A Conceptual Model of Groundwater Flow in the Blossom Aquifer

Shirley C. Wade, Ph.D., P.G.,
Radu Boghici, P.G.,
and Roberto Anaya, P.G.
Texas Water Development Board
April, 2021

This document is released for the purpose of interim review under the authority of Shirley C. Wade, P.G. 525, Radu Boghici, P.G. 482, and Roberto Anaya, P.G. 480 on April 26, 2021. Materials and findings are subject to change and should not be applied for public use until the work is finalized.

This page is intentionally blank.

A Conceptual Model of Groundwater Flow in the Blossom Aquifer

Shirley C. Wade, Ph.D., P.G.,
Radu Boghici, P.G.,
and Roberto Anaya, P.G.
Texas Water Development Board
April, 2021

This page is intentionally blank.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

A Conceptual Model of Groundwater Flow in the Blossom Aquifer

Shirley C. Wade, Ph.D., P.G.,
Radu Boghici, P.G.,
and Roberto Anaya, P.G.
Texas Water Development Board
April, 2021

EXECUTIVE SUMMARY

The Blossom Aquifer, located in portions of Bowie, Red River, and Lamar counties, provides water for the City of Clarksville and the Red River Water Supply Corporation in Red River County, as well as for domestic and livestock wells in all three counties. In order to better understand the Blossom Aquifer flow system and to provide a tool for local and regional water planning, the Texas Water Development Board (TWDB) is developing a groundwater flow model of the Blossom Aquifer as part of the groundwater availability modeling program. In the first phase of the model development, all available hydrogeological data for the area were compiled, reviewed, and analyzed. These hydrogeological data were then used to develop a conceptual model of the groundwater flow system. The final phase of the project is to build and calibrate a numerical groundwater model based on the conceptual model.

The Blossom Aquifer is the water producing portion of the Blossom Sand which is part of an Upper Cretaceous ramp-like shelf margin depositional package in the Gulf Coast Region. The deposits include carbonates, sandstones, basinal marls, and mudrocks. The Blossom Sand dips toward the east and the south thickening downdip and eastward along strike with a maximum thickness in the subsurface of about 350 feet.

The study area has a subtropical humid climate and receives 46 to 50 inches precipitation per year. The average daily maximum temperatures range from 74 to 75 degrees Fahrenheit and average daily minimum temperatures range from 50 to 53 degrees

Fahrenheit. Vegetation consists primarily of pine and hardwood forests and native and introduced grasses.

Much of the Blossom Sand outcrop is covered by thin, high-level terrace alluvium deposits. Terrace alluvium deposits are loose, unconsolidated sediment deposited by rivers over time. Groundwater in the study area is produced from both the Blossom Sand and overlying alluvium deposits. Adjacent to the Red River, thicker deposits of alluvium overlie the Blossom Sand. In some locations, the alluvium directly overlies the Blossom Sand and they are hydraulically connected. South of the Blossom Sand outcrop, the terrace deposits and alluvium overlie the Brownstown Formation, and do not directly overly the Blossom Aquifer. The median hydraulic conductivity, a term to describe the ability of material to transmit fluid, of the Blossom Sand from 19 measurements is 5.3 feet per day, and the median for the alluvium deposits based on 13 measurements is 80 feet per day.

Water levels in the Blossom Aquifer range from more than 550 feet above mean sea level in the northwest part of the outcrop area to less than 150 feet above mean sea level in the deepest part of the subcrop. Recharge enters the aquifer on the outcrop where the aquifer is exposed at land surface and moves slowly downdip, eventually discharging through seepage into other formations in the subsurface, particularly along the Luling-Mexia-Talco fault system. Isotope data suggest the groundwater is older than 10,000 years in the deeper portions of the aquifer. Estimates of annual recharge range from zero, for a dry year, to 4 inches, for a wet year. The estimated recharge for an average year is about 1 inch per year.

Groundwater leaves the Blossom Aquifer through natural processes in the outcrop, such as evapotranspiration (groundwater loss to the atmosphere through plants) and leakage to streams, and through groundwater pumping in the outcrop and subcrop. The Blossom Aquifer also discharges to other formations downdip, especially along the Luling-Mexia-Talco fault system. Most groundwater pumping from the Blossom Aquifer is for municipal supply in Red River County. The municipal pumping amounts range from about 300 acre-feet per year to about 1,000 acre-feet per year for 1957 through 2012. Lesser amounts are produced for domestic supply and livestock use. Water is also produced for irrigation from the Red River Alluvium in the study area.

Laboratory analyses extracted from the TWDB groundwater database for 67 groundwater samples from the Blossom Aquifer samples collected from 1953 through 2006 show the groundwater to be predominantly of calcium-sodium-bicarbonate-chloride facies. The groundwater in the Blossom Aquifer is mostly fresh, with 43 samples having total dissolved solids concentrations of 1,000 milligrams per liter or less. Two samples exceeded the maximum contaminant level for nitrate and one sample exceeded the maximum contaminant level for arsenic. The secondary standards were exceeded for total dissolved solids in 24 samples, chloride in 12 samples, sulfate in 12 samples, zinc in ten samples, fluoride in six samples, iron (dissolved) in three samples, and manganese in two samples. The range of total dissolved solids was from 15 milligrams per liter to 16,834 milligrams per liter. Generally, the freshest water occurred in and near the outcrop of the Blossom

Sand, and the more saline groundwater occurred downdip. The downdip limits of the Blossom Aquifer correspond to an estimated total dissolved solids maximum concentration of 3,000 milligrams per liter. One well about three miles beyond the downdip aquifer boundary has total dissolved solids concentration of more than 15,000 milligrams per liter.

1.0 INTRODUCTION

The Blossom Aquifer is located in portions of Bowie, Red River, and Lamar counties in northeast Texas. While most of the water used in these three counties is supplied by surface water, the Blossom Aquifer provides water for the City of Clarksville and the Red River Water Supply Corporation, as well as a number of domestic and livestock wells (Ridgeway and Hamlin, 2005). In order to better understand the groundwater flow system and to provide a tool for local and regional water planning, the Texas Water Development Board (TWDB) is developing a groundwater flow model of the Blossom Aquifer as part of the Groundwater Availability Modeling Program. The goal of the Groundwater Availability Modeling Program is to provide useful and timely information for determining groundwater availability for the citizens of Texas. The program produces standardized, thoroughly documented, and publicly available groundwater flow models (TWDB, 2013a). This report will discuss the study area, including physiography, climate, and geology; previous studies in the area; and the hydrogeologic setting. The hydrogeologic setting includes information on the structural framework of the aquifer, groundwater levels, groundwater flow, recharge to the aquifer, surface water, evapotranspiration, groundwater discharge, and water quality, including estimated age of the groundwater.

2.0 STUDY AREA

The Blossom Sand outcrops in the northeast Texas counties of Bowie, Lamar, and Red River (Figure 1). The Blossom Aquifer is the part of the Blossom Sand, which is a productive source of water to wells. The outcrop and subcrop portions of the aquifer cover about 277 square miles and extend about 55 miles west of the Red River. The Blossom Aquifer is in the North East Texas Regional Water Planning Area and in Groundwater Management Area 8 (Figure 2). There are no groundwater conservation districts in the study area.

The Blossom Aquifer outcrop intersects the divide between the Sulphur and the Red River basins (Figure 3). The Red River flows northwest to southeast along the eastern boundary of the aquifer. Pecan Bayou is a tributary of the Red River at the eastern extent of the Blossom outcrop and much of its course flows over the Blossom outcrop (Gordon, 1911).

The study area is largely rural (Bucher Willis and Ratliff Corporation, 2010). The city of Paris in Lamar County has the largest population in the study area with about 25,000 people (Ludeman, 2015). The remainder of the towns have populations much lower than 10,000. The main economic base is agribusiness, including a variety of crops, cattle, and poultry production. Timber is also an important industry. There is also some oil and gas production in the area (Bucher Willis and Ratliff Corporation, 2010).

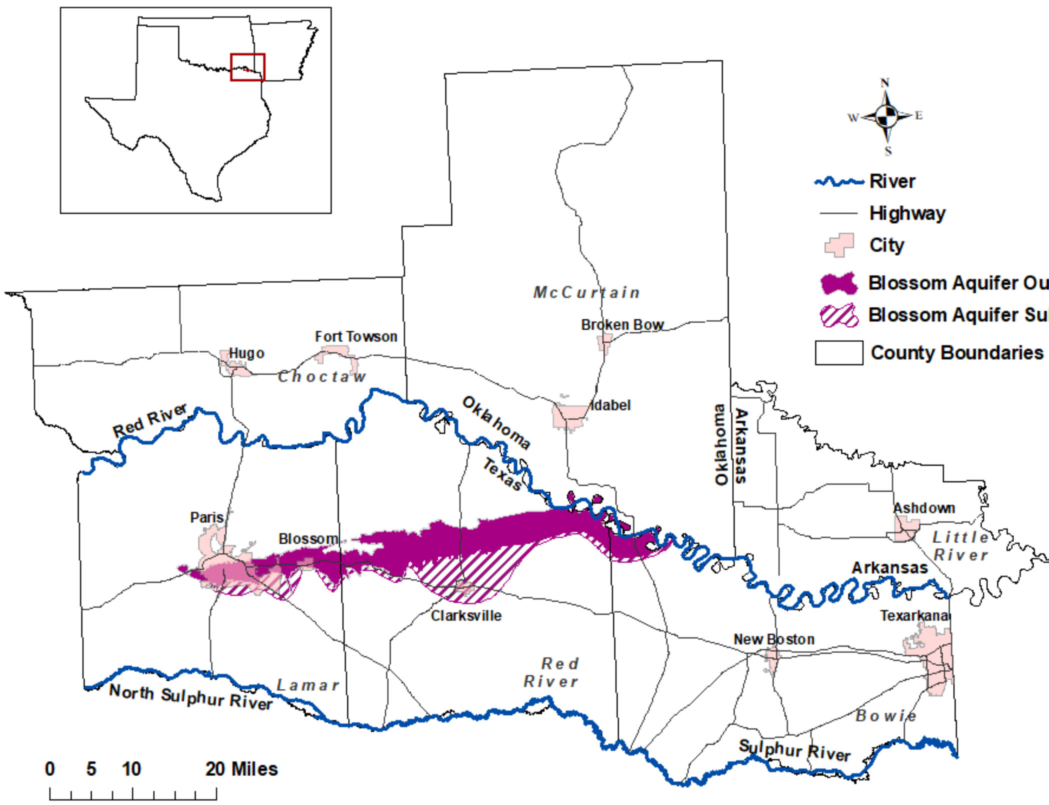

FIGURE 1. STUDY AREA. COUNTY LOCATIONS ARE FROM THE U.S. CENSUS BUREAU (2013). CITY LOCATIONS ARE FROM ARKANSAS GIS OFFICE (2013), OKLAHOMA CENTER FOR GEOSPATIAL INFORMATION (2013), AND TWDB (2013C). ROADS ARE FROM ARKANSAS GIS OFFICE (2013), OKLAHOMA CENTER FOR GEOSPATIAL INFORMATION (2013), AND TWDB (2013C).

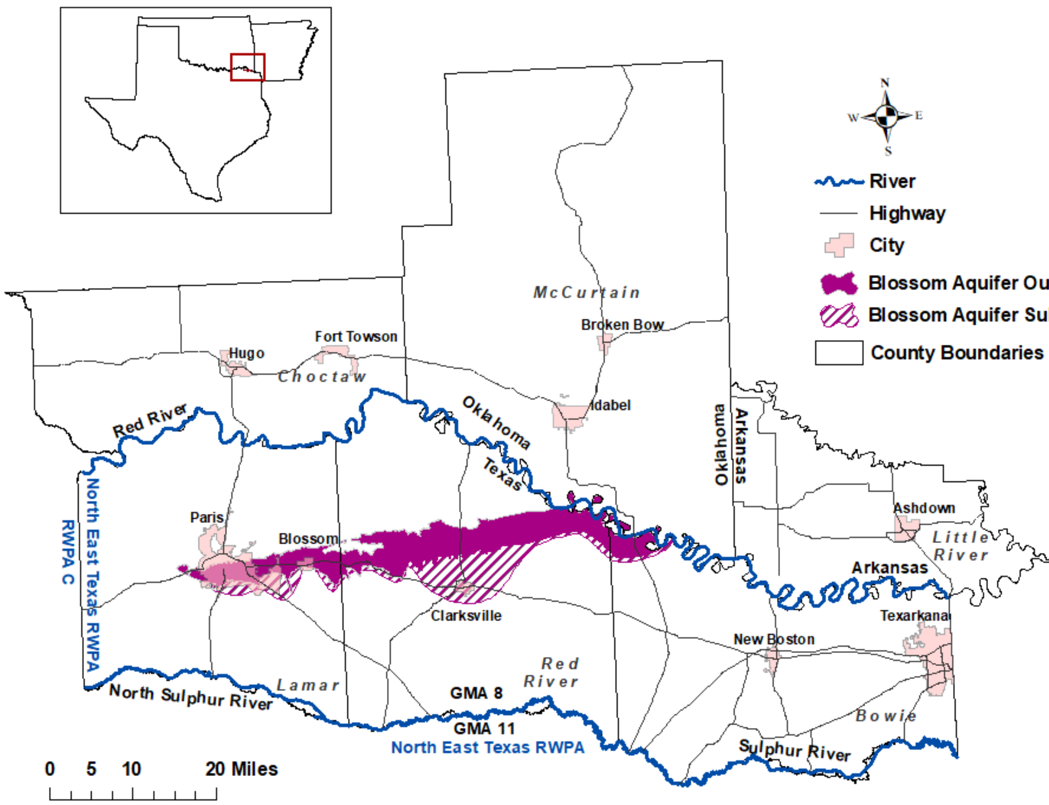

FIGURE 2. REGIONAL WATER PLANNING AREAS (RWPA) AND GROUNDWATER MANAGEMENT AREAS (GMA) IN STUDY AREA. COUNTY LOCATIONS ARE FROM THE U.S. CENSUS BUREAU (2013). CITY LOCATIONS ARE FROM ARKANSAS GIS OFFICE (2013), OKLAHOMA CENTER FOR GEOSPATIAL INFORMATION (2013), AND TWDB (2013C). ROADS ARE FROM ARKANSAS GIS OFFICE (2013), OKLAHOMA CENTER FOR GEOSPATIAL INFORMATION (2013), AND TEXAS DEPARTMENT OF TRANSPORTATION (2006).

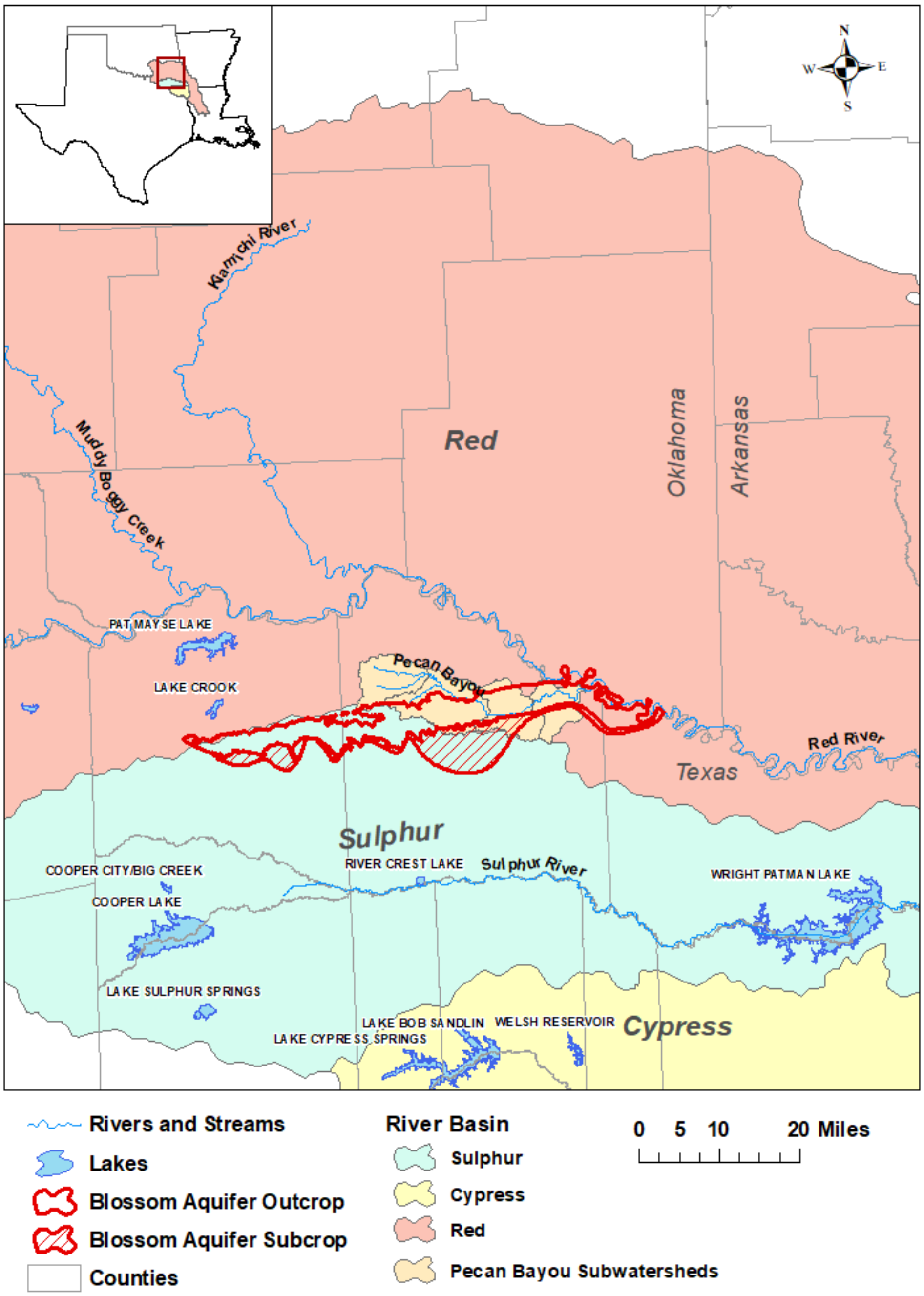

FIGURE 3. MAJOR RIVER BASINS AND SURFACE WATER FEATURES NEAR THE STUDY AREA.

2.1 Physiography and Climate

The total relief of the aquifer outcrop area is about 280 feet ranging from about 320 feet above sea level along the Red River in Bowie County to about 600 feet above sea level in central Lamar County (Figure 4).

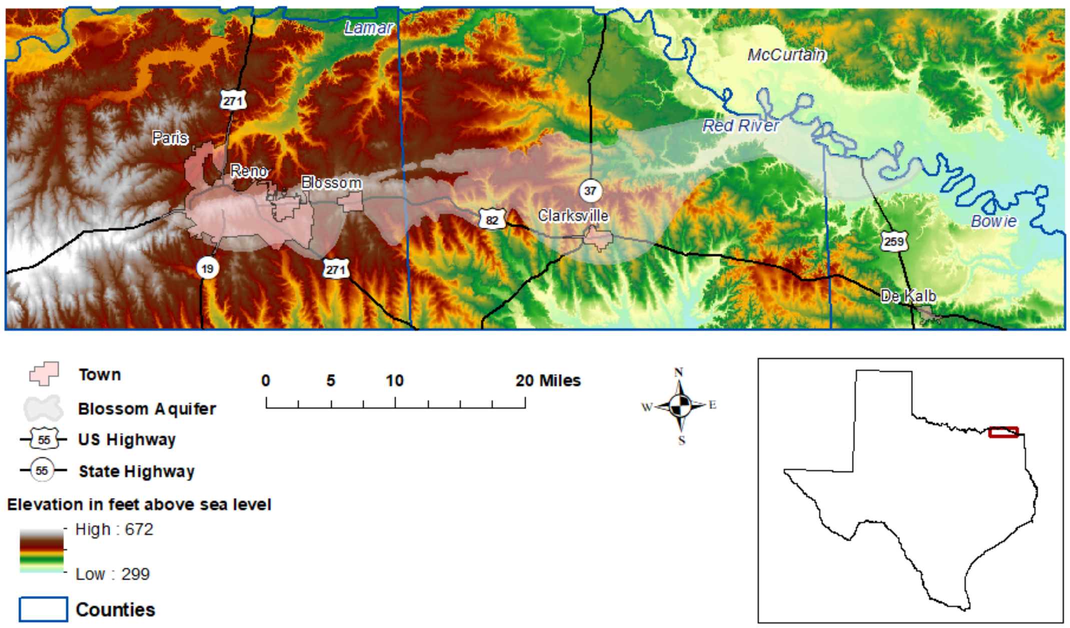

FIGURE 4. TOPOGRAPHIC ELEVATION IN THE AREA OF THE BLOSSOM AQUIFER (U.S. GEOLOGICAL SURVEY, 2014A).

The study area is located within the Blackland Prairies subprovince of the Gulf Coastal Plains (Figure 5; U. S. Geological Survey, 2014b; Fenneman and Johnson, 1946; Wermund, 1996). All of Lamar County and most of Red River County are underlain by Cretaceous strata, including marls, glauconitic sands, clays, and chalk. The strata have been eroded into an undulating surface of low relief, called a rolling prairie, and weathered to thick, black, fertile clay soils. The Blackland Prairies are characterized by these gentle undulating surfaces and soils (Wermund, 1996; Gordon, 1911). Over most of the Blossom Aquifer outcrop the saturated hydraulic conductivity of the soil is less than 0.8 feet day (Figure 6). Along the Red River the soil saturated hydraulic conductivity is higher and ranges from 2.6 up to 8.0 feet per day (Figure 6). The soil available water storage ranges from 7 to 12 inches in the top approximately 5 feet (150 cm) of soil (Figure 7).

The climate in northeast Texas is classified as subtropical humid (Figure 8; Larkin and Bomar, 1983). Vegetation consists primarily of pine and hardwood forests and native and introduced grasses (Figure 9). Average annual rainfall ranges from 46 to 50 inches per year (Figure 10; PRISM Climate Group, 2012). At a collection station in Paris, annual rainfall from 1931 to 2011 ranged from a low of about 25 inches per year in 1963 to a high of about 75 inches per year in 1957 (Figure 11, NCEI, 2013). At another station located in Clarksville, annual rainfall amounts ranged from a low of about 23 inches per year in 2003 to a high of about 78 inches per year in 2009 (Figure 12, NCEI, 2013).

The average daily maximum temperatures range from 74 to 75 degrees Fahrenheit and average daily minimum temperatures range from 50 to 53 degrees Fahrenheit (Figure 13; PRISM Climate Group, 2013a, b, and c). Both the potential evapotranspiration (theoretical rate of evapotranspiration defined roughly as the potential evaporation from soils plus transpiration– water taken up by plants) and released back into the atmosphere –and lake evaporation for the study area range from about 50 to about 60 inches per year (Figures 14 and 15; Scanlon and others, 2005; Narasimhan and others, 2005).

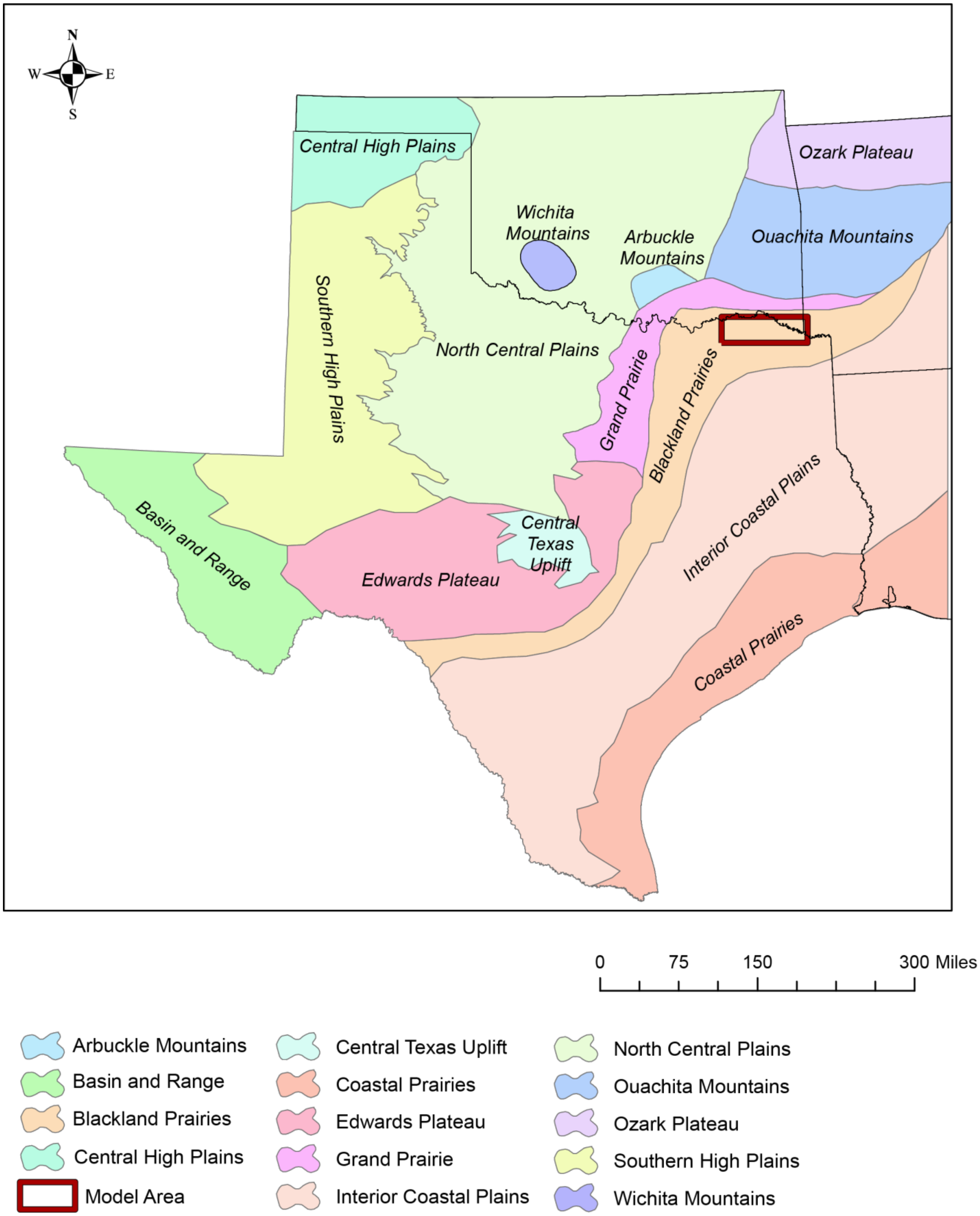

FIGURE 5. PHYSIOGRAPHIC PROVINCES IN TEXAS AND NEIGHBORING STATES (U.S. GEOLOGICAL SURVEY, 2014; FENNEMAN AND JOHNSON, 1946).

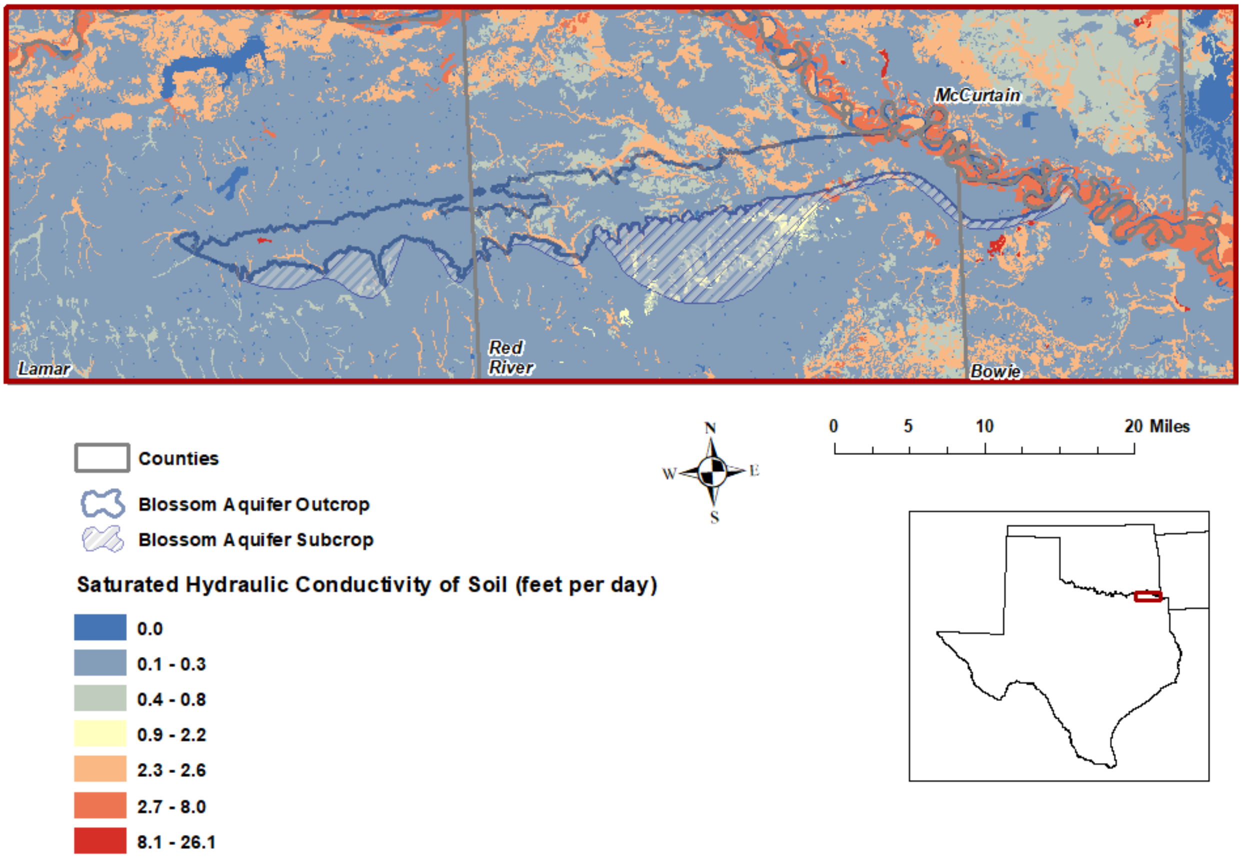

FIGURE 6. SATURATED HYDRAULIC CONDUCTIVITY OF SOIL IN THE STUDY AREA (NATURAL RESOURCES CONSERVATION SERVICE, 2021).

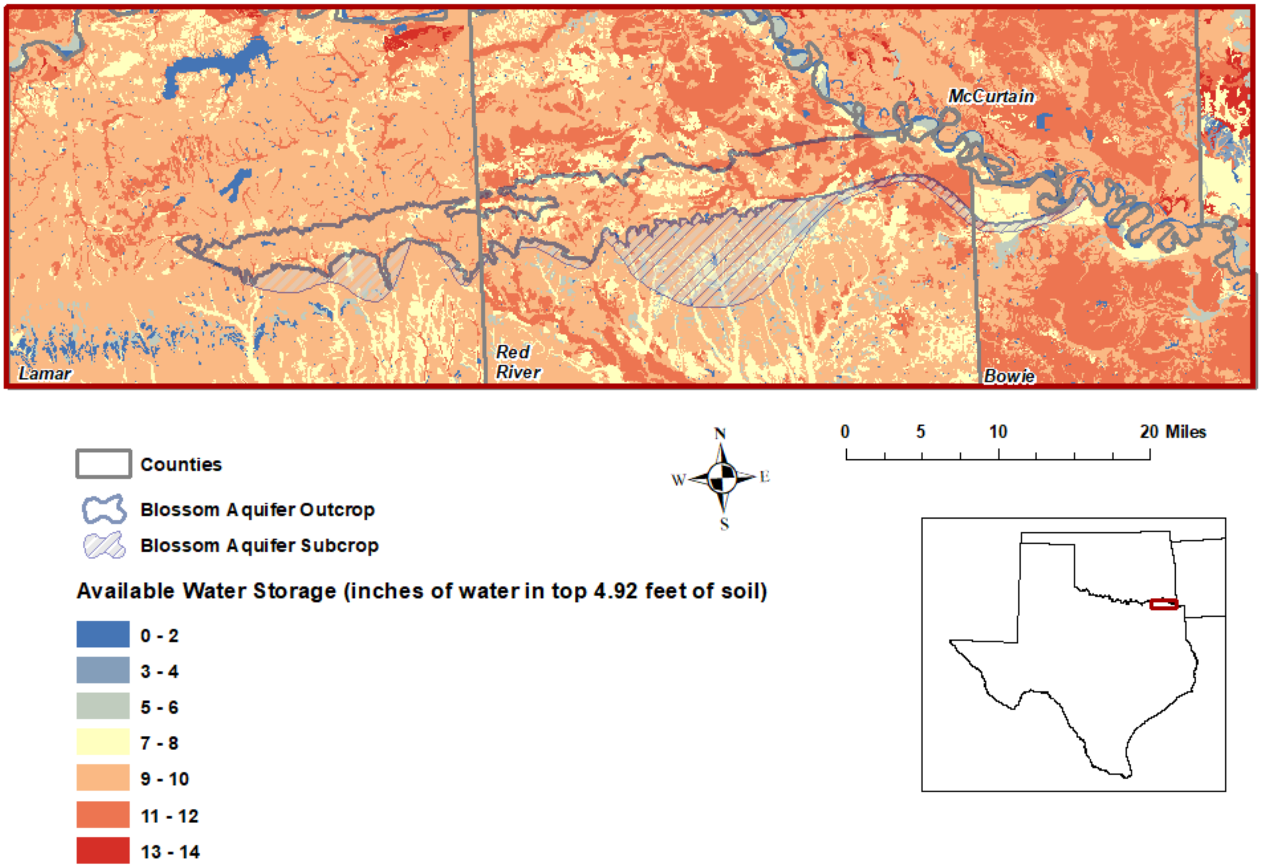

FIGURE 7. AVAILABLE WATER STORAGE OF THE SOIL IN THE STUDY AREA (NATURAL RESOURCES CONSERVATION SERVICE, 2021).

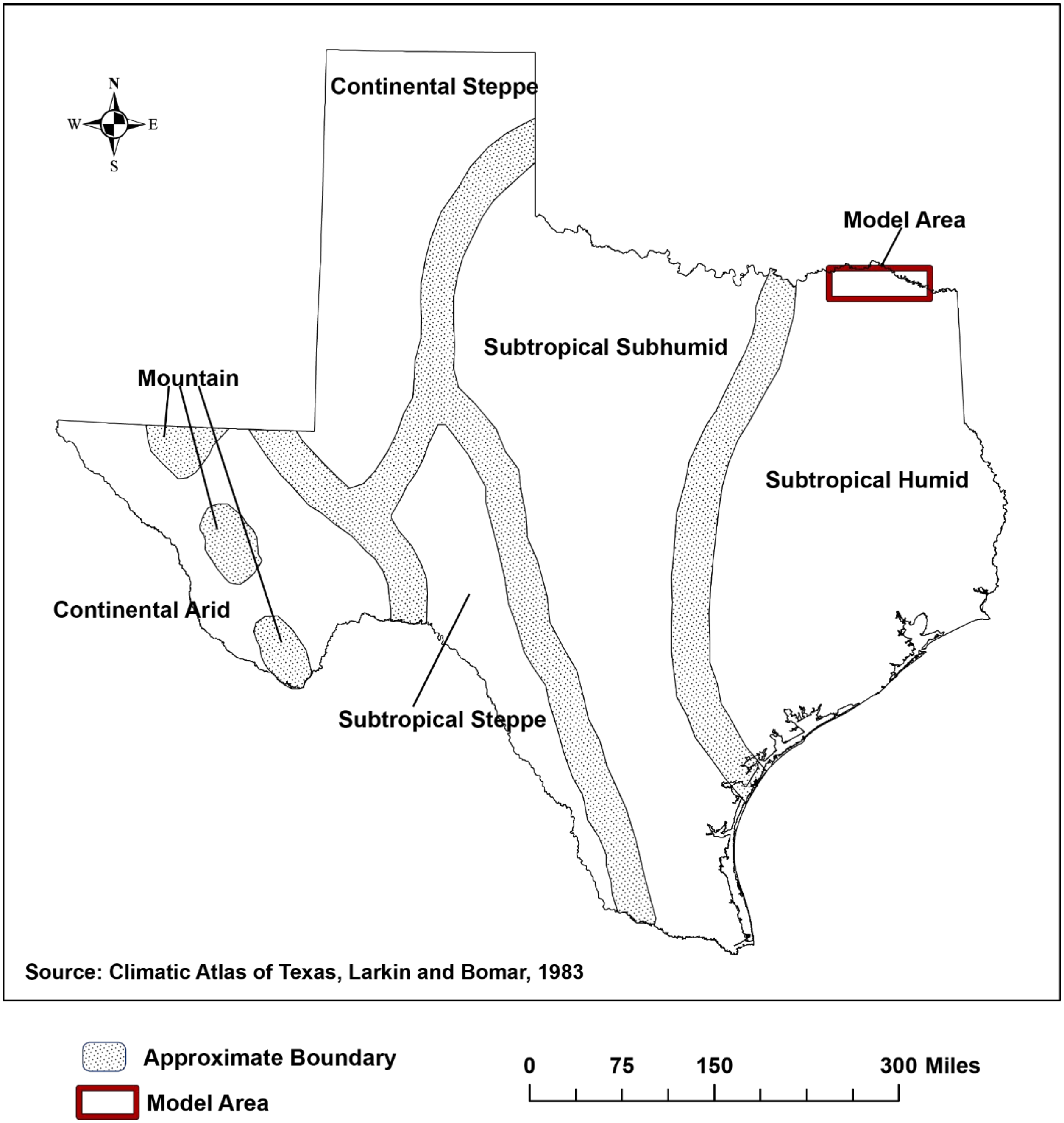

FIGURE 8. CLIMATE CLASSIFICATIONS FOR TEXAS (LARKIN AND BOMAR, 1983).

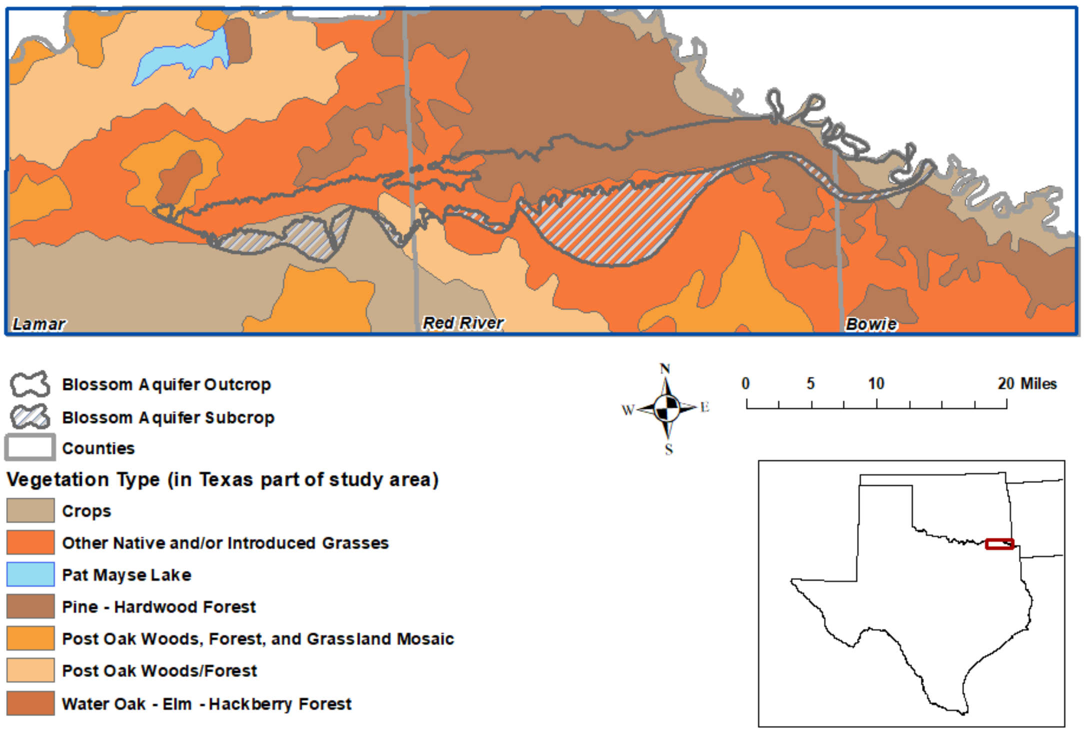

FIGURE 9. VEGETATION TYPES IN TEXAS PART OF STUDY AREA (FRYE AND OTHERS, 1984).

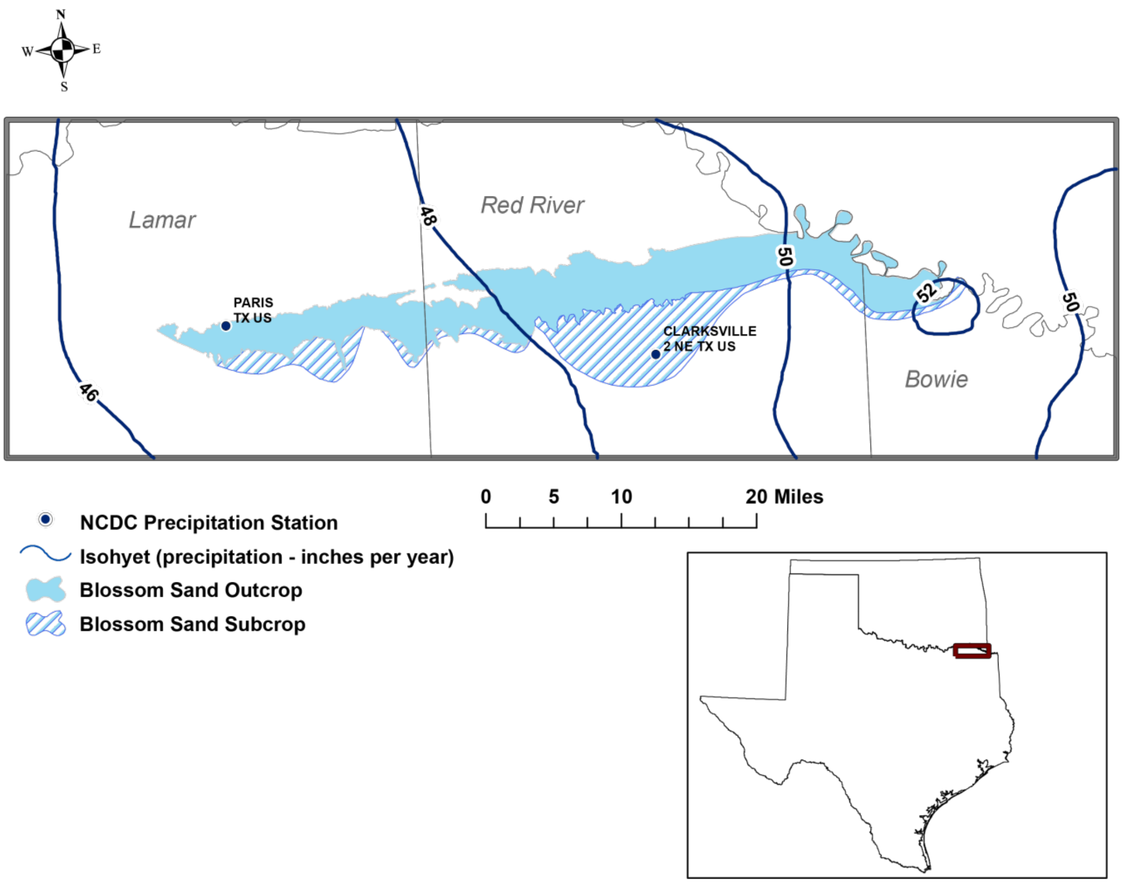

FIGURE 10. AVERAGE ANNUAL RAINFALL IN THE STUDY AREA FOR THE PERIOD 1981 TO 2010. CONTOURS BASED ON PRISM CLIMATE GROUP (2012) DATA.

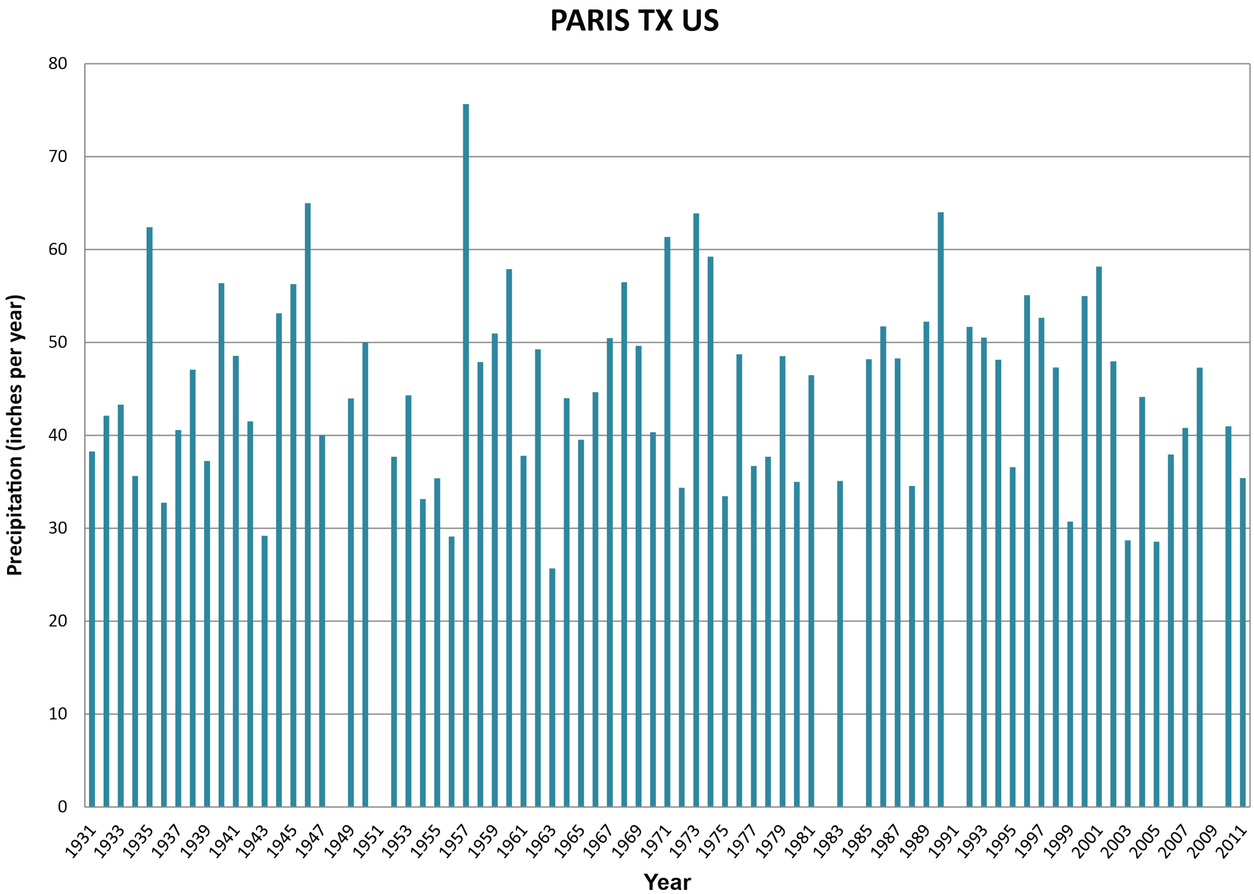

FIGURE 11. ANNUAL RAINFALL AT A STATION IN PARIS, TEXAS. STATION LOCATION IS SHOWN IN FIGURE 10 (NATIONAL CENTERS FOR ENVIRONMENTAL INFORMATION, 2013).

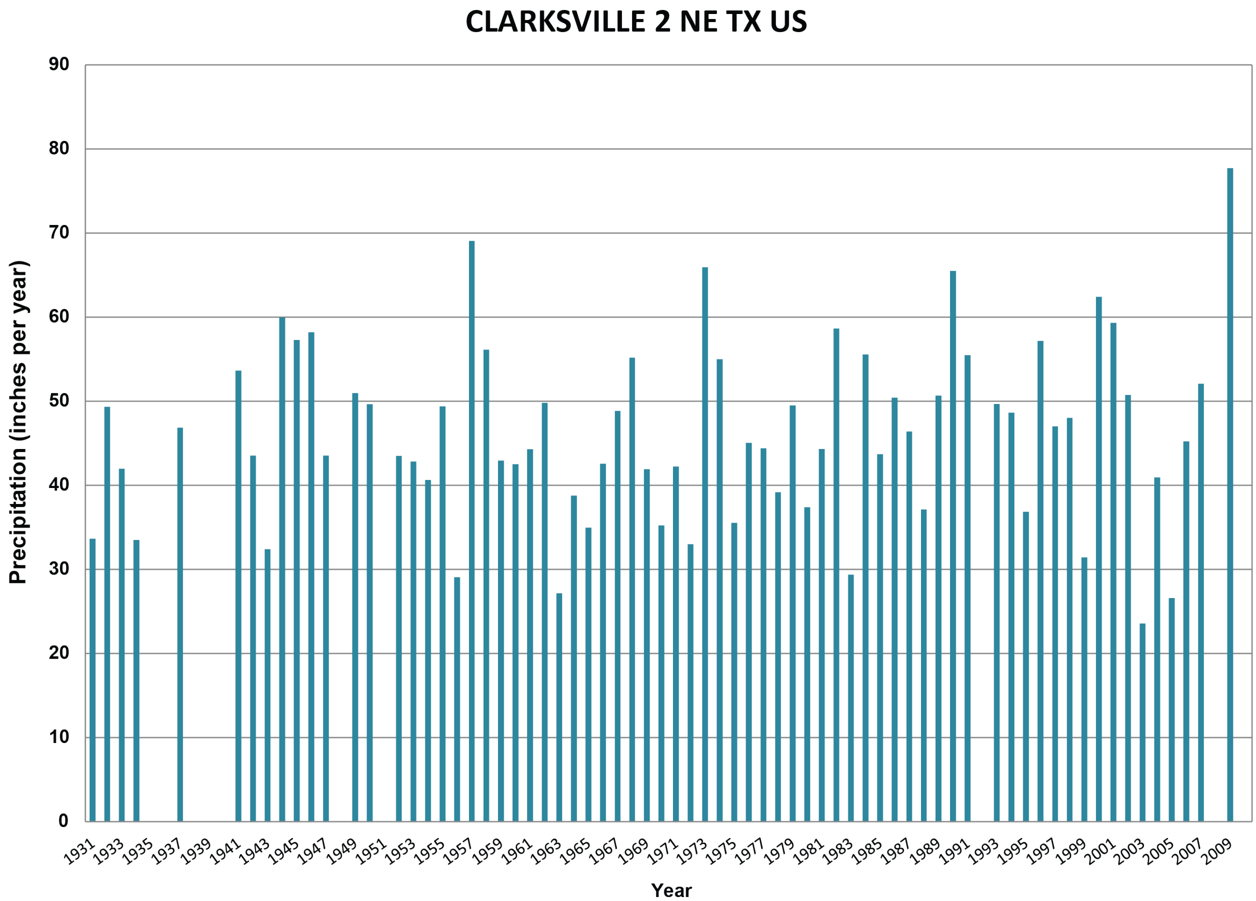

FIGURE 12. ANNUAL RAINFALL IN INCHES AT A STATION IN CLARKSVILLE, TEXAS. STATION LOCATION IS SHOWN IN FIGURE 10 (NATIONAL CENTERS FOR ENVIRONMENTAL INFORMATION, 2013).

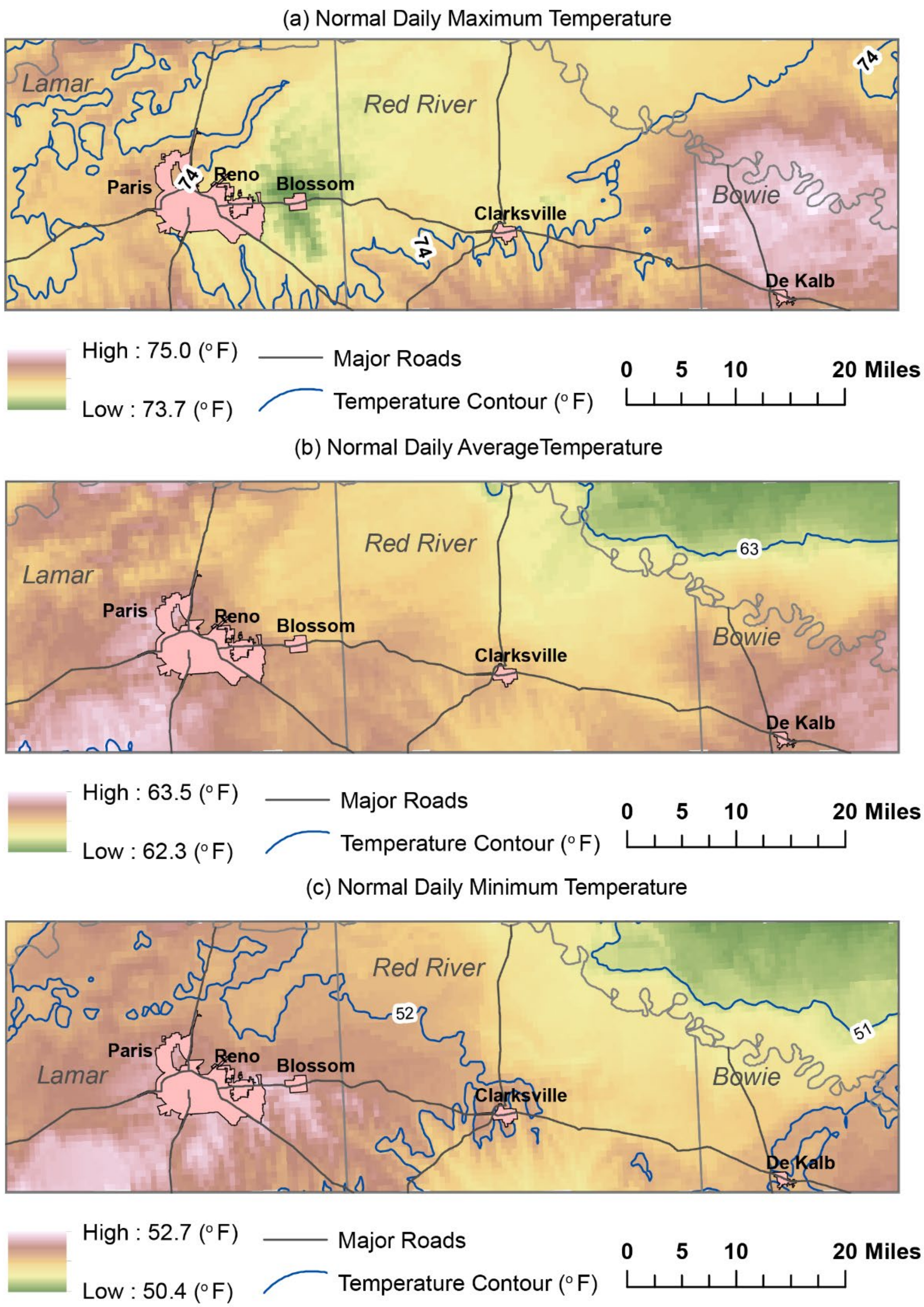

FIGURE 13. NORMAL (1981 TO 2010 AVERAGE) MAXIMUM, AVERAGE, AND MINIMUM DAILY TEMPERATURE FOR THE STUDY AREA (PRISM CLIMATE GROUP, 2013a, b, and c).

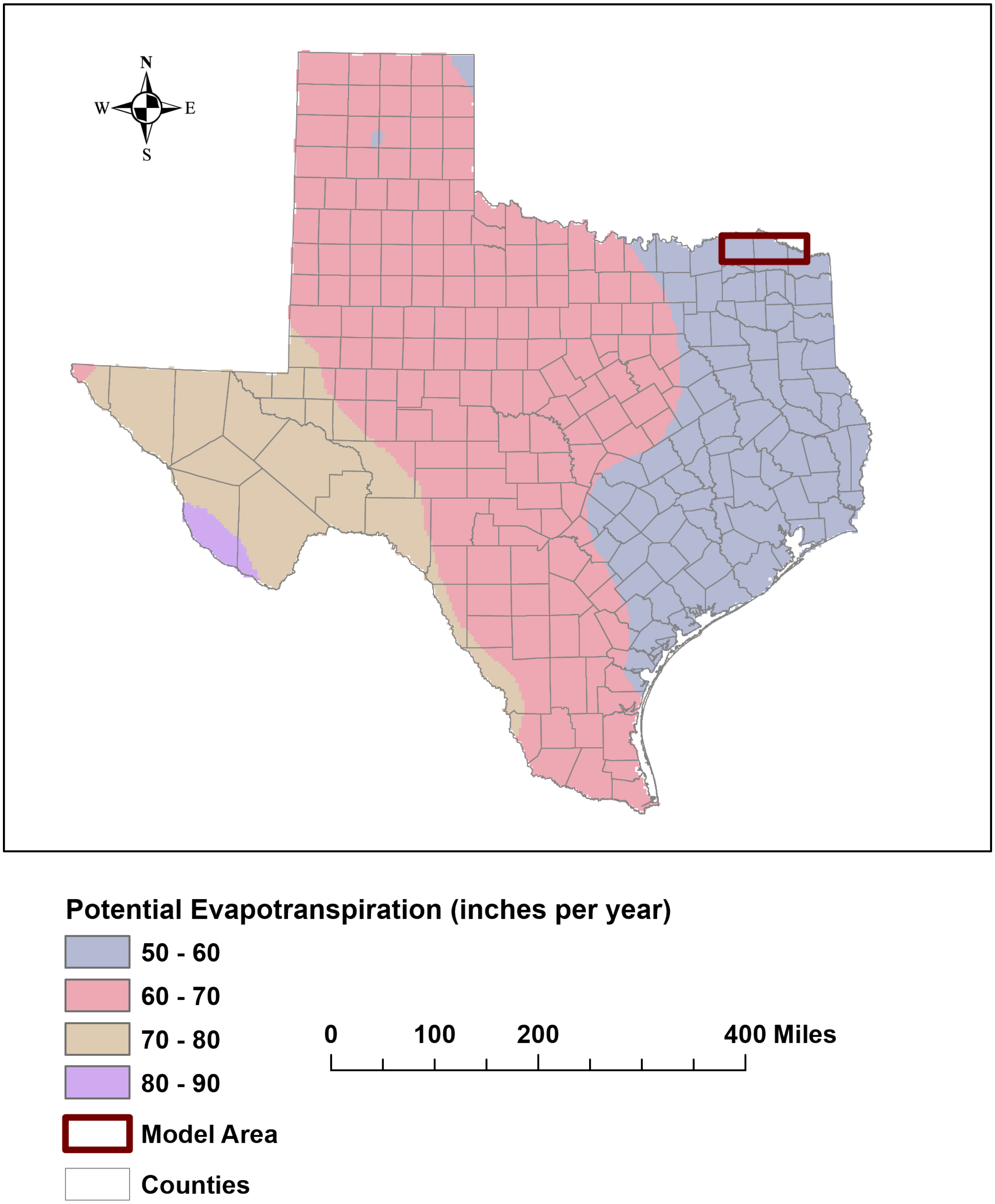

FIGURE 14. POTENTIAL EVAPOTRANSPIRATION FOR TEXAS (SCANLON AND OTHERS, 2005).

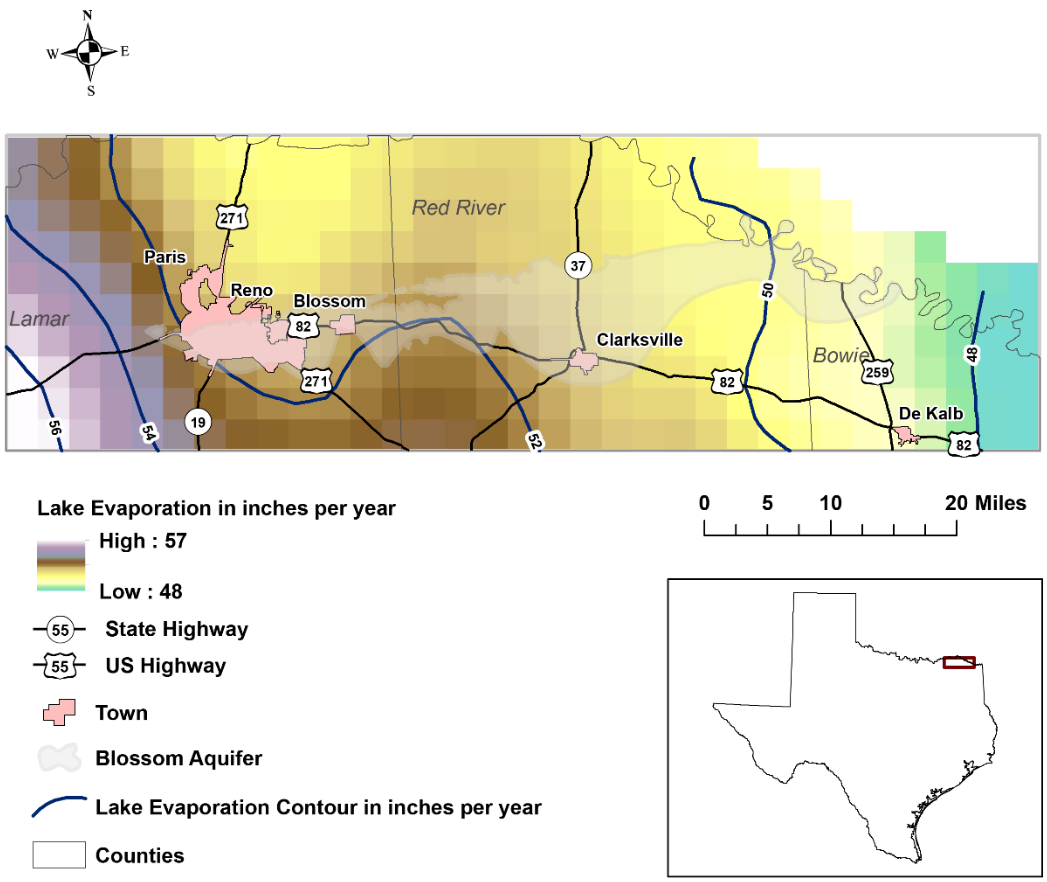

FIGURE 15. LAKE EVAPORATION IN THE STUDY AREA (NARASIMHAN AND OTHERS, 2005).

2.2 Geology

The Blossom Sand outcrops (Figure 16) in a narrow one to two-mile wide, east-west trending band in Fannin, Lamar, and Red River counties (Gordon, 1911; McLaurin, 1988). In Red River and Bowie counties, much of the outcrop is covered by alluvial terrace deposits – loose, unconsolidated sediment deposited by rivers over a long period of time (Figure 16; Baker and others, 1963). The western most extent of the outcrop is in central Fannin County, where the Blossom merges laterally into marl and chalk (Nordstrom, 1982). The Blossom Sand west of the Blossom Aquifer delineation is not productive so that part of the formation is not considered part of the Blossom Aquifer (Figure 16). The Blossom Sand is important because it is the only available water-bearing unit over a considerable portion of south Lamar and Red River counties (Gordon, 1911).The Blossom Sand, together with the underlying Bonham Marl in Texas, are facies equivalent to the Tokio Formation in Oklahoma, Arkansas, and Louisiana (McLaurin, 1988; Cushing and others, 1964; Stephenson, 1936).

The Blossom Sand is part of an Upper Cretaceous ramp-like shelf margin depositional package in the Gulf Coast Region (Roberts-Ashby and others, 2014). The deposits (Figure 17) include carbonate, sandstone, basinal marl, and mudrock (Roberts-Ashby and others, 2014). The Austin Group was deposited when seas advanced northeastward and onlapped the Monroe uplift (Figure 18) and south Arkansas highlands. Sediments were carried to this sea from the northeast (Foote and others, 1988), probably the Ouachita Mountains (McLaurin, 1988). During the deposition of the Austin Group, structural movement occurred on the Sabine Uplift and Mexia/Talco Fault Zone (Foote and others, 1988). The Blossom Sand was deposited during minor regressive phases of the Upper Cretaceous transgression (McLaurin, 1988).

Above the Austin Group is the Taylor Group (Figure 17), which is up to 1,500 feet thick. The Taylor Group includes, from bottom to top, the Ozan Chalk, the Wolfe City Sandstone, the Pecan Gap Chalk, and the Marlbrook Marl. The Pecan Gap overlies the Wolfe City unconformably (Foote and others, 1988). Unconformities occur in rock strata when the rocks were not deposited in unbroken sequence either due to erosion or periods of nondeposition (Press and Siever, 1982).

Following the Cretaceous, repeated transgression (landward movement) and regression (withdrawal) of the seas resulted in an alternating sequence of marine and continental deposits. During the Tertiary, the land surface was eroded and modified by streams. During the Quaternary, multiple stages of stream sediments were deposited. Surfaces were modified by downcutting of streams and subsequent formation of terraces along the water courses (Baker and others, 1963). The older terrace deposits sit above the present stream valley alluvium deposits (McLaurin, 1988).

The Blossom Sand consists of unconsolidated ferruginous glauconitic fine to medium sand interbedded with light to dark sandy marl and chalky marl (Baker and others, 1963). The Blossom Sand beds are discontinuous and individual beds, for the most part, extend over a few square miles and do not change lithology in short distances, although facies changes in a few tens of miles are common (Baker and others, 1963). Where the Blossom is missing, the overlying Brownstown and underlying Bonham are indistinguishable on electric logs (McLaurin, 1988; Figures 17 and 19).

The Blossom and other formations dip toward the east and the south (Figures 19 and 20). The Blossom Sand thickens downdip and eastward along strike (Baker and others, 1963) and has a maximum thickness in the subsurface of about 350 feet (Cushing and others, 1964). Additional cross-sections of the Blossom Sand prepared as part of a brackish aquifer production study are shown in Appendix A (Beach and Laughlin, 2017: Figures A.1 through A.3).

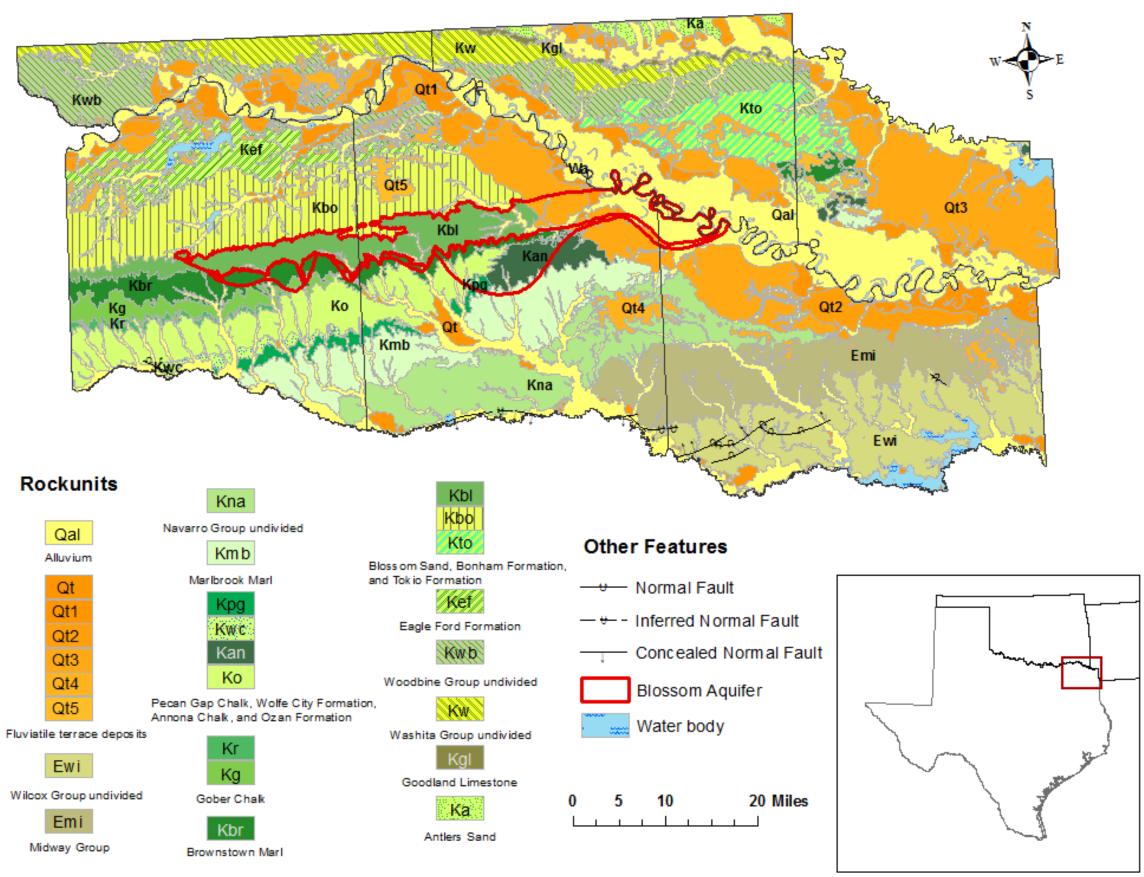

FIGURE 16. SURFACE GEOLOGY IN STUDY AREA (BUREAU OF ECONOMIC GEOLOGY, 2007).

Stratigraphy and Hydrostratigraphy

(after McLaurin, 1988)

Era	System	Series	Group	Formation	Approximate maximum thickness (ft)	Lithology[1]	Water-bearing characteristics
Cenozoic	Quaternary	Recent		Alluvium	75	Sand, silt, clay, and gravel	Yields small[2] to moderate[3] quantities of water to wells along the Red River
		Pleis-tocene		Fluviatile, terrace deposits			
Mesozoic	Cretaceous	Gulf	Taylor	Marlbrook Marl Pecan Gap Chalk Wolfe City-Ozan Formation	1,500	Clay, marl, shale, chalk, mudstone, and sandstone, very fine-grained	Yields small quantities of water to shallow wells
			Austin	Gober Chalk	700	Chalk, discontinuous	Not known to yield water to wells
				Brownstown		Clay or shale	Not known to yield water to wells
				Blossom Sand	226	Fine to medium sand interbedded with light to dark marl and chalky marl	Yields small to moderate quantities of water to municipal, domestic, and livestock wells
				Bonham	400	Clay or shale	Not known to yield water to wells
				Ector		Chalk	Not known to yield water to wells
			Eagle Ford		650	Shale with thin beds of sandstone and limestone	Yields small quantities of water to shallow wells

1. Lithology from Wood and Guevara (1981) and Nordstrom (1982).)
2. Small quantities of water are generally less than 100 gallons per minute
3. Moderate quantities of water are generally 100 to 1,000 gallons per minute

FIGURE 17. STRATIGRAPHY AND HYDROSTRATIGRAPHY FOR THE BLOSSOM AQUIFER STUDY AREA (NORDSTROM, 1982; WOOD AND GUEVARA, 1981).

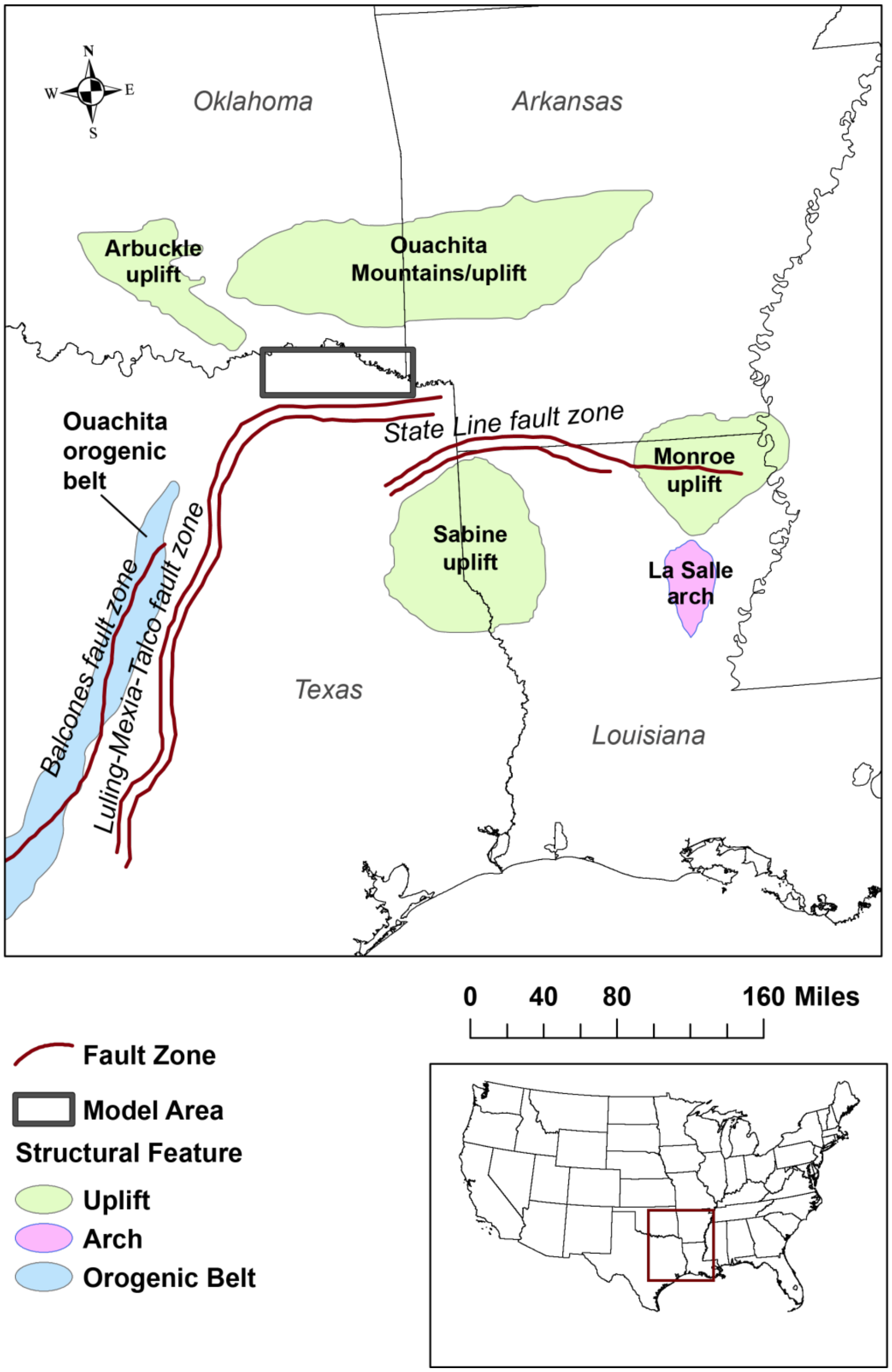

FIGURE 18. MAJOR STRUCTURAL FEATURES IN THE VICINITY OF THE BLOSSOM AQUIFER (AFTER ROBERTS-ASHBY, 2012).

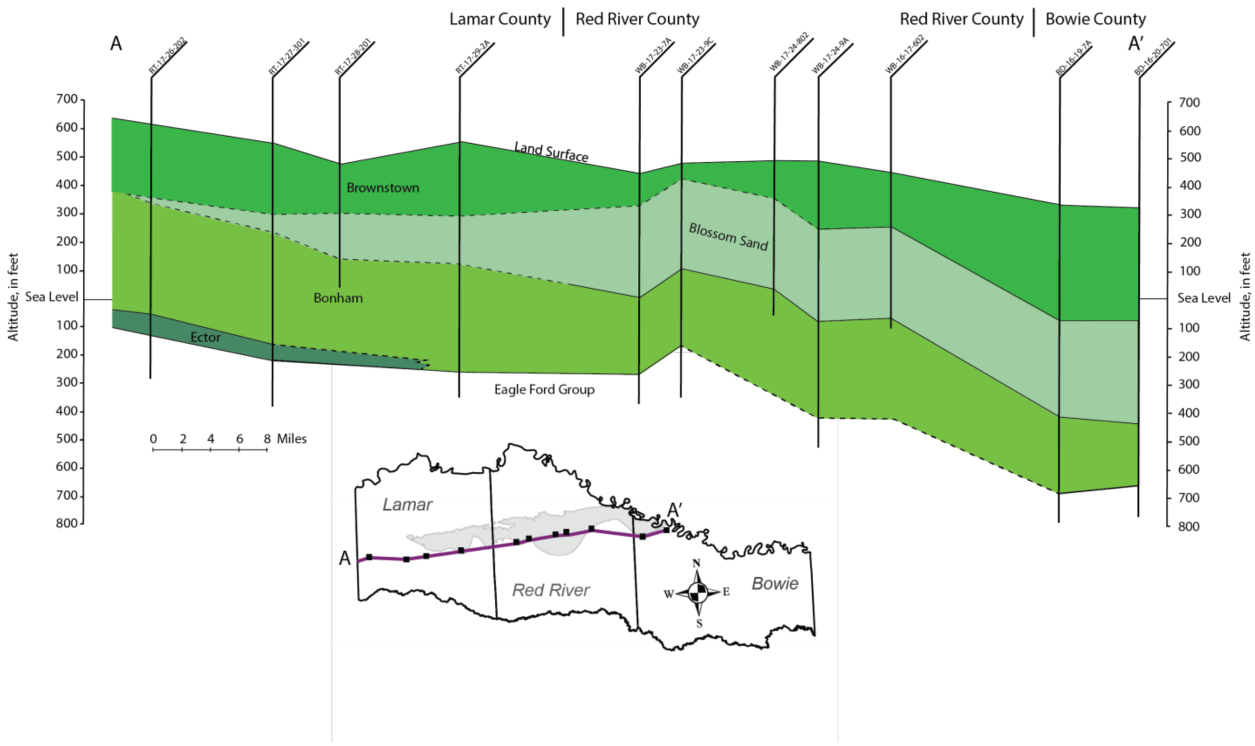

FIGURE 19. WEST TO EAST CROSS-SECTION THROUGH THE BLOSSOM AQUIFER STUDY AREA (FROM MCLAURIN, 1988).

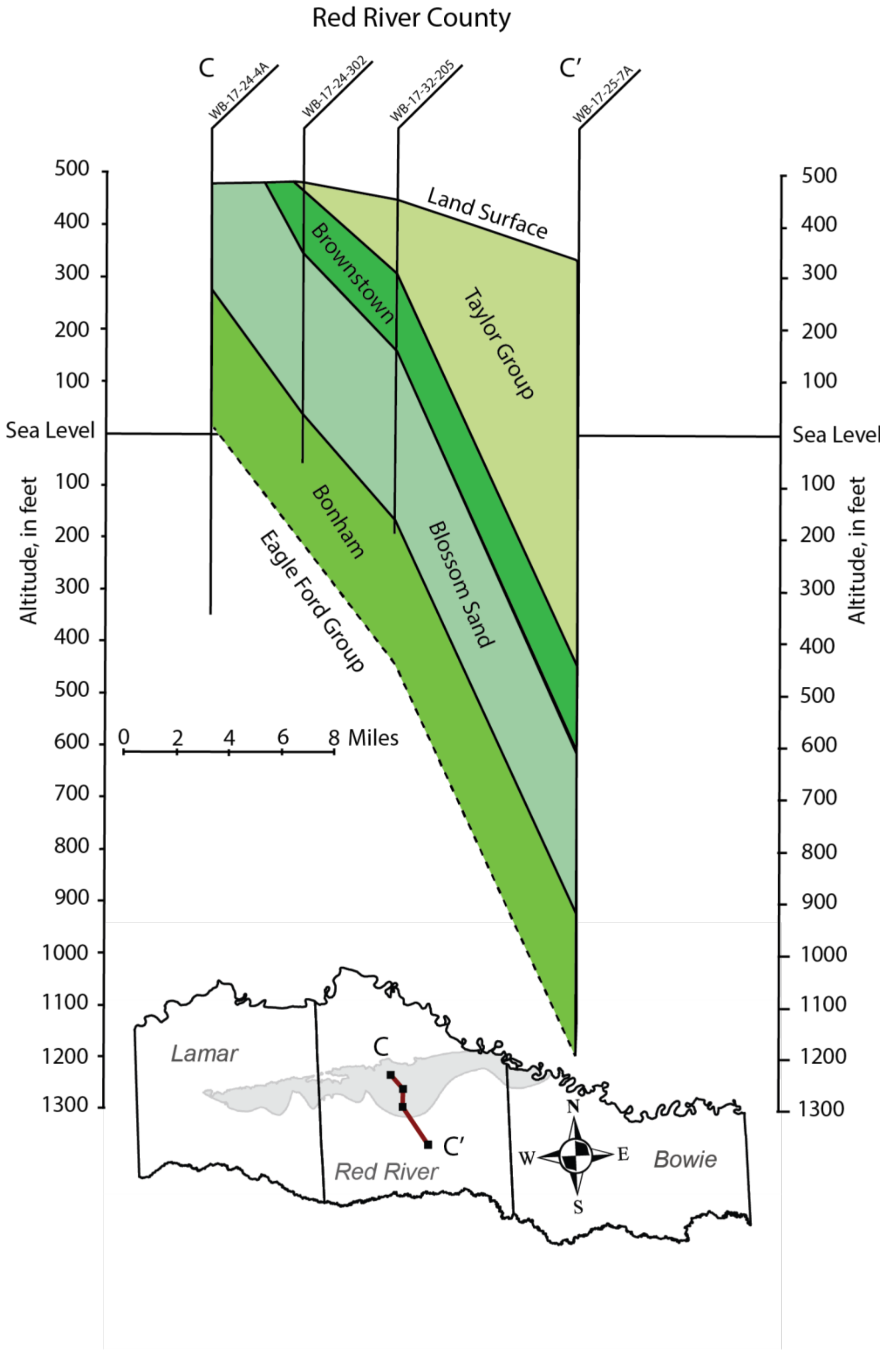

FIGURE 20. NORTHWEST TO SOUTHEAST CROSS-SECTION THROUGH BLOSSOM AQUIFER STUDY AREA (FROM MCLAURIN, 1988).

3.0 PREVIOUS WORK

Several studies over the years have focused on the geology of the Blossom Sand and/or on the groundwater resources of the region. Two previous groundwater modeling studies have included the Blossom Sand (Figure 21; Morton, 1992; Ridgeway and Hamlin, 2005).

Gordon (1911) described the geology and groundwater resources of Northeastern Texas. He classified the Blossom Sand as a member of the Eagle Ford Clay Formation. He describes the Blossom Sand as "brown sandy ferruginous glauconitic beds interlaminated with thin beds of clay" (Gordon, 1911). The paper includes descriptions of two Blossom Sand outcrop sections in the study area. Gordon (1911) noted that the towns of Blossom, Paris, and Detroit are located on the outcrop of the Blossom Sand, and that shallow wells along the outcrop commonly range from 25 to 75 feet in depth and produce water of variable quality. He reports that the quality of the water from the confined portion of the aquifer seems to be good, including the Clarksville water wells (Gordon, 1911).

Stephenson (1918) interpreted new stratigraphic and age relationships for many Gulfian (Late Cretaceous) formations and he reclassified the Blossom with the Austin Group.

Baker and others (1963) conducted a reconnaissance investigation of the groundwater resources of the Red River, Sulphur River, and Cypress Creek Basins. They describe the Blossom Sand as dipping southward in Fannin, Red River, and Lamar counties with a slope of about 85 feet per mile and they indicate the main source of recharge is precipitation on the outcrop (Baker and others,1963). Thin, high-level terrace deposits in Red River County overly the Blossom also allowing recharge to the Blossom (Baker and others,1963). Water moves southward from the recharge areas towards discharge points (Baker and others,1963). Discharge includes plant transpiration, pumping wells and seepage downdip into other formations especially along the Luling-Mexia-Talco fault system (Baker and others,1963).

Baker and others (1963) noted that although water levels in the Blossom Aquifer had declined since the start of development, the declines were small and restricted to the artesian part of the aquifer, indicating a decline in pressure rather than dewatering. They estimated a decline rate of about one-half foot per year from the time the first well was drilled for the City of Clarksville in 1905 until 1960. Based on a pumping test from a well in Clarksville, they estimated a transmissivity of 3,800 gallons per day per foot and a storage coefficient of 0.00004 (Baker and others,1963).

Nordstrom (1982) analyzed water-level data from Baker and others (1963) and estimated the average annual ground-water availability within the study area was to be 625 acre-feet. The estimate was based on a comparison of pumpage and water level trends (Nordstrom, 1982).

This current study draws heavily on background information and aquifer data from McLaurin (1988). In 1982 and 1983, the TWDB conducted a field investigation of the Blossom Aquifer to determine the extent, quality, and quantity of groundwater, to characterize the aquifer, and to estimate annual recharge and discharge (McLaurin, 1988). The project included well inventory, review of geophysical and driller's logs, and aquifer tests. Water level data were collected from November 1982 through January 1983 (McLaurin, 1988). Details of that information are provided in the relevant sections of this report.

The United States Geological Survey (USGS) developed a model of the Antlers Aquifer in Southeastern Oklahoma and Northeastern Texas (Morton, 1992). The model covers all or parts of Bowie, Cooke, Fannin, Grayson, Lamar, and Red River counties in Texas (Figure 21). The model consists of one layer representing the lower Cretaceous Antlers Sandstone Aquifer. In Bowie, Lamar, and Red River counties, the Antlers Aquifer is under confined conditions and the overlying Upper Cretaceous Rocks and Quaternary rocks are represented with a specified head boundary condition (Morton, 1992). Most of the study area for the Blossom Aquifer groundwater availability model is included in the Antlers Aquifer model as part of the overlying Upper Cretaceous and Quaternary Rocks boundary condition.

Ridgeway and Hamlin (2005) developed a steady-state numerical groundwater model of the Blossom Aquifer (Figure 21). The model was developed as a class project to form the basis of the TWDB groundwater availability model. The model included two layers representing the overlying shales, marls, and chalks in the Austin and Taylor Groups with the Red River alluvium (layer 1) and the Blossom Aquifer (layer 2).

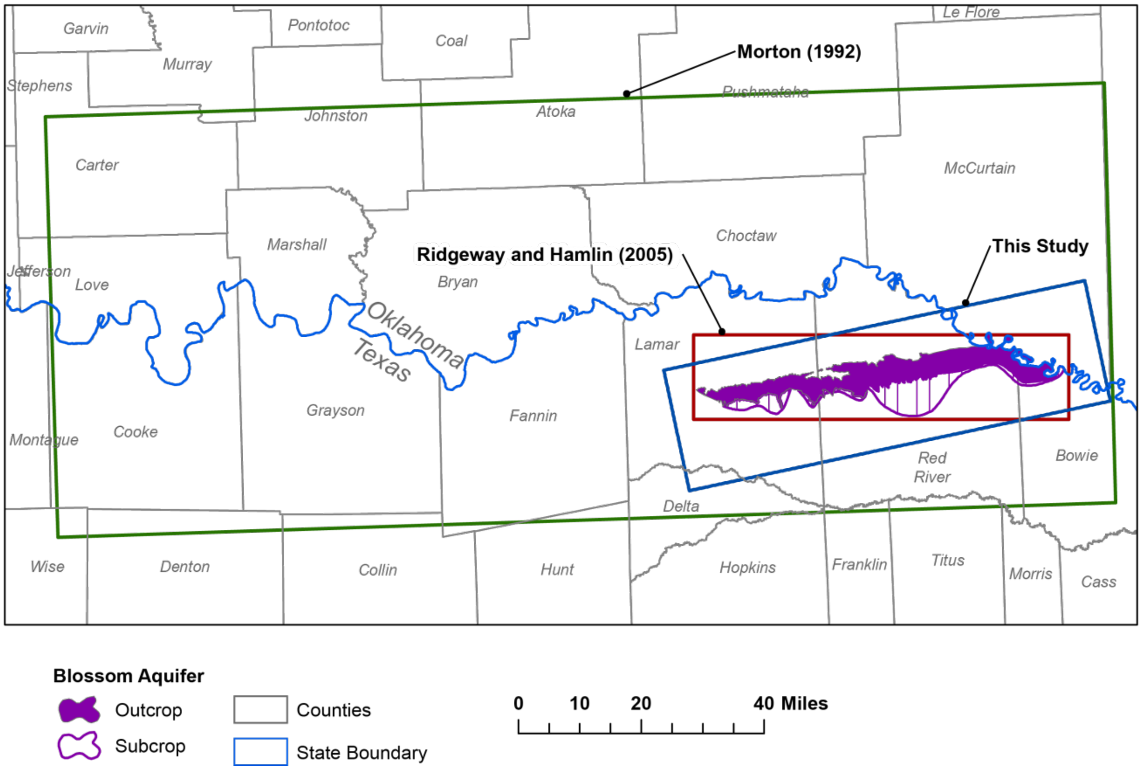

FIGURE 21. LOCATION OF PREVIOUS MODELS IN THE STUDY AREA (MORTON, 1992; RIDGEWAY AND HAMLIN, 2005).

4.0 HYDROLOGIC SETTING

The hydrologic setting describes the aquifer, groundwater flow system, and groundwater conditions. Elements of the hydrologic setting include the layering of the geologic units comprising the aquifer system (hydrostratigraphy), groundwater levels and the groundwater flow system, groundwater flow (hydraulic) properties of the aquifer units, and inflows to and outflows from the groundwater system. Inflows include recharge from precipitation and recharge from surface water features. Outflows can include spring discharge, discharge to surface water features, discharge from evapotranspiration, and groundwater pumping. Although it will not be included in the groundwater model, the groundwater chemistry is also described as part of the hydrologic setting because it is important for understanding the conditions of the groundwater resource.

4.1 Hydrostratigraphy and Structural Framework

The groundwater availability model for the Blossom Aquifer will include three geologic layers (Figure 22). Layer one will represent the terrace alluvium and Red River Alluvium deposits within the footprint of the Blossom Aquifer. Layer two will principally represent the Brownstown Formation and other overlying younger units (acting as confining units) and layer 3 will represent the Blossom Sand in Texas and the Tokio Formation in Oklahoma (Figures 16 and 17). In central Red River County the terrace alluvium directly overlies the Blossom Sand outcrop and the confining units are not present. In that area, model layer 2 will be present, but it will have a nominal thickness of 20 feet beneath the alluvium to provide a connection between the Blossom Sand and overlying alluvium (Figure 22).

The surfaces for the structural framework for our conceptual model of the Blossom Aquifer are based on the previous work of McLaurin (1988), Baker and others (1963), the Geological Atlas of Texas (Bureau of Economic Geology (BEG), 2007), and topographic elevations (U.S. Geological Survey, 2014a).

4.1.1 Hydrologic Description of Layers

Groundwater in the study area is produced from both the Blossom Sand and the overlying Quaternary terrace and alluvium deposits (Figure 17). Within the footprint of the Blossom Aquifer much of the Blossom Sand outcrop is covered by thin, high-level terrace alluvium deposits. Adjacent to the Red River, thicker deposits of alluvium overlie the Blossom Sand. In some locations the alluvium directly overlies the Blossom Sand, and they are hydraulically connected (Baker and others, 1963; McLaurin, 1988). South of the outcrop, the terrace deposits and alluvium overlie the younger Brownstown Formation, and do not directly overly the Blossom Sand.

The Quaternary alluvium deposits yield small to moderate quantities of water to wells along the Red River (McLaurin, 1988; Figure 17). The deposits consist of unconsolidated, cross-bedded, very fine to very coarse sand interbedded with clay, silt, and gravel. The gravel is generally near the base. The alluvium thickness ranges from zero to 100 feet or more in northeastern Bowie County (Baker and others, 1963).

The Blossom Sand consists of layers of fine to medium-grained glauconitic sand separated by layers of shale, clay, marl, and chalk, and the net sand thickness is only about 25 percent (Baker and others, 1963; McLaurin, 1988). The thickest continuous sand bed is about 60 feet thick and occurs at the base of the formation. Another continuous sand bed about 20 feet thick occurs at the top of the formation. These two beds are separated by impermeable clays and are probably not hydraulically connected (Baker and others, 1963; McLaurin, 1988).

South of the outcrop, the Blossom Sand is overlain by the younger Brownstown Formation, which consists of clay or shale and is not known to yield water to wells (McLaurin, 1988; Figure 17).The Bonham Shale underlies the Blossom Sand and, where the Blossom Sand pinches out in the west, the Bonham Shale is indistinguishable from the Brownstown Formation on electric logs (McLaurin, 1988).

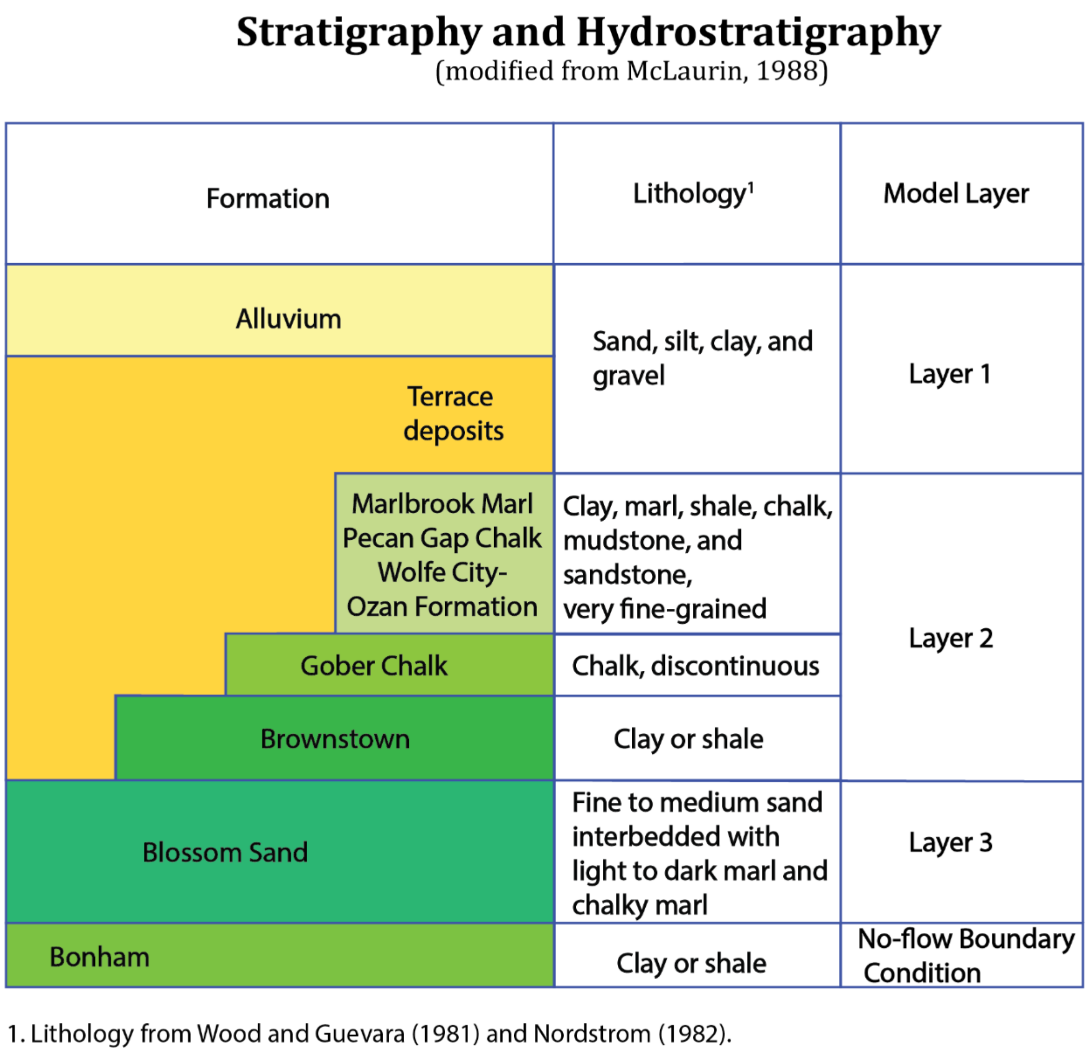

FIGURE 22. STRATIGRAPHY AND HYDROSTRATIGRAPHY OF THE BLOSSOM AQUIFER GROUNDWATER AVAILABILITY MODEL.

4.1.2 Structural Framework Surfaces

The top of layer one is land surface (Figure 4). The extent of layer 1 includes the portion of the Blossom Aquifer footprint covered by terrace deposits and alluvium (Figures 16, 17 and 23). To estimate the bottom of the Red River and Pecan Bayou alluvium, the outcrop boundary of the alluvium, as delineated on the Geological Atlas of Texas, was intersected with DEM elevations to provide input data for surface interpolation. Additionally, point locations were manually digitized along the stream channels and intersected with the DEM (Figure 4). The stream channel points were assumed to have an alluvial thickness of 20 feet along the Red River main channel and 10 feet of thickness along the minor tributary channels. The collection of points and outcrop boundary elevations were then interpolated using ordinary kriging to create an initial bottom surface for the alluvium. The base of the alluvium was further adjusted by comparing the depth of clay from eight driller's log to the original estimated alluvium thickness. The average difference between the depth to clay from the eight driller's logs and the original estimated alluvium thickness was 35 feet. From this comparison we increased the thickness of the alluvium (and hence lowered the base) 35 feet. The final estimated alluvium thickness ranges from 35 feet to about 85 feet (Figure 23).

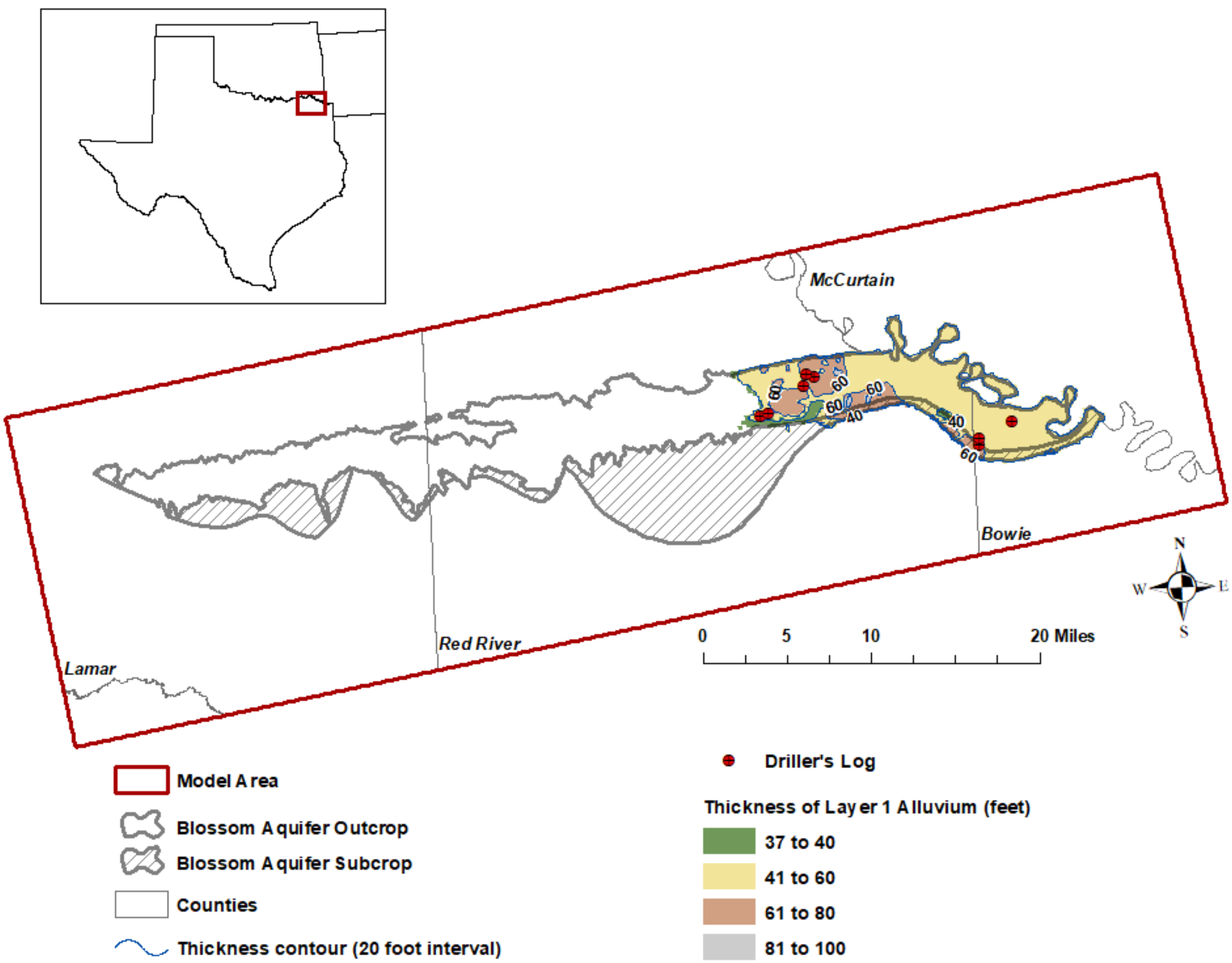

FIGURE 23. THICKNESS OF LAYER 1 (ALLUVIUM DEPOSITS).

Note in Figures 24, 25, 28, 29, and 30 the extent of the Brownstown Formation (Layer 2) and Blossom Sand (Layer 3) are shown only for the active extent of the numerical model. In the western part of the model area, the Blossom Sand thins out and the formation is no longer considered an aquifer even in the outcrop. The thin part of the Blossom Sand is therefore not included in the model and is not shown in the structural framework figures.

The top of layer two (Figure 24) is land surface elevation minus the layer 1 (alluvium) thickness. Where the alluvium is absent, the top of layer two is the land surface. The thickness of layer 2 (Figure 25) is based on the estimated depth to the top of the Blossom Sand minus the alluvium thickness (see discussion below). The alluvium directly overlies the Blossom Sand outcrop in central Red River County. In that area, model layer 2 will have a nominal thickness of 20 feet beneath the alluvium to connect to the Blossom Sand in layer 3.

The elevation of the top and the base of the Blossom Sand were estimated using McLaurin's (1988) surfaces supplemented with additional information. Control points from McLaurin's (1988) surface maps were digitized (Figures 26 and 27) and control points from Baker and others (1963) were also included. Extrapolation points were added based on land surface elevation along the updip and downdip outcrop contacts of the Blossom Sand and Tokio Formations and surfaces were interpolated using kriging in ArcGIS 10.1. The top of the Blossom Sand is equal to land surface elevation in the outcrop (Figure 28).

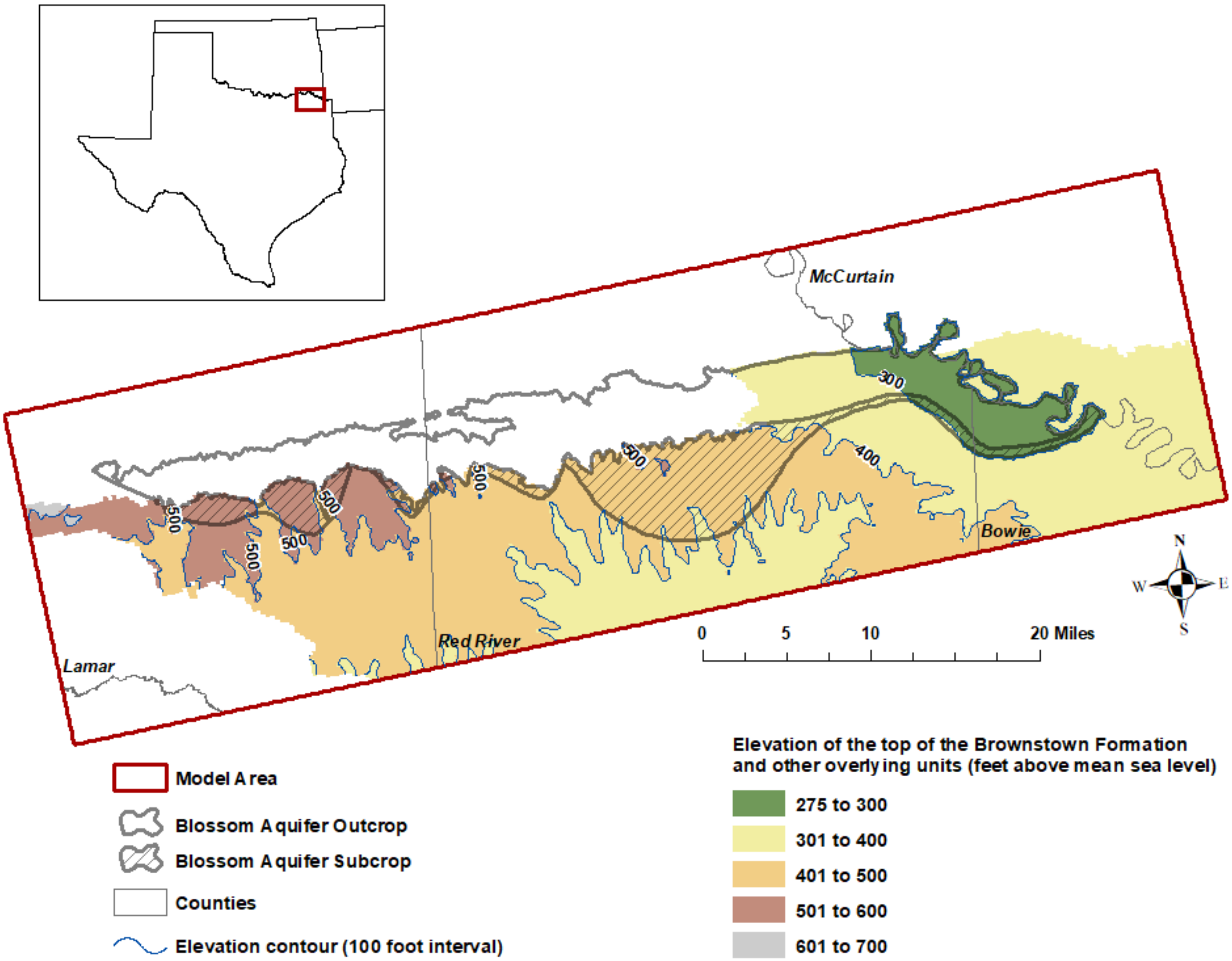

FIGURE 24. ELEVATION OF THE TOP OF LAYER 2, THE BROWNSTOWN FORMATION AND OTHER OVERLYING UNITS.

In the model area, the base of the Blossom Sand ranges from 500 feet elevation at the outcrop to 900 feet below sea level at the downdip (Figure 29). Blossom Sand thickness (Figure 30) ranges from less than 100 feet in the outcrop and in the west where it pinches out to over 300 feet in the confined portions. The estimated thickness of the Tokio Formation in Oklahoma ranges up to over 700 feet.

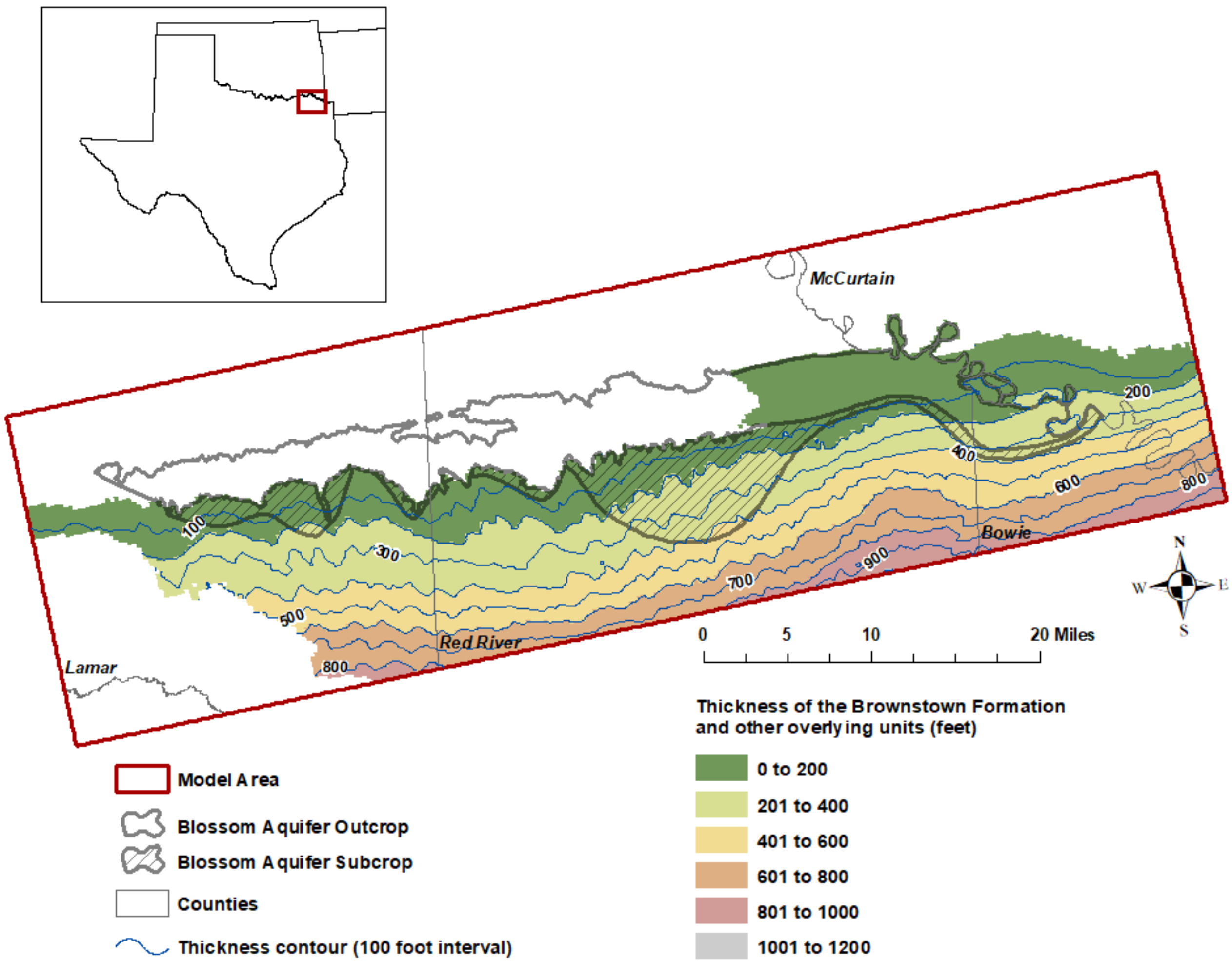

FIGURE 25. THICKNESS OF LAYER 2, THE BROWNSTOWN FORMATION AND OTHER OVERLYING UNITS. IN THE AREA WHERE THE ALLUVIUM DIRECTLY OVERLIES THE BLOSSOM SAND OUTCROP IN CENTRAL RED RIVER COUNTY MODEL LAYER 2 HAS A NOMINAL THICKNESS OF 20 FEET BENEATH THE ALLUVIUM TO CONNECT TO THE BLOSSOM SAND IN LAYER 3.

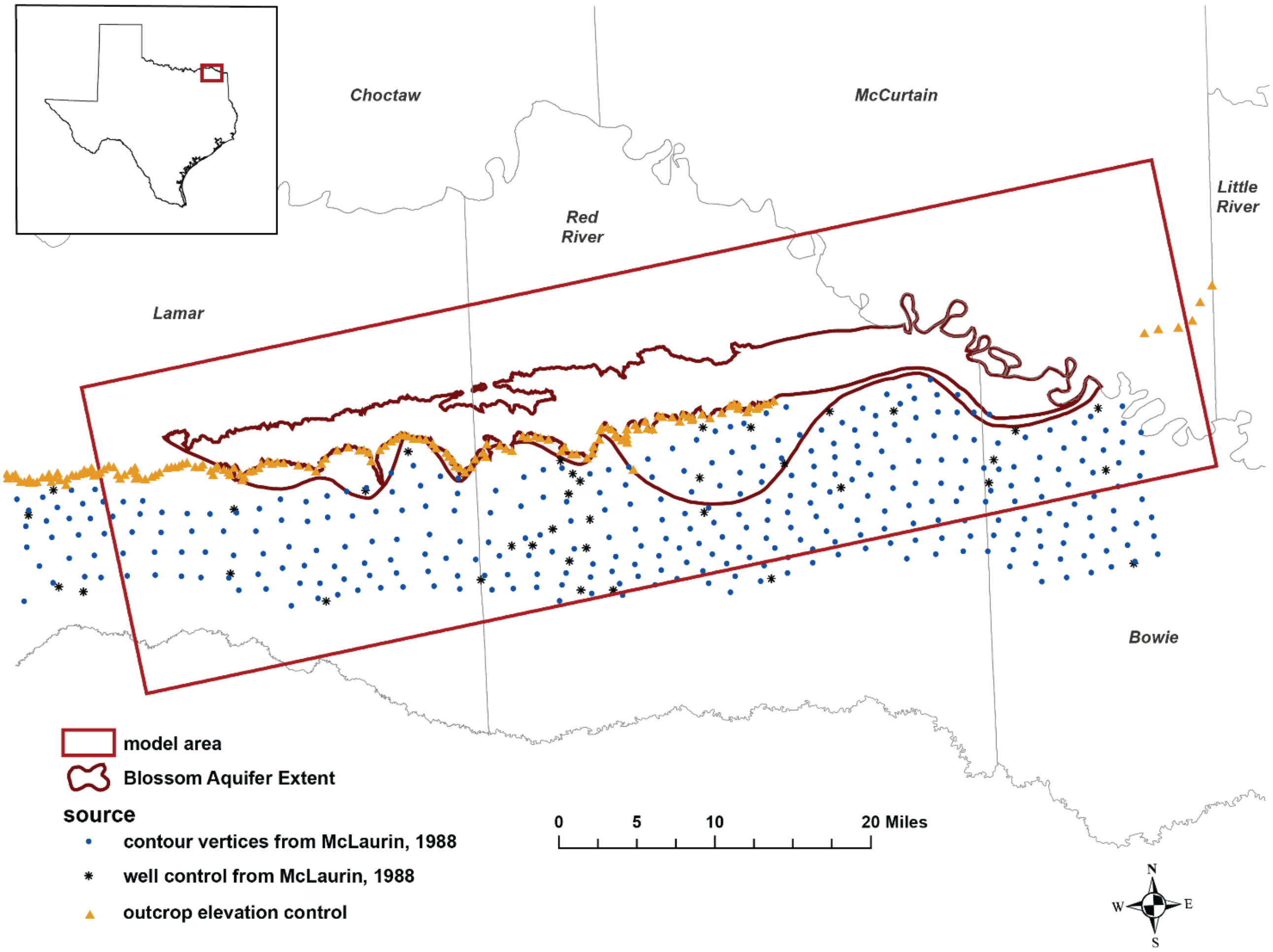

FIGURE 26. CONTROL POINTS USED TO ESTIMATE THE TOP OF THE BLOSSOM SAND.

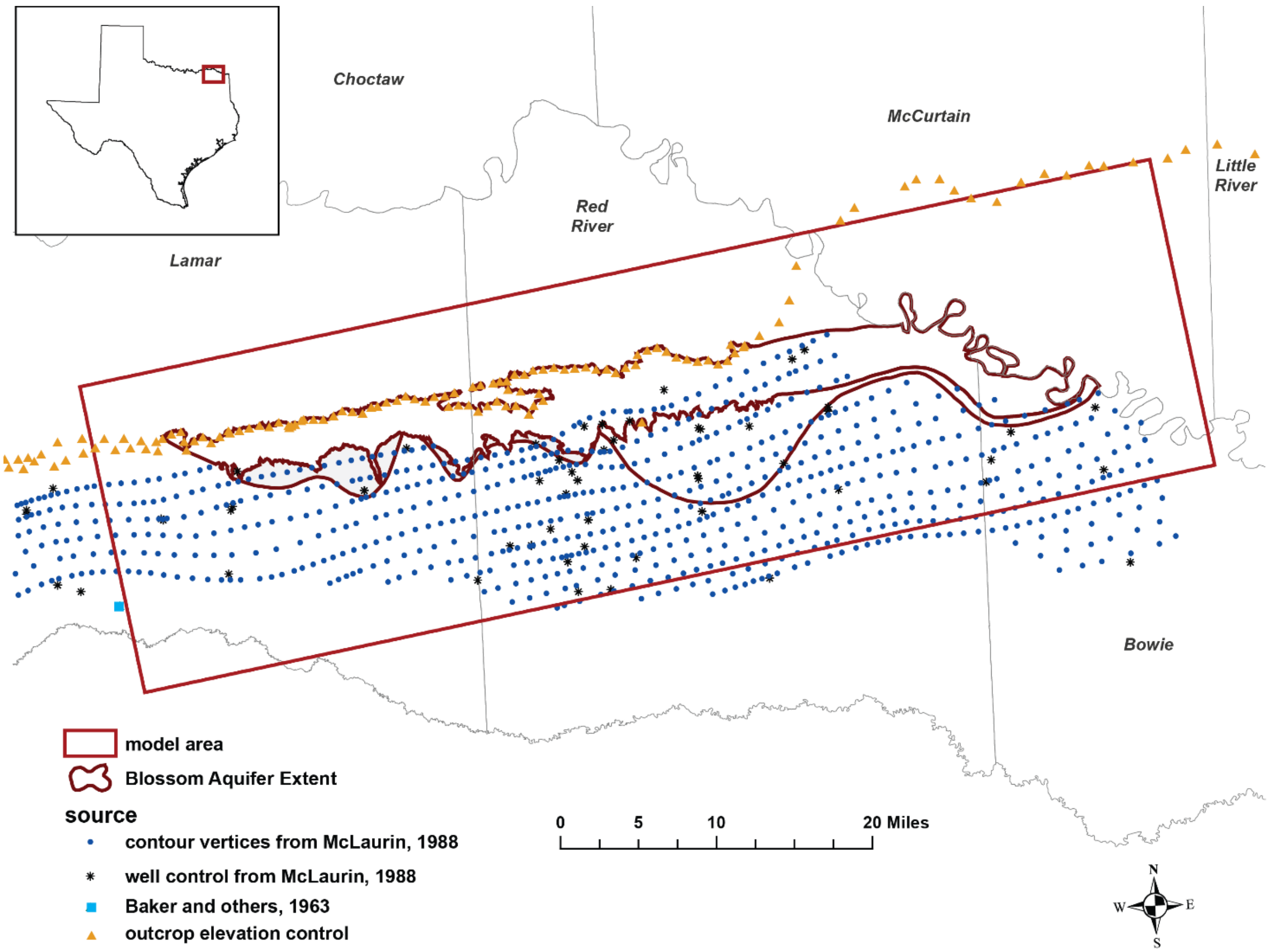

FIGURE 27. CONTROL POINTS USED TO ESTIMATE THE BASE OF THE BLOSSOM SAND.

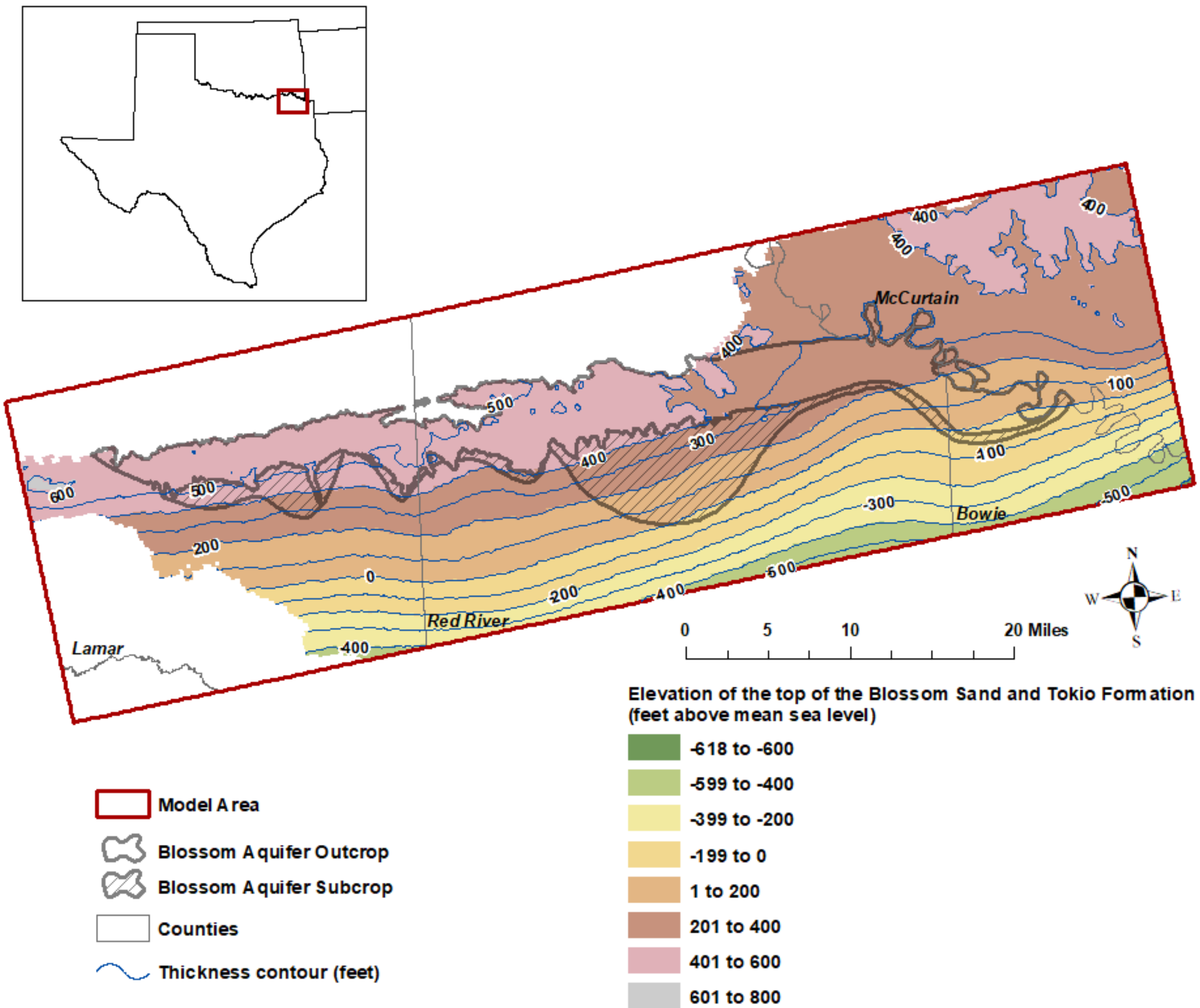

FIGURE 28. ELEVATION OF THE TOP OF LAYER THREE (THE BLOSSOM SAND).

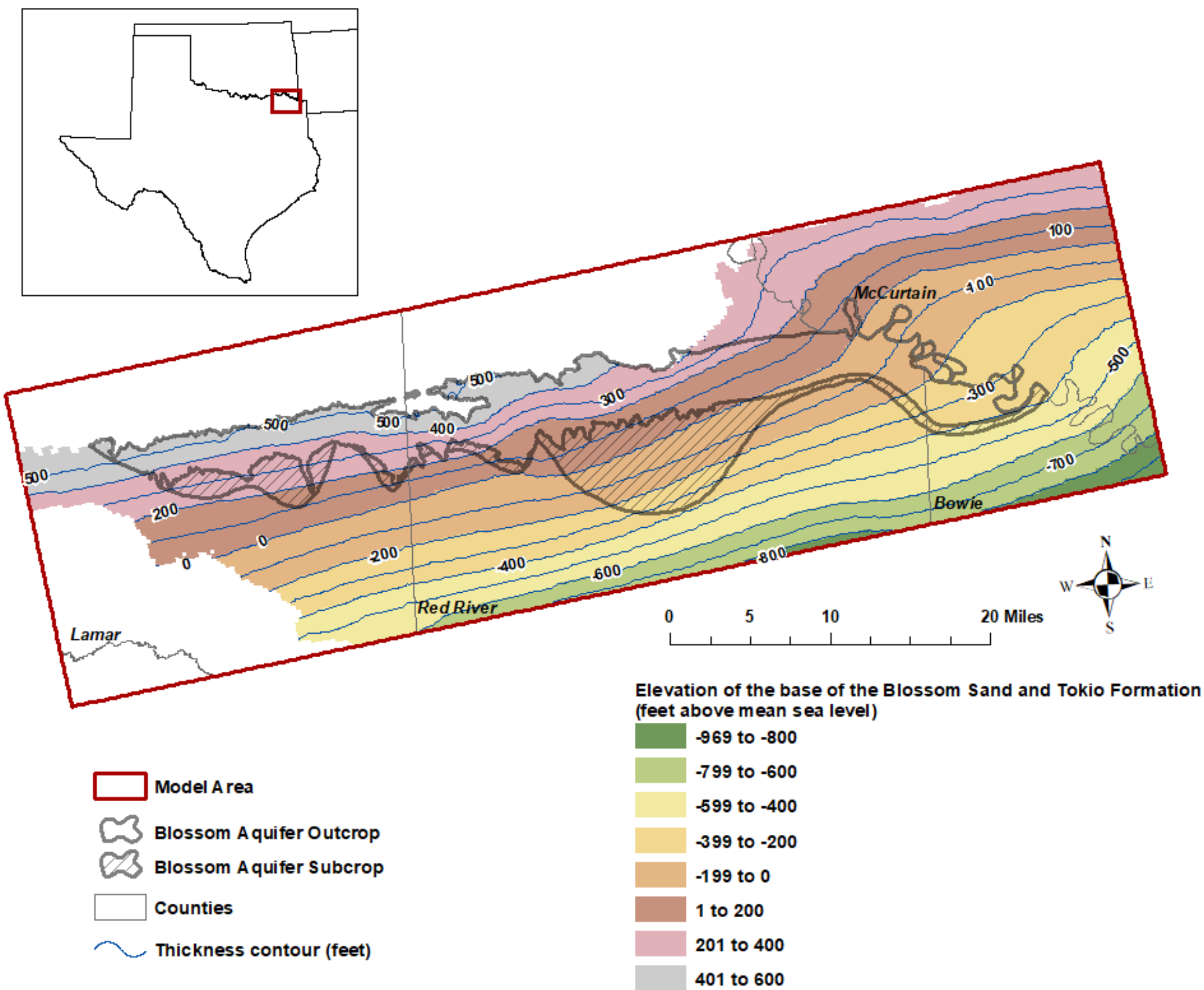

FIGURE 29. ELEVATION OF THE BASE OF LAYER THREE (THE BLOSSOM SAND).

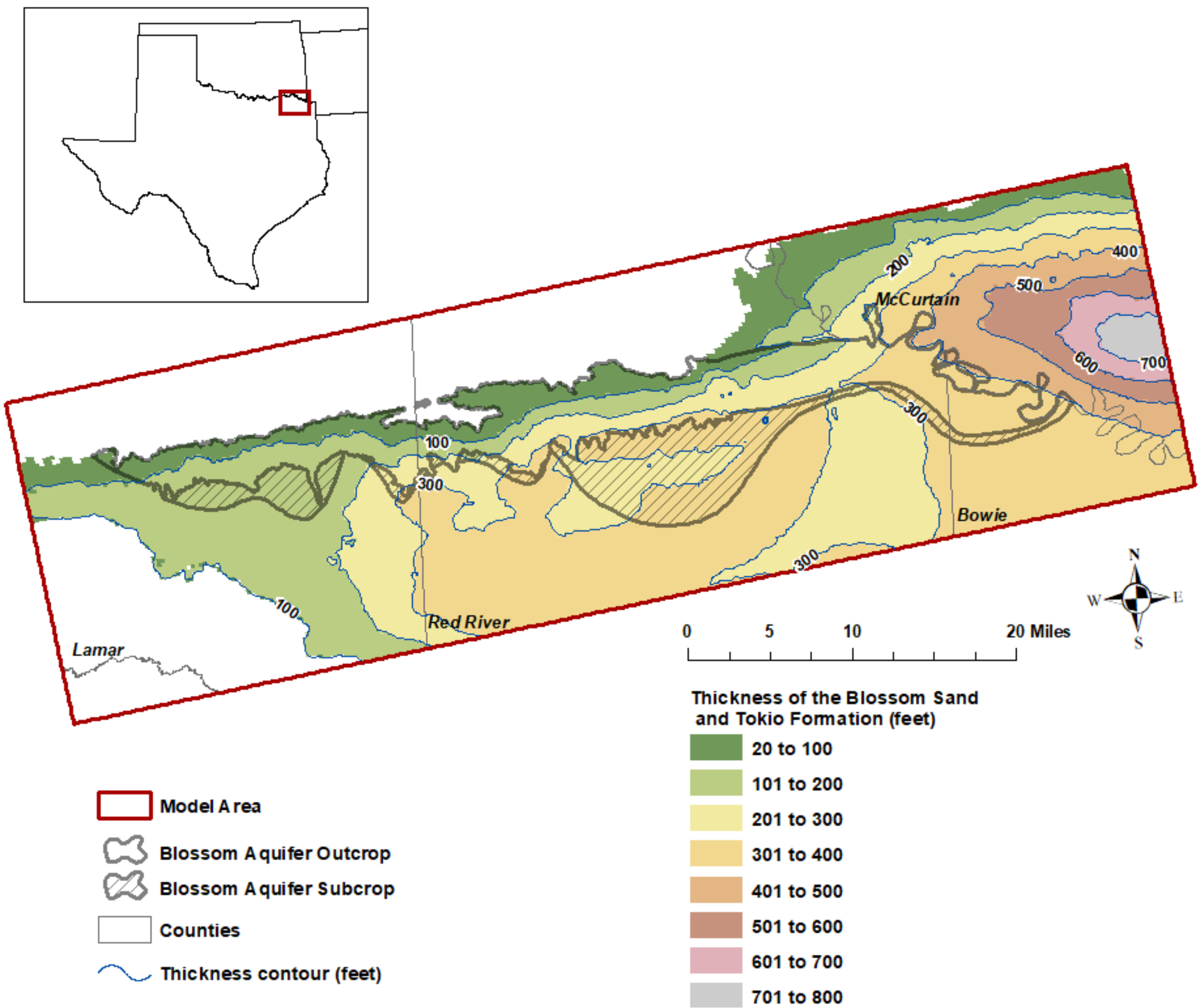

FIGURE 30. ESTIMATED THICKNESS OF THE BLOSSOM SAND (LAYER 3).

4.2 Water Levels and Regional Groundwater Flow

Water levels in the Blossom Aquifer range from more than 550 above sea level in the northwest part of the outcrop area to less than 150 feet (above mean sea level) in the deepest part of the subcrop (Figures 31 and 32). Recharge enters the aquifer on the outcrop and moves slowly downdip eventually discharging through seepage into other formations in the subsurface, particularly along the Luling Mexia-Talco fault system (Figure 18; Baker, 1963). Geochemistry data suggest the groundwater is more than 10,000 years old in the deeper portions of the aquifer (see section 4.7 for details).

Most of the water level data collected from the Blossom Aquifer are post-development and represent the aquifer after it has been stressed. However, Baker and others (1963) note that between 1905, when the first well was drilled in Clarksville, and 1960, water levels declined from 144 below land surface to 170 feet below land surface – a decline of 26 feet. This information allows us to estimate one predevelopment water level elevation as equal to the 1960 water level measurement plus 26 feet at the oldest Clarksville well (State Well Number 1732202), or 296 feet above mean sea level.

A set of water levels were collected in the fall and winter of 1982-1983 (Figure 31) and a second set in the winter of 2006 (Figure 32). Water levels in the outcrop show little change; however, water levels in the subcrop in Red River County dropped by almost 100 feet northeast of Clarksville from 1982 to 2006.

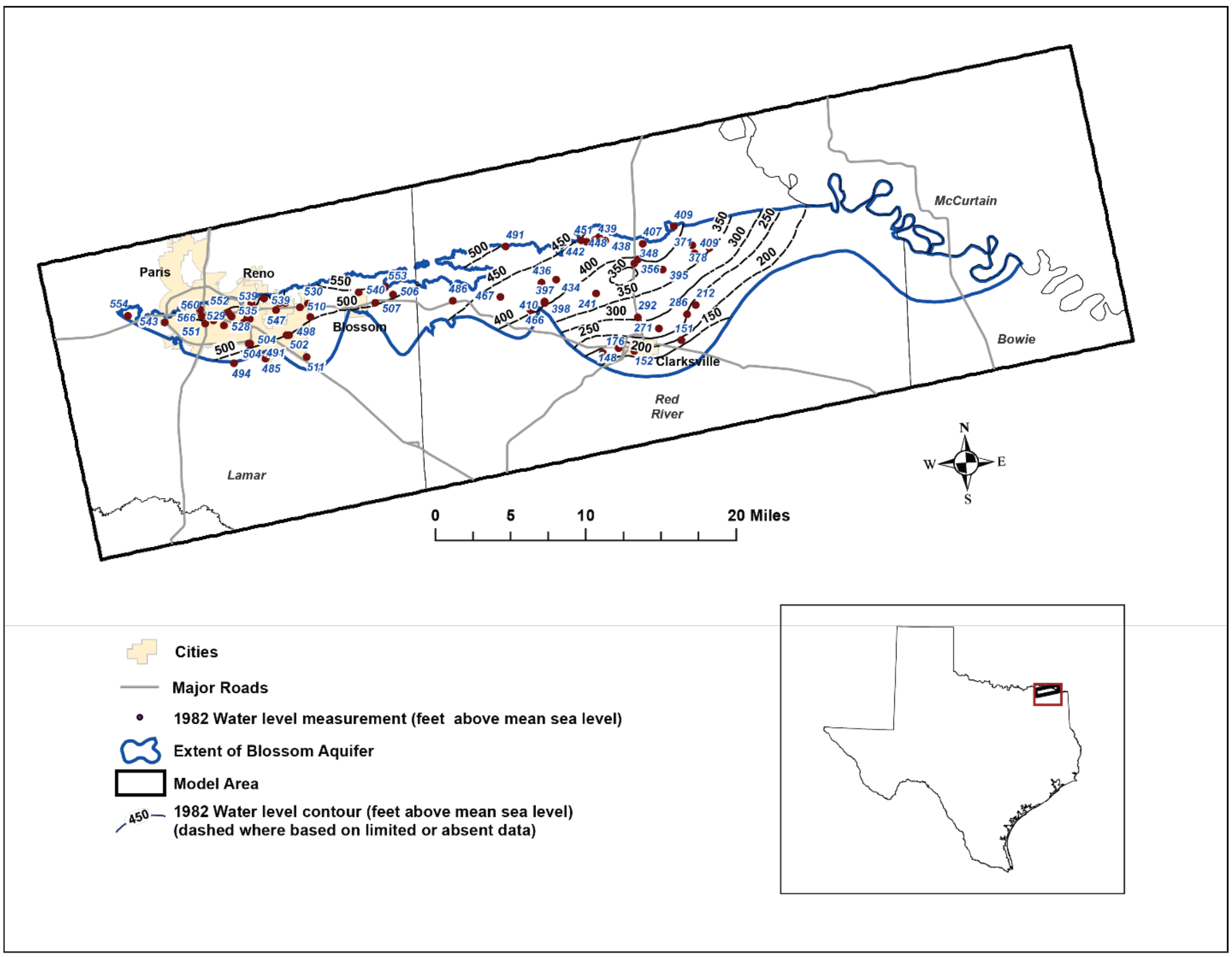

FIGURE 31. ESTIMATED 1982 WATER LEVELS FOR THE BLOSSOM AQUIFER (MODIFIED FROM MCLAURIN, 1988).

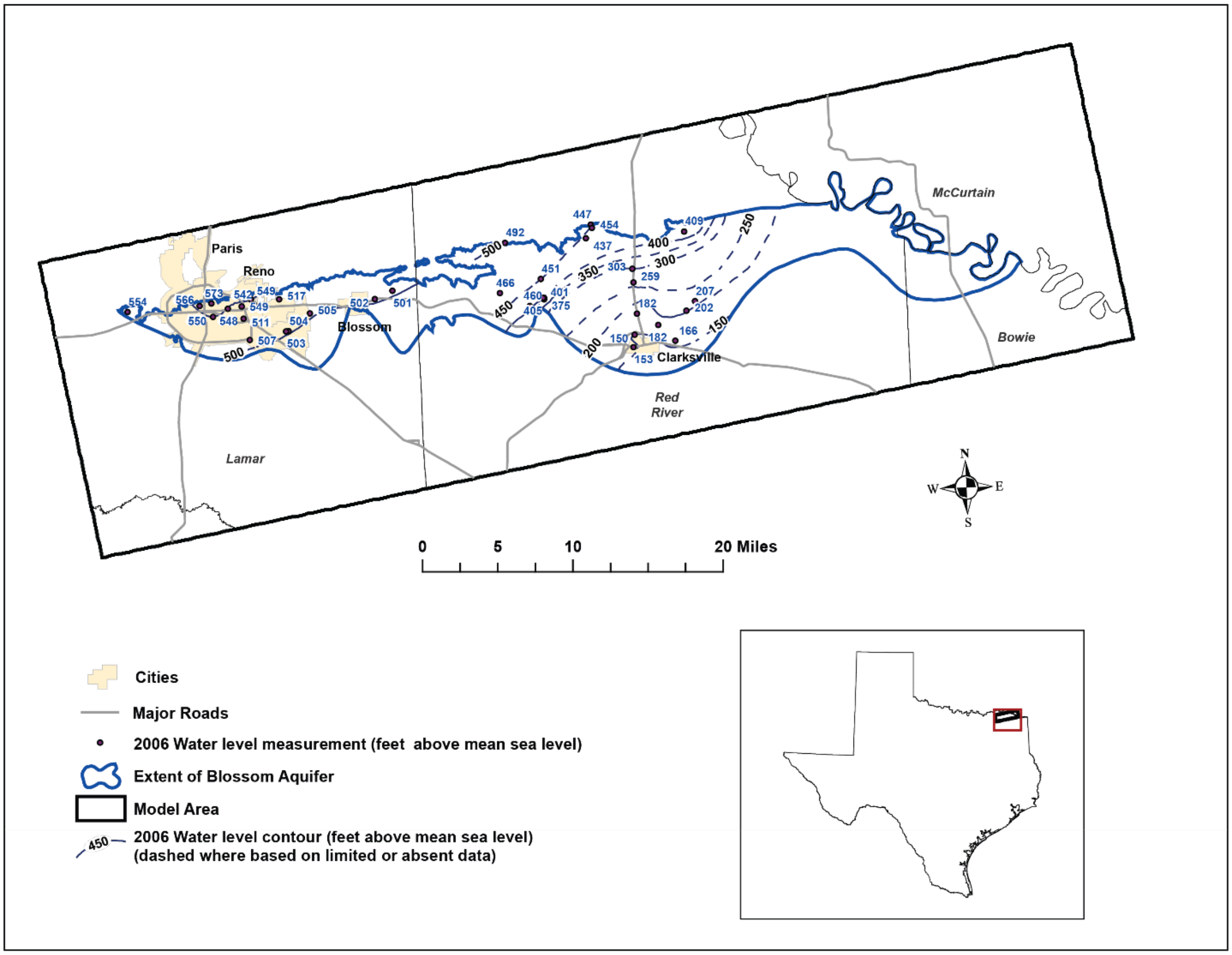

FIGURE 32. ESTIMATED 2006 WATER LEVELS FOR THE BLOSSOM AQUIFER (TWDB, 2013B).

Six wells in the Blossom Aquifer have at least 4 water levels measurements through time (Figures 33, 34, and 35). In addition, three Blossom Aquifer wells with three measurements are shown to expand the areal coverage of the hydrographs. Two wells from the Red River Alluvium in Bowie County within the footprint of the Blossom Aquifer have at least 4 measurements (Figure 36).

Three wells from Lamar County located in the outcrop or close to the outcrop show very little change in water levels in 70 years (Figure 33). In Red River County, water levels in the subcrop have declined from 50 to as much as 200 feet (Figures 34 and 35). One well showing the most decline (State Well Number 1732201) has seen some recovery. In Bowie County, the water levels in the Red River alluvium wells changed little in 25 years (Figure 36).

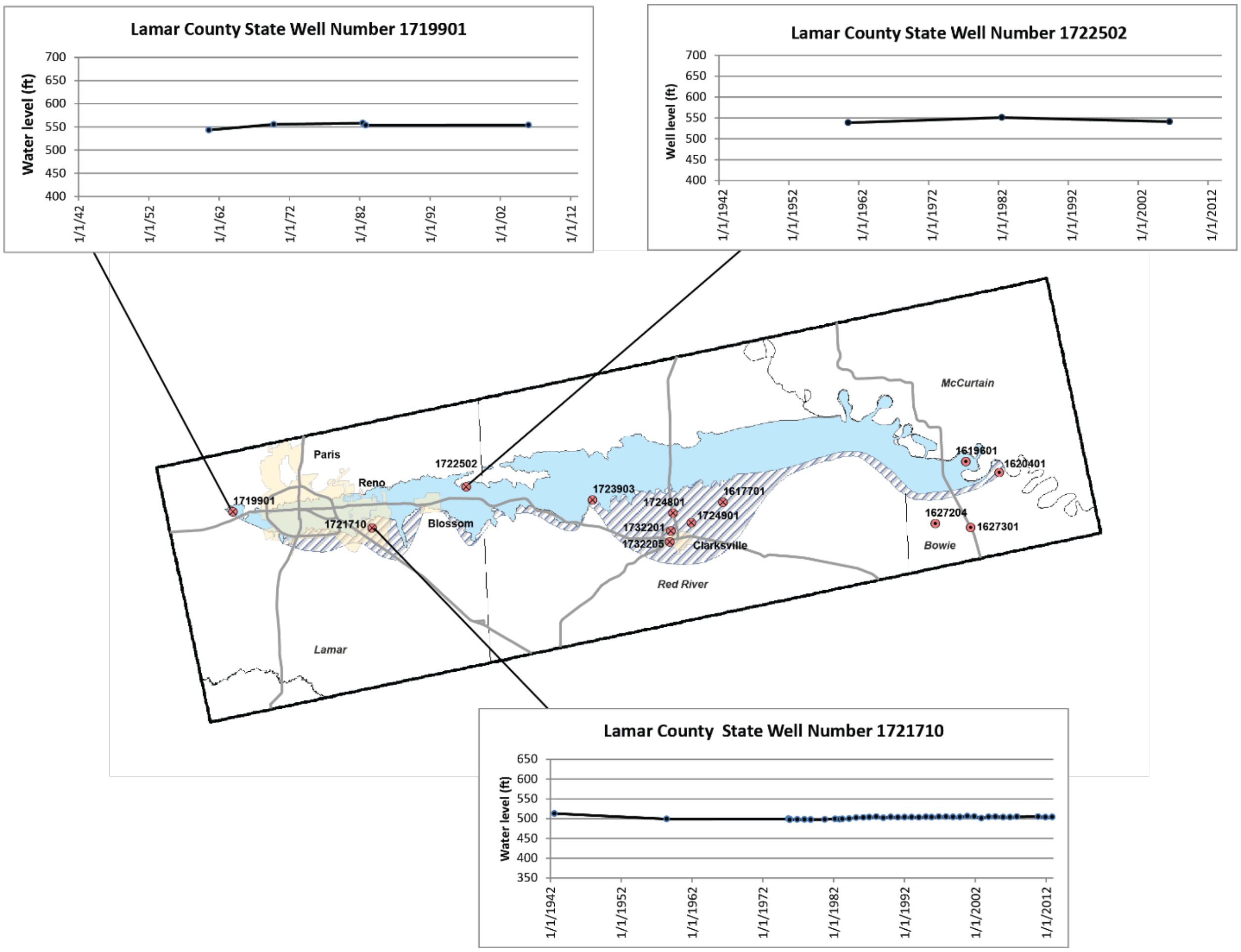

FIGURE 33. WATER LEVEL MEASUREMENTS FROM THREE WELLS IN LAMAR COUNTY (TWDB, 2013B).

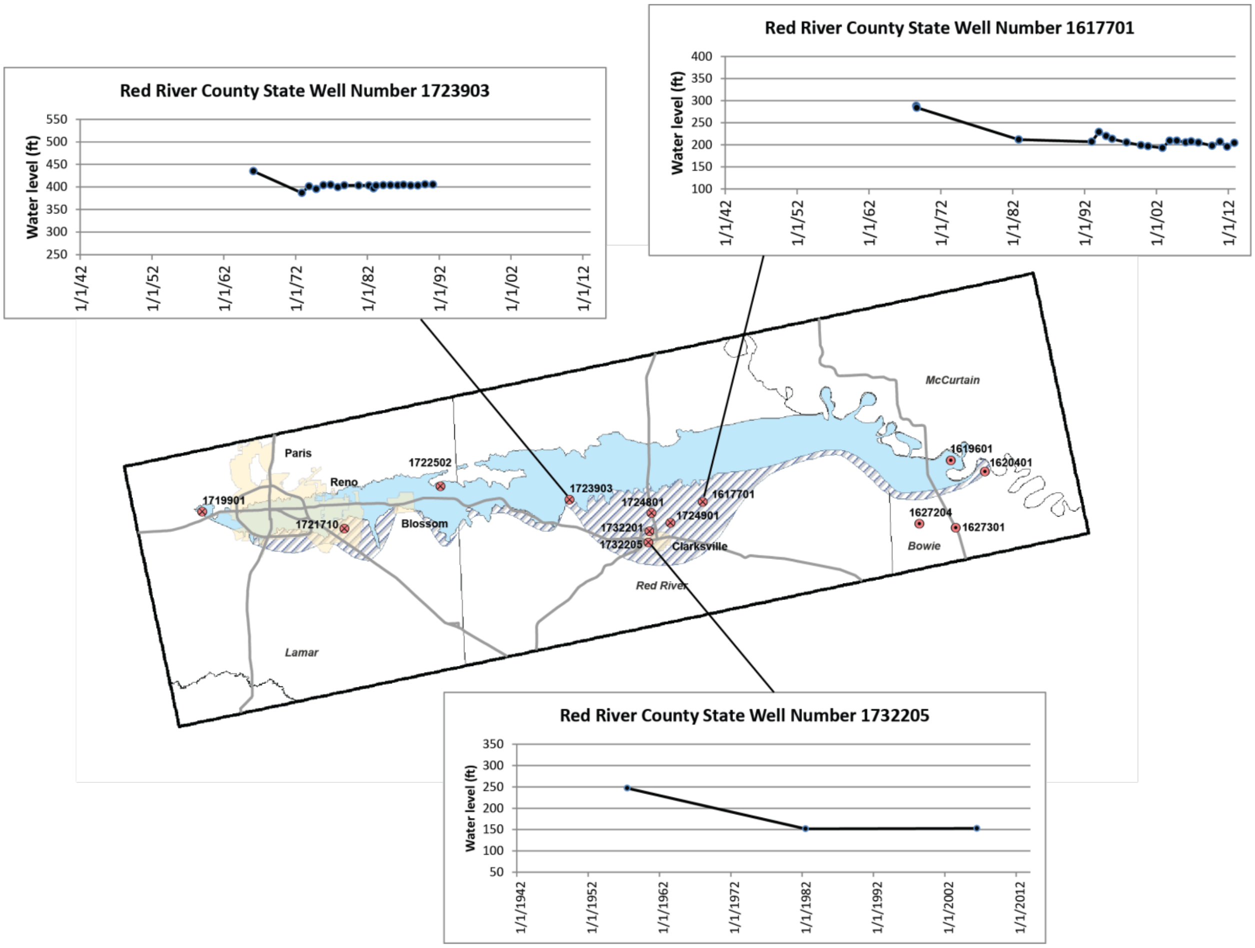

FIGURE 34. WATER LEVEL MEASUREMENTS FROM THREE WELLS IN RED RIVER COUNTY (TWDB, 2013B).

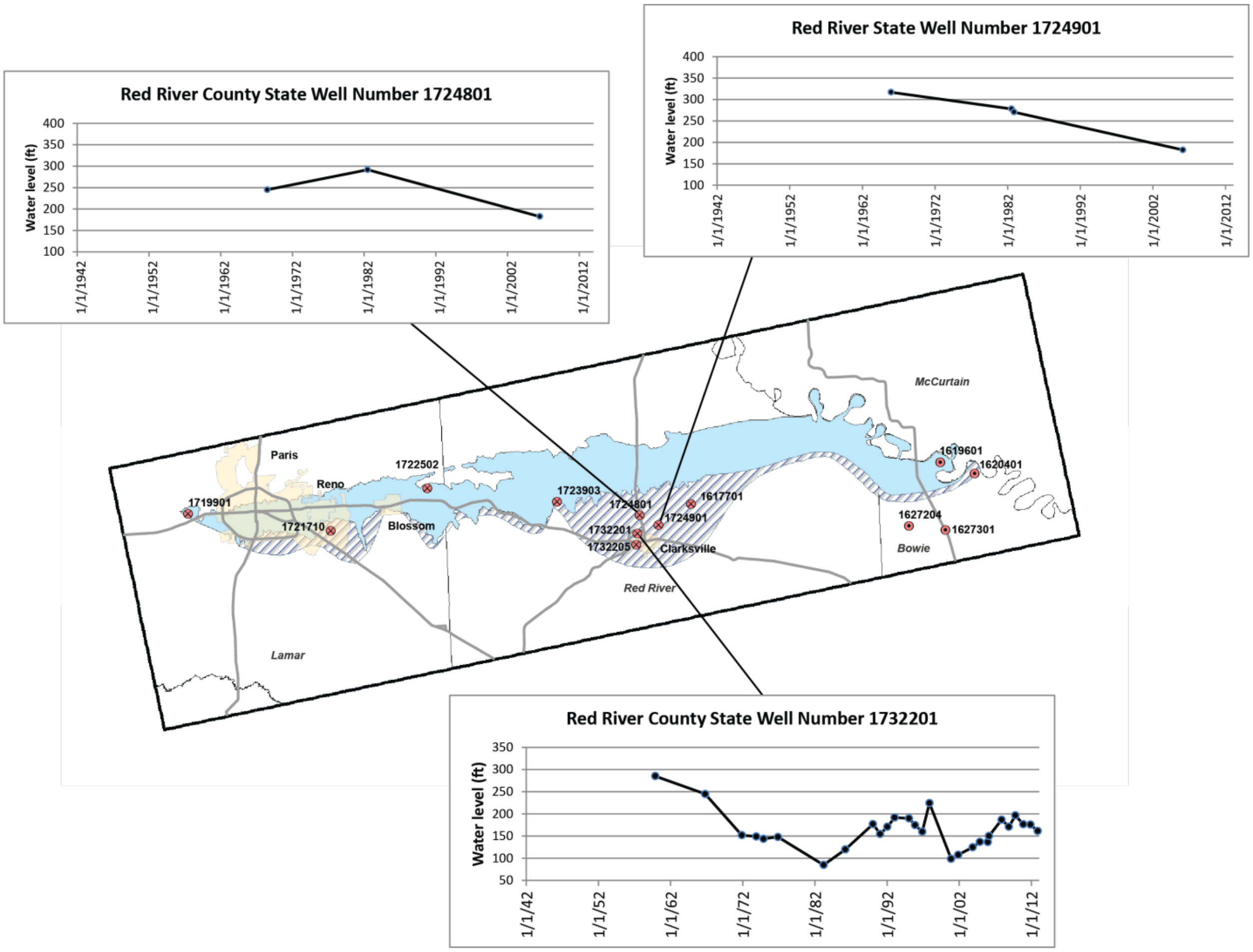

FIGURE 35. WATER LEVEL MEASUREMENTS FROM THREE ADDITIONAL WELLS IN RED RIVER COUNTY (TWDB, 2013B).

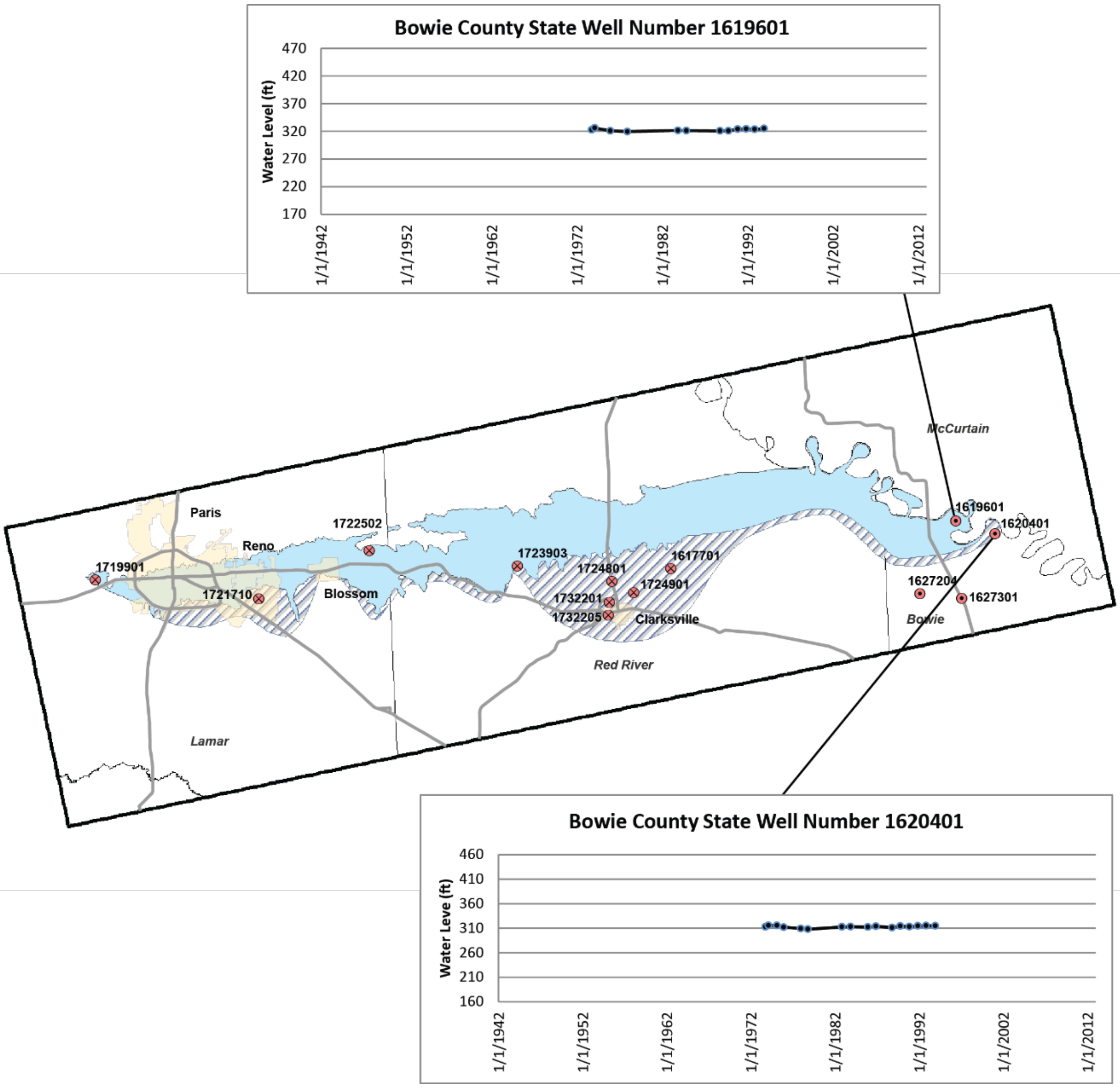

FIGURE 36. WATER LEVEL MEASUREMENTS FROM TWO WELLS IN BOWIE COUNTY (TWDB, 2013B).

4.3 Recharge

Recharge is the amount of water that reaches the water table and becomes part of the groundwater flow system (Anderson and Woessner, 1992). Factors that may influence aquifer recharge include the amount and frequency of precipitation, outcrop extent, topography, vegetation, soil properties, and infiltration capacity of the aquifer itself (McLaurin, 1988).

Based on analysis of the nearby Nacatoch Aquifer, McLaurin (1988) estimated that the annual effective recharge for the Blossom Aquifer is one-half of one percent of the annual precipitation that falls on the sandy portion of the outcrop. Cores from test holes and aquifer pump tests indicated that the two aquifers have similar properties (McLaurin, 1988).

McLaurin (1988) divided the Blossom Aquifer outcrop into three zones and estimated a total of 67 square miles of formation and alluvium outcrop that contribute recharge to the Blossom Aquifer. In the western part of Bowie County and in the eastern one-third of Red River County, the aquifer outcrop is totally covered by easily-infiltrated, permeable alluvium (McLaurin, 1988). In the central and western two-thirds of Red River County, about 29 percent of the Blossom Aquifer outcrop is sandy and about 15 percent of the outcrop is sandy in the eastern half of Lamar County. From central Lamar County westward, the Blossom Sand merges into a marl facies and the aquifer does not receive significant recharge (McLaurin, 1988). Assuming one-half of one percent (0.005) of the annual precipitation and 67 square miles of recharge area, McLaurin's (1988) estimated average annual effective recharge for the Blossom Aquifer is 811 acre-feet.

Chowdhury (2010) used the chloride mass balance method to estimate recharge in the Blossom Aquifer and in the nearby Red River Alluvium. Estimates ranged from 0.17 to 3.74 inches per year with an average of 0.93 inches per year. Higher values were estimated for the Red River Alluvium than for the Blossom Aquifer (Chowdhury, 2010).

In 2010, TWDB contracted with HydroBio Advanced Remote Sensing to develop a model to estimate annual groundwater recharge for Groundwater Management Area 8. The recharge model includes a buffer area and extends into Oklahoma and Arkansas (Kirk and others, 2012). The model area includes the Blossom Aquifer outcrop and the Tokio Formation outcrop directly across the Red River. The time period covered by the model is 1960 through 2009.

The HydroBio recharge model estimates groundwater recharge, *GWr*, as a water balance between annual precipitation, stream discharge, and evapotranspiration:

$$GWr = Ppt - Q - ETa$$

Where *Ppt* is precipitation, *Q* is total discharge, and *Eta* is annual evapotranspiration (Kirk and others, 2012).

The precipitation and total discharge used in the recharge model are based on spatially discrete data which were interpolated and extrapolated onto continuous rasters (Kirk and others, 2012). Precipitation was interpolated from point measurements of rainfall data throughout the model area. Discharge was based on representative watersheds that were free from disturbances such as reservoirs or urbanization. The discharge for the entire model area was then extrapolated from the representative watersheds. Annual evapotranspiration, *Eta*, was estimated from satellite data, which were scaled from reference evapotranspiration, ET_o. Reference evapotranspiration was estimated using a regression relationship with precipitation (Kirk and others, 2012). The model results consist of annual recharge rasters in inches per year for 1960 through 2009.

In order to compare a possible range of recharge rates for the study area, a dry year (2003) (Figure 37), an average year (1987) (Figure 38), and a wet year (2009) (Figure 39) were selected based on rainfall data from stations in Paris and Clarksville (Figures 11 and 12). Using zonal statistics in ArcGIS 10.2 the average recharge was calculated for the Blossom Sand and Tokio Formation outcrops within the study area (Table 1).

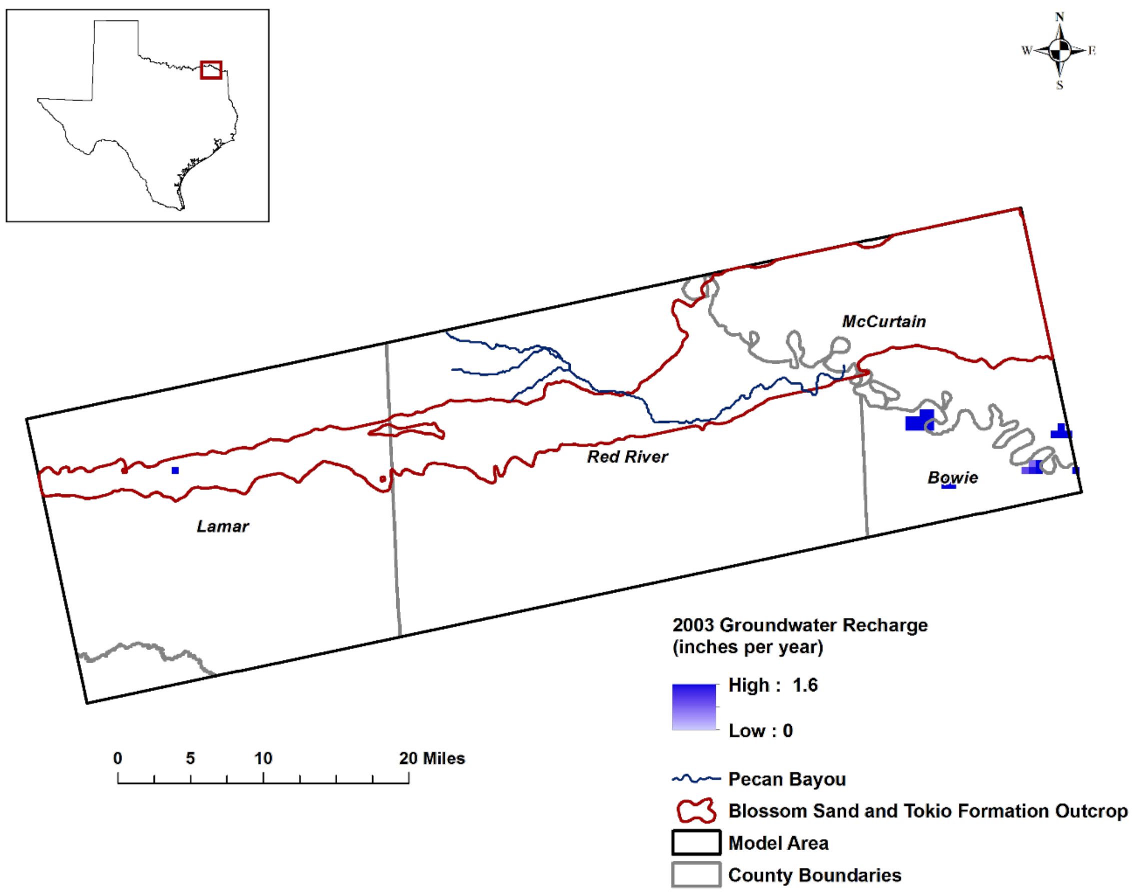

FIGURE 37. RECHARGE RATES FOR 2003, A DRY YEAR, ESTIMATED FROM HYDROBIO RECHARGE MODEL (KIRK AND OTHERS, 2012).

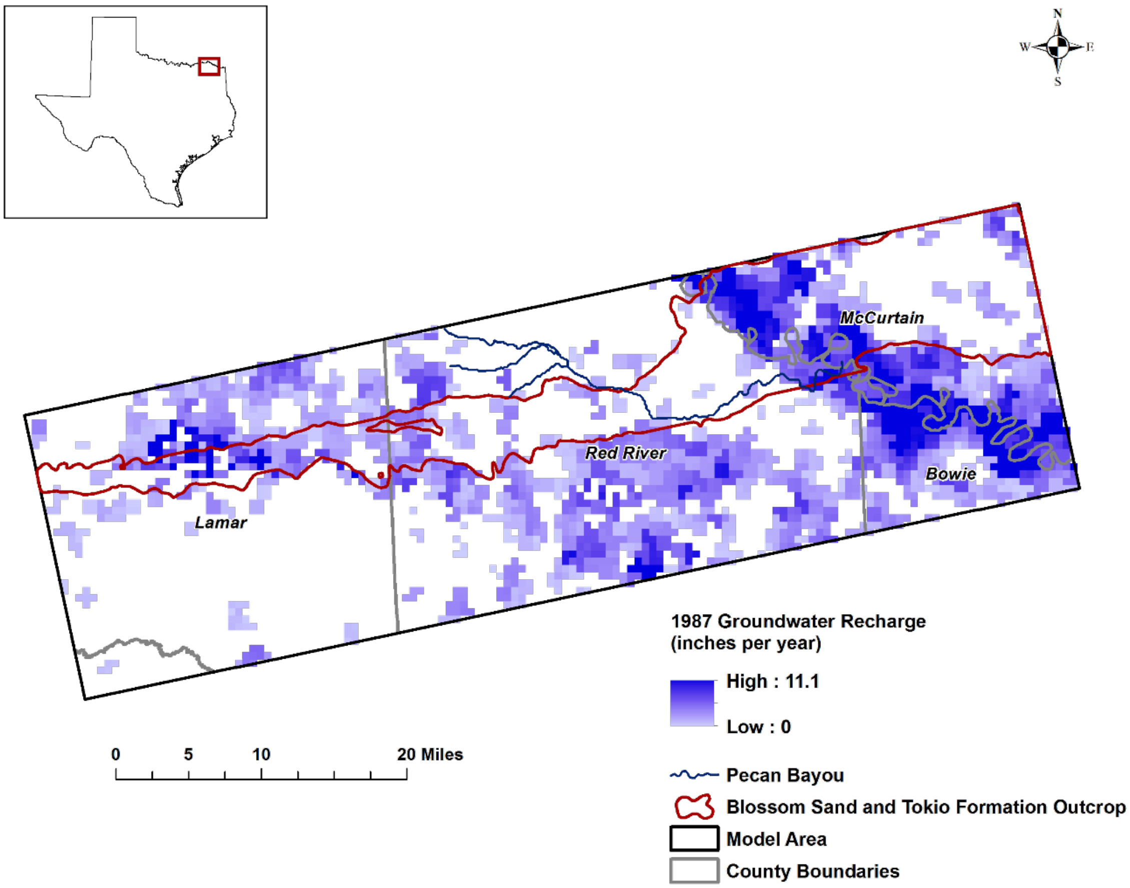

FIGURE 38. RECHARGE RATES FOR 1987, AN AVERAGE YEAR, ESTIMATED FROM HYDROBIO RECHARGE MODEL (KIRK AND OTHERS, 2012).

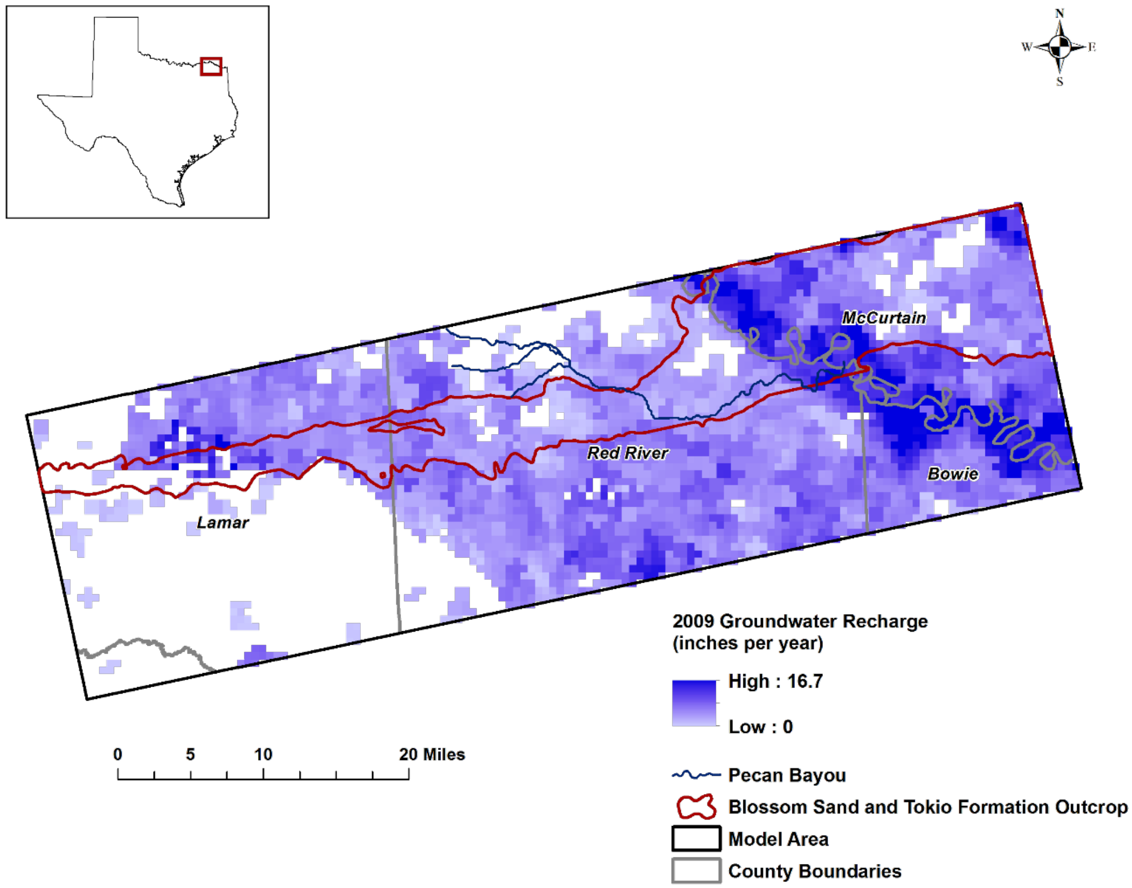

FIGURE 39. RECHARGE RATES FOR 2009, A WET YEAR, ESTIMATED FROM HYDROBIO RECHARGE MODEL (KIRK AND OTHERS, 2012).

Two U.S. Geological Survey programs (RECESS and RORA (Rutledge, 1998 and Barlow and others, 2014)) were used to estimate the annual groundwater recharge rate for Pecan Bayou watershed (Figure 3). Details of the analysis are given in Section 4.4 below. The mean annual estimated groundwater recharge rate for Pecan Bayou watershed for the years 1962 to 1977 is 3.73 inches per year (Table 1). This estimate is in the range of the recharge rates estimated using the HydroBio recharge model (Kirk and others, 2012).

The estimated average recharge rates for the Blossom Sand and Tokio Formation outcrop areas based on the HydroBio model range from zero for a dry year to 4.06 inches per year for a wet year. The mean annual recharge rate estimated by McLaurin (1988) is only about 20 percent of the rate for an average year estimated by the HydroBio recharge model. However, McLaurin's (1988) estimate is an effective (downdip) recharge rate. Chowdhury's (2010) estimated average of 0.93 inches per year is consistent with the HydroBio (Kirk and Others, 2012) estimate of 1.31 inches per year for an average year.

TABLE 1. ESTIMATED AVERAGE RECHARGE RATES FOR THE STUDY AREA.

Year	Spatially Average recharge (inches per year)	Area (square miles)	Source
2003 (dry)	0	Blossom Sand and Tokio Formation outcrop (369)	Kirk and others (2012)
1987 (average)	1.31	Blossom Sand and Tokio Formation outcrop (369)	Kirk and others (2012)
2009 (wet)	4.06	Blossom Sand and Tokio Formation outcrop (369)	Kirk and others (2012)
1962 to 1977 mean	3.73	Pecan Bayou watershed upstream of gauge, site 07336800 (100)	Barlow and others (2014)
1962 to 1977 mean	0.6	Pecan Bayou watershed upstream of gauge, site 07336800 (100)	Based on Base-Flow Index estimate
Mean annual	0.23	Part of Blossom Aquifer outcrop (67)	McLaurin (1988)
1970 – 2000 (rainfall data) 1996 – 2006 (chloride data)	0.93	Not applicable	Chowdhury (2010)

4.4 Rivers, Streams, Springs, and Lakes

4.4.1 Red River and Pecan Bayou

The two major surface water features in the model area are the Red River and Pecan Bayou (Figure 40) and there are no lakes or reservoirs located within the Blossom Aquifer outcrop. The Red River flows from northwest to southeast along the Texas-Oklahoma state line and forms the eastern boundary of the Blossom Aquifer. Pecan Bayou is a tributary to the Red River and flows for the majority of its course on the Blossom Aquifer outcrop and the terrace alluvium overlying the Blossom Sand (Gordon, 1911; Figure 40).

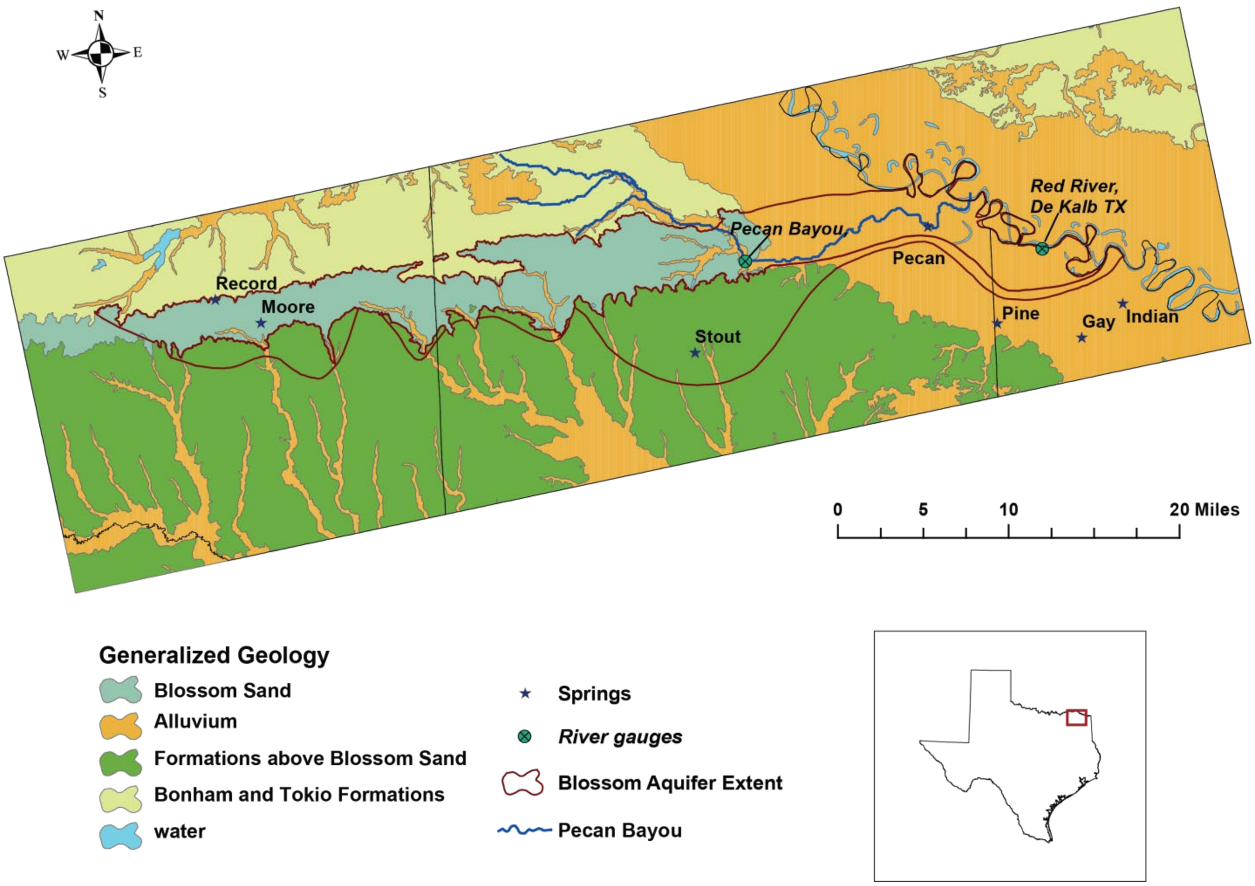

FIGURE 40. LOCATION OF SPRINGS AND RIVERS GAUGES IN THE STUDY AREA (MODIFIED FROM BUREAU OF ECONOMIC GEOLOGY, 2007).

The Red River Basin adjacent to the Blossom Aquifer is part of the Lower Red River (Main Stem) Basin. The Red River is influenced by four reservoirs in this subbasin. The total drainage area for the subbasin is 3,600 square miles and the total upstream drainage area for the U.S. Geological Survey stream gauge at De Kalb (Figure 41) is 47,268 square miles (Baldys and Hamilton, 2014). Consequently, any interaction between the Red River, the Blossom Aquifer, and overlying alluvium is likely to be a very minor contribution to the total gauged flow at De Kalb (Figure 41). A surface water/groundwater interaction study prepared for Texas Natural Resource Conservation Commission (now Texas Commission on Environmental Quality) suggests that, because the Blossom Aquifer is located on the watershed divide between the Sulphur and Red River Basins (Figure 3), the aquifer may not contribute groundwater directly to Red River or to Sulphur River (Parsons Engineering Science, Inc., 1999).

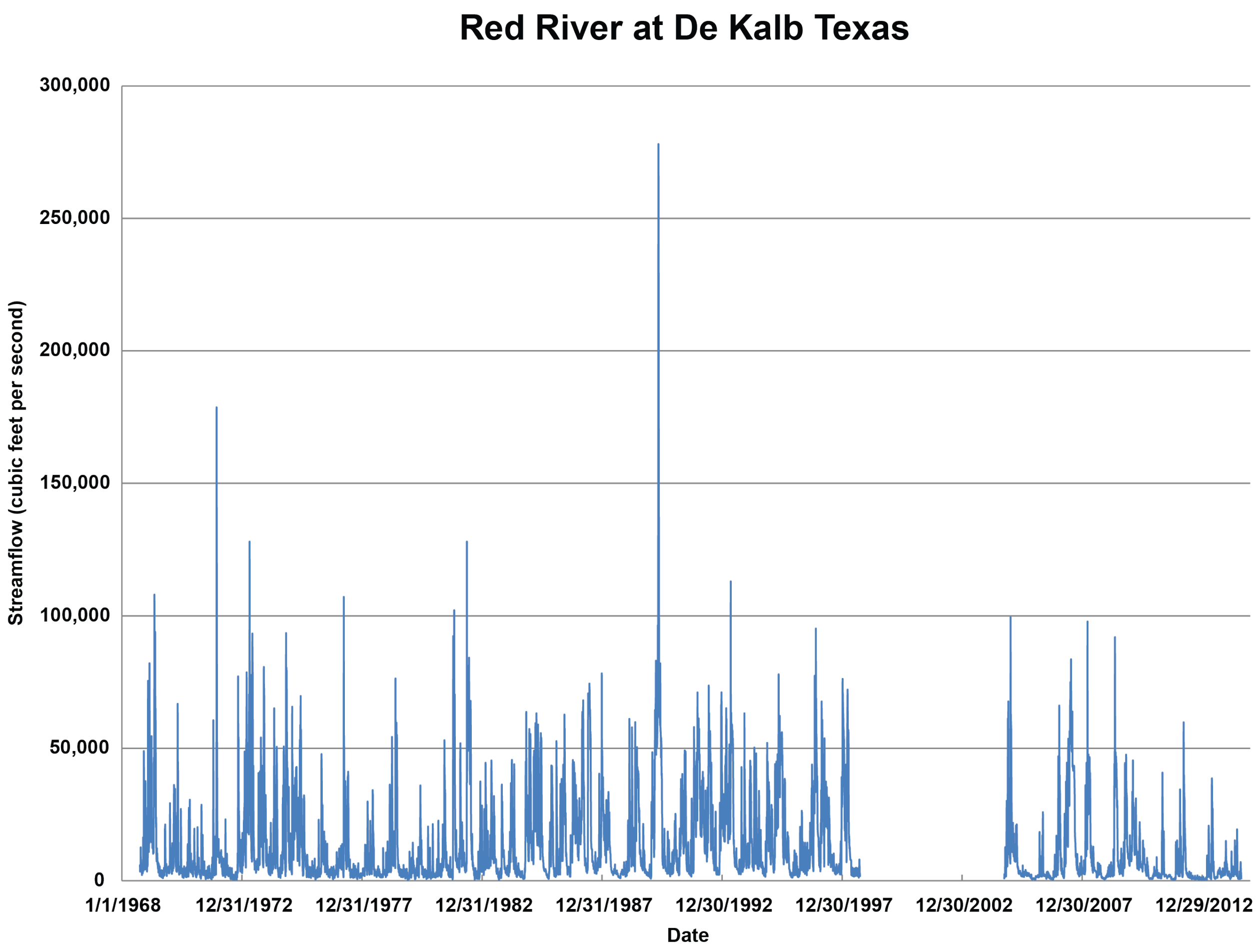

FIGURE 41. RED RIVER STREAMFLOW NEAR DE KALB TEXAS (SITE 07336820; U.S. GEOLOGICAL SURVEY, 2014C). FLOW DATA MISSING FROM OCTOBER 1998 THROUGH OCTOBER 2004.

The Pecan Bayou watershed (shown on Figure 3) is one of the largest undammed watersheds in northeast Texas (Bucher Willis and Ratliff Corporation, 2010) and the 2011 North East Texas Regional Water Plan (Region D) and the 2012 State Water Plan recommended that the Texas legislature designate Pecan Bayou as an ecologically unique stream segment (Bucher Willis and Ratliff Corporation, 2010; TWDB, 2012).

One reference describes the flow in Pecan Bayou as intermittent at places in its upper and middle reaches (Handbook of Texas Online, 2015). However, the U.S. Geological Survey National Hydrography Dataset (NHD) lists Pecan Bayou as mostly perennial (U.S. Geological Survey, 2015). The Pecan Bayou streamflow at the U.S. Geological Survey gauge

(Figure 42; site 07336800) ranges from zero to over 14,000 cubic feet per second. The mean flow is 80 cubic feet per second and the median flow is 1.2 cubic feet per second. The first Pecan Bayou gauge measurements were in January 1962 and the gauge was discontinued in October 1977. The daily discharge data set includes flow measurements for each day during that time period; however, some of the measurement flow rates shown in Figure 42 are actually measured flow rates that are very low or zero(U.S. Geological Survey, 2014c).

Streamflow is generally made up of three components: surface runoff, interflow, and baseflow. Surface runoff travels directly over the ground surface to the stream channel. Interflow is water which infiltrates the soil and moves laterally through the upper soil layers until it enters a stream channel (Linsley and others, 1982). Baseflow is the component resulting from groundwater discharge to the stream. The surface runoff and interflow are often combined and the streamflow is considered to consist of two components, direct runoff and baseflow (Linsley and others, 1982). Streamflow hydrographs can be separated, using various techniques, into the two components. The premise behind separation is that the rising limb of a hydrograph peak is influenced by the storm event (Linsley and others, 1982). The point of inflection at the peak marks the time at which surface inflow ends (Linsley and others, 1982). The receding or falling limb represents withdrawal of water from storage within the basin (Linsley and others, 1982).

The Base-Flow Index (BFI) method (Barlow and others, 2014; Wahl and Wahl, 1995) was used to estimate baseflow from Pecan Bayou (Figure 43). The Base-FIow Index method finds local minimums in the stream flow combined with a recession slope test (Wahl, 2015). Because Pecan Bayou may be intermittent upstream from the gauge, estimated baseflow should be treated with caution (Barlow and others, 2014). The time average of the Base-Flow Index estimate (Figure 43) averaged over the 100 square mile area of Pecan Bayou watershed upstream from the gauge is 0.6 inches per year. This estimate may be a lower bound on the groundwater recharge in the Pecan Bayou watershed.

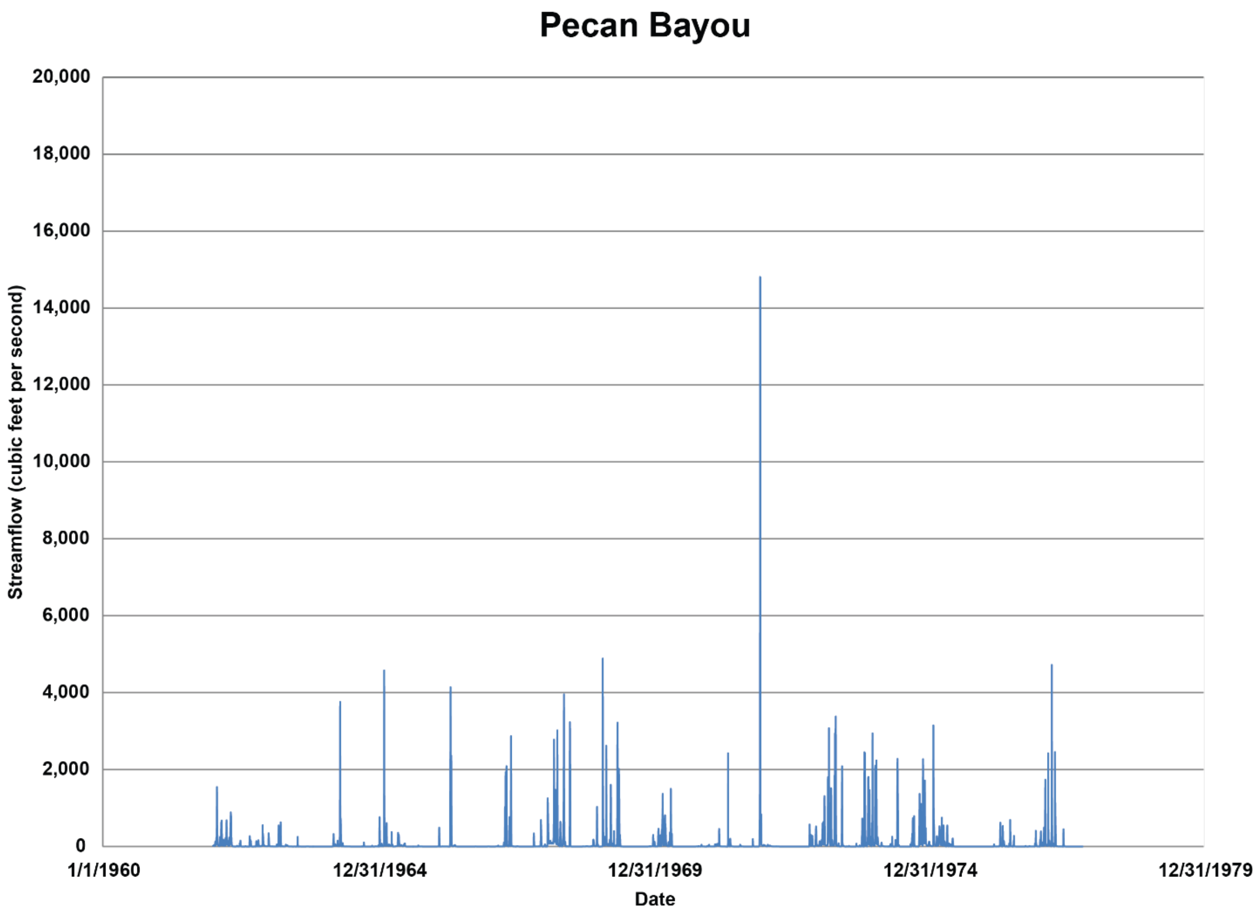

FIGURE 42. PECAN BAYOU STREAMFLOW NEAR CLARKSVILLE TEXAS (SITE 07336800; U.S. GEOLOGICAL SURVEY, 2014C).

The falling limb, or recession, of a streamflow hydrograph is a function of the groundwater discharge rate for the basin (Linsley and others, 1982). The U.S. Geological Survey programs RECESS and RORA (Rutledge, 1998 and Barlow and others, 2014) were used to estimate the annual groundwater recharge rate for Pecan Bayou watershed. The program RECESS determines the master recession curve of streamflow for times when all flow can be considered groundwater discharge (Rutledge, 1998). The program RORA is used for a long period of record to obtain an estimate of the mean groundwater recharge. It uses the recession-curve displacement method to estimate the recharge for each peak in the streamflow record (Rutledge, 1998). The mean annual estimated groundwater recharge rate for Pecan Bayou watershed for the years 1962 to 1977 is 3.73 inches per year (Table 1). This estimate is relevant only for the Pecan Bayou watershed and represents the entire watershed not just the portion over the Blossom Aquifer. The methods assume that groundwater withdrawal due to pumping is not a significant part of the system (Rutledge, 1998).

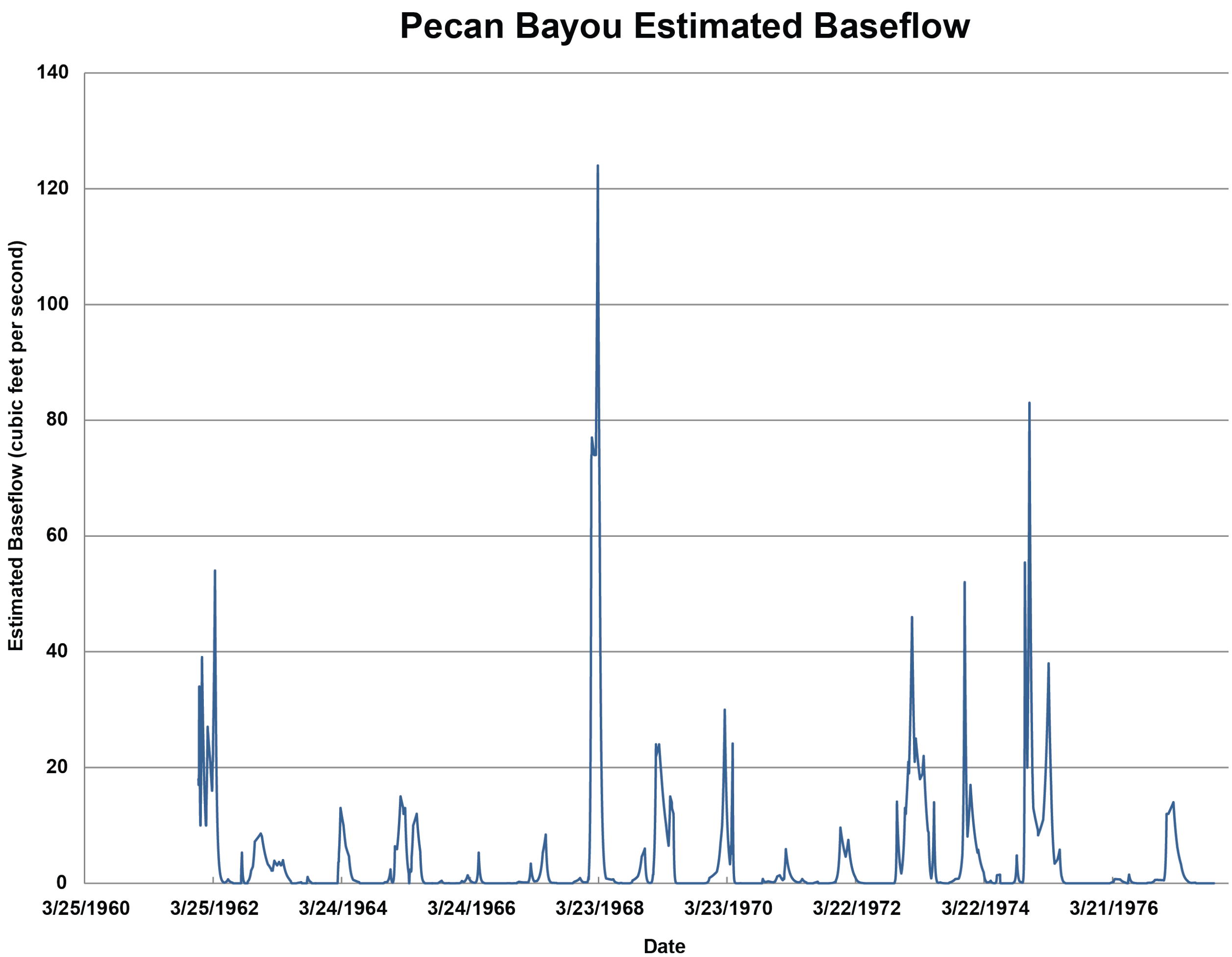

FIGURE 43. ESTIMATED BASEFLOW FOR PECAN BAYOU USING BASE-FLOW INDEX METHOD.

4.4.2 Springs

Brune (1981) surveyed historical and current springs throughout Texas and measured flow for existing springs. Seven springs are listed in the study area (Figure 40; Table 2). We did not locate any additional discharge data for the springs in Table 2 besides Brune's (1981) data.

According to Brune (1981), based on 1976 flowrates, Indian Spring was a medium spring and Record, Pine, and Gay Springs were small springs. Moore Springs are historical and are no longer flowing, probably because of lowered water levels in the aquifer (Brune, 1981). The site of Stout Spring is now located underneath a building in Clarksville and Brune (1981) suggests it probably is dry because of the groundwater pumping in the area. Pecan Springs flowed strongly until 1975, when a well was installed and the springflow ceased (Brune, 1981).

TABLE 2. SPRINGS LOCATED IN MODEL AREA (BRUNE, 1981).

County	Spring Name	Surface Formation	Flow (liters per second)	Flow (cubic feet per second)	Year
Lamar	Record	Blossom	0.65	0.00021	1976
Lamar	Moore	Blossom	0	0	1976
Red River	Stout	Annona Chalk	0	0	1976
Red River	Pecan	River Terrace	0	0	1976
Bowie	Pine	River Terrace	0.33	0.00011	1976
Bowie	Gay	River Terrace	0.52	0.00017	1976
Bowie	Indian	River Terrace	6.1	0.00200	1976

4.5 Hydraulic Properties

The ability of an aquifer to transmit water is determined by hydraulic conductivity and transmissivity. Hydraulic conductivity is a measure of an aquifer's ability to move water under a hydraulic gradient and transmissivity is a measure of the aquifer's ability to transmit water through its entire thickness (Bear, 1979). These properties affect how much water levels change due to pumping. The storage properties of specific yield and confined storage coefficient are measures of how much water a given volume of aquifer can release. Storage properties also affect water level changes through time.

A recent brackish groundwater production study of the Blossom Aquifer was completed for the TWDB Brackish Resources Aquifer Characterization System (Andrews and Croskrey, 2019). One of the results of the study was a map of net sands produced from 188 wells with lithology records (Andrews and Croskrey, 2019). The net sands thickness ranged from 0 to 274 feet with a mean of 133 feet and the map showed the net sand in the Blossom increasing from west to east (Andrews and Croskrey, 2019). This result is consistent with earlier studies indicating that the productivity of the Blossom Sand decreases westward (McLaurin, 1988).

Storage and hydraulic properties can be estimated from aquifer pumping test data. McLaurin (1988) reported eight estimates of hydraulic conductivity and two estimates of confined storage coefficient (Table 3) based on aquifer tests from the Blossom Aquifer. In addition to these data, specific capacity data from 24 driller's logs for the Blossom Aquifer and the overlying alluvium are available (TWDB, 2014). Specific capacity is the pumping rate of a well divided by the amount of drawdown in the well. Transmissivity and hydraulic conductivity can be estimated from specific capacity data using several different approaches. There are also ways to correct for non-ideal situations such as partial penetration and well-losses (Mace, 2001).

An equation developed by Theis and others (1963) relating specific capacity to transmissivity was further adjusted by Sternberg (1973) to account for partial penetration of the well into the aquifer (Mace, 2001):

$$S_c = \frac{4\pi T}{\left[\ln\left(\frac{2.25Tt}{r_w^2 S}\right)+2s_p\right]}, \qquad (1)$$

where S_c is specific capacity, T is transmissivity, r_w is the well radius, S is the storage coefficient of the aquifer, t is the pumping time, and s_p is the partial penetration factor. The partial penetration factor is given by (Mace, 2001; Brons and Marting, 1961):

$$s_p = \frac{1-\left(\frac{L_w}{b_a}\right)}{\left(\frac{L_w}{b_a}\right)}\left[\ln\left(\frac{b_a}{r_w}\right) - G\left(\frac{L_w}{b_a}\right)\right], \qquad (2)$$

where b_a is the aquifer thickness, L_w is the length of the well screened in the aquifer, and G is a function of the ratio of L_w to b_a. A polynomial estimate of G is given by (Mace, 2001; Brons and Marting, 1961; and Bradbury and Rothschild, 1985):

$$G\left(\frac{L_w}{b_a}\right) = 2.948 - 7.363\left(\frac{L_w}{b_a}\right) + 11.447\left(\frac{L_w}{b_a}\right)^2 - 4.675\left(\frac{L_w}{b_a}\right)^3 (3)$$

Sternberg's equation (1) does not account for well loss; however, well loss may not be significant as long as pumping rates are less than 340 gallons per minute (Mace, 2001).

The equation relating specific capacity to transmissivity (equation 1) cannot be solved directly because transmissivity occurs in both the numerator and denominator. To solve for transmissivity, an iterative spreadsheet approach was used as suggested by Mace (2001). An initial guess was entered for the transmissivity and the spreadsheet iteratively updated the value until equation 1 was solved for the specific capacity data from the 24 driller's logs (Table 3; Figure 44). The hydraulic conductivity was calculated by dividing transmissivity by aquifer thickness.

The hydraulic conductivity data were initially grouped into three categories according to where the data were collected -- alluvium, Blossom Sand outcrop, or Blossom Sand subcrop (Table 3). However, the subcrop and outcrop values did not seem significantly different so those categories were combined for statistical analyses. Histograms of the log transformed hydraulic conductivity estimates (Figure 45) indicate that the values are approximately normally distributed. The deviation from a normal distribution may be due to the relatively limited number of measured values. The maximum hydraulic conductivity estimate for the

Blossom Sand, 97 feet per day (Tables 3 and 4), is much higher than the rest of the Blossom Sand values. This estimate is from a well located close to the alluvium (Figure 44) and it is possible the well is actually completed in the alluvium.

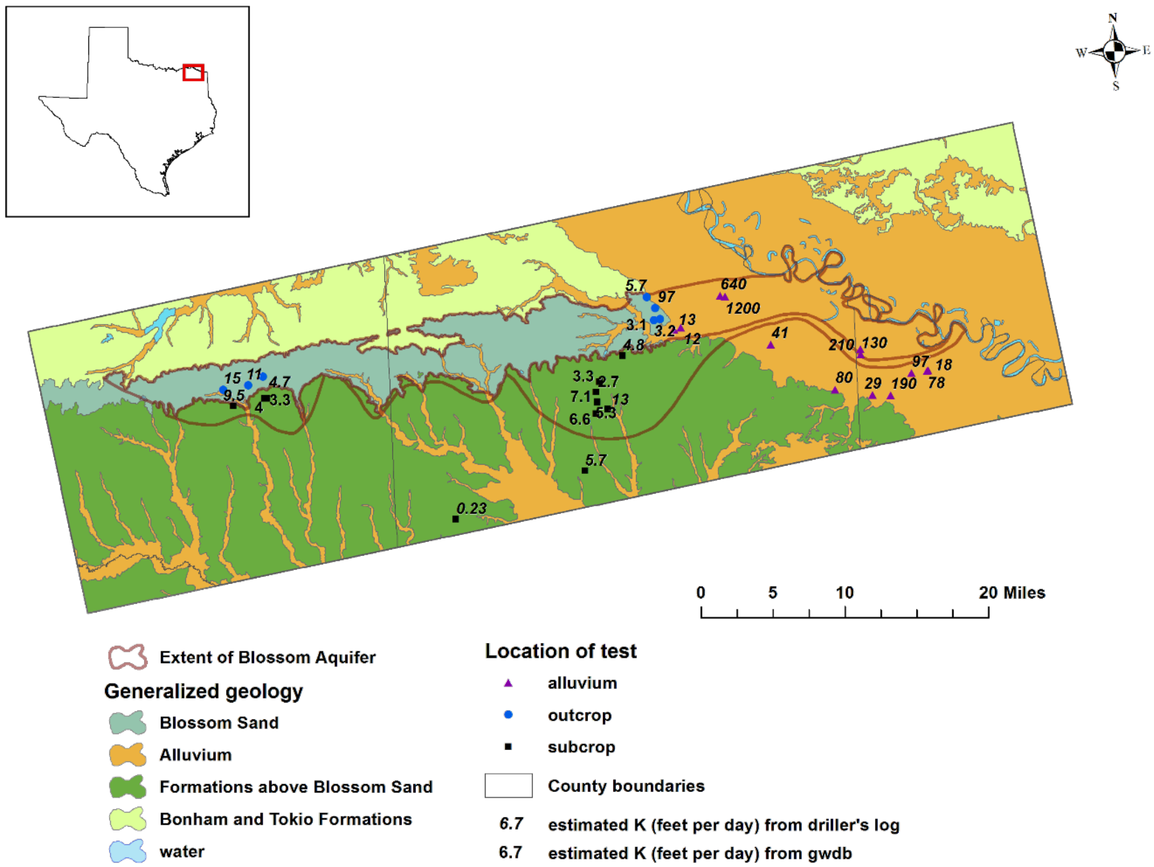

FIGURE 44. LOCATION OF WELL TEST ESTIMATES OF HYDRAULIC CONDUCTIVITY (K) FOR THE BLOSSOM SAND AND ALLUVIUM. GENERALIZED GEOLOGY MODIFIED FROM BUREAU OF ECONOMIC GEOLOGY (2007).

TABLE 3. HYDRAULIC PROPERTY ESTIMATES.

Tracking Number	Transmissivity (feet squared per day)	Hydraulic Conductivity (feet per day)	Storage Coefficient	Location	Source
13824	3,162	210.8	*Na	alluvium	TWDB (2014)
13825	2,658	132.9	Na	alluvium	TWDB (2014)
26436	256	12.8	Na	alluvium	TWDB (2014)
26541	802	80.2	Na	alluvium	TWDB (2014)
28353	249	11.9	Na	alluvium	TWDB (2014)
39181	782	78.2	Na	alluvium	TWDB (2014)
40057	411	41.1	Na	alluvium	TWDB (2014)
64266	1,861	186.1	Na	alluvium	TWDB (2014)
72001	6,382	638.2	Na	alluvium	TWDB (2014)
80662	971	97.1	Na	alluvium	TWDB (2014)
82981	12,273	1227.3	Na	alluvium	TWDB (2014)
85064	294	29.4	Na	alluvium	TWDB (2014)
119783	362	18.1	Na	alluvium	TWDB (2014)
27705	615	15.4	Na	outcrop	TWDB (2014)
227780	128	3.2	Na	outcrop	TWDB (2014)
237852	1,937	96.9	Na	outcrop	TWDB (2014)
268686	430	10.8	Na	outcrop	TWDB (2014)
284283	182	5.7	Na	outcrop	TWDB (2014)
347619	332	4.7	Na	outcrop	TWDB (2014)
160396	459	5.7	Na	subcrop	TWDB (2014)
209547	1,031	13.1	Na	subcrop	TWDB (2014)

Tracking Number	Transmissivity (feet squared per day)	Hydraulic Conductivity (feet per day)	Storage Coefficient	Location	Source
221885	317	0.2	Na	subcrop	TWDB (2014)
309242	323	4.8	Na	subcrop	TWDB (2014)
312938	379	9.5	Na	subcrop	TWDB (2014)
1617402	235	3.1	Na	outcrop	TWDB (2013b)/McLaurin (1988)
1721710	89	4.0	Na	subcrop	TWDB (2013b)/McLaurin (1988)
1721711	85	3.3	Na	subcrop	TWDB (2013b)/McLaurin (1988)
1724801	165	3.3	Na	subcrop	TWDB (2013b)/McLaurin (1988)
1724803	176	2.7	Na	subcrop	TWDB (2013b)/McLaurin (1988)
1732201	549	7.1	7.00E-05	subcrop	TWDB (2013b)/McLaurin (1988)
1732203	494	5.3	3.00E-05	subcrop	TWDB (2013b)/McLaurin (1988)
1732205	530	6.6	Na	subcrop	TWDB (2013b)/McLaurin (1988)

*Na: Not applicable

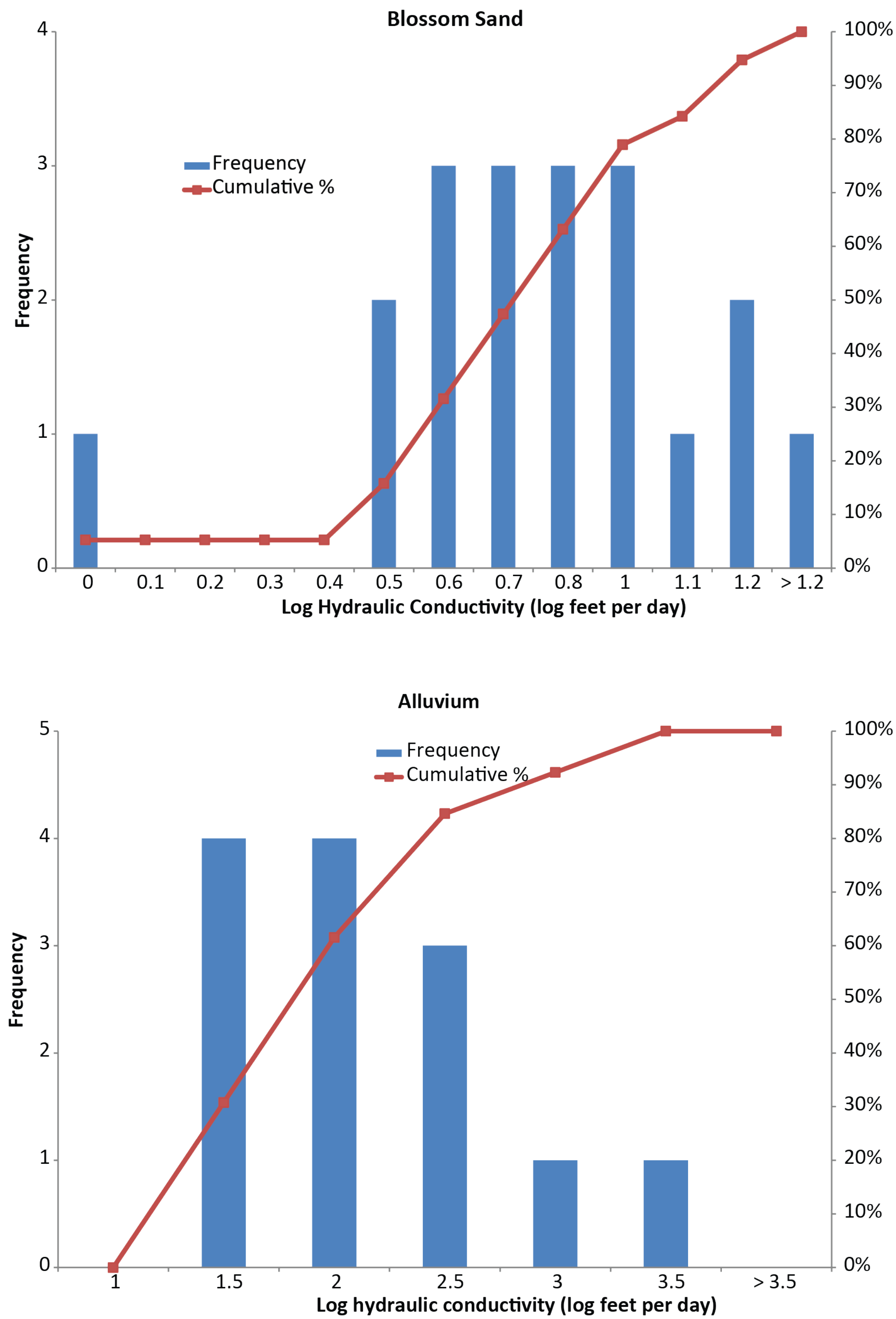

FIGURE 45. HISTOGRAMS OF LOG TRANSFORMED HYDRAULIC CONDUCTIVITY ESTIMATES.

TABLE 4. HYDRAULIC CONDUCTIVITY STATISTICS.

Hydraulic Conductivity Statistic	Alluvium	Blossom Sand
Count	13	19
Mean (feet per day)	212	10.8
Median (feet per day)	80	5.3
Standard Deviation (feet per day)	347	21.2
Minimum (feet per day)	12	0.23
Maximum (feet per day)	1,227	97

4.6 Discharge

Groundwater leaves the Blossom Aquifer through natural processes in the outcrop, such as evapotranspiration and leakage to streams and through groundwater pumping in the outcrop and subcrop. The Blossom Aquifer also discharges to other formations downdip, especially along the Luling-Mexia-Talco fault system (Baker and others, 1963). Discharge to springs and streams are described above in Section 4.4. In the following subsections, we discuss evapotranspiration and groundwater pumping in more detail.

4.6.1 Evapotranspiration

Evapotranspiration is the extraction of water due to direct evaporation from bare soil and transpiration of soil water and groundwater by plants. Evapotranspiration is a function of water supply and energy supply (Scanlon and others, 2005). Groundwater evapotranspiration can be significant for aquifers where the water table is shallow or where phreatophytes are abundant (Scanlon and others, 2005). Phreatophytes are plants that have their roots in the capillary fringe and use groundwater all or most of the growing season (Dressen and Fenchel, 2010).

The potential evapotranspiration in the study area ranges from 50 to 60 inches per year (Figure 14). There are no published site-specific evapotranspiration data for the study area. However, field data from Sarasota County Florida, which has a similar amount of annual rainfall (54 inches per year), suggest riparian evapotranspiration rates for trees ranging from about 30 to 46 inches per year (Scanlon and others, 2005). Evapotranspiration will not be explicitly considered in the groundwater flow model. Most of the groundwater evapotranspiration will occur adjacent to Pecan Bayou and Red River where the water table is shallow and the groundwater evapotranspiration will be a component of the discharge to streams in the numerical model.

4.6.2 Groundwater Pumping

Groundwater is pumped from the Blossom Aquifer mainly for municipal use (Figure 46, Table 5). Other historical uses include livestock, domestic, and limited irrigation. Many domestic wells have been abandoned in favor of public water supplies (McLaurin, 1988). McLaurin (1988) and Baker and others (1963) note that water from the Blossom Aquifer is generally unsuitable for irrigation, although it might be used for watering lawns or as a supplemental source. The TWDB Survey of Irrigation in Texas (1991) also indicates no significant groundwater pumping for irrigation in the study area. However, water for irrigation may be used from the Red River Alluvium and Terrace deposits near the river. The TWDB groundwater database (TWDB, 2013b) shows several irrigation wells located in the alluvium. Imagery from Google Earth (Google Inc., 2015) also suggests wells associated with irrigated acreage.

Present and historical municipal groundwater users from the Blossom Aquifer include, in decreasing order of annual use, the City of Clarksville, Red River Water Supply Corporation, Bagwell Water Supply, and Paris Airport (Figures 46 and 47). The town of English receives its municipal water supply from terrace alluvium deposits overlying the Blossom Sand and confining units (Figures 16 and 47). Annual pumping amounts for the municipal users are from the TWDB Water Use Survey (TWDB, 2015a) and from McLaurin (1988) for data prior to 1980. Municipal pumping will be assigned to point locations in the numerical model, based on well locations from the TWDB groundwater database (TWDB, 2013b; Figure 47). If a municipal user has more than one well the pumping will be evenly distributed between the wells.

TWDB (2015a) estimates of livestock pumping from the Blossom Aquifer from 1980 through 2012 range from zero in 2004 in Bowie County up to 208 acre-feet per year in 2008 in Lamar County (Table 6). Baker and others (1963) estimated water use from the Blossom Aquifer for domestic, livestock, and miscellaneous purposes made up about 25 percent of the total use. McLaurin (1988) updated this estimate to less than 10 percent of total use because of the increased use of public supply systems. Two major public water supplies, Lamar County Water Supply District and Red River County Water Supply Corporation, were incorporated in 1969. Therefore, for the numerical model, domestic, livestock, and miscellaneous pumping prior to 1969 will be assumed to total one-third of municipal pumping, and after 1969 the total will be assumed as one-ninth the total. The livestock, domestic, and miscellaneous pumping will be distributed in the model to well locations from the TWDB groundwater database identified as domestic supply or livestock supply for the primary, secondary, or tertiary use type (Figure 48).

TABLE 5. ESTIMATED ANNUAL MUNICIPAL WATER USE (MCLAURIN, 1988; TWDB, 2015A).

Year	Bagwell Water Supply (acre-feet per year)	City of Clarksville (acre-feet per year)	Paris Airport (acre-feet per year)	Red River Water Supply Corporation (acre-feet per year)	Town of English (acre-feet per year)	Total (acre-feet per year)
1957		310.0				310.0
1958		370.0				370.0
1959		345.0				345.0
1960		330.0				330.0
1961		325.0				325.0
1962		370.0				370.0
1963		495.0			14.0	509.0
1964		448.0			14.0	462.0
1965		520.0			14.0	534.0
1966		525.0			14.0	539.0
1967		430.0			14.0	444.0
1968		445.0			14.0	459.0
1969		510.0		95.0	14.0	619.0
1970		545.0		185.0	14.0	744.0
1971		515.0		215.0	14.0	744.0
1972	4.1	580.0		215.0	14.0	813.1
1973	4.1	530.0		205.0	14.0	753.1
1974	4.1	600.0		220.0	14.0	838.1
1975	4.1	565.0		230.0	14.0	813.1
1976	4.1	510.0		185.0	14.0	713.1
1977	4.1	570.0		190.0	14.0	778.1
1978	4.1	620.0		260.0	14.0	898.1
1979	4.1	565.0		240.0	14.0	823.1
1980		605.1	0.3	217.6	12.2	835.3
1981		573.7	0.2	218.5	10.2	802.5
1982		589.0	0.2	224.0	10.1	823.3
1983		630.8		243.0	10.5	884.3
1984		641.0		247.1	12.3	900.4
1985		606.6		228.7	11.8	847.0
1986		767.2		232.6	13.5	1,013.3
1987		535.7		220.9	13.0	769.6
1988		461.5		232.3	14.3	710.6
1989		347.5		217.5	13.2	580.6
1990		324.9		235.3	10.1	572.9
1991		341.2		233.8	16.7	594.3
1992		305.7		242.5	17.6	568.5

Year	Bagwell Water Supply (acre-feet per year)	City of Clarksville (acre-feet per year)	Paris Airport (acre-feet per year)	Red River Water Supply Corporation (acre-feet per year)	Town of English (acre-feet per year)	Total (acre-feet per year)
1993		240.2		229.8	15.3	485.5
1994		264.4		231.9	15.5	514.7
1995		301.9		260.1	15.3	580.2
1996		335.4		257.8	15.3	611.5
1997		295.7		288.0	14.6	601.2
1998		385.5		331.1	15.9	735.6
1999		390.4		351.4	17.5	762.3
2000		374.8		392.0	16.4	786.1
2001		358.2		404.9	17.2	783.3
2002		289.4		402.3		694.7
2003		276.1		408.5		687.6
2004		276.1		408.5		687.5
2005		320.2		370.5		693.7
2006		576.8		390.7		970.5
2007		235.0		275.7		513.7
2008		222.8		398.1		623.8
2009		243.3		398.1		643.0
2010		243.3		322.3		567.1
2011		292.5		302.6		596.0
2012		273.0		295.0		568.8

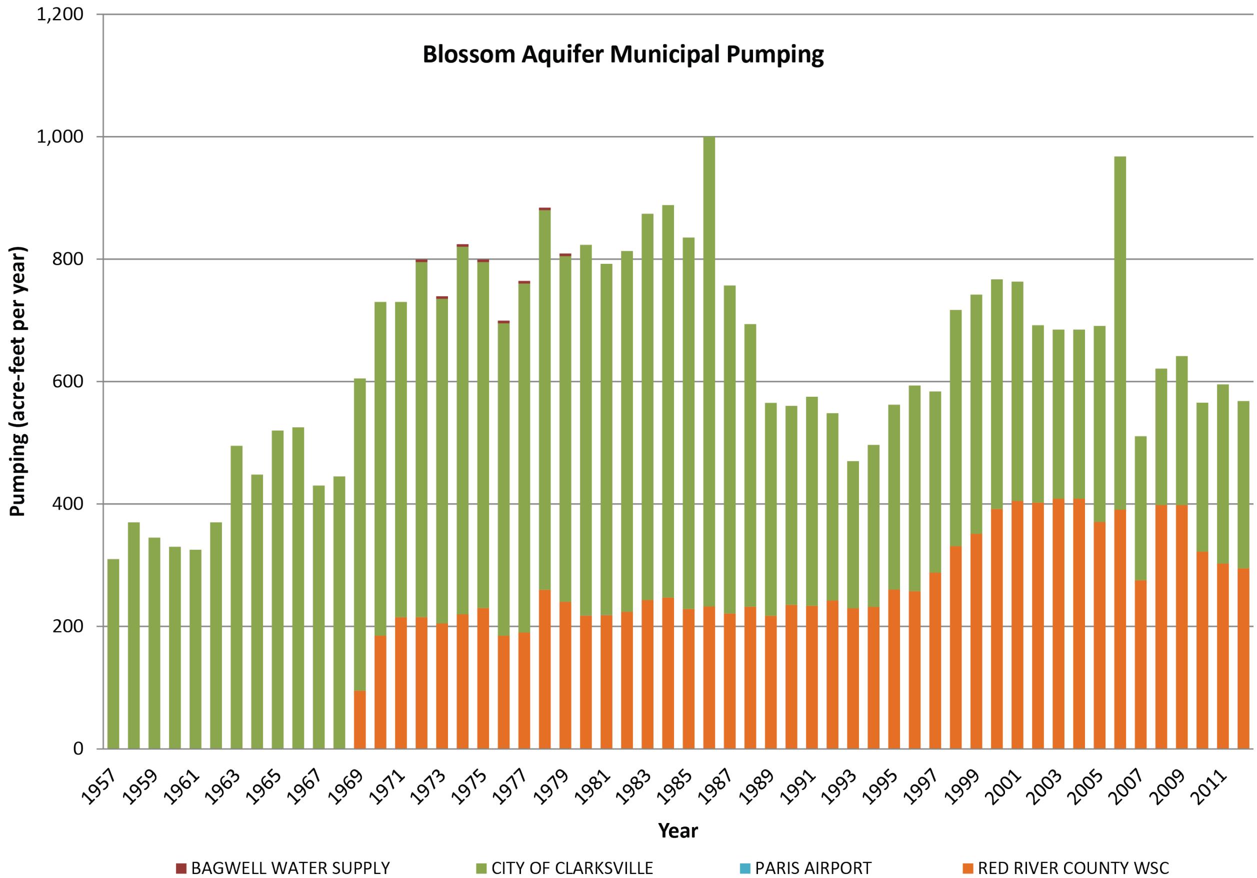

FIGURE 46. ANNUAL MUNICIPAL PUMPING VOLUMES FOR THE MODEL AREA (MCLAURIN, 1988; TWDB, 2015A).

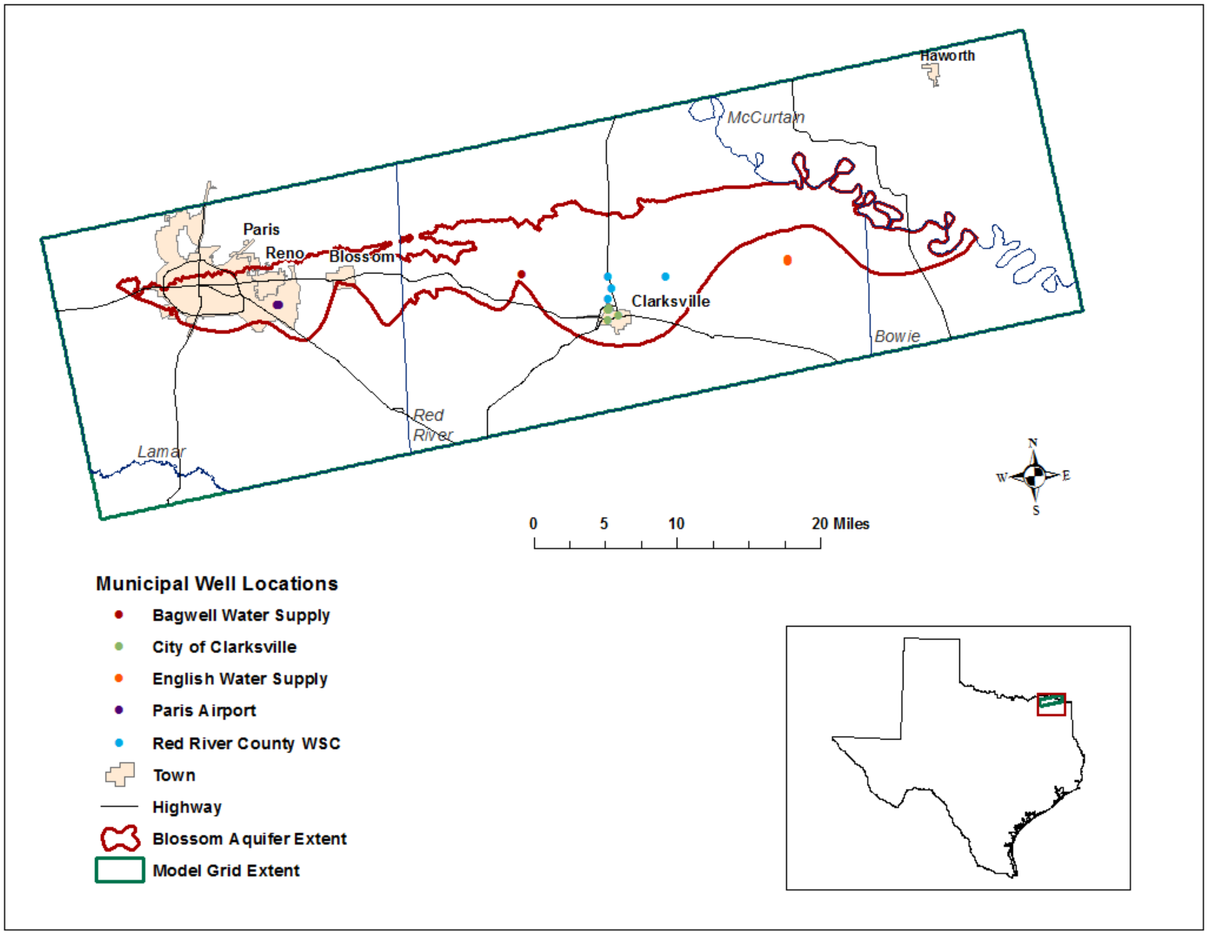

FIGURE 47. LOCATION OF MUNICIPAL WATER USERS AND THEIR WELLS IN THE MODEL AREA.

TABLE 6. ESTIMATED ANNUAL LIVESTOCK WATER USE (TWDB, 2015).

Year	Bowie County (acre-feet per year)	Lamar County (acre-feet per year)	Red River County (acre-feet per year)	Total (acre-feet per year)
1980	20.0	38.0	116.0	174.0
1981	20.5	36.8	115.0	172.3
1982	21.0	35.5	114.0	170.5
1983	21.5	34.3	113.0	168.8
1984	22.0	33.0	112.0	167.0
1985	19.0	36.0	128.0	183.0
1986	21.0	29.0	106.0	156.0
1987	20.0	29.0	98.0	147.0
1988	20.0	30.0	106.0	156.0
1989	20.0	29.0	108.0	157.0
1990	22.0	32.0	112.0	166.0
1991	22.0	32.0	114.0	168.0
1992	18.0	32.0	112.0	162.0
1993	19.0	32.0	110.0	161.0
1994	21.0	41.0	130.0	192.0
1995	20.0	39.0	137.0	196.0
1996	27.0	41.0	183.0	251.0
1997	18.0	36.0	116.0	170.0
1998	NA	NA	NA	NA
1999	NA	NA	NA	NA
2000	19.9	17.3	152.4	189.7
2001	6.9	22.0	88.3	117.2
2002	6.5	21.9	85.6	114.0
2003	6.5	20.9	81.6	109.0
2004	0.0	54.3	18.7	73.0
2005	0.0	151.4	4.2	155.6
2006	0.0	148.8	4.2	152.9
2007	0.0	143.5	4.6	148.1
2008	0.0	208.3	0.0	208.3
2009	0.0	177.7	0.0	177.7
2010	0.0	47.3	4.1	51.3
2011	0.0	47.3	4.3	51.6
2012	0.0	43.8	2.9	46.6

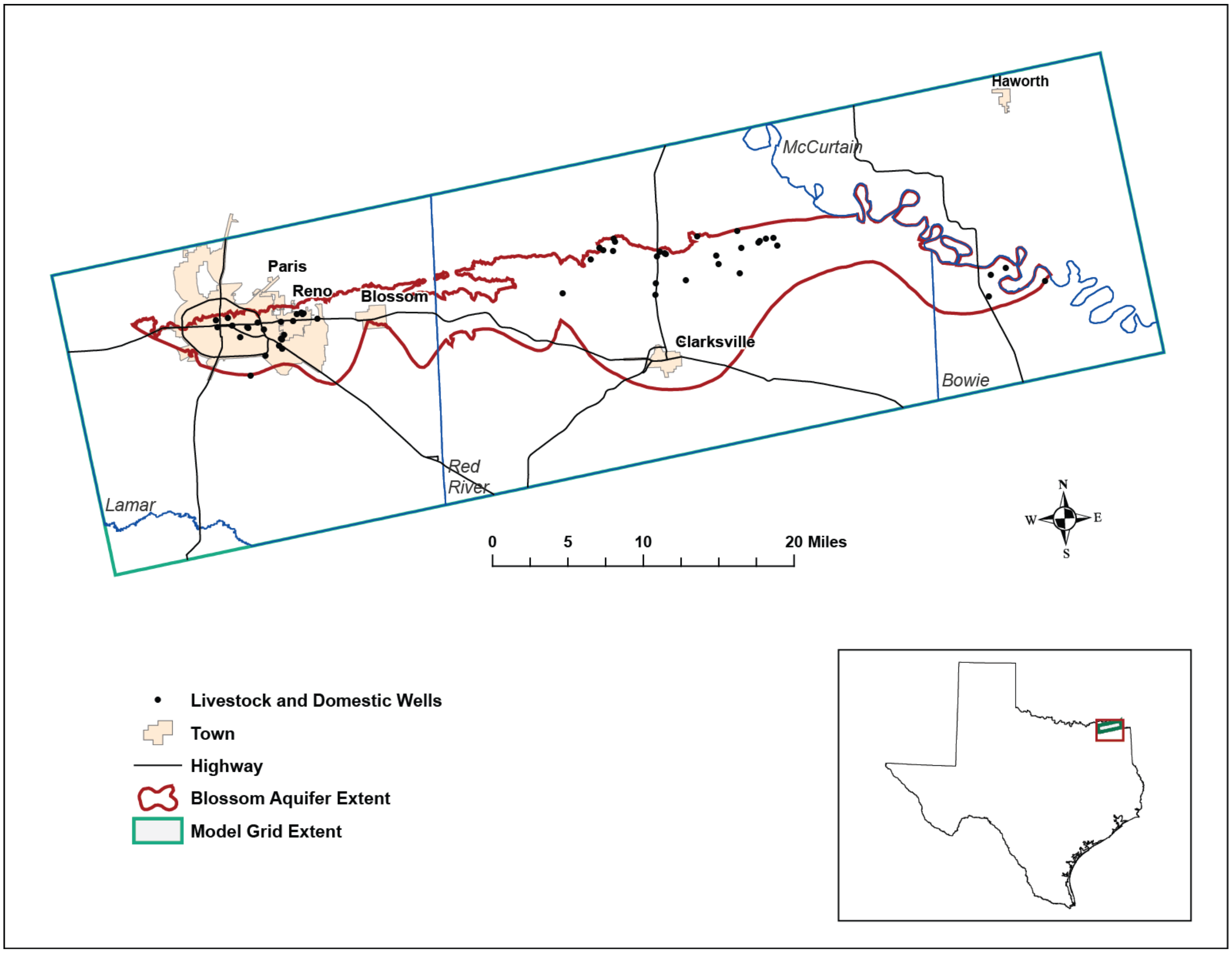

FIGURE 48. LOCATION OF WELLS FROM TWDB GROUNDWATER DATABASE IDENTIFIED WITH LIVESTOCK OR DOMESTIC USE (TWDB, 2015B).

Although the groundwater from the Blossom Sand is generally unsuitable for large scale irrigation (McLaurin, 1988), water for irrigation is pumped from the Red River Alluvium in Bowie County and eastern Red River County (Table 7). The Red River Alluvium is identified as "Other Aquifer" for TWDB irrigation pumping estimates and consists of Quaternary alluvium deposits overlying the confining units above the Blossom Sand. To the west of the Red River Alluvium, fluvial terrace deposits directly overly the Blossom Sand outcrop (Figures 16 and 49). In the study area, the Quaternary alluvium deposits within the footprint of the Blossom Aquifer are considered part of the aquifer. For the purposes of this report, it is assumed that the TWDB estimates of irrigation pumping identified as coming from "Other Aquifer" also include pumping from the Red River Alluvium within the Blossom Aquifer footprint (Figure 49; Table 7). Approximately 7.3 percent of the Red River Alluvium in Bowie County is within the footprint of the Blossom Aquifer, so the irrigation pumping for the Blossom Aquifer adjacent to the Red River was estimated as 7.3 percent of the total Bowie County "Other Aquifer" irrigation pumping estimates (Table 7). No pumping irrigation estimates were available prior to 1980, so the mean pumping for 1980 and 1984 through 2012 was used for model years with no data.

Very few TWDB groundwater database wells are identified as irrigation wells in the study area and only one is located in the Red River Alluvium. To supplement the irrigation well locations, possible locations were identified and digitized using imagery from Google Earth (Google, Inc., 2015). In the numerical model of the Blossom Aquifer, the estimated irrigation pumping will be uniformly distributed among these wells (Figure 49). Since the wells were identified from Google Earth (Google, Inc., 2015) rather than the TWDB groundwater database, there is no information about when the wells were drilled. For the purposes of this report, all wells will be assumed as active throughout the modeling period.

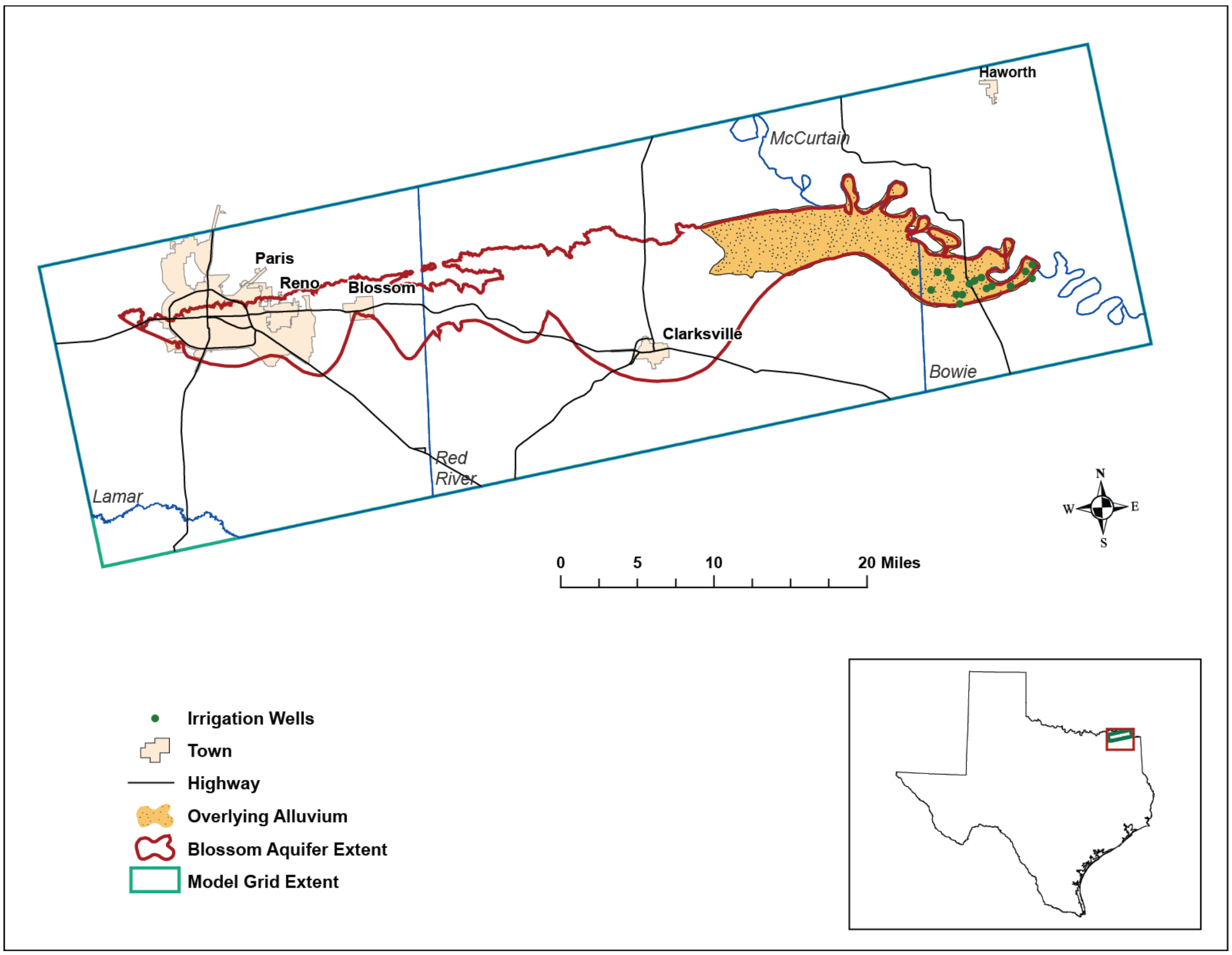

FIGURE 49. LOCATION OF IRRIGATION WELLS (TWDB GROUNDWATER DATABASE, 2015B; GOOGLE INC., 2015).

TABLE 7. ESTIMATED IRRIGATION PUMPING.

Year	Bowie County Other Aquifer (acre-feet per year)	Blossom Aquifer portion (acre-feet per year)
1980	515	38
1981	1,374	100
1982	1,239	90
1983	1,834	134
1984	1,500	110
1985	1,425	104
1986	774	57
1987	938	68
1988	0	0
1989	0	0
1990	422	31
1991	0	0
1992	0	0
1993	0	0
1994	0	0
1995	0	0
1996	0	0
1997	0	0
1998	0	0
1999	0	0
2000	0	0
2001	0	0
2002	0	0
2003	0	0
2004	3,440	251
2005	3,239	236
2006	70	5
2007	750	55
2008	955	70
2009	6,146	449
2010	6,099	445
2011	3,749	274
2012	6,802	497

Municipal pumping from the Blossom Aquifer is concentrated in the subcrop in central Red River County near Clarksville (Figures 50, 51, and 52). The domestic and irrigation pumping are principally located in the outcrop and the irrigation pumping is located in Bowie County near the Red River (Figures 50, 51, and 52).

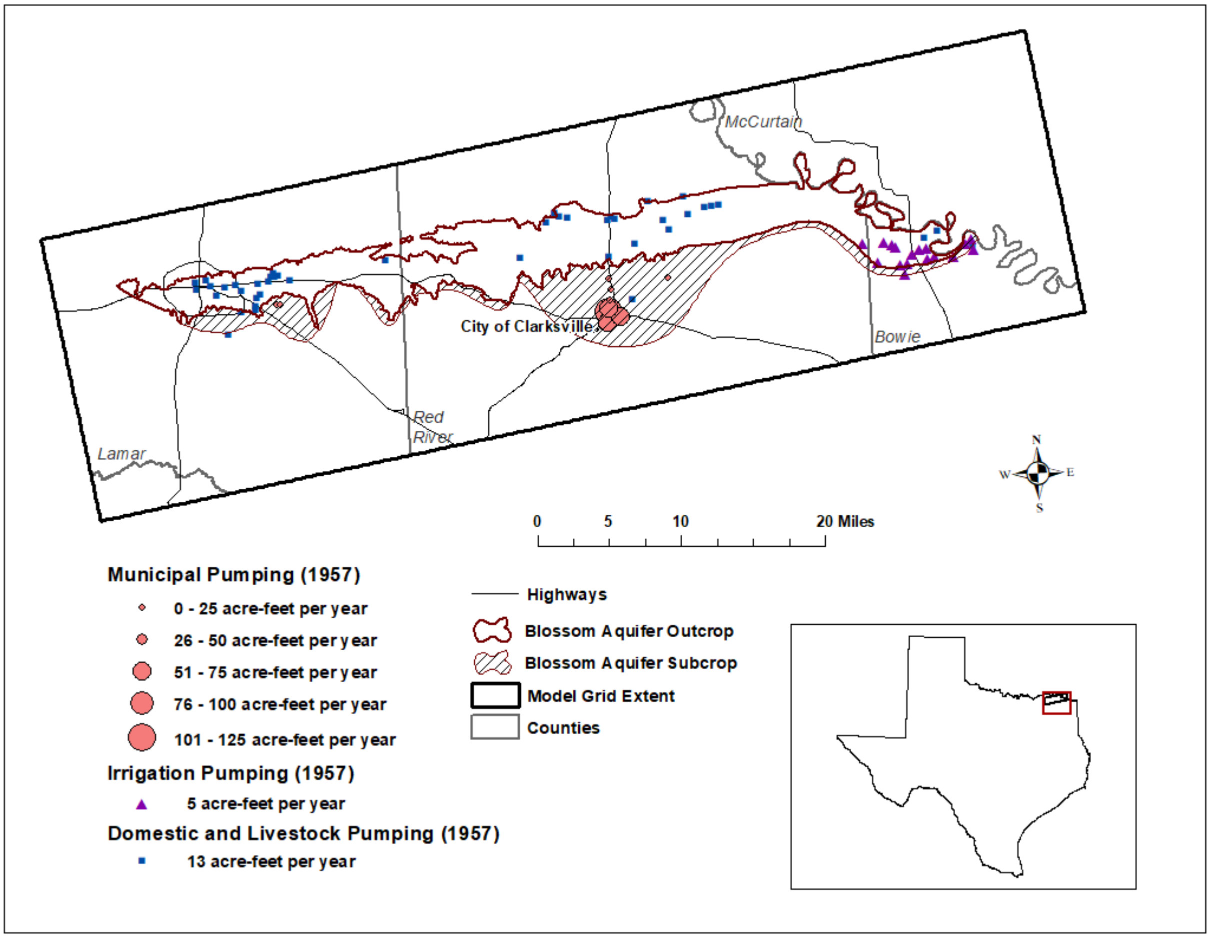

FIGURE 50. 1957 PUMPING DISTRIBUTION BY USER GROUP.

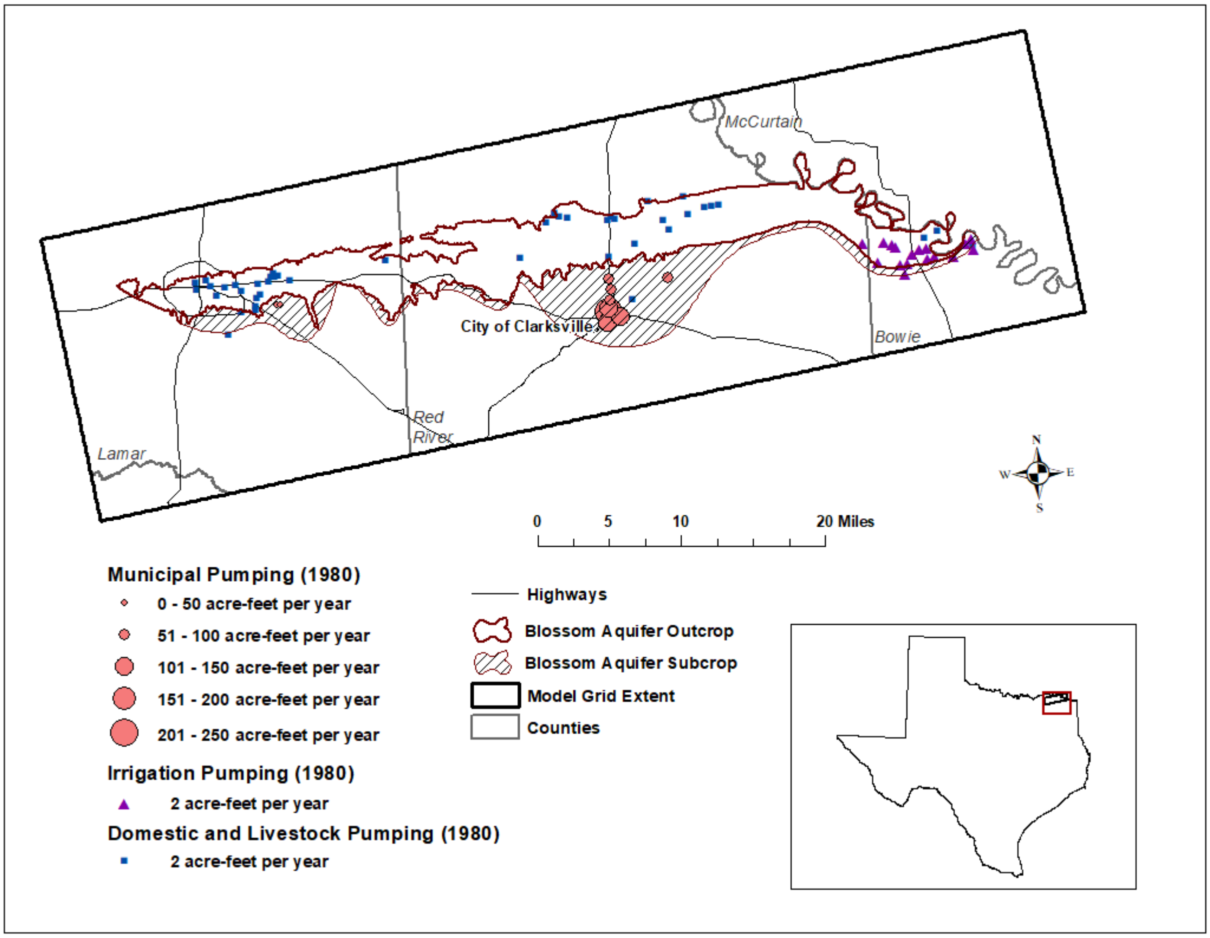

FIGURE 51. 1980 PUMPING DISTRIBUTION BY USER GROUP.

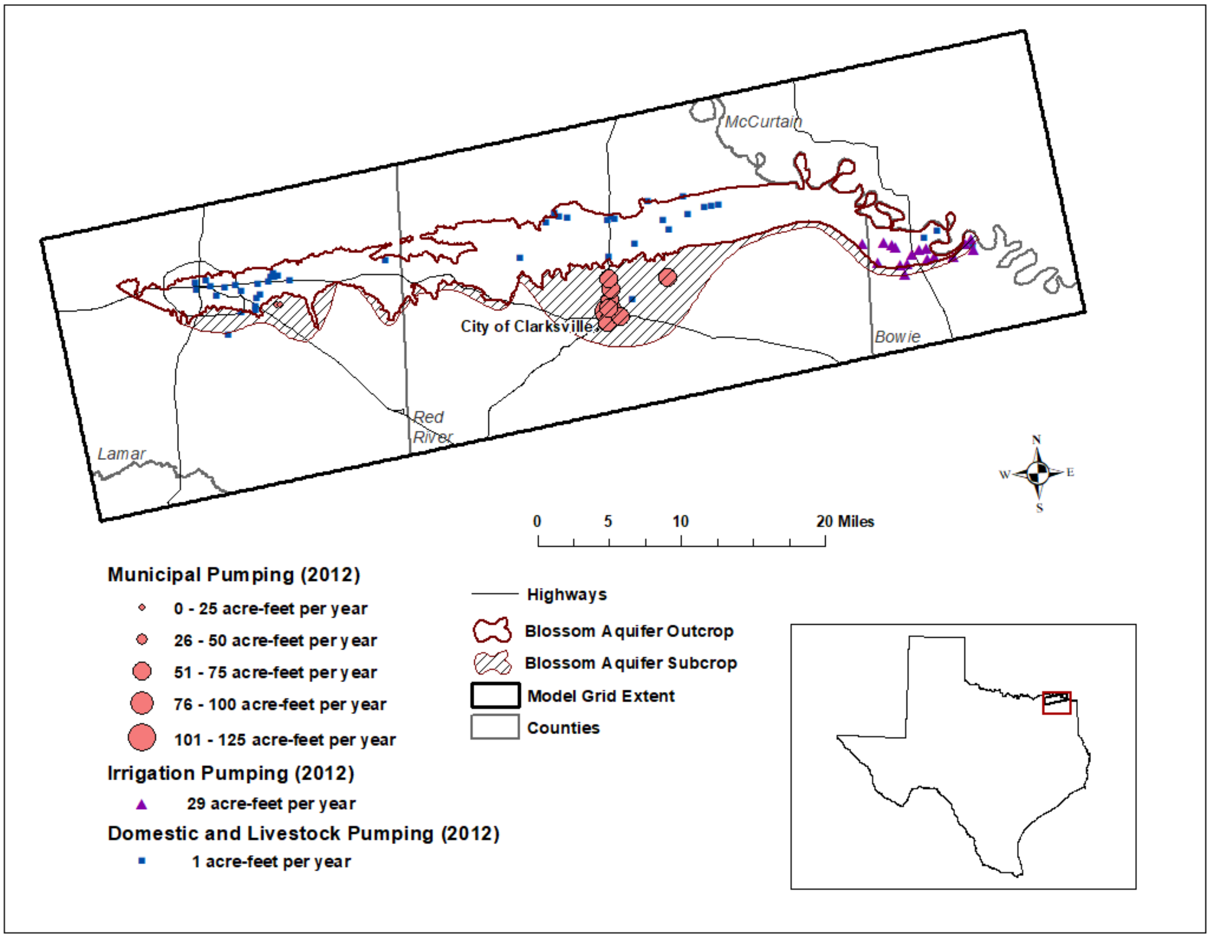

FIGURE 52. 2012 PUMPING DISTRIBUTION BY USER GROUP.

4.7 Water Quality

For this report, we used groundwater quality and isotopic data available in the TWDB groundwater database to perform this analysis. These data are the product of years of water quality monitoring by TWDB personnel.

We reviewed results of previous hydrogeologic studies performed in the three-county area and examined groundwater quality in the Blossom Aquifer mostly as part of studies that focused on regional aquifers of North Texas, such as the Carrizo-Wilcox, Trinity, Woodbine, and Nacatoch aquifers. Only one study (McLaurin, 1988) has focused solely on the hydrogeology of Blossom Aquifer.

Early publications by the U.S. Geological Survey listed concentrations of several major ions and trace metals in wells completed in the Blossom Aquifer in Red River, Lamar, and Bowie counties. Gordon (1911) observed that "waters from the Blossom sand member at Blossom are very high in calcium, magnesium, alkalies, and sulfates, being similar in these respects to the waters tested from the Eagle Ford clay". Sundstrom and others (1948) published the analytical lab results for a groundwater sample collected in 1943 from Clarksville well #3.

More recently, Baker and others (1963) noted that "the Blossom contains fresh to slightly saline water only in the Red River basin and the northern part of the Sulphur River Basin; in the rest of the area, the water is more saline". The authors also evaluated the suitability of groundwater for irrigation, for public water supply, and for industrial uses. Taylor (1976) listed the Blossom Aquifer field parameters and ion concentrations for wells in Red River and Lamar counties. McLaurin (1988) took a more in-depth look at the chemical quality of Blossom Aquifer by delineating the areal and vertical extent of usable-quality groundwater, presenting simple statistics of constituents' concentrations, and plotting Piper diagrams for samples from Lamar and Red River counties. Chowdhury (2010) provided the most comprehensive analysis to date of the groundwater chemistry and isotopy in the Blossom Aquifer.

For this report, we examined laboratory analyses extracted from the TWDB groundwater database for 67 Blossom Aquifer groundwater quality samples collected from 1953 through 2006. Groundwater in the Blossom Aquifer is mostly fresh, with 43 samples having total dissolved solids concentrations of 1,000 mg/l or less (Figure 53). The Piper diagram developed for the Blossom Aquifer (Figure 54) shows the groundwater to be predominantly of calcium-sodium-bicarbonate-chloride facies. The transition from fresh, calcium-dominated to saline, sodium-dominated groundwater (see the cation triangle in the Piper diagram) indicates evolution along flow paths through calcium-sodium ion exchange mechanisms, as expected of groundwaters in clastic aquifers.

The Texas Commission on Environmental Quality (TCEQ) enforces safe drinking water standards and Maximum Contaminant Levels (MCLs) in the state of Texas. The MCL is the lowest concentration of any dissolved material at which the water is considered unfit for human consumption. The TCEQ also prescribes secondary standards for drinking water quality – non-enforceable recommendations having to do with the olfactory and aesthetic appearance of the water.

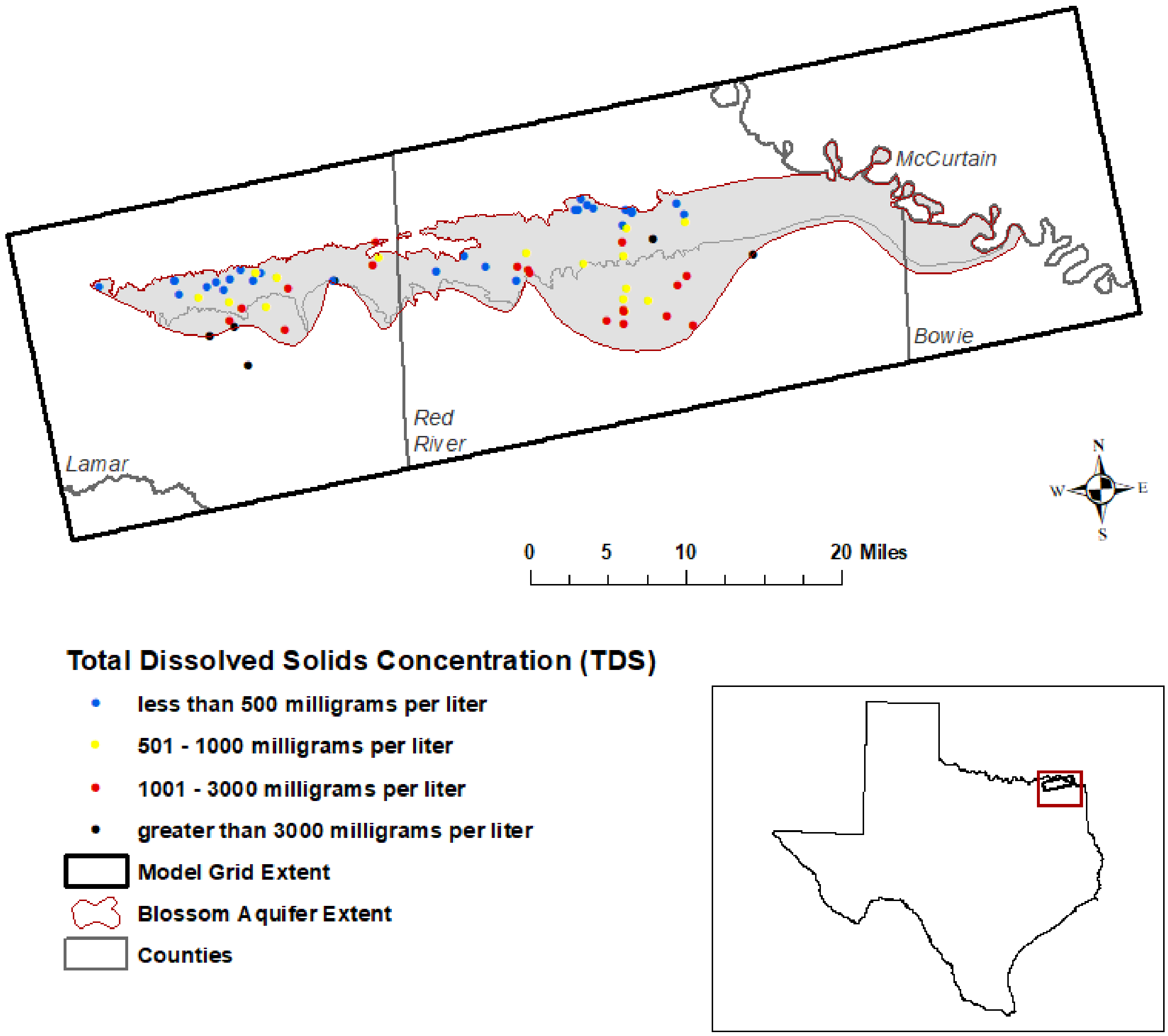

FIGURE 53. LOCATION OF WATER QUALITY SAMPLES.

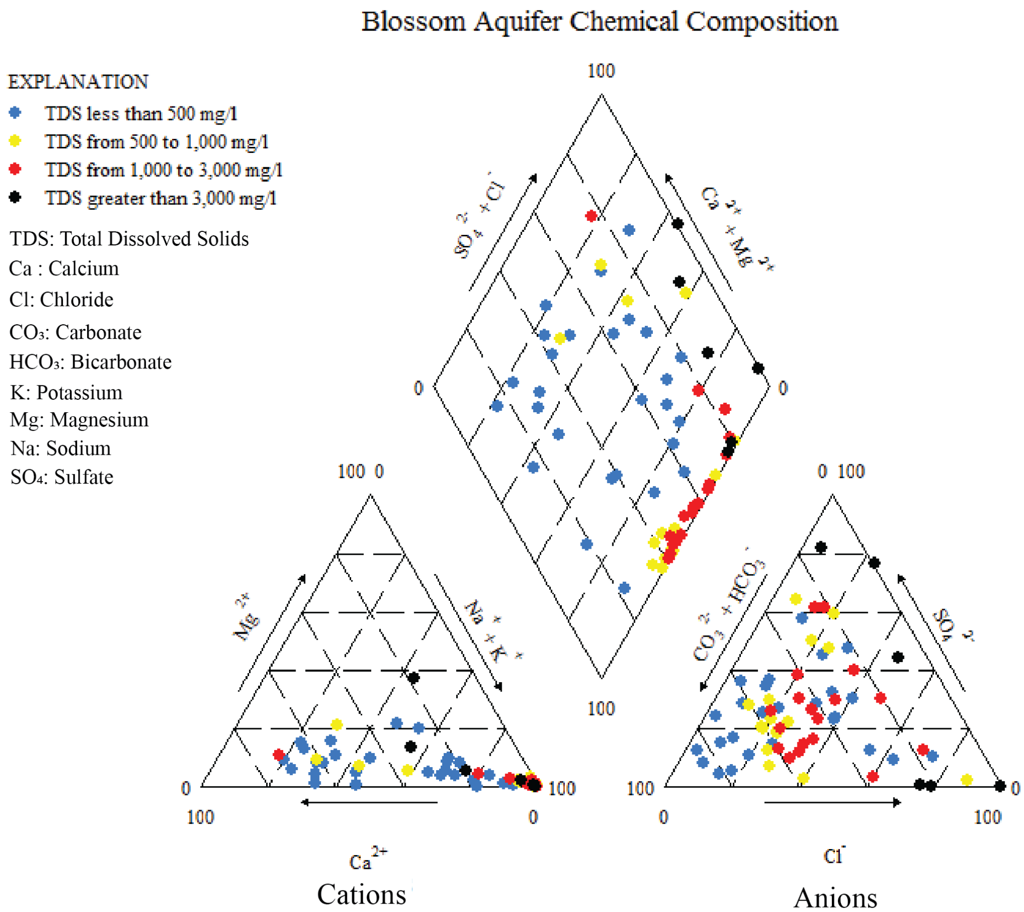

FIGURE 54. PIPER DIAGRAM BASED ON WATER QUALITY SAMPLES FROM THE BLOSSOM AQUIFER.

Groundwater from the Blossom Aquifer exceeded the MCL for nitrate in two samples and for arsenic in one sample. The secondary standards were exceeded for total dissolved solids in 24 samples, chloride in 12 samples, sulfate in 12 samples, zinc in ten samples, fluoride in six samples, iron (dissolved) in three samples, and manganese in two samples. The range in total dissolved solids was from 15 milligrams per liter to 16,834 milligrams per liter. Generally, the freshest water occurred in and near the outcrop of the Blossom Sand, and the more saline groundwater occurred downdip. The downdip limits of the Blossom Aquifer correspond to the estimated iso-concentration line of 3,000 mg/l total dissolved solids. One well about 3 miles downdip beyond the aquifer boundary concentration has total dissolved solids of more than 15,000 mg/l (McLaurin, 1988).

A recent brackish groundwater production study of the Blossom Aquifer was completed for the TWDB Brackish Resources Aquifer Characterization System (Andrews and Croskrey, 2019). The authors used 129 measured values of total dissolved solids and 211 values estimated from geophysical logs to produce a map of salinity classes for the Blossom Sand (Figure 55; Andrews and Croskrey, 2019). The map was used to recommend three brackish groundwater production zones (Andrews and Croskrey, 2019).

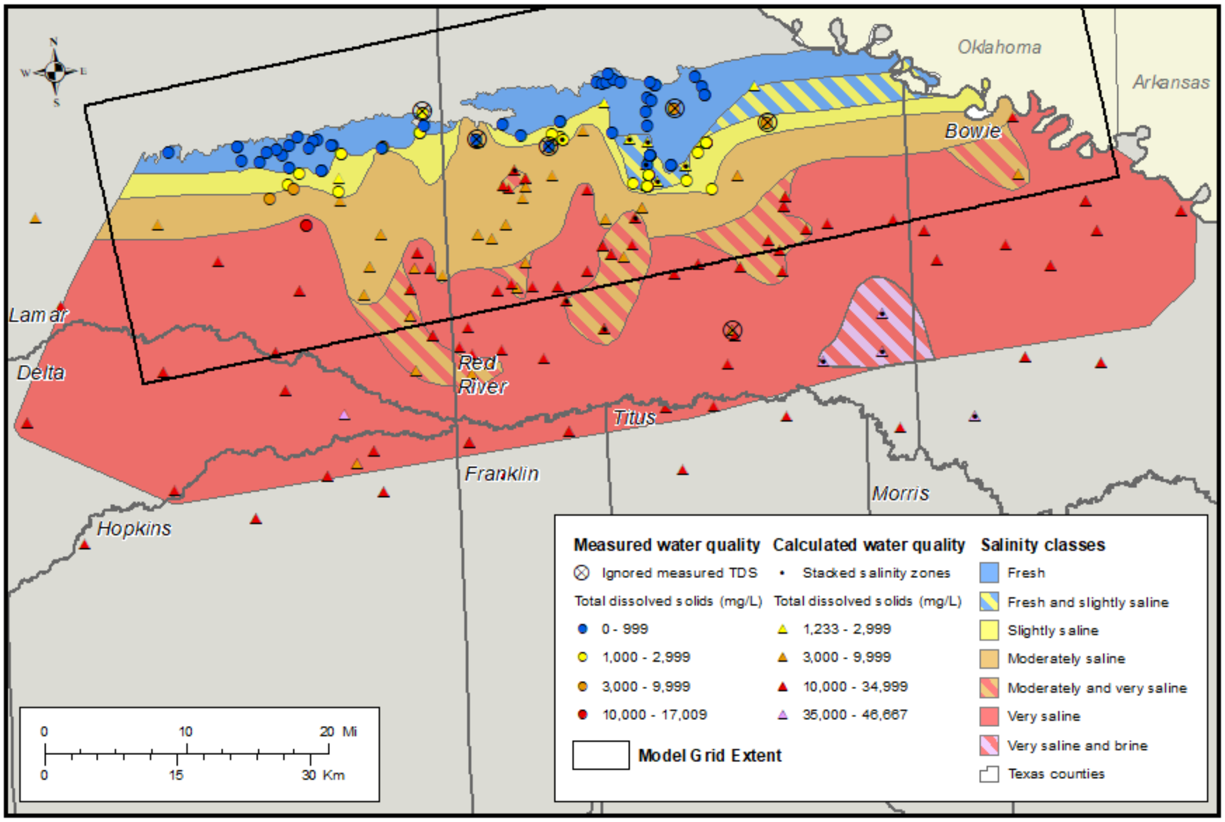

FIGURE 55. SALINITY CLASSES OF THE BLOSSOM SAND (MODIFIED FROM ANDREWS AND CROSKREY, 2019).

4.7.1 Age of Blossom Aquifer groundwater

Carbon-14 (radiocarbon) and tritium are two radiogenic isotopes commonly employed in the determination of groundwater ages. One can estimate the age of the groundwater by measuring present-day radiocarbon and adjusting for its rate of radioactive decay, provided that initial concentration of radiocarbon in the groundwater sample is known, and that gains and losses of carbon-14 can be accounted for. Radiocarbon is a useful dating tool for waters up to 30,000 years old (Clark and Fritz, 1997). Cosmogenic tritium has been used for dating young waters recharged from 1952 onward (Clark and Fritz, 1997). Thermonuclear tests performed from 1951 to 1980 have added tritium to global precipitation, which has since reached the aquifers. Measurable (greater than 1 tritium unit) tritium activities in groundwater indicate active recharge.

Carbon-14 activities measured in two groundwater samples in the Blossom Aquifer during 2015 range from less than 0.4 percent modern carbon to 2.7 percent modern carbon. Both values are typical of groundwaters in slow-moving groundwater systems. The samples were collected from subcrop wells in Red River County and they indicate apparent, uncorrected groundwater ages much older than 10,000 years. This age suggests very low recharge rates. Tritium levels were also measured for the same two wells and showed much less than 1.0 Tritium units also indicating old water.

5.0 CONCEPTUAL MODEL OF GROUNDWATER FLOW IN THE BLOSSOM AQUIFER

A conceptual model is a simplified graphical representation of a groundwater flow system (Anderson and Woessner, 1992). One purpose of the conceptual model is to organize data so that it can be translated into a mathematical model. Building a conceptual model includes defining hydrostratigraphic units, preparing a water budget, and defining the flow system (Anderson and Woessner, 1992).

The groundwater flow system in the study area includes the Blossom Aquifer, which is overlain by Quaternary terrace and alluvium deposits adjacent to the Red River (Figures 16, 49, and 56). Downdip, south of the outcrop, the Blossom Sand dips below the younger Brownstown Formation. South of the outcrop, the terrace deposits and alluvium overlie the younger Brownstown Formation and do not directly overly the Blossom Sand (Figures 16, 20, and 56). Generally, the freshest water occurs in and near the outcrop of the Blossom Sand, and the more saline groundwater occurs downdip. The downdip limits of the Blossom Aquifer are based on a maximum concentration of 3,000 mg/l total dissolved solids. One well located about 3 miles downdip of the aquifer boundary has total dissolved solids of more than 15,000 mg/l (McLaurin, 1988).

Recharge enters the Blossom Aquifer through precipitation on the outcrop and moves very slowly downdip, eventually discharging through seepage into other formations in the subsurface, particularly along the Luling Mexia-Talco fault system (Figures 18 and 56 Baker, 1963). Recharge estimates range from zero for a dry year to 4 inches for a wet year (Table 1). We expect that part of the recharge discharges locally in the outcrop through interaction with streams and through groundwater evapotranspiration. The lower reaches of Pecan Bayou (Figure 40) are identified as perennial by the U.S. Geological Survey and therefore, are likely to be locations of groundwater discharge (U.S. Geological Survey, 2015). The Red River may also receive Blossom discharge; however, there are no data available to quantify discharge to the Red River or discharge to Pecan Bayou below the U.S. Geological Survey stream gauge (Figures 40 and 42). Several springs are located in the study area (Figure 40), but the total discharge from the springs is a very small component of the total flow system (Table 2). Discharge also occurs through groundwater pumping in the outcrop and downdip. Most of the groundwater pumping is for municipal use in Red River County. Total municipal pumping has ranged from about 300 to about 1,000 acre-feet per year (Figure 46).

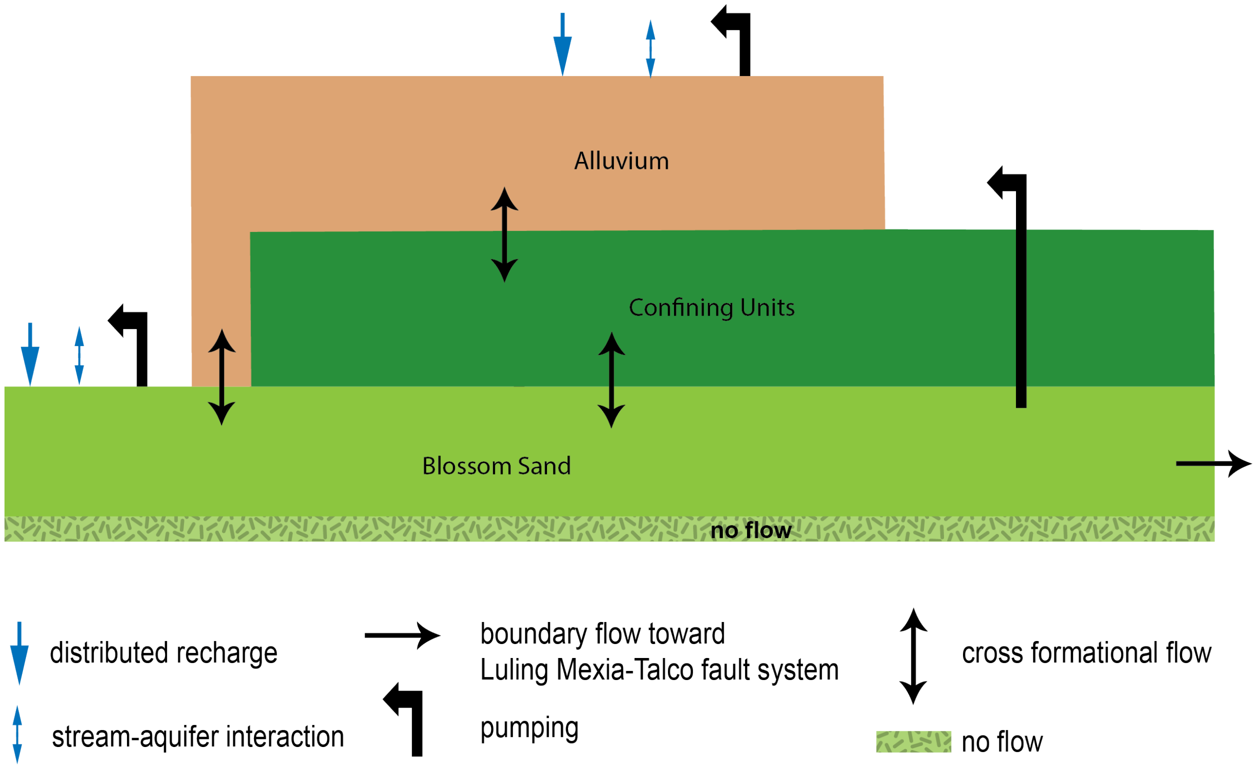

FIGURE 56. CONCEPTUAL MODEL OF GROUNDWATER FLOW (DIP VIEW) IN THE BLOSSOM AQUIFER AND OVERLYING UNITS.

6.0 FUTURE IMPROVEMENTS

As with most groundwater modeling studies, recharge is one of the more uncertain inputs. For this study we have made use of recharge estimates from a regional study based on a water balance between annual precipitation, stream discharge, and evapotranspiration (Kirk and others, 2012). More local estimates of recharge for the Blossom Aquifer based on geochemical tracers and groundwater/surface water studies could help make the model results more accurate by reducing uncertainty in the water balance for the groundwater system.

The structural framework for this conceptual model was based on the previous work of McLaurin (1988), Baker and others (1963), the Geological Atlas of Texas (Bureau of Economic Geology (BEG), 2007), and topographic elevations (U.S. Geological Survey, 2014a). A brackish groundwater production study of the Blossom Aquifer was recently completed for the TWDB Brackish Resources Aquifer Characterization System (Andrews and Croskrey, 2019). As part of that study the authors estimated surfaces for the top and the bottom of the Blossom Sand based on geophysical logs of 176 wells for the top surface and 187 wells for the bottom surface (Andrews and Croskrey, 2019). This additional structural information will be very beneficial to future updates for the Blossom Aquifer groundwater model.

Our analysis of hydraulic properties was based on 8 aquifer pumping test and 24 specific capacity tests. However, the distribution of the hydraulic property estimates is not uniform and some areas of the aquifer outcrop and subcrop have no measurements (Figure 43) Additional pumping test data in areas with no data could reduce the uncertainty in the overall estimates of hydraulic properties. In addition, the brackish groundwater production study produced a map of net sands (Andrews and Croskrey, 2019). Net sands can be used to estimate the distribution of hydraulic conductivity in aquifers (Panday and others, 2020).

7.0 ACKNOWLEDGEMENTS

This project has benefited from previous unpublished studies of the Blossom Aquifer by Ali Chowdhury, Scott Hamlin, and Cindy Ridgeway. We greatly appreciate the information their work provided for this report. We are grateful to Chelsea Seiter-Weatherford for her help with the water level data analysis. We also greatly appreciate the technical and editorial reviews of Larry French, Cindy Ridgeway, and Kayla Shearhart which have made this a better report. We would also like to thank Wendell Davis of the Red River Water Supply Corporation for providing us with well information for the project. We appreciate Daingerfield State Park allowing us to use their beautiful meeting facilities for our first stakeholder advisory forum.

8.0 REFERENCES

Anderson, M.P. and Woessner, W.W., 1992, *Applied groundwater modeling simulation of flow and advective transport*, Academic Press, Inc., 381 p.

Andrews, A.G., and Croskrey, A., 2019, Brackish Groundwater Production Zone Recommendations for the Blossom Aquifer, Texas, TWDB Open File Report 19-01, 19 p., https://www.twdb.texas.gov/publications/reports/Open-File/doc/Open-File19-01.pdf

Arkansas GIS Office, 2013, Geostor Spatial Data, http://www.geostor.arkansas.gov, accessed September, 2013.

Baker, E.T., Long, A.T., Reeves, R.D., and Wood, L.A., 1963, Reconnaissance Investigation of the Ground-Water Resources of the Red River, Sulphur River, and Cypress Creek Basins, Texas. Texas Water Commission Bulletin 6306, 127 p.

Baldys III, S. and Hamilton, D.K., 2014, Assessment of Selected Water-Quality Data Collected in the Lower Red River (Main Stem) Basin, Texas, 1997 – 98, U.S. Geological Fact Sheet, 106-03, http://pubs.usgs.gov/fs/fs10603/

Barlow, P.M., Cunningham, W. L., Zhai, T., and Gray, M., 2014, U.S. Geological Survey Groundwater Toolbox, A Graphical and Mapping Interface for Analysis of Hydrologic Data (Version 1.0)—User Guide for Estimation of Base Flow, Runoff, and Groundwater Recharge From Streamflow Data, Techniques and Methods, Book 3, Chapter B10, U.S. Geological Survey, 27 p.

Beach, J. and Laughlin, K., 2017, Identification of Potential Groundwater Production Areas - Blossom Aquifer, TWDB Contract Report prepared by LBG-Guyton and Associates, Contract Number 1600011951, 101 p., http://www.twdb.texas.gov/publications/reports/contracted_reports/doc/1600011951_Blossom.pdf

Bear, J., 1972, *Dynamics of Fluids in Porous Media*, Dover Publications, Inc., New York, 764 p.

Bradbury, K.R., and Rothschild, E.R., 1985, A computerized technique for estimating the hydraulic conductivity of aquifers from specific capacity data: Ground Water, v. 23 no. 2, p. 240-246.

Brons, F. and Marting, V.E.,1961, The effect of restricted fluid entry on well productivity: Journal of Petroleum Technology, v. 13, no. 2, p. 172-174.

Brune, G., 1981, Springs of Texas Volume I, Texas A&M University agricultures series: no.5, 566 p.

Bucher Willis and Ratliff Corporation, 2010, Region D – North East Texas Regional Water Planning Group, 2011 Regional Water Plan, 356 p., http://www.twdb.texas.gov/waterplanning/rwp/plans/2011/D/Region_D_2011_RWPV1.pdf

Bureau of Economic Geology (BEG), 2007. Geologic Atlas of Texas. Compiled in cooperation with the US Geological Survey and the Texas Water Development Board. Geodatabase available at http://www.tnris.org/get-data?quicktabs_maps_data=1.

Chowdhury A.H., 2010, Groundwater recharge, hydraulic interaction, and flow characterization in the Blossom and Red River Alluvium Aquifers, Northeast Texas: Evidence from water levels, isotopic, and geochemical data, unpublished report, 73 p.

Clark, I. D., and Fritz, P., 1997, *Environmental isotopes in hydrogeology*, CRC Press/Lewis Publishers, Boca Raton, FL, 328 p.

Cushing, E.M., Boswell, E.H., and Hosman, R.L., 1964, General Geology of the Mississippi Embayment, Geological Survey Professional Paper 448-B, 28 p.

Dreesen, D.R. and Fenchel, G.A., 2010, Deep-planting techniques to establish riparian vegetation in arid and semiarid regions, Native Plants Journal, vol. 11, no. 1, p. 15 – 22.

Fenneman, N.M. and Johnson, D.W., 1946, Physical Divisions of the United States: U.S. Geological Survey special map series, scale 1:7,000,000.

Foote, R.Q, Massingill, L.M., and Wells, R.H., 1988, Petroleum geology and the distribution of conventional crude oil, natural gas, and natural gas liquids, East Texas Basin, U.S. Geological Survey Open-File Report 88-450k, 118 p., http://pubs.usgs.gov/of/1988/0450k/report.pdf

Frye, R.G., Brown, K.L., and McMahan, C.A., 1984, Vegetation Types of Texas, Texas Parks and Wildlife, https://tpwd.texas.gov/publications/pwdpubs/pwd_bn_w7000_0120/crops/.

Google Inc., 2015, Google Earth Pro, accessed August 2015.

Gordon, C.H., 1911, Geology and Underground Waters of Northeastern Texas. USGS Water Supply Paper 276, 78 p.

Handbook of Texas Online, 2015, "PECAN BAYOU (RED RIVER COUNTY)," Published by the Texas State Historical Association, accessed February 06, 2015, Uploaded on June 15, 2010, http://www.tshaonline.org/handbook/online/articles/rhp04.

Kirk, A., Groeneveld, D., Barz, D., Herring, J., and Murray, S., 2012, Ground Water Recharge Model: Calibration and Validation for Remotely-Sensed Dual Coefficient (RDC) GMA

8 ET Estimation, Final Contract Report prepared for TWDB, 164 p., http://www.twdb.texas.gov/publications/reports/contracted_reports/doc/1004831114_HydroBio.pdf

Larkin, T.J. and Bomar, G.W., 1983, Climatic Atlas of Texas: Texas Department of Water Resources Report LP-192, 151 p.

Linsley, R.K. Jr., Kohler, M.A., and Paulhus, J.L.H., 1982, *Hydrology for Engineers*, McGraw-Hill Book Company, New York, 508 p.

Ludeman, M. M., 2015, "LAMAR COUNTY," Handbook of Texas Online, accessed October 12, 2015, Uploaded on June 15, 2010, Modified on October 9, 2015, Published by the Texas State Historical Association, http://www.tshaonline.org/handbook/online/articles/hcl01.

McLaurin, C., 1988, Occurrence, Availability, and Chemical Quality of Ground Water in the Blossom Sand Aquifer, TWDB Report 307, 31 p., http://www.twdb.texas.gov/publications/reports/numbered_reports/doc/R307/Report307.asp

Mace, R.E., 2001, Estimating transmissivity using specific-capacity: The University of Texas at Austin, Bureau of Economic Geology, Geological Circular No. 01-2, 44 p.

Morton, R.B., 1992, Simulation of Ground-Water Flow in the Antlers Aquifer in Southeastern Oklahoma and Northeastern Texas, U.S. Geological Survey, Water-Resources Investigations Report 88-4208, 22p., http://pubs.er.usgs.gov/publication/wri884208

Narasimhan, B., Srinivasan, R., Quiring, S., Nielsen-Gammon, J.W., 2005, Digital Climate Atlas of Texas, prepared for TWDB, 108 p., http://www.twdb.texas.gov/groundwater/docs/Texas_Digital_Climate_Atlas.pdf

National Centers for Environmental Information (NCEI, formerly National Climate Data Center), 2013, Global Historical Climatological Network-Daily, http://www.ncdc.noaa.gov/data-access/quick-links.

Natural Resources Conservation Service, Soil Survey Staff, United States Department of Agriculture. Web Soil Survey, 2021, Available online at https://websoilsurvey.nrcs.usda.gov/, Accessed February 23, 2021.

Nordstrom, P.L., 1982, Occurrence, Availability, and Chemical Quality of Ground Water in the Cretaceous Aquifers of North-Central Texas, TWDB Report 269, 61 p., http://www.twdb.texas.gov/publications/reports/numbered_reports/doc/R269/Report269.asp

Oklahoma Center for Geospatial Information, 2013, Oklahoma City Boundaries and Roads Shapefiles.

Panday, S., Rumbaugh, J., Hutchison, W.R., and Schorr, S., 2020, Numerical Model Report for the Northern Portion of the Queen City, Sparta, and Carrizo-Wilcox Aquifers, Texas Water Development Board Contract Report, 322 p.

Parsons Engineering Science, Inc., 1999, Surface Water/Groundwater Interaction Evaluation of 22 Texas River Basins, Prepared for Texas Natural Resource Conservation Commission, 201 p.

Press, F. and Siever, R., 1982, *Earth*, W. H. Freeman and Company, 613 p.

PRISM Climate Group, 2012, United States Average Annual Precipitation, 1981 - 2010, Oregon State University, http://www.prism.oregonstate.edu/, created 2012.

PRISM Climate Group, 2013a, United States Average Annual Maximum Temperature, 1981 - 2010, Oregon State University, http://www.prism.oregonstate.edu/, created August 8, 2013.

PRISM Climate Group, 2013b, United States Average Annual Mean Temperature, 1981 - 2010, Oregon State University, http://www.prism.oregonstate.edu/, created August 8, 2013.

PRISM Climate Group, 2013c, United States Average Annual Minimum Temperature, 1981 - 2010, Oregon State University, http://www.prism.oregonstate.edu/, created August 8, 2013.

Ridgeway, C. K. and Hamlin, S., 2005, Steady-state numerical groundwater flow model of the Blossom aquifer in Texas, unpublished University of Texas Geology class project, 25 p.

Roberts-Ashby, T.L., Brennan, S.T., Buursink, M.L., Covault, J.A., Craddock, W.H., Drake, R.M., Merrill, M.D., Slucher, E.R., Warwick, P.D., Blondes, M.S., Gosai, M.A., Freeman, P.A., Cahan, S.M., DeVera, C.A., and Lohr, C.D., 2014, Geologic Framework for the National Assessment of Carbon Dioxide Storage Resources-U.S. Gulf Coast, U.S. Geological Survey Open-File Report 2012-1024-H, 77 p., http://pubs.usgs.gov/of/2012/1024/h/

Rutledge, A. T., 1998, Computer Programs for Describing the Recession of Ground-Water Discharge and for Estimating Mean Ground-Water Recharge and Discharge from Streamflow Records—Update, Water-Resources Investigations Report 98-4148, U.S. Geological Survey, 52 p.

Scanlon, B., Keese, K., Bonal, N., Deeds, N., Kelley, V., and Litvak, M., 2005, Evapotranspiration Estimates with Emphasis on Groundwater Evapotranspiration in Texas: Contract report prepared for the Texas Water Development Board by The Bureau of Economic Geology (prime contractor), variously paginated, http://www.twdb.texas.gov/groundwater/docs/BEG_ET.pdf.

Stephenson, L.W., 1918, A Contribution to the geology of northeastern Texas and southern Oklahoma, U. S. Geological Survey Professional Paper 120-H, 206 p., http://pubs.usgs.gov/pp/0120h/report.pdf

Stephenson, L.W., 1936, Stratigraphic Relations of the Austin, Taylor, and Equivalent Formations in Texas, Geological Survey Professional Paper 186-G, 237 p., http://pubs.usgs.gov/pp/0186g/report.pdf

Sternberg, Y.M., 1973, Efficiency of partially penetrating wells: Ground Water, v. 11, no. 3, p. 5-7.

Sundstrom, R.W., Hastings, W.W., and Broadhurst, W.L., 1948, Public Water Supplies in Eastern Texas. USGS Water Supply Paper 1047, 285 p.

Taylor, H.D., 1976, Water-Level and Water-Quality Data From Observation Wells in Northeast Texas. Texas Water Development Board Report 198, 294 p.

Theis, C.V., Brown, R.H., and Meyers, R.R., 1963, Estimating the transmissibility of aquifers from the specific capacity of wells. Methods of determining permeability, transmissivity, and drawdowns: U.S. Geological Survey Water Supply Papers, 1536-I, p. 331–341.

Texas Department of Transportation, 2006, TxDOT_Routes04, Shapefile of Texas Roads and Highways.

TWDB, 1991, Surveys of Irrigation in Texas – 1958, 1964, 1969, 1974, 1979, 1984, and 1989, TWDB Report 329, 124 p., http://www.twdb.texas.gov/publications/reports/numbered_reports/doc/R329/R329.pdf

TWDB, 2012, Water for Texas 2012 State Water Plan, 314 p., http://www.twdb.texas.gov/publications/state_water_plan/2012/2012_SWP.pdf

TWDB, 2013a, Water for Texas: Groundwater Availability Modeling, Online Program Information Sheet, http://www.twdb.texas.gov/publications/shells/GAM.pdf

TWDB, 2013b, Groundwater Database Well data, accessed July 23, 2013.

TWDB, 2013c, Texas Natural Resources Information System, Texas Strategic Mapping Program (StratMap), Texas City Boundary Shapefile.

TWDB, 2014, Submitted Drillers Reports (SDR) Database, http://www.twdb.texas.gov/groundwater/data/drillersdb.asp, accessed June 2014.

TWDB, 2015a, Water Use Survey, Historical Groundwater Pumpage, http://www.twdb.texas.gov/waterplanning/waterusesurvey/historical-pumpage.asp, accessed February 2015.

TWDB, 2015b, Groundwater Database Well data, accessed July, 2015.

Wahl, K.L., and Wahl, T.L., 1995, Determining the flow of Comal Springs at New Braunfels, Texas, in Proceedings of Texas Water '95, August 16-17, 1995, San Antonio, Texas: American Society of Civil Engineers, p. 77-86.

Wahl, T. L., 2015, BFI- A computer Program for Determining an Index to Base Flow, online documentation, http://www.usbr.gov/pmts/hydraulics_lab/twahl/bfi/

Wermund, E. G., 1996, Physiography of Texas, http://www.beg.utexas.edu/UTopia/images/pagesizemaps/physiography.pdf.

Wood, D.H., and Guevara, E.H., 1981, Regional structural cross sections and general stratigraphy, East Texas basin: Univ. Texas at Austin, Bureau of Economic Geology, 21 p.

U.S. Census Bureau, 2013, TIGER/Line Shapefiles of U.S. County Boundaries.

U.S. Geological Survey, 2014a, National Elevation Dataset (NED), http://www.usgs.gov/pubprod/, accessed April 2014.

U.S. Geological Survey, 2014b, Physiographic Provinces of the United States, GIS Shapefile, http://water.usgs.gov/GIS.

U.S. Geological Survey, 2014c, National Water Information System, http://waterdata.usgs.gov/nwis, accessed August 18, 2014.

U. S. Geological Survey, 2015, National Hydrography Dataset, http://nhd.usgs.gov/index.html, accessed February, 2015.

Appendix A: Cross-Sections from Brackish Groundwater Production Areas for the Blossom Aquifer Report

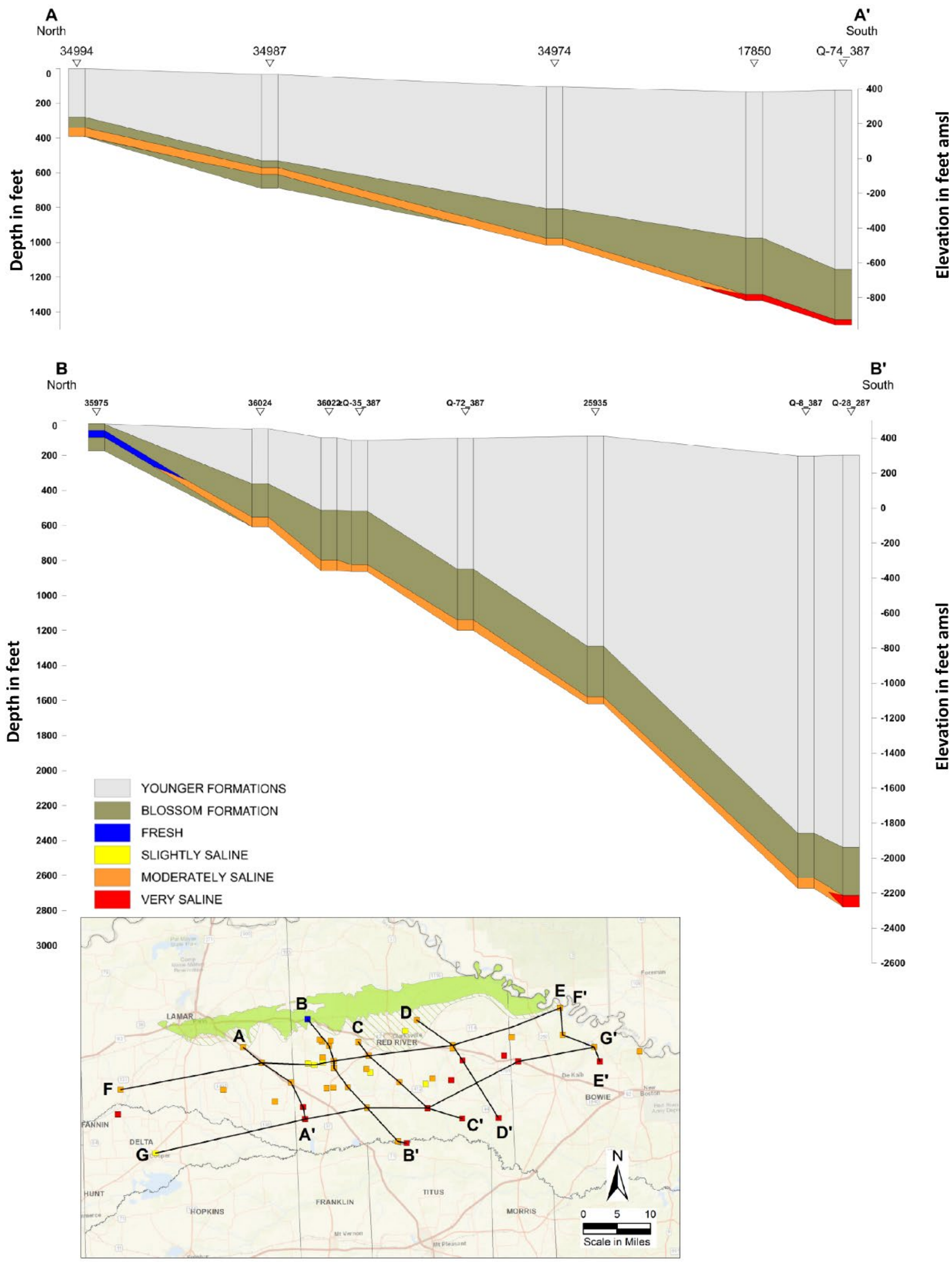

FIGURE A. 1 CROSS SECTIONS A-A' AND B-B' WITH DEPTH IN FEET AND ELEVATION IN FEET ABOVE MEAN SEA LEVEL (FROM BEACH AND LAUGHLIN, 2017).

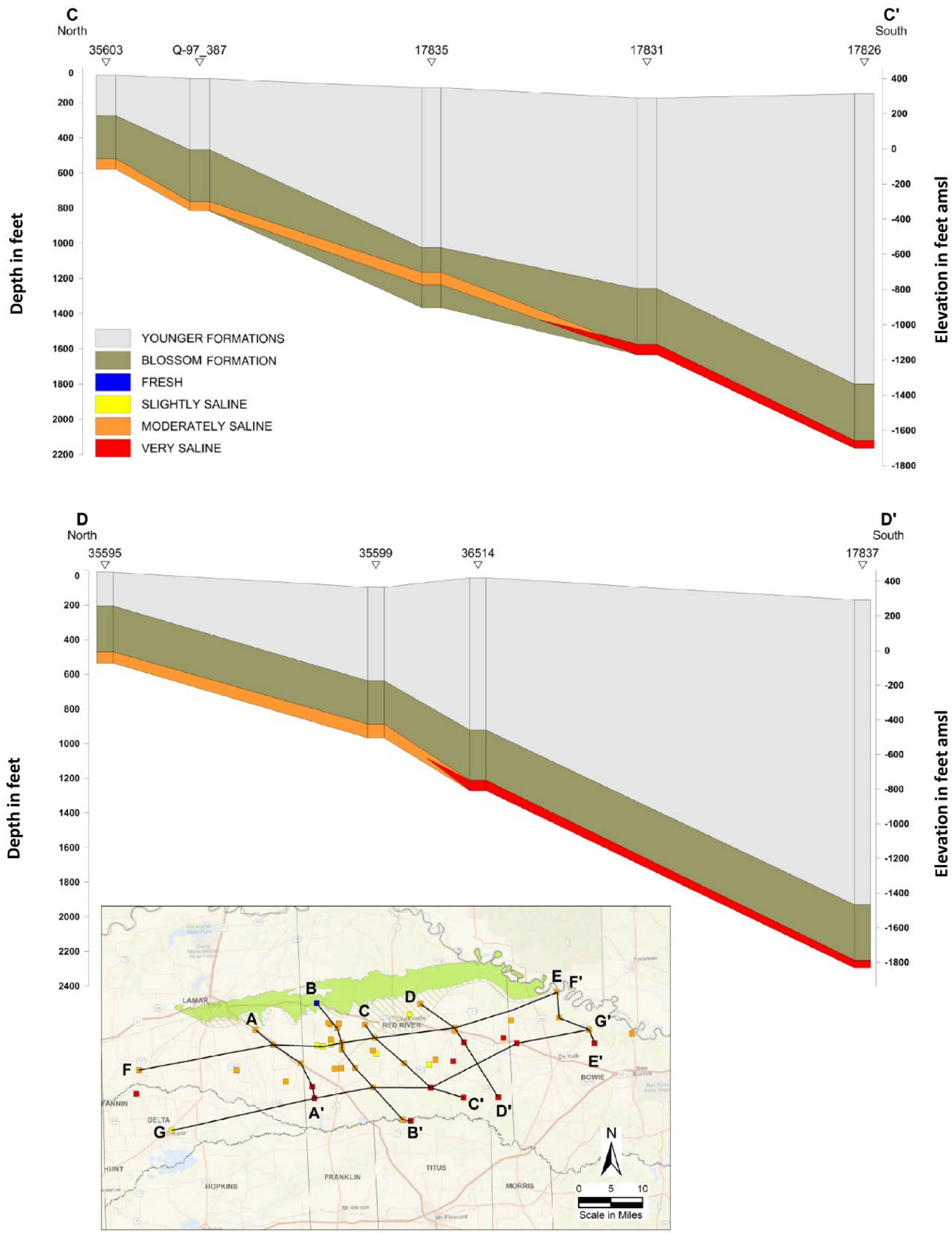

FIGURE A. 2 CROSS SECTIONS C-C' AND D-D' WITH DEPTH IN FEET AND ELEVATION IN FEET ABOVE MEAN SEA LEVEL (FROM BEACH AND LAUGHLIN, 2017).

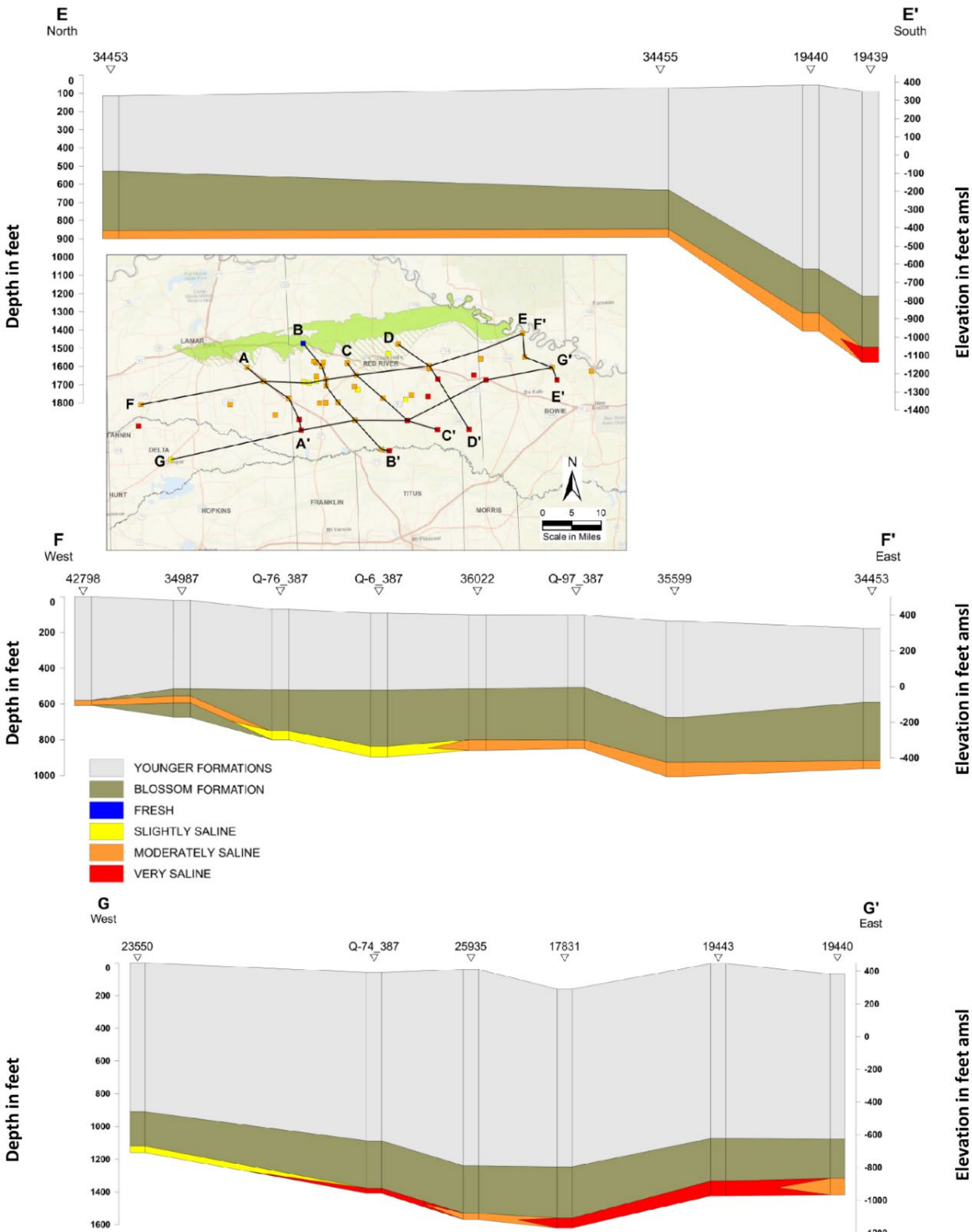

FIGURE A. 3 CROSS SECTIONS E-E', F-F' AND G-G' WITH DEPTH IN FEET AND ELEVATION IN FEET ABOVE MEAN SEA LEVEL (FROM BEACH AND LAUGHLIN, 2017).

Appendix B:
Responses to Stakeholder Comments