of the Weches aquitard ranges from about 806 feet from vertical datum in the northwest and decreases to about -5,904 feet from vertical datum in the southeast. The thickness of the Weches aquitard (also shown on Figure 2-8) was prepared from subtracting the bottom elevation surface from the top elevation surface. A total of 875 wells had both a top and bottom stratigraphic contact to provide thickness control. The Weches aquitard thickness ranges from 0 at the updip outcrop edge to 365 feet, with the vast majority of the unit being less than 200 feet thick.

2.1.8 *Queen City Aquifer*

The Queen City Aquifer is composed of sands deposited as a high-destructive, wave-dominated delta system (Guevara and Garcia, 1972). The Queen City Aquifer wholly comprises the Queen City Formation northeast of the Frio River which unconformably underlies the Weches Formation and conformably overlies the Reklaw Formation (Meyers and others, 2019, unpublished). In this region, the Queen City Aquifer is easily distinguished from the shales of the overlying Weches aquitard and underlying Reklaw aquitard. Southwest of the Frio River, the Queen City Aquifer is composed of the shale-dominated El Pico Clay and sandy intervals of the Bigford Formation (Klemt and others, 1976). Although the outcrop delineations change across the Frio River, several regional studies have shown the aquifers in the subsurface are continuous across the entire study area (Ricoy and Brown, 1977; Guevara and Garcia, 1972; Kelley and others, 2004; Hamlin and others, 2019).

2.1.8.1 Stratigraphic Analysis

Stratigraphic interpretations for the Queen City Aquifer were based on the methodology used by Meyers and others (2019, unpublished). According to Meyers and others (2019, unpublished), the top of the Queen City Aquifer is defined as the “top of the shallowest sand subjacent to the base of the shale of the Weches Formation” while the bottom contact is the “base of the upward coarsening sand package above the uppermost shale signature of the Reklaw Formation”. Meyers and others (2019, unpublished) noted the bottom contacts can be difficult to distinguish in areas where the Reklaw contains thin sand packages. Wise (2014) also notes the bottom contact can be difficult to ascertain due to the lower portions of the Queen City Aquifer containing more clay with thinner sand deposits which presents a more gradational contact. West of the Frio River and in the updip area, the shale of the overlying Weches aquitard and underlying Reklaw aquitard thin considerably, which makes the Queen City Aquifer contacts less distinct than in other regions of the study area. In these instances, the top of the shallowest sand below the Sparta coarsening upwards sequence was used and the deepest sand above the thin shale or reworked sand of the Reklaw aquitard. In the downdip area west of the Frio River, the shale of the overlying Weches aquitard and underlying Reklaw aquitard are thicker and the contact can be distinguished with the established methodology northeast of the Frio River.

2.1.8.2 Well Control and Formation Top, Bottom, Thickness

Top and bottom elevation maps for the Queen City Aquifer are shown on Figure 2-9 and were prepared using 1,080 and 1,273 stratigraphic contacts, respectively, from wells within the study area as well as some wells immediately outside of the study area to control surface edge effects. The top elevation of the Queen City Aquifer ranges from about 889 feet from vertical datum in the northwest portion of the study area to -5,902 feet from vertical datum in the southeast portion. The bottom elevation of the Queen City Aquifer ranges from about 851 feet from vertical datum in the northwest and decreases to about -6,750 feet from vertical datum in the southeast. The thickness of the Queen City Aquifer (also shown on Figure 2-9) was prepared from subtracting the bottom elevation surface from the top elevation surface. A total of 1,010 wells had both a top and bottom stratigraphic contact to provide thickness control. The Queen City Aquifer thickness ranges from 0 at the updip outcrop edge to 1,969 feet.

2.1.9 *Reklaw Aquitard*

The Reklaw aquitard wholly comprises the Reklaw Formation (George and others, 2011), which conformably underlies the Queen City Formation and unconformably overlies the Carrizo Formation (Meyers and others, 2019, unpublished). Southwest of the Frio River, the Reklaw aquitard is the equivalent of the lower interval of the Bigford Formation. The Reklaw Formation consists of transgressive shales with the lower interval containing several sands representing re-worked or cannibalized sand during the transgression from the underlying Carrizo Formation (Bulling and Breyer, 1989; Sams, 1991; Meyers and others, 2019, unpublished). Although there is a change in geologic formation across the Frio River, several regional studies have shown the Reklaw aquitard in the subsurface is continuous across study area in the downdip area with limited or missing shale in updip portions of Frio, Zavala, Dimmit, and Webb counties (Hargis, 2009; Hamlin and others, 2019). This study used the same methodology as Meyers and others (2019, unpublished) for the stratigraphic interpretations of the Reklaw aquitard and thus results in a thin, limited Reklaw interval in these counties, which is considered to be more fine-grained than the upward coarsening sand at the base of the Queen City and the massive sand of the underlying Carrizo.

2.1.9.1 Stratigraphic Analysis

Stratigraphic interpretations for the Reklaw aquitard were based on the methodology used by Meyers and others (2019, unpublished). According to Meyers and others (2019, unpublished), the top of the Reklaw aquitard is defined as the “top of the shale subjacent to the base of the first progradational of the Queen City Formation” while the bottom contact is the “base of a shale or sand marker above the massive sand signature of the Carrizo Formation” Meyers and others (2019, unpublished) noted the bottom contact can be difficult to distinguish where significant re-working of the underlying Carrizo Formation has occurred. West of the Frio River in the updip portion, the shale core and marker shale of the Reklaw is essentially non-existent. This study distinguished a thin transition zone equivalent to the fine-grained Reklaw with a lower overall deep resistivity signature between the overlying coarsening upward sequence of the Queen City Aquifer and the underlying massive sand of the Carrizo Aquifer.

2.1.9.2 Well Control and Formation Top, Bottom, Thickness

Top and bottom elevation maps for the Reklaw aquitard are shown on Figure 2-10 and were prepared using 1,354 and 1,231 stratigraphic contacts, respectively, from wells within the study area as well as some wells immediately outside of the study area to control surface edge effects. The top elevation of the Reklaw aquitard ranges from about 928 feet from vertical datum in the northwest portion of the study area to -6,751 feet from vertical datum in the southeast portion. The bottom elevation of the Reklaw aquitard ranges from about 876 feet from vertical datum in the northwest and decreases to about -7,080 feet from vertical datum in the southeast. The thickness of the Reklaw aquitard (also shown on Figure 2-10) was prepared from subtracting the bottom elevation surface from the top elevation surface. A total of 1,161 wells had both a top and bottom stratigraphic contact to provide thickness control. The Reklaw aquitard thickness ranges from 0 at the updip outcrop edge to 467 feet.

2.1.10 *Carrizo-Upper Wilcox*

The Carrizo-upper Wilcox interval wholly comprises the Carrizo Formation and the upper Wilcox interval of the Wilcox Group. Hargis (2009) described the upper Wilcox as the updip equivalent of the Carrizo Formation. Hamlin (1988) characterizes the fluvial facies of the Carrizo Formation in the updip region as contiguous with the deltaic facies in the downdip region. The Carrizo-upper Wilcox interval includes the bed-load fluvial channel-fill sandstones with the lower interval consisting of a mixed alluvial system with fluvial-channel sandstones and minor shale (Hamlin, 1988). In the Rio Grande Embayment, the lower portion of the Carrizo-upper Wilcox transitions to include more sandstone (Bebout and others, 1982).

2.1.10.1 Stratigraphic Analysis

Stratigraphic interpretations for the Carrizo-upper Wilcox interval were based on the methodology used by Meyers and others (2019, unpublished). According to Meyers and others (2019, unpublished), the top of the Carrizo-upper Wilcox interval is defined as the "top of the massive Carrizo Formation sands" while the bottom contact is the "base of the first significant sharp-based sand superjacent to a regional marine shale marker equivalent to the top of the Middle Wilcox". Importantly, re-worked sands overlying the massive sand, which have a lower overall deep resistivity signature and limited areal extent, are included in the overlying Reklaw aquitard instead of the Carrizo.

2.1.10.2 Well Control and Formation Top, Bottom, Thickness

Top and bottom elevation maps for the Carrizo-upper Wilcox interval are shown on Figure 2-11 and were prepared using 1,351 and 1,284 stratigraphic contacts, respectively, from wells within the study area as well as some wells immediately outside of the study area to control surface edge effects. The top elevation of the Carrizo-upper Wilcox interval ranges from about 908 feet from vertical datum in the northwest portion of the study area to -7,080 feet from vertical datum in the southeast portion. The bottom elevation of the Carrizo-upper Wilcox interval ranges from about 905 feet from vertical datum in the northwest and decreases to about -8,017 feet from vertical datum in the southeast. The thickness of the Carrizo-upper Wilcox interval (also shown on Figure 2-11) was prepared from subtracting the bottom elevation surface from the top elevation surface. A total of 1,181 wells had both a top and bottom stratigraphic contact to provide thickness control. The Carrizo-upper Wilcox interval thickness ranges from 0 at the updip outcrop edge to 1,690 feet.

2.1.11 *Middle Wilcox*

The middle Wilcox interval is part of the Wilcox Group which was deposited in a coastal plain and marine environment (Hamlin and others, 2019). The sequence of the middle Wilcox interval includes a brief depositional episode which is bounded by transgressive marine shales (Galloway and others, 2000). The middle Wilcox interval is shale-dominated with 20 to 40 percent sandstone and is defined by the maximum flooding surfaces of the Yoakum shale (Xue and Galloway, 1995). The deposition of the middle Wilcox is associated with the incision of submarine canyons which cut into the underlying lower Wilcox interval (Galloway and others, 2000). The incised channel was then later filled with the Yoakum shale during the following transgression (Galloway and others, 2000). In the Rio Grande Embayment area, a resurgence of progradation occurred toward the end of the middle Wilcox interval accumulation (Ayers and Lewis, 1985) resulting in an increase in sand lenses in the updip region. The middle Wilcox interval acts as a confining unit between the overlying Carrizo-upper Wilcox interval and underlying lower Wilcox interval (Hamlin and others, 2019).

2.1.11.1 Stratigraphic Analysis

Stratigraphic interpretations for the middle Wilcox interval were based on the methodology used by Meyers and others (2019, unpublished) to determine the top of the Wilcox Group which is composed of the middle and lower Wilcox intervals. According to Meyers and others (2019, unpublished), the top of the middle Wilcox interval is defined as the “top of a regional shale subjacent to the lowest significant sharp-based sand of the Carrizo Formation” which can either be the base of the massive sand complex or the base of the interbedded sand and shale units of the upper Wilcox. The bottom contact is interpreted as the bottom of a regional shale (known as the Tilden Shale) or above the uppermost sand signature in the lower Wilcox interval. This methodology is consistent with Hamlin and others (2019). Near the San Marcos Arch, this sand signature correlates to the Simsboro Formation. In the extreme downdip area, the lower Wilcox is dominated by thick shale-dominated deltaic successions (Olariu and Zeng, 2018) and the contact between the middle and lower Wilcox interval is less defined.

2.1.11.2 Well Control and Formation Top, Bottom, Thickness

Top and bottom elevation maps for the middle Wilcox interval are shown on Figure 2-12 and were prepared using 1,455 and 723 stratigraphic contacts, respectively, from wells within the study area as well as some wells immediately outside of the study area to control surface edge effects. The top elevation of the middle Wilcox interval ranges from about 941 feet from vertical datum in the northwest portion of the study area to -8,016 feet from vertical datum in the southeast portion. The bottom elevation of the middle Wilcox interval ranges from about 929 feet from vertical datum in the northwest and decreases to about -9,606 feet from vertical datum in the southeast. The thickness of the middle Wilcox interval (also shown on Figure 2-12) was prepared from subtracting the bottom elevation surface from the top elevation surface. A total of 692 wells had both a top and bottom stratigraphic contact to provide thickness control. The middle Wilcox interval thickness ranges from 0 at the updip outcrop edge to 2,116 feet.

2.1.12 *Lower Wilcox*

The lower Wilcox interval is part of the Wilcox Group which was deposited in a coastal plain and marine environment (Hamlin and others, 2019). The lower Wilcox interval is conformable with the overlying middle Wilcox interval and the Midway Group (Galloway and others, 2000). The Midway Group is thought to be the prodelta marine deposit base of the lower Wilcox fluvial and deltaic system (Bebout and others, 1982).

2.1.12.1 Stratigraphic Analysis

Stratigraphic interpretations for the lower Wilcox interval were based on the methodology used by Hamlin and others (2019) and Meyers and others (2019, unpublished) to determine the top and bottom, respectively, of the Wilcox Group which is composed of the middle and lower Wilcox intervals. The top contact of the lower Wilcox was selected to be the first sand adjacent to the Tilden Shale. According to Meyers and others (2019, unpublished), the bottom of the lower Wilcox interval is defined as the “base of the first significant sand-based, upward coarsening, progradational sequence superjacent to a regional marine shale marker equivalent to the Poth Shale core of Hargis (2009)”. Meyers and others (2019, unpublished) noted the extreme downdip contact was difficult to ascertain due to the basal Wilcox consisting of thick shale-dominated deltaic successions making the Poth Shale core difficult to discern (Olariu and Zeng, 2018).

2.1.12.2 Well Control and Formation Top, Bottom, Thickness

Top and bottom elevation maps for the lower Wilcox interval are shown on Figure 2-13 and were prepared using 902 and 1,486 stratigraphic contacts, respectively, from wells within the study area as well as some wells immediately outside of the study area to control surface edge effects. The top elevation of the lower Wilcox interval ranges from about 997 feet from vertical datum in the northwest portion of the study area to -9,606 feet from vertical datum in the southeast portion. The bottom elevation of the lower Wilcox interval ranges from about 977 feet from vertical datum in the northwest and decreases to about -10,507 feet from vertical datum in the southeast. The thickness of the lower Wilcox interval (also shown on Figure 2-13) was prepared from subtracting the bottom elevation surface from the top elevation surface. A total of 652 wells had both a top and bottom stratigraphic contact to provide thickness control. The lower Wilcox interval thickness ranges from 0 at the updip outcrop edge to 2,953 feet.

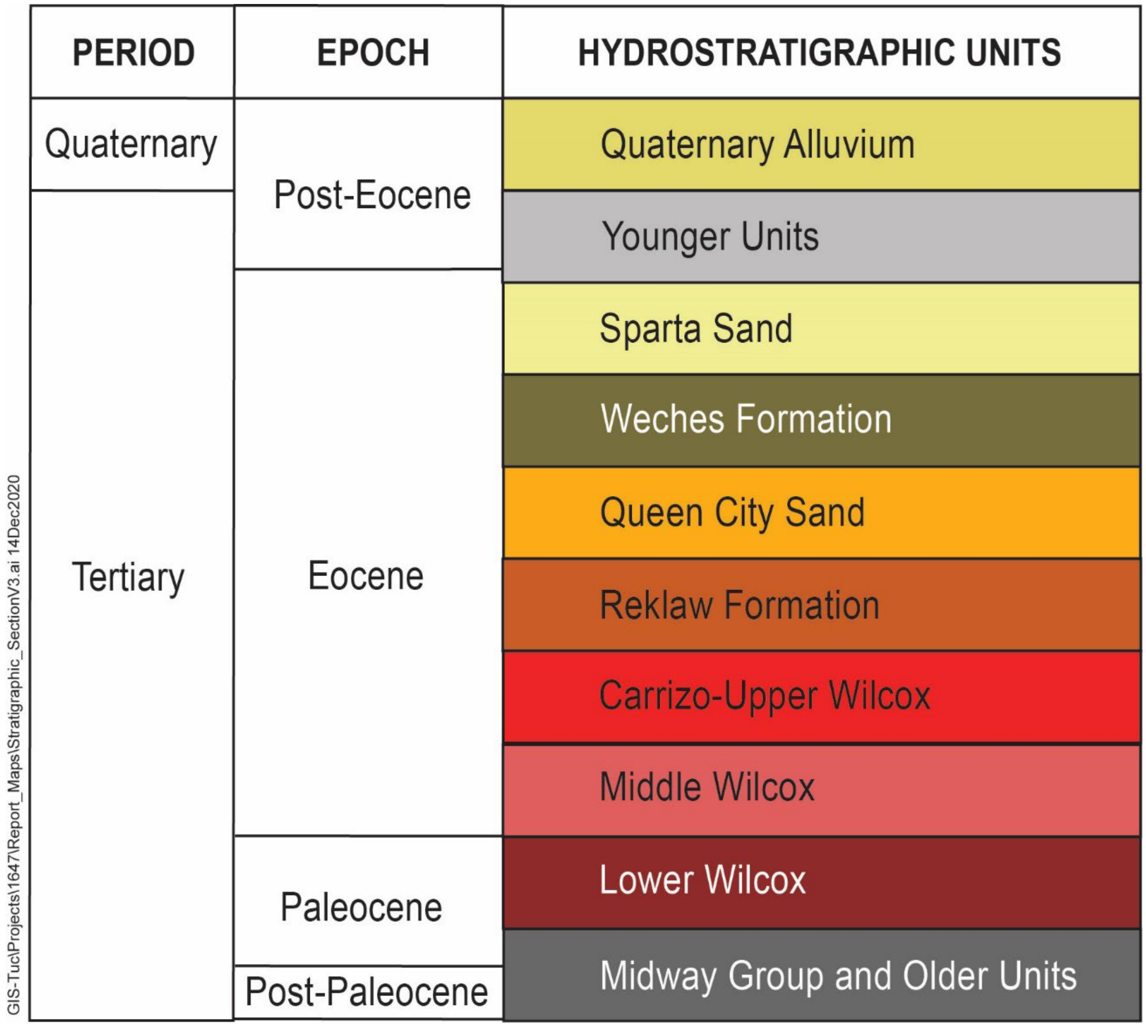

Figure 2-1. Hydrostratigraphic units in the updated groundwater availability model.

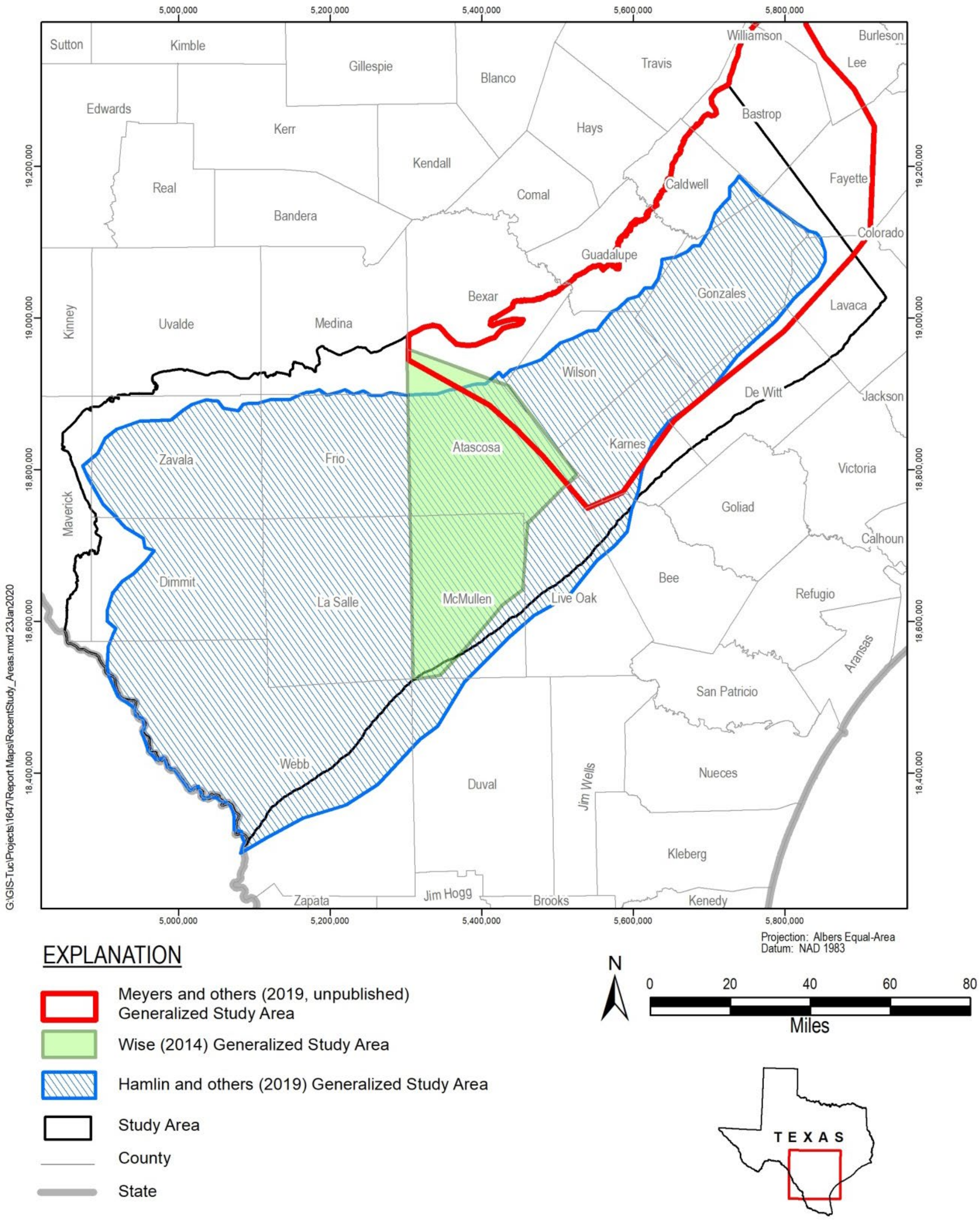

Figure 2-2. Recent studies map.

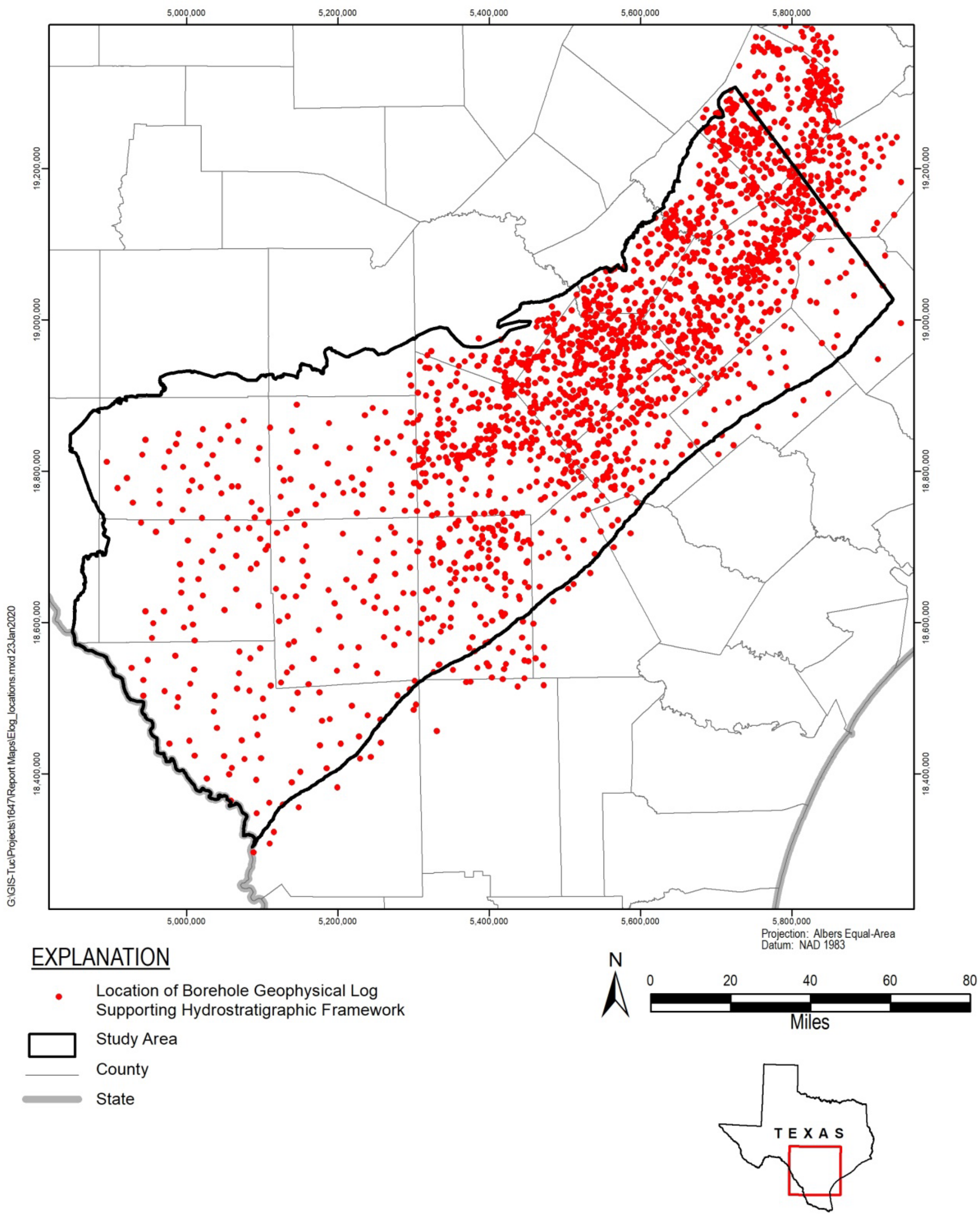

Figure 2-3. Locations of borehole geophysical logs supporting framework development.

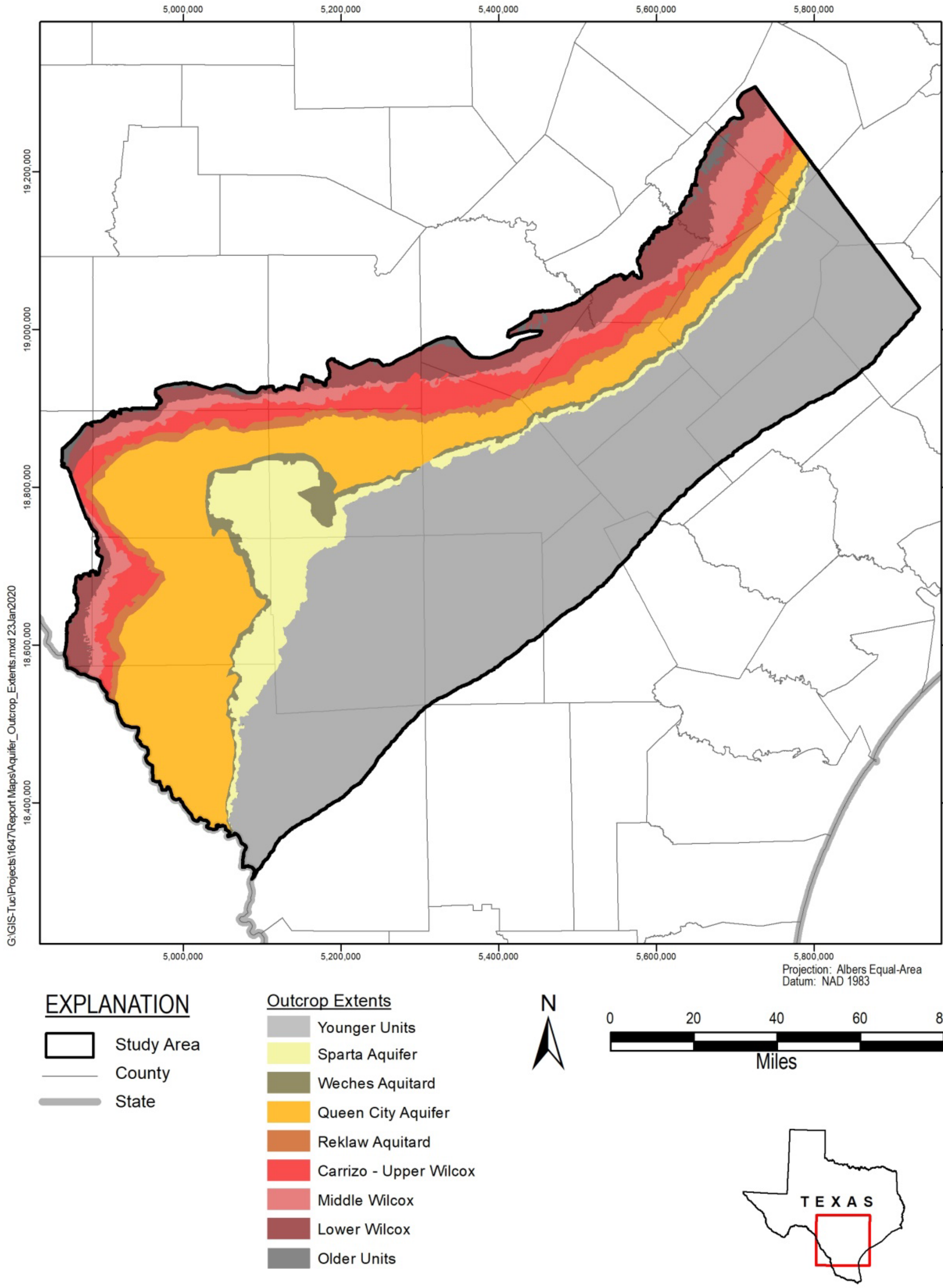

Figure 2-4. Aquifer outcrops from framework; Quaternary deposits not shown.

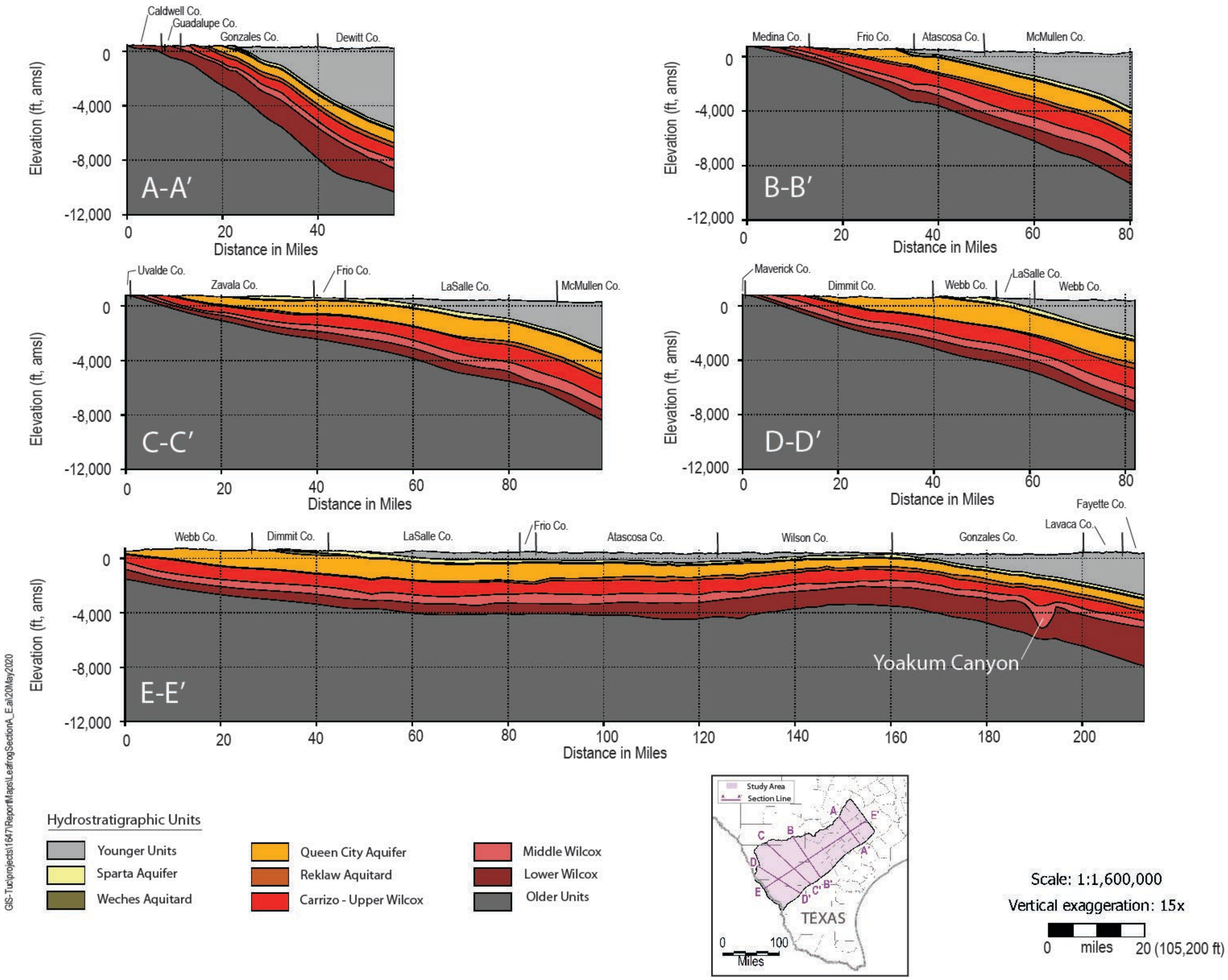

Figure 2-5. Hydrostratigraphic sections.

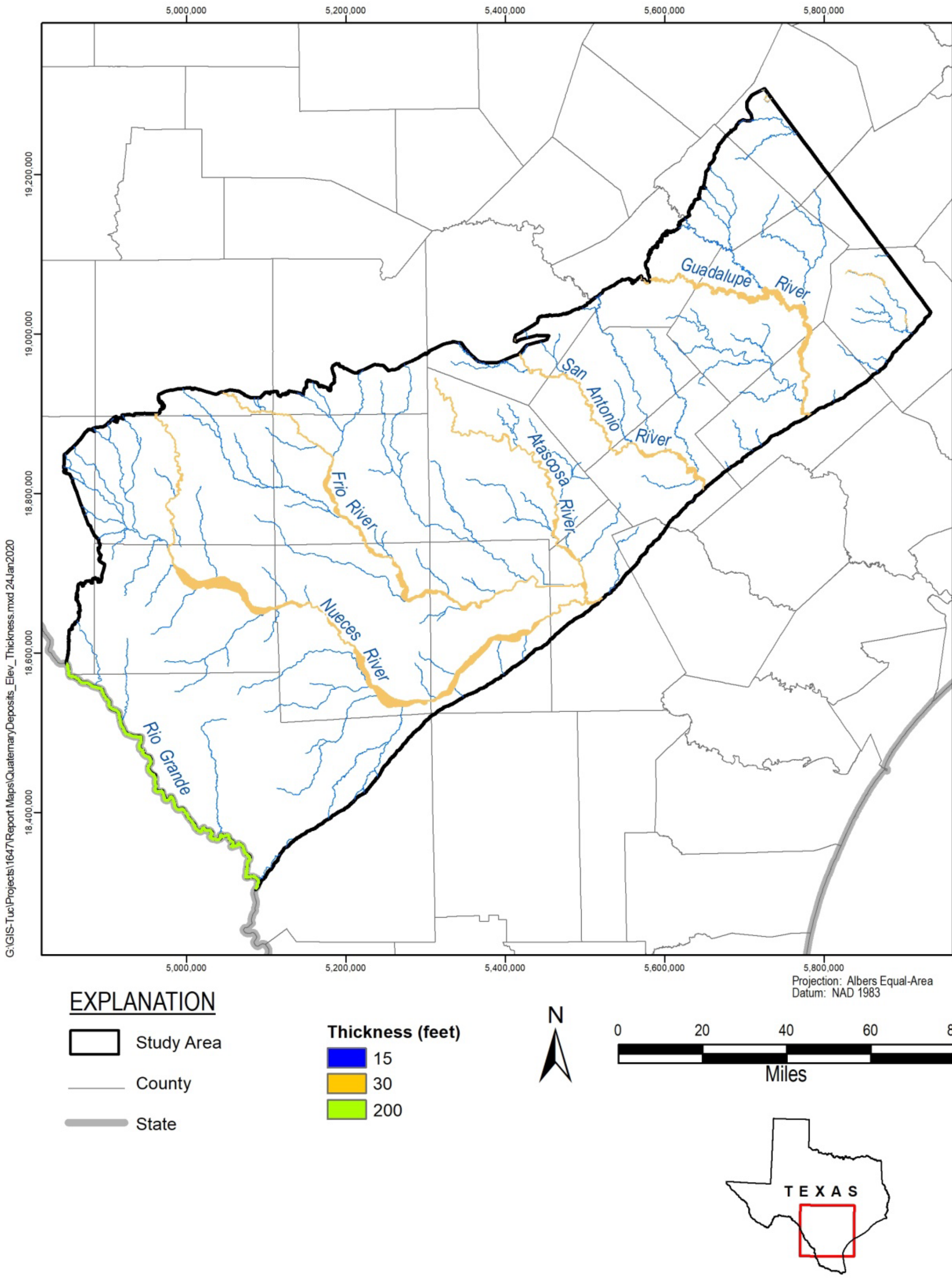

Figure 2-6. Thickness of Quaternary deposits.

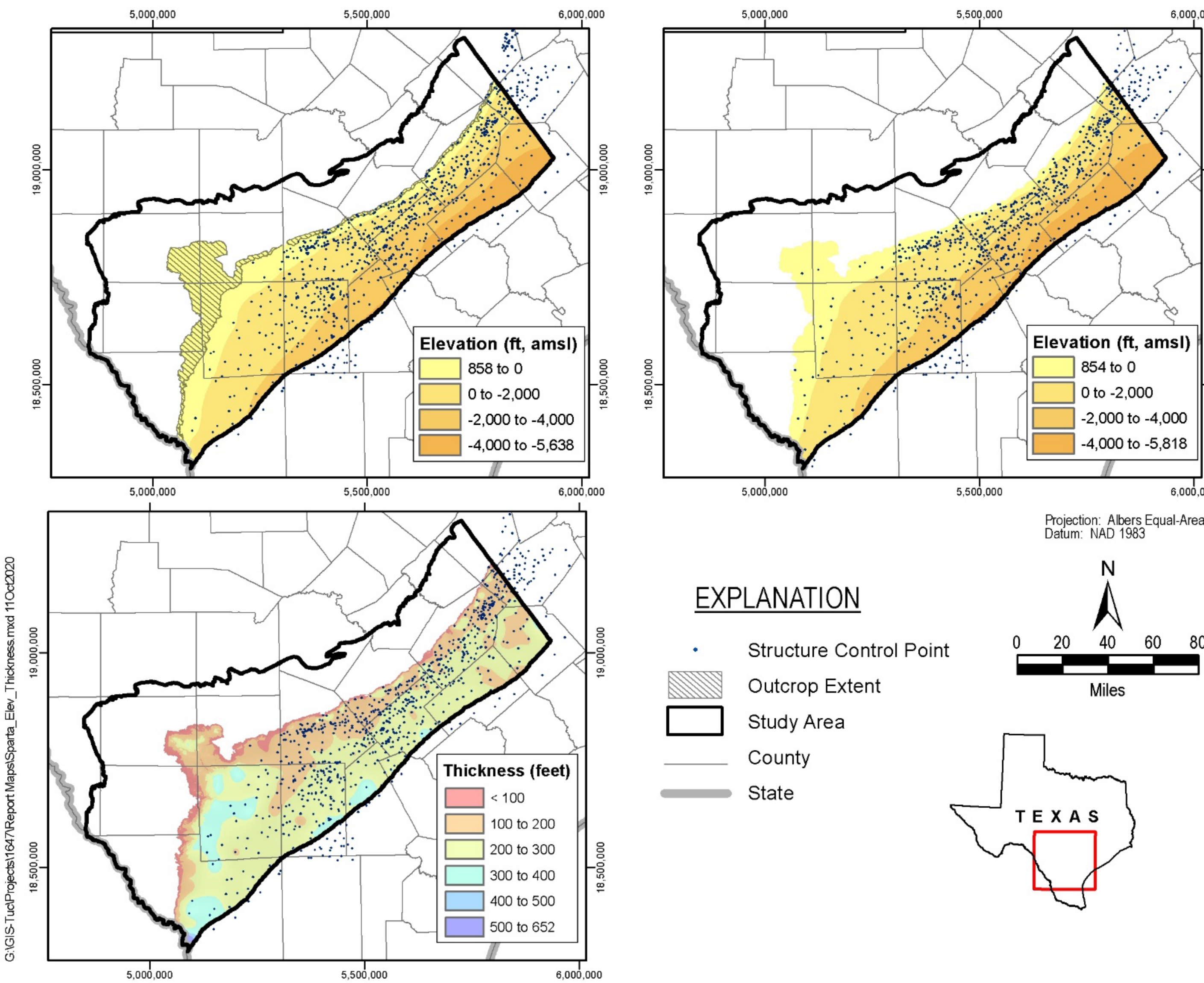

Figure 2-7. Surface elevations and thickness of Sparta Aquifer.

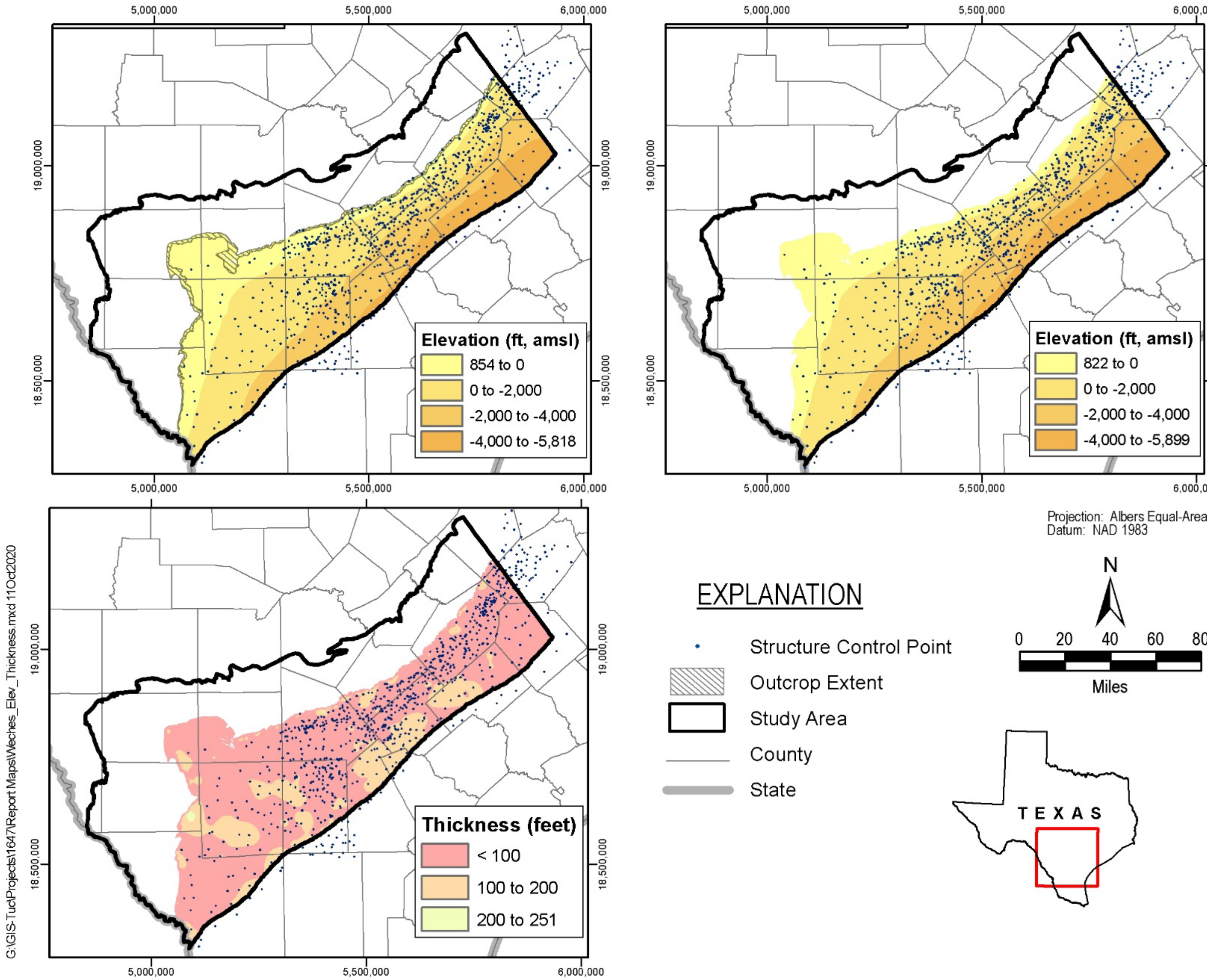

Figure 2-8. Surface elevations and thickness of Weches aquitard.

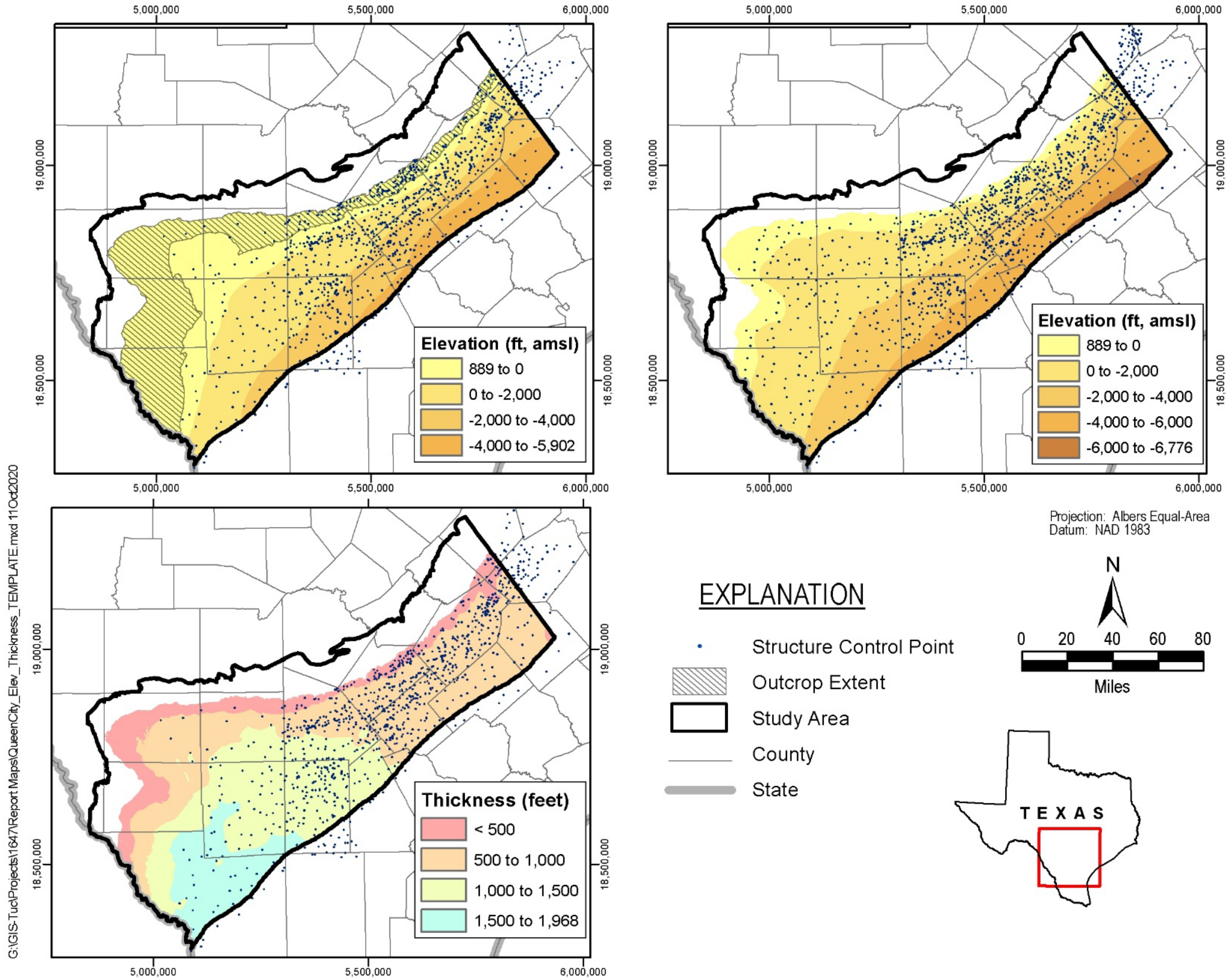

Figure 2-9. Surface elevations and thickness of Queen City Aquifer.

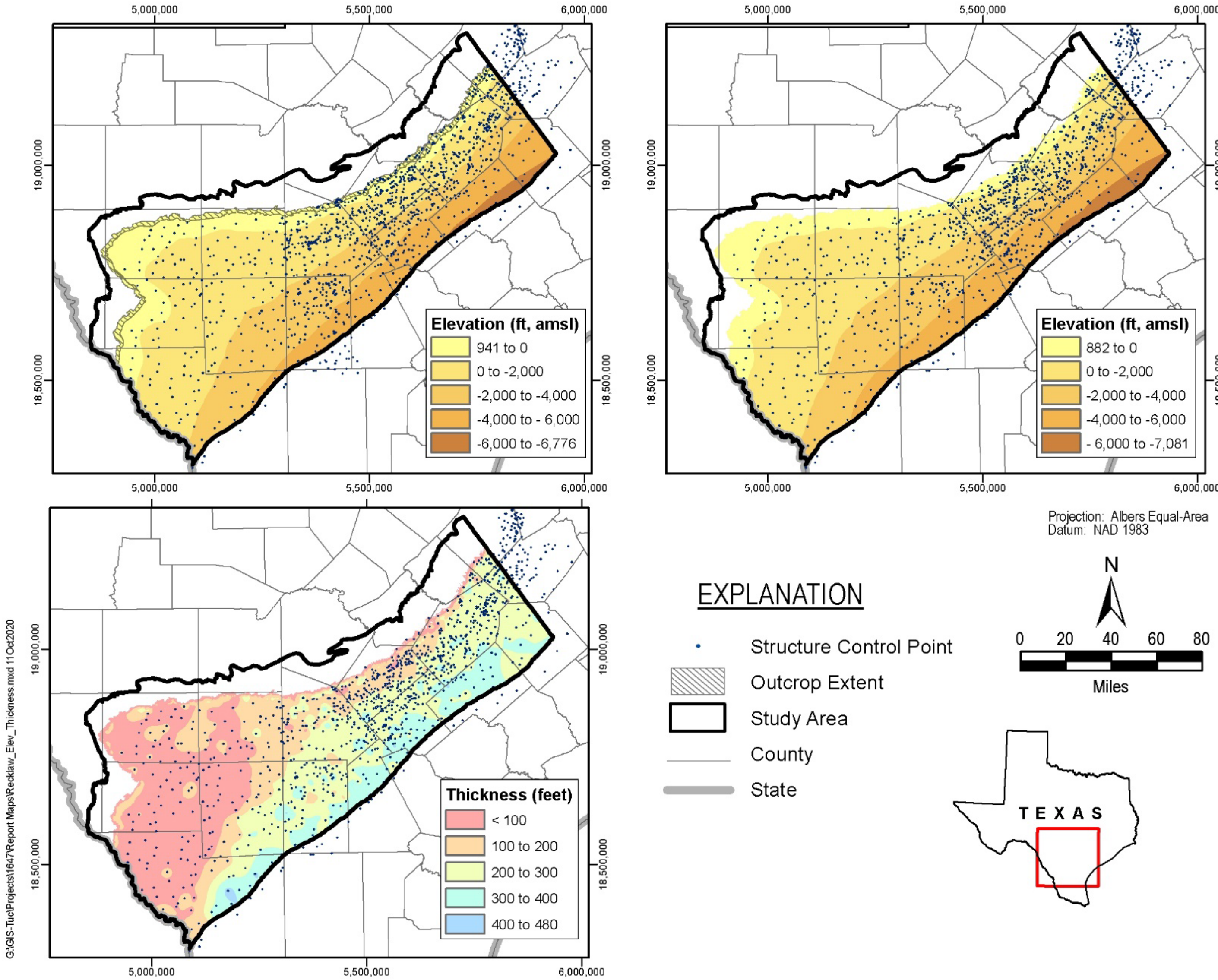

Figure 2-10. Surface elevations and thickness of Reklaw aquitard.

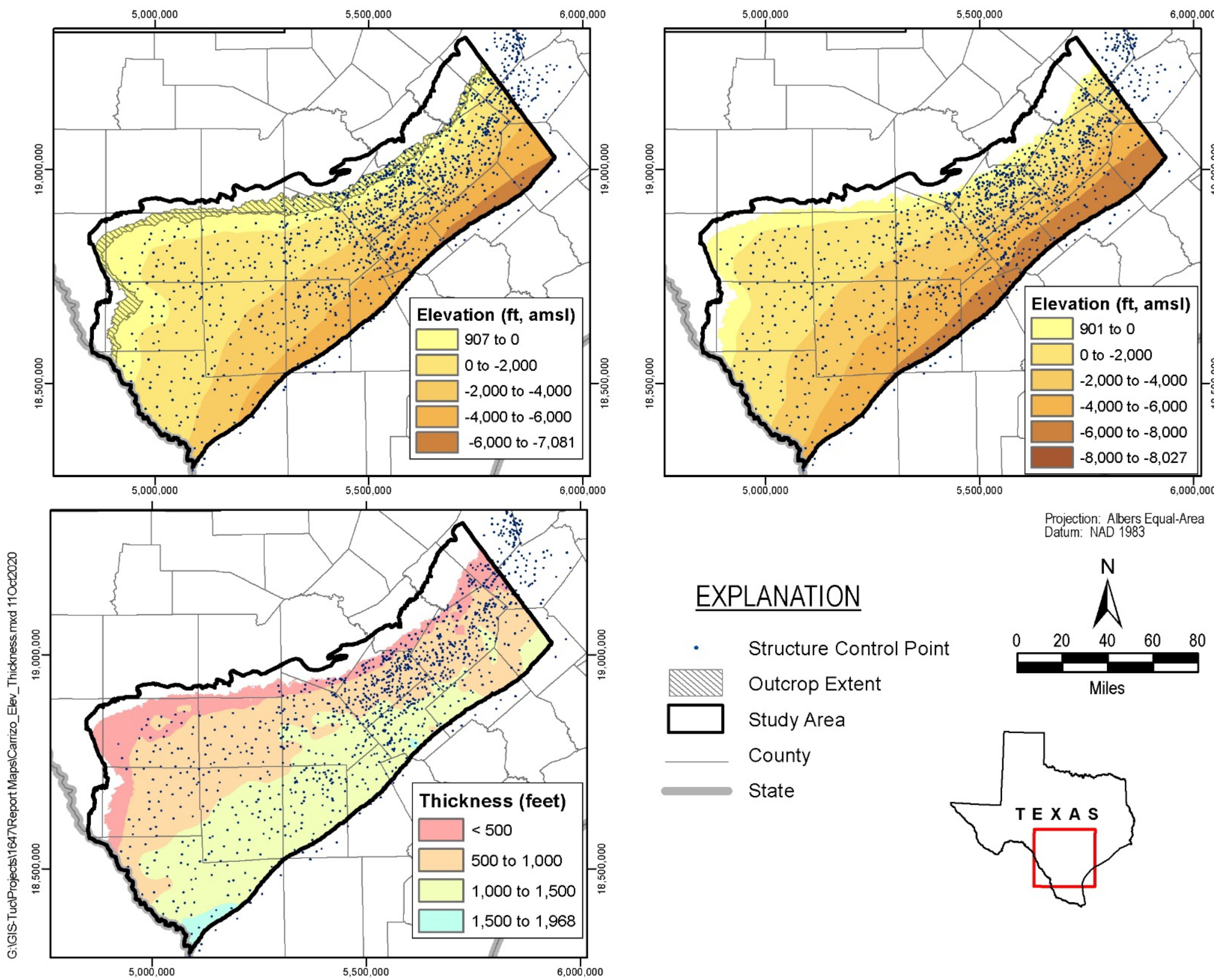

Figure 2-11. Surface elevations and thickness of Carrizo-upper Wilcox interval.

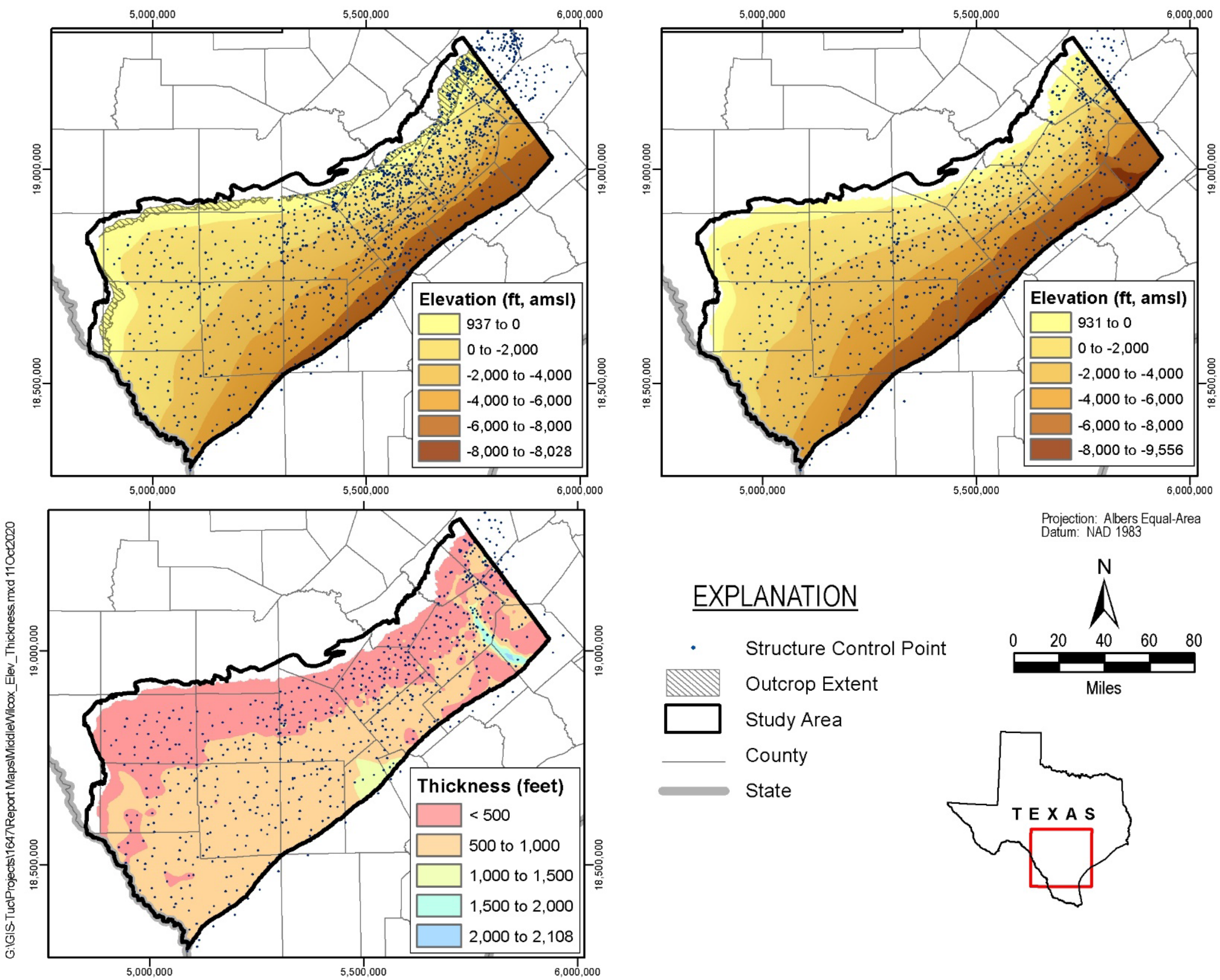

Figure 2-12. Surface elevations and thickness of middle Wilcox interval.

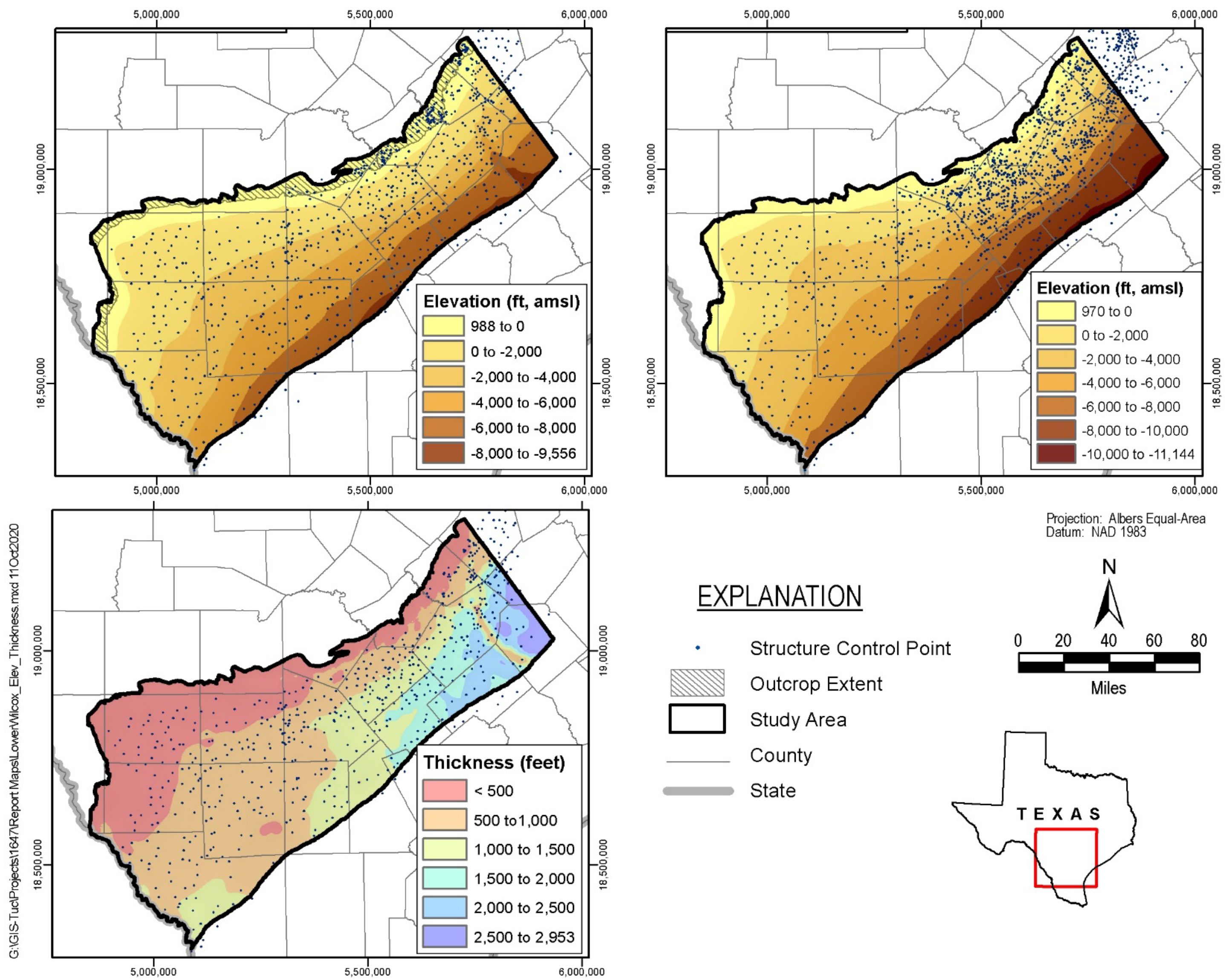

Figure 2-13. Surface elevations and thickness of lower Wilcox interval.

2.2 Groundwater Levels and Flow

Groundwater in the southern 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. Regional groundwater movement is generally from higher elevations in the northwest to lower elevations along drainages and to the southeast towards the Gulf of Mexico. As described by Deeds 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 and Carrizo units are generally hydraulically connected and behave as a single aquifer in the northeastern and southwestern-most margins of the study area. As described by Deeds and others (2003), the sands of the Wilcox Group are either not mentioned as an aquifer or not considered to be an aquifer due to salinity levels. An assessment of screened intervals compared to the hydrostratigraphic framework layers indicates distinct Carrizo and Wilcox wells in the outcrop area while the downdip area is more concentrated with Carrizo wells (Figure 2-14).

2.2.1 *Previous Studies*

An extensive literature search and analysis was conducted by Deeds 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 2019 for this study.

The investigations by Deeds 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 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 post-1950 as data pre-1950 was not available for the study area.

2.2.2 *Distribution of Groundwater Level Measurements*

Information for well locations, well construction, and groundwater level measurements was obtained from the TWDB Groundwater Database (TWDB, 2019c), the Brackish Resources Aquifer Characterization System database (TWDB, 2019b), and data provided by stakeholders from Groundwater Conservation Districts. For many wells, the Brackish Resources Aquifer Characterization System database and well information from Groundwater Conservation Districts included the state identification number for linking to the TWDB 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 and completion information 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 55,0518 approved groundwater level measurement records are available from 4,175 wells located in the study area with aquifer designations beginning in the early 1900s. This 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. These results were confirmed with studies from the Brackish Resources Aquifer Characterization System database to distinguish the representative aquifer for a well. If no information for the screened interval was available for a well, the well was assumed to represent the aquifer designated by the Brackish Resources Aquifers Characterization System group or the TWDB. A confidence level was assigned to each well to provide context on the information used to determine the aquifer designation and therefore the degree of confidence with this designation.

Locations of all wells with available groundwater measurements for the aquifers of interest in the study area are shown on Figure 2-14. The spatial distributions of selected groundwater level measurements for the Sparta Aquifer, Queen City Aquifer and the Carrizo-Wilcox Aquifer are shown on Figure 2-15, Figure 2-16, and Figure 2-17, respectively. Measurements at these locations were selected to either verify or evaluate and prepare the time-series groundwater level contours for 1980, 1999, and 2017, as discussed in the next section of this report. All available groundwater level measurements with aquifer designations will be used for calibration of the groundwater model. Many of the wells are located in the outcrop areas and many have just one or a few measurements available. Relatively few measurements are available for the deep, downdip portions of the aquifers of interest in the southeast (Figure 2-14).

2.2.3 *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, outcrop areas in northwest and lower groundwater level elevations occurring to the southeast in the downdip areas.

Contours of regional groundwater level elevation were evaluated for the aquifer units 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) 2017 to represent conditions at the end of the groundwater model calibration period. Contours for predevelopment, 1980, and 1999 were prepared by Deeds and others (2003) and Kelley and others (2004) for the previous groundwater availability models for the aquifer system.

Predevelopment groundwater conditions are defined as the conditions of the groundwater system prior to the start of disturbances to natural groundwater flows as a result of groundwater development (pumping withdrawals). Predevelopment groundwater level elevation contours maps were developed by Kelley and others (2004) for the Sparta Aquifer and Queen City Aquifer (Figure 2-18 and Figure 2-19) and by Deeds and others (2003) for the Carrizo-Wilcox Aquifer (Figure 2-20). The predevelopment groundwater levels contours could be used as a guide for calibration of a steady-state groundwater model.

The previously prepared contours for 1980 and 1999 were compared with control data associated with this study. The updated control data included water level measurement data and aquifer determinations based on the evaluation of the hydrostratigraphic framework model to screened intervals and water level points, where available, and with consideration to the aquifer designations determined by the Brackish Resources Aquifer Characterization System group (Meyers and others (2019, unpublished); Wise (2014)). The water level measurements used for verification represented winter conditions as subsequently described in the contouring of the 2017 dataset. It was determined that the previous contours were representative of the available historic data and, thus, are sufficient for use in this study with minor modifications. These modifications were made due to some reclassified aquifer designations and the addition of compatible designations in the region southwest of the Frio River which is more traditionally not grouped as Sparta and Queen City aquifers based on the delineation of minor aquifers by the TWDB (Figure 1-5). Certain portions of the 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 2017 were prepared for this study using groundwater level measurements obtained from the TWDB Groundwater Database (TWDB, 2019c), the TWDB Brackish Resources Aquifer Characterization System database (TWDB, 2019b), and Groundwater Conservation District stakeholders. 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 measurements utilized were from winter months (November through February); therefore the 2017 contours generally represent winter conditions which may have less pumping interference. Since the amount of data specifically for the winter of 2016 to 2017 was insufficient for developing regional contours, data within the period of 2014 to 2019 were used based on the following criteria:

1. Highest priority was given to a measurement collected during the winter of 2016 to 2017. If a well had multiple measurements for a winter period, then the water levels were averaged;
2. If no data were available for the winter of 2016 to 2017, then winter measurements for adjacent years were used, first going back one year then forward one year;
3. If no winter measurements were available for the four-year window, then summer measurements were used.

4. Both the Sparta and Queen City Aquifer did not have sufficient data in the southwest portion of the study area for the four-year window, and therefore the period was extended to 2012 and 2013 to increase available control data in this region.

Groundwater level elevation contour maps for 1980, 1999, and 2017 for the Sparta, Queen City, Carrizo-Wilcox Aquifer are shown on Figure 2-21. Figure 2-22, and Figure 2-23 respectively. Contours were not drawn for the Weches and Reklaw confining units due to the lack of data for these units. Similar to the previous groundwater availability model, little water level data is available for the Wilcox unit downdip of the outcrop, therefore, groundwater level contours focused on the Carrizo (Deeds and others, 2003).

The groundwater elevation contour maps show that regional groundwater movement in the study area is generally to the southeast from the outcrop areas in the northwest. The highest groundwater level elevations in the study area occur in the northwest in Zavala and Frio counties. In general, relatively steep hydraulic gradients occur between outcrop and down-dip areas, and also at any cones of depression caused by groundwater pumping. Some of the changes in groundwater elevations presented on Figure 2-21. Figure 2-22, and Figure 2-23 are likely a result of limited availability of measurements at individual wells and inconsistent monitoring schedules. However, some of the changes could be a result of changes in groundwater pumping in a given area through time.

Inspection of groundwater level data and results of previous groundwater availability models suggest that regional hydraulic connections occur between the aquifer units in certain areas in the study area. The similarity of groundwater levels in adjacent aquifers suggests that the aquifers are hydraulically connected, particularly at or near outcrop areas.

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 2019. 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, and Carrizo-Wilcox aquifers are shown on Figure 2-24 through Figure 2-30.

Groundwater levels have remained relatively stable in the Sparta Aquifer, with variations generally less than 10 feet at most wells (Figure 2-24). Hydrographs of the Sparta Aquifer are represented by wells in the outcrop region due to the availability of long periods of groundwater level measurements in this area. Measurements at a well in Fayette County indicate a gradual decline in groundwater levels of approximately 30 feet over a period of 10 years but show signs of stabilizing in recent years. Measurements at wells in Gonzales and La Salle counties suggest a gradual and slight recovery to the Sparta Aquifer from decades of stable conditions.

Similar to the Sparta Aquifer, hydrographs of the Queen City Aquifer are represented by wells in the outcrop region primarily in the central portion of the study area due to the availability of groundwater level measurements through time in this area. Groundwater levels have remained relatively stable in the Queen City Aquifer, with variations generally less than 10 feet at wells in Atascosa and Wilson counties (Figure 2-25). However, during this period, groundwater level declines have occurred at a few wells in the aquifer including two wells in Frio County which have declined between 60 to 70 feet.

Groundwater levels in the Carrizo-Wilcox Aquifer have remained stable in the outcrop areas and have gradually declined through time at many hydrograph locations in the down-dip areas (Figure 2-26 and Figure 2-27). Hydrographs for Carrizo and Wilcox wells in the Carrizo-Wilcox outcrop area have remained mostly stable with fluctuations generally less than 20 feet. Hydrographs for wells in the down-dip area show substantial decline in groundwater levels (on the order of 150 to 200 feet) since the 1950s with many wells in the southern portion of the model in Dimmit and La Salle counties experiencing a more abrupt decline starting around the year 2010 (Figures 2-28 through 2-30).

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

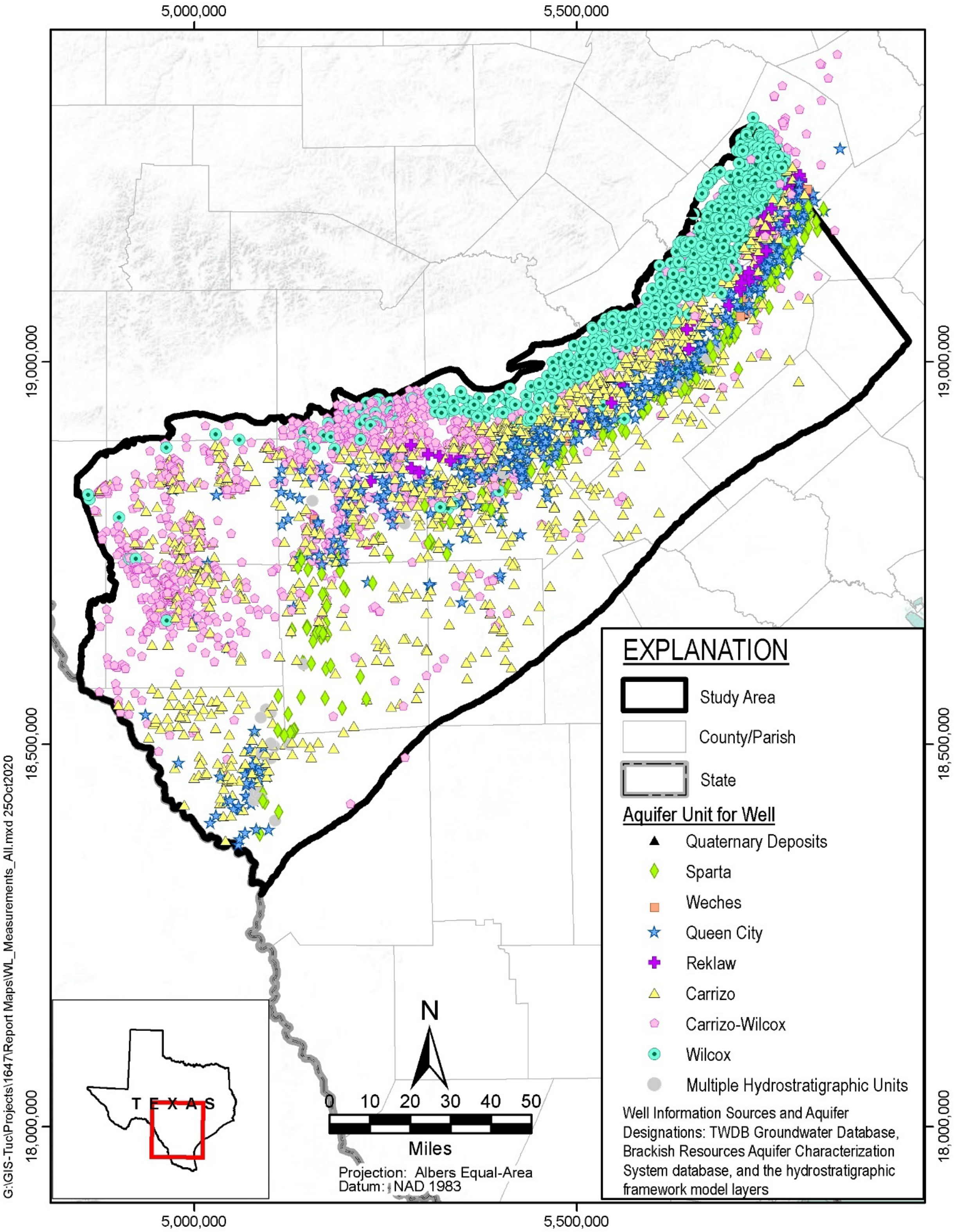

Figure 2-14. Locations of wells with groundwater level measurements.

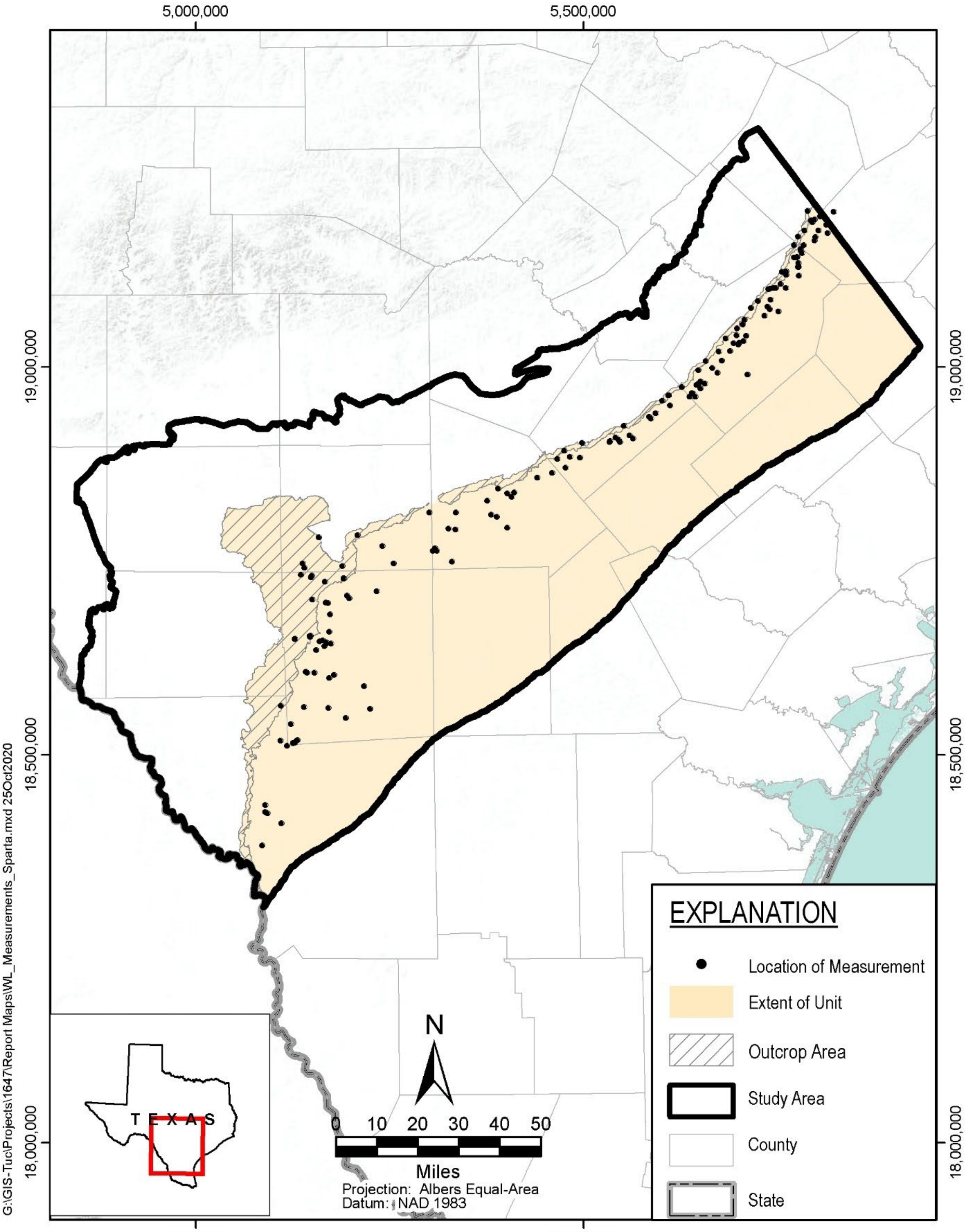

Figure 2-15. Locations of selected groundwater level measurements for Sparta Aquifer.

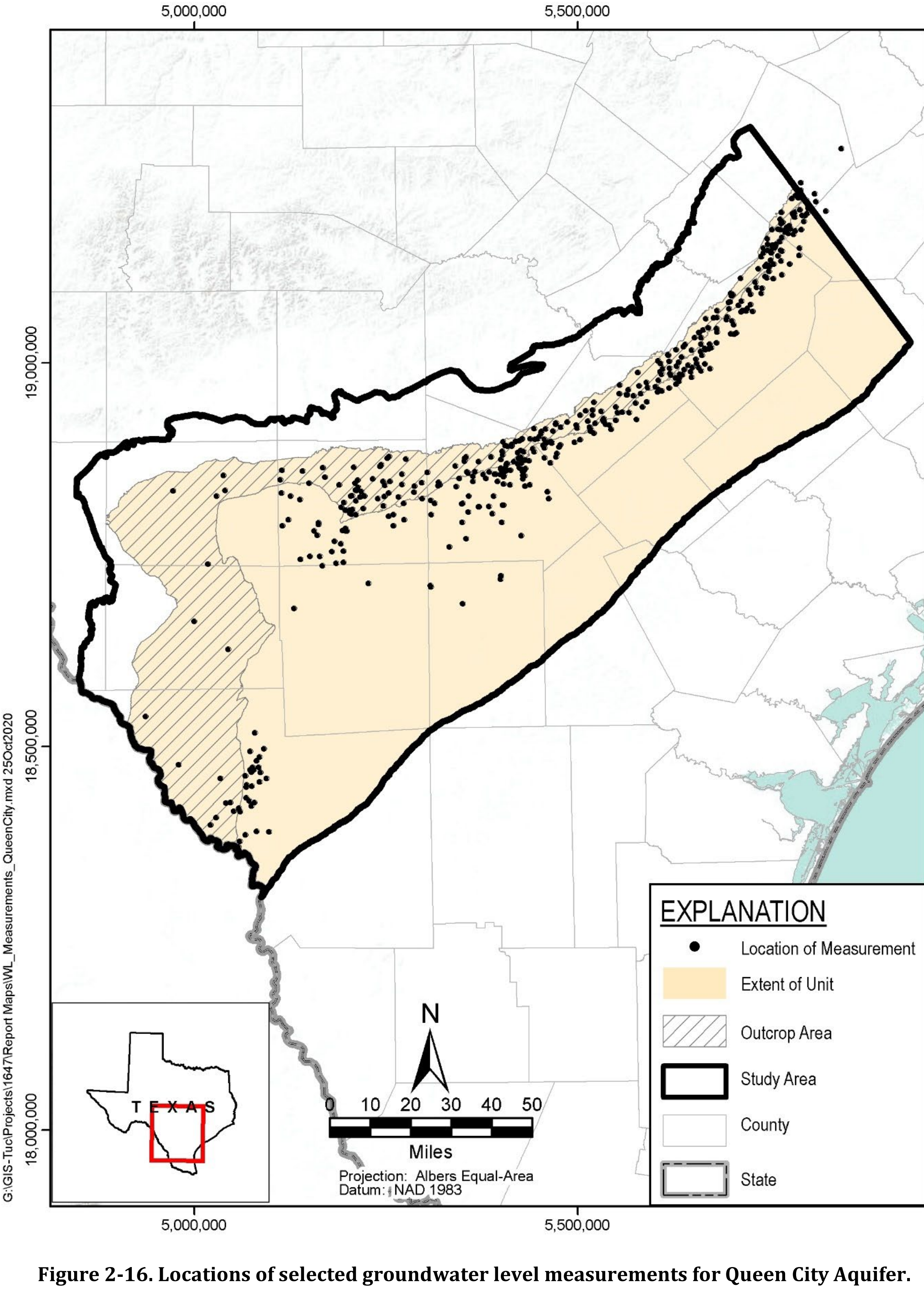

Figure 2-16. Locations of selected groundwater level measurements for Queen City Aquifer.

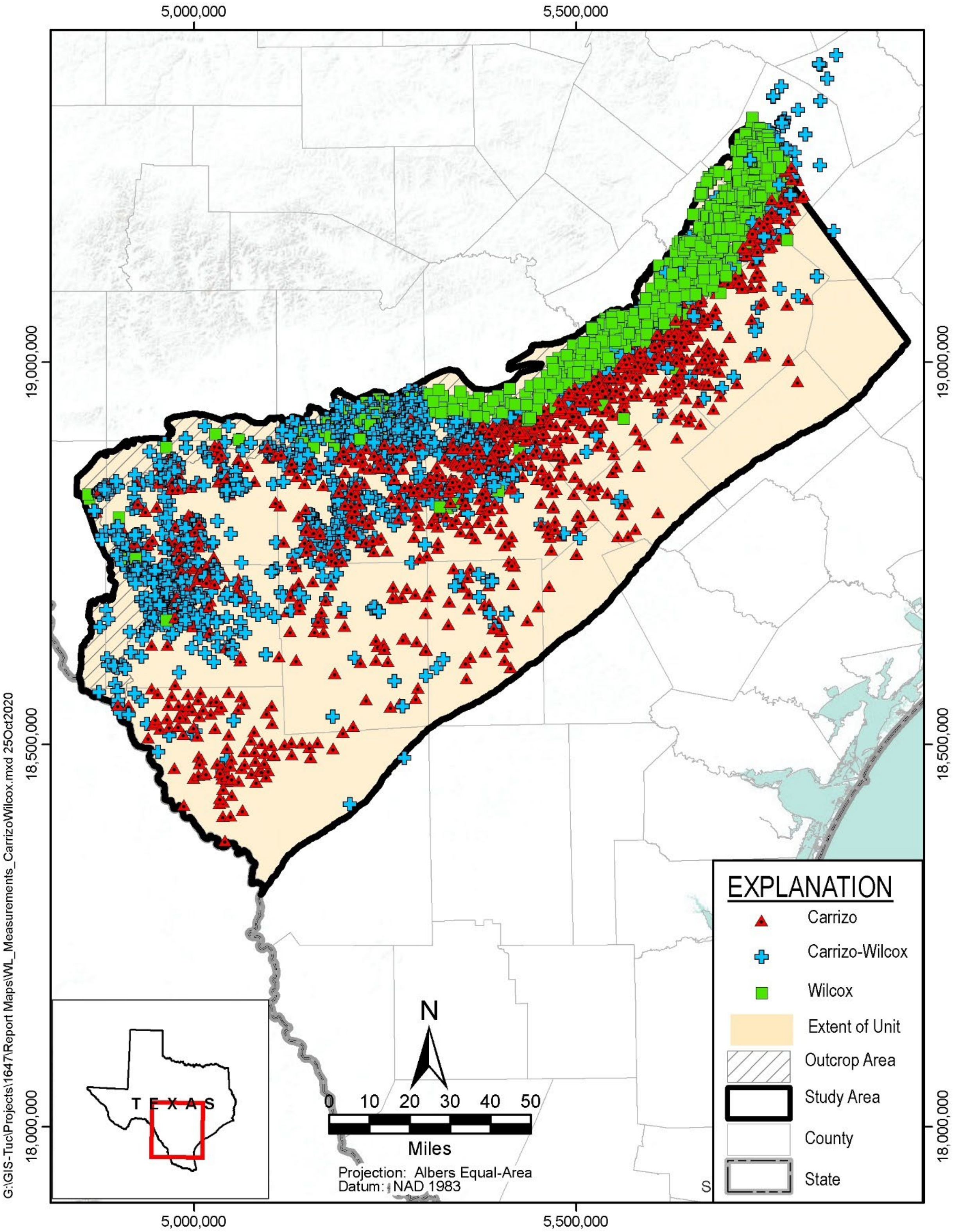

Figure 2-17. Locations selected groundwater level measurements for Carrizo-Wilcox Aquifer.

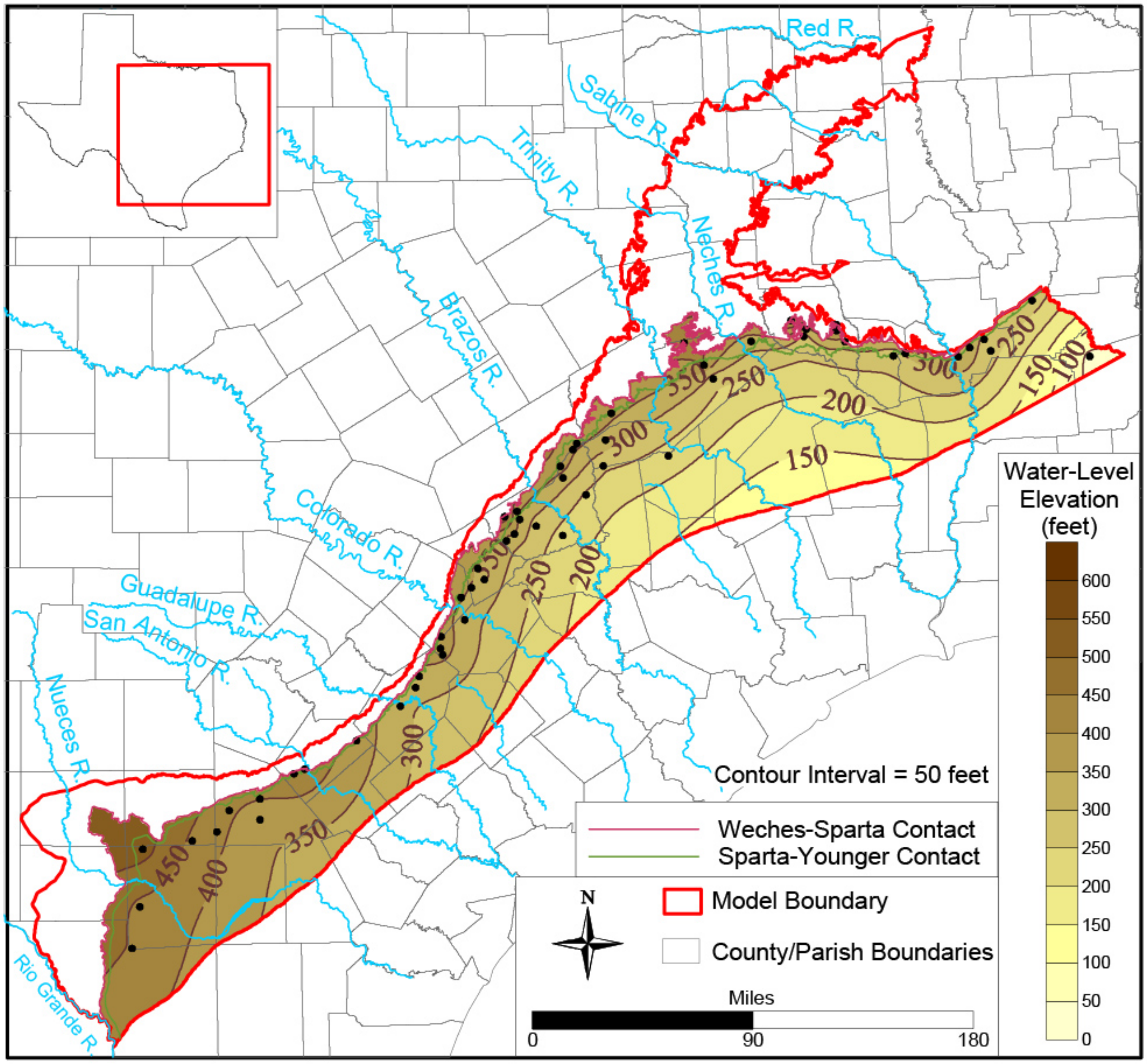

Figure 2-18. Estimated groundwater level elevation contours for predevelopment conditions in Sparta Aquifer; from Kelley and others (2004).

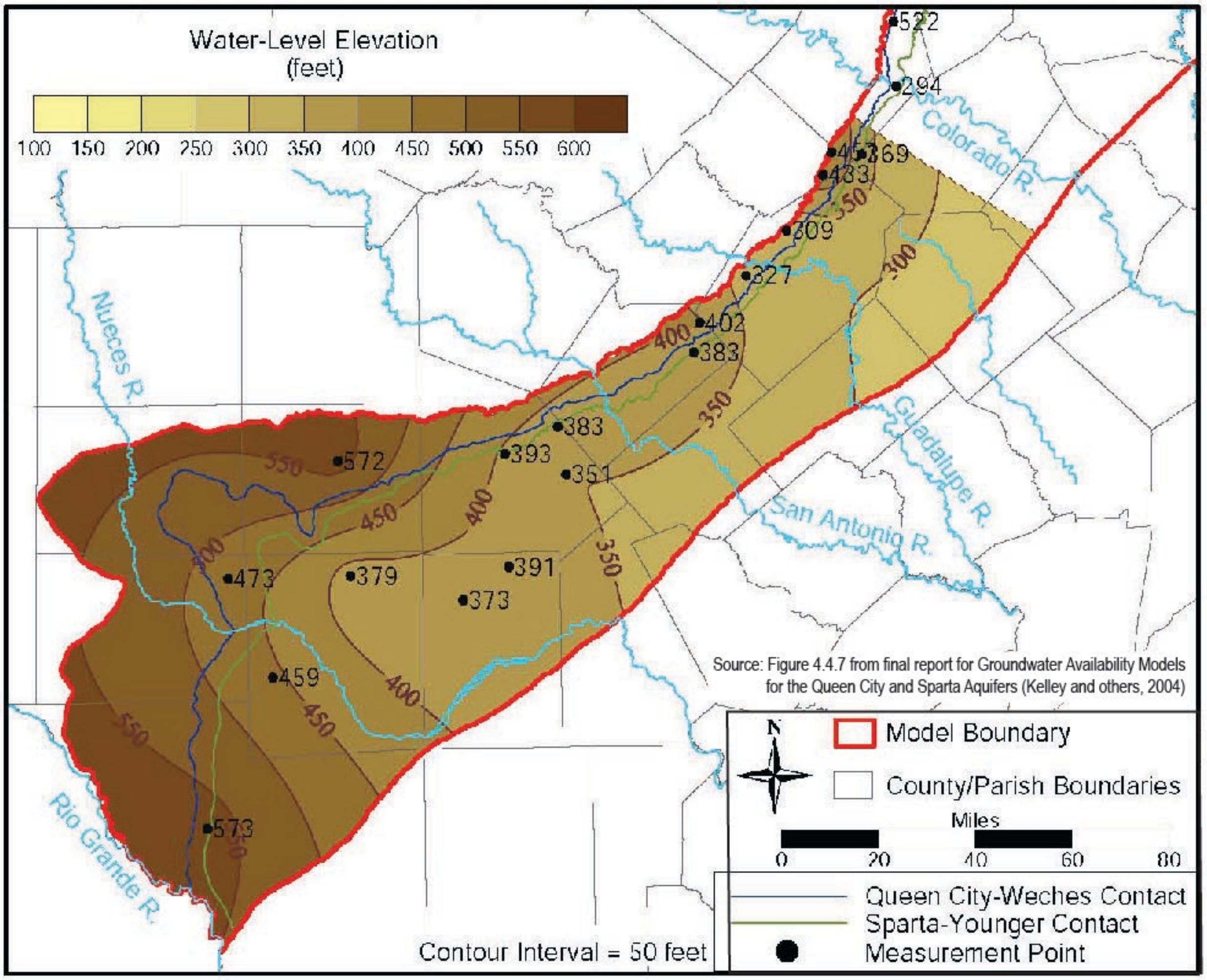

Figure 2-19. Estimated groundwater level elevation contours for predevelopment conditions in Queen City Aquifer; from Kelley and others (2004).

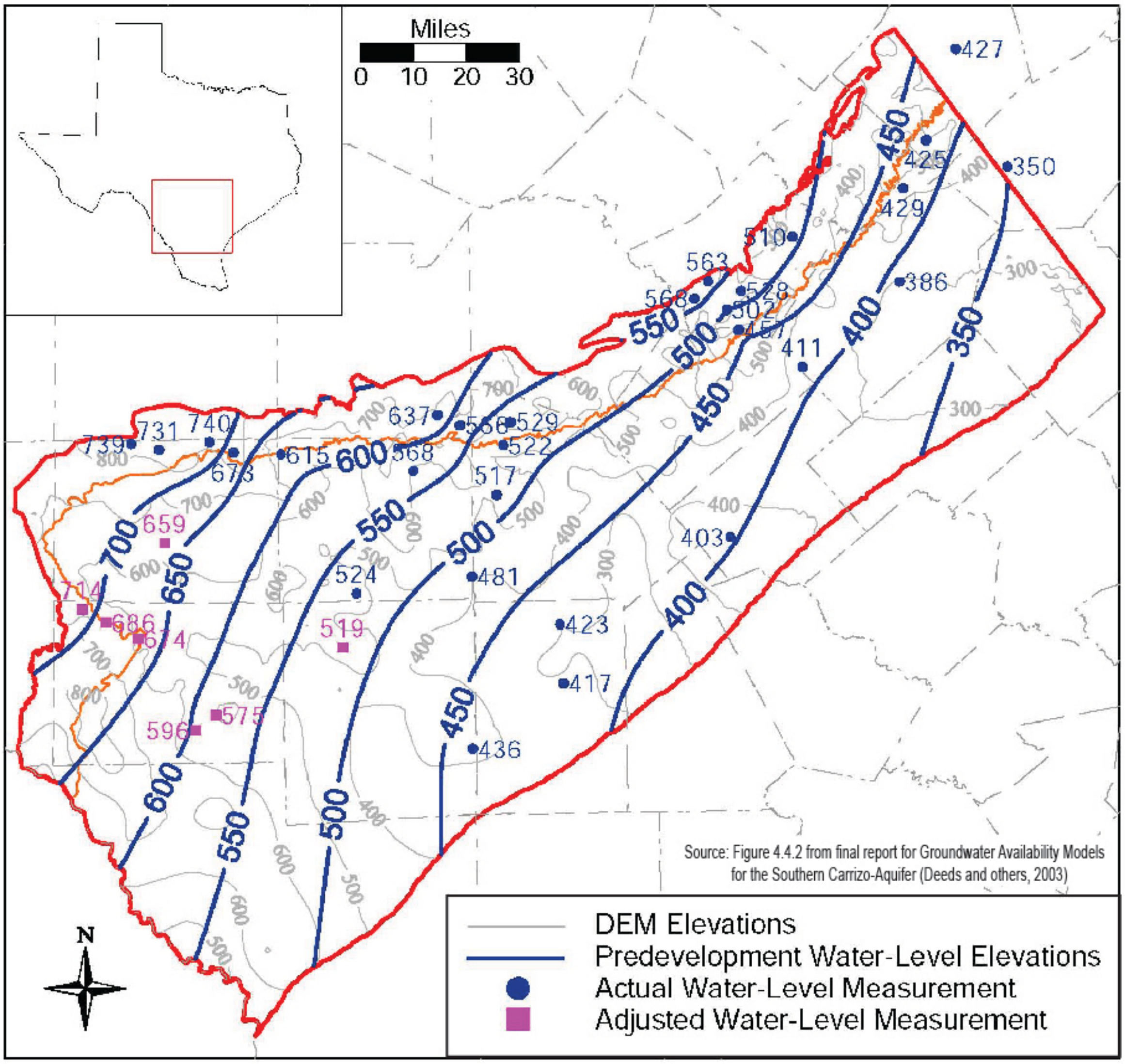

Figure 2-20. Estimated groundwater level elevation contours for predevelopment conditions in Carrizo-Wilcox Aquifer; from Deeds and others (2003).

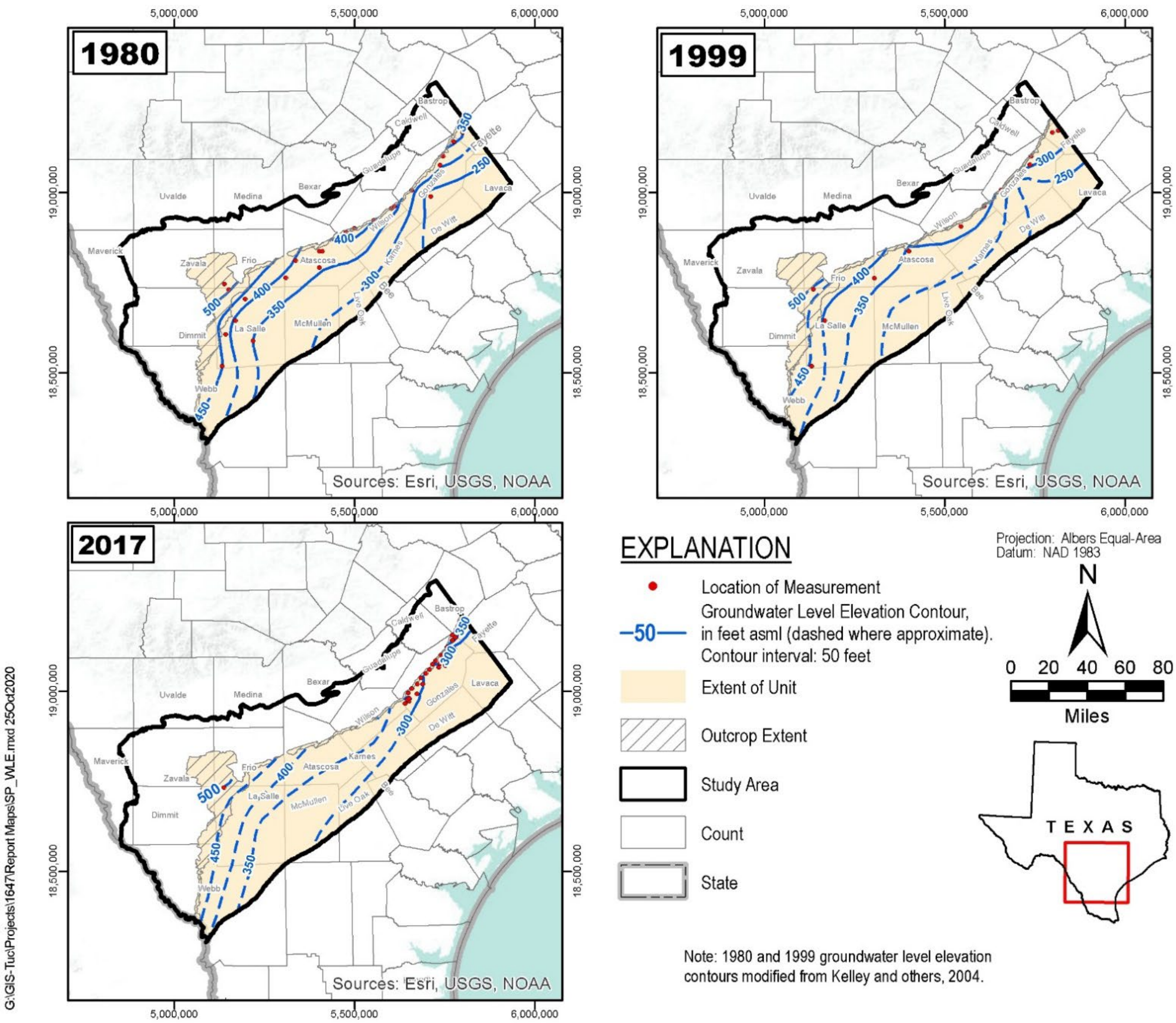

Figure 2-21. Groundwater level elevation contours for Sparta Aquifer.

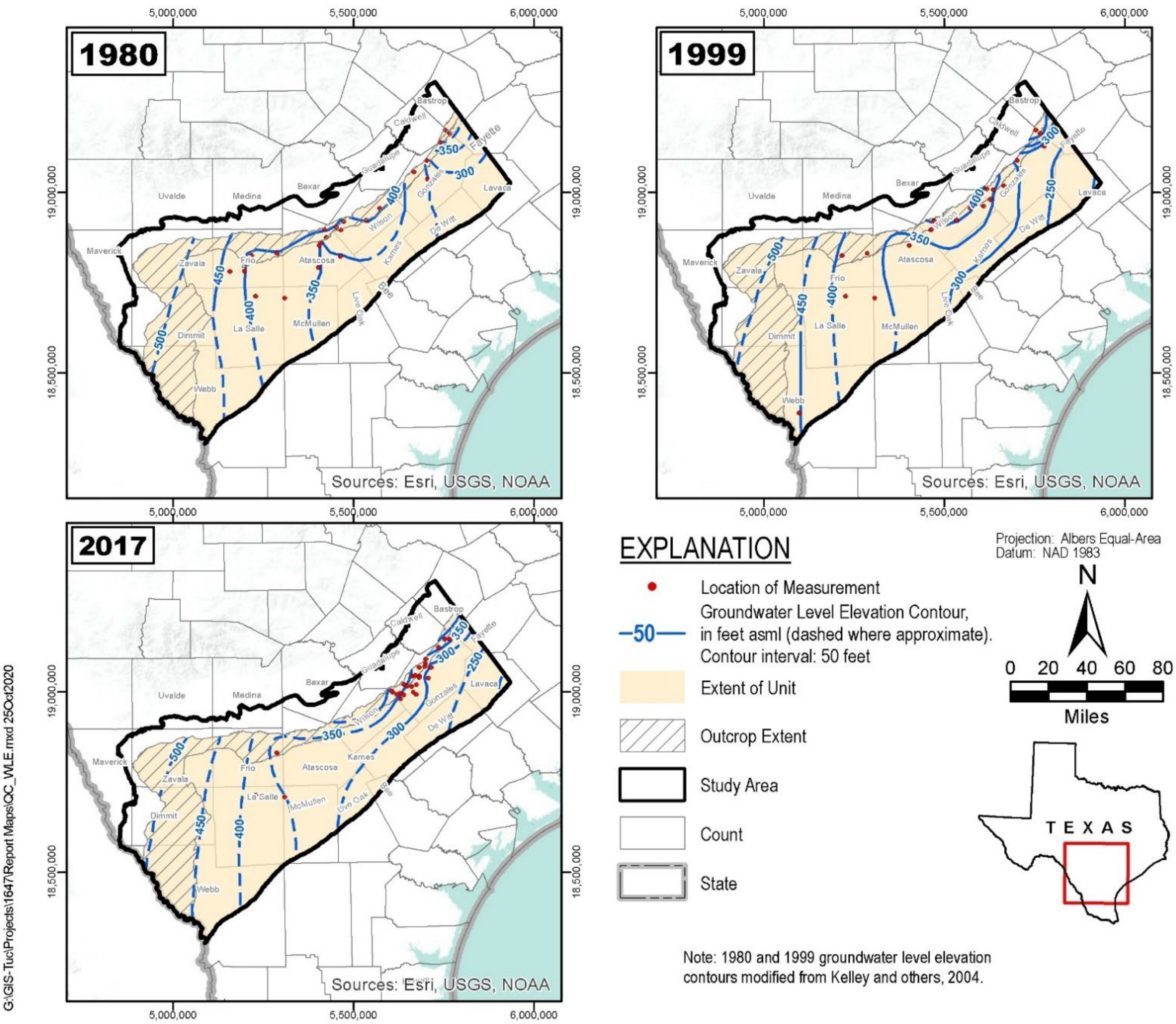

Figure 2-22. Groundwater level elevation contours for Queen City Aquifer.

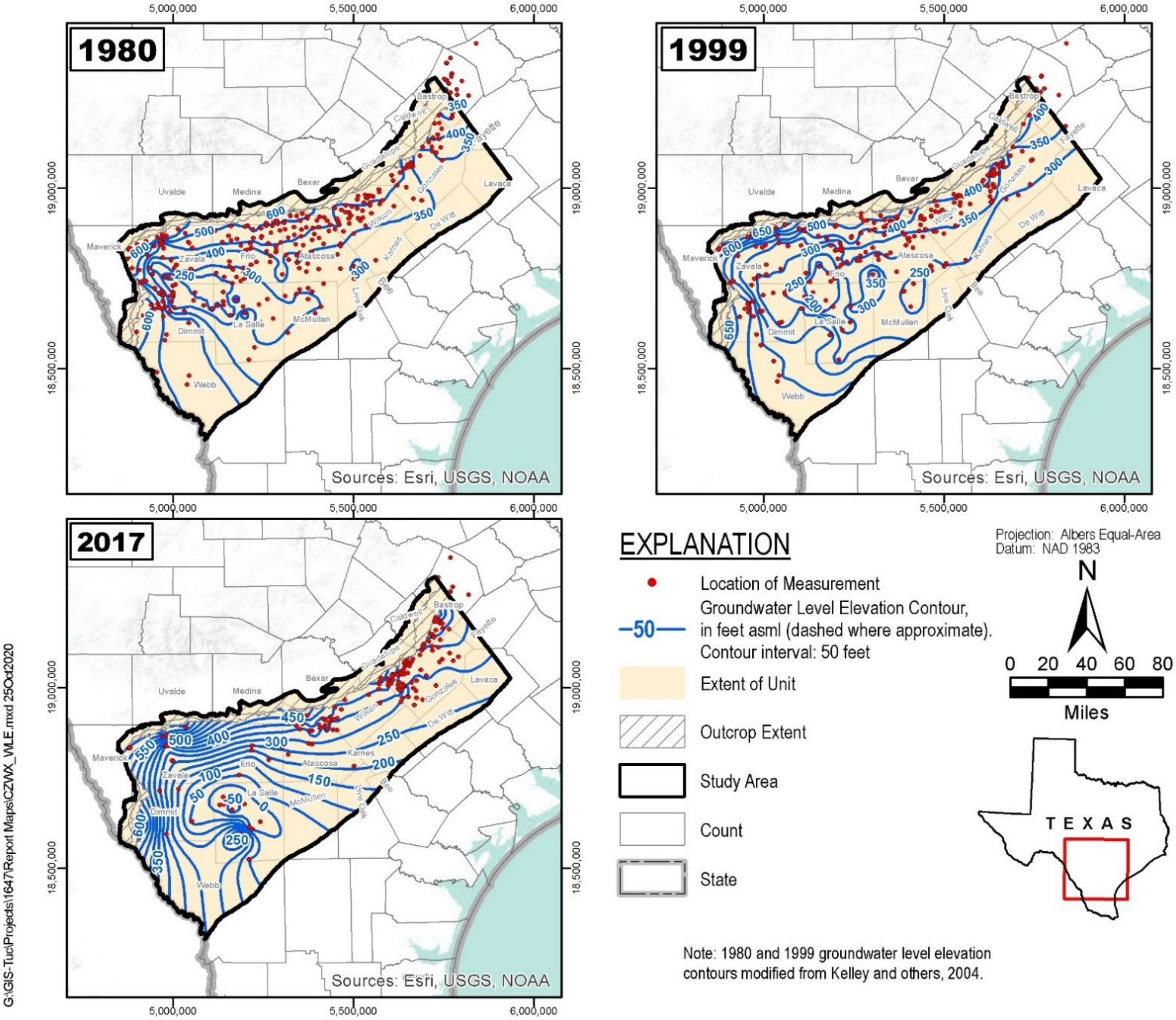

Figure 2-23. Groundwater level elevation contours for Carrizo-Wilcox Aquifer.

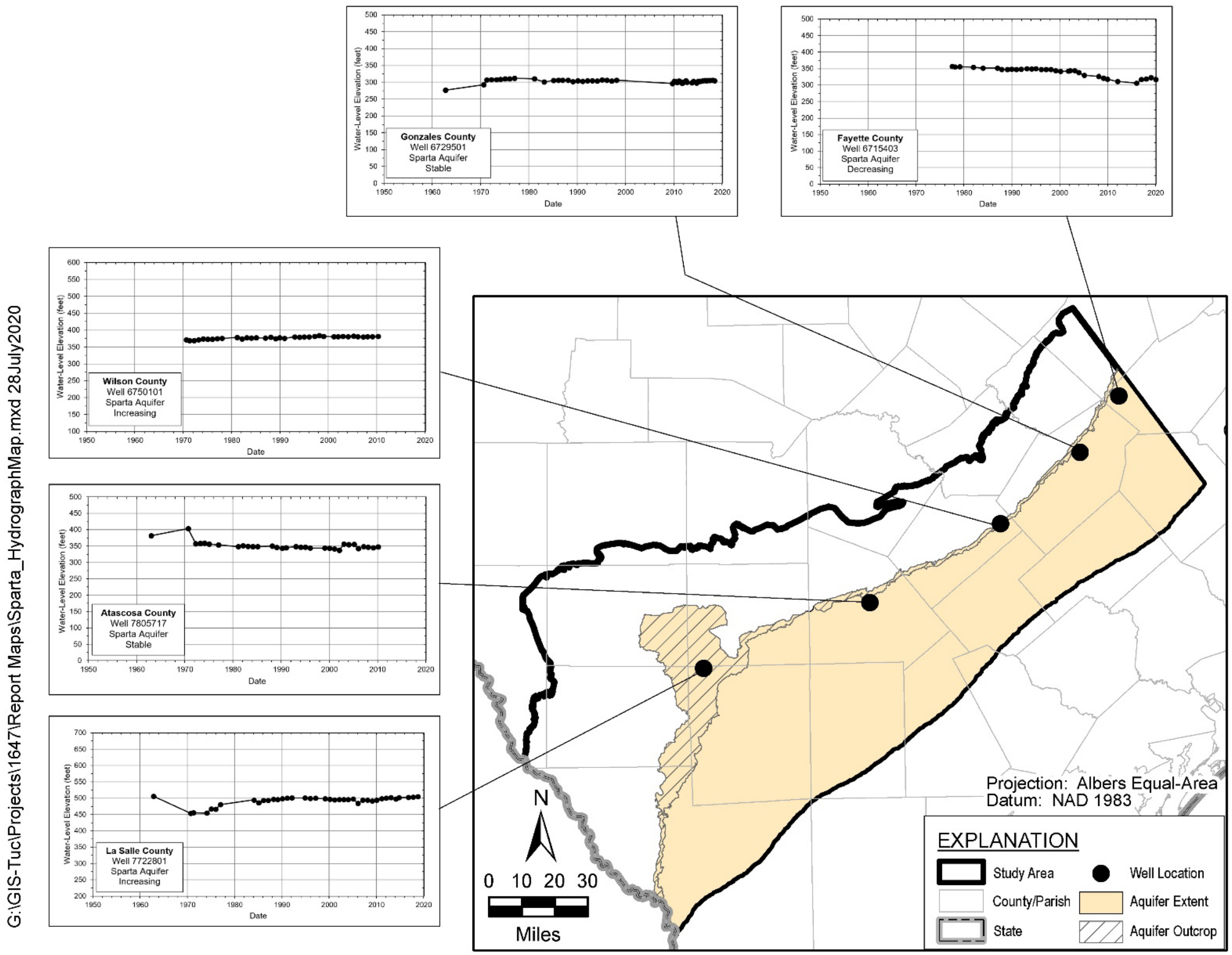

Figure 2-24. Selected groundwater level elevation hydrographs for Sparta Aquifer.

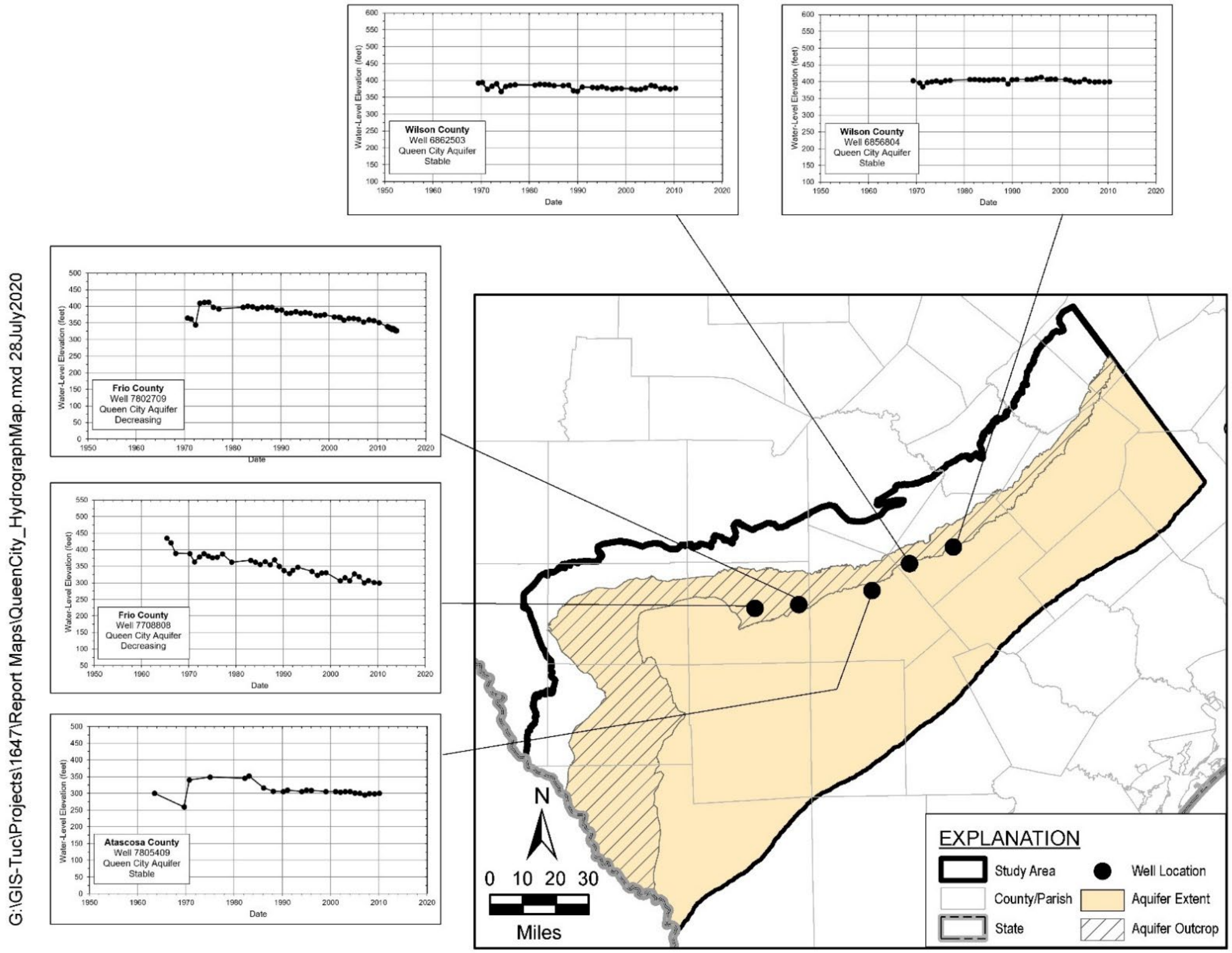

Figure 2-25. Selected groundwater level elevation hydrographs for Queen City Aquifer.

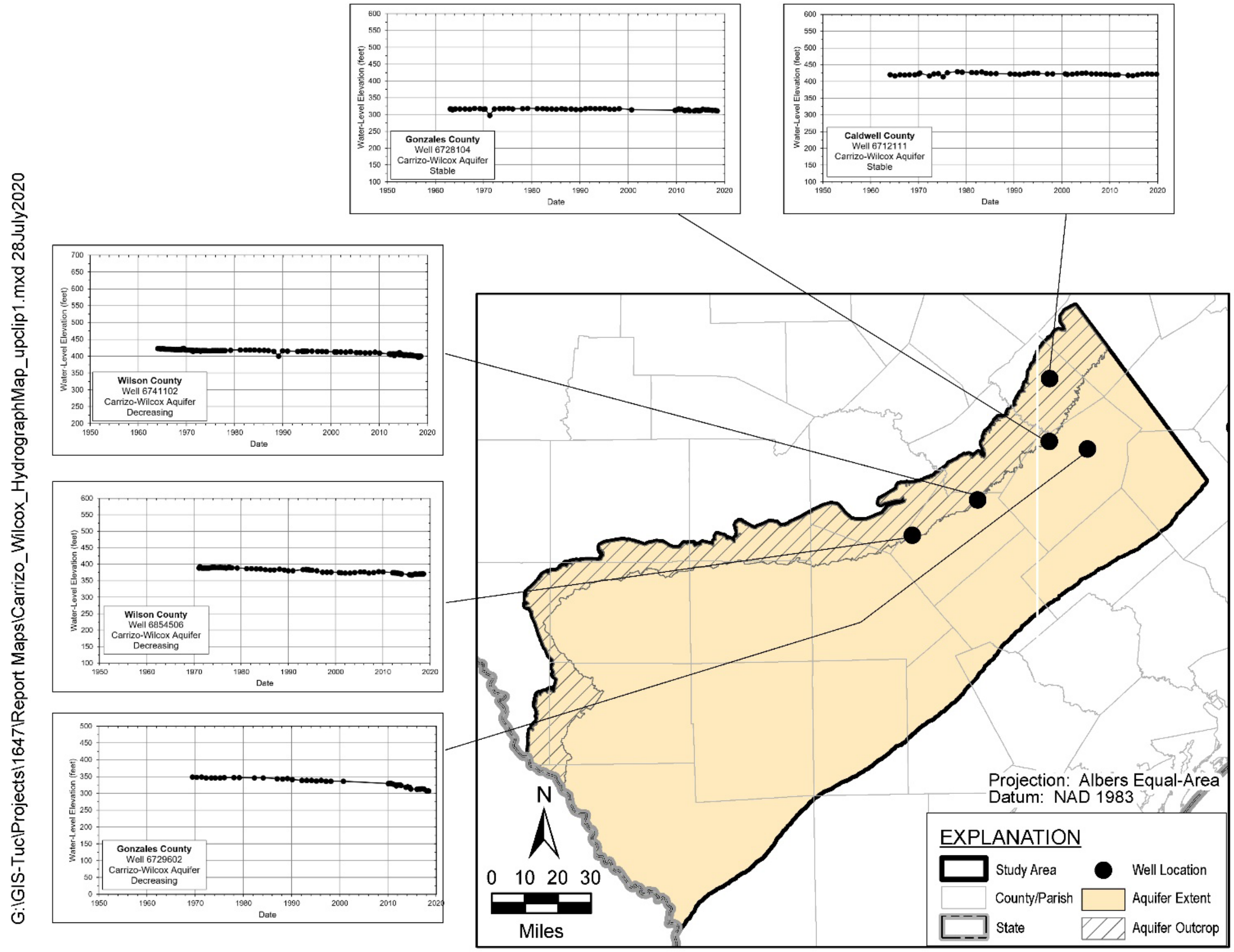

Figure 2-26. Selected groundwater level elevation hydrographs for Carrizo-Wilcox Aquifer in northern Bastrop, Caldwell, Gonzales, and Wilson counties.

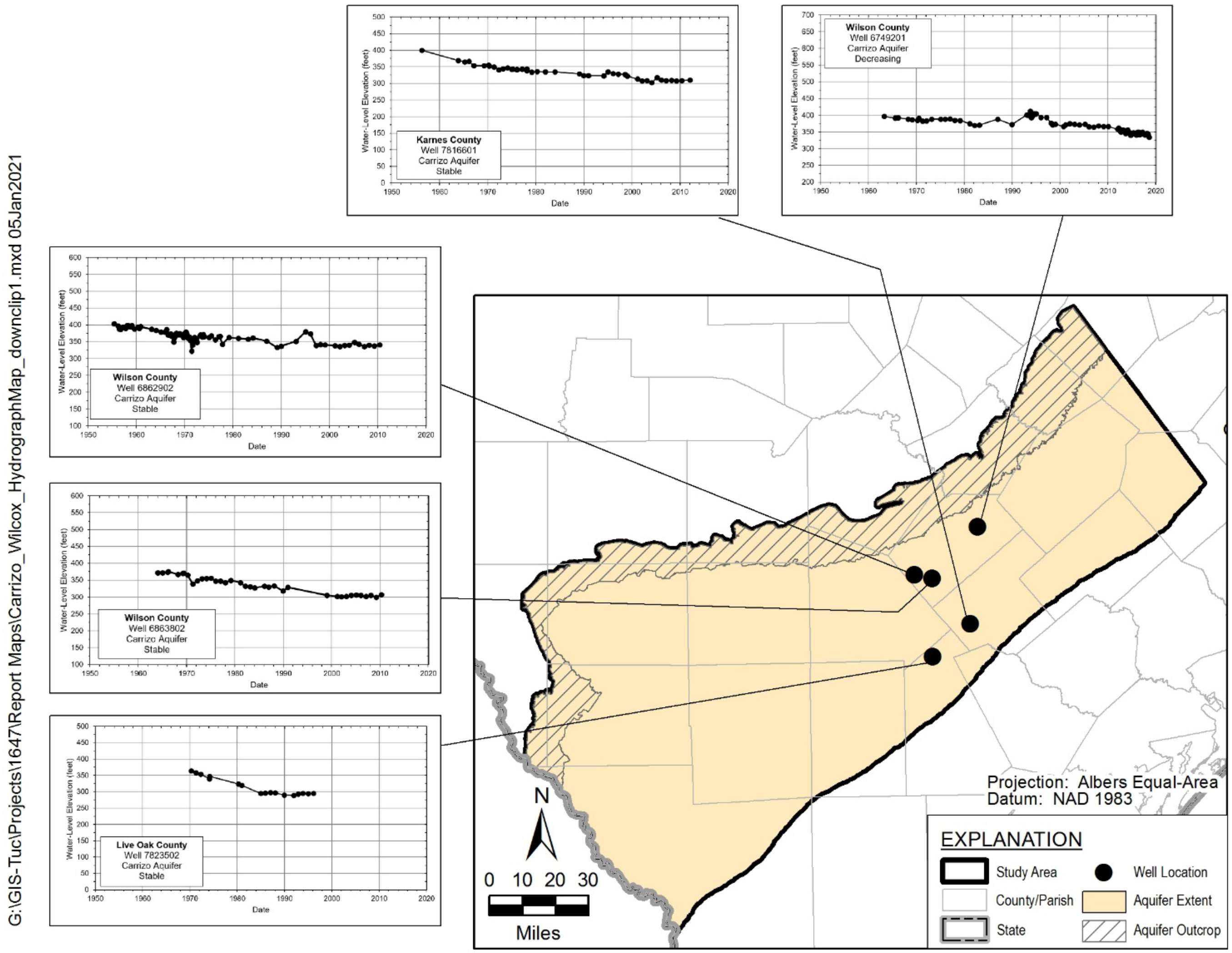

Figure 2-27. Selected groundwater level elevation hydrographs for Carrizo-Wilcox Aquifer in southern Wilson County and Karnes and Live Oak counties.

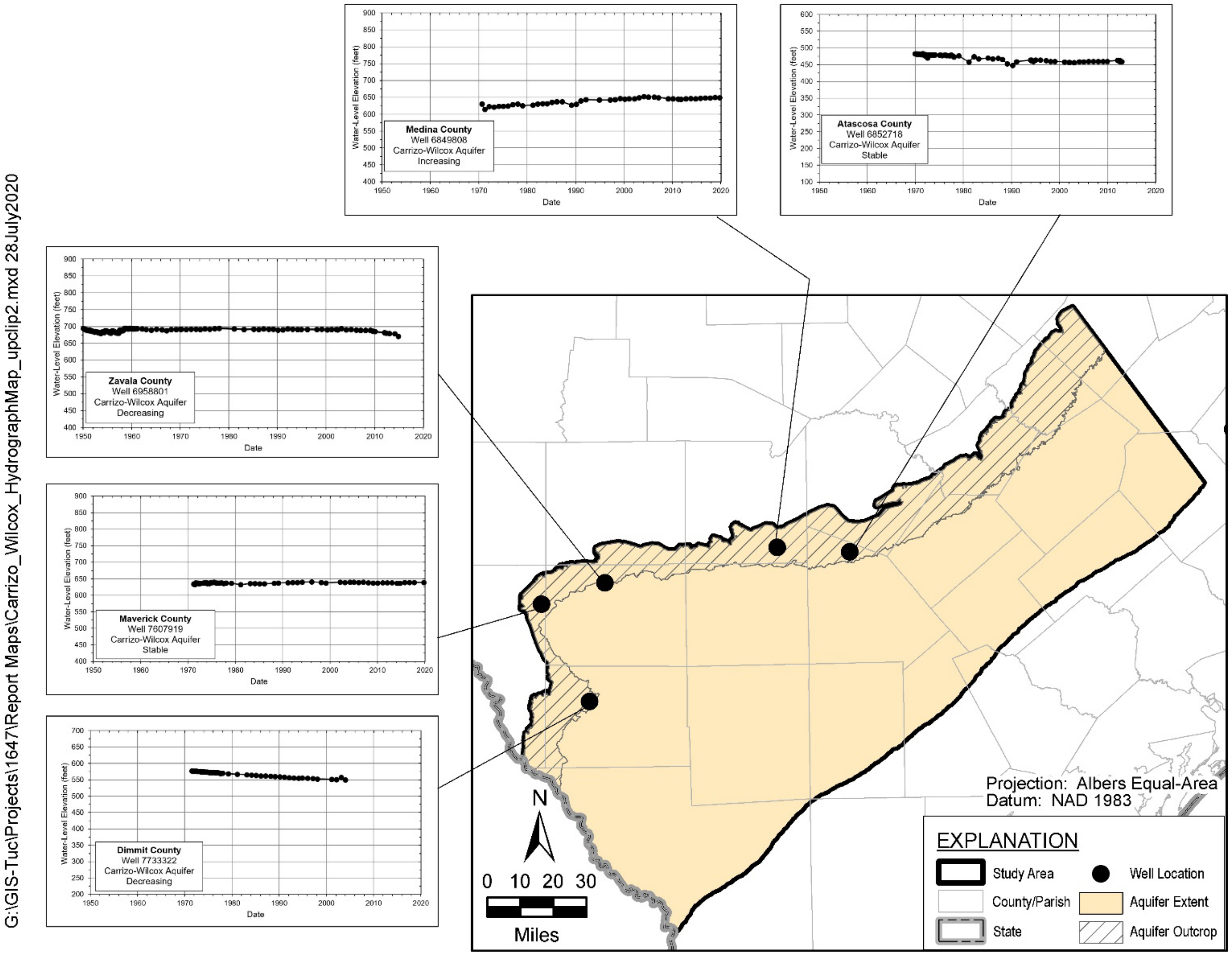

Figure 2-28. Selected groundwater level elevation hydrographs for Carrizo-Wilcox Aquifer in outcrop areas of Atascosa, Medina, Zavala, Maverick, and Dimmit counties.

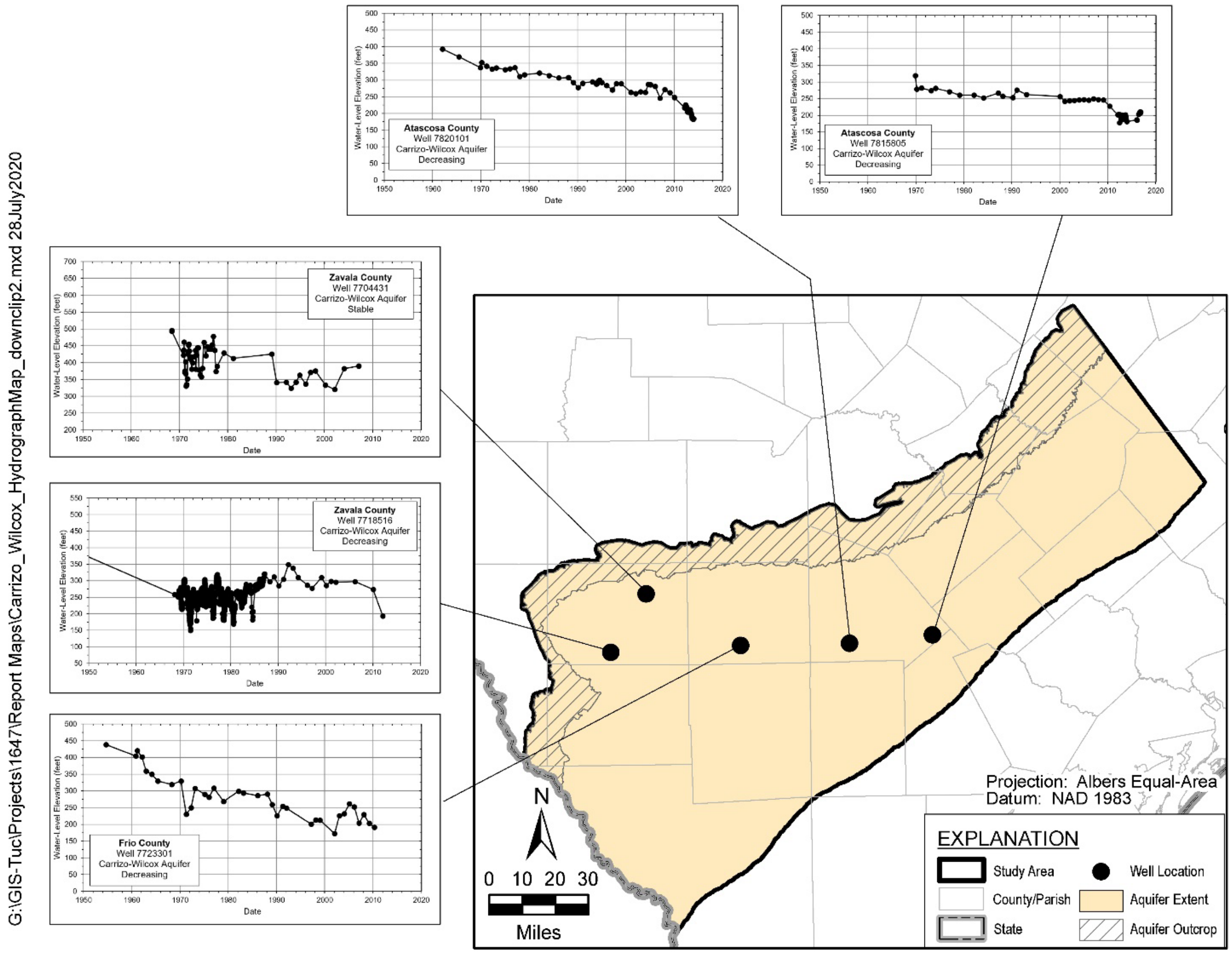

Figure 2-29. Selected groundwater level elevation hydrographs for Carrizo-Wilcox Aquifer in the downdip areas of Atascosa, Frio, and Zavala counties.

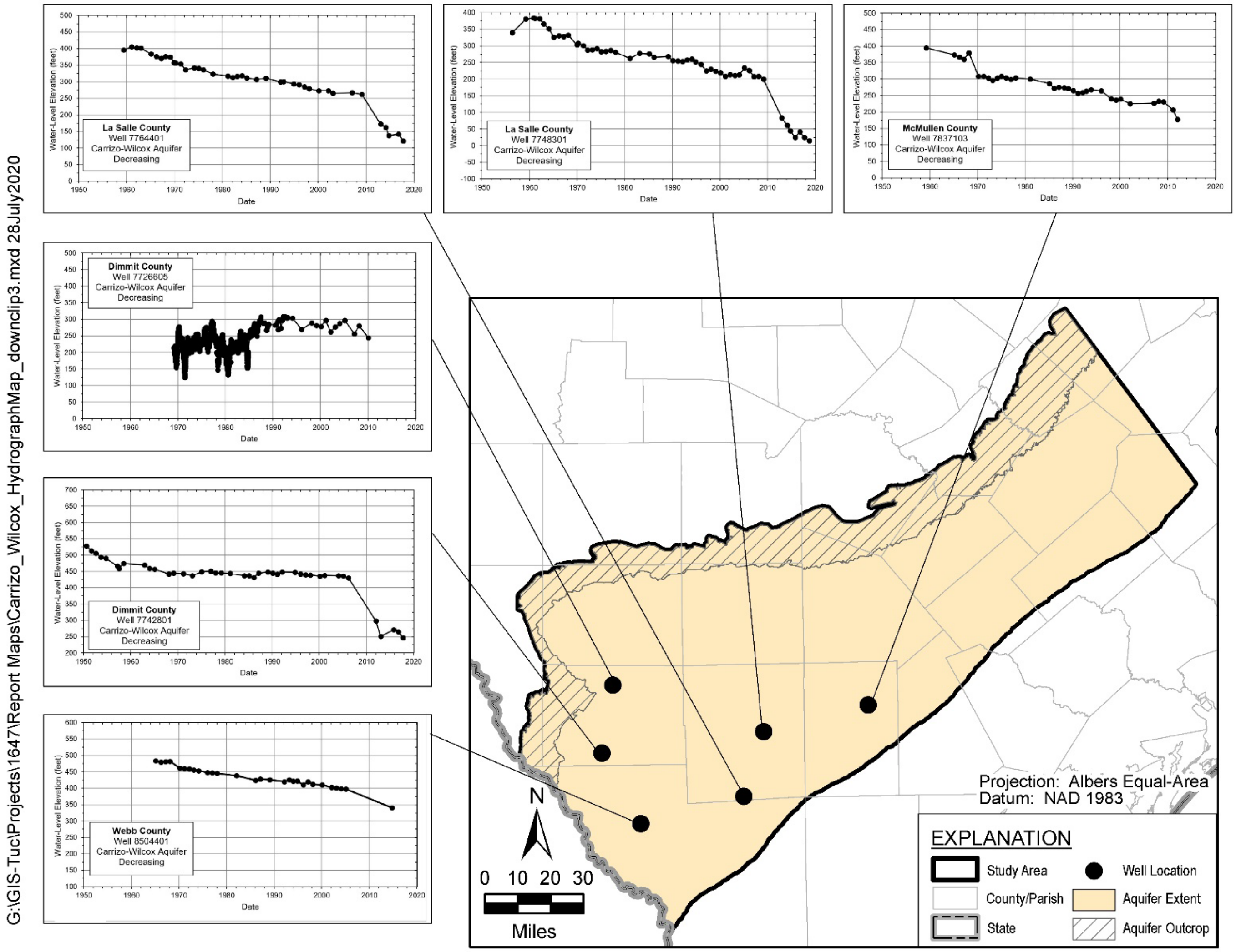

Figure 2-30. Selected groundwater level elevation hydrographs for Carrizo-Wilcox Aquifer for wells in McMullen, La Salle, Webb, and the downdip area of Dimmit counties.

2.3 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.

Aquifer recharge from Class II injection wells occurs below or in the deep, downdip portions of the aquifers of interest in the study area and is assumed to occur at relatively small rates. Any recharge from injection wells in the study area occurs below the base of useable quality water and would not impact groundwater conditions related to the groundwater availability model. For these reasons, injection wells are not included in the groundwater model for this study.

Springs often occur in topographically low areas along river valleys and in outcrop areas where hydrogeologic conditions generally preferentially reject recharge (Kelley and others, 2004).

2.3.1 *Diffuse Recharge from Precipitation*

Diffuse 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 southern Queen City, Sparta, and Carrizo-Wilcox aquifers vary due to varied hydraulic conductivity, rainfall distribution, evapotranspiration rates, and groundwater-surface water interactions.

The distribution of average recharge rates specified in the previous groundwater availability model by Kelley and others (2004) are shown on Figure 2-31. 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. This distribution is based on extensive unsaturated zone simulations conducted by Scanlon and others (2003) using the widely used Unites States Department of Agriculture National Resources Conservation Service State Soil Geographic database and Soil Survey Geographic Database for soils information along with weather and vegetation data for the major aquifers in Texas in 14 study areas. Kelley and others (2004) then scaled recharge up in local topographic highs and down at local topographic lows to account for discharge to the stream channels. This was then scaled by geology depending on each layer's hydraulic properties. The previous southern model estimated an average recharge rate (before evapotranspiration) of 0.8 inches per year (Kelley and others, 2004). Annual recharge volumes specified in the previous southern groundwater availability model are summarized by aquifer layer in Table 2-1.

Table 2-1. Summary of annual recharge from previous groundwater availability model by Kelley and others (2004).

Aquifer Layer	Recharge (AF/yr)
Sparta	24,486
Weches	4,714
Queen City	69,019
Reklaw	6,689
Carrizo + Upper Wilcox	66,504
Middle Wilcox	22,849
Lower Wilcox	24,249
TOTAL	*218,510*

AF/yr = acre-feet per year

The recharge estimation approaches presented in this section could be used as a starting point for calibration of recharge. Annual scaling factors could be applied to the distribution of average recharge from Kelley and others (2004), shown on Figure 2-31, during model calibration if annual variation is required to match calibration targets, such as groundwater levels and streamflows. Any adjustments will be summarized herein in the future after model calibration is complete.

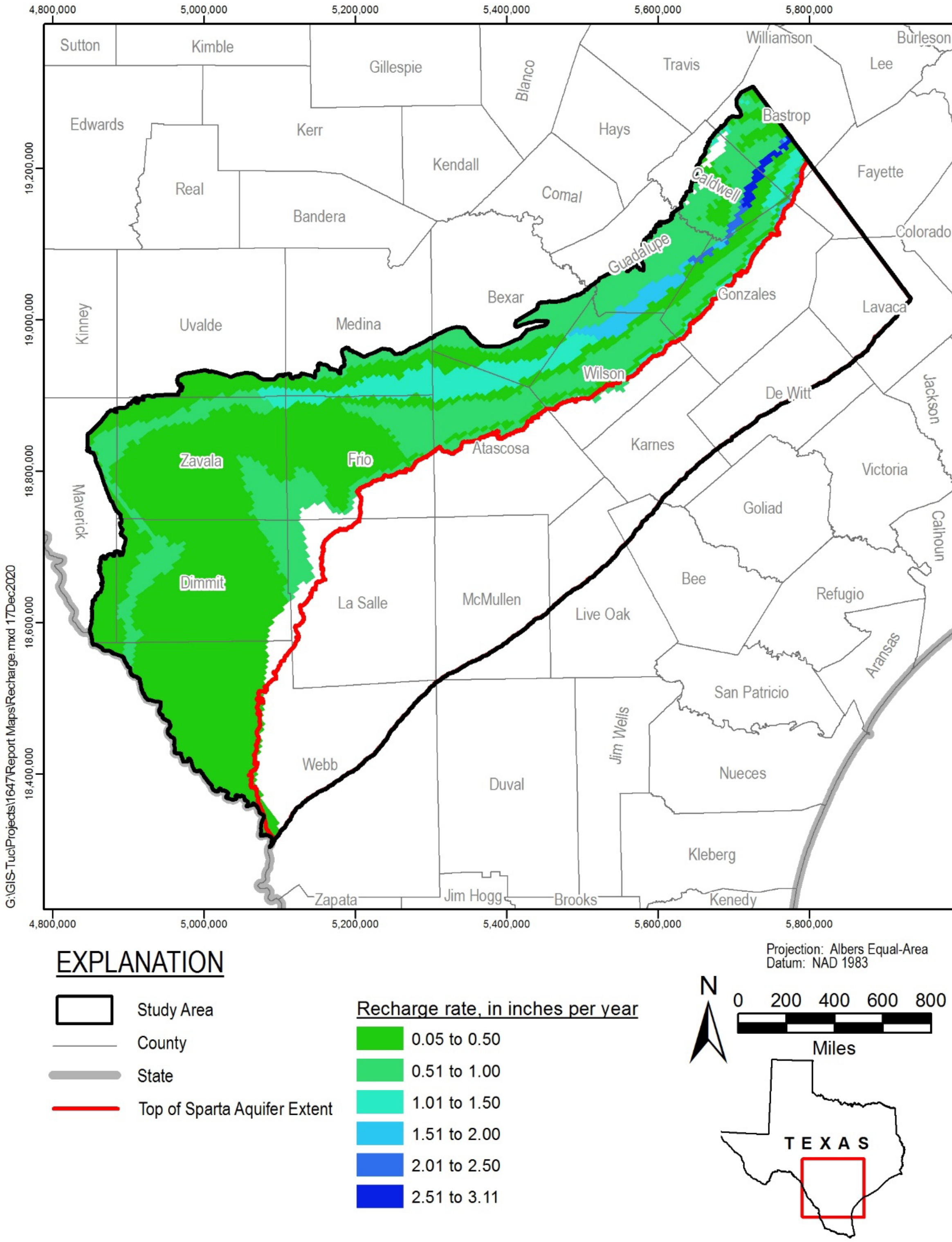

Figure 2-31. Distribution of average recharge rates simulated in previous groundwater availability model by Kelley and others (2004).

2.3.2 *Recharge from Reservoirs*

In total there are five reservoirs with surface areas greater than half a square mile in the study area (Figure 2-32). These reservoirs provide potential areas of focused recharge to the underlying aquifers of interest. Table 2-2 lists the names, owners, and year impounded for each reservoir. This information was sourced from the TWDB (2020a, b) and Deeds and others (2003). Figure 2-33 includes historic lake stage (water level) elevations obtained from the United States Geological Survey (2020a) and the previous groundwater availability model by Deeds and others (2003). The hydrographs show only minor variations in lake levels over the period of interest. Reservoir locations and stage measurements will be incorporated in the groundwater model.

Table 2-2. Major reservoirs in the study area.

Reservoir	Reservoir Name	Owner	Date Impounded
1	Calaveras Lake	City Public Service Energy of San Antonio	1969
2	Lake Casa Blanca	Webb County	1949
3	Mitchell Lake	--	1967
4	Victor Braunig Lake	City Public Service Energy of San Antonio	1962
5	Yarbrough Lake (Choke Canyon Reservoir)	City of Corpus Christi and Nueces River Authority	1982

--- = Not available

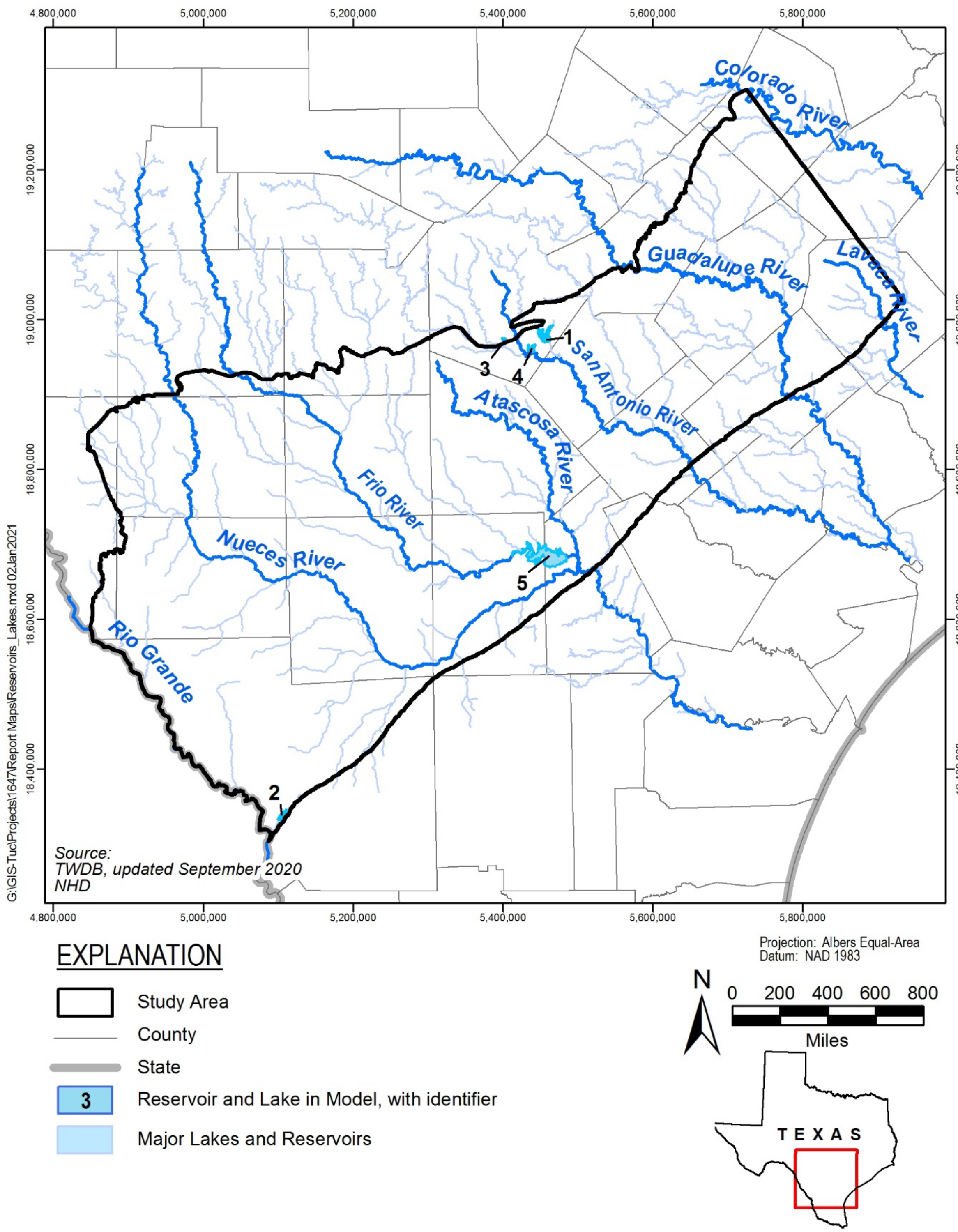

Figure 2-32. Locations of major reservoirs in study area.

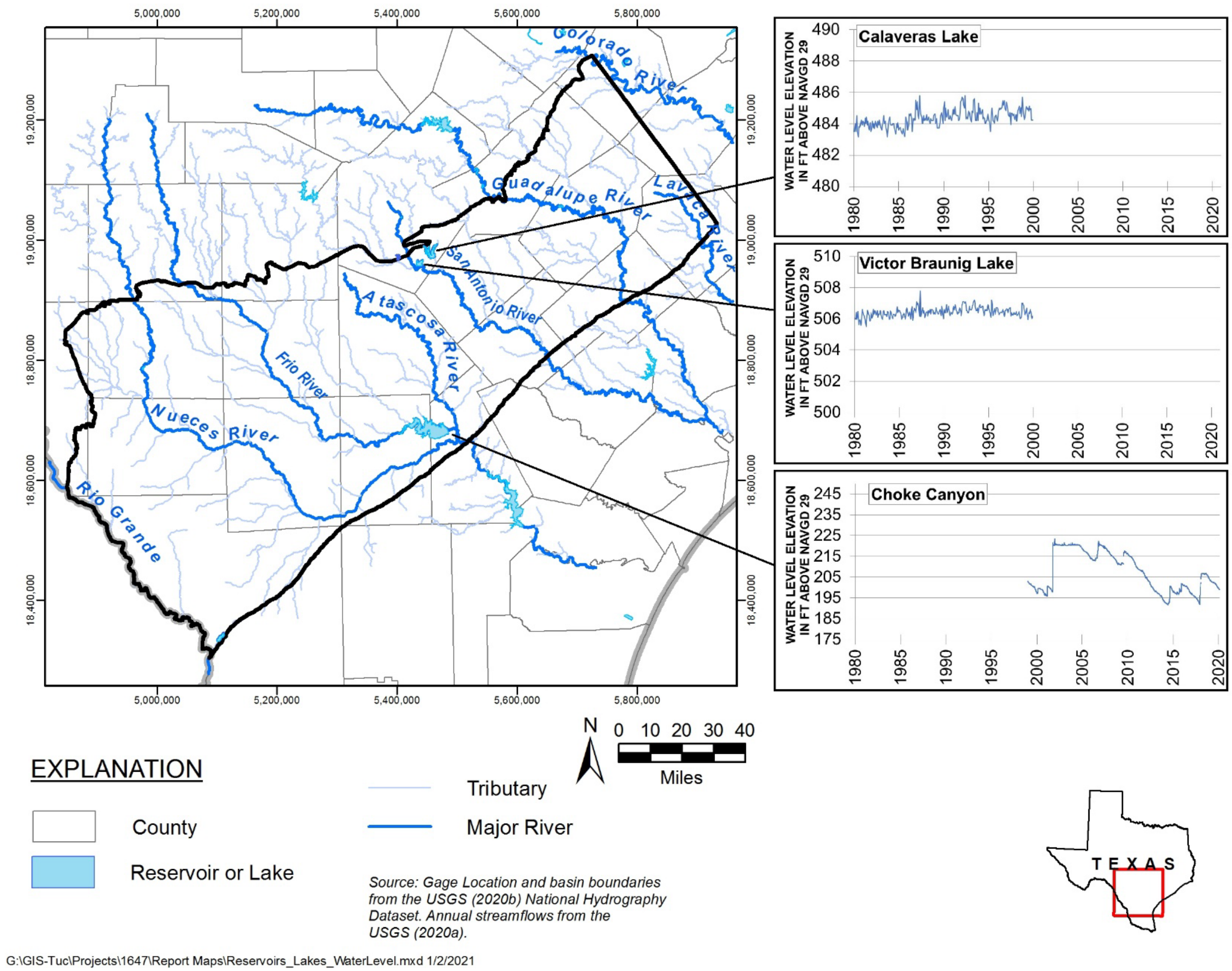

Figure 2-33. Water level hydrographs for selected reservoirs in study area.

2.4 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.

2.4.1 *River Flows*

The major rivers intersecting the study area include the Frio River, Atascosa River, Nueces River, Rio Grande, San Antonio River, Guadalupe River, and Lavaca River (Figure 2-34). The Frio River and Atascosa Rivers are tributaries to the Nueces River. Numerous other smaller river and streams are also included in the study area.

2.4.1.1 Previous Studies on Surface Water Gains and Losses

Gaining or losing streams is an indication of the contribution of groundwater to reaches along a stream. Several stream gain/loss studies have been conducted along rivers and tributaries in the study area. Deeds and others (2003) provide a comprehensive summary of these studies. Studies along the Cibolo Creek and Medina River in the Guadalupe River Basin, Lavaca River, Atascosa River, Frio River, Leona River and Nueces River in the Nueces River Basin, Cibolo Creek in the San Antonio River Basin, and the Rio Grande within the study area. The summary provided by Deeds and others (2003) indicate a spatial patten that streams are gaining and perennial in the eastern portion of the study area and trend towards non-perennial and losing westward. Previous studies also show temporal variation as gaining streams were more prevalent at the onset of the 20th century and those reaches noted as losing stream reaches by the mid-century.

A literature survey was conducted to research updated studies on the status of discharge to rivers and springs in the study area. Only one relevant article was found along a limited segment of the Guadalupe River in the eastern portion of the study area (Figure 2-35). Ikard and others (2017) conducted a surface and groundwater exchange study along the Guadalupe River downstream from Seguin, Texas. The study integrated methods of electric resistivity tomography (ERT) and floating gradient self-potential (SP) profiling in order to map subsurface geology and water flowing through those geologic materials (Ikard and others, 2017). Ikard and others (2017) concludes that the first segment of the Guadalupe River reach studied appears to be losing but transitions to a gaining stream before ending with a more neutral signal. This study does not quantify flow rates between the surface and groundwater. No other information was found on the rate of exchange between groundwater and surface water along streams.

2.4.1.2 Historical River Flows

Flows along the rivers are measured by the United States Geological Survey (2020a) at several streamflow gages along the major rivers in the study area, except for Rio Grande which is monitored by the International Boundary Water Commission (2020). Daily streamflow data are available from the United States Geological Survey for the period of 1905 through 2020. Annual streamflows are assessed for this study because annual stress periods will be simulated in the updated groundwater availability model. Measured river flows will be used as a guide during calibration of the groundwater model. Annual streamflows at selected gaging stations along the major rivers in the study area are shown on Figures 2-36 through 2-42. These hydrographs indicate that flow conditions vary between gaining and losing streams with generally losing flows observed more frequently during the 21st century.

Historical annual streamflows along the Rio Grande vary from year to year from about 660,000 to over 7,000,000 AF/year. Streamflow measurements are limited along the Rio Grande and while gaging stations exist throughout the system, historic data are only available within the study area from the International Boundary Water Commission (2020) from 1903 to 2011 at a gaging station 8459000 near Laredo, Texas (Figure 2-36). Streamflow measurements are not available for gage station 8458800 at Palafax near Laredo for the study period.

Historical annual streamflows along the Nueces River vary substantially from around 200 AF/year to over 2,250,000 AF/year. Streamflow measurements indicate a general increase in flow along the length of the river (Figure 2-37). Annual flows are generally larger than 50,000 AF/year in the upper reaches near Asherton, Texas and increase to mostly larger than 300,000 AF/year in the lower reach near Three Rivers, Texas which is below the confluences of the Frio River and Atascosa River as well as downstream from the Choke Canyon Reservoir.

Historical annual streamflows along the Frio River vary substantially from year to year, ranging from about 460 to over 900,000 AF/year. Streamflow measurements indicate a general increase in flow along its length (Figure 2-38), in some years there is a minor decline in flow. Annual flows are generally larger than 25,000 AF/year in the upper reaches near Derby, Texas and increase to mostly larger than 40,000 AF/year downstream at Tilden, Texas.

Historical annual streamflows along the Atascosa River vary substantially from year to year, ranging from less than 1,500 AF/year to over 325,000 AF/year. Streamflow measurements indicate a general increase in flow along its length except in 2007 where a decrease in streamflow along the reach was observed (Figure 2-39). Annual flows are generally larger than 2,500 AF/year in the upper reaches near McCoy, Texas and increase to mostly over 10,000 AF/year in the lower reach at Whitsett, Texas.

Historical annual streamflows along the San Antonio River vary from year to year, ranging from about 35,000 to over 1,500,000 AF/year. Streamflow measurements indicate a general increase in flow along its length except between Floresville, Texas and Falls City, Texas where a decline in flow is observed on average. However, the record for this stream is shorter than others and data were only available at two of the gages for 2006 to 2020 (Figure 2-40). Over the entire span of the stream within the study area, annual flows are generally larger than 200,000 AF/year in the upper reaches near Elemdorf, Texas and increase to larger than 300,000 AF/year in the lower reach near Runge, Texas. These trends between gages are not consistent and harder to generalize since the record of available data vary between gages.

Historical annual streamflows along the Guadalupe River vary from year to year, ranging from about 80,000 to over 4,500,000 AF/year. Streamflow measurements indicate a general increase in flow along its length but that increase in flow decrease over the period of record and since 2008 there were two years where flow declined toward the lower reach (Figure 2-41). Annual flows are generally less than 500,000 AF/year in the upper reaches near Seguin, Texas and increase to over 7000,000 AF/year in the lower reaches at Cuero, Texas. The oldest observed flow along the Guadalupe River within the study area is 1964.

Historical annual streamflows along the Lavaca River vary from year to year, ranging from less than 500 to over 100,000 AF/year. Streamflow measurements within the study area were only available at one gaging station near Hallesttsville, Texas (Figure 2-42). Available measurements contain gaps in data and trends are hard to decipher along the reach within the study area.

Differences in measured annual streamflows were evaluated to note overall gains or losses along a specific river during the model simulation period from 1980 through 2019. Gages along unregulated reaches of the major rivers were selected for this evaluation. The annual differences between selected upstream and downstream gages along the major rivers are summarized in Table 2-3. Rio Grande and Lavaca River are not included in Table 2-3 because solely one streamflow measurement gage is located along these rivers in the study area. Gage locations are shown on Figures 2-36 through 2-40. Gage data indicate that all major rivers generally have experienced gaining flow conditions during most years since 1980. It is important to note that these streamflow data do not represent baseflows; rather, the data are used as a generally guide for model calibration regarding general flow conditions along the rivers.

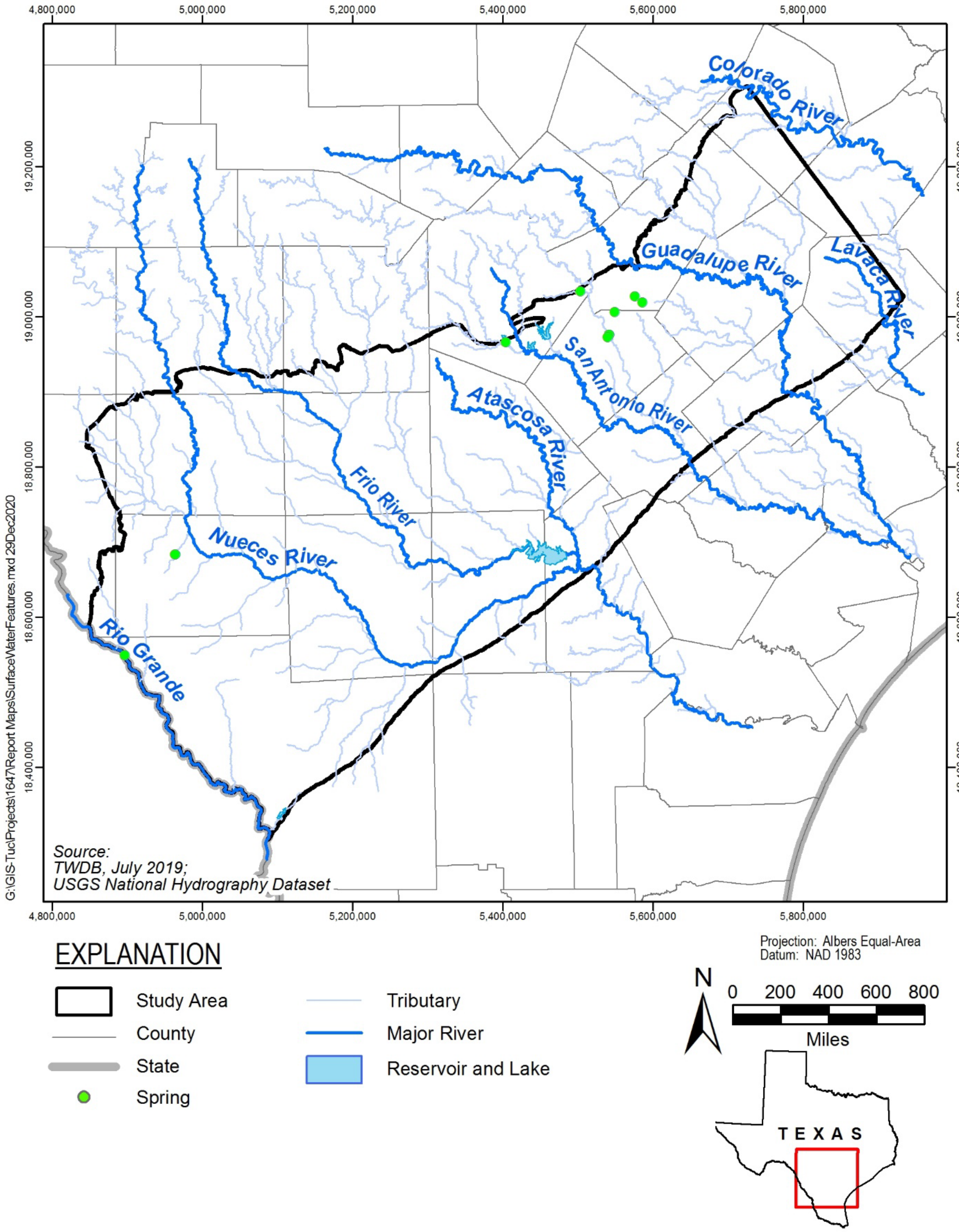

Figure 2-34. Surface water features in study area.

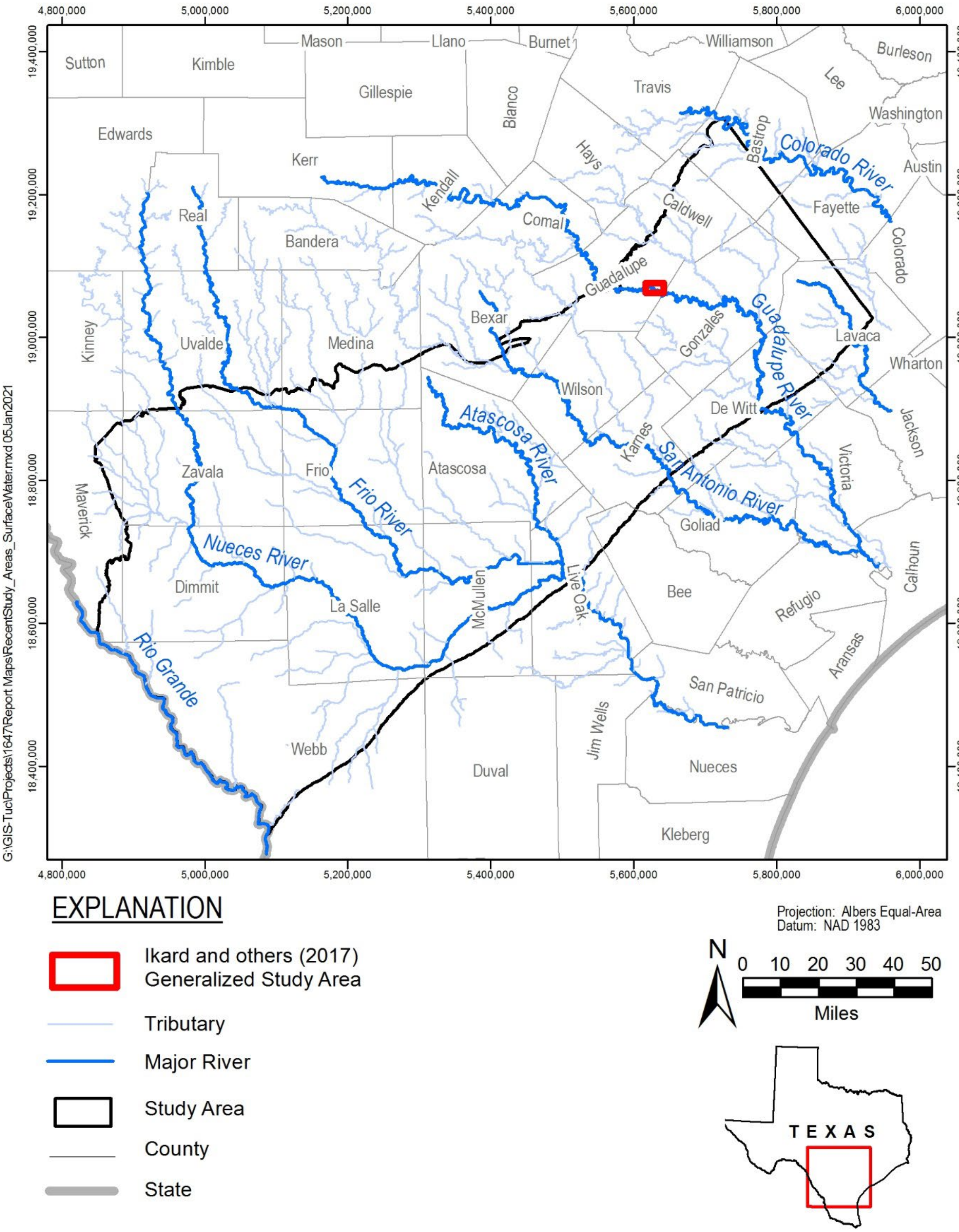

Figure 2-35. Location of recent surface water study area.

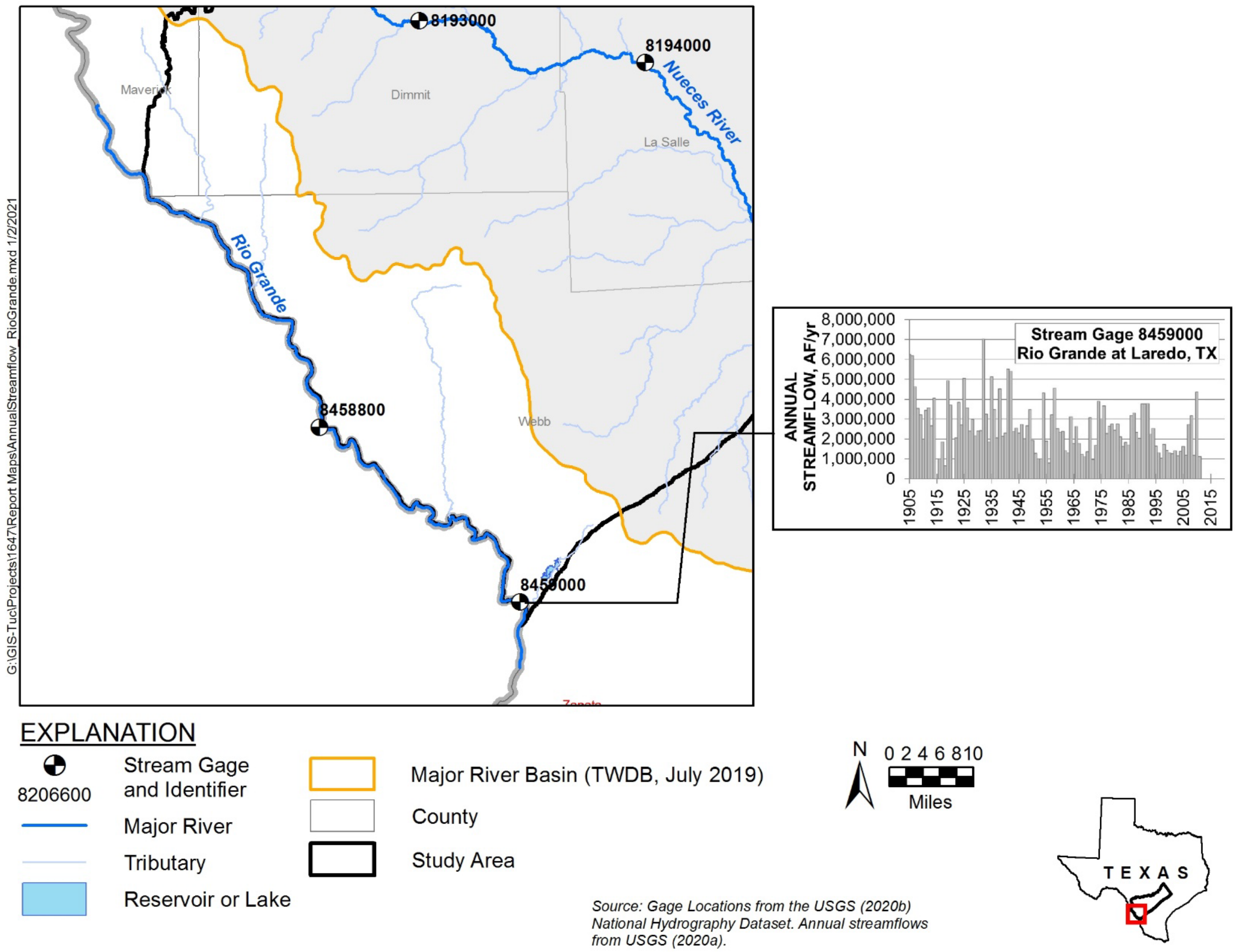

Figure 2-36. Annual streamflows along Rio Grande.

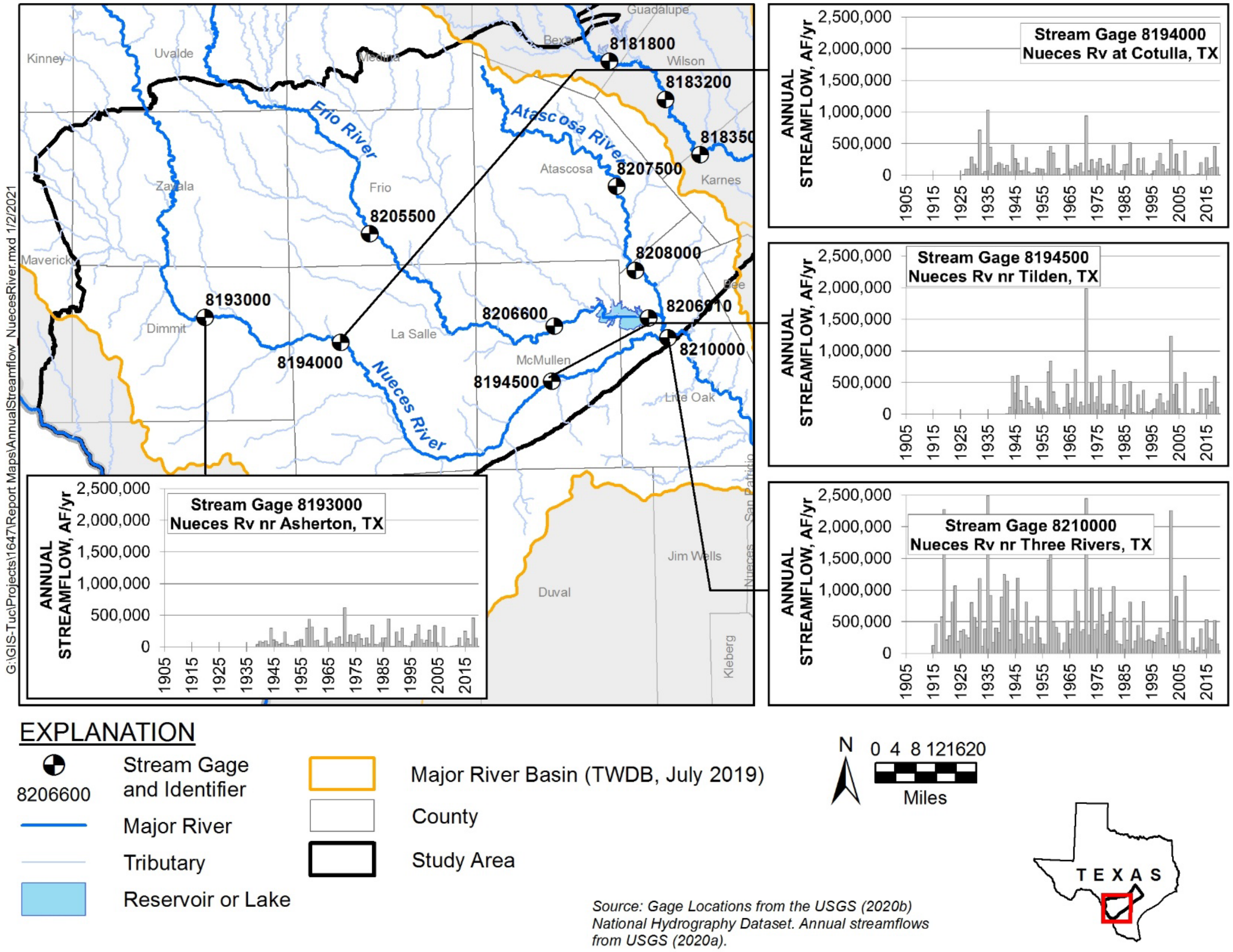

Figure 2-37. Annual streamflows along Nueces River.

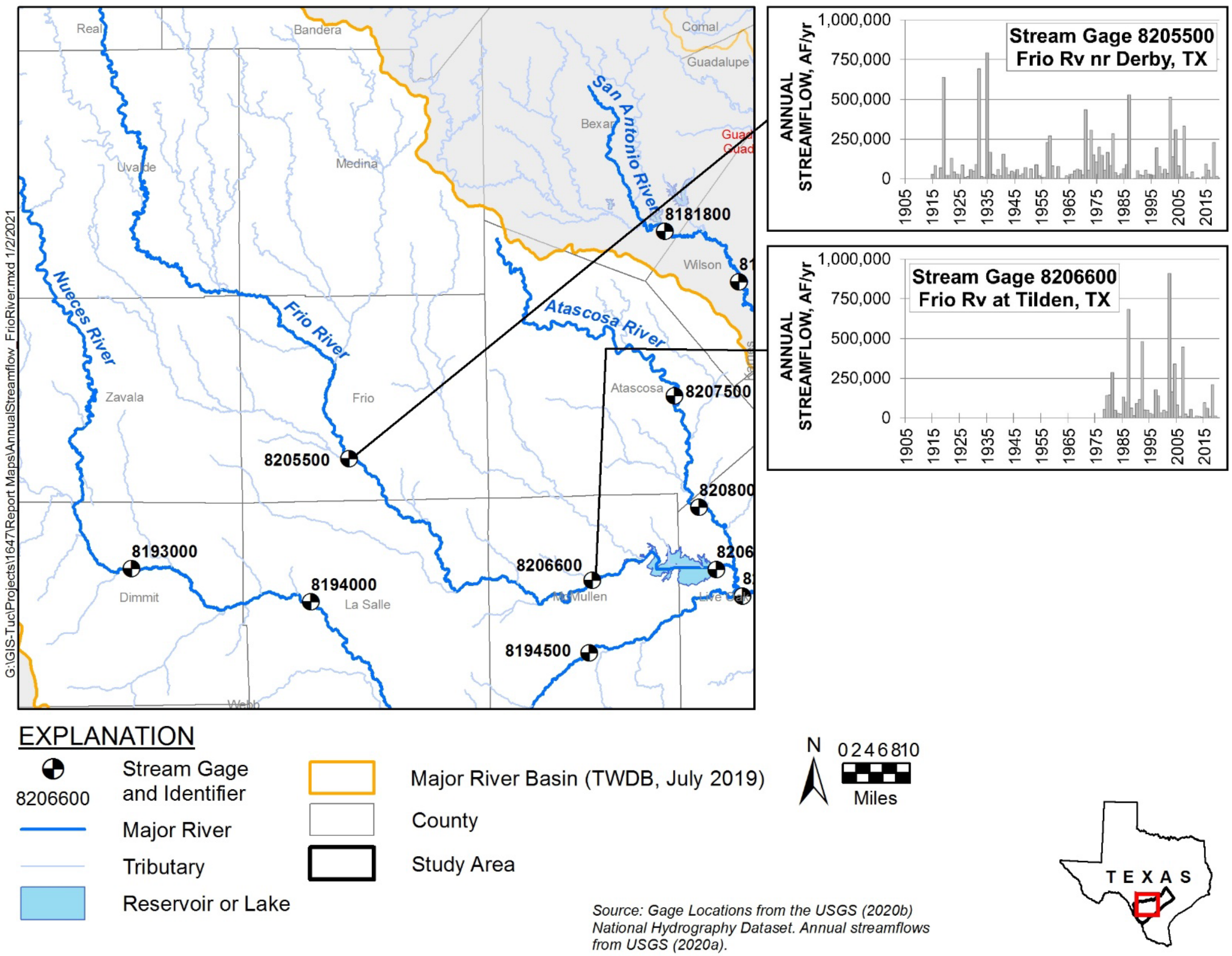

Figure 2-38. Annual streamflows along Frio River.

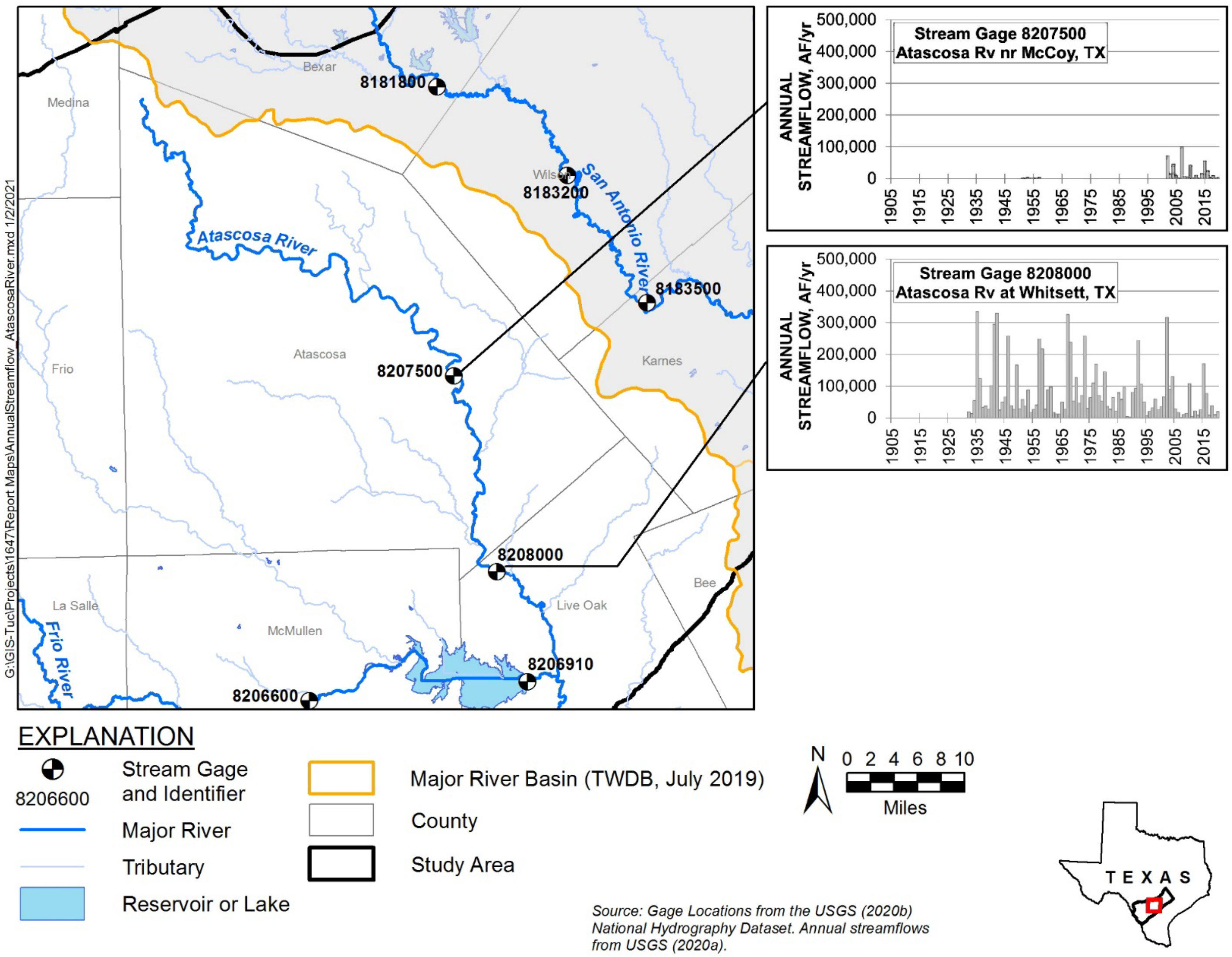

Figure 2-39. Annual streamflows along Atascosa River.

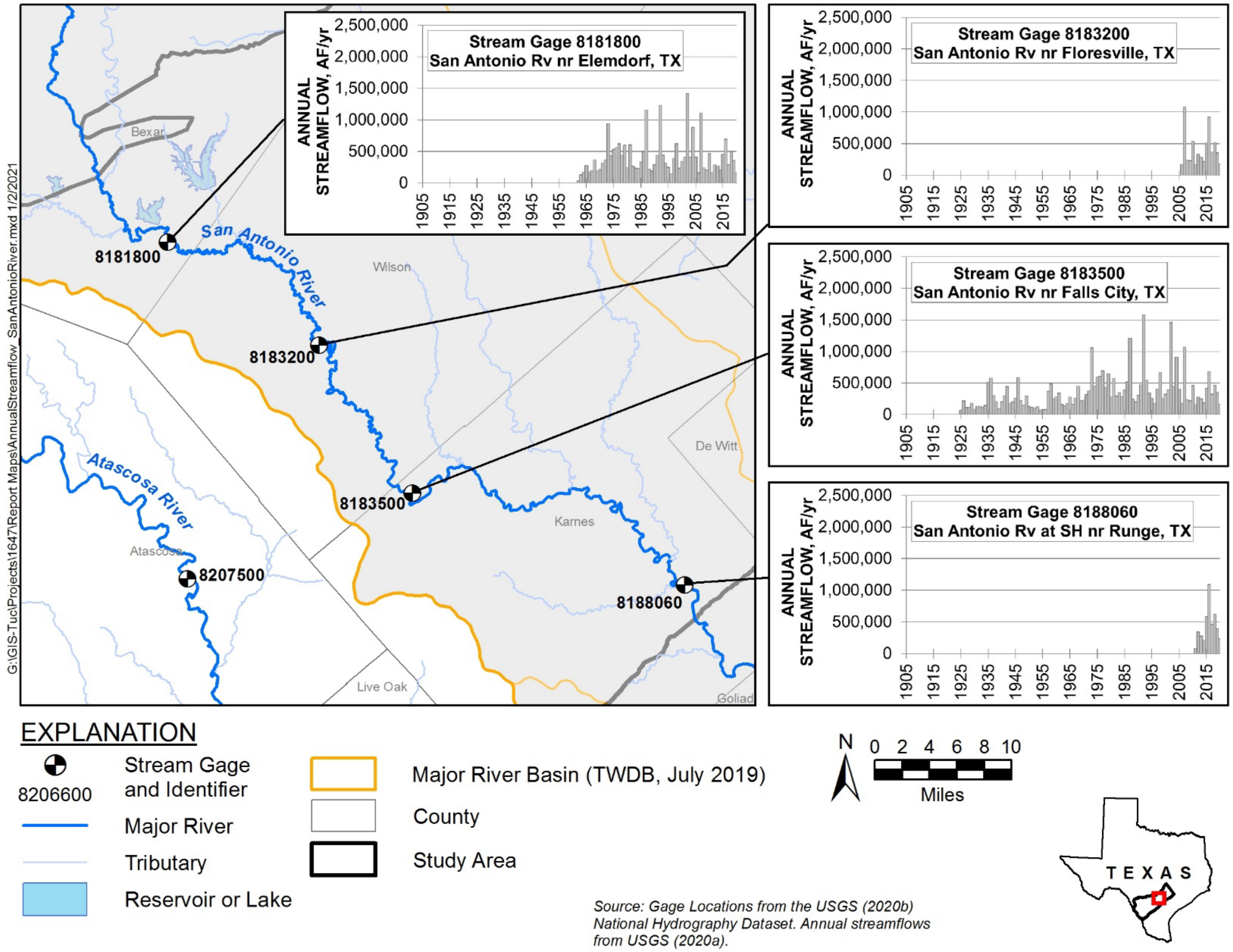

Figure 2-40. Annual streamflows along San Antonio River.

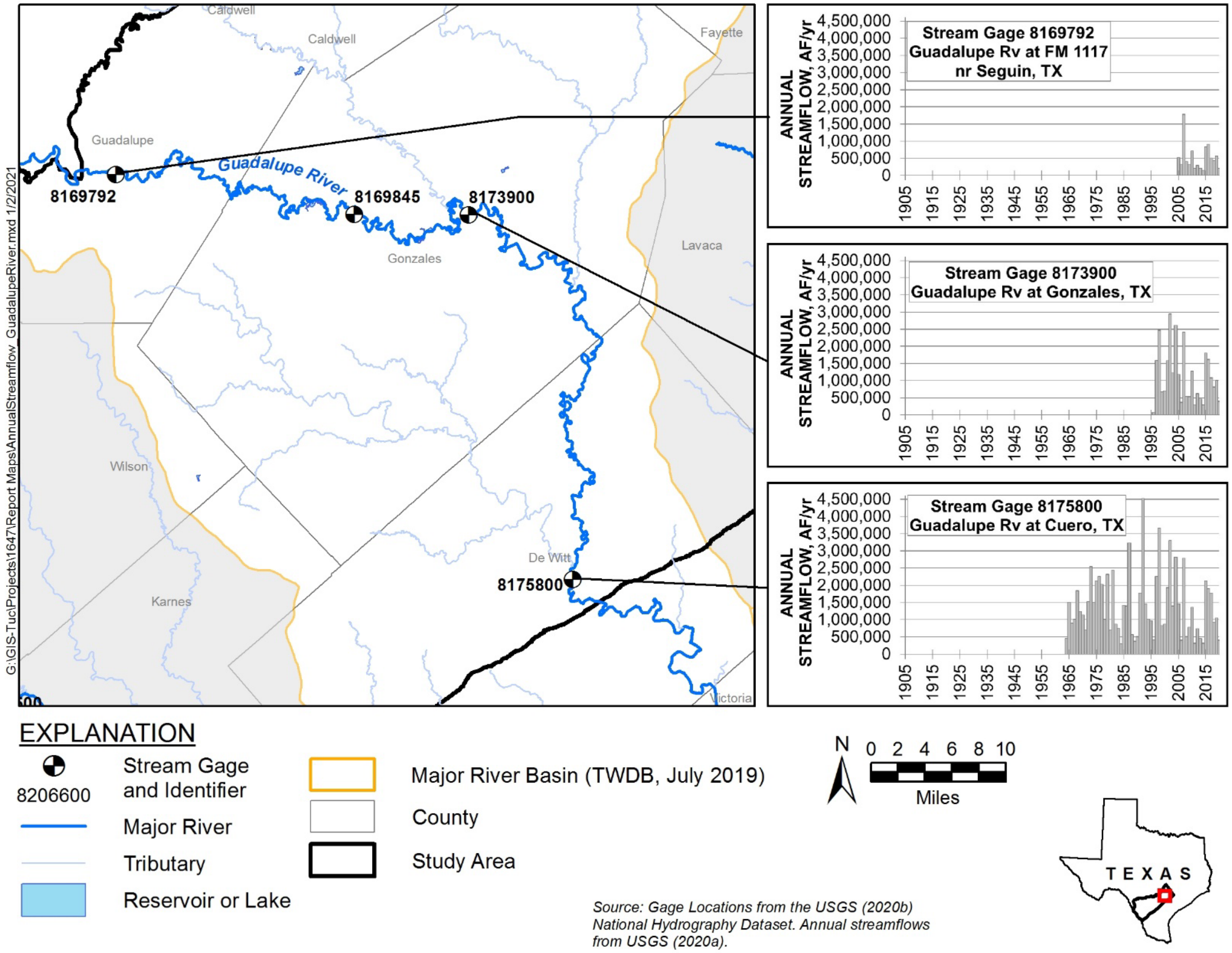

Figure 2-41. Annual streamflows along Guadalupe River.

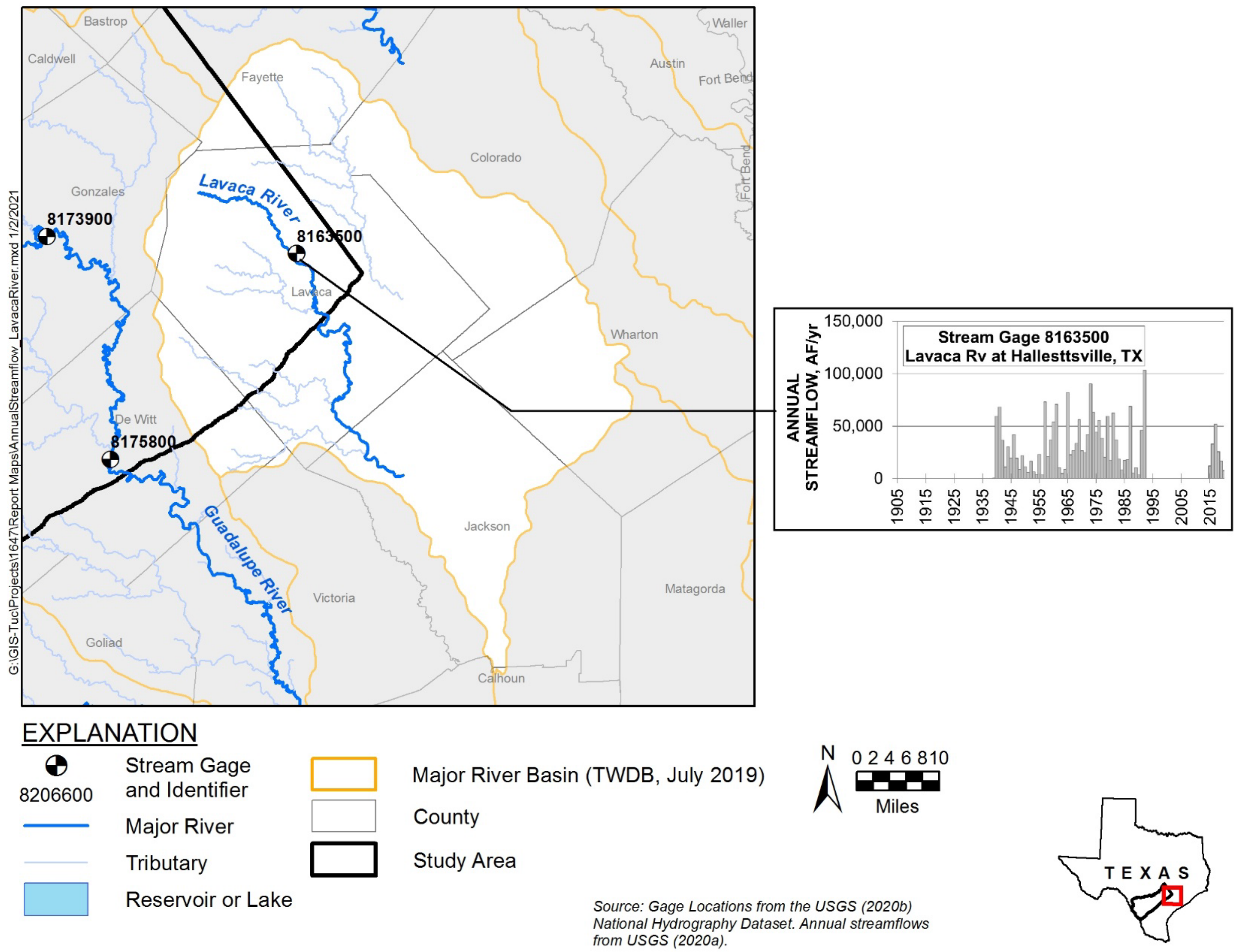

Figure 2-42. Annual streamflows along Lavaca River.

Table 2-3. Difference in annual streamflows along major rivers.

River	Nueces River			Frio River	Atascosa River	San Antonio River		Guadalupe River	
Upstream Gage	8193000	8194000	8194500	8205500	8207500	8181800	8181800	8169792	8173900
Downstream Gage	8194000	8194500	8210000	8206600	8208000	8183200	8183500	8173900	8175800
Year	Acre-Feet								
1980	43,613	69,753	483,367	60,939	---	---	28,340	---	---
1981	128,626	214,998	360,231	4,315	---	---	-37,482	---	---
1982	4,259	87,795	70,492	8,793	---	---	26,273	---	---
1983	-10,196	-7,443	137,371	8,924	---	---	116,926	---	---
1984	6,409	-4,899	67,530	-6,380	---	---	59,839	---	---
1985	21,235	300,858	86,126	68,782	---	---	54,062	---	---
1986	28,545	-28,689	65,746	10,983	---	---	15,552	---	---
1987	62,343	6,782	293,180	156,996	---	---	59,292	---	---
1988	1,514	14,703	45,635	---	---	---	20,694	---	---
1989	2,790	2,520	194,774	14,134	---	---	17,851	---	---
1990	21,952	50,966	134,318	39,496	---	---	16,729	---	---
1991	-17,001	13,237	157,606	90,143	---	---	37,672	---	---
1992	-25,463	103,476	444,287	458,371	---	---	350,137	---	---
1993	-1,337	13,422	159,315	-4,126	---	---	103,010	---	---
1994	-4,973	17,201	188,326	19,862	---	---	26,991	---	---
1995	8,894	31,306	146,163	4,020	---	---	14,454	---	---
1996	-15,428	9,965	87,426	237	---	---	23,484	---	333,295
1997	14,053	17,191	49,972	-18,059	---	---	12,718	---	669,685
1998	-762	-22,352	78,320	62,402	---	---	40,330	---	1,193,277
1999	51,387	11,984	51,720	-439	---	---	20,652	---	149,300
2000	-3,417	2,111	65,511	-11,527	---	---	-24,700	---	158,624
2001	-10,270	114,011	117,294	4,033	---	---	-19,402	---	357,238
2002	296,159	673,404	1,026,709	396,872	246,812	---	48,633	---	365,386
2003	16,930	225,847	210,214	23,156	74,795	---	42,187	---	180,401
2004	-4,622	137,990	429,223	30,241	84,180	---	29,683	---	213,170
2005	-2,364	21,415	105,299	-158	20,110	---	-2,700	651,907	284,863
2006	-200	16,946	45,323	-2,227	14,804	14,215	15,312	61,222	32,301
2007	71,591	277,430	557,598	115,479	-96,527	-30,399	-46,766	626,929	384,927
2008	883	5,810	43,158	-5,211	6,064	634	-855	135,202	-38,991
2009	204	1,011	36,240	-2,659	9,817	21,853	9,327	213,729	246,600
2010	11,405	67,171	167,983	11,291	65,395	61,095	-9,386	558,795	79,502
2011	-8,485	-2,196	26,413	-1,647	3,980	-3,528	-11,821	85,228	21,213
2012	-3,811	10,344	64,499	7,297	11,716	42,393	-5,707	330,650	115,629
2013	50,085	199,964	-7,229	---	6,300	15,370	-21,509	258,637	-21,926
2014	1,350	-824	46,679	-5,743	8,612	5,007	-24,416	134,272	24,908
2015	36,731	114,943	135,256	2,535	116,082	54,136	-36,354	969,551	332,280
2016	-16,870	32,803	94,202	6,584	52,806	227,415	-19,964	697,243	285,622
2017	88,032	73,258	23,446	-183	5,940	73,817	32,755	581,928	689,879
2018	-1,712	137,379	-69,851	-17,585	30,036	15,066	-36,692	380,796	121,984
2019	-7,644	-12,827	34,003	-3,916	7,699	-3,779	3,027	430,539	43,664

--- = data not available for calculation

2.4.2 *Reservoirs, Lakes, and Springs*

Reservoirs, lakes, and springs can be found throughout the study area (Figure 2-34). Reservoirs overlying the aquifers of interest in the study area larger than one-half square mile in area are summarized in Section 2.3.2 of this report and shown on Figure 2-32. Discharge information is available from the United States Geological Survey (2020b) for solely one reservoir in the study area. Available daily discharge flows from the Choke Canyon reservoir are shown on Figure 2-43. Peak average daily discharges are generally on the order of 70 cubic feet per second (cfs) or smaller from Choke Canyon Reservoir but vary up to 3,500 cfs. Discharges in the other reservoirs were not accessible through the public domain.

A handful of springs are documented within the study area (Figure 2-34). 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 (Deeds and others, 2003). Spring discharges are summarized in Section 2.7.2 of this report.

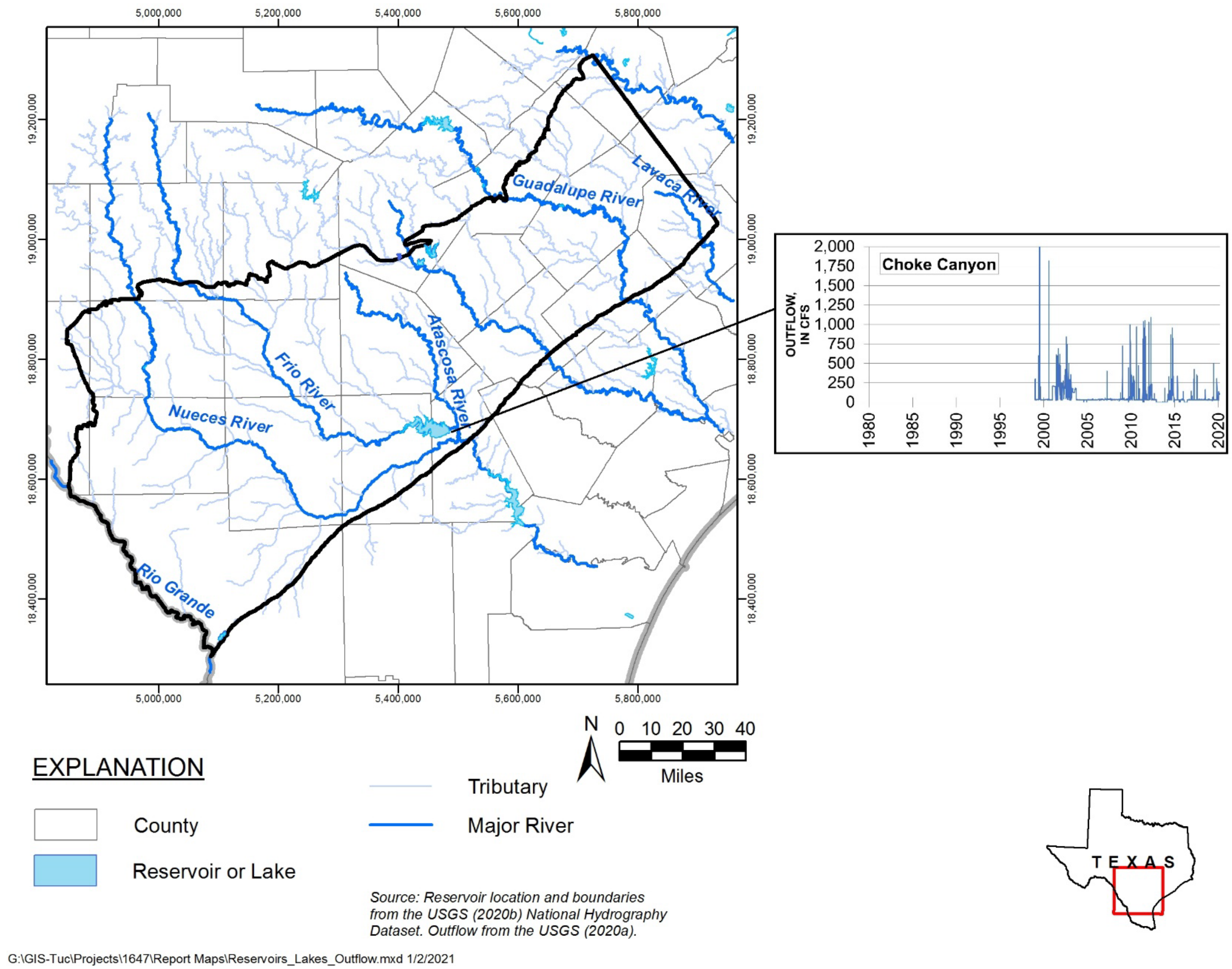

Figure 2-43. Daily discharge flows for selected reservoirs in study area.

2.5 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 (feet^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 (feet/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).

For this study, the results from previous studies by Deeds and others (2003) and Kelley and others (2004) were updated with an additional analysis using recent well test data from the TWDB Groundwater Database (TWDB, 2019c). The previous studies utilized a large dataset developed by Mace and others (2002) to estimate aquifer transmissivity and hydraulic conductivity for the aquifer layers simulated in the previous groundwater availability models for the aquifer system. The measurements in the Mace and others (2002) database were compiled from the TWDB and the Texas Commission on Environmental Quality. The final datasets used for the previous modeling studies were obtained from the associated source databases for this model update. The data processing and analysis conducted for the previous studies are described in detail in reports by Deeds and others (2003) and Kelley and others (2004). Each measurement was assigned to an aquifer layer based on well screen or well depth information and elevations of the updated hydrostratigraphic framework described in Section 2.1 of this report, or the assigned layer in the previous model if screen information was not readily available. This process yielded more than 1,220 values of hydraulic conductivity. A total of 112 TWDB measurements from the TWDB (2019c) Groundwater Database were added to the previous dataset using data collected since 2004. 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. Using this method, transmissivity is equal to specific capacity divided by drawdown multiplied by a factor of 1,500. Transmissivity values were converted to hydraulic conductivity values by dividing by the screen length in the measurement well. Hydraulic conductivity is equal to transmissivity divided by the aquifer thickness at the well based on well screen information.

2.5.1 *Hydraulic Conductivity*

Hydraulic conductivity is specified in the groundwater model. Aquifer horizontal hydraulic conductivity values from previous studies and current analysis are summarized in Table 2-4. Histograms for estimated hydraulic conductivity values for each aquifer unit are shown on Figure 2-44. The hydraulic properties for each aquifer unit are summarized below. The aquifer properties reported herein are based on available aquifer testing results from datasets previously described, except for the river alluvium which is described using values reported in literature. The range and geometric mean values are representative of the aquifer testing data and might not represent actual properties throughout the entire aquifer layer. The testing data provide a range of possible values for constraining model calibration. Vertical conductance will be evaluated during model calibration. Distributions of aquifer property measurements in the upper aquifer units (Sparta, Weches, Queen City, and Reklaw) and the lower aquifer units (Carrizo and Wilcox Group) are shown on Figure 2-45 through Figure 2-48, respectively. The vast majority of data available for all aquifer units are from wells located at or very near outcrop areas. No hydraulic conductivity data are available for deep, downdip portions of the aquifer system.

Table 2-4. Summary of estimated aquifer hydraulic conductivity measurements.

	Hydraulic Conductivity (feet per day)			
Aquifer Layer	**Count**	**Minimum**	**Maximum**	**Geometric mean**
Sparta Aquifer	2	20	100	45.6
Weches Aquitard	--	--	--	--
Queen City Aquifer	279	0.01	750	31.5
Reklaw Aquitard	130	0.01	575	18.5
Carrizo-upper Wilcox	736	0.06	975	32.3
Middle Wilcox	215	0.08	487	8.4
Lower Wilcox	173	0.08	332	5.0
Wilcox (All)*	425	0.08	487	6.9

-- = Not available
*Wilcox (All) includes measurements reported for the upper, middle, and lower Wilcox layers plus measurements from the TWDB Groundwater Database assigned to “Carrizo-Wilcox” or “Wilcox” based on large well screen intervals at the tested wells.
Source: Deeds and others (2003), Kelley and others (2004), TWDB Groundwater Database (2019c).

Most available measurements for the Wilcox aquifer layers are within logarithmic values near 0 and up to 1 which represents a more constrained distribution of hydraulic conductivity. Hydraulic conductivity distribution is less constrained in the Queen City, Reklaw, and Carrizo aquifer layers. There is a degree of variation in hydraulic conductivity measurements that suggests levels of heterogeneity within the layers. There was abundant data for most layers, except for the Sparta Aquifer, Weches Aquitard, and upper Wilcox aquifer layer.

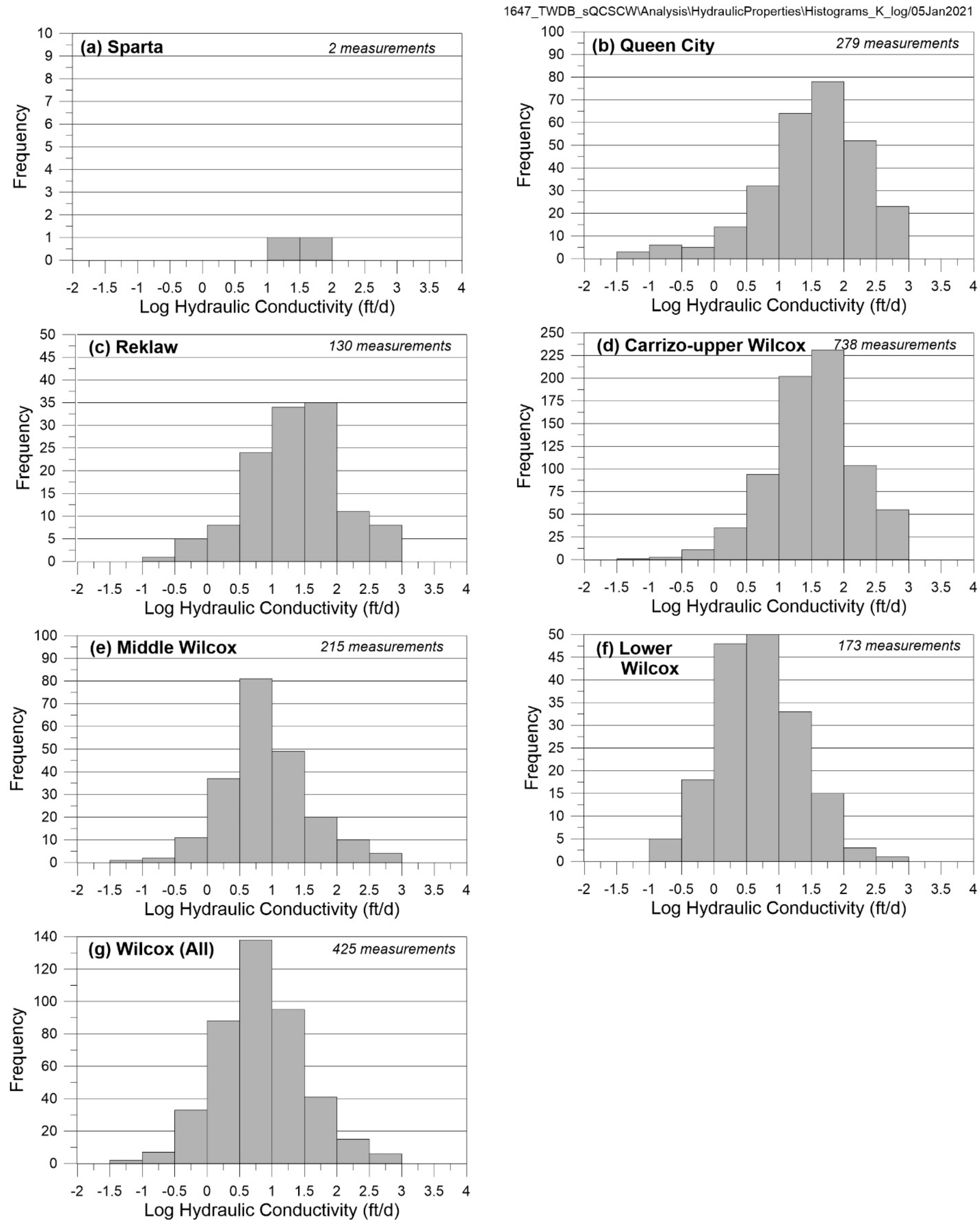

Figure 2-44. Histograms of measured hydraulic conductivity.

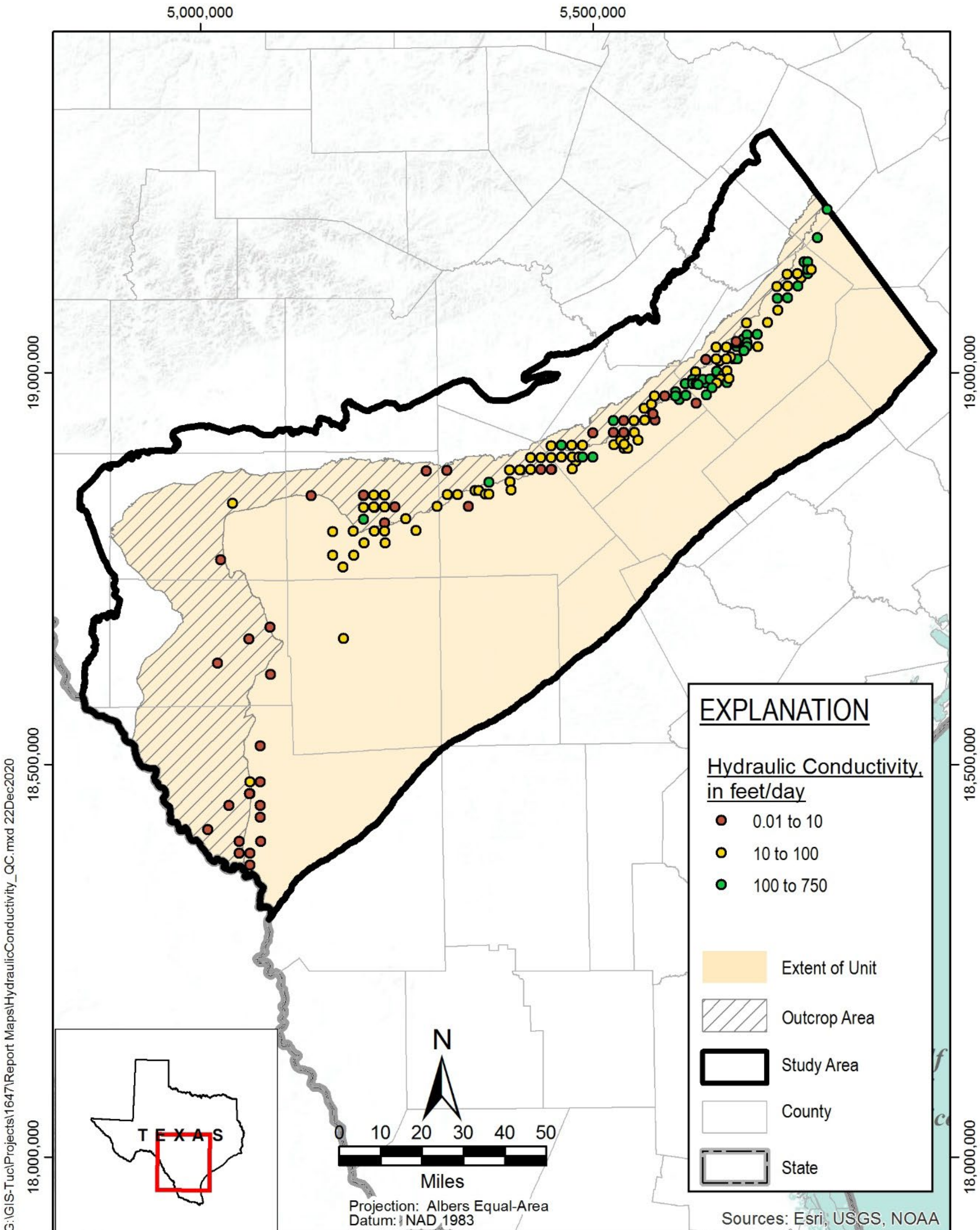

Figure 2-45. Hydraulic conductivity measurement locations for Queen City Aquifer.

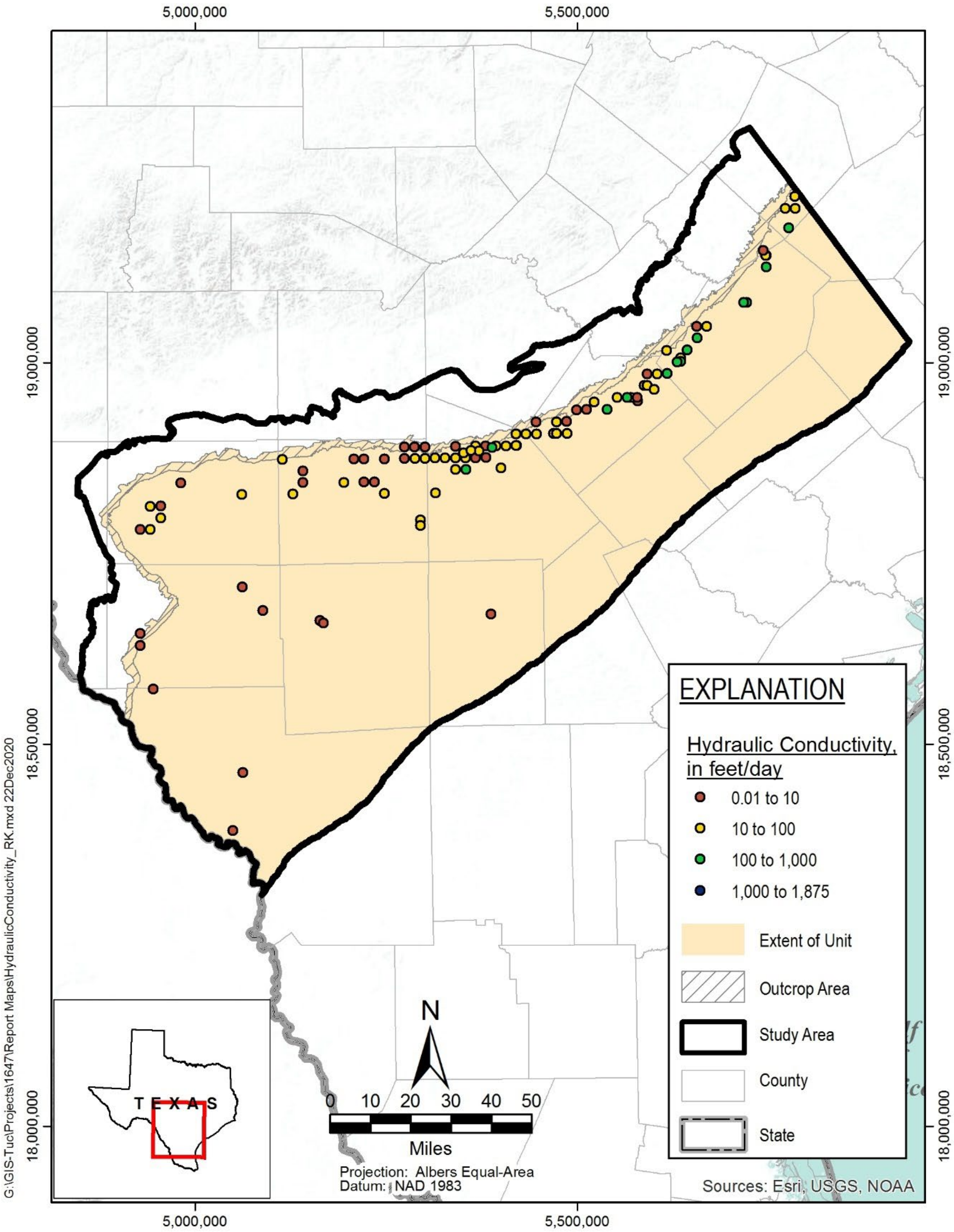

Figure 2-46. Hydraulic conductivity measurement locations for Reklaw Aquitard.

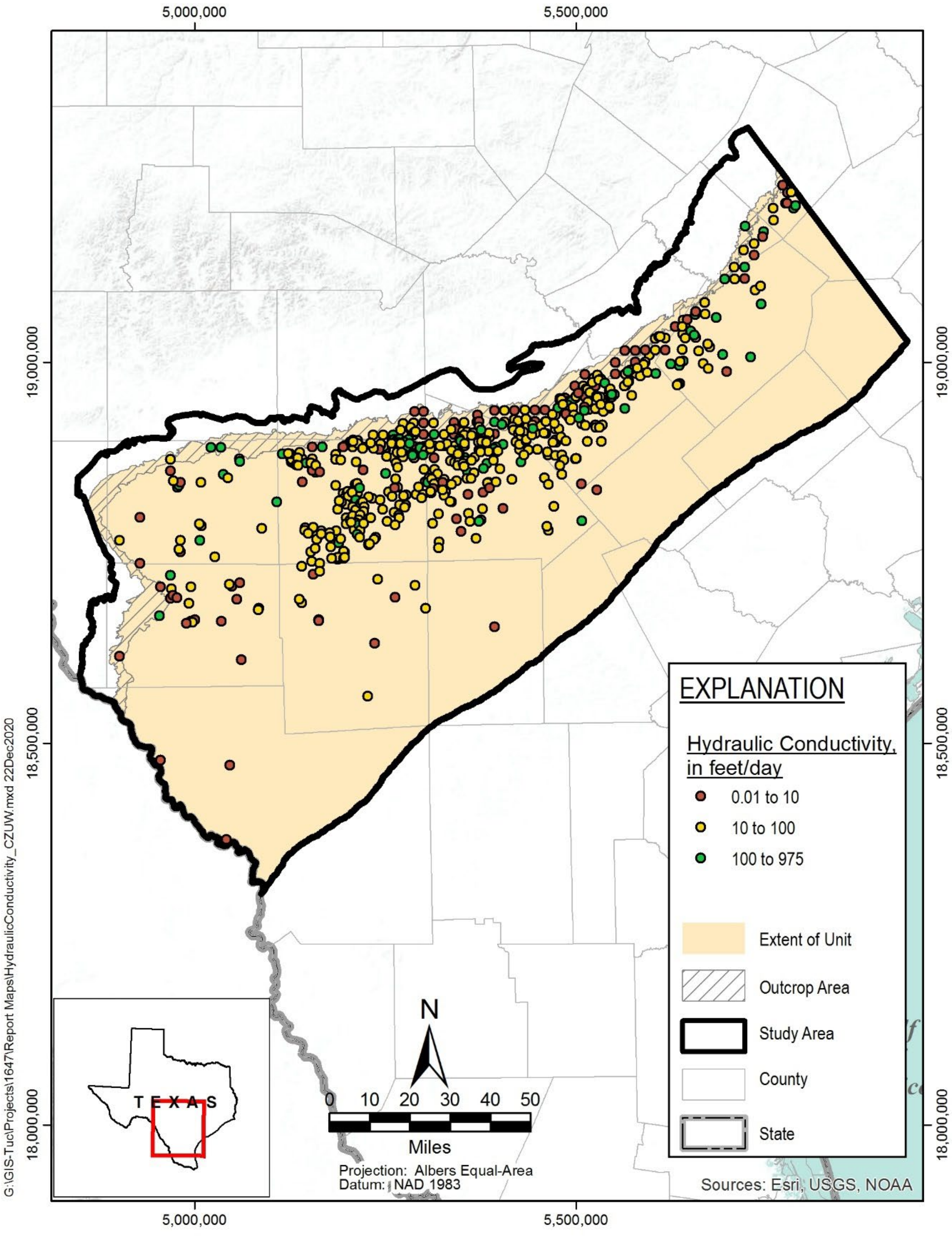

Figure 2-47. Hydraulic conductivity measurement locations for Carrizo-Upper Wilcox aquifer interval.

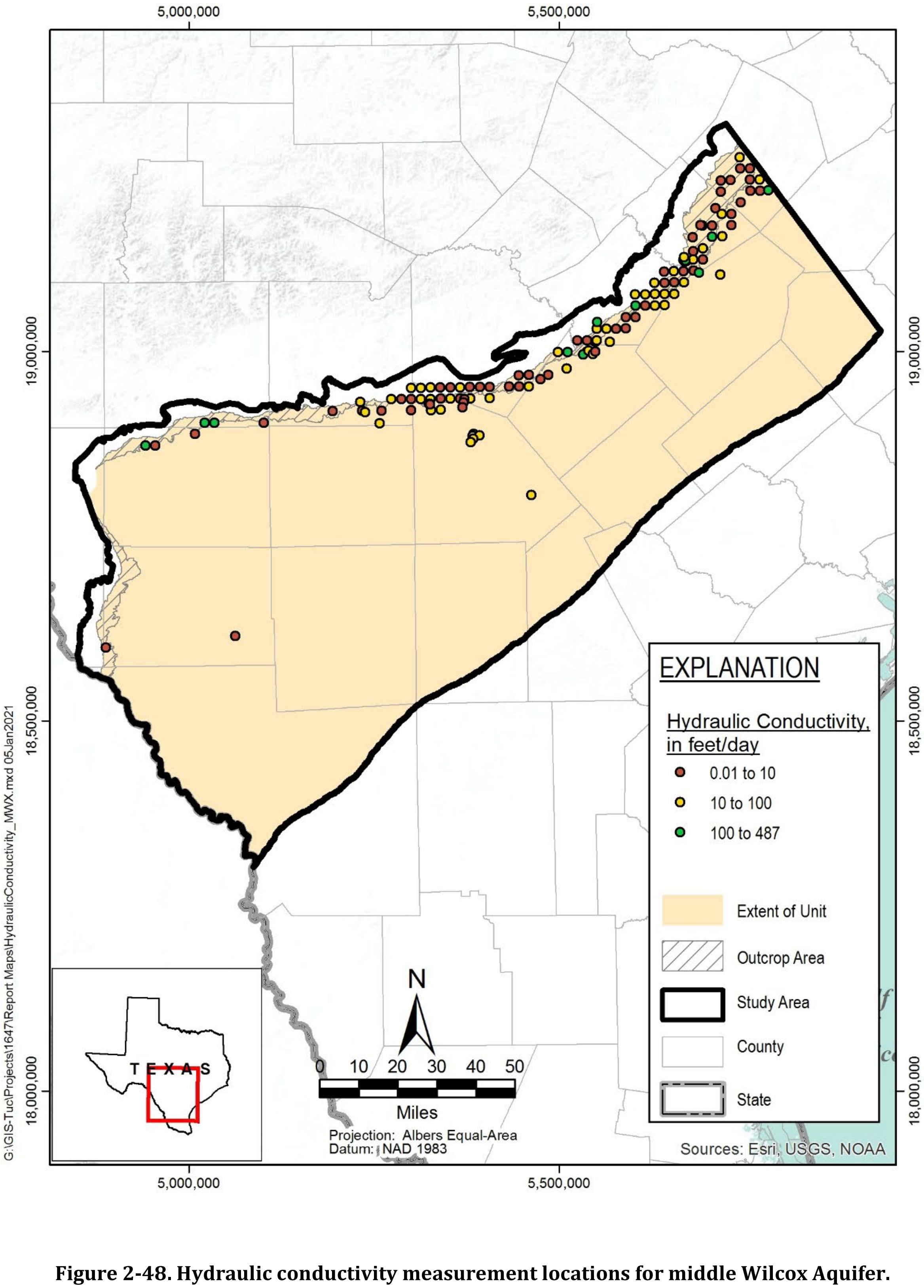

Figure 2-48. Hydraulic conductivity measurement locations for middle Wilcox Aquifer.

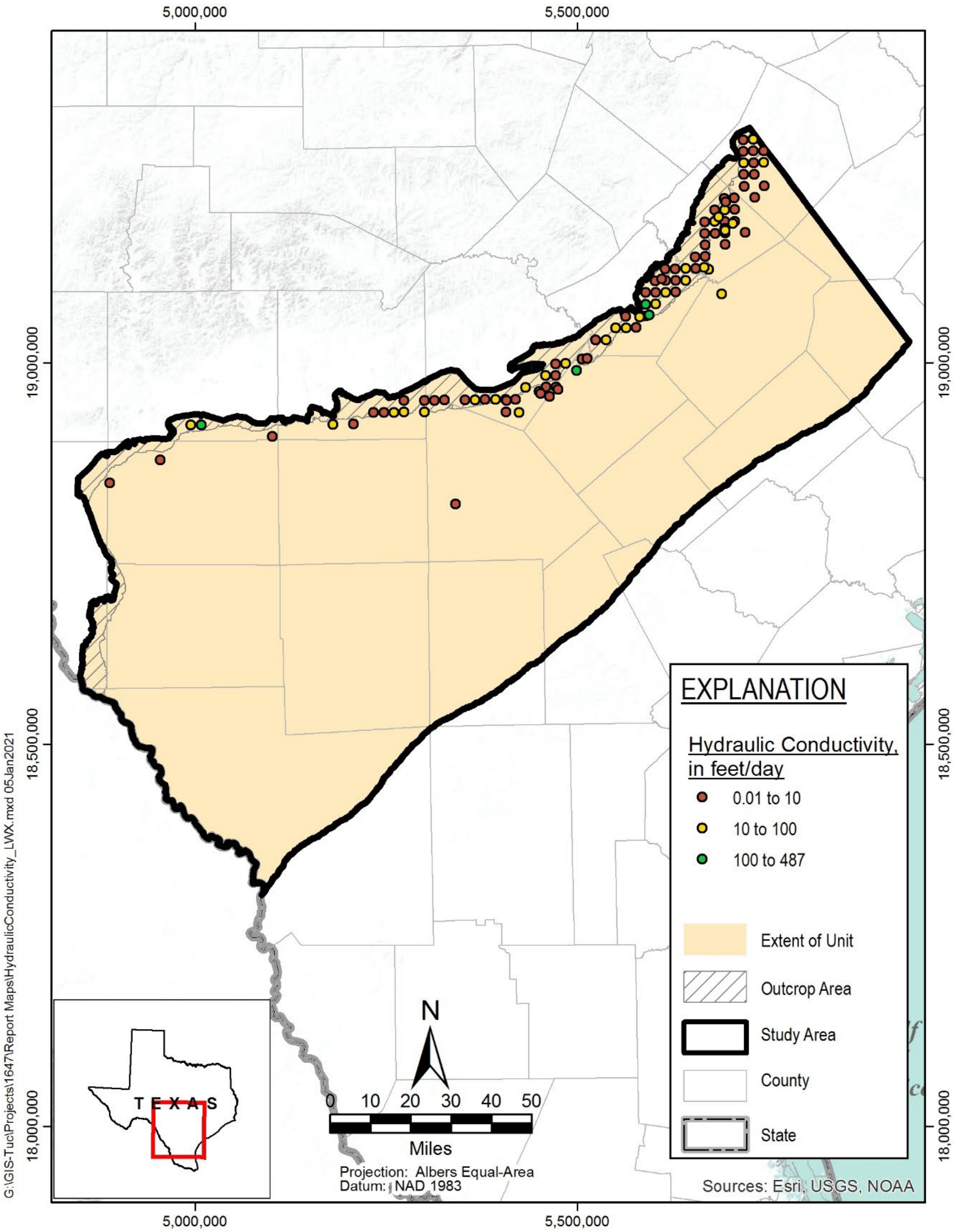

Figure 2-49. Hydraulic conductivity measurement locations for lower Wilcox Aquifer.

2.5.1.1 River Alluvium

No measurements of hydraulic properties for river alluvium were available for the study area. Assuming a lithology of sandy gravel, hydraulic conductivity values for the river alluvium deposits range from approximately 10 feet/day to 1,000 feet/day (Freeze and Cherry, 1979).

2.5.1.2 Sparta Aquifer

Aquifer test data for the Sparta Aquifer are very limited (2 measurements) (Table 4-5). Based on these measurements, hydraulic conductivity values range from 20 feet/day to 100 feet/day, with a geometric mean of approximately 45.6 feet/day. Hydraulic conductivity values simulated in the previous groundwater availability model by Kelley and others (2004) for this area ranged from 3 to 5 feet/day in the outcrop to less than 0.1 feet/day in the deep, downdip portions of the layer.

2.5.1.3 Weches Aquitard

No aquifer test data are available from wells constructed in the Weches Aquitard. The previous groundwater availability model by Kelley and others (2004) specified a vertical hydraulic conductivity value equal to 1×10^{-4} feet/day.

2.5.1.4 Queen City Aquifer

Estimated hydraulic conductivity values for the Queen City Aquifer range from 0.1 feet/day to 750 feet/day, with a geometric mean of 31.5 feet/day. The measurement values are distributed principally in the outcrop areas in the eastern parts of the study area (Figure 2-45).

2.5.1.5 Reklaw Aquitard

Estimated hydraulic conductivity values range from 0.01 feet/day to 575 feet/day, with a geometric mean of 18.5 feet/day. The measurement values are distributed principally in the outcrop areas in the eastern parts of the study area (Figure 2-46). The previous groundwater availability model by Kelley and others (2004) specified a vertical hydraulic conductivity value equal to 1×10^{-4} feet/day. Data suggest that zones of higher conductivity could occur in local areas of this aquitard layer, which is consistent with observations of cross-formational flows from the Carrizo-Wilcox Aquifer to the Queen City Aquifer discussed in Section 2.8.4 of this report.

2.5.1.6 Carrizo-Upper Wilcox

Estimated hydraulic conductivity values for the Carrizo-upper Wilcox aquifer layer range from 0.06 feet/day to 975 feet/day, with a geometric mean of 32.3 feet/day. More measurement values are available for this aquifer layer than other layers, which indicates that this layer is the principal groundwater source in the study area. The measurement values are distributed principally in the outcrop areas; however, a relatively large number of measurement values are available for down-dip areas as well (Figure 2-47).

2.5.1.7 Middle Wilcox

Estimated hydraulic conductivity values for the middle Wilcox range from 0.08 feet/day to 487 feet/day, with a geometric mean of 8.4 feet/day. Locations of measured data for the middle Wilcox are principally in the outcrop area with less points in the downdip portions than upper Wilcox interval (Figure 4-48).

2.5.1.8 Lower Wilcox

Estimated hydraulic conductivity values for the lower Wilcox range from 0.11 feet/day to 332 feet/day, with a geometric mean of 5 feet/day. Similar to the upper Wilcox interval, locations of measured data for the lower Wilcox are limited to the outcrop areas with very few measurements in downdip portions of the aquifer layer (Figure 4-49).

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, downdip portions of the aquifer units.

The previous groundwater availability model by Kelley and others (2004) scaled initial hydraulic conductivities as a function of sand fraction and representative conductivities for clay and sand. Values were generally unchanged during calibration. Vertical conductivity throughout the Reklaw aquitard was decreased to better represent a confining unit.

Calibrated hydraulic conductivity distributions from the previous groundwater availability model by Kelley and others (2004) were evaluated for this study. Simulated hydraulic conductivities in the study area for the Sparta Aquifer ranged from less than 0.1 to about 5 feet/day. Simulated hydraulic conductivities in the Queen City Aquifer are similar to the Sparta Aquifer, with a range from less than 0.1 to about 10 feet/day. The Carrizo Aquifer is specified with the largest hydraulic conductivities, ranging from less than 0.1 to about 100 feet/day. The upper and middle Wilcox both have minimum specified hydraulic conductivities of 1 feet/day, but with maximums of 7 and 10 feet/day, respectively. The lower Wilcox unit has the second highest specified hydraulic conductivities in the model area, ranging from 2 feet/day to 30 feet/day, with an average of 2.2 feet/day. The confining layers of Weches and Reklaw both were specified with a hydraulic conductivity of 1 feet/day.

Data for vertical hydraulic conductivity within the southern portions of the Carrizo-Wilcox, Queen City, and Sparta aquifer system are not available for this study. Groundwater models are often used to estimate vertical hydraulic conductivity at a regional scale. A typical ratio of horizontal to vertical hydraulic conductivity (vertical anisotropy) ranges from 1 to 1,000 for model applications. The previous groundwater availability model estimated vertical hydraulic conductivity based on sand and clay fractions. In that model, a vertical hydraulic conductivity value of 1×10^{-4} feet/day was specified for confining units, which is equivalent to the approximate conductivity for a clay material. This value was selected based on the expectation that vertical hydraulic conductivity is controlled by depositional environmental and lithofacies (Kelley and others, 2004). Model input datasets for the previous groundwater availability model for the southern portions of the Queen City and Sparta aquifers indicate horizontal isotropic hydraulic conductivity properties, which means horizontal conductivity is equal in all directions.

2.5.2 *Storage Properties*

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

Storativity values from the previous groundwater availability model by Kelley and others (2004) were unchanged during calibration. For the Weches, Queen City, Reklaw, and Carrizo aquifer layers, storativity was estimated for the model by calculating specific storage as a function of sand fraction, specific storage of sand and clay, and depth and then multiplying by layer thickness. Average storativity values specified for these layers are $1.1x10^{-3}$, $3.4x10^{-4}$, $3.8x10^{-3}$, $1.3x10^{-3}$, and $1.3x10^{-3}$ (dimensionless), respectively. Average specified specific storage values for these layers are $3.7x10^{-6}$, $5.3x10^{-6}$, $3.4x10^{-6}$, $4.5x10^{-6}$, and $2.8x10^{-6}$ 1/feet, respectively. Storativity values specified for the three Wilcox layers in a previous groundwater availability model by Deeds and others (2003) were also specified in the groundwater availability model by Kelley and others (2004). Storativity for the Wilcox layers is not explicitly reported by Kelley and others (2004); however, specific storage is reported to be $4.5x10^{-6}$ 1/feet for all Carrizo-Wilcox aquifer layers.

2.5.3 *Net Sand Thickness*

The aquifer units in the study area comprise of 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.

Sand distribution and thickness are important aquifer properties in quantifying groundwater volumes and estimating hydraulic properties of the hydrostratigraphic units of the study area. Geological formations within the study are generally comprised of interbedded layers of sand and clay. Those units which contain higher sand content or cumulative sand thickness are more capable of producing groundwater economically. Units which are chiefly comprised of clay act as aquitards, which may also contain smaller amounts of groundwater but restrict the movement of groundwater from one aquifer to another.

Net sand and percent sand thickness maps were prepared for each hydrostratigraphic unit using lithologic interval data from existing and updated interpretations of geophysical well logs and existing descriptions of lithology from driller's logs. The primary source of data was from the TWDB Brackish Resources Aquifer Characterization System Database which includes lithologic interpretations from Hamlin and others (2019), Meyers and others (2019, unpublished), Wise (2014), and Kelley and others (2004). Source data for lithologic intervals from geophysical interpretations were classified using a two-tier system (100 percent sand or 100 percent clay per interpreted interval) or a four-tier system which provided varied sand percentages. Source data from driller's logs, which inherently vary widely in description, were simplified to a four-tier system by Meyers and others (2019, unpublished). For this study, existing interval data with four-tier classification were modified to a two-tier system for consistency among sources.

In total, 3,469 wells had lithologic interpretations. The lithologic interpretations were grouped by hydrostratigraphic unit as determined by existing or updated hydrostratigraphic contact interpretations from borehole electrical logs in the Brackish Resources Aquifer Characterization System Database. Where hydrostratigraphic contact interpretations were not available, the updated model framework raster layers were evaluated to the wells to group the lithologic interpretations by the inferred hydrostratigraphic unit and were included in the net sand analysis where more spatial representation was needed such as outcrop areas.

For each hydrostratigraphic unit, the net sand analysis prioritized well locations where the lithologic interpretations represented the full hydrostratigraphic interval. These locations were determined by wells fully penetrating the unit based on hydrostratigraphic contacts from the borehole electrical log analysis. Where needed for adequate spatial distribution, select locations were included if the lithologic interpretation represented at least 80 percent of the hydrostratigraphic unit thickness. In a few instances, some locations were disregarded if they did not support the regional trend, particularly from driller's log source data.

Net sand thickness was calculated at each well as the sum of the sand intervals, as classified by the two-tier system, for each hydrostratigraphic model layer. Percent sand was calculated at each well by the ratio of the net sand to hydrostratigraphic model layer thickness. Table 2-5 provides the number of wells used for each hydrostratigraphic unit and the average percent sand for all wells.

Table 2-5. Summary of percent sand for aquifer units.

Hydrostratigraphic Unit	Number of Well Locations Used	Average Percent Sand
Sparta	293	0.35
Weches	421	0.08
Queen City	460	0.39
Reklaw	465	0.15
Carrizo - Upper Wilcox	527	0.65
Middle Wilcox	571	0.27
Lower Wilcox	535	0.45

Percent sand raster files were prepared by interpolating the percent sand values at each well using the inverse distance weighted method in ArcGIS. These raster files were then converted into net sand raster files using GIS spatial analysis tools and the framework model layer thickness raster files. Percent sand was interpolated first to ensure the net sand thickness did not exceed the hydrostratigraphic unit thickness particularly for the thinning outcrop areas with limited data availability.

2.5.3.1 Sparta Aquifer

A total of 293 well locations were used to prepare the net sand thickness and percent sand maps of the Sparta Aquifer (Figure 2-50). Net sand thickness values ranged from 0 at the updip outcrop edge to over 350 feet in the southwestern portion of the study area in Webb county. A depocenter of maximum sand thickness is formed in the southwest portion of the study area and generally trends northeast-southwest.

2.5.3.2 Weches Aquitard

A total of 421 well locations were used to prepare the net sand and percent sand maps of the Weches aquitard (Figure 2-51). The Weches aquitard is relatively thin and generally greater than 80 percent shale/clay (less than 20 percent sand) across most of the study area.

2.5.3.3 Queen City Aquifer

A total of 460 well locations were used to prepare the net sand thickness and percent sand maps of the Queen City aquifer (Figure 2-52). Net sand thickness values ranged from 0 at the updip outcrop edge to over 1,100 feet in the large depocenter that trends southwest-northeast from Webb County to Atascosa County, similar to the net sand trend in the Sparta Aquifer.

2.5.3.4 Reklaw Aquitard

A total of 465 well locations were used to prepare the net sand thickness and percent sand maps of the Reklaw aquitard (Figure 2-53). The Reklaw aquitard, similar to the Weches, is relatively thin and generally greater than 80 percent shale/clay (less than 20 percent sand), although localized zones of increased sand exist.

2.5.3.5 Carrizo-Upper Wilcox

A total of 527 well locations were used to prepare the net sand thickness and percent sand maps of the Carrizo-upper Wilcox interval (Figure 2-54). Net sand thickness values ranged from 0 at the updip outcrop edge to over 1,000 feet in the depocenter formed in the central area of Atascosa, Karnes, and Wilson counties. This depocenter is chiefly composed of coarse-grained bed-load fluvial channel deposits (Hamlin, 1988). As the principal aquifer source, the Carrizo-upper Wilcox interval comprises the highest sand content of the model area. Sand percent ranges from greater than 90 percent in the eastern updip area to about 50 percent or less to the west and along the Rio Grande.

2.5.3.6 Middle Wilcox

A total of 571 well locations were used to prepare the net sand thickness and percent sand maps of the middle Wilcox interval (Figure 2-55). Net sand thickness ranged from 0 to over 600 feet in the northeastern corner but is generally less than 300 feet across the study area. The middle Wilcox interval varies significantly in some areas but is generally about 70 percent shale/clay (30 percent sand) and may act as an aquitard and flow barrier between the Carrizo-upper Wilcox and lower Wilcox intervals in certain areas. The middle Wilcox interval also includes the distinct Yoakum canyon which trends generally north-south in Gonzales, DeWitt, and Lavaca counties and results in a thick wedge of shale which is not discernable on the net sand thickness map but is apparent on the percent sand map and where sand content is less than 10 percent. The Yoakum canyon was a large submarine channel that was filled with shale deposits of the Middle Wilcox (Hargis, 2009).

2.5.3.7 Lower Wilcox

A total of 535 well locations were used to prepare the net sand thickness and percent sand maps of the Lower Wilcox interval (Figure 2-56). Net sand thickness values ranged from 0 at the updip outcrop edge to over 1,800 feet in the depocenter in the northeast, down-dip portion of the study area which then thins with a trend to the southwest. The elongated depocenter is generally about 60 percent sand and decreases in sand content both in the updip and downdip direction. In Gonzales, DeWitt, and Lavaca counties, the effect of the Yoakum canyon incision into the lower Wilcox interval which resulted in a thinner overall unit thickness along the canyon is apparent due to the generally north-south trend of decreased sand thickness.

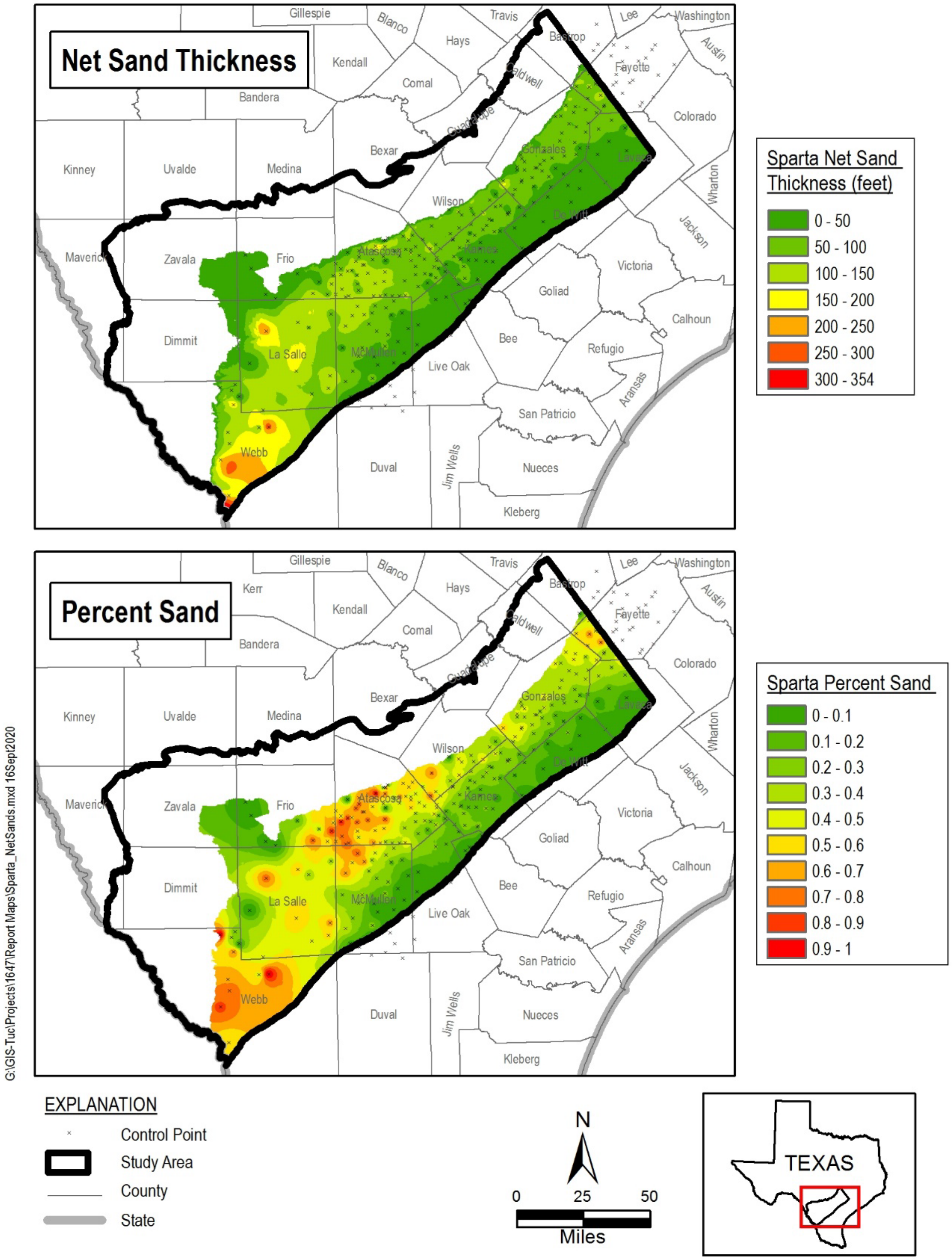

Figure 2-50. Net sand thickness and percent sand for Sparta Aquifer.

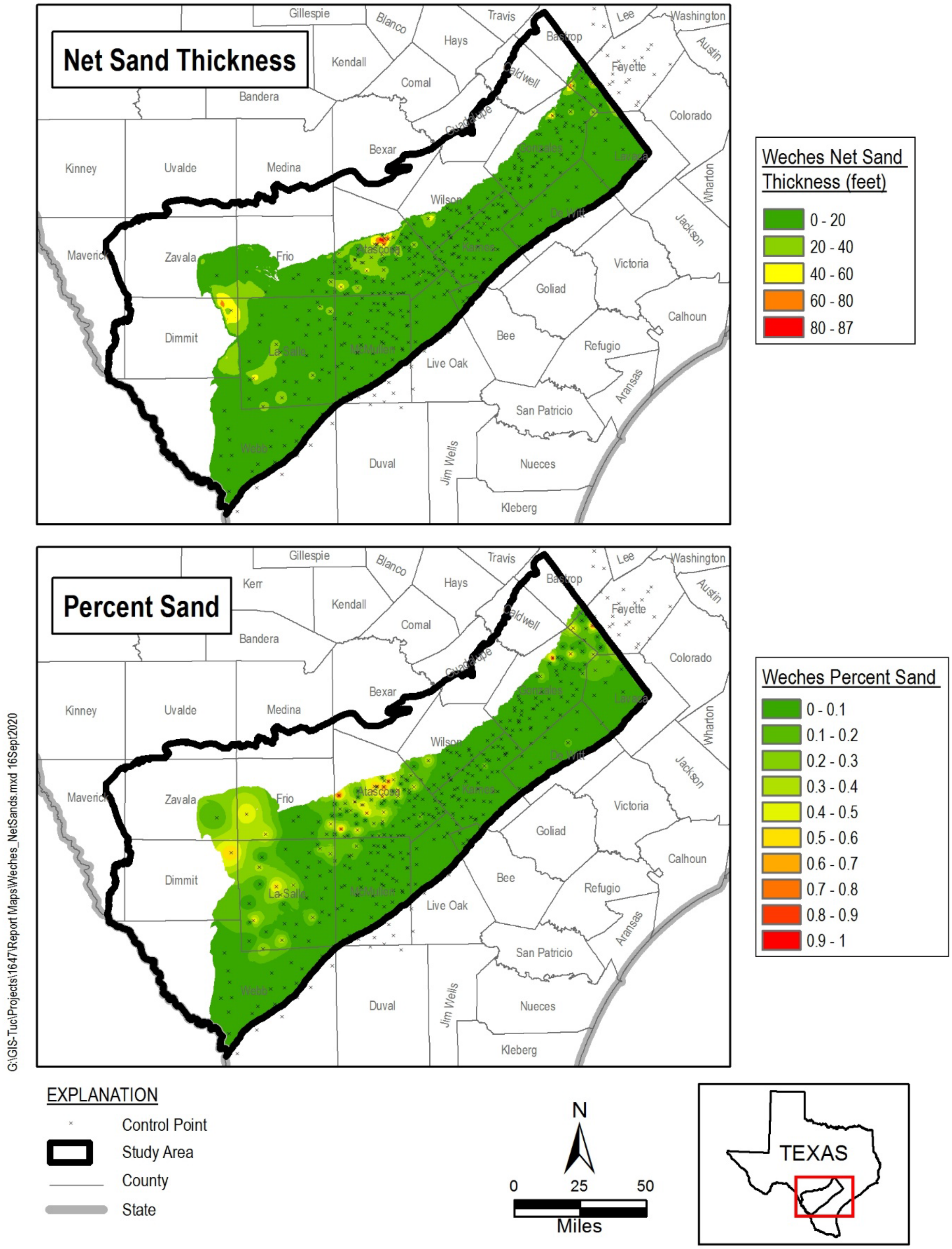

Figure 2-51. Net sand thickness and percent sand for Weches Aquitard.

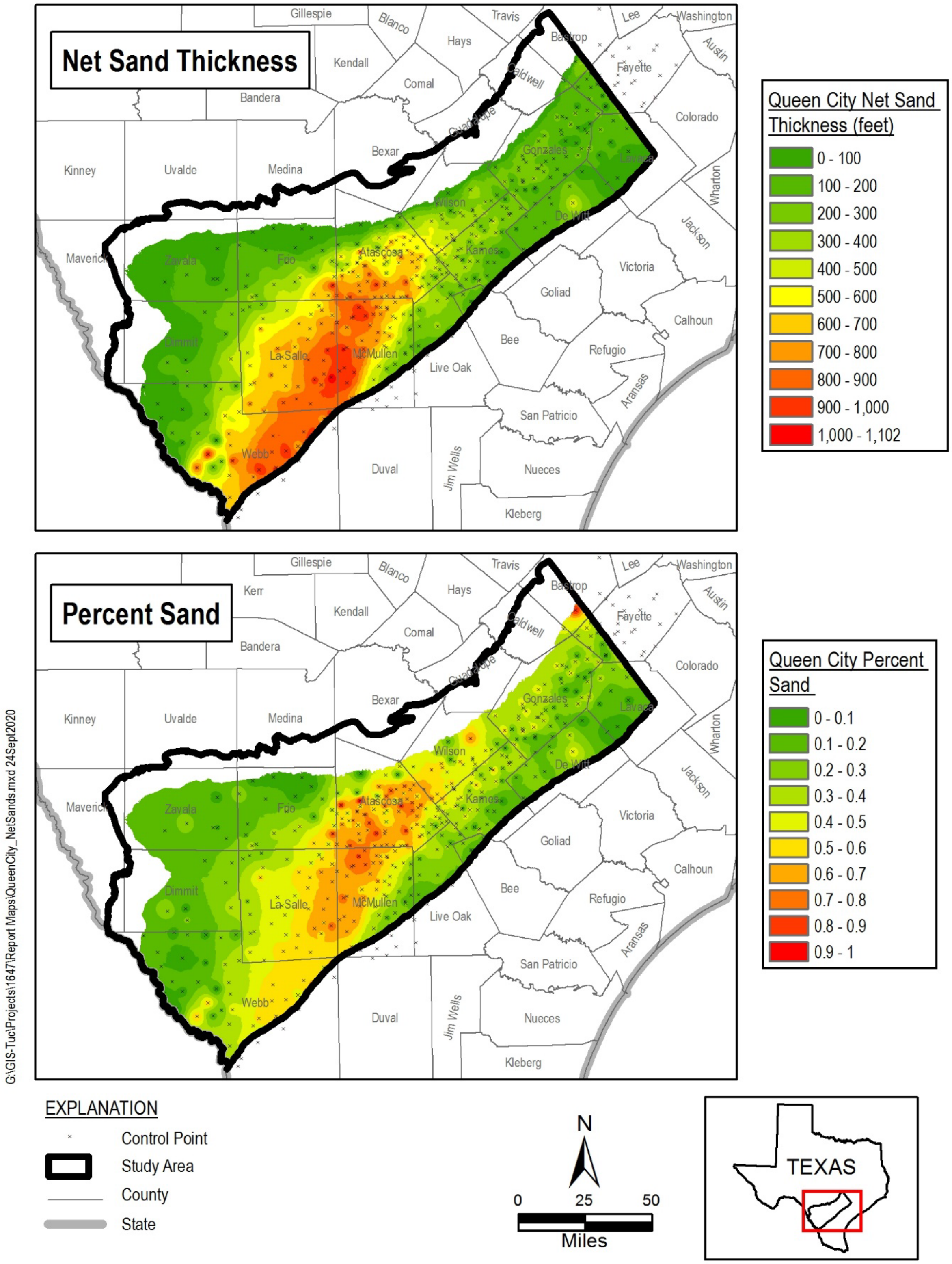

Figure 2-52. Net sand thickness and percent sand for Queen City Aquifer.

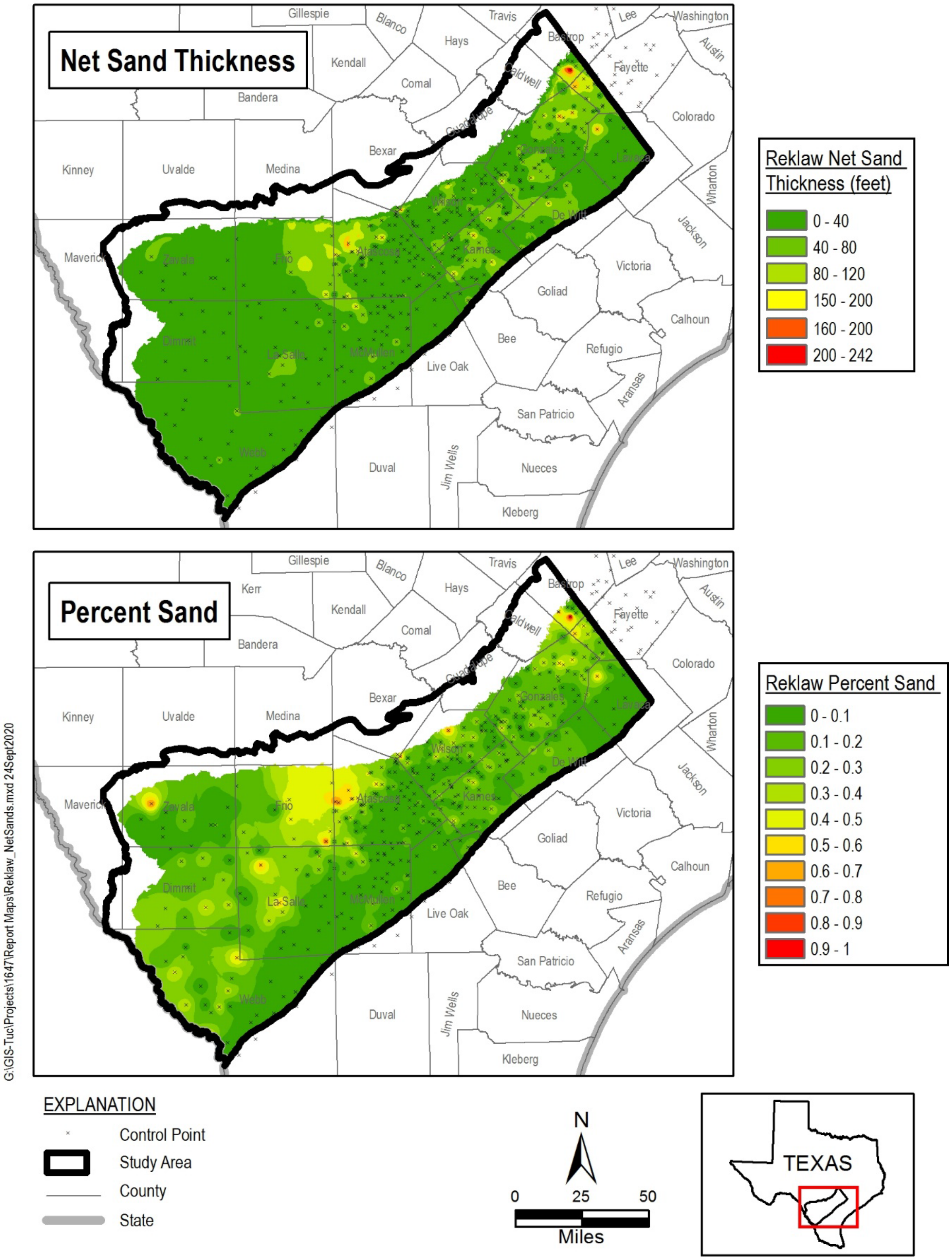

Figure 2-53. Net sand thickness and percent sand for Reklaw Aquitard.

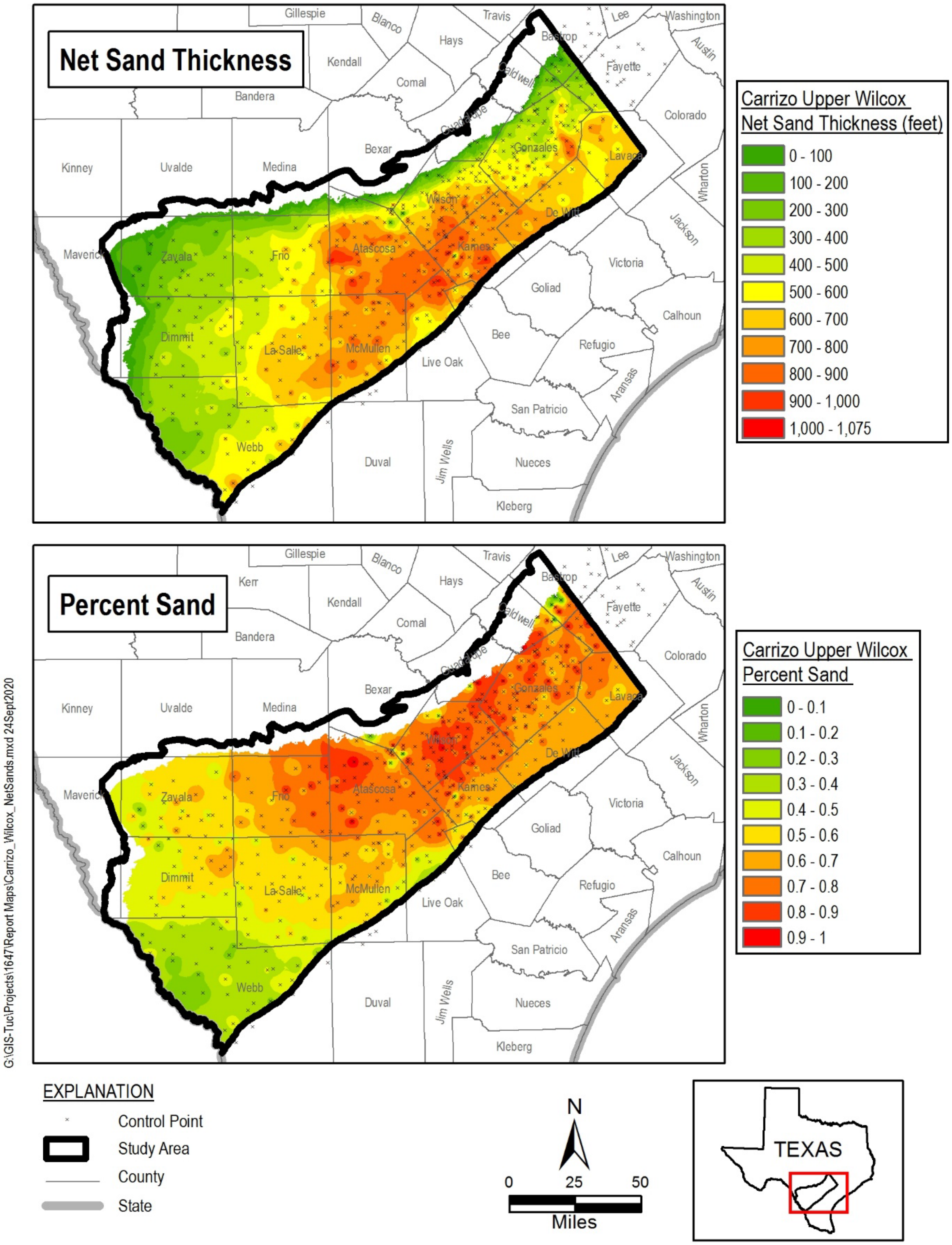

Figure 2-54. Net sand thickness and percent sand for Carrizo-Upper Wilcox Aquifer Interval.

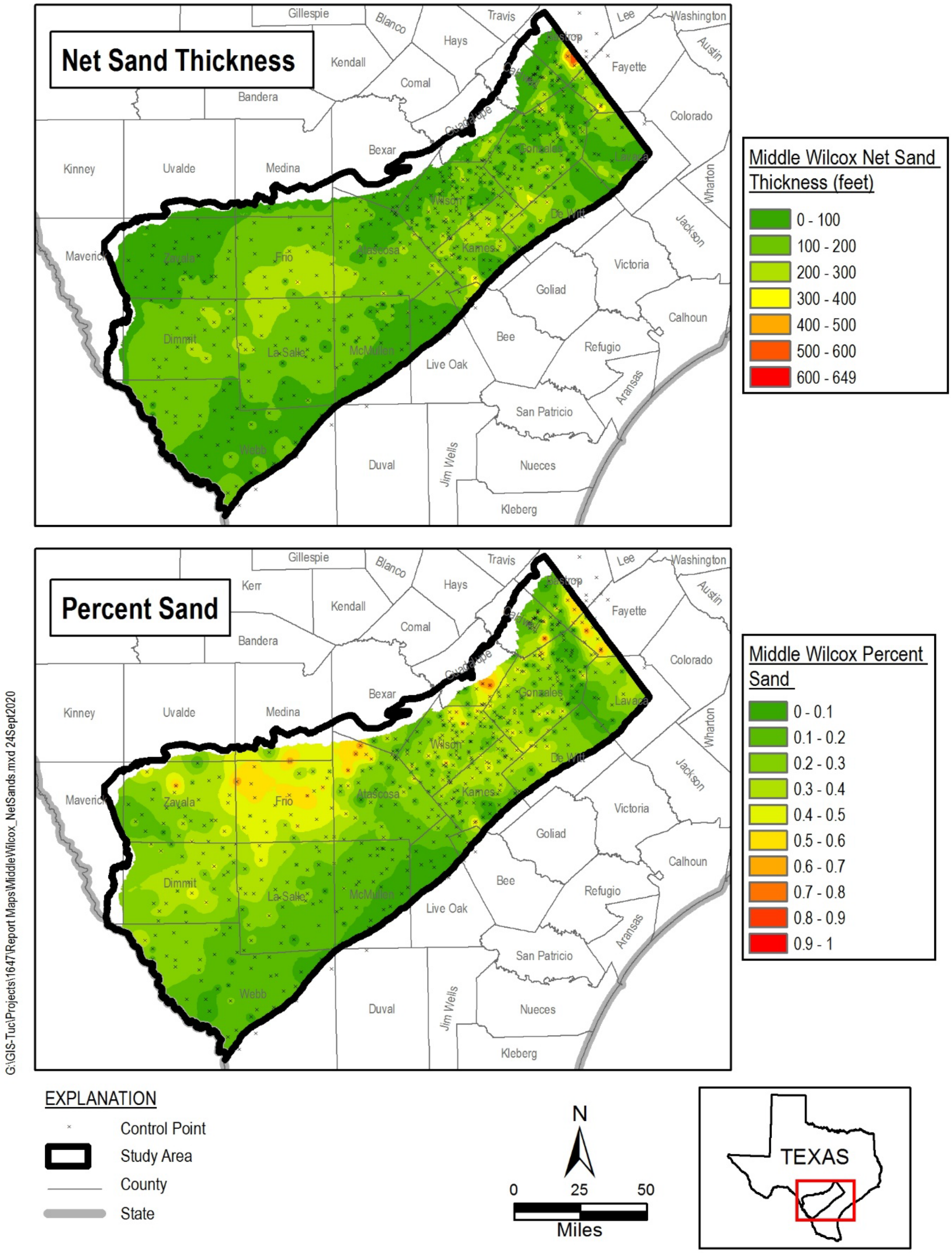

Figure 2-55. Net sand thickness and percent sand for Middle Wilcox Aquifer.

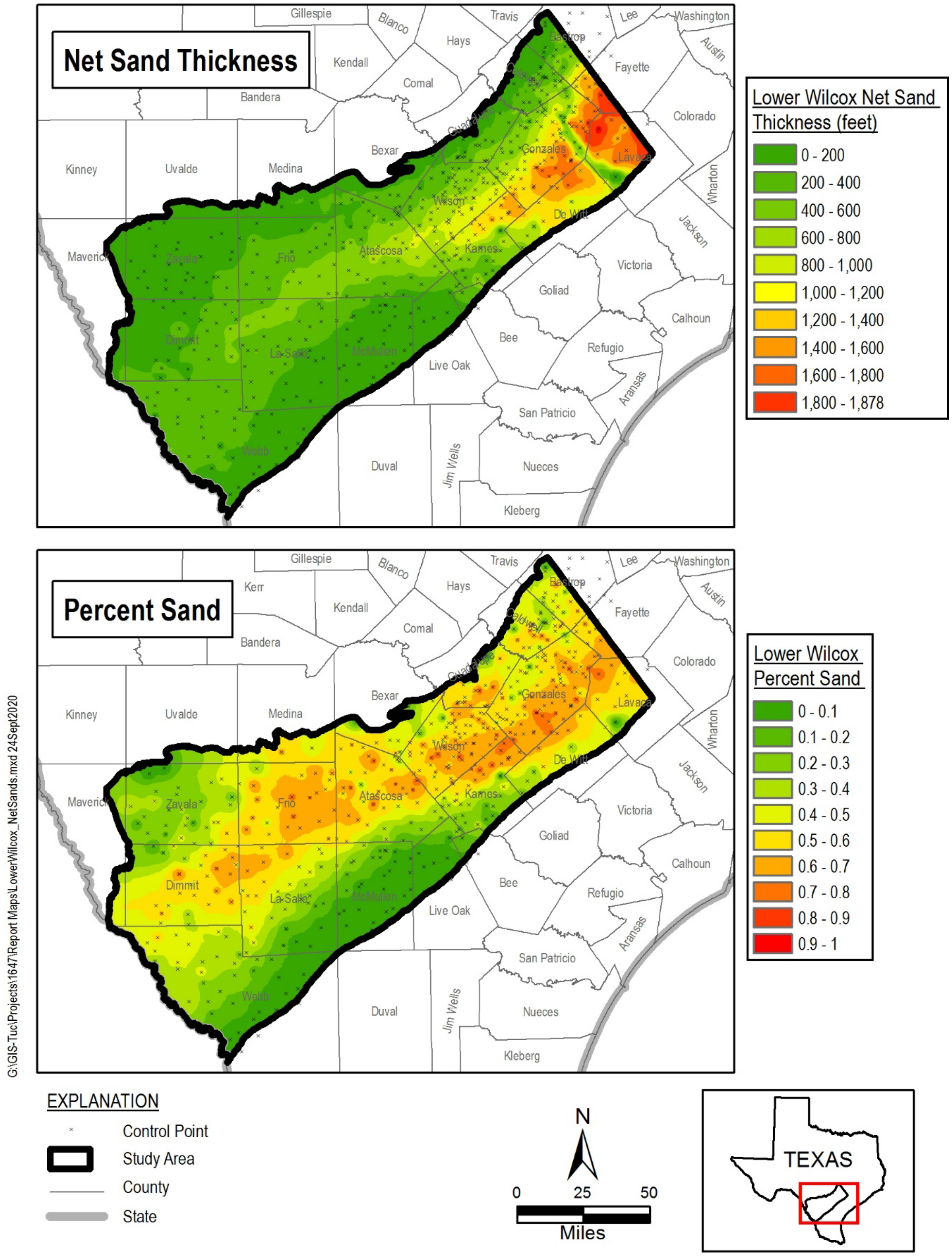

Figure 2-56. Net sand thickness and percent sand for Lower Wilcox Aquifer.

2.6 Potential for Subsidence

Subsidence is the gradual lowering of land surface elevation and typically occurs when large amounts of groundwater have been extracted from unconsolidated aquifers where compressible lithofacies exist. The southern portion of the Carrizo-Wilcox, Queen City, and Sparta 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 study area. A Subsidence District is not present in the study area. Land subsidence will be evaluated during the numerical modeling process if model results indicate large groundwater level drawdown will occur from increased pumping in the region.

A study on variability of Texas aquifers to pumping-induced subsidence was recently conducted by Furnans and others (2017) for the TWDB. That study estimated the risk for subsidence for major and minor aquifers throughout Texas, including the Sparta, Queen City, and Carrizo-Wilcox aquifers. Subsidence risk was evaluated by developing a risk matrix that incorporated three factors: (1) distribution, thickness, and compressibility of clay layers, (2) amount and timing of water level changes, and (3) lowest historical water level. Subsidence risk value was assigned to individual wells with data. Subsidence risks at well locations throughout the Sparta Aquifer, the Queen City Aquifer, and the Carrizo-Wilcox Aquifer are shown on Figure 2-57, Figure 2-58, and Figure 2-59, respectively. Results of the Furnans and others (2017) study suggest that the southern portion of the Carrizo-Wilcox Aquifer has a medium to high risk for future subsidence due to pumping in the northeast portion of the study area and a generally low risk in the southwestern portion of the study area west of the Frio. The southern portion of the Queen City and Sparta aquifers have a generally medium risk of subsidence in the study area.

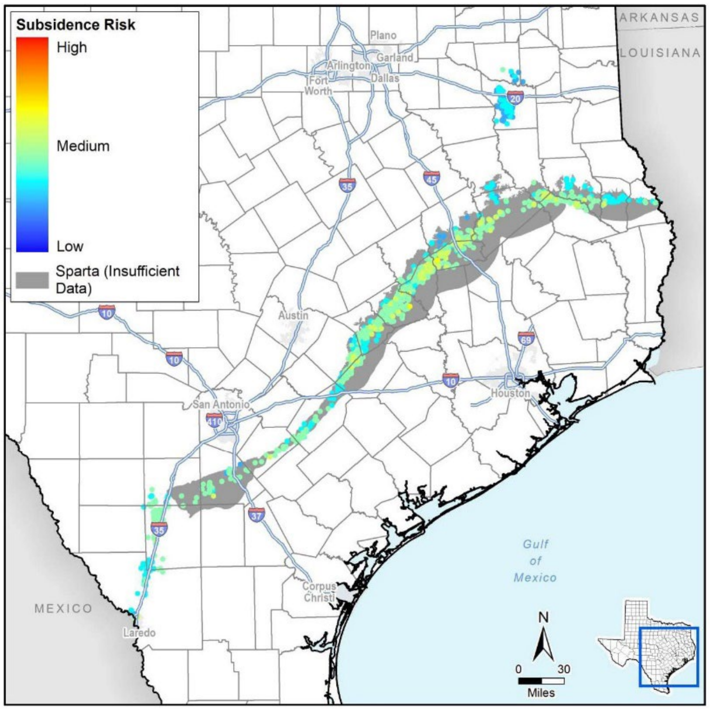

Figure 2-57. Sparta Aquifer subsidence risk vulnerability at well locations; from Furnans and others (2017).

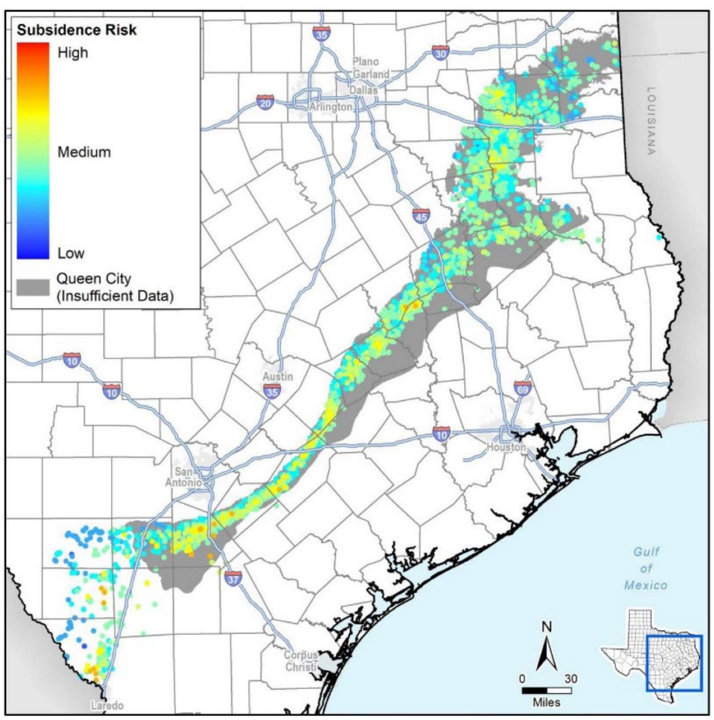

Figure 2-58. Queen City Aquifer subsidence risk vulnerability at well locations; from Furnans and others (2017).

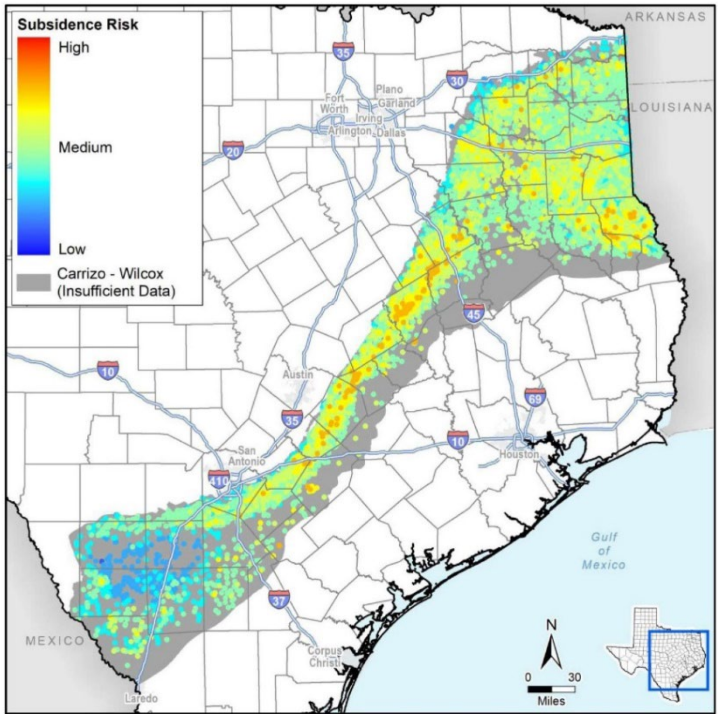

Figure 2-59. Carrizo-Wilcox Aquifer subsidence risk vulnerability at well locations; from Furnans and others (2017).

2.7 Aquifer Discharge

Aquifer discharge refers to the groundwater exiting a groundwater system. Groundwater discharge mechanisms in the southern portion of the Carrizo-Wilcox, Queen City, and Sparta 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 about 9 percent of recharge in the study area and groundwater discharge to streams consumes about 84 percent of recharge; these discharges are components of rejected recharge. The following sections describe the components of groundwater discharge that occur in the study area.

2.7.1 *Groundwater Withdrawals by Pumping*

Groundwater pumping data were compiled for this study primarily from TWDB records of pumping estimates and are summarized herein. These data will be processed and spatially allocated or distributed for the groundwater flow model. Implementation of groundwater pumping in the groundwater model will be discussed in subsequent chapters of this report once model calibration is complete.

Groundwater pumping estimates from annual TWDB water use surveys were obtained for the years 1980 through 2017 for counties in Texas within the study area (TWDB, 2020c) except for the time period of 1981 through 1983 where data were not available. For counties that are located partially outside the study area, annual pumping estimates for the entire county are reported. Data for the years 1981 through 1983 were estimated by linear interpolation of the available water use estimates. 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.

Estimated annual pumping by primary aquifer source from 1980 to 2017 for the study area is shown on Figure 2-60. The primary aquifers summarized in these datasets include the Sparta, Queen City, Carrizo-Wilcox, and “Other” aquifers. “Other Aquifer” estimates included in this study comprises data from six counties in the study area that are located west of Frio River, where pumping estimates for the Queen City and Sparta aquifers are not classified by the historical TWDB dataset. In the area west of Frio River, the Sparta and Queen City aquifers have been historically recognized as their geological equivalents: the Laredo Formation and El Pico Clay, respectively. According to TWDB, pumping estimates categorized as “Other Aquifer” may include data from wells completed in alluvium and in any other units shallower than the Carrizo Formation but deeper than the Yegua-Jackson aquifer. At least a portion of the reported pumping from this aquifer designation is assumed to include pumping from the continuation of the Sparta and Queen City model layers in this region of the study area. The six counties include Dimmit, Frio, LaSalle, McMullen, Webb, and Zavala. Data for “Other Aquifer” were not included for Maverick and Uvalde counties since only a small portion of those counties intersect the model boundary and the areas are outside of the extents of the Queen City and Sparta aquifers.

TWDB water use estimates indicate that total annual groundwater pumping from all included aquifers has varied in some years but has generally decreased slightly since 1980 (Figure 2-61). Total annual groundwater withdrawals average about 290,000 AF and range from approximately 192,000 AF in 2007 to approximately 362,000 AF in 2011. The peak in 2011 directly correlated with a large increase in estimates for irrigation water use in Frio county as well as general increases in irrigation and municipal water use in the most actively pumped counties in the study area. A similar spike in 2002 directly correlated with an abnormally large increase in irrigation water use specifically in Zavala county. For the most recent year considered for this study, 2017, pumping is estimated to be approximately 300,000 AF, which is an increase from the previous two years but follows a generally declining trend since 2011.

Average annual pumping is summarized by aquifer source, time period, and percent of total pumping in Table 2-6. 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 2-60). About 96 percent of pumping in the model domain from 1980 to 2017 has occurred from the Carrizo-Wilcox Aquifer, which includes the Carrizo-upper Wilcox, middle Wilcox, and lower Wilcox intervals. The Sparta and Queen City aquifers are relatively minor sources of total groundwater supply across the study area but are important sources of groundwater in some areas. Annual groundwater withdrawal estimates for the Sparta, Queen City, and “Other” aquifers have generally increased since the year 2000. Although “Other Aquifer” estimates account for a relatively small portion of total pumping, it is uncertain if this increase could be a result of changes in reporting by TWDB rather than actual pumping. There is an apparent shift in the estimated pumping values for "Other Aquifer" in Zavala county where there were no estimates prior to 2000 and an average of about 5,000 acre-feet per year reported from 2000 through 2017. About 85 percent of all pumping from the "Other Aquifer" category within the model domain was reported from Zavala County in the years 2000 to 2017. Annual pumping estimates for individual counties are summarized by aquifer source in charts in Appendix A.

Table 2-6. Summary of annual water use by aquifer.

	ESTIMATED ANNUAL PUMPING IN ACRE FEET					
Aquifer Source	**Average 1980-1999**	**Percent of Total 1980-1999**	**Average 2000-2017**	**Percent of Total 2000-2017**	**Average 1980-2017**	**Percent of Total 1980-2017**
Sparta Aquifer	2,640	0.9%	6,444	2.3%	4,442	1.5%
Queen City Aquifer	3,084	1.0%	6,754	2.4%	4,822	1.7%
Carrizo-Wilcox Aquifer	288,321	98.0%	266,001	93.2%	277,748	95.8%
Other Aquifer	253	0.1%	6,004	2.1%	2,977	1.0%

Estimated annual pumping by water use sector from 1980 to 2017 for the study area is shown on Figure 2-61. Annual pumping is summarized by water use and aquifer source in Table 2-7. Groundwater withdrawals during this time period occurred largely for irrigation uses and, to a lesser degree, municipal and rural domestic water supply. With the exception of abnormally high years in 2002 and 2011, groundwater withdrawals for irrigation water use have generally decreased through time from approximately 287,000 AF or 85 percent of total withdrawals in 1980 to approximately 154,000 AF or about 52 percent of total withdrawals in 2017. Pumping for municipal use has increased from about 25,000 AF or 7 percent of total pumping in 1980 to approximately 91,000 AF or 30 percent of total pumping in 2017. Withdrawals for rural domestic use are estimated to have increased from about 4 percent of total pumping in 1980 to about 11 percent in 2017. Manufacturing withdrawals have been relatively stable accounting for a small portion of total withdrawals averaging less than 1 percent since 1980. Mining withdrawals also have historically accounted for a small portion of total withdrawals, but significantly decreased after 1999 according to TWDB estimates. Steam-electric generation and livestock withdrawals have slightly increased over time but still accounted for an average of less than 5 percent each of total withdrawals in the study area since 1980.

Estimated annual pumping is summarized by county and water use sector in Appendix B. Annual pumping is summarized by county and average percent of total pumping in Table 2-8. Based on the TWDB water use surveys, the majority of groundwater pumping from the Queen City, Sparta, and Carrizo-Wilcox aquifers has historically occurred in Atascosa, Frio, and Zavala counties. On average, those three counties have combined for over 70 percent of total withdrawals in the study area since 1980. In more recent years, Gonzales county has accounted for an increasing percentage of total pumping in the study area, while pumping has generally decreased in Atascosa, Frio, and Zavala counties.

Groundwater use in Gonzales county has been predominantly for municipal growth beginning in 2011. Annual pumping estimates for individual counties are summarized by aquifer source in charts in Appendix A.

Domestic pumping estimates were not available from TWDB. Data were compiled from various sources to estimate rural domestic groundwater withdrawals from 1980 through 2017. For the period of 1980 through 1999, historical domestic pumping values for the Carrizo-Wilcox aquifer were extracted from the previous Southern Carrizo-Wilcox groundwater availability model dataset (Deeds and others, 2003). In that study, data from previously available TWDB rural domestic pumping that were not aquifer specific, were processed to include estimates for the years 1981 to 1983 and 1997 to 1999 using linear regression methods, then spatially and vertically distributed to individual model grid cells using census block data and interpolated well depths (Deeds and others, 2003). Historical domestic pumping values for the Queen City and Sparta aquifers for 1980 through 1999 were extracted from the previous Queen City and Sparta groundwater availability model update dataset (Kelley and others, 2004). In that study, data that were not aquifer specific were similarly processed to interpolate for missing years in the previously available TWDB records, then spatially and vertically distributed to individual model grid cells using census block data and aquifer allocation ratios based on the previous groundwater availability model and measured head levels in rural domestic wells in the TWDB database (Kelley and others, 2004). Groundwater withdrawals for the years 2000 through 2017, were estimated based on population density from 2000 and 2010 census block data and a water use assumption of 140 gallons per day (1.2 AF/year) per capita. The per capita water use rate is based on reported domestic water use estimates from the 2016 South Central Texas Regional Water Plan for Region L (South Central Texas Regional Water Planning Group and others, 2015). Census blocks for 1980 and 1990, obtained from the United States Census Bureau (2020), are shown on Figure 2-62, overlain by extents of urban areas which were omitted from this analysis. Withdrawal estimates distributed by county and basin were then vertically assigned to an aquifer based on the vertical allocation factors defined by the previous groundwater availability model.

Distribution of groundwater use from each aquifer are shown through time on Figures 2-63 through 2-66. The time periods coincide with the water level contour maps shown on Figures 2-21 through 2-23. The source for the majority of groundwater pumped from in the study area is the Carrizo-Wilcox Aquifer, particularly in Zavala, Frio, Atascosa, and Wilson counties. Estimated pumping for the Carrizo-Wilcox will be distributed vertically to the Carrizo-upper Wilcox, middle Wilcox, and lower Wilcox intervals based on the vertical allocations defined by the previous groundwater availability model. Vertical distributions could be adjusted during model calibration for consistency with water level trends. This section will be updated to incorporate any adjustments to pumping volumes and distributions after completion of model calibration.

Data requests for groundwater pumping information were submitted to the Groundwater Conservation Districts in the study area. As of this report date, pumping data were obtained from one district (Plum Creek). Annual groundwater pumping for this district is summarized in Table 2-9.

Table 2-7. Annual estimated groundwater pumping by water use sector and aquifer source.

Aquifer Source	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999
Municipal																				
Sparta Aquifer	23,980	25,433	26,894	28,354	29,807	24,141	26,386	27,696	31,164	32,576	30,214	29,843	28,120	31,507	31,481	32,298	36,483	33,949	36,535	37,556
Queen City Aquifer	296	308	319	331	343	3,443	170	200	182	207	350	384	365	340	334	304	296	228	237	240
Carrizo-Wilcox Aquifer	431	414	396	380	363	404	347	395	416	453	474	447	430	464	457	515	530	507	640	541
Other Aquifer	37	35	32	30	28	45	40	21	9	43	60	183	78	304	23	325	256	296	375	275
Manufacturing																				
Sparta Aquifer	1,354	1,638	1,923	2,207	2,491	1,361	1,921	1,773	2,474	1,516	1,540	1,755	2,053	1,208	1,033	1,088	943	860	837	1,455
Queen City Aquifer	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	0	0	0
Carrizo-Wilcox Aquifer	0	0	1	2	2	2	2	0	0	0	0	0	0	0	0	0	0	108	43	43
Other Aquifer	52	42	33	24	14	11	10	0	8	4	2	0	0	11	9	14	0	12	1	19
Mining																				
Sparta Aquifer	4,309	3,902	3,497	3,091	2,684	4,148	1,680	3,751	3,875	2,718	2,802	4,028	4,011	4,034	3,831	3,903	3,904	3,748	3,476	3,700
Queen City Aquifer	0	1	2	4	5	5	0	6	6	6	6	14	8	8	8	8	8	8	8	7
Carrizo-Wilcox Aquifer	0	1	2	4	5	4	0	4	5	5	5	7	7	7	7	7	7	7	7	6
Other Aquifer	85	75	65	55	45	20	0	30	41	44	44	53	46	46	26	31	31	25	17	25
Electric Power																				
Sparta Aquifer	682	2,047	3,411	4,776	6,140	4,239	5,623	5,718	7,146	5,539	6,037	6,688	6,037	6,585	6,331	6,172	6,075	6,964	7,343	6,973
Queen City Aquifer	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Carrizo-Wilcox Aquifer	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Other Aquifer	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Irrigation																				
Sparta Aquifer	277,648	276,660	275,673	274,686	273,698	208,317	173,148	145,368	223,103	265,484	237,405	239,196	214,624	214,685	233,512	233,666	232,193	168,805	224,450	190,550
Queen City Aquifer	5,204	4,305	3,406	2,510	1,611	1,129	1,552	1,210	1,592	2,012	1,794	1,813	1,538	1,767	880	958	1,003	751	1,105	888
Carrizo-Wilcox Aquifer	3,831	3,167	2,504	1,842	1,178	130	114	113	122	247	263	248	306	245	965	869	1,250	826	666	626
Other Aquifer	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Livestock																				
Sparta Aquifer	4,248	3,804	3,360	2,915	2,471	2,221	2,149	2,359	2,296	2,269	2,316	2,350	2,252	2,303	2,489	2,439	2,341	2,084	1,837	2,010
Queen City Aquifer	855	704	554	404	253	248	243	243	240	240	249	254	289	305	287	290	246	238	256	278
Carrizo-Wilcox Aquifer	382	318	252	186	122	120	121	121	118	119	123	126	143	145	127	128	106	107	113	123
Other Aquifer	91	88	84	81	78	79	85	87	91	89	88	90	48	42	54	57	78	51	69	72
Domestic																				
Sparta Aquifer	12,167	13,613	14,137	15,009	16,195	15,612	15,833	16,318	16,821	17,492	16,211	16,443	16,026	16,896	15,888	16,427	16,353	15,402	16,172	16,547
Queen City Aquifer	324	345	356	371	393	393	399	408	421	452	468	471	467	485	504	519	532	541	551	572
Carrizo-Wilcox Aquifer	761	806	831	859	903	902	901	918	950	1,053	1,090	1,098	1,091	1,137	1,172	1,218	1,250	1,281	1,312	1,351
Other Aquifer	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
TOTAL																				
Sparta Aquifer	324,388	327,097	328,895	331,038	333,486	260,039	226,740	202,983	286,879	327,594	296,525	300,303	273,123	277,218	294,565	295,993	298,292	231,812	290,650	258,791
Queen City Aquifer	6,679	5,663	4,637	3,620	2,605	5,218	2,364	2,067	2,441	2,917	2,867	2,936	2,667	2,905	2,013	2,079	2,089	1,766	2,157	1,985
Carrizo-Wilcox Aquifer	5,405	4,706	3,986	3,273	2,573	1,562	1,485	1,551	1,611	1,877	1,955	1,926	1,977	1,998	2,728	2,737	3,143	2,836	2,781	2,690
Other Aquifer	265	240	214	190	165	155	135	138	149	180	194	326	172	403	112	427	365	384	462	391

Aquifer Source	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
Municipal																		
Sparta Aquifer	39,707	36,855	37,043	36,477	35,094	37,055	41,594	31,672	39,045	46,897	31,393	53,716	51,350	63,505	79,105	90,042	76,511	88,771
Queen City Aquifer	47	49	50	52	21	26	1,000	186	206	282	700	864	797	1,846	1,570	1,546	1,466	1,562
Carrizo-Wilcox Aquifer	475	476	480	506	516	576	651	860	1,156	815	917	1,281	1,232	850	949	943	959	834
Other Aquifer	107	115	110	115	114	126	293	245	271	228	251	348	497	423	242	218	206	196
Manufacturing																		
Sparta Aquifer	971	798	1,451	958	1,009	1,134	1,171	771	639	1,656	1,188	1,235	1,032	1,112	1,089	1,215	1,222	1,155
Queen City Aquifer	0	0	0	0	0	0	0	0	0	293	238	418	317	302	306	336	339	335
Carrizo-Wilcox Aquifer	705	861	836	787	826	792	877	780	802	0	7	7	0	0	0	0	0	0
Other Aquifer	19	16	16	16	16	22	11	9	8	0	0	0	0	0	0	0	0	0
Mining																		
Sparta Aquifer	660	515	407	425	2,330	737	360	584	538	514	322	332	431	415	391	410	547	679
Queen City Aquifer	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Carrizo-Wilcox Aquifer	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Other Aquifer	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Electric Power																		
Sparta Aquifer	7,706	7,583	7,580	7,551	7,425	7,516	8,410	3,937	6,637	8,048	7,247	8,078	8,491	8,022	9,238	9,051	8,348	13,085
Queen City Aquifer	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Carrizo-Wilcox Aquifer	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Other Aquifer	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Irrigation																		
Sparta Aquifer	210,761	200,949	266,918	160,719	178,322	183,630	172,293	112,400	162,556	186,613	156,246	235,439	176,516	179,465	170,604	127,584	130,932	144,457
Queen City Aquifer	3,998	3,210	3,219	2,690	3,664	3,981	4,197	2,410	4,177	4,336	4,983	6,434	4,280	4,631	4,789	3,635	3,504	4,293
Carrizo-Wilcox Aquifer	2,330	1,953	2,302	1,881	1,923	2,000	2,270	1,331	1,866	2,178	1,850	3,269	2,432	2,309	1,915	1,240	1,499	1,836
Other Aquifer	4,472	5,095	13,379	5,127	6,465	6,609	5,459	4,243	3,321	5,484	4,814	7,075	5,736	5,298	5,356	3,800	3,955	4,354
Livestock																		
Sparta Aquifer	1,620	1,732	1,237	1,229	1,200	5,149	5,405	5,004	5,493	5,608	8,045	8,164	6,363	6,398	6,560	6,761	6,968	4,600
Queen City Aquifer	320	416	278	282	186	1,060	1,018	1,011	950	970	1,677	1,684	1,333	1,362	1,392	1,436	1,475	921
Carrizo-Wilcox Aquifer	140	140	127	129	150	771	784	729	741	746	1,260	1,266	1,018	1,010	1,019	1,046	1,072	636
Other Aquifer	107	56	70	65	70	268	315	273	294	342	269	277	231	224	237	237	245	217
Domestic																		
Sparta Aquifer	22,363	22,363	22,363	22,363	22,363	22,363	22,363	22,363	22,363	22,363	28,784	28,784	28,784	28,784	28,784	28,784	28,784	28,784
Queen City Aquifer	799	799	799	799	799	799	799	799	799	799	1,028	1,028	1,028	1,028	1,028	1,028	1,028	1,028
Carrizo-Wilcox Aquifer	2,217	2,217	2,217	2,217	2,217	2,217	2,217	2,217	2,217	2,217	2,863	2,863	2,863	2,863	2,863	2,863	2,863	2,863
Other Aquifer	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
TOTAL																		
Sparta Aquifer	283,788	270,795	336,999	229,722	247,743	257,584	251,596	176,731	237,271	271,699	233,225	335,748	272,967	287,701	295,771	263,847	253,312	281,531
Queen City Aquifer	5,164	4,474	4,346	3,823	4,670	5,866	7,014	4,406	6,132	6,680	8,626	10,428	7,755	9,169	9,085	7,981	7,812	8,139
Carrizo-Wilcox Aquifer	5,867	5,647	5,962	5,520	5,632	6,356	6,799	5,917	6,782	5,956	6,897	8,686	7,545	7,032	6,746	6,092	6,393	6,169
Other Aquifer	4,705	5,282	13,575	5,323	6,665	7,025	6,078	4,770	3,894	6,054	5,334	7,700	6,464	5,945	5,835	4,255	4,406	4,767

Units in acre-feet
Source: Texas Water Development Board water use surveys (TWDB, 2020b).

Table 2-8. Summary of groundwater pumping by county.

Estimated Groundwater Pumping, in acre-feet				
County	**Average 1980-2017**	**Average Percent of Total 1980-2017**	**Total in 2017**	**Percent of Total in 2017**
Atascosa	52,225	18.0%	41,876	13.9%
Bastrop	12,058	4.2%	25,488	8.5%
Bexar	9,739	3.4%	11,154	3.7%
Caldwell	3,812	1.3%	6,389	2.1%
Dimmit	10,875	3.8%	5,207	1.7%
Fayette	345	0.1%	847	0.3%
Frio	85,007	29.3%	68,448	22.8%
Gonzales	11,782	4.1%	50,021	16.6%
Guadalupe	3,741	1.3%	6,910	2.3%
Karnes	1,103	0.4%	1,721	0.6%
La Salle	7,195	2.5%	6,128	2.0%
Maverick	855	0.3%	340	0.1%
McMullen	602	0.2%	474	0.2%
Medina	8,290	2.9%	8,733	2.9%
Uvalde	479	0.2%	181	0.1%
Webb	1,134	0.4%	1,056	0.4%
Wilson	19,421	6.7%	25,985	8.6%
Zavala	61,328	21.1%	39,649	13.2%
Total	**289,990**	**100.0%**	**300,606**	**100.0%**

Table 2-9. Annual reported groundwater pumping by groundwater conservation districts in study area.

Groundwater Conservation District	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Plum Creek	566	601	549	913	1,169	682	1,185	1,717	1,524	1,705	1,684	1,495	1,563	1,707	1,416

Units in acre-feet
Source: Plum Creek Groundwater Conservation District; other districts either did not respond to requests for pumping data or did not have data to provide.

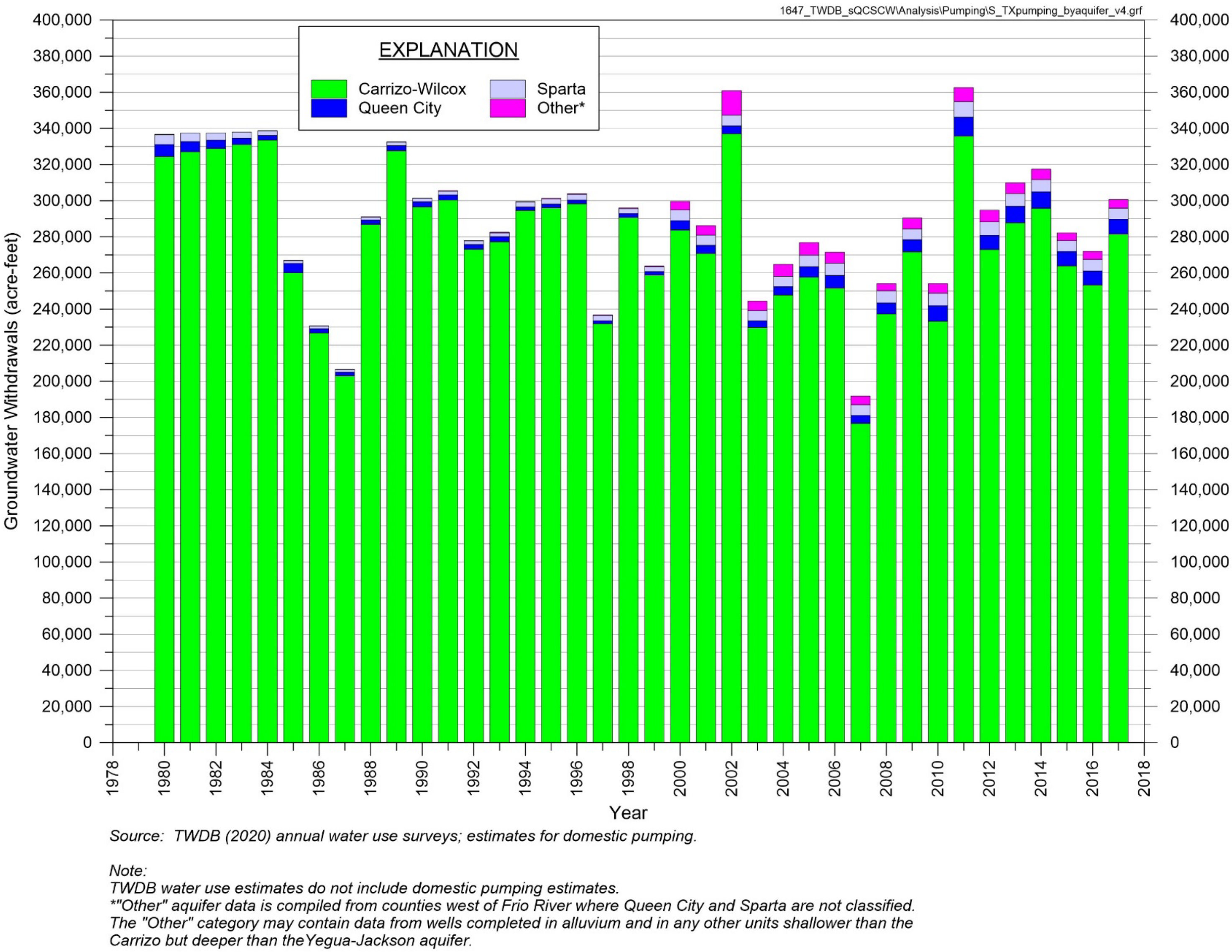

Figure 2-60. Estimated annual groundwater pumping by aquifer source in counties in study area: 1980 through 2017.

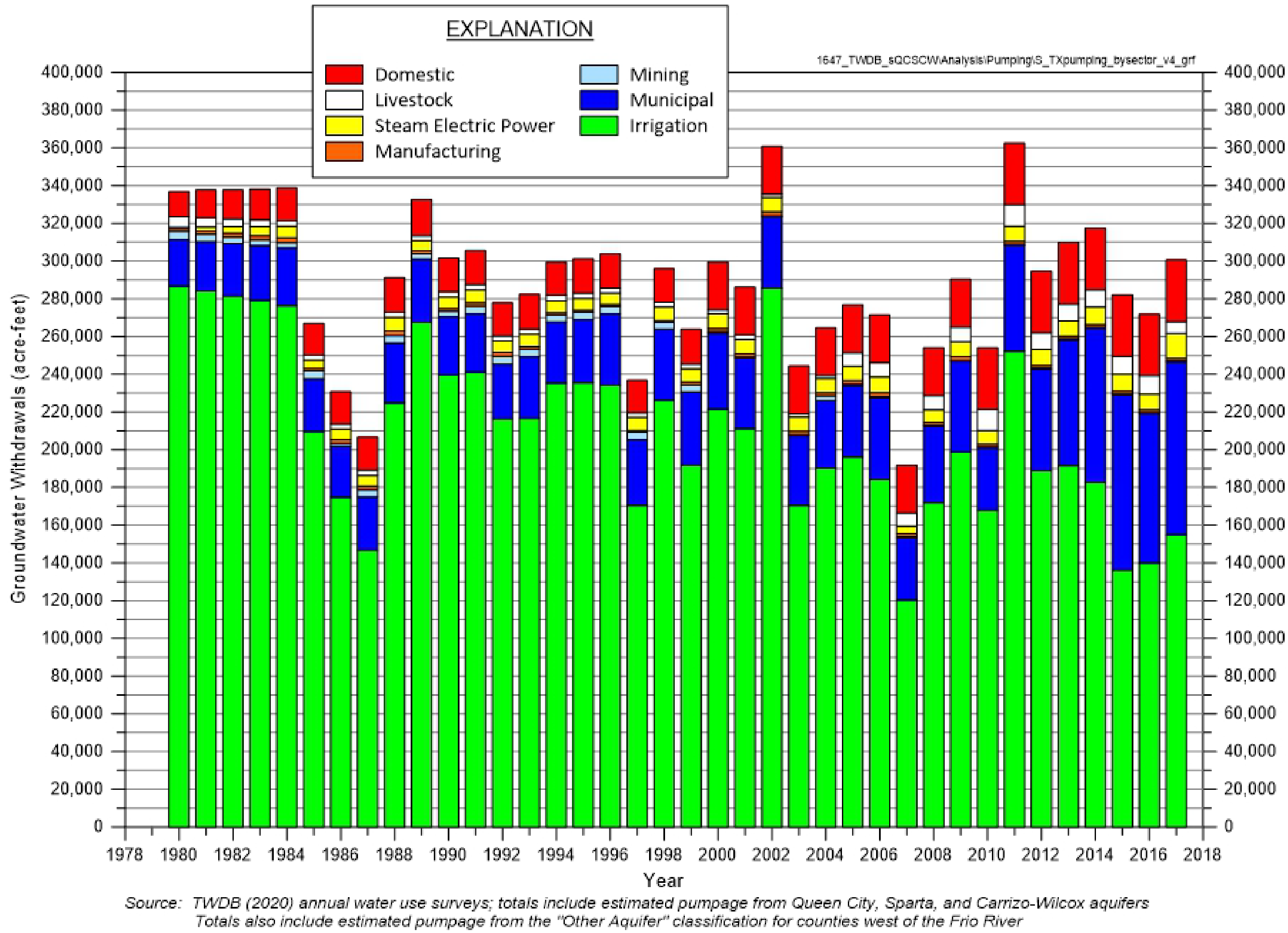

Figure 2-61. Estimated annual groundwater pumping by water use sector in counties in study area: 1980 through 2017.

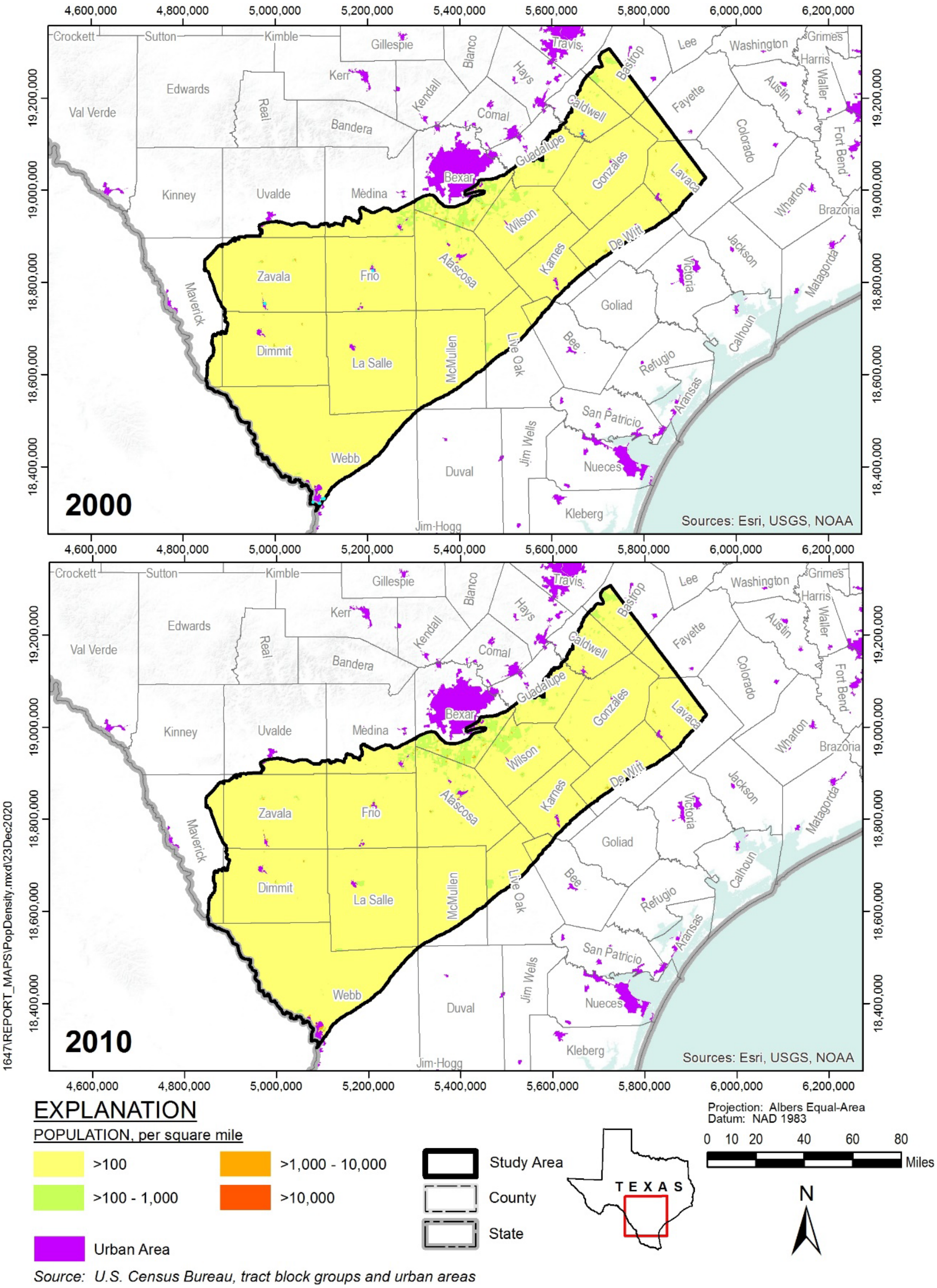

Figure 2-62. Census blocks for 2000 and 2010.

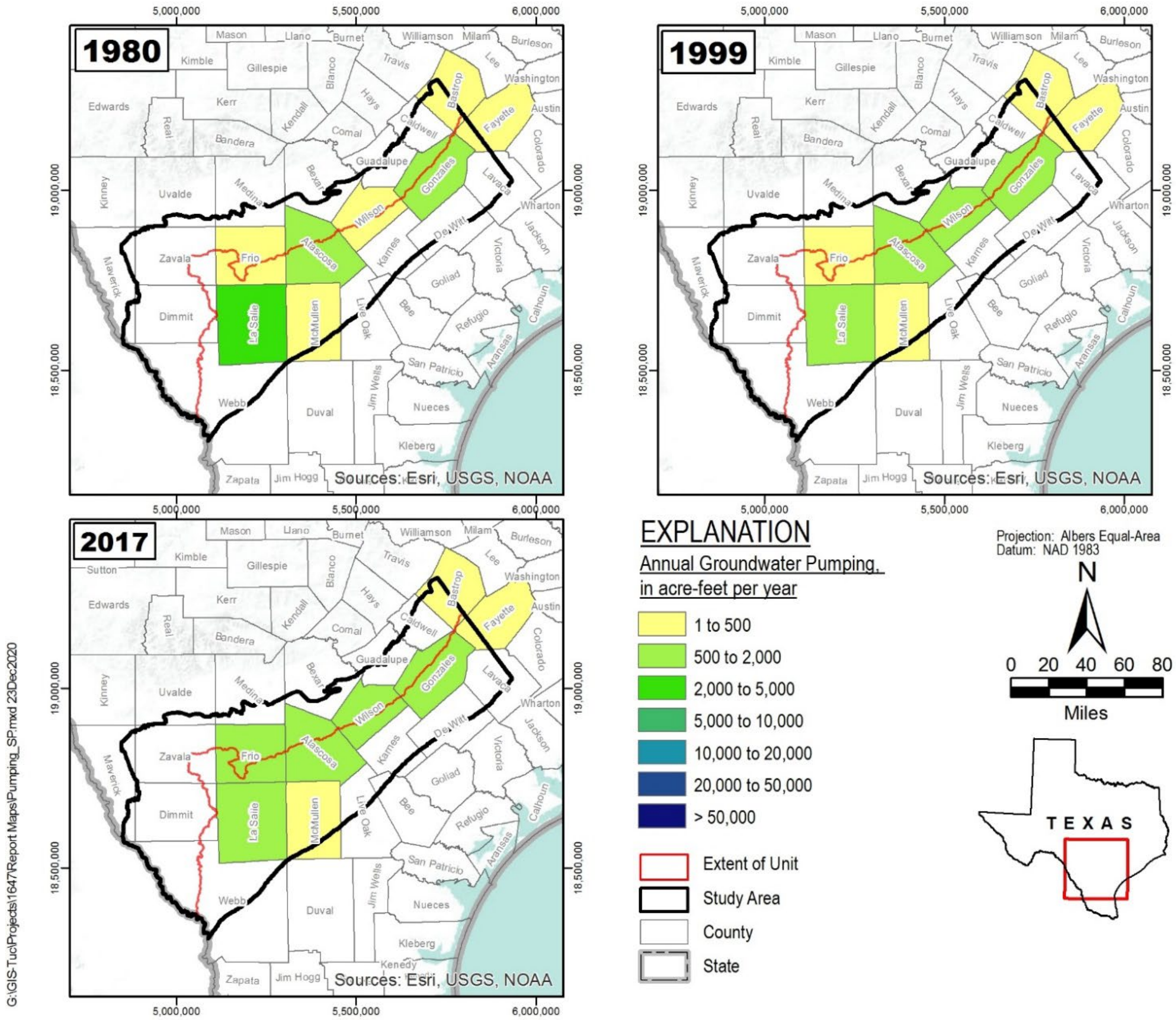

Figure 2-63. Distribution of groundwater pumping from the Sparta Aquifer.

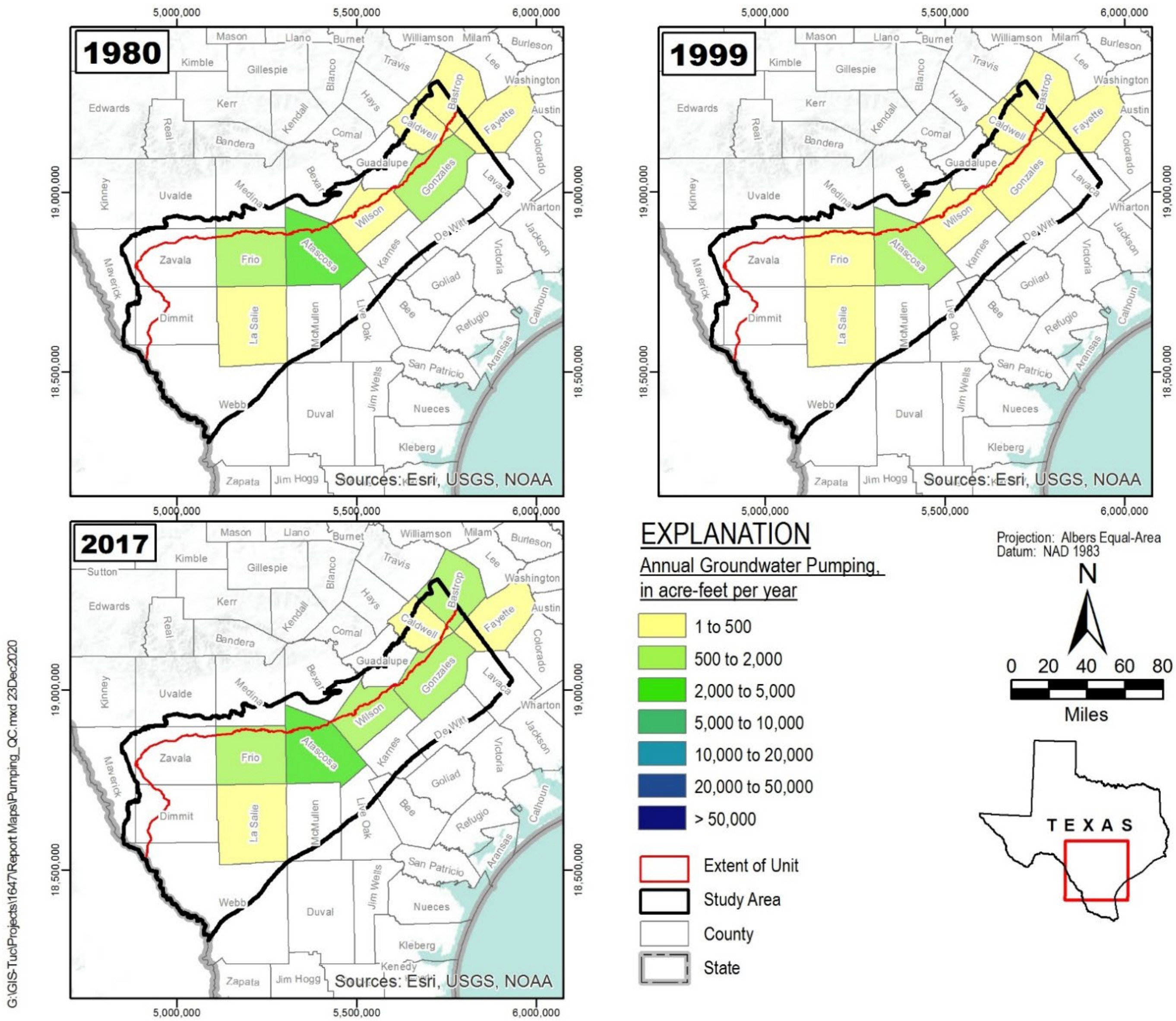

Figure 2-64. Distribution of groundwater pumping from the Queen City Aquifer.

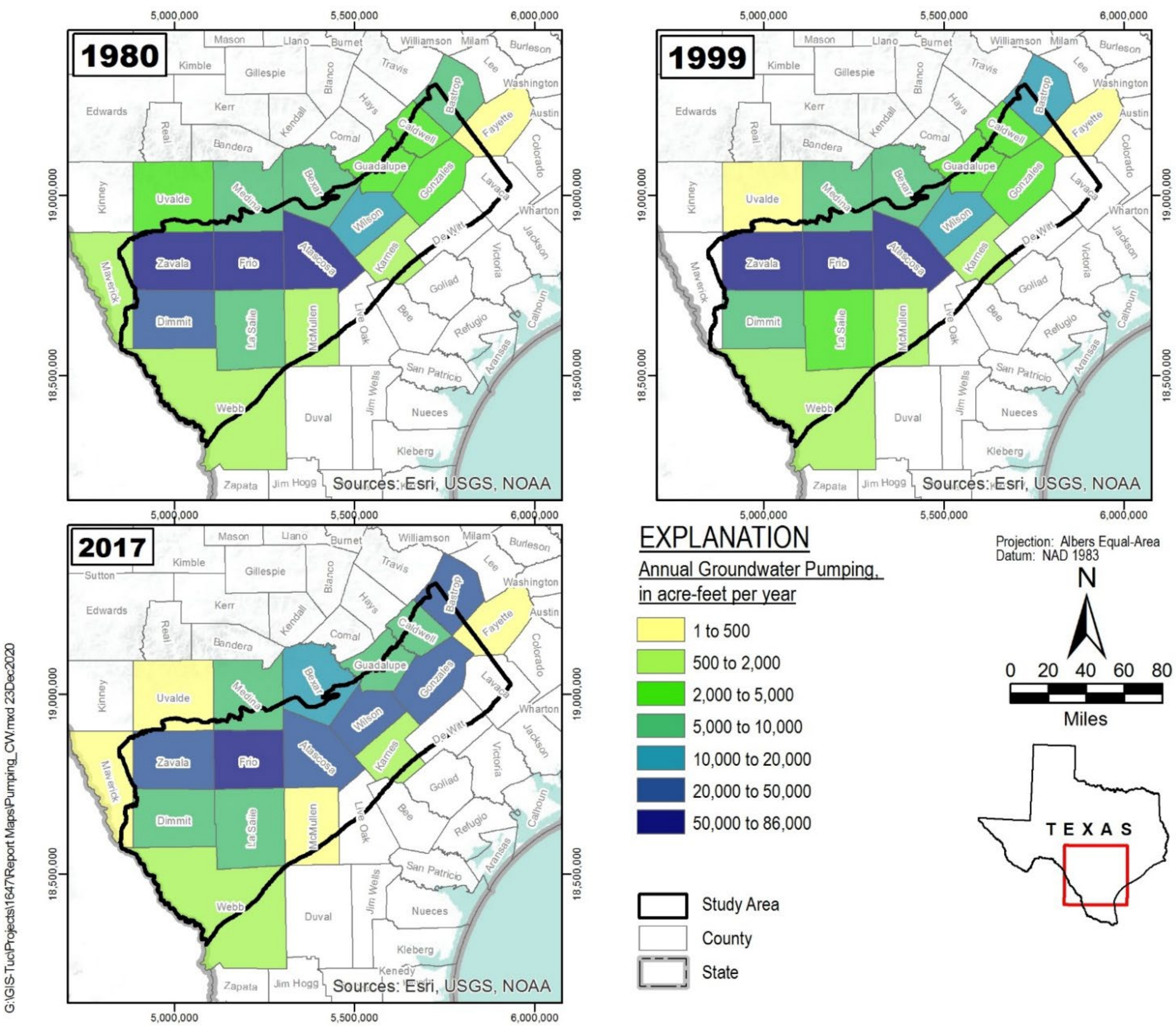

Figure 2-65. Distribution of groundwater pumping from the Carrizo-Wilcox Aquifer.

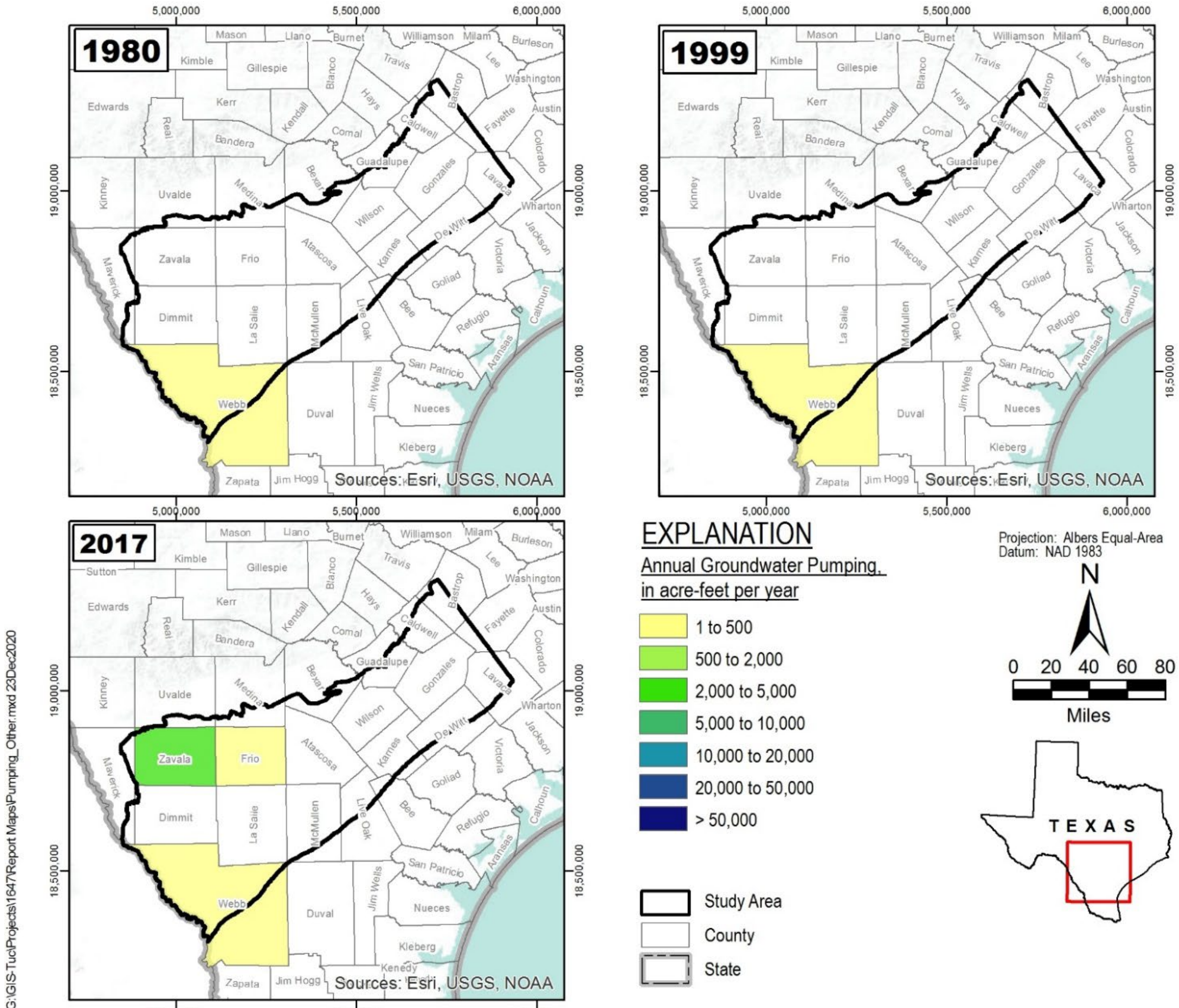

Figure 2-66. Distribution of groundwater pumping from the "Other" Aquifer.

2.7.2 *Discharge to Rivers and Springs*

Base streamflow is the contribution of groundwater to gaining reaches along a stream. The differences in streamflows measured at gages along unregulated river reaches indicate that most major rivers in the study area have gaining streamflow conditions, as previously summarized in Section 2.4.1 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 (Deeds and others, 2003). Locations of springs in the area are shown on Figure 2-34. Deeds and others (2003) conducted a literature survey of springs in the study area. For this study, the springs dataset was updated with spring features listed in the United States Geological Survey (2020b) National Hydrography Dataset. Information from 13 springs was compiled from these sources. There are a limited number of springs in the study area because of drier climate and most wells that were previously flowing are only intermittent to date (Deeds and others, 2003). Declining spring flow in the area is attributed to pumping and free-flowing wells in the counties around these springs (Brune, 1975). Deeds and others (2003) summarized flow rates ranging from a low of 0.01 cubic feet per second (feet^3/second) (7 AF/year) to a high of 1.6 feet^3/second (1,158 AF/year) measured at Martinez Springs in Bexar County; a higher flow rate was observed at Mitchell Lake Springs but was attributed reservoir leakage and was discarded as unrepresentative of natural springs in the area. According to the prior literature survey, there are no significant springs flowing in the model area that are not coincident with stream reaches (Deeds and others, 2003).

2.7.3 *Evapotranspiration*

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

Limited information exists regarding groundwater use by native vegetation and crops within the study area. Vegetation present in the Texas portions of the study area includes mesquite and oak woodlands and grasslands (Figure 1-12). These tree types have deep root depths and might be sustained in part by groundwater consumption.

The Unites States Geological Survey's Gap Analysis Project (USGS, 2011) land cover dataset was obtained for a continuous and consistent coverage of vegetation and land cover. The Unites States Geological Survey's Gap Analysis Project land cover dataset for the study area is shown on Figure 2-67. Although the United States Geological Survey dataset lacks the details vegetation species provided by the Texas vegetation dataset, it can be useful for understanding the complex distributions of vegetation across the entire study area.

Potential evapotranspiration was simulated in the previous Groundwater Availability Model developed by Kelley and others (2004) for the southern portions of the Queen City and Sparta aquifers. For that Groundwater Availability Model, the United States Department of Agriculture's Soil Water Assessment Tool was used to estimate groundwater evapotranspiration and evapotranspiration extinction depth. The United States Department of Agriculture's Soil Water Assessment Tool was used because it is a physically based method for estimating regional components of a groundwater system. Potential evapotranspiration is converted to actual evapotranspiration based on vegetation type and model-calculated soil water availability, using user-specified climate and vegetation information. For each stress period of the previous groundwater availability model, the United States Department of Agriculture's Soil Water Assessment Tool was used to calculate max evapotranspiration rate and evapotranspiration extinction depth for every model grid cell. The average maximum evapotranspiration rate for each evapotranspiration cell in the previous groundwater availability model is shown on Figure 2-68. Note that evapotranspiration was not simulated south of the interface between the Sparta Sand and overlying younger units which are not a part of this study. Maximum evapotranspiration rates specified in the model range from less than 0.5 inch per year to 20 inches per year. Evapotranspiration rates are generally small in the northern and southern portions of the study area. The largest evapotranspiration rates occur in the central portions of the study area. Evapotranspiration extinction depths were also estimated for each grid cell and remained constant through the simulation period. Extinction depths ranged from less than 1 foot to 7.2 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).

2.7.4 *Cross-Formational Flows*

Groundwater discharge also occurs as cross-formational groundwater flows from one aquifer unit to an adjacent unit and is a natural mechanism for aquifer discharge from the aquifers in this study. Previous studies have determined that the hydraulic head in the Carrizo-Wilcox Aquifer are higher than hydraulic heads in the overlying younger strata such as the Reklaw (Deeds and others, 2003; Harris, 1965; Kreitler, 1979). This is consistent with the findings of this analysis for the model update. Groundwater flow across the Reklaw Formation, which is a confining unit, is generally upward from the Carrizo-Wilcox Aquifer to the Queen City Aquifer (Deeds and others, 2003). A groundwater chemistry study by Hamlin (1988) also supports the upward flow from the Carrizo Sands to overlying sands. Deeds and others (2003) also determined that the upward gradient in groundwater movement continues between the Queen City aquifer and the regional water table in the confined, down-dip portions. Cross-formational groundwater flows are not directly measurable and are generally better estimated by groundwater modeling studies such as this groundwater availability model update.

The natural balance between aquifer recharge and cross-formational flow has changed over time due to the development of the aquifer system. In some areas with extensive groundwater pumping, hydraulic gradients have reversed between the Carrizo-Wilcox and overlying units. This reversal creates a potential for cross-formation flows from younger units into the underlying Carrizo aquifer interval (Deeds and others, 2003; Hamlin, 1988; Klemt and others, 1976; Mason, 1960).

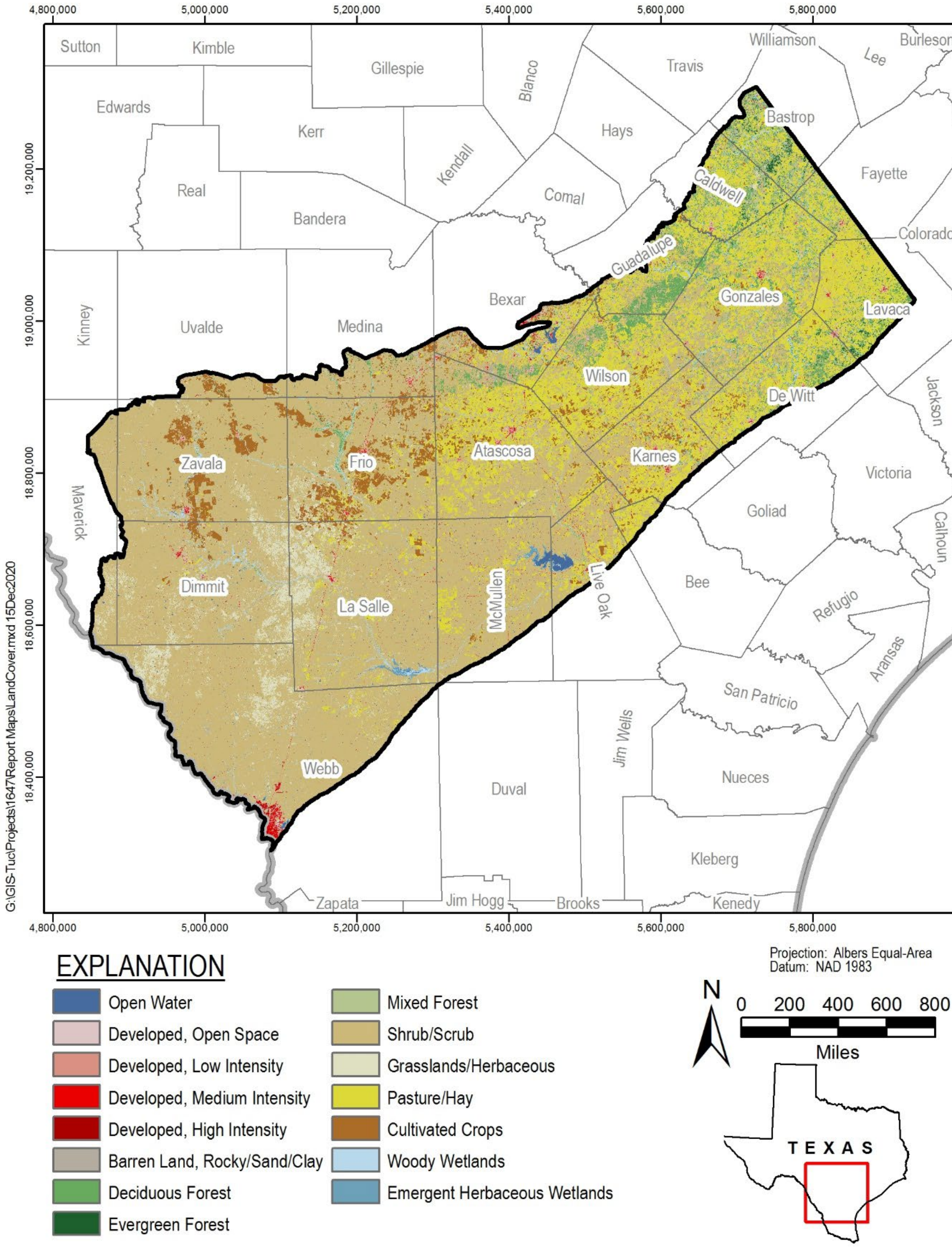

Figure 2-67. Land cover distribution in study area.

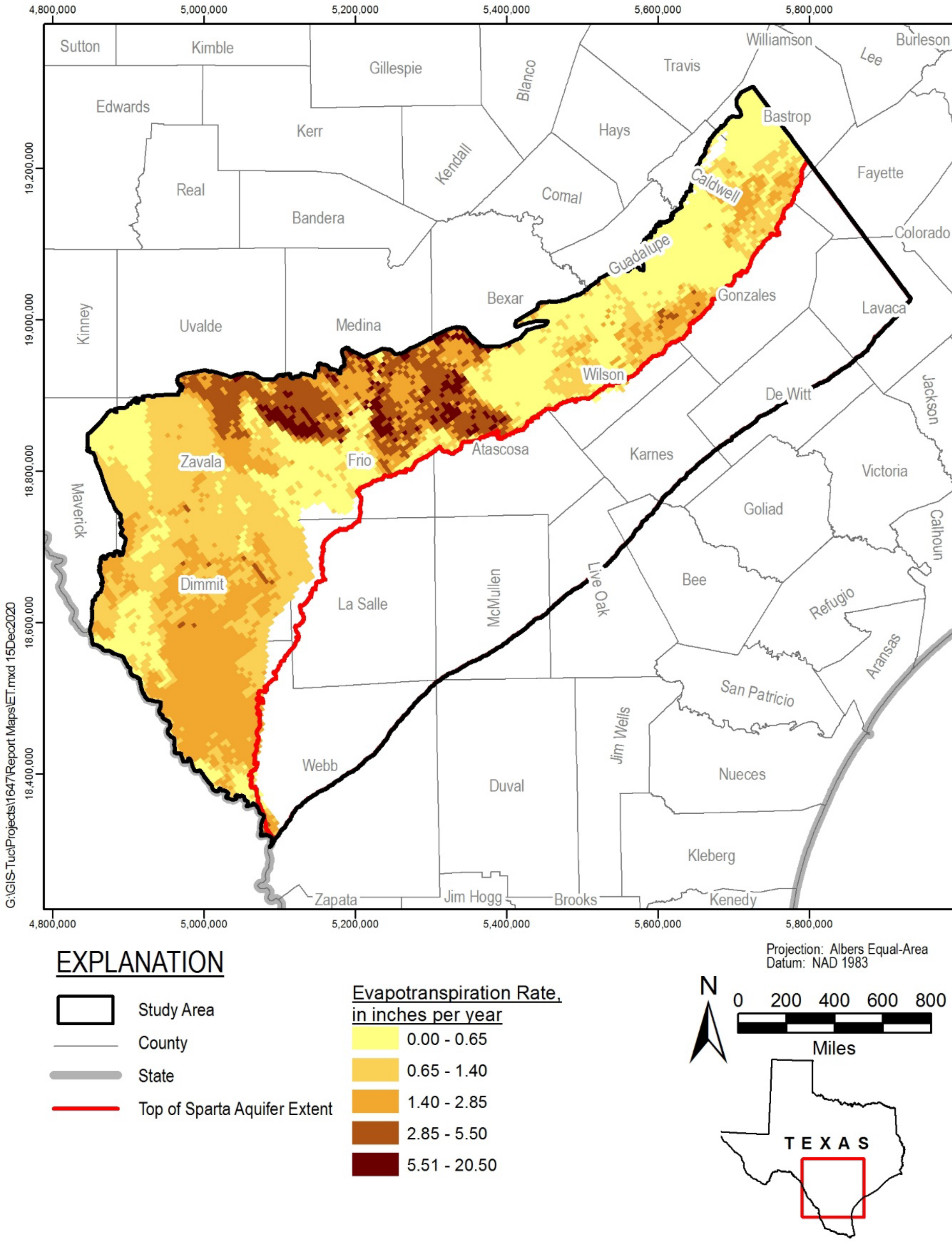

Figure 2-68. Average maximum evapotranspiration rate specified in the previous groundwater availability model by Kelley and others (2004).

2.8 Water Quality

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

2.8.1 *Data Sources*

In this report, groundwater quality data was compiled for wells within the model boundary from the TWDB (2019c) Groundwater Database and the Brackish Resources Aquifer Characterization System database water quality. General water quality was evaluated in terms of drinking, irrigation, and industrial water quality based on screening levels developed by Fryar and others (2003), using only samples taken since 2010. A more detailed analysis of the spatial and temporal distribution of total dissolved solids was performed to evaluate salinity in the study area.

A detailed characterization of salinity (represented as total dissolved solids) is not required for the current groundwater flow model. Recent studies by both the Brackish Resources Aquifer Characterization System group (Meyer and others, 2019, unpublished) and the Bureau of Economic Geology (Hamlin and others, 2019) conducted comprehensive analyses using geophysical well logs to calculate an interpreted total dissolved solids concentration across the entire depth range for each aquifer unit for their respective study areas. The study conducted by Hamlin and others (2019) covers a similar study area to the Groundwater Availability Model and the overall resulting net sand thickness distribution is relatively similar despite modest differences in the interpretation of the hydrostratigraphic framework contacts. Therefore, to provide some context to the changing salinity as evidenced by geophysical well logs, this report provides the salinity distribution maps from Hamlin and others (2019) for reference.

2.8.2 *Water Quality Evaluation Based on Water Use*

To evaluate drinking water quality, samples since 2010 were analyzed to find exceedances of any constituent with a United States Environmental Protection Agency designated primary or secondary maximum contaminant levels. Results for those constituents for which exceedances were found are summarized in Table 2-10. Since 2010, there have been primary maximum contaminant level exceedances in at least one well within the model boundary of arsenic, fluoride, selenium, and uranium, and secondary maximum contaminant level exceedances of aluminum, chloride, fluoride, iron, manganese, sulfate, and total dissolved solids. Constituents with the largest percentage of wells showing exceedances are iron (20 percent), manganese (16 percent), and total dissolved solids (26 percent).

For irrigation use, salinity hazard was evaluated based on specific conductance and sodium adsorption ratio. High or very high specific conductance was found in 33 percent of wells, and high or very high sodium adsorption ratio in 20 percent of wells. Boron, chloride, silica, and total dissolved solids 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 4 percent of wells, and hardness in 27 percent of wells.

Table 2-10. Summary of exceedances of water quality standards for selected constituents at wells in study area.

Constituent	Screening Level (mg/L)[a]	Type of Exceedance	Number of Wells Sampled Since 2010	Number of Wells with Exceedance Since 2010	Percent of Wells with Exceedance Since 2010
Arsenic	10	Primary MCL[b]	297	1	0.3%
Fluoride	4	Primary MCL	318	3	0.9%
Selenium	50	Primary MCL	297	7	2.4%
Uranium	30	Primary MCL	297	1	0.3%
Aluminum	200	Secondary MCL	297	1	0.3%
Chloride	250	Secondary MCL	356	30	8.4%
Fluoride	2	Secondary MCL	318	8	2.5%
Iron	300	Secondary MCL	317	65	20.5%
Manganese	50	Secondary MCL	292	47	16.1%
Sulfate	250	Secondary MCL	335	17	5.1%
Total Dissolved Solids	500	Secondary MCL	355	91	25.6%
Hardness	180	Industrial	335	91	27.2%
Silica	40	Industrial	297	10	3.4%
Boron	2,000	Irrigation	334	9	2.7%
Chloride	1,000	Irrigation	356	4	1.1%
Chloride	1,000	Irrigation	356	4	1.1%
Sodium Adsorption Ratio (High)	18	Irrigation	334	45	13.5%
Sodium Adsorption Ratio (Very High)	26	Irrigation	334	38	11.4%
Specific Conductance (High)	750	Irrigation	332	88	26.5%
Specific Conductance (Very High)	2,250	Irrigation	332	21	6.3%
Total Dissolved Solids	2,100	Irrigation	355	7	2.0%

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

2.8.3 *Water Quality Evaluation Based on Total Dissolved Solids Distribution*

Selected total dissolved solids hydrographs for each aquifer are also shown on Figure 2-69 through Figure 2-74**,** with wells selected based on data availability. Each well measurement was assigned to an aquifer using well construction information and the elevations of aquifers in the hydrostratigraphic framework. Due to lack of sampling frequency in many areas, temporal trends throughout several of the aquifer units could not be confidently established.

Figure 2-75 through Figure 2-79 provide the results from Hamlin and others (2019) of net sand thickness by salinity category for each aquifer unit. The analysis conducted by Hamlin and others (2019) used standard subsurface mapping techniques and groundwater salinity estimations based on the following two methods to construct separate net sand thickness maps for freshwater and brackish: 1) the empirical relationship between the resistivity of water-filled formation (R_0) and formation water salinity; and 2) calculation of formation water resistivity (R_w) (Hamlin and others, 2019). The review of electrical logs for this report's hydrostratigraphic framework resulted in minor changes to the hydrostratigraphic unit contacts compared to Hamlin and others (2019) to correlate to the Brackish Resources Aquifer Characterization System group hydrostratigraphic interpretations; however, these changes are relatively minor and therefore these salinity maps are sufficient for providing a general indication of salinity in the study area.

<u>Sparta Sand</u>

Available total dissolved solids measurements indicate that groundwater in the outcrop areas of the Sparta Sand can vary between freshwater to moderately saline, but data is limited (Figure 2-69). In the Sparta Aquifer, the greatest observed total dissolved solids concentration was classified as moderately saline (3,153 mg/L) from a well in La Salle County in 1986. Moderately saline concentrations occur in Atascosa, La Salle, Webb, and Wilson counties in sample dates ranging from 1971 through 2002. Slightly saline concentrations occur in Atascosa, Fayette, Frio, Gonzales, La Salle, Webb, and Wilson counties in sample dates ranging from 1932 through 2017. No salt domes are known to exist in these areas. A few of the selected hydrographs suggest that total dissolved solids concentrations have decreased slightly over time in some areas of the aquifer while other area experienced a spike in the early 2000s before returning to normal conditions (Figure 2-69). No data exist for the deep, down-dip portions of the aquifer unit.

<u>Queen City Sand</u>

Similar to the Sparta Sand, total dissolved solids measurements indicate that groundwater in the outcrop portions of the Queen City Sand varies between freshwater to moderately saline (Figure 2-70). The greatest observed total dissolved solids concentration was classified as moderately saline (8,378 mg/L) from a well in Atascosa County in 1975. There are instances of moderately saline concentrations in Atascosa, Dimmit, Frio, Gonzales, La Salle, McMullen, Webb, and Zavala counties in samples dates ranging from 1928 through 2014. Slightly saline concentrations occur in Atascosa, Caldwell, Frio, Gonzales, La Salle, McMullen, and Webb counties in sample dates ranging from 1940 through 2017. No salt domes are known to exist in these areas. A few of the selected hydrographs suggest that total dissolved solids have remained relatively stable through time in some areas and has slightly increased in other areas (Figure 2-70). Data is limited in the deep, downdip portions of the aquifer unit.

Carrizo Sand

In the Carrizo Aquifer, groundwater is mostly freshwater in the outcrop area, with some areas with slightly saline concentrations (Figure 2-71 and Figure 2-72). The greatest observed total dissolved solids concentration was a single occurrence classified as brine (48,644 mg/L) from a well in De Witt County in 2013. A single occurrence of a total dissolved solids concentration classified as very saline was observed at a well in Karnes County in 2010. Moderately saline concentrations occur in Atascosa, Dimmit, Gonzales, La Salle, McMullen, and Zavala counties in sample dates ranging from 1959 through 2011. Slightly saline concentrations occur in Atascosa, Dimmit, Frio, Gonzales, Karnes, La Salle, McMullen, Medina, Webb, Wilson, and Zavala counties in sample dates ranging from 1913 through 2018. No salt domes are known to exist in these areas. A few of the selected hydrographs suggest that total dissolved solids have remained relatively stable through time in some areas and have slightly increased in other areas (Figure 2-71 and Figure 2-72).

Carrizo-Wilcox Undifferentiated and Wilcox Group

The water quality of the Carrizo-Wilcox undifferentiated wells and Wilcox outcrop wells are discussed separately in this report from the wells distinguished as solely Carrizo. Similar to the Carrizo Sand, groundwater is mostly freshwater in the outcrop area, with some areas with slightly saline concentrations (Figure 2-73 and Figure 2-74). The greatest observed total dissolved solids concentration was classified as moderately saline (6,681 mg/L) from a well in Dimmit County in 2006. Moderately saline concentrations occur in Dimmit, La Salle, Gonzales, Webb, and Zavala counties in sample dates ranging from 1960 through 2010. Slightly saline concentrations occur in Atascosa, Bastrop, Bexar, Caldwell, Dimmit, Frio, Gonzales, Guadalupe, La Salle, Maverick, McMullen, Medina, Webb, Wilson, and Zavala counties in sample dates ranging from 1930 through 2014. A few of the selected hydrographs suggest that total dissolved solids have remained relatively stable through time in some areas and have slightly increased in other areas (Figure 2-73 and Figure 2-74).

The geometric mean of the total dissolved solids concentration in each aquifer unit was calculated using the most recent concentration at each sampling location. The previously noted trend of down-dip increase in total dissolved solids concentration (Kelley and others, 2004) was verified, as seen in the concentrations in Table 2-11, with the exception of the Wilcox Aquifer where the mean concentrations are very similar.

Table 2-11. Geometric mean of total dissolved solids concentrations measured in each aquifer.

Aquifer	Overall Mean (mg/L)	Outcrop (Unconfined) Mean (mg/L)	Downdip (Confined) Mean (mg/L)
Sparta	1,394.1	963.4	1,564.7
Queen City	1,062.7	947.7	1,384.4
Carrizo	455.7	288.4	473.4
Carrizo-Wilcox Undifferentiated and Wilcox Group	600.0	557.7	633.8

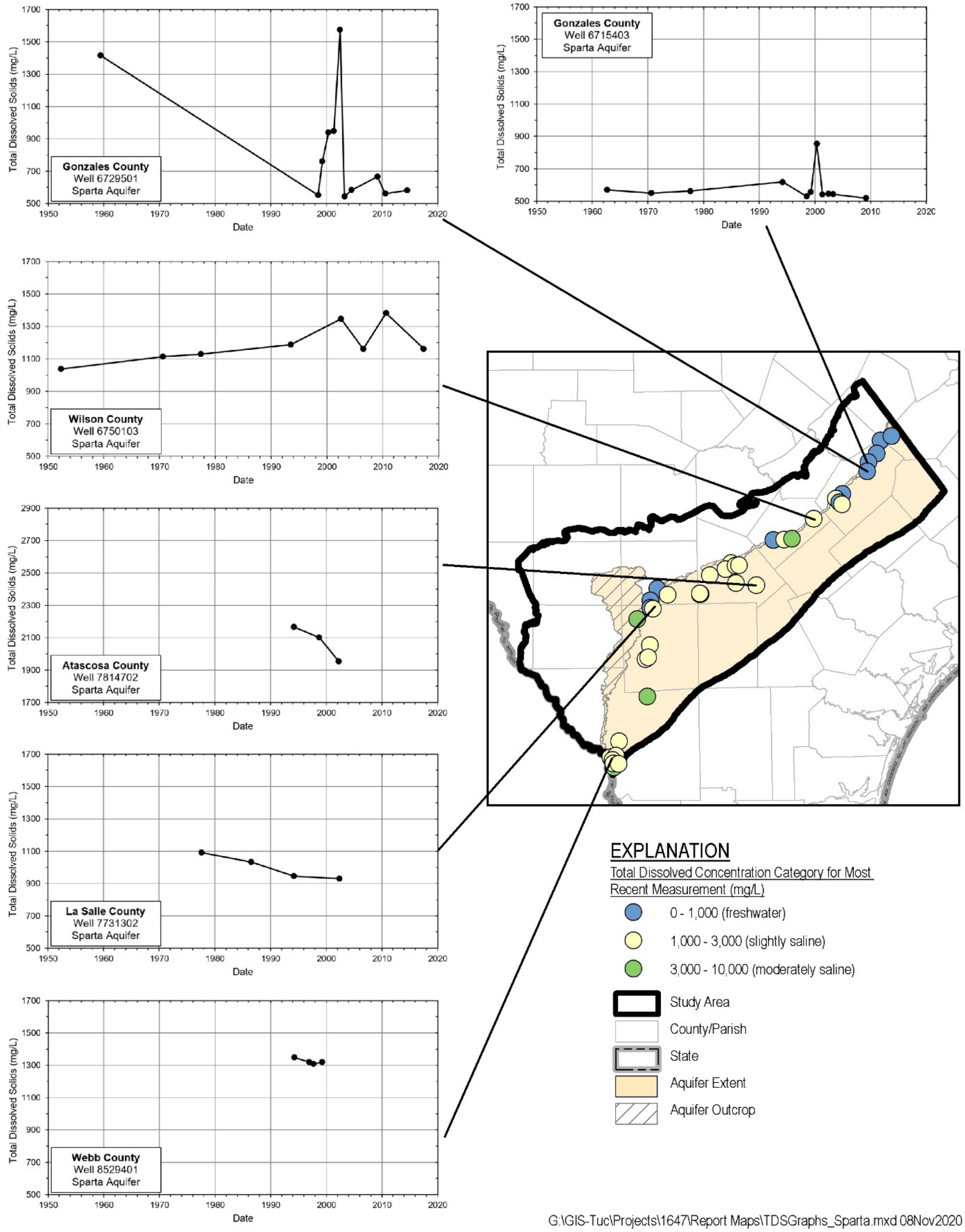

Figure 2-69. Total dissolved solids distribution and selected historic concentration for Sparta Aquifer wells in study area.

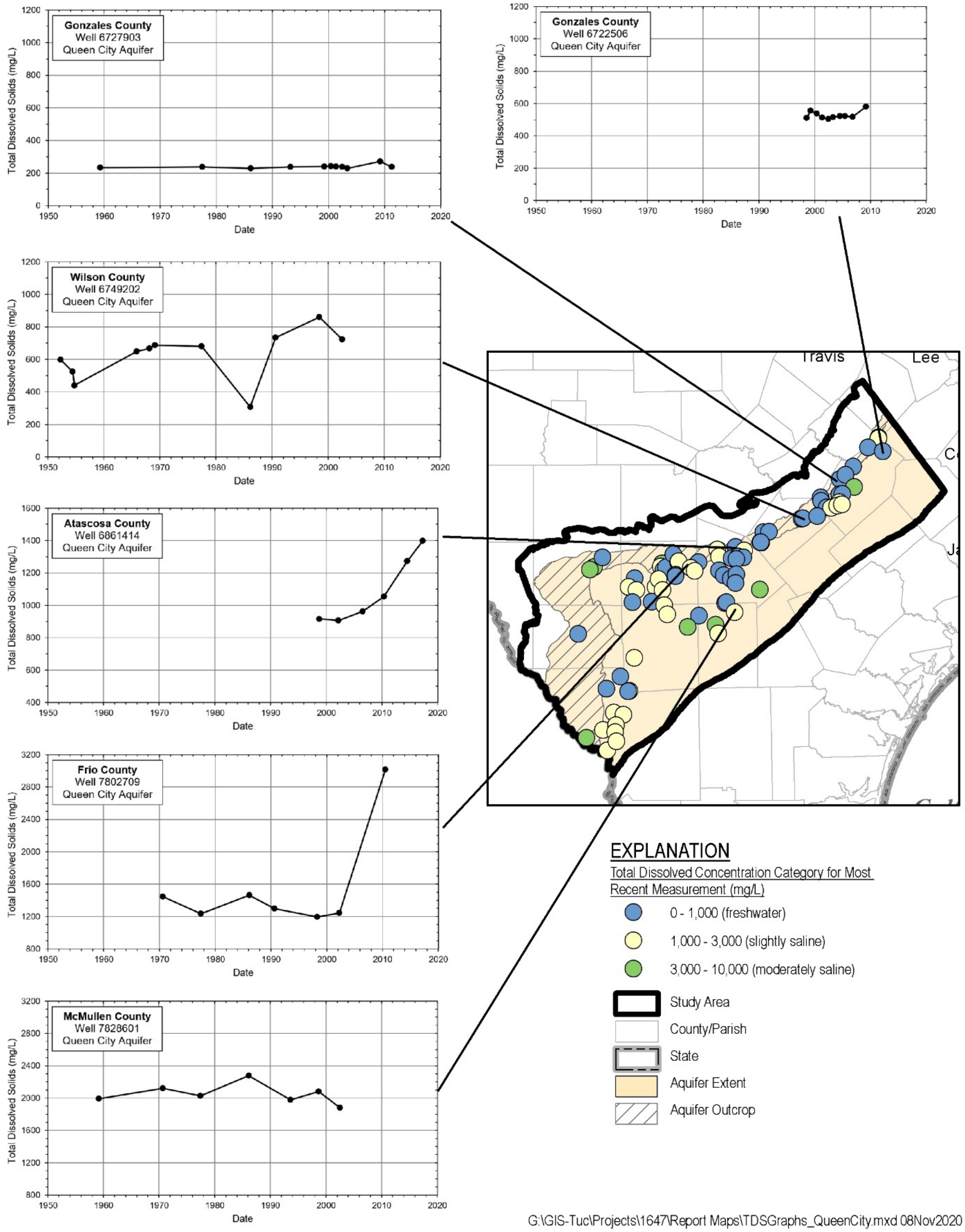

Figure 2-70. Total dissolved solids distribution and selected historic concentration for Queen City Aquifer wells in study area.

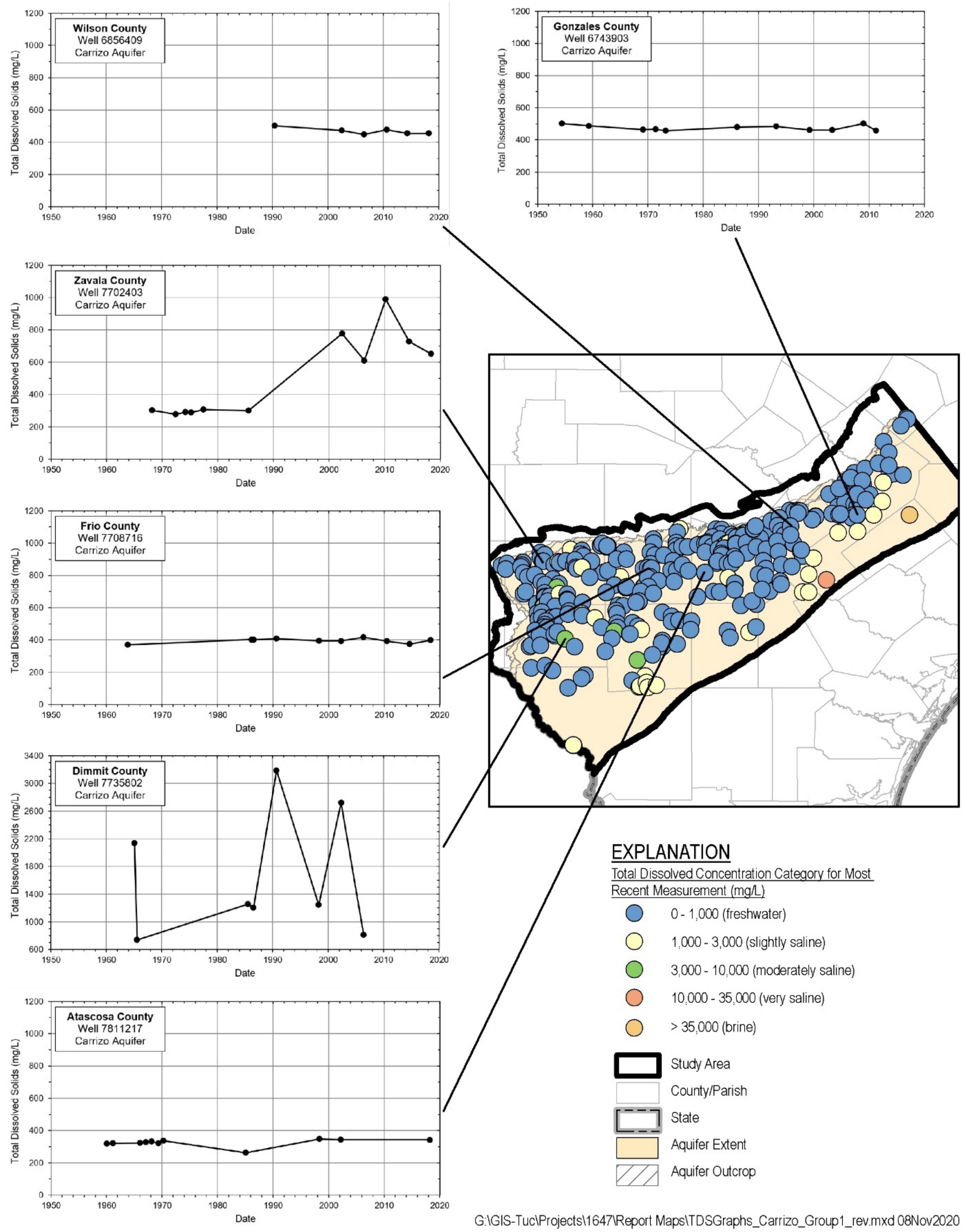

Figure 2-71. Total dissolved solids distribution and selected historic concentration for Carrizo wells in Gonzales, Wilson, Atascosa, Frio, Zavala, and Dimmit counties.

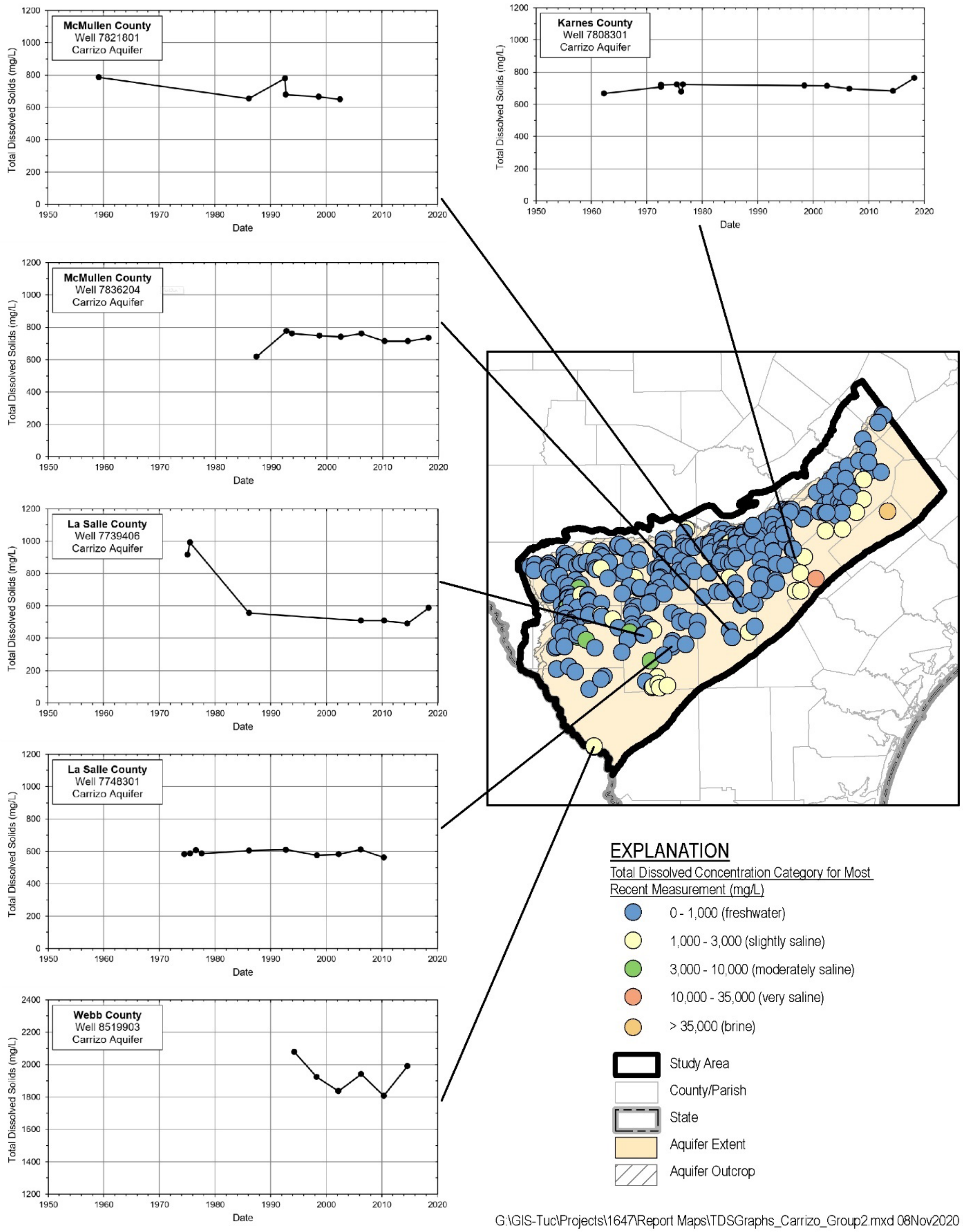

Figure 2-72. Total dissolved solids distribution and selected historic concentration for Carrizo wells in Karnes, McMullen, and La Salle counties.

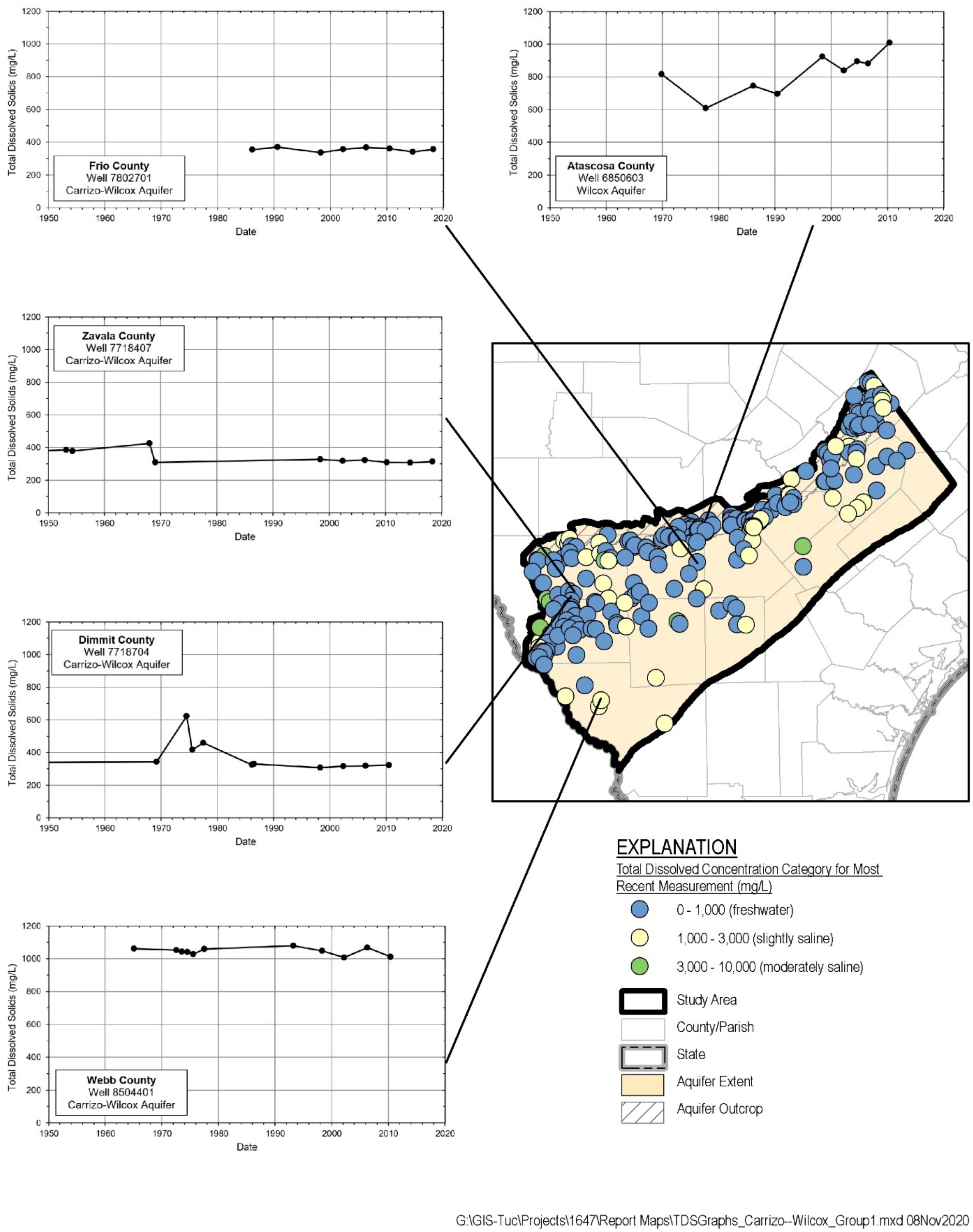

Figure 2-73. Total dissolved solids distribution and selected historic concentration for Carrizo-Wilcox wells (undifferentiated) in Atascosa, Frio, Zavala, Dimmit, and Webb counties.

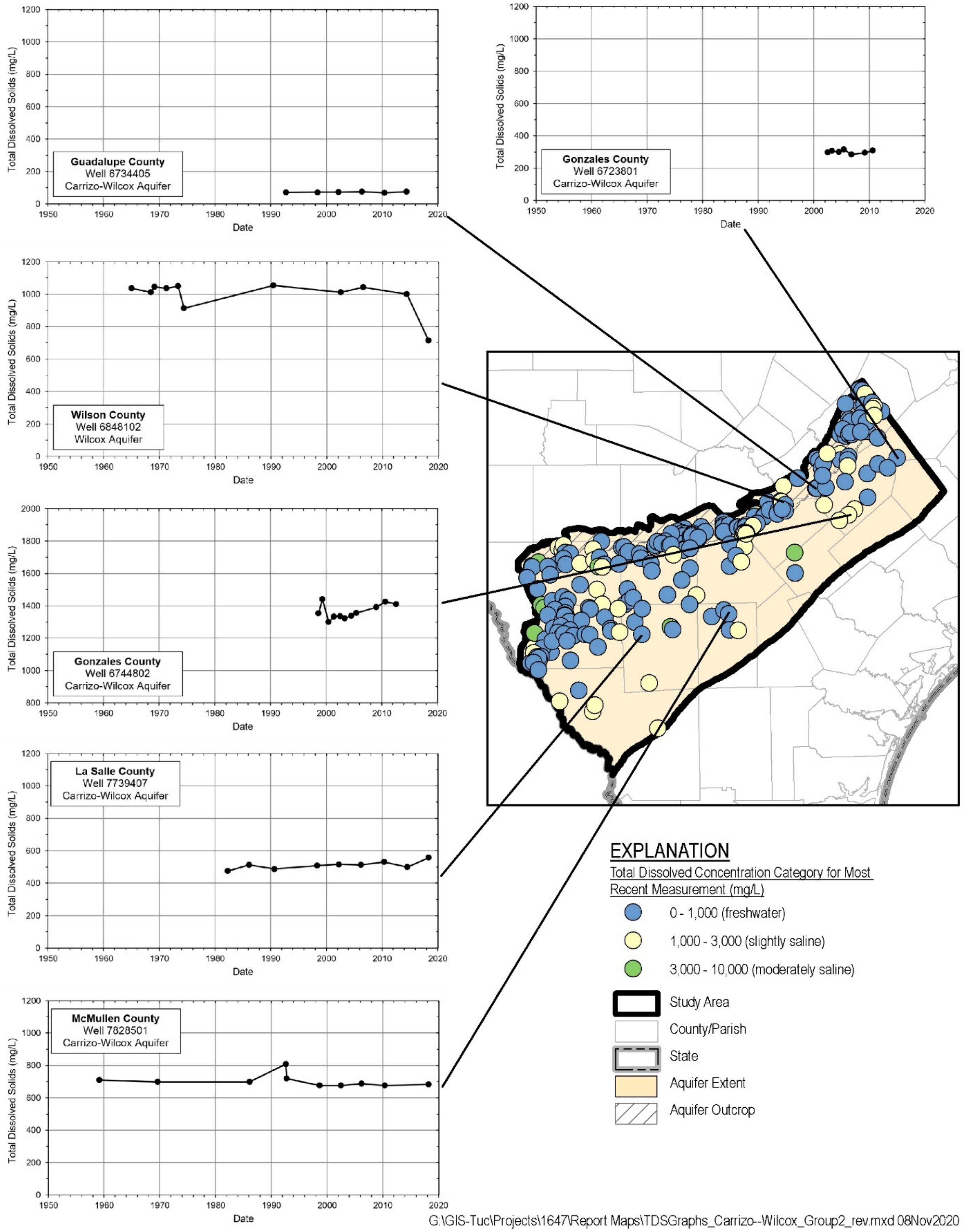

Figure 2-74. Total dissolved solids distribution and selected historic concentration for Carrizo-Wilcox wells (undifferentiated) in Gonzales, Guadalupe, Wilson, McMullen, and La Salle counties.

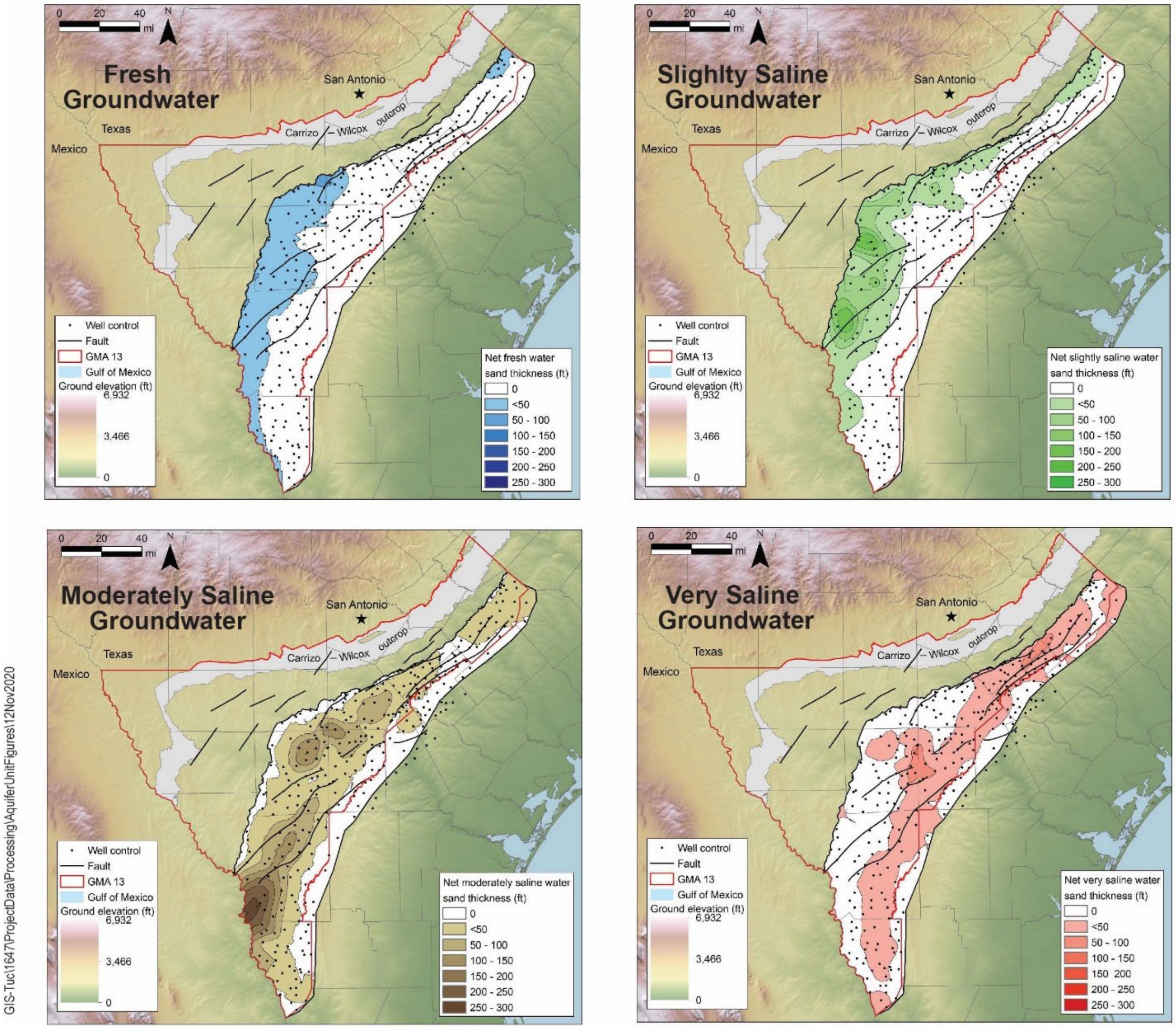

Figure 2-75. Net thickness of sand by salinity level for the Sparta Aquifer from Hamlin and others (2019).

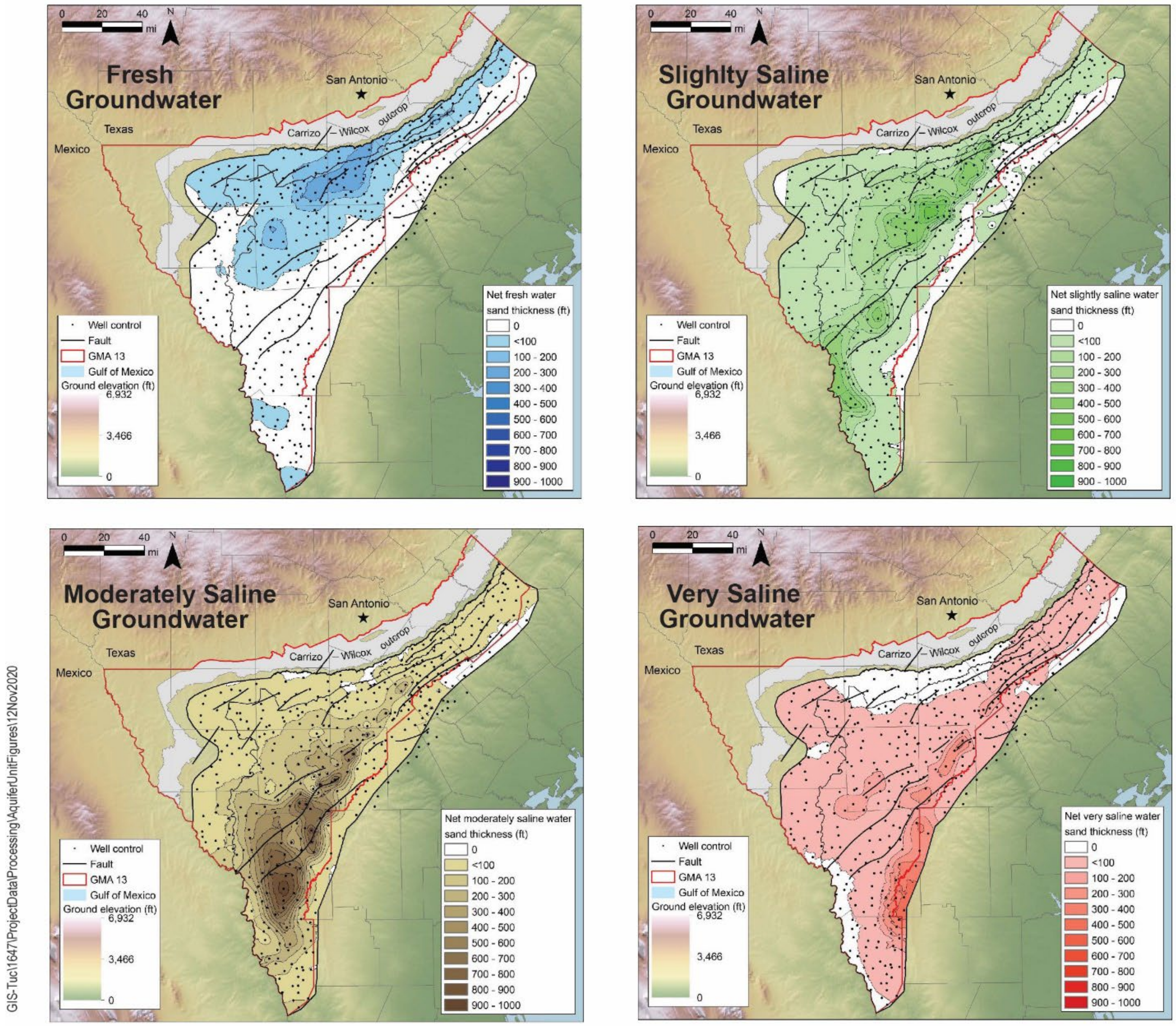

Figure 2-76. Net thickness of sand by salinity level for the Queen City Aquifer from Hamlin and others (2019).

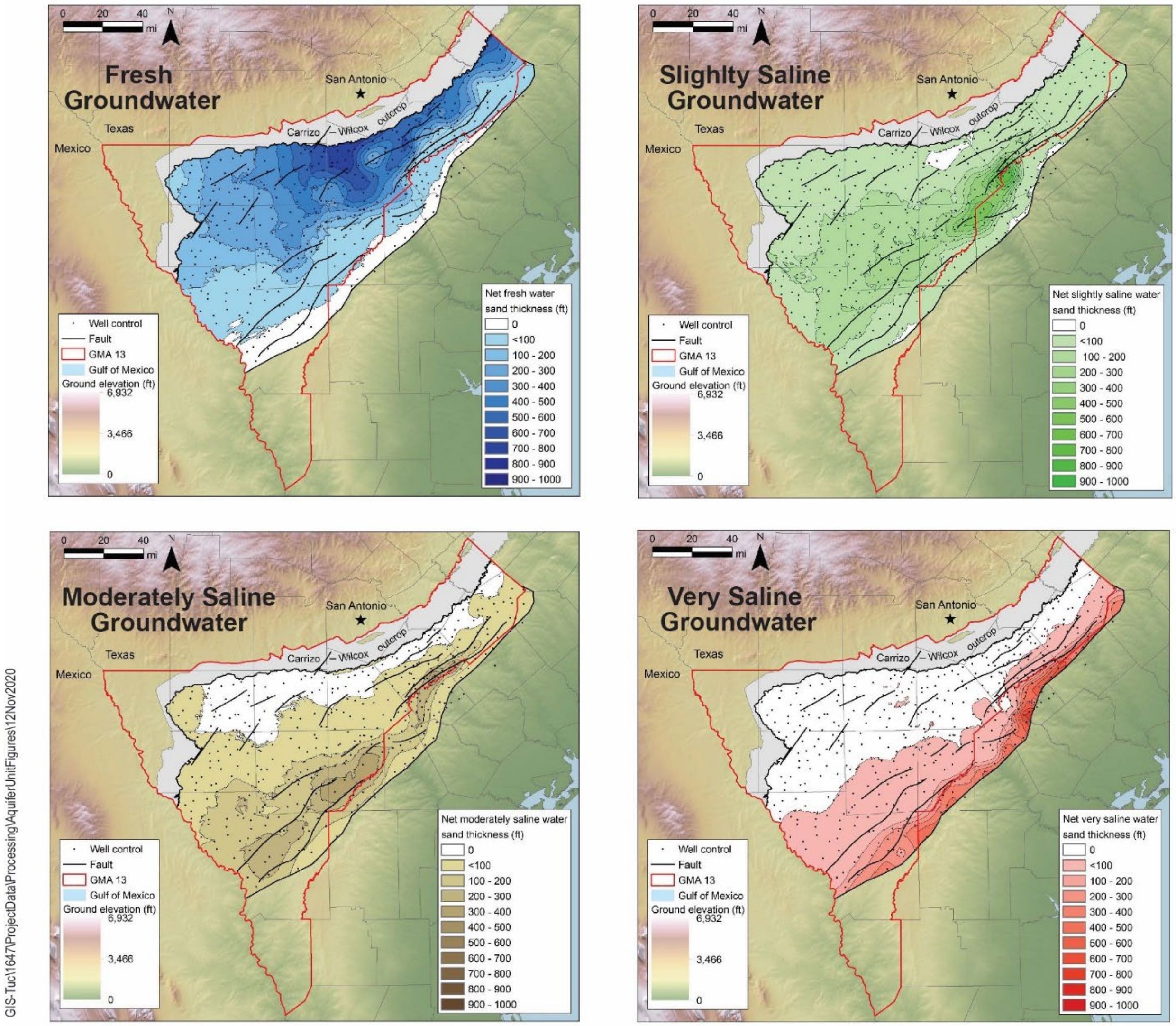

Figure 2-77. Net thickness of sand by salinity level for the Carrizo-upper Wilcox Aquifer from Hamlin and others (2019).

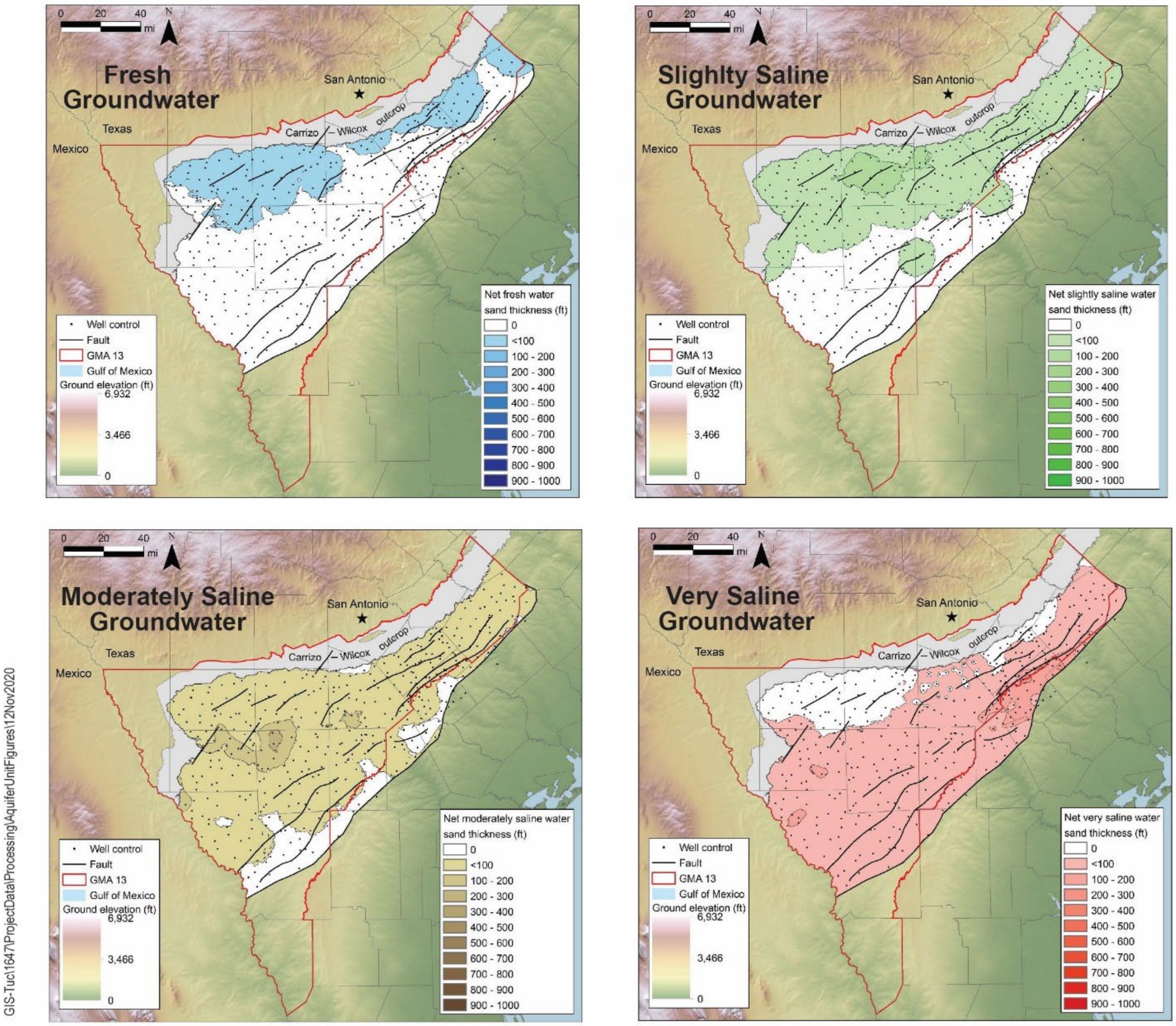

Figure 2-78. Net thickness of sand by salinity level for the Middle Wilcox from Hamlin and others (2019).

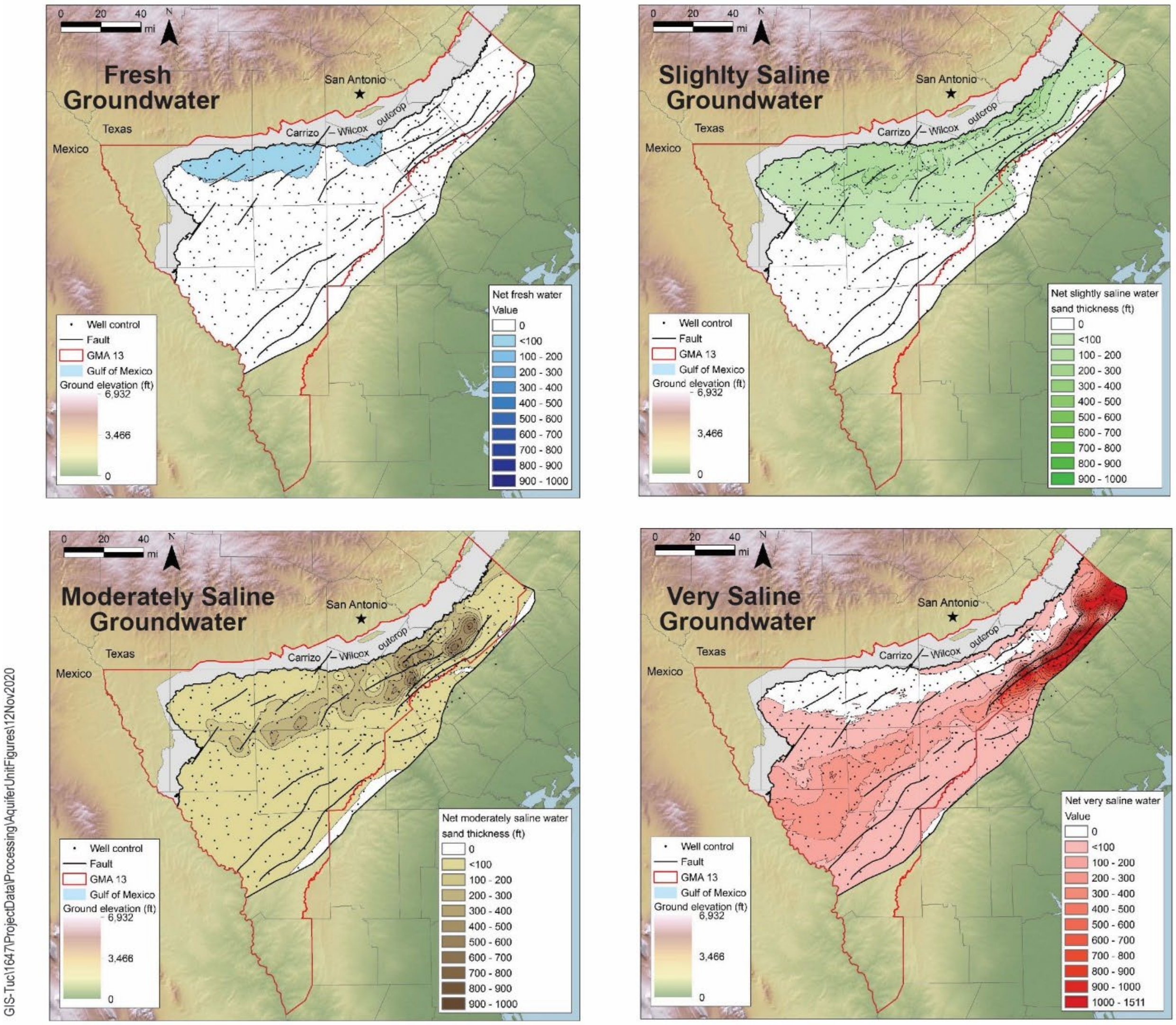

Figure 2-79. Net thickness of sand by salinity level for the Lower Wilcox from Hamlin and others (2019).

2.9 Summary of Conceptual Model

The conceptual hydrogeologic model for this study is based on the hydrogeologic setting described herein. 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 2-80.

The groundwater system in this conceptual model is an eight-layer system. Each model layer represents an individual hydrostratigraphic unit within the groundwater system. The eight layers represented in the model include the following, from top to bottom: river alluvium, Sparta aquifer, Weches aquitard, Queen City aquifer, Reklaw aquitard, Carrizo-upper Wilcox, and the middle and lower units of the Wilcox Group. The Sparta, Queen City, Carrizo, and the three Wilcox units are capable of producing adequate volumes of groundwater for use. These aquifer units are separated by two confining aquitards. The Weches Formation separates the Sparta Aquifer from the underlying Queen City Aquifer, and the Reklaw Formation separates the Queen City Aquifer from the Carrizo-Wilcox Aquifer. A representative hydrogeologic cross-section of the nine-layer groundwater system is shown on Figure 2-80. The aquifer units in this model dip eastward into the subsurface towards the Gulf Coast Basin and are overlain by a wedge of younger sediments (including the Gulf Coast Aquifer System and the Yegua-Jackson Aquifer), which are not included in this model.

Groundwater in the southern portions of the Carrizo-Wilcox, Queen City, and Sparta aquifer system occurs under unconfined (or water-table) conditions in the outcrop areas and confined conditions in down-dip areas. Regional groundwater movement is generally from the west-northwest in upland areas to the east towards the Gulf of Mexico, following the dip of the aquifer units. The sands of the Wilcox and Carrizo units are hydraulically connected and behave as a single aquifer in counties throughout 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 eastern 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 a few springs. The gaining stream reaches is a result of climate, shallow groundwater levels, and gently dipping and dissected topography. These factors contribute to rejected recharge and runoff in the study area.

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

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

This conceptual model encompasses the southern portions of the Carrizo-Wilcox, Queen City, and Sparta aquifer systems in south central Texas. The model boundaries are defined based on surface and groundwater features. The western boundary is the western-most extent of the lower Wilcox aquifer layer. The eastern boundary is the same as defined for the previous groundwater availability models, which is the up-dip limit of the Wilcox growth fault zone as defined by Bebout and others (1982). The southern boundary is the Rio Grande. The northern boundary is the approximate watershed drainage divide between the Guadalupe and Colorado 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 defined as the bottom of the Wilcox Group (top of the older Midway Formation). The lateral extent of the model area is the same as the previous groundwater availability model for this aquifer system.

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

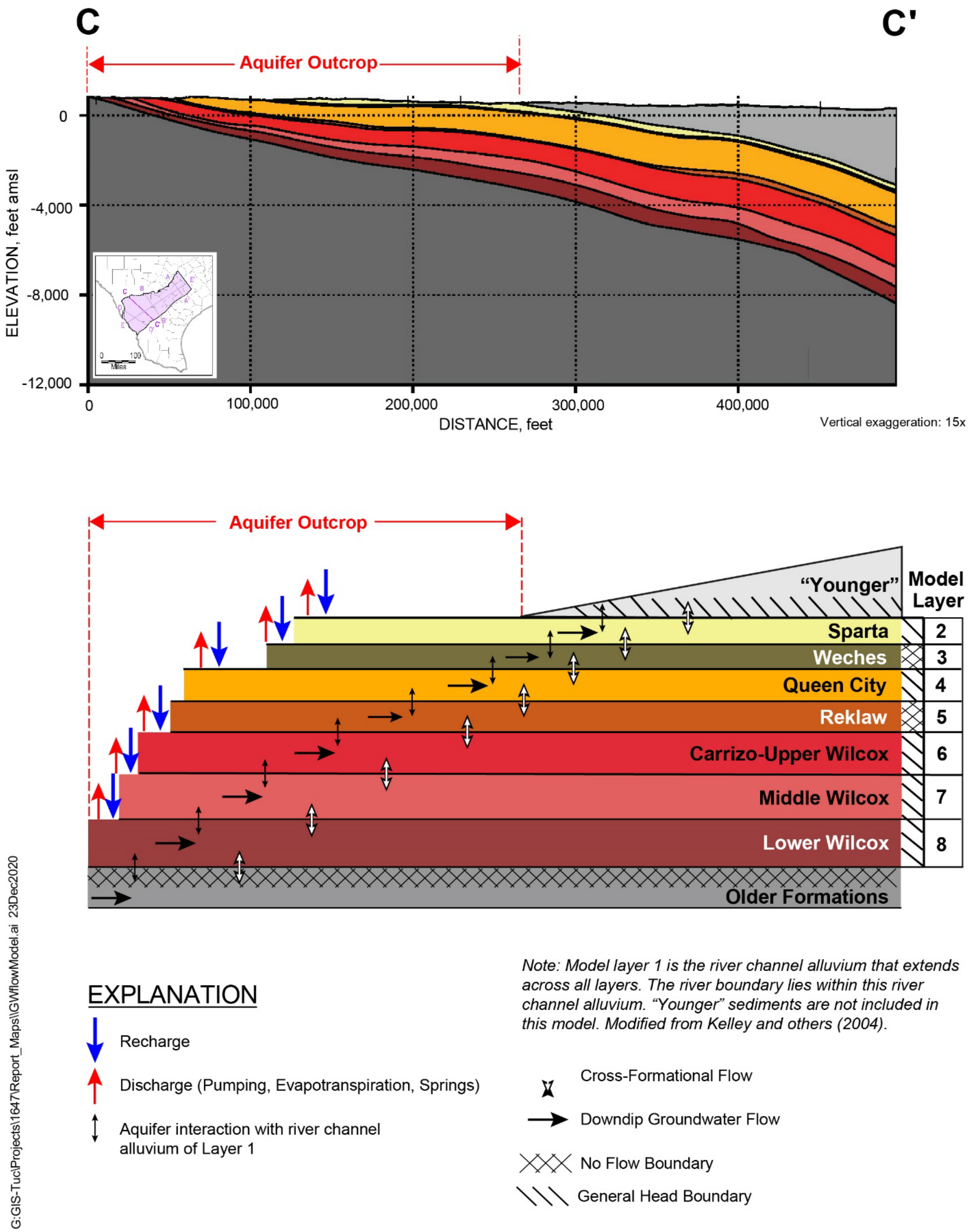

Figure 2-80. Conceptual groundwater flow model diagram for southern portions of Queen City, Sparta, and Carrizo-Wilcox aquifers groundwater availability model update.

2.10 Historical Transient Conditions

The transient model period represents historical hydrogeologic conditions from 1980 through 2017. This time period was selected principally based on pumping data availability. Initial conditions for the transient model will represent conditions prior to 1980. 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 southern portions of the Carrizo-Wilcox, Queen City, and Sparta 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. 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 southern portions of the Carrizo-Wilcox, Queen City, and Sparta aquifers include: (1) groundwater withdrawals by pumping, (2) discharge to surface waters such as rivers, creeks, and springs, and (3) evapotranspiration. Pumping will be assigned to aquifer units based on the hydrostratigraphic framework and reported well construction information for each pumping well. The distribution of evapotranspiration will be initially based on average maximum evapotranspiration rate and evapotranspiration extinction depths. Components of evapotranspiration outputs could be scaled, if necessary, based on climatic factors and/or distributions of land cover.

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

Changes in groundwater levels have varied through time and among the aquifer layers. Measurements at wells indicate rising, declining, or stable groundwater levels depending on location, with no overall regional trend. Groundwater levels have declined steadily in down-dip portions of the aquifers, and some local at or near the outcrop area. Declining groundwater levels are likely principally due to groundwater pumping.

3 Future Improvements

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

Recharge is an important component to the groundwater availability model because it can be used to constrain hydraulic properties during model calibration. Although regional-scale relationships were determined to be reasonable for this study, the accuracy of future predictions of groundwater conditions would improve with additional recharge studies conducted in the study area.

Uncertainties regarding groundwater pumping in the study area exist due to limited reported information. The best available pumping information for the area is provided in the annual TWDB water use surveys. However, inconsistent or inaccurate information is likely reported in the surveys. The methods used by TWDB and users to estimate and report groundwater use also changed over time, which resulted in shifts in the reported data. Furthermore, the distribution of pumping within areas 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.

4 Acknowledgements

The groundwater modeling team for this study would like to thank the stakeholders for their continued support and participation in the development of the conceptual hydrogeologic model.

Special appreciation goes to the TWDB personnel: Jean Perez for his support and guidance through the process; John Meyer, Andrea Croskrey, and the Brackish Resources Aquifer Characterization System Group for providing insight on their database and for providing geophysical well logs; David Thorkildsen for providing geospatial and model datasets for groundwater availability models; and Cindy Ridgeway and the groundwater availability modeling group for their support and leadership during the development of the conceptual model.

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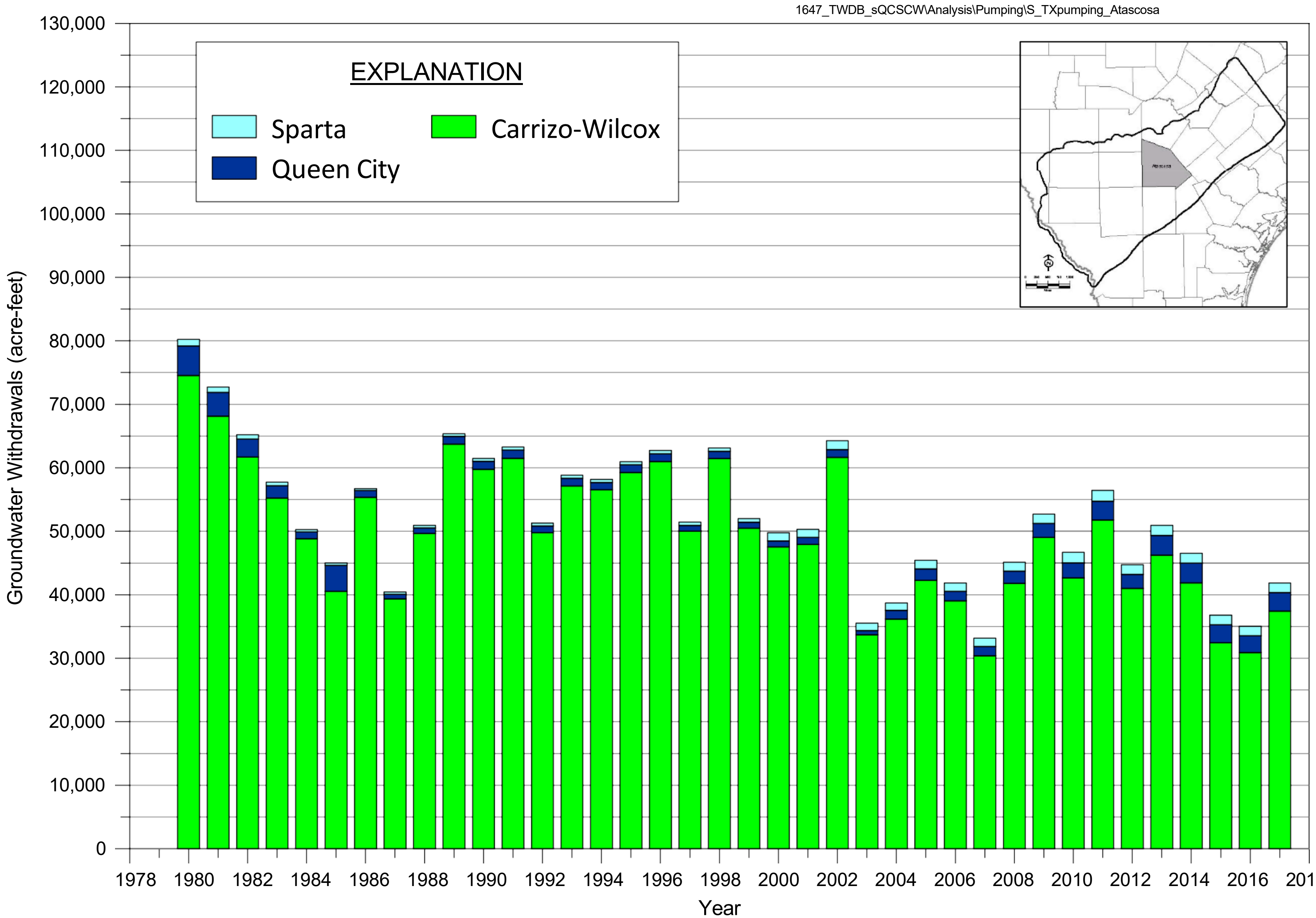
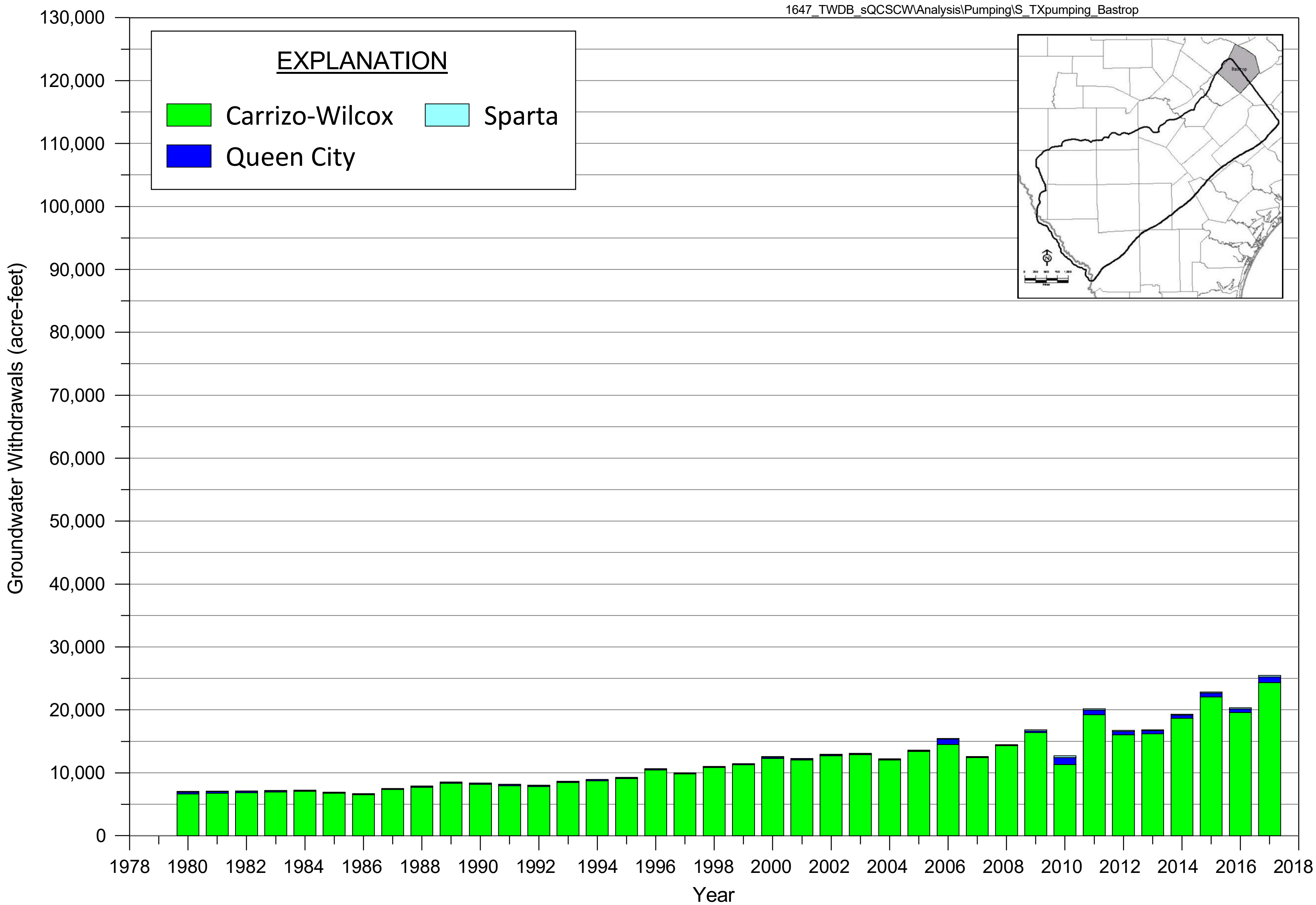
6 Appendices

Appendix A

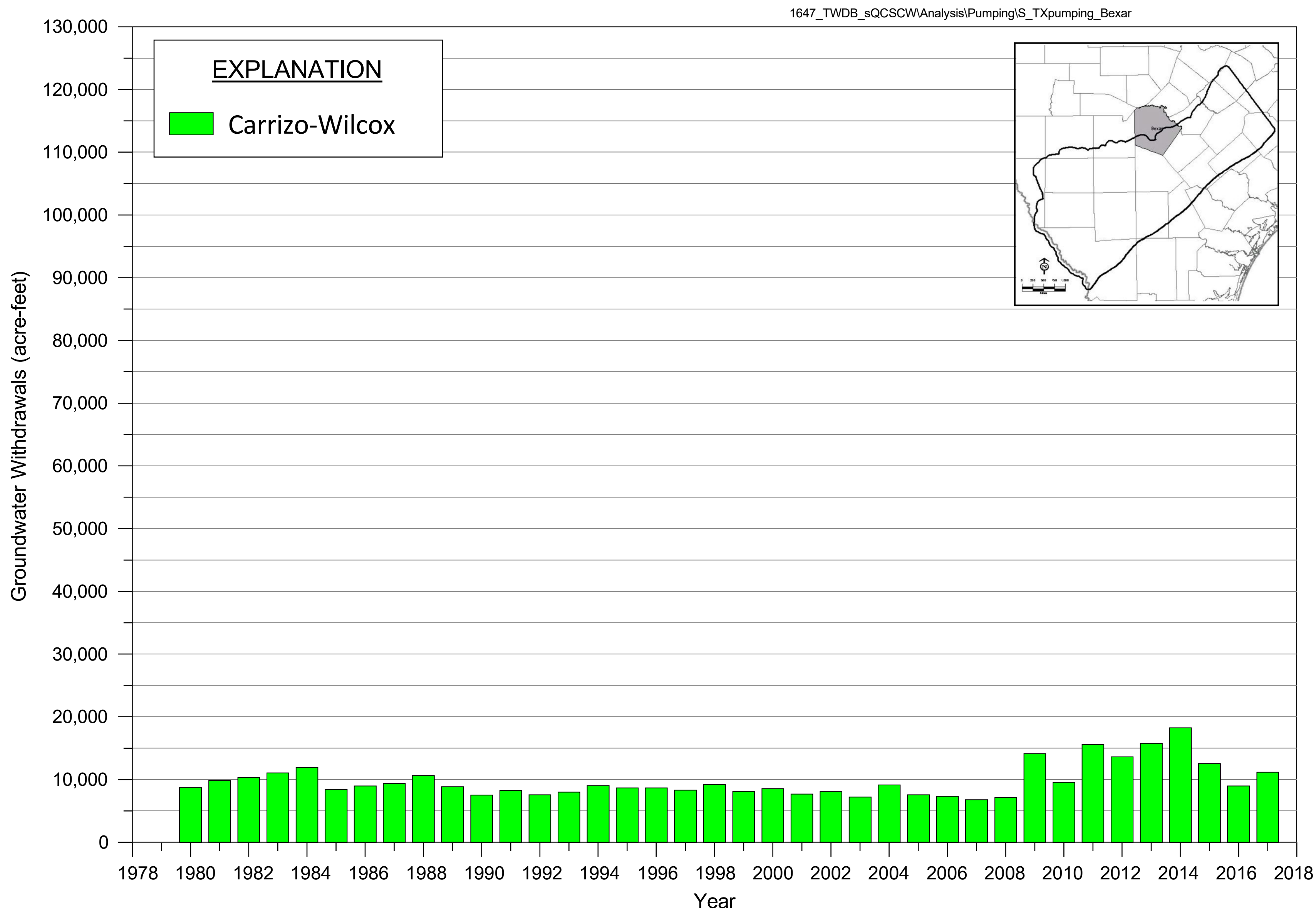
Charts of Estimated Groundwater Pumping by County and Aquifer Source for Southern Portions of the Queen City, Sparta, and Carrizo-Wilcox Aquifers



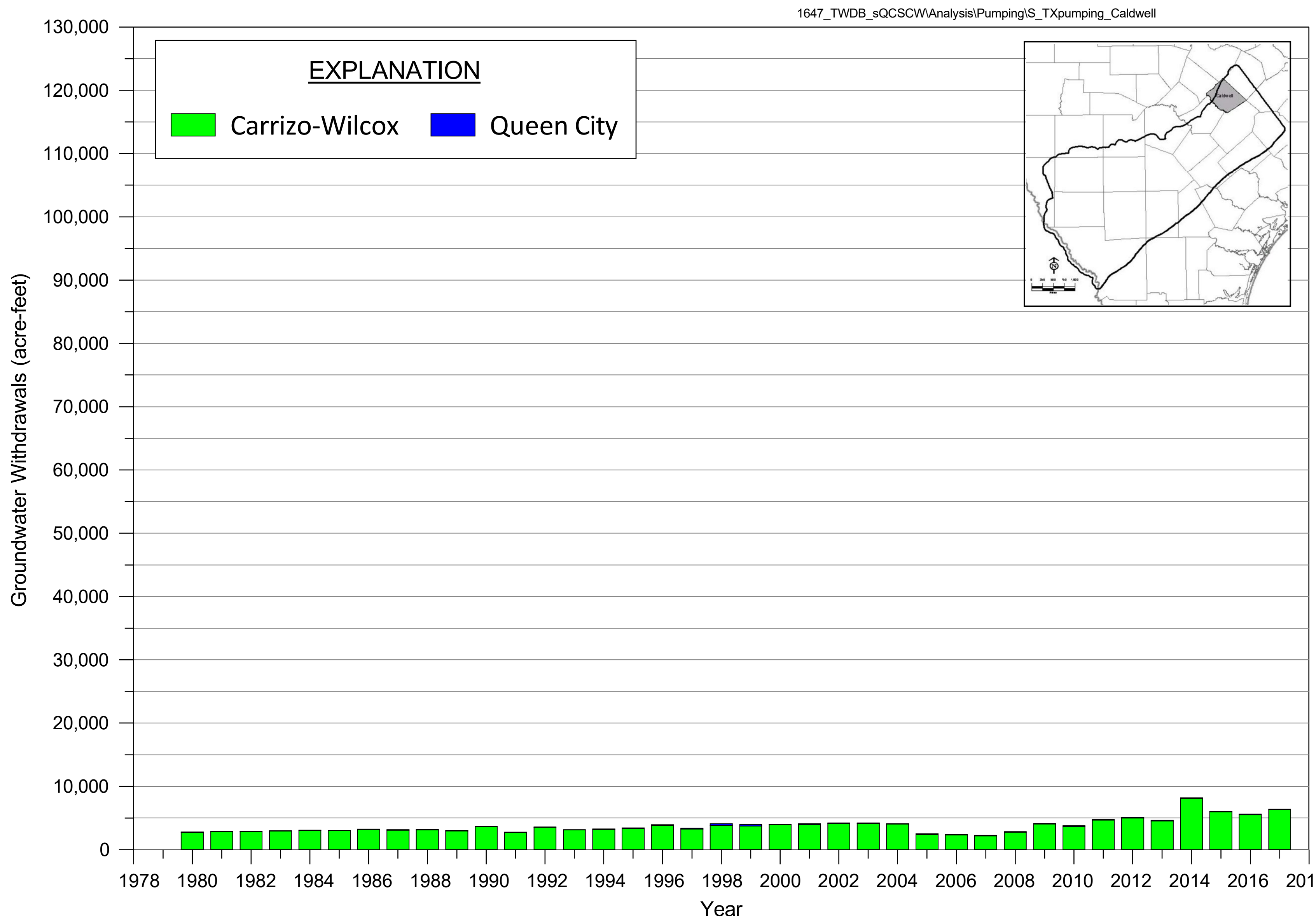
Source: TWDB annual water use surveys; totals include estimated pumpage from Queen City, Sparta, and Carrizo-Wilcox aquifers



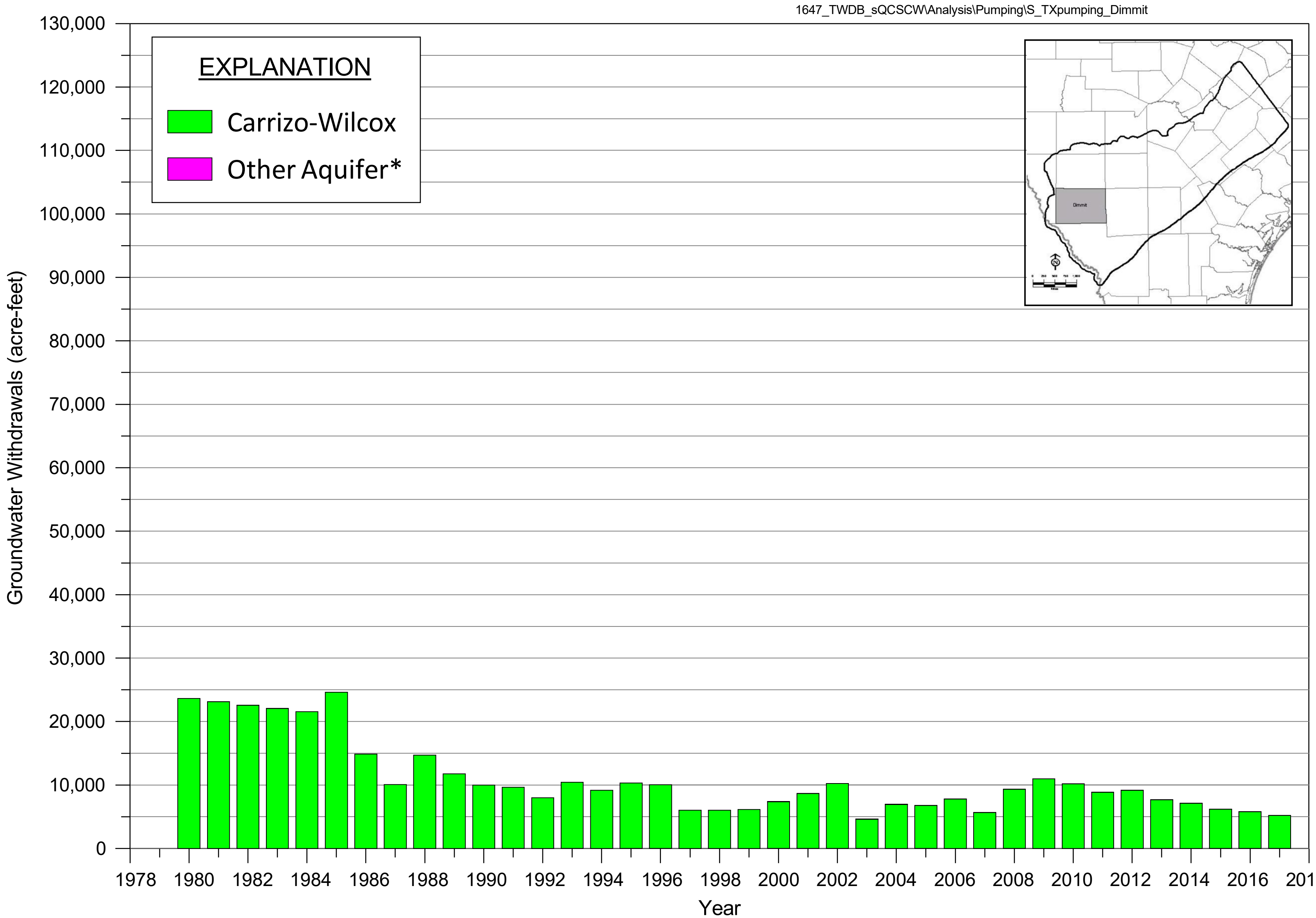
Source: TWDB annual water use surveys; totals include estimated pumpage from Queen City, Sparta, and Carrizo-Wilcox aquifers



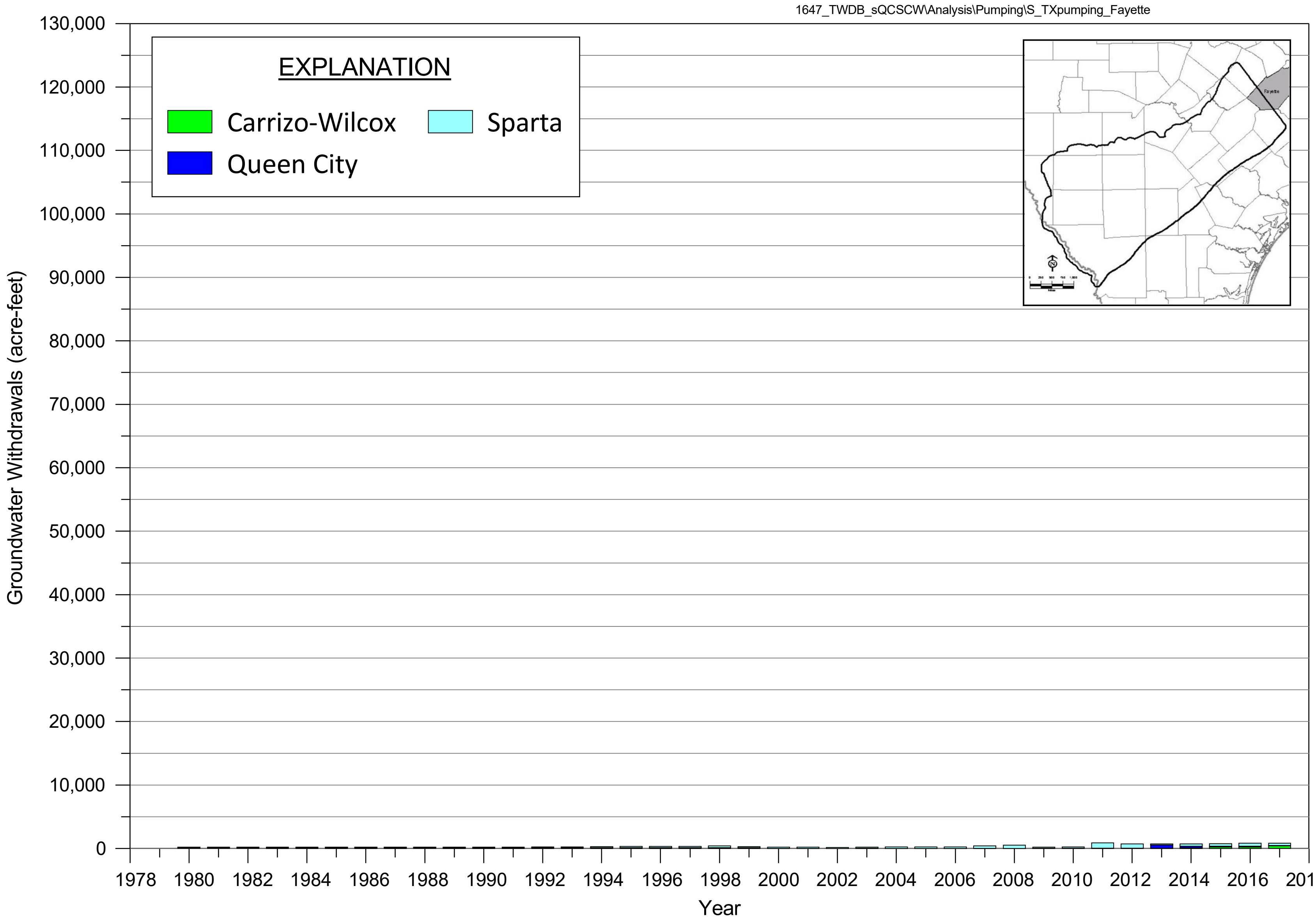
Source: TWDB annual water use surveys; totals include estimated pumpage from Queen City, Sparta, and Carrizo-Wilcox aquifers
** No reported values for Queen City or Sparta aquifers*



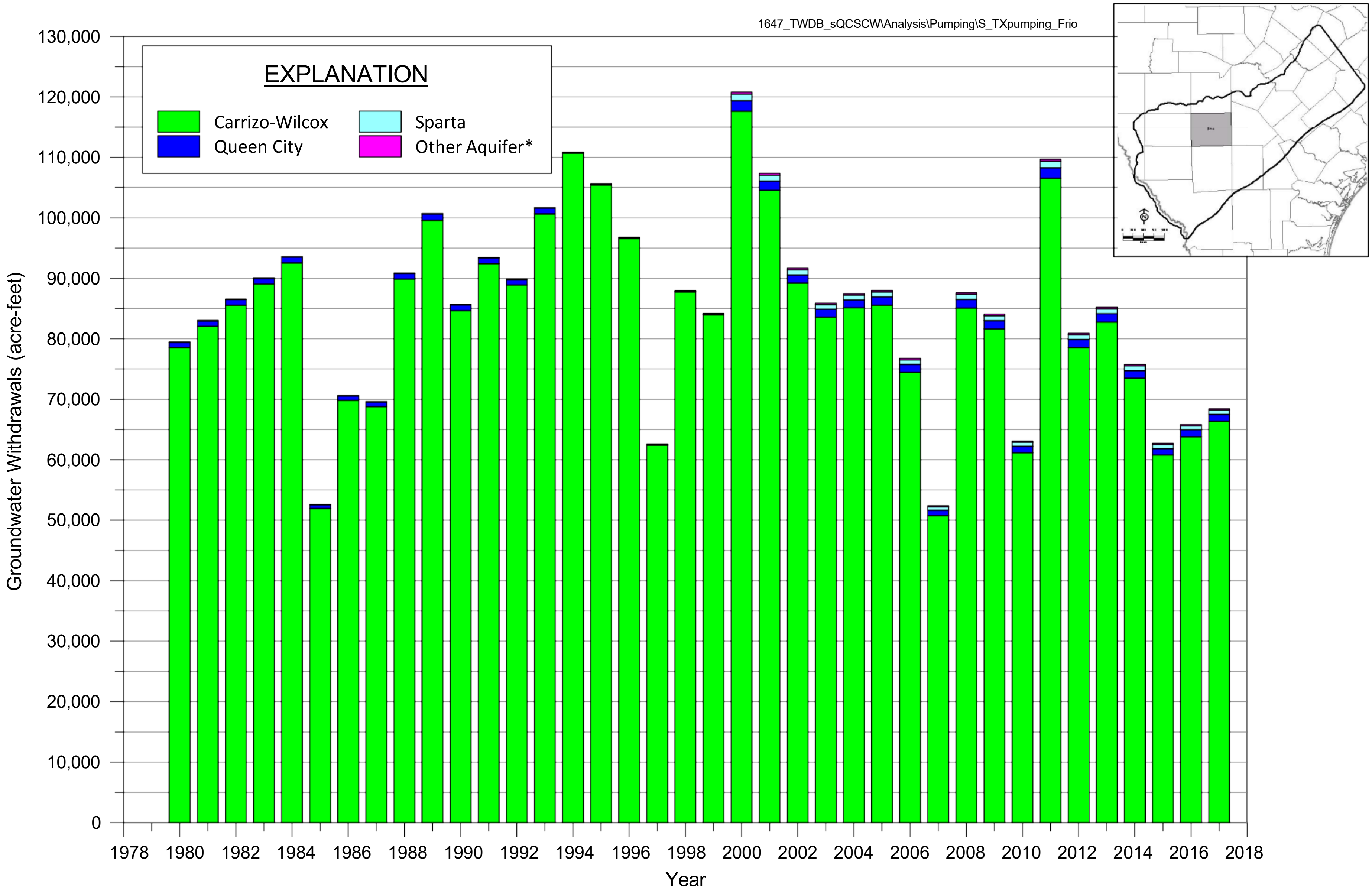
Source: TWDB annual water use surveys; totals include estimated pumpage from Queen City, Sparta, and Carrizo-Wilcox aquifers
** No reported values for Sparta Aquifer*



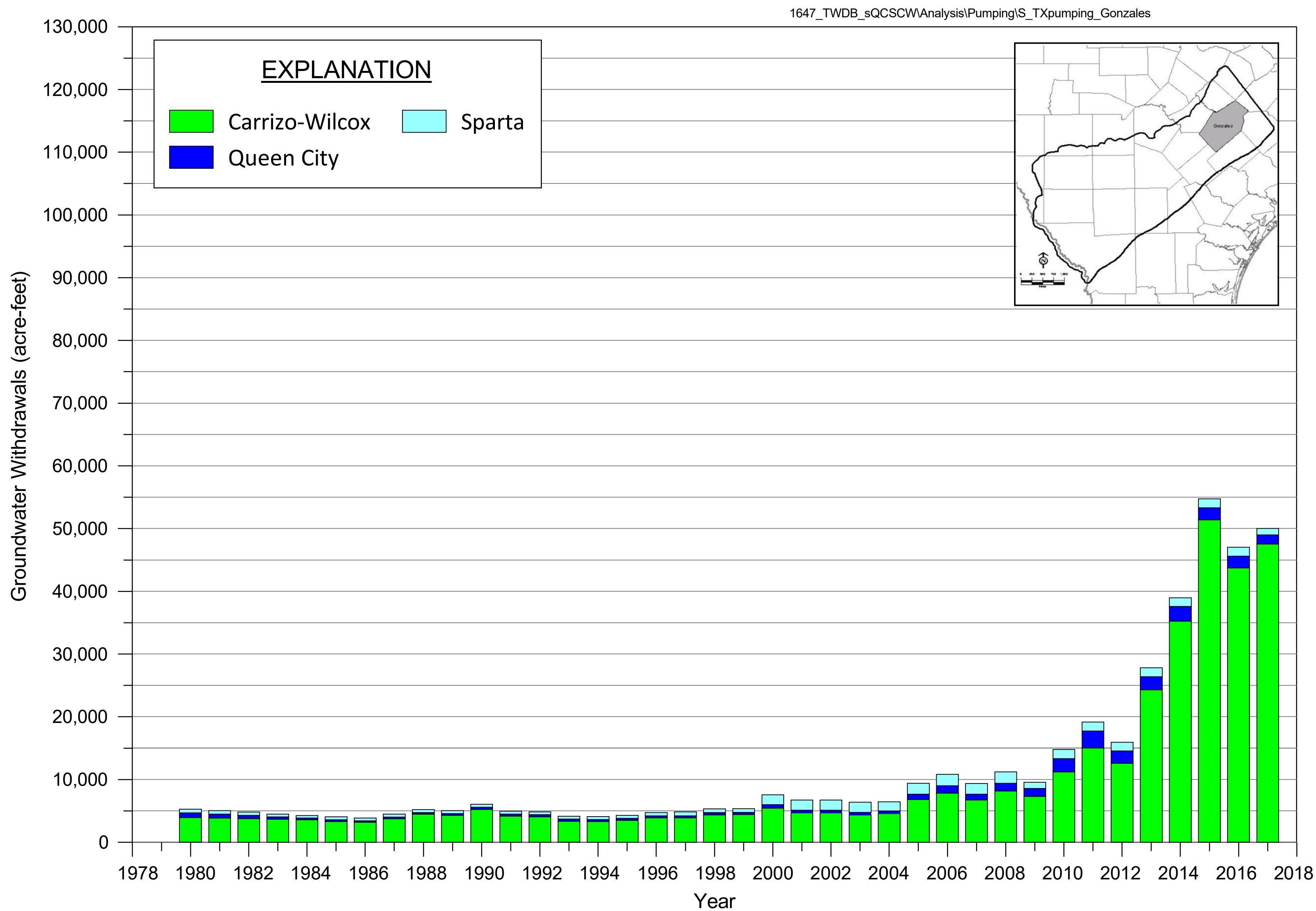
Source: TWDB annual water use surveys; totals include estimated pumpage from Queen City, Sparta, and Carrizo-Wilcox aquifers
**Other category may contain data from wells completed in alluvium and in any other units shallower than the Carrizo but deeper than the Yegua-Jackson aquifer.*
No reported values for Sparta or Queen City aquifers



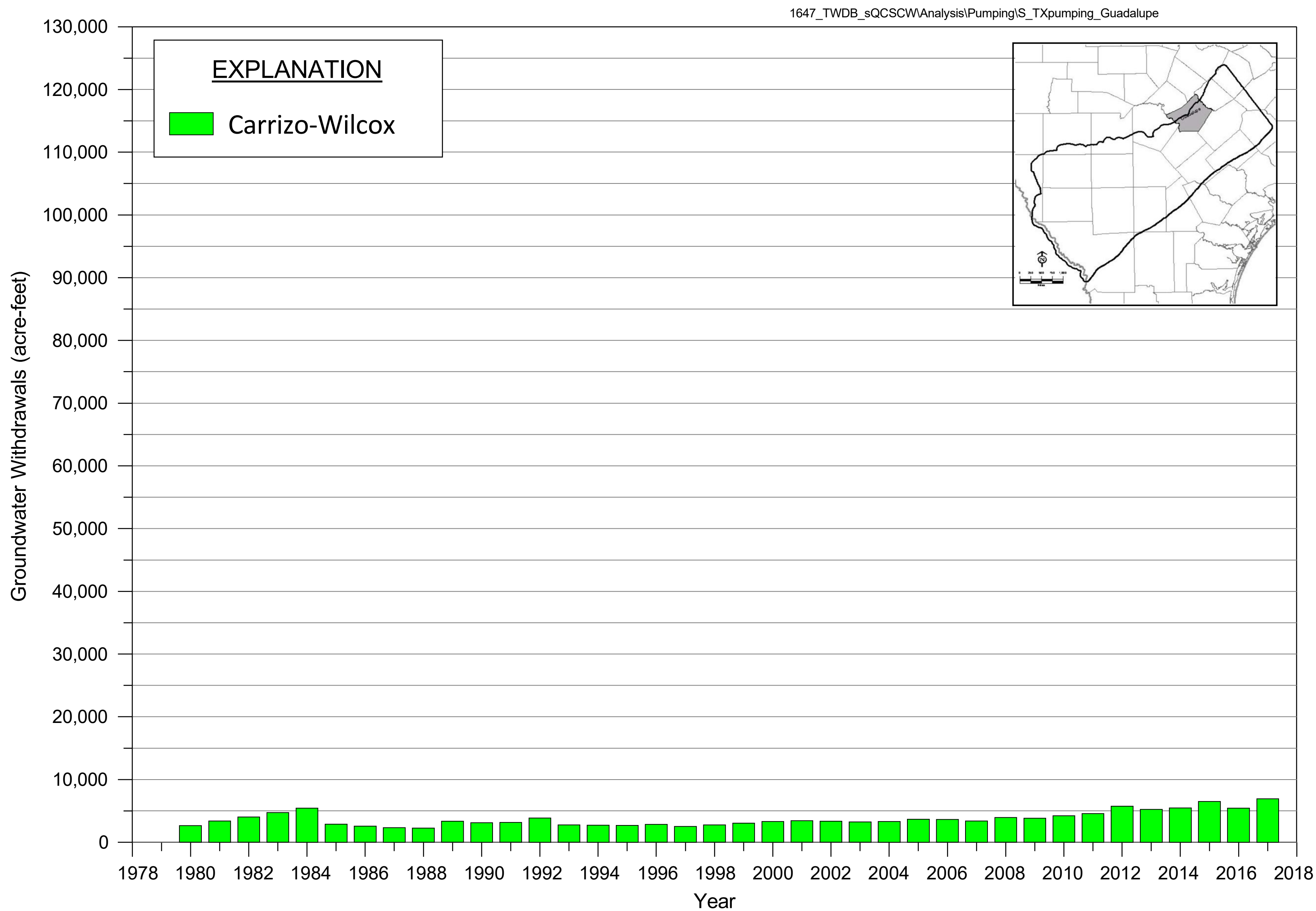
Source: TWDB annual water use surveys; totals include estimated pumpage from Queen City, Sparta, and Carrizo-Wilcox aquifers



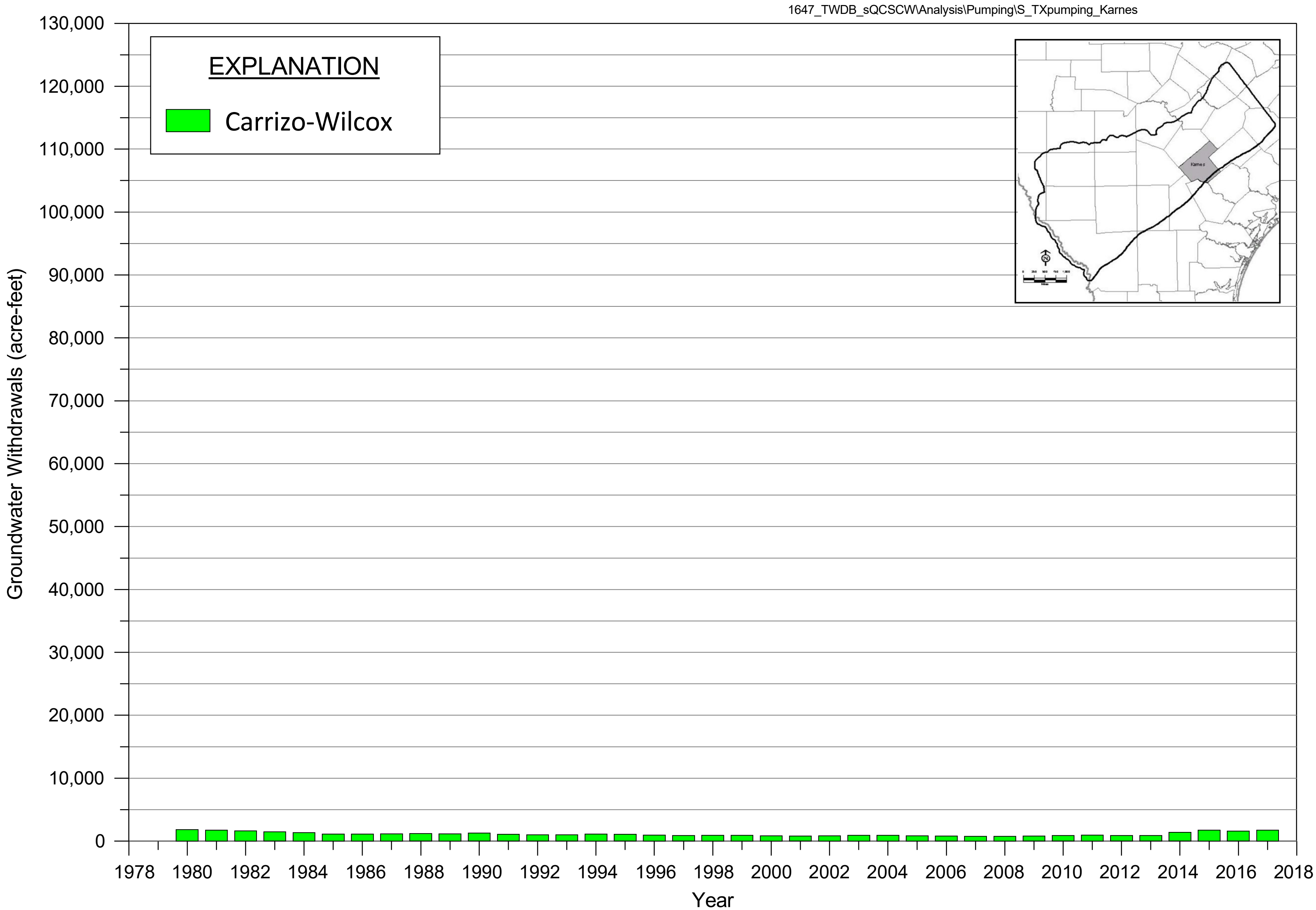
Source: TWDB annual water use surveys; totals include estimated pumpage from Queen City, Sparta, and Carrizo-Wilcox aquifers
**Other category may contain data from wells completed in alluvium and in any other units shallower than the Carrizo but deeper than the Yegua-Jackson aquifer.*



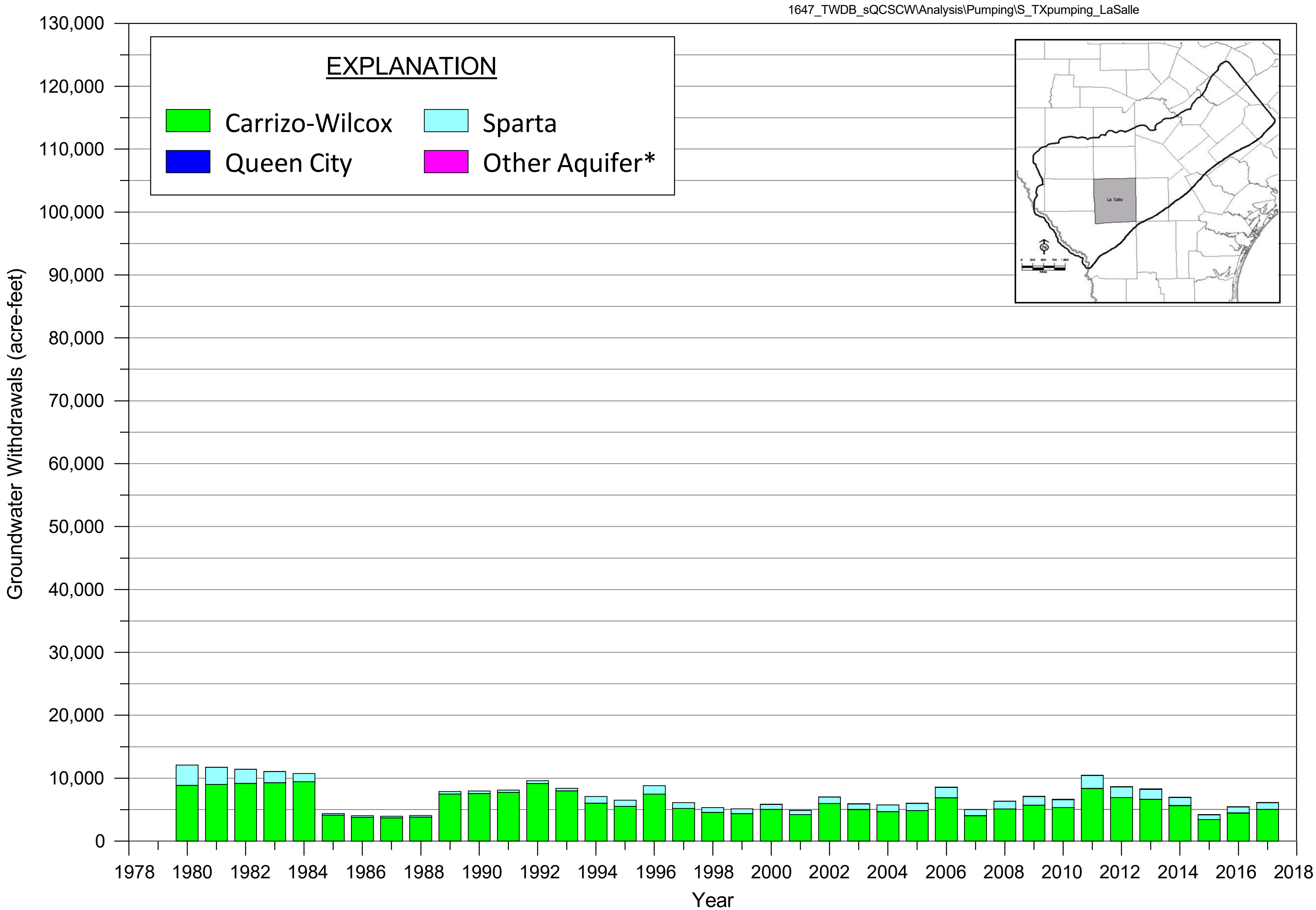
Source: TWDB annual water use surveys; totals include estimated pumpage from Queen City, Sparta, and Carrizo-Wilcox aquifers



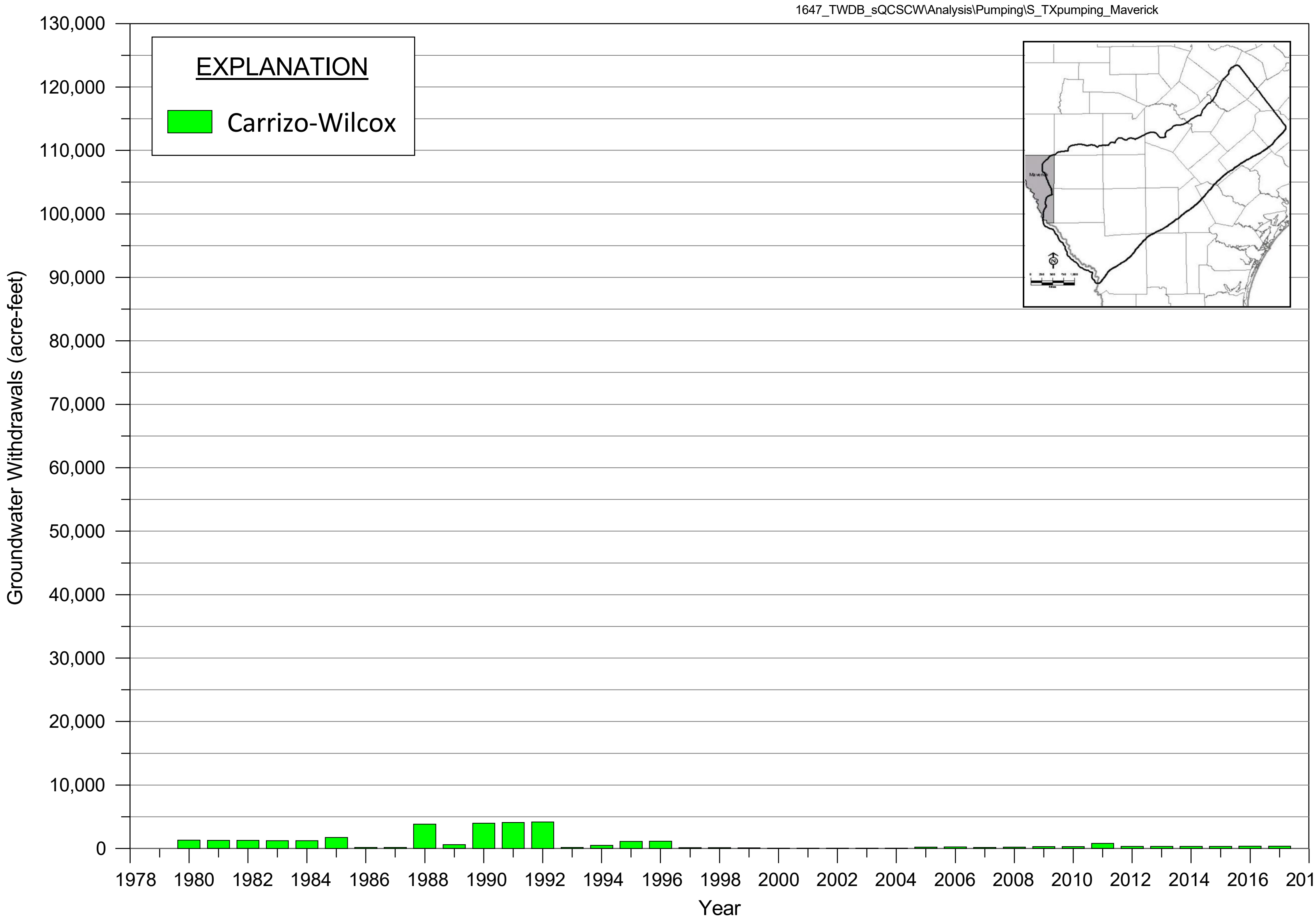
Source: TWDB annual water use surveys; totals include estimated pumpage from Queen City, Sparta, and Carrizo-Wilcox aquifers
** No values reported for Queen City and Sparta aquifers*



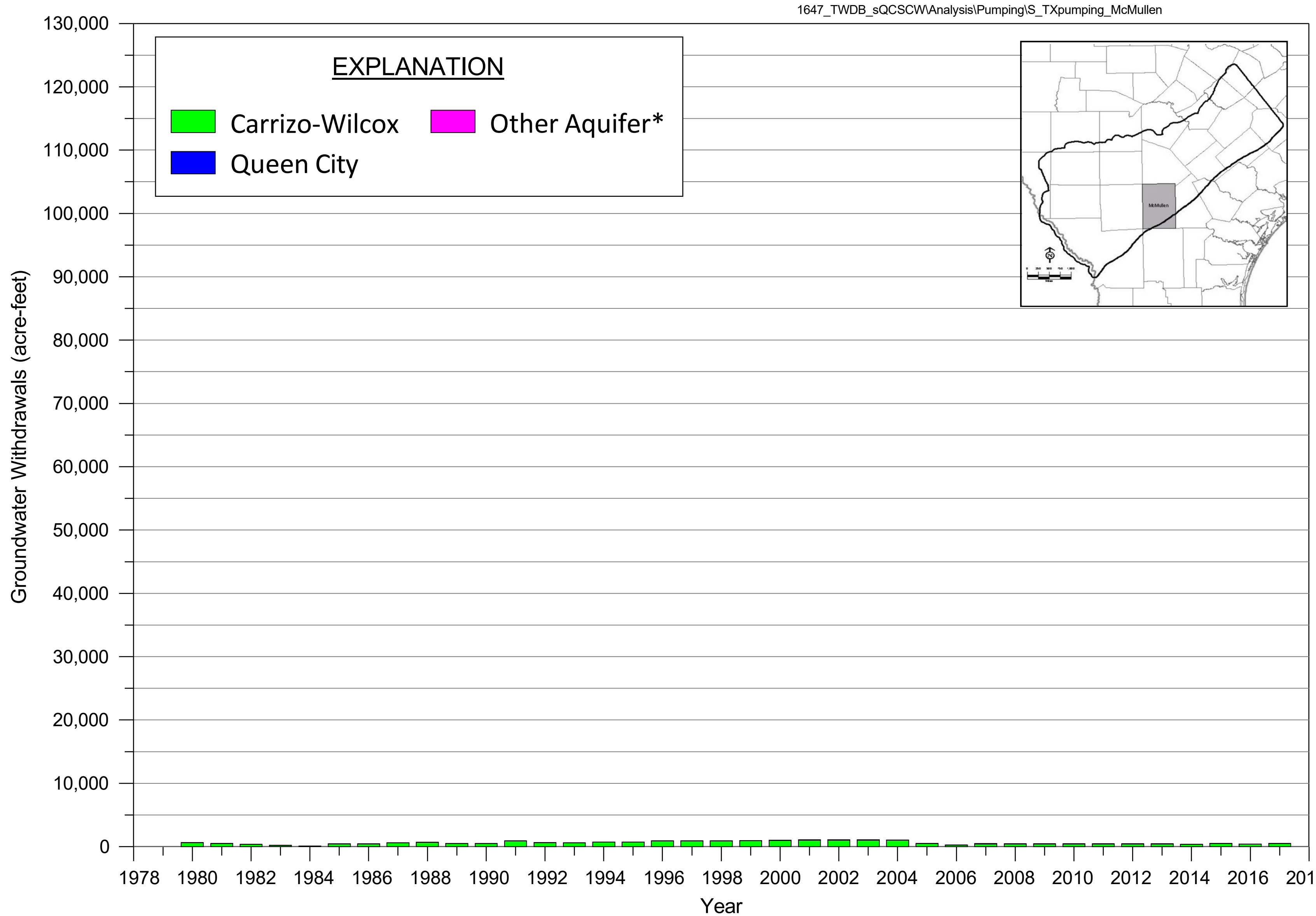
Source: TWDB annual water use surveys; totals include estimated pumpage from Queen City, Sparta, and Carrizo-Wilcox aquifers
** No values reported for Queen City and Sparta aquifers*



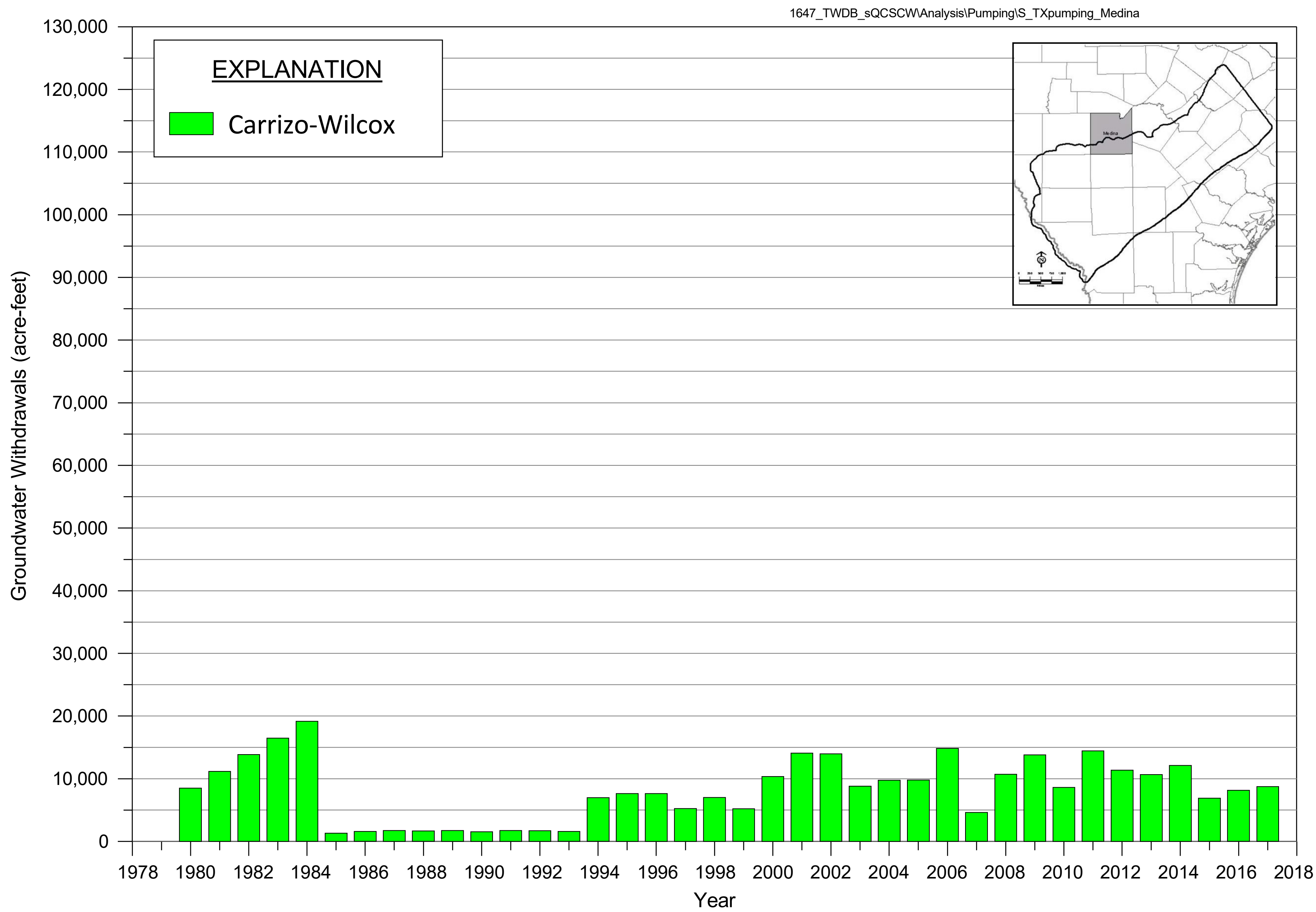
Source: TWDB annual water use surveys; totals include estimated pumpage from Queen City, Sparta, and Carrizo-Wilcox aquifers
**Other category may contain data from wells completed in alluvium and in any other units shallower than the Carrizo but deeper than the Yegua-Jackson aquifer.*



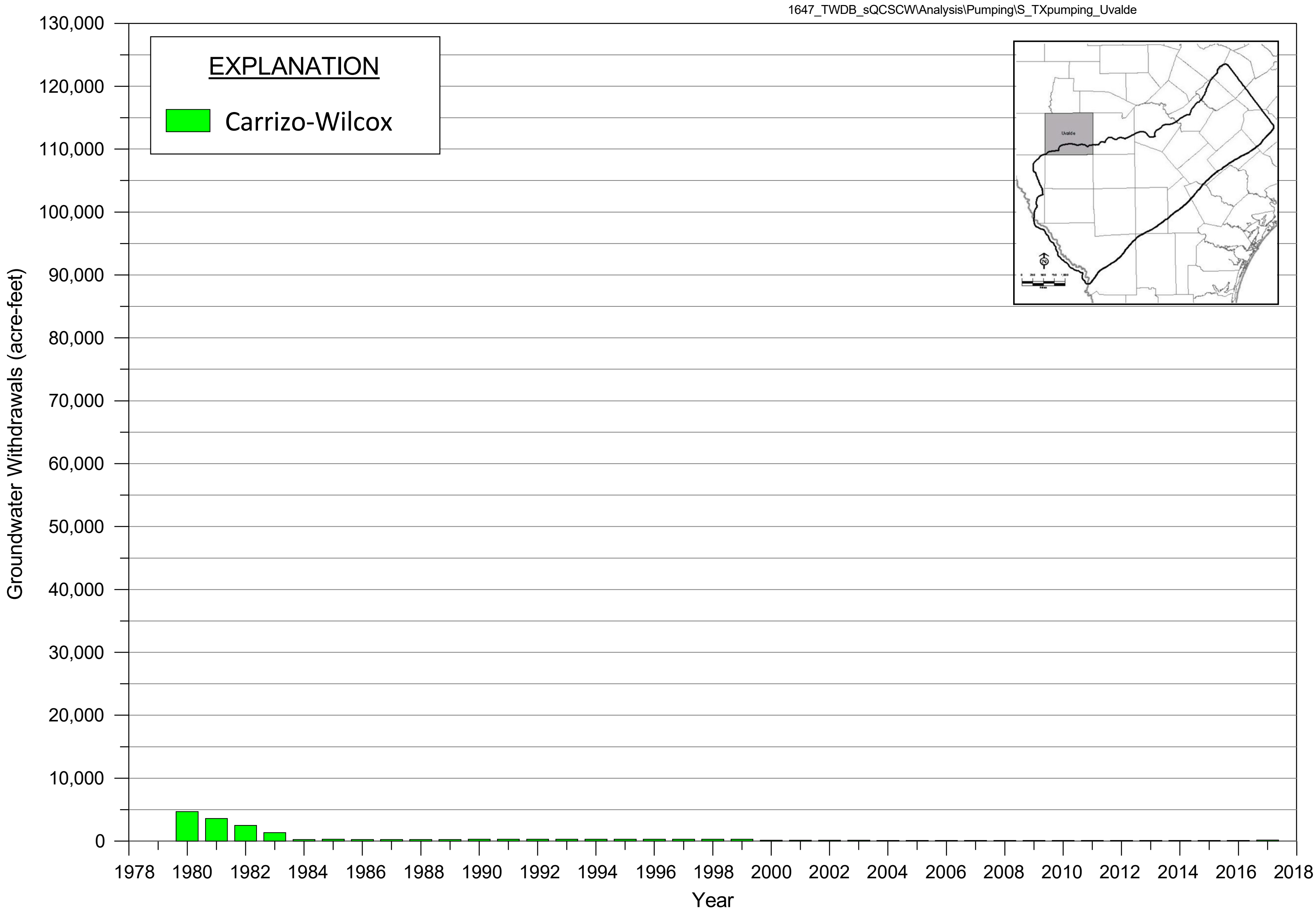
Source: TWDB annual water use surveys; totals include estimated pumpage from Queen City, Sparta, and Carrizo-Wilcox aquifers



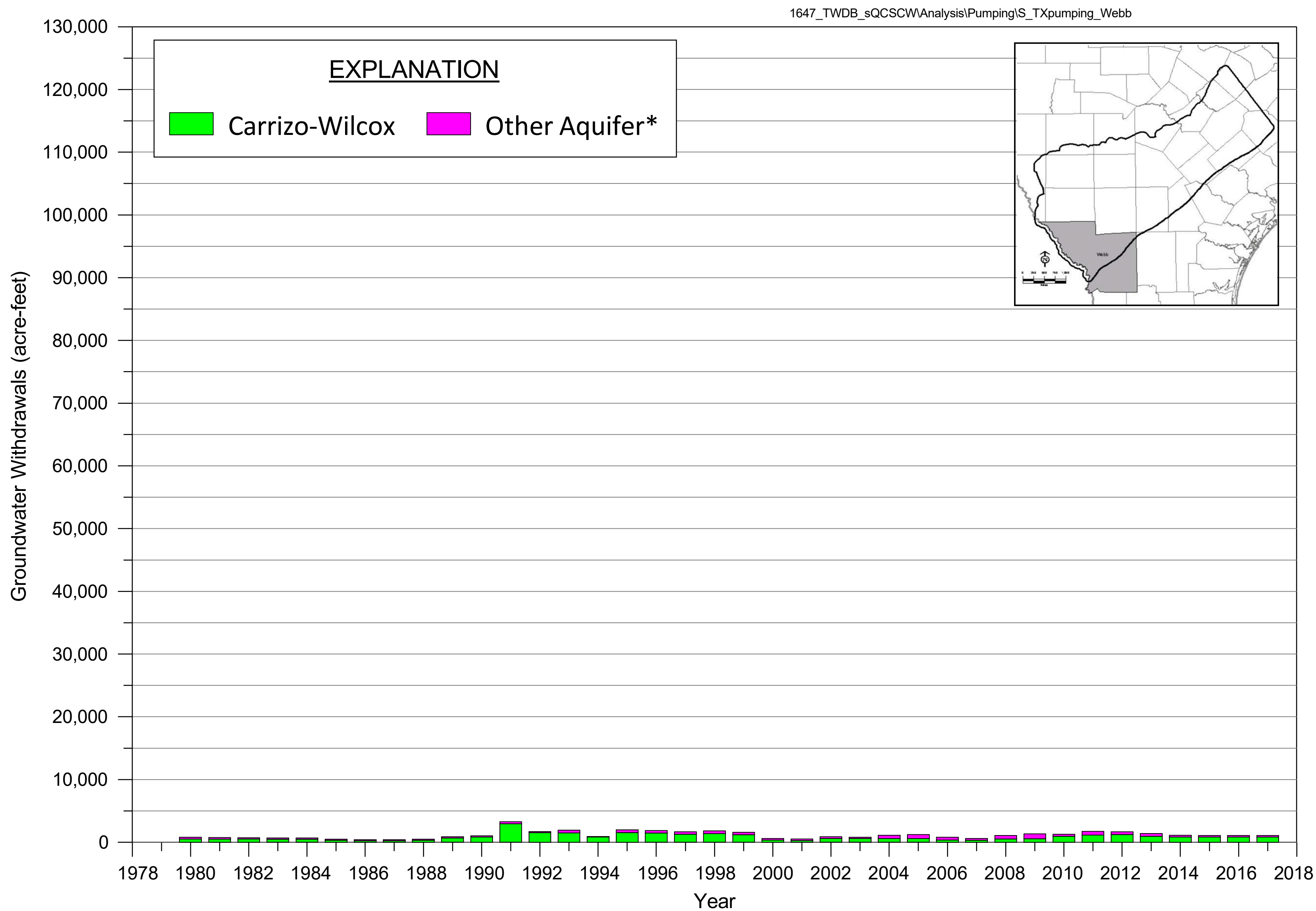
Source: TWDB annual water use surveys; totals include estimated pumpage from Queen City, Sparta, and Carrizo-Wilcox aquifers
**Other category may contain data from wells completed in alluvium and in any other units shallower than the Carrizo but deeper than the Yegua-Jackson aquifer.*
No reported values for Sparta aquifer



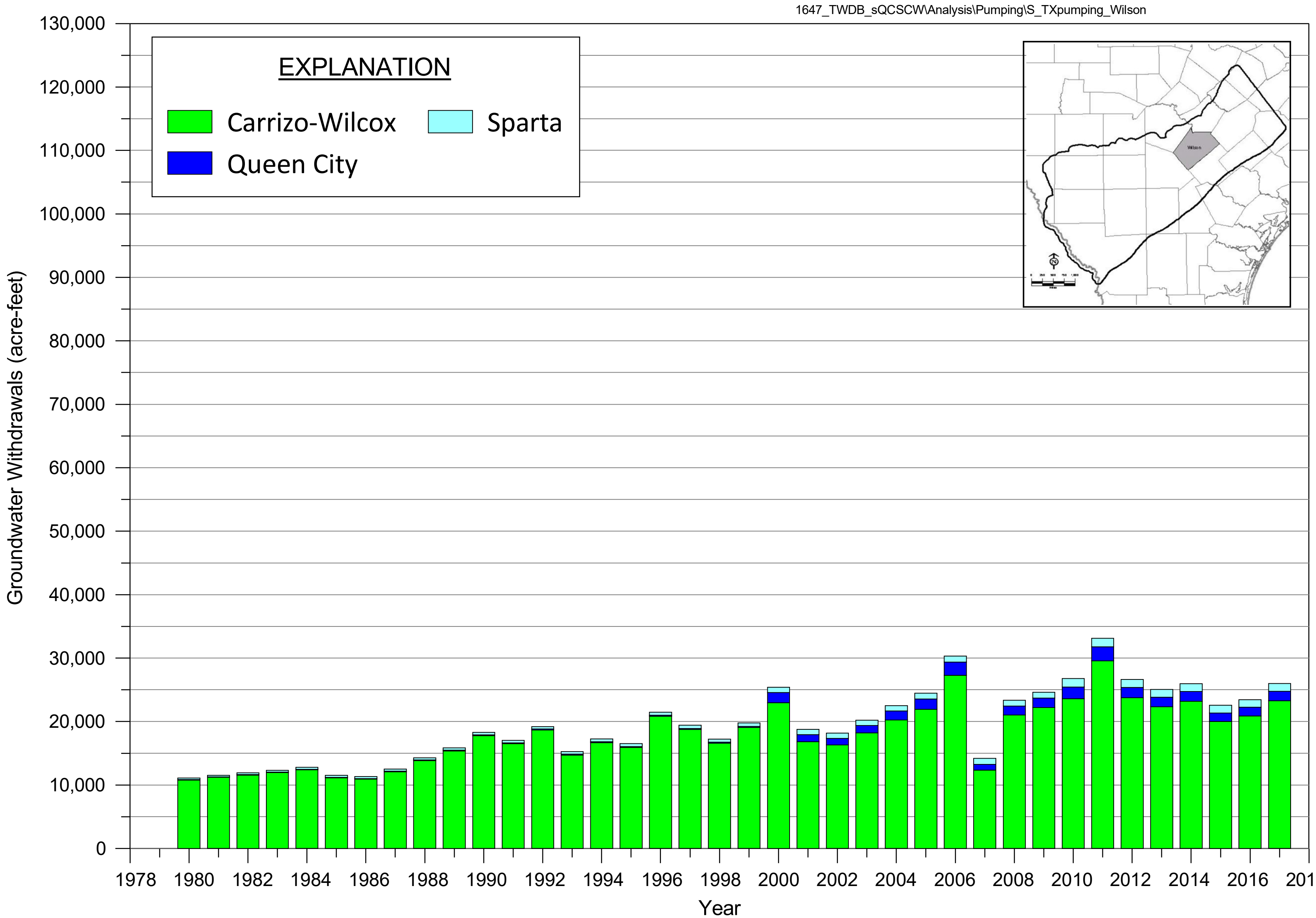
Source: TWDB annual water use surveys; totals include estimated pumpage from Queen City, Sparta, and Carrizo-Wilcox aquifers
** No values reported for Queen City and Sparta Aquifers*



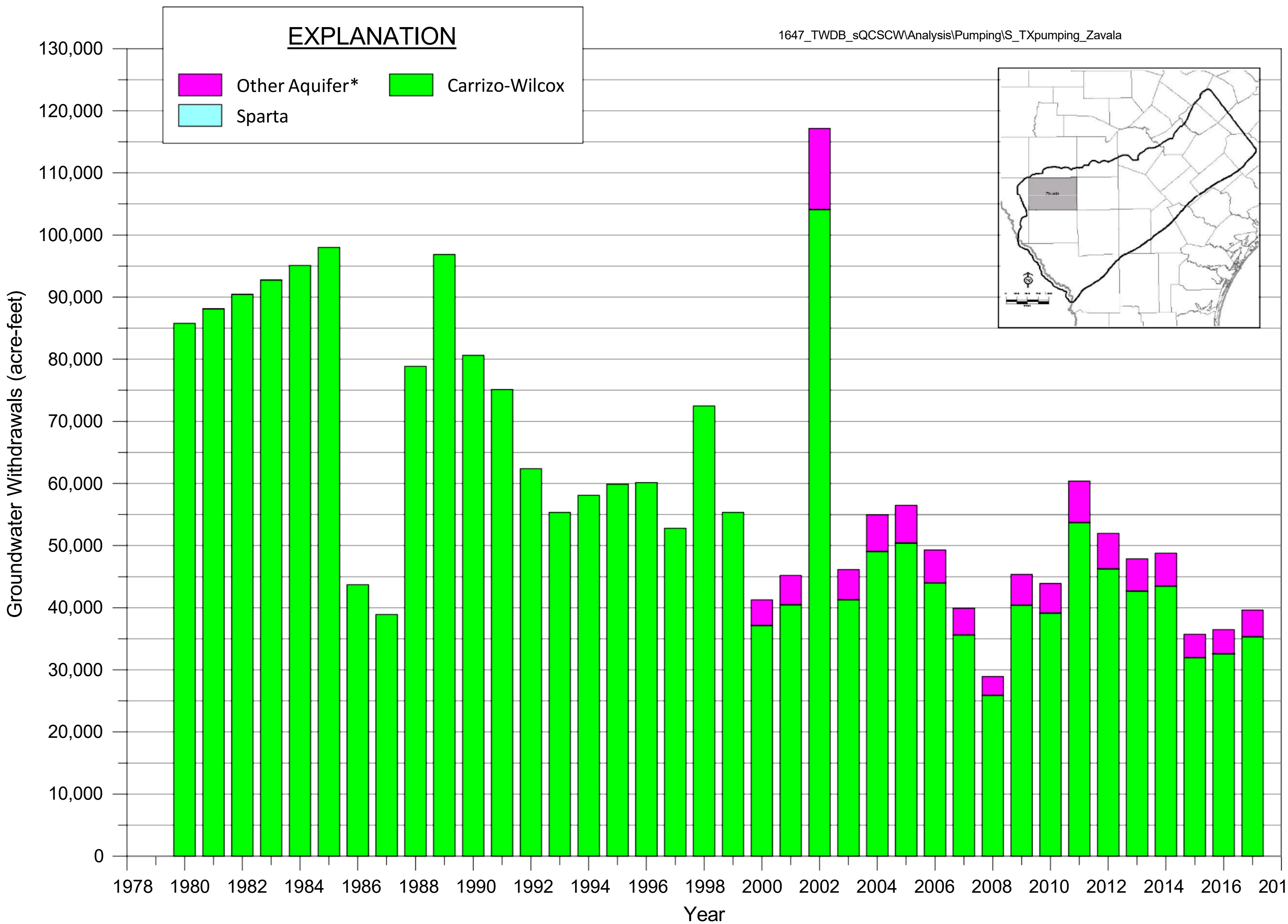
Source: TWDB annual water use surveys; totals include estimated pumpage from Queen City, Sparta, and Carrizo-Wilcox aquifers
** No values reported for Queen City and Sparta aquifers.*



Source: TWDB annual water use surveys; totals include estimated pumpage from Queen City, Sparta, and Carrizo-Wilcox aquifers
**Other category may contain data from wells completed in alluvium and in any other units shallower than the Carrizo but deeper than the Yegua-Jackson aquifer.*
No reported values for Sparta or Queen City aquifers



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



Source: TWDB annual water use surveys; totals include estimated pumpage from Queen City, Sparta, and Carrizo-Wilcox aquifers
**Other category may contain data from wells completed in alluvium and in any other units shallower than the Carrizo but deeper than the Yegua-Jackson aquifer.*
No reported values for Queen City aquifer; Values for Sparta aquifer are only reported after 1999.

Appendix B

Summary Table of Estimated Groundwater Pumping by County and Water Use Sector for Southern Portions of the Queen City, Sparta, and Carrizo-Wilcox Aquifers

Appendix B. Summary of estimated groundwater pumping by water use sector in counties in the study area.

	County	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998
Municipal																				
	ATASCOSA	3,735	4,434	5,133	5,832	6,531	5,752	4,630	4,701	5,757	6,065	5,195	3,140	4,453	4,842	4,909	4,992	5,436	4,881	4,910
	BASTROP	3,963	4,377	4,791	5,205	5,619	5,532	5,312	6,172	6,494	6,844	6,635	6,416	6,260	6,927	6,890	7,151	8,358	7,893	8,929
	BEXAR	814	999	1,184	1,370	1,555	779	777	819	1,019	862	886	1,453	875	1,023	938	1,061	1,473	1,419	1,431
	CALDWELL	2,061	2,069	2,078	2,086	2,094	2,199	2,353	2,200	2,250	2,166	2,270	1,861	1,988	2,116	2,184	2,217	2,697	2,233	2,379
	DIMMIT	2,829	2,698	2,568	2,438	2,307	2,221	2,347	2,122	2,573	2,685	2,210	3,906	2,376	2,617	2,522	2,704	2,816	2,408	2,488
	FAYETTE	62	56	51	47	41	38	38	37	36	42	59	57	68	71	66	106	83	83	167
	FRIO	2,946	2,935	2,924	2,915	2,904	2,714	2,690	2,490	3,026	3,337	3,045	3,059	2,598	3,033	2,951	2,542	3,063	2,617	2,586
	GONZALES	1,626	1,578	1,531	1,483	1,435	1,368	1,328	1,748	2,061	1,977	2,146	1,854	1,605	2,004	2,010	1,983	2,415	2,750	3,021
	GUADALUPE	538	506	475	444	412	553	465	441	473	661	413	576	1,045	1,233	1,154	1,086	1,112	998	1,035
	KARNES	192	201	210	219	228	194	213	211	209	225	326	197	207	216	212	231	237	198	251
	LA SALLE	998	1,036	1,074	1,112	1,150	964	953	1,030	1,161	1,302	1,232	1,336	1,300	1,328	1,268	1,307	1,383	1,183	1,435
	MAVERICK	39	54	69	84	99	130	60	84	7	93	133	150	99	92	140	129	91	85	74
	MCMULLEN	83	62	42	21	0	118	113	170	181	174	193	458	173	179	259	279	463	473	476
	MEDINA	97	124	150	176	203	207	201	202	221	159	110	109	117	130	266	267	136	422	488
	UVALDE	55	47	38	30	22	60	45	47	43	46	18	19	20	20	20	18	18	18	21
	WEBB	55	53	51	50	48	61	48	26	16	59	90	390	153	663	37	708	554	642	813
	WILSON	2,504	2,697	2,890	3,083	3,276	2,944	2,958	3,389	3,558	3,971	3,775	3,384	3,343	3,601	3,886	4,084	4,529	4,205	4,486
	ZAVALA	2,147	2,264	2,382	2,500	2,617	2,199	2,412	2,423	2,686	2,611	2,362	2,492	2,313	2,520	2,583	2,577	2,701	2,472	2,797
Manufacturing																				
	ATASCOSA	0	1	2	2	3	3	3	0	0	0	0	0	0	0	0	0	0	0	0
	BASTROP	152	147	142	138	133	128	132	59	24	24	23	10	12	62	67	62	69	65	19
	BEXAR	0	207	414	620	827	50	664	664	1,378	24	1	449	673	23	15	40	3	58	1
	CALDWELL	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	DIMMIT	22	19	16	13	10	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	FAYETTE	0	0	1	2	2	2	2	0	0	0	0	0	0	0	0	0	0	0	0
	FRIO	12	12	12	12	12	12	12	0	0	0	0	0	0	0	0	0	0	0	0
	GONZALES	0	0	0	0	0	0	0	0	0	0	0	0	0	0	37	167	154	157	141
	GUADALUPE	19	14	10	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	KARNES	0	74	148	223	297	96	90	122	105	211	176	213	107	85	190	127	10	1	0
	LA SALLE	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	MAVERICK	0	3	6	10	13	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	MCMULLEN	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	MEDINA	0	0	0	0	0	0	0	0	0	0	0	0	0	1	2	4	0	2	7
	UVALDE	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	WEBB	52	42	33	24	14	11	10	0	8	4	2	0	0	11	9	14	0	12	1
	WILSON	175	164	153	142	131	167	140	93	76	43	47	0	0	0	0	0	1	0	0
	ZAVALA	974	997	1,020	1,042	1,065	905	880	835	891	1,214	1,293	1,083	1,261	1,037	722	688	710	685	712
Mining																				
	ATASCOSA	1,171	1,116	1,060	1,004	949	1,752	1,002	1,373	1,313	597	664	1,428	1,412	1,344	1,264	1,377	1,377	1,256	1,125
	BASTROP	0	2	5	8	10	10	10	12	10	10	10	26	20	20	20	22	22	22	22
	BEXAR	53	104	156	208	259	207	0	183	158	147	147	168	168	168	168	168	168	168	74
	CALDWELL	0	1	2	2	3	21	1	22	19	21	21	11	11	10	10	10	10	10	10
	DIMMIT	732	657	582	507	432	582	74	587	498	506	506	920	920	920	920	919	919	919	919
	FAYETTE	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Appendix B. Summary of estimated groundwater pumping by water use sector in counties in the study area.

County	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998
FRIO	341	336	332	328	323	438	7	388	339	313	313	222	222	215	214	139	139	139	139
GONZALES	0	4	8	14	18	18	0	20	22	22	22	33	33	33	33	33	33	33	33
GUADALUPE	0	0	0	0	0	14	0	8	202	8	8	15	15	157	157	157	157	157	157
KARNES	1,102	885	668	450	233	255	257	266	334	149	162	102	132	132	132	133	133	128	115
LA SALLE	0	0	0	0	0	86	91	131	177	190	190	193	0	0	0	0	0	0	0
MAVERICK	0	2	4	7	9	25	0	22	22	20	20	11	11	11	11	11	11	11	11
MCMULLEN	446	334	223	112	0	226	238	256	258	235	239	391	399	390	390	390	390	399	399
MEDINA	0	6	12	18	24	31	0	28	28	26	26	24	24	24	24	24	24	24	24
UVALDE	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
WEBB	253	217	180	143	107	60	0	91	123	132	132	159	306	280	138	175	176	131	89
WILSON	228	230	232	235	237	309	0	277	300	281	281	285	285	277	277	277	277	277	277
ZAVALA	68	85	102	118	135	143	0	127	124	116	116	114	114	114	114	114	114	114	114
Electric Power																			
ATASCOSA	0	1,448	2,896	4,344	5,792	3,950	5,550	5,626	6,352	5,532	6,036	6,637	5,987	6,474	6,146	5,980	5,848	6,839	7,209
BASTROP	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
BEXAR	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
CALDWELL	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
DIMMIT	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FAYETTE	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FRIO	682	599	515	432	348	289	73	92	794	7	1	51	50	111	185	192	227	125	134
GONZALES	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
GUADALUPE	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
KARNES	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LA SALLE	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MAVERICK	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MCMULLEN	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MEDINA	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
UVALDE	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
WEBB	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
WILSON	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ZAVALA	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Irrigation																			
ATASCOSA	73,608	63,966	54,323	44,681	35,039	31,571	43,600	26,783	35,450	50,914	47,208	49,666	37,072	43,729	43,327	46,042	47,415	35,842	47,135
BASTROP	1,474	1,185	896	609	320	103	50	50	74	267	317	316	317	177	423	443	443	395	343
BEXAR	3,385	3,174	2,962	2,750	2,539	1,018	997	777	936	1,098	1,644	1,123	1,067	1,683	3,950	3,358	3,576	3,256	4,292
CALDWELL	50	86	123	160	196	104	105	105	105	108	488	0	741	147	147	220	227	203	715
DIMMIT	19,051	18,708	18,365	18,022	17,679	20,821	11,529	6,225	10,497	7,382	6,085	3,579	3,652	5,886	4,507	5,489	5,185	1,706	1,786
FAYETTE	23	18	14	9	4	7	6	9	9	9	3	3	2	19	49	41	40	40	41
FRIO	74,763	78,393	82,022	85,653	89,283	48,460	67,217	65,970	86,068	96,369	81,568	89,352	86,200	97,561	106,657	101,885	92,487	58,877	84,215
GONZALES	600	722	844	967	1,089	940	840	976	1,429	1,335	2,125	1,294	1,376	159	170	241	351	156	264
GUADALUPE	1,249	1,926	2,602	3,279	3,956	1,251	980	737	389	1,359	1,376	1,214	1,488	8	23	6	41	41	41
KARNES	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LA SALLE	10,759	10,379	10,001	9,622	9,242	3,003	2,666	2,467	2,426	6,051	6,198	6,278	7,974	6,750	5,524	4,895	7,137	4,721	3,618
MAVERICK	1,200	1,151	1,102	1,053	1,004	1,500	0	0	3,756	428	3,759	3,867	4,006	0	250	942	998	0	0
MCMULLEN	0	0	0	0	0	0	0	93	116	0	0	0	0	0	0	0	0	0	0
MEDINA	7,787	10,403	13,020	15,636	18,252	424	702	797	696	746	574	760	718	489	5,733	6,380	6,439	3,751	5,475

Appendix B. Summary of estimated groundwater pumping by water use sector in counties in the study area.

County	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998
UVALDE	4,435	3,326	2,218	1,109	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
WEBB	0	0	0	0	0	0	0	0	0	168	179	2,093	699	327	228	337	389	187	211
WILSON	6,499	6,677	6,855	7,033	7,211	6,174	6,257	6,734	8,245	9,139	11,642	10,818	13,031	8,677	10,274	9,300	13,656	11,919	9,432
ZAVALA	81,800	84,018	86,236	88,455	90,673	94,200	39,865	34,968	74,621	92,370	76,296	70,894	58,125	51,085	54,095	55,914	56,062	49,288	68,653
Livestock																			
ATASCOSA	211	206	202	196	191	201	176	151	156	154	160	164	180	191	214	196	183	167	156
BASTROP	998	874	751	629	505	456	423	453	478	470	463	474	494	493	512	485	570	413	474
BEXAR	29	26	24	21	18	38	40	34	35	35	38	38	42	44	31	29	51	50	32
CALDWELL	127	114	100	86	73	12	13	13	14	13	13	14	14	13	15	15	13	15	14
DIMMIT	674	695	716	736	757	633	596	841	795	783	790	807	617	590	789	788	682	655	401
FAYETTE	14	13	11	10	9	9	9	9	9	9	10	10	13	12	12	12	9	10	10
FRIO	215	195	176	154	134	119	107	111	109	107	109	112	119	131	148	149	91	90	125
GONZALES	1,966	1,569	1,172	774	377	382	404	401	377	384	410	419	507	544	452	483	342	403	419
GUADALUPE	119	102	86	70	53	64	75	72	76	75	76	79	85	85	87	84	137	77	76
KARNES	57	57	57	57	57	46	45	46	46	45	46	25	24	23	21	22	31	21	21
LA SALLE	118	121	122	125	128	104	105	101	100	99	98	101	108	100	77	75	57	61	61
MAVERICK	54	61	68	75	82	77	77	58	38	37	41	43	42	49	57	38	23	23	17
MCMULLEN	45	34	22	11	0	21	22	23	25	25	24	25	16	15	24	23	36	26	24
MEDINA	90	82	75	68	60	50	49	59	56	56	57	58	70	88	72	77	71	62	45
UVALDE	31	31	30	30	30	28	20	21	20	20	20	21	30	29	28	28	39	28	29
WEBB	176	170	163	157	151	153	164	167	175	172	170	174	93	81	105	111	152	99	134
WILSON	255	234	212	191	170	162	181	167	167	165	180	183	190	218	217	207	203	194	168
ZAVALA	397	330	263	196	129	113	92	83	69	68	71	73	88	89	96	92	81	86	69
Domestic																			
ATASCOSA	1,519	1,584	1,631	1,691	1,782	1,791	1,784	1,809	1,914	2,137	2,216	2,262	2,224	2,269	2,334	2,390	2,489	2,487	2,625
BASTROP	440	509	547	596	661	704	755	771	807	914	942	946	938	969	1,031	1,098	1,178	1,191	1,224
BEXAR	4,402	5,305	5,551	6,068	6,723	6,312	6,503	6,872	7,086	6,669	4,815	5,041	4,712	5,036	3,911	4,005	3,369	3,330	3,360
CALDWELL	562	602	622	659	710	709	770	795	803	717	880	869	848	882	917	947	993	937	956
DIMMIT	341	330	341	348	361	350	321	311	337	392	400	406	414	425	415	412	426	321	445
FAYETTE	118	128	135	135	138	137	141	140	135	139	146	145	146	154	152	166	169	170	162
FRIO	549	570	583	588	602	569	562	568	579	616	627	650	654	656	729	765	791	770	797
GONZALES	1,092	1,176	1,232	1,267	1,327	1,330	1,305	1,333	1,316	1,333	1,362	1,349	1,326	1,409	1,392	1,392	1,434	1,323	1,426
GUADALUPE	727	820	852	913	994	991	1,033	1,057	1,105	1,257	1,257	1,259	1,244	1,276	1,303	1,334	1,394	1,244	1,464
KARNES	480	505	515	514	521	500	484	493	486	520	546	535	525	542	531	553	555	517	522
LA SALLE	198	196	202	207	215	208	186	191	176	212	209	204	210	216	201	212	220	143	201
MAVERICK	10	11	12	12	13	13	13	14	14	17	14	15	14	15	16	3	3	3	3
MCMULLEN	55	59	59	67	77	81	73	70	82	40	39	39	38	27	29	32	33	30	24
MEDINA	522	563	576	590	614	603	625	636	639	764	776	764	764	850	852	878	963	970	977
UVALDE	164	174	178	185	196	185	161	173	167	192	233	224	227	234	236	237	242	238	244
WEBB	252	280	295	312	336	204	169	106	148	333	444	467	460	558	410	608	568	581	576
WILSON	1,428	1,535	1,570	1,641	1,745	1,757	1,784	1,832	1,926	2,251	2,354	2,343	2,355	2,503	2,604	2,642	2,818	2,816	2,878
ZAVALA	393	417	425	445	474	464	465	472	471	496	509	494	484	497	499	490	490	152	153

County	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998

Appendix B. Summary of estimated groundwater pumping by water use sector in counties in the study area.

TOTALS

County	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998
ATASCOSA	80,244	72,755	65,247	57,750	50,287	45,020	56,745	40,443	50,942	65,399	61,479	63,297	51,328	58,849	58,194	60,977	62,748	51,472	63,160
BASTROP	7,027	7,094	7,132	7,185	7,248	6,933	6,682	7,517	7,887	8,529	8,390	8,188	8,041	8,648	8,943	9,261	10,640	9,979	11,011
BEXAR	8,683	9,815	10,291	11,037	11,921	8,404	8,981	9,349	10,612	8,835	7,531	8,272	7,537	7,977	9,013	8,661	8,640	8,281	9,190
CALDWELL	2,800	2,872	2,925	2,993	3,076	3,045	3,242	3,135	3,191	3,025	3,672	2,755	3,602	3,168	3,273	3,409	3,940	3,398	4,074
DIMMIT	23,649	23,107	22,588	22,064	21,546	24,607	14,867	10,086	14,700	11,748	9,991	9,618	7,979	10,438	9,153	10,312	10,028	6,009	6,039
FAYETTE	217	215	212	203	194	193	196	195	189	199	218	215	229	256	279	325	301	303	380
FRIO	79,508	83,039	86,564	90,081	93,606	52,601	70,668	69,619	90,915	100,749	85,663	93,446	89,843	101,707	110,884	105,672	96,798	62,618	87,996
GONZALES	5,284	5,049	4,787	4,505	4,246	4,038	3,877	4,478	5,205	5,051	6,065	4,949	4,847	4,149	4,094	4,299	4,729	4,822	5,304
GUADALUPE	2,652	3,368	4,025	4,711	5,415	2,873	2,553	2,315	2,245	3,360	3,130	3,143	3,877	2,759	2,724	2,667	2,841	2,517	2,773
KARNES	1,831	1,722	1,598	1,463	1,336	1,091	1,089	1,138	1,180	1,150	1,256	1,072	995	998	1,086	1,066	966	865	909
LA SALLE	12,073	11,732	11,399	11,066	10,735	4,365	4,001	3,920	4,040	7,854	7,927	8,112	9,592	8,394	7,070	6,489	8,797	6,108	5,315
MAVERICK	1,303	1,282	1,261	1,241	1,220	1,745	150	178	3,837	595	3,967	4,086	4,172	167	474	1,123	1,126	122	105
MCMULLEN	629	489	346	211	77	446	446	612	662	474	495	913	626	611	702	724	922	928	923
MEDINA	8,496	11,178	13,833	16,488	19,153	1,315	1,577	1,722	1,640	1,751	1,543	1,715	1,693	1,582	6,949	7,630	7,633	5,231	7,016
UVALDE	4,685	3,578	2,464	1,354	248	273	226	241	230	258	271	264	277	283	284	283	299	284	294
WEBB	788	762	722	686	656	489	391	390	470	868	1,017	3,283	1,711	1,920	927	1,953	1,839	1,652	1,824
WILSON	11,089	11,537	11,912	12,325	12,770	11,513	11,320	12,492	14,272	15,850	18,279	17,013	19,204	15,276	17,258	16,510	21,484	19,411	17,241
ZAVALA	85,779	88,111	90,428	92,756	95,093	98,024	43,714	38,908	78,862	96,875	80,647	75,150	62,385	55,342	58,109	59,875	60,158	52,797	72,498
TOTAL	336,737	337,705	337,733	338,120	338,828	266,974	230,724	206,738	291,080	332,569	301,542	305,491	277,939	282,524	299,418	301,236	303,889	236,798	296,050

Appendix B. Summary of estimated groundwater pumping by water use sector in counties in the study area.

	County	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
Municipal																				
	ATASCOSA	4,995	5,123	5,120	4,745	4,678	4,640	5,027	7,716	4,036	4,944	5,369	6,643	6,749	6,976	6,467	6,669	6,294	5,975	6,076
	BASTROP	9,395	9,181	9,140	9,822	10,373	9,398	10,768	12,635	10,035	11,903	11,713	3,459	13,354	10,965	11,364	10,531	11,177	11,243	12,245
	BEXAR	1,532	1,150	43	41	43	42	35	43	36	61	6,064	734	6,558	4,428	6,886	9,562	3,823	228	2,182
	CALDWELL	2,363	2,568	2,581	2,695	2,803	2,717	1,017	908	889	1,381	2,131	1,424	2,235	2,781	2,424	5,954	3,931	3,451	4,208
	DIMMIT	2,543	2,531	2,424	2,274	2,078	1,983	2,331	2,383	1,805	2,267	2,303	2,180	2,437	2,460	2,475	2,042	2,053	1,998	2,000
	FAYETTE	85	32	42	35	27	25	20	25	239	421	21	76	416	366	515	487	520	521	510
	FRIO	2,956	3,169	3,194	2,576	2,414	2,565	2,938	3,115	2,593	2,518	3,387	2,700	3,446	3,385	3,401	3,480	3,214	3,209	3,401
	GONZALES	2,702	2,728	2,671	2,663	2,428	2,373	2,735	2,911	2,518	3,303	3,028	3,257	5,840	5,637	16,858	26,825	44,566	36,909	42,616
	GUADALUPE	1,225	1,054	1,209	1,122	1,062	1,132	1,154	994	976	1,514	1,231	948	677	2,535	2,199	2,376	3,481	2,447	3,838
	KARNES	251	137	130	148	248	246	150	111	99	98	109	83	144	111	112	577	1,008	814	949
	LA SALLE	1,537	1,568	1,460	1,460	1,138	1,148	1,194	1,405	1,287	1,403	1,582	1,703	1,739	1,745	1,731	1,831	1,716	1,938	1,863
	MAVERICK	40	22	22	23	25	24	26	8	7	7	93	181	198	180	162	136	121	133	114
	MCMULLEN	521	649	690	712	708	705	166	142	139	133	130	346	347	347	343	292	394	323	392
	MEDINA	481	898	956	1,098	1,078	1,118	1,252	1,835	417	1,519	1,654	394	1,038	1,185	1,148	1,167	1,008	971	959
	UVALDE	23	2	3	3	3	3	3	19	15	17	18	19	22	18	16	15	13	11	108
	WEBB	597	214	213	497	506	407	362	268	225	341	221	230	430	748	421	159	151	147	150
	WILSON	4,823	4,884	4,501	4,680	4,807	4,492	5,737	6,105	4,859	6,040	6,336	6,092	7,654	7,103	7,262	6,962	6,551	6,586	7,519
	ZAVALA	2,543	4,426	3,096	3,089	2,731	2,727	2,868	2,915	2,788	2,808	2,832	2,792	2,925	2,906	2,840	2,801	2,728	2,238	2,233
Manufacturing																				
	ATASCOSA	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	BASTROP	30	46	25	27	18	14	19	49	52	61	64	68	74	53	76	83	76	61	161
	BEXAR	1	1	4	4	8	2	1	8	1	1	1	4	5	4	7	8	17	5	4
	CALDWELL	0	0	0	0	0	0	0	0	0	0	630	182	220	142	122	112	133	171	179
	DIMMIT	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	FAYETTE	0	0	0	0	0	0	0	0	0	0	34	33	34	24	29	37	52	48	61
	FRIO	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	GONZALES	356	705	861	836	787	826	792	877	780	802	654	556	781	581	581	507	548	548	570
	GUADALUPE	0	0	4	0	4	3	3	3	3	3	3	0	0	2	2	0	0	2	2
	KARNES	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	LA SALLE	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	MAVERICK	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	MCMULLEN	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	MEDINA	10	1	1	3	3	3	3	3	3	3	3	12	14	12	10	9	11	10	9
	UVALDE	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	WEBB	19	19	16	16	16	16	22	11	9	8	0	0	0	0	0	0	0	0	0
	WILSON	1	1	6	5	5	5	5	5	5	5	19	37	37	36	36	36	46	54	48
	ZAVALA	1,100	922	758	1,412	920	982	1,103	1,103	707	566	541	541	495	495	551	603	668	662	456
Mining																				
	ATASCOSA	1,256	0	0	0	0	0	0	159	152	132	87	72	82	93	113	97	114	280	396
	BASTROP	22	0	0	0	0	0	0	0	0	0	0	0	0	45	44	22	44	22	29
	BEXAR	168	109	250	153	164	2,070	482	164	177	187	199	209	215	221	227	229	231	234	252
	CALDWELL	10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	DIMMIT	919	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	FAYETTE	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Appendix B. Summary of estimated groundwater pumping by water use sector in counties in the study area.

County	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
FRIO	139	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
GONZALES	30	313	39	36	36	36	36	36	36	0	3	40	34	10	0	0	0	0	0
GUADALUPE	157	0	0	0	0	0	0	0	0	0	0	0	0	56	22	35	15	10	0
KARNES	115	4	6	0	0	0	0	1	0	0	6	1	1	1	3	2	1	0	1
LA SALLE	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MAVERICK	11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MCMULLEN	399	221	220	218	220	219	219	0	219	219	219	0	0	0	0	0	0	0	0
MEDINA	24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
UVALDE	0	0	0	0	0	0	0	0	0	0	0	0	0	5	6	6	5	1	1
WEBB	97	13	0	0	5	5	0	0	0	0	0	0	0	0	0	0	0	0	0
WILSON	277	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ZAVALA	114	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Electric Power																			
ATASCOSA	6,839	7,379	7,379	7,363	7,363	7,363	7,363	8,196	3,816	6,448	7,879	7,197	7,954	8,427	7,934	5,750	3,478	5,036	7,962
BASTROP	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3,400	5,519	3,272	5,080
BEXAR	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
CALDWELL	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
DIMMIT	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FAYETTE	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FRIO	134	327	204	217	188	62	153	214	121	189	169	50	124	64	88	88	54	40	43
GONZALES	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
GUADALUPE	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
KARNES	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LA SALLE	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MAVERICK	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MCMULLEN	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MEDINA	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
UVALDE	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
WEBB	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
WILSON	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ZAVALA	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Irrigation																			
ATASCOSA	36,072	33,434	33,386	48,362	19,674	22,927	28,469	21,243	20,553	28,768	34,422	26,674	35,511	23,710	30,890	28,440	21,280	18,112	21,842
BASTROP	234	905	835	835	400	539	627	596	365	371	2,915	6,299	3,861	2,829	2,533	2,443	3,204	2,872	5,092
BEXAR	3,017	1,004	1,102	1,623	743	782	798	855	325	607	1,606	766	970	1,178	841	642	665	714	920
CALDWELL	616	137	223	223	129	83	156	181	32	136	77	373	533	395	300	339	210	206	202
DIMMIT	1,792	3,793	5,230	7,015	1,643	4,055	3,612	4,507	3,041	6,191	7,831	7,170	5,570	5,894	4,433	4,323	3,353	3,022	2,416
FAYETTE	40	83	79	77	105	125	150	126	65	0	77	42	330	228	87	88	79	146	179
FRIO	80,040	116,538	103,227	88,091	82,548	84,080	83,641	72,150	48,495	83,726	79,212	59,000	104,755	76,209	80,348	70,601	57,809	60,913	63,570
GONZALES	358	1,675	1,029	1,071	962	1,064	1,321	2,441	1,668	2,664	1,552	3,316	4,964	2,425	3,060	4,450	2,263	2,083	2,475
GUADALUPE	41	157	154	182	114	135	144	294	36	132	291	250	868	503	339	364	261	253	343
KARNES	0	0	0	0	0	0	0	0	0	0	0	107	131	78	94	146	68	89	96
LA SALLE	3,292	4,003	3,134	5,286	4,518	4,334	4,370	6,636	3,337	4,491	5,087	4,229	8,026	6,248	5,924	4,492	1,850	2,864	3,701
MAVERICK	0	0	0	0	0	0	0	0	0	0	0	0	444	6	4	10	38	48	57
MCMULLEN	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MEDINA	3,642	8,462	12,132	11,865	6,730	7,623	7,297	11,733	2,926	8,005	10,966	6,724	11,908	8,888	8,194	9,645	4,537	5,858	6,419

Appendix B. Summary of estimated groundwater pumping by water use sector in counties in the study area.

	County	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
	UVALDE	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	WEBB	143	59	91	136	47	460	512	168	0	335	692	92	392	4	23	1	1	4	11
	WILSON	11,424	16,171	9,968	9,179	11,112	13,686	13,727	19,270	4,300	12,211	13,201	13,553	18,309	13,019	11,265	12,434	9,448	10,276	11,858
	ZAVALA	51,353	35,140	40,617	111,873	41,692	50,481	51,396	44,019	35,241	24,283	40,682	39,298	55,645	47,350	43,368	44,246	31,193	32,430	35,759
Livestock																				
	ATASCOSA	168	151	772	123	140	135	931	863	965	1,175	1,291	1,479	1,535	908	915	951	978	987	955
	BASTROP	510	494	313	313	341	319	235	235	167	190	183	192	192	158	142	153	156	158	199
	BEXAR	34	33	31	32	27	3	13	12	11	33	34	61	61	24	27	23	24	24	26
	CALDWELL	16	30	14	15	15	16	58	41	44	36	34	41	40	36	36	37	38	39	51
	DIMMIT	442	442	405	327	300	300	217	294	217	258	233	228	233	203	156	150	152	155	179
	FAYETTE	11	11	3	3	3	12	21	21	21	20	20	20	19	17	14	16	18	18	17
	FRIO	131	121	82	126	98	101	632	619	522	533	674	484	491	420	535	717	776	817	554
	GONZALES	460	332	321	337	346	342	2,717	2,749	2,560	2,638	2,528	5,549	5,496	5,222	5,246	5,151	5,288	5,455	2,310
	GUADALUPE	81	74	49	49	51	44	337	323	369	293	295	601	611	253	280	299	313	326	324
	KARNES	21	21	8	9	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	LA SALLE	69	57	71	56	49	52	225	313	164	238	238	234	236	204	156	169	169	173	88
	MAVERICK	15	17	8	10	7	12	158	233	170	174	188	97	143	123	140	165	172	180	167
	MCMULLEN	25	15	47	28	28	6	12	9	9	9	9	12	9	6	6	6	6	6	6
	MEDINA	51	15	11	13	13	23	264	272	278	194	200	323	327	155	163	165	167	170	203
	UVALDE	28	27	25	25	23	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	WEBB	140	129	31	56	45	45	193	203	203	211	275	173	175	147	166	172	165	169	140
	WILSON	190	143	101	113	109	109	815	751	847	903	867	1,244	1,267	621	654	677	695	705	726
	ZAVALA	91	75	52	77	101	87	420	584	470	573	597	513	556	448	358	357	363	378	429
Domestic																				
	ATASCOSA	2,686	3,679	3,679	3,679	3,679	3,679	3,679	3,679	3,679	3,679	3,679	4,645	4,645	4,645	4,645	4,645	4,645	4,645	4,645
	BASTROP	1,266	1,947	1,947	1,947	1,947	1,947	1,947	1,947	1,947	1,947	1,947	2,682	2,682	2,682	2,682	2,682	2,682	2,682	2,682
	BEXAR	3,369	6,230	6,230	6,230	6,230	6,230	6,230	6,230	6,230	6,230	6,230	7,770	7,770	7,770	7,770	7,770	7,770	7,770	7,770
	CALDWELL	963	1,275	1,275	1,275	1,275	1,275	1,275	1,275	1,275	1,275	1,275	1,749	1,749	1,749	1,749	1,749	1,749	1,749	1,749
	DIMMIT	448	613	613	613	613	613	613	613	613	613	613	612	612	612	612	612	612	612	612
	FAYETTE	163	65	65	65	65	65	65	65	65	65	65	80	80	80	80	80	80	80	80
	FRIO	808	671	671	671	671	671	671	671	671	671	671	880	880	880	880	880	880	880	880
	GONZALES	1,439	1,802	1,802	1,802	1,802	1,802	1,802	1,802	1,802	1,802	1,802	2,050	2,050	2,050	2,050	2,050	2,050	2,050	2,050
	GUADALUPE	1,529	2,012	2,012	2,012	2,012	2,012	2,012	2,012	2,012	2,012	2,012	2,403	2,403	2,403	2,403	2,403	2,403	2,403	2,403
	KARNES	524	665	665	665	665	665	665	665	665	665	665	675	675	675	675	675	675	675	675
	LA SALLE	201	217	217	217	217	217	217	217	217	217	217	476	476	476	476	476	476	476	476
	MAVERICK	3	1	1	1	1	1	1	1	1	1	1	2	2	2	2	2	2	2	2
	MCMULLEN	21	90	90	90	90	90	90	90	90	90	90	76	76	76	76	76	76	76	76
	MEDINA	1,005	985	985	985	985	985	985	985	985	985	985	1,143	1,143	1,143	1,143	1,143	1,143	1,143	1,143
	UVALDE	247	81	81	81	81	81	81	81	81	81	81	72	72	72	72	72	72	72	72
	WEBB	595	153	153	153	153	153	153	153	153	153	153	755	755	755	755	755	755	755	755
	WILSON	3,052	4,190	4,190	4,190	4,190	4,190	4,190	4,190	4,190	4,190	4,190	5,834	5,834	5,834	5,834	5,834	5,834	5,834	5,834
	ZAVALA	153	704	704	704	704	704	704	704	704	704	704	772	772	772	772	772	772	772	772

County	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017

Appendix B. Summary of estimated groundwater pumping by water use sector in counties in the study area.

TOTALS

County	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
ATASCOSA	52,016	49,766	50,336	64,272	35,534	38,744	45,469	41,856	33,201	45,146	52,727	46,710	56,476	44,759	50,964	46,552	36,789	35,035	41,876
BASTROP	11,457	12,573	12,260	12,944	13,079	12,217	13,596	15,462	12,566	14,472	16,822	12,700	20,163	16,732	16,841	19,314	22,858	20,310	25,488
BEXAR	8,121	8,527	7,660	8,083	7,215	9,129	7,559	7,312	6,780	7,119	14,134	9,544	15,579	13,625	15,758	18,234	12,530	8,975	11,154
CALDWELL	3,968	4,010	4,093	4,208	4,222	4,091	2,506	2,405	2,240	2,828	4,147	3,769	4,777	5,103	4,631	8,191	6,061	5,616	6,389
DIMMIT	6,144	7,379	8,672	10,229	4,634	6,951	6,773	7,797	5,676	9,329	10,980	10,190	8,852	9,169	7,676	7,127	6,170	5,787	5,207
FAYETTE	299	191	189	180	200	227	256	237	390	506	217	251	879	715	725	708	749	813	847
FRIO	84,208	120,826	107,378	91,681	85,919	87,479	88,035	76,769	52,402	87,637	84,113	63,114	109,696	80,958	85,252	75,766	62,733	65,859	68,448
GONZALES	5,345	7,555	6,723	6,745	6,361	6,443	9,403	10,816	9,364	11,209	9,567	14,768	19,165	15,925	27,795	38,983	54,715	47,045	50,021
GUADALUPE	3,033	3,297	3,428	3,365	3,243	3,326	3,650	3,626	3,396	3,954	3,832	4,202	4,559	5,752	5,245	5,477	6,473	5,441	6,910
KARNES	911	827	809	822	922	911	815	777	764	763	780	866	951	865	884	1,400	1,752	1,578	1,721
LA SALLE	5,099	5,845	4,882	7,019	5,922	5,751	6,006	8,571	5,005	6,349	7,124	6,642	10,477	8,673	8,287	6,968	4,211	5,451	6,128
MAVERICK	69	40	31	34	33	37	185	242	178	182	282	280	787	311	308	313	333	363	340
MCMULLEN	966	975	1,047	1,048	1,046	1,020	487	241	457	451	448	434	432	429	425	374	476	405	474
MEDINA	5,213	10,361	14,085	13,964	8,809	9,752	9,801	14,828	4,609	10,706	13,808	8,596	14,430	11,383	10,658	12,129	6,866	8,152	8,733
UVALDE	298	110	109	109	107	84	84	100	96	98	99	91	94	95	94	93	90	84	181
WEBB	1,591	587	504	858	772	1,086	1,242	803	590	1,048	1,341	1,250	1,752	1,654	1,365	1,087	1,072	1,075	1,056
WILSON	19,767	25,389	18,766	18,167	20,223	22,482	24,474	30,321	14,201	23,349	24,613	26,760	33,101	26,613	25,051	25,943	22,574	23,455	25,985
ZAVALA	55,354	41,267	45,227	117,155	46,148	54,981	56,491	49,325	39,910	28,934	45,356	43,916	60,393	51,971	47,889	48,779	35,724	36,480	39,649
TOTAL	263,857	299,524	286,198	360,882	244,388	264,710	276,831	271,487	191,824	254,079	290,389	254,082	362,562	294,731	309,847	317,437	282,175	271,923	300,606

Appendix C

Responses to Comments on Interim Draft Framework

Appendix C

The following report and data review comments shall be addressed and included in the final draft deliverables by no later than March 30, 2020. Please note that the suggested comments noted may improve the readability of the report and/or the usability of the data deliverables.

Note: Responses to comments related to the interim draft framework and associated report chapter are shown below in italic font.

Framework Report comments:

1. Per the Contract Section II, Article III, item 9, page 4 of 16, no acronyms except TWDB (Texas Water Development Board) will be used in the report. Please use groundwater availability model instead of GAM or re-word to “model” as appropriate. GAM is used at least 18 times in the interim draft report.
Acronyms of GAM were changed accordingly to either groundwater availability model or simply model.

2. Per the Contract Section II, Article III, item 9, page 4 of 16, no acronyms except TWDB (Texas Water Development Board) will be used in the report. Page 3, Section 2.4.1.1, First sentence: Please spell out BRACS when referring to the group, Brackish Resources Aquifer Characterization System Group.
Acronyms of BRACS were changed accordingly to Brackish Resources Aquifer Characterization System Group.

3. Per the Contract Section II, Article III, item 9, page 4 of 16, no acronyms except TWDB (Texas Water Development Board) will be used in the report. Page 4, first paragraph, last sentence: Please spell out BRACS throughout the report when referring to the program or group; BRACS should only be used when citing the BRACS geodatabase.
Acronyms of BRACS were changed accordingly to Brackish Resources Aquifer Characterization System Group.

4. Per the Contract, Appendix A: GAM Standards, Attachment 4: Guidelines for Authors Submitting Contract Reports to the Texas Water Development Board, Section 4.2 on page 5 of 10, all sources that are cited within the report should be listed at the end of the paper under the heading References. Page 4, third paragraph, Section 2.4.1.2, end of paragraph: Stoeser and others, 2007 is not listed in the reference section. Please include this reference.
The reference section was updated to include this reference.

5. Per the Contract Section II, Article III, item 9, page 4 of 16, no acronyms except TWDB (Texas Water Development Board) will be used in the report. Page 7, fourth paragraph, Section 2.4.1.4, last two lines: Please spell out Bureau of Economic Geology (BEG), Brackish Resources Aquifer Characterization System (BRACS), Montgomery & Associates (M&A), and United States Geological Survey (USGS).

These acronyms were changed accordingly.

6. Per the Contract Section II, Article III, item 9, page 4 of 16, no acronyms except TWDB (Texas Water Development Board) will be used in the report. Page 8, second paragraph, Section 2.4.1.4, last line: Please spell out groundwater availability modeling and please clarify what is meant by GAM aquifer system. Please consider re-wording to aquifers in the study or aquifers to be modeled.
This acronym was changed accordingly and the GAM aquifer system was reworded to "aquifer system in the groundwater availability model".

7. Per the Contract Section II, Article III, item 9, page 4 of 16, no acronyms except TWDB (Texas Water Development Board) will be used in the report. Page 7, first paragraph and page 8, fourth paragraph, Section 2.4.1.5: Please spell out Texas Natural Resource Information System.
This acronym was changed accordingly.

8. Per the Contract Section II, Article III, item 9, page 4 of 16, no acronyms except TWDB (Texas Water Development Board) will be used in the report. Page 8, fifth paragraph, Section 2.4.1.5, fourth line: Please spell out United States Geological Survey on this page and the other four times USGS is used in the report.
This acronym was changed accordingly.

Suggested comments to be addressed on Framework text:

9. Please capitalize aquifer when used with the aquifer name; for example, Sparta Aquifer, Queen City Aquifer, and so on.
The word aquifer was changed to be capitalized when a part of the aquifer name.

10. Page 2, paragraph 2, last sentence: Section 2.4.2 is cited for the hydrostratigraphic framework discussion; however, that section is 2.4.1.4. Please verify and update if appropriate.
The section reference was updated accordingly to the correct section. Please note: the draft report has the framework section in Section 2.2.

11. Page 3, third line: Section 2.4.1.5 is cited for discussion of the upper Wilcox and Carrizo; however, that section is 2.4.1.10. Please verify and update if appropriate.
The section reference was updated accordingly to the correct section. Please note: the draft report has the framework section in Section 2.2.

12. Page 3, second paragraph: The content of the second paragraph seems to be part of the first paragraph. We recommend combining paragraphs one and two on page 3.
This comment is addressed by combining the content of these paragraphs into one paragraph.

13. Page 7, fifth paragraph, Section 2.4.1.4, first sentence and Figure 2.27 on page 24: Text states "Quaternary Deposits within the stream channels and tributaries in the study area are shown on Figure 2.27"; however, the figure caption states that Quaternary Deposits are not shown.

This comment is addressed by removing the in-text reference since the figure did not show the Quaternary Deposits. Please note, this figure is now currently Figure 2.4 in the draft report and the framework section in Section 2.2.

14. Page 8, fifth paragraph, Section 2.4.1.5, second line: Bastrop is spelled as Batrop. Please update with correct spelling.
The spelling of Bastrop was corrected. Please note: the draft report has the framework section in Section 2.2.

15. Page 15, second paragraph, Section 2.4.11, fifth line: Please spell out percent rather than use the % symbol. In other words, 20 to 40 percent, rather than 20 to 40%.
Percent was spelled out instead of using the % symbol.

16. Page 25, Figure 2.28: Please consider marking and labeling county boundaries along the top of the cross-sections.
The county boundaries were labelled along the top of the cross-sections.

17. We suggest using miles rather than feet for the distance axis. Also please add commas to delineate multiples of 1,000s.
The horizontal axis distance was changed to mile units and commas were added to the vertical axis labels.

18. For the legends of formation elevations, please consider using “to” instead of hyphen. For example, -1,000 to -1,200 instead of -1,000 - -1,200.
The separator between formation elevation values in the explanation were changed to “to” instead of “-“.