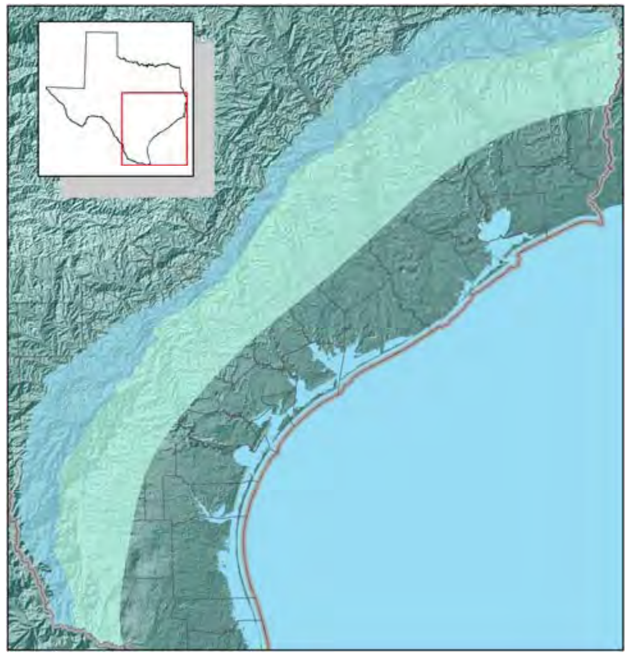
Final Report
Groundwater Availability Model for the Yegua-Jackson Aquifer



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Prepared for the:

Texas Water Development Board

March 2010

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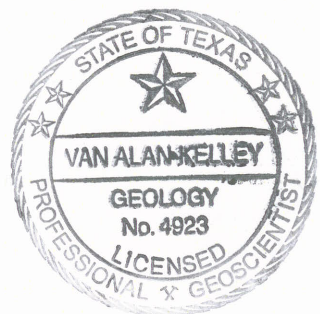
Mr. Kelley was the Project Manager for this work and was responsible for oversight on the project.



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Dr. Deeds was responsible for development of the conceptual model and development and calibration of the Yegua-Jackson Aquifer groundwater availability model.

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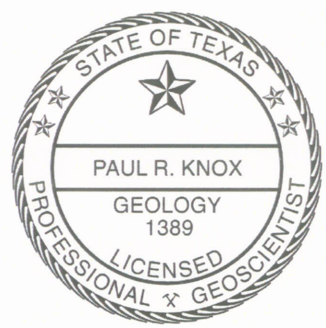

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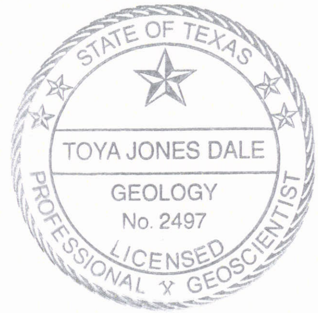

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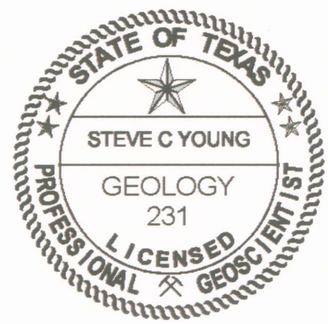
Dr. Young was responsible for the evaluation of hydraulic properties of the Yegua-Jackson Aquifer for the conceptual model.



Steven C Young

Signature

3/31/2010

Date

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Executive Summary

This report documents the development of a three-dimensional groundwater model for the Yegua-Jackson Aquifer, which exists predominantly in the outcrop or near-outcrop areas of the Yegua Formation and Jackson Group. Water quality is typically poor in the confined sections gulfward of the outcrop, and use is limited in these sections. In Texas, the outcrop area stretches in a relatively thin band approximately parallel to the coastline, from Star County in the Rio Grande Valley to Sabine County in east Texas. The Yegua-Jackson Aquifer is a minor aquifer in Texas with rural domestic being the largest water use type. Head declines occur in a few areas due to municipal or industrial pumping.

The groundwater availability model was developed using MODFLOW 2000 and consists of five layers. The first layer represents the shallow outcrop section for the Yegua-Jackson Aquifer as well as the Catahoula Formation gulfward of the outcrop. The deeper sections of the four units making up the Yegua-Jackson Aquifer, the Upper Jackson Unit, the Lower Jackson Unit, the Upper Yegua Unit, and the Lower Yegua Unit, are represented by model layers 2 through 5, respectively. The model consists of about 150,000 active grid cells. The model grid for the Yegua-Jackson Aquifer groundwater availability model is oriented along strike (approximately parallel to the coast). The model incorporates the available information on structure, hydrostratigraphy, hydraulic properties, streamflow, recharge, evapotranspiration, and pumping for the Yegua-Jackson Aquifer. The underlying data for these parameters are presented and discussed in detail.

The model is calibrated for two time periods, one representing pre-development conditions and the other representing transient conditions. The pre-development calibration considers the time period prior to 1900, which represents a period prior to significant development of the aquifer. The transient calibration period is from 1980 through 1997. The actual transient simulation consists of a steady-state period followed by a transient period beginning in 1901 to account for the development and associated impact on storage prior to the 1980 through 1997 calibration period. Both the pre-development and transient calibrations reproduced aquifer water levels well and within the uncertainty in the water-level estimates. In addition, the model performs well in the historical period before 1980. In a few local areas, good evidence of significant drawdowns is present in the hydrographs. The model performs well in matching those drawdowns.

For both the steady-state and transient models, the dominant recharge and discharge mechanisms were areal recharge (which averaged about 1 inch per year) and baseflow to streams. The second highest discharge mechanism is groundwater evapotranspiration. In the transient model, a few percent of the overall discharge is due to pumping.

Because water levels are relatively constant in many regions of the Yegua-Jackson Aquifer, and the steady-state heads are used to initialize the transient model, transient heads were sensitive to many of the same property and boundary condition parameters as the steady-state model. Heads were most sensitive to horizontal hydraulic conductivities, especially in the shallow layer. Heads were also sensitive to areal recharge rates and stream conductance.

The purpose of the Yegua-Jackson Aquifer groundwater availability model is to provide a calibrated numerical model that can be used to assess groundwater availability in regional water plans and to assess the effects of various proposed water management strategies on the aquifer system. The applicability of the Yegua-Jackson Aquifer model is limited to regional-scale assessments of groundwater availability (e.g., an area smaller than a county and larger than a square mile) due to the relatively large grid blocks (one square mile) over which pumping and hydraulic property data are averaged. At the scale of the model, it is not capable of predicting aquifer responses at a specific point such as a particular well. In addition to uncertainty in pumping and hydraulic property data, the model is limited to a first-order approach of coupling surface water and groundwater and does not provide a rigorous solution to surface-water flow in the region.

The Yegua-Jackson Aquifer groundwater availability model provides a documented, publicly-available, integrated tool for use by state planners, Regional Water Planning Groups, Groundwater Conservation Districts, Groundwater Management Area, and other interested stakeholders.

1.0 Introduction

The Texas Water Development Board (TWDB) has identified the major and minor aquifers in Texas on the basis of regional extent and amount of water produced. The major and minor aquifers are shown in Figures 1.0.1 and 1.0.2, respectively. General discussion of the major and minor aquifers is given in Ashworth and Hopkins (1995). Aquifers that supply large quantities of water over large areas of the state are defined as major aquifers and those that supply relatively small quantities of water over large areas of the state or supply large quantities of water over small areas of the state are defined as minor aquifers.

The Yegua-Jackson Aquifer, which is the focus of this study, was not specifically described in the original version of Ashworth and Hopkins (1995), having been delineated by the TWDB as a minor aquifer in preparation for the 2002 State Water Plan (Preston, 2006). The Yegua-Jackson Aquifer can be seen in Figure 1.0.2 as the southernmost minor aquifer, running all the way across Texas from the Rio Grande in the southwest to the Sabine River in the northeast. Prior to 2002, the units forming the Yegua-Jackson Aquifer were categorized, along with other minor sources of water, as “other aquifer”. The large number of wells in the Yegua-Jackson Aquifer and corresponding substantial use of the resource motivated the recategorization (Preston, 2006).

This report documents the development of a groundwater availability model for the Yegua-Jackson Aquifer. Sections 1 through 5 describe the conceptual model for the Yegua-Jackson Aquifer. All aspects of the numerical modeling are discussed in Sections 6 through 9. Section 10 discusses the limitations of the model. Section 11 provides suggestions for future improvements to the model, and Section 12 presents conclusions.

Utilization of the Yegua-Jackson Aquifer, which consists of the Yegua Formation and Jackson Group, occurs almost exclusively in the unconfined portion of the aquifer. The Yegua Formation and Jackson Group, following typical Texas Gulf Coast geology, dip deep beneath land surface all the way to the coast and beyond. However, water quality degrades quickly moving into the confined portion, rendering it unsuitable for use without further treatment. Even in the outcrop, both the yield and water quality can vary significantly over small differences in location and depth. In spite of these challenges, the Yegua-Jackson Aquifer represents an important groundwater supply in many counties in or near the outcrop. Domestic, livestock, irrigation, and some municipal and manufacturing use occur from the Yegua-Jackson Aquifer. Thirty four counties intersect the Yegua-Jackson Aquifer as currently delineated by Preston (2006).

The 2007 State Water Plan (TWDB, 2007) identifies the existing groundwater supply in the Yegua-Jackson Aquifer as 7,285 acre-feet per year with a total availability estimated at 25,000 acre-feet per year. Several regions have developed water management strategies in the 2007 State Water plan that include the drilling of new wells and water desalination in the Yegua-Jackson Aquifer. With the implementation of the proposed water management strategies, production from the aquifer is expected to exceed 15,000 acre-feet per year by 2040.

The Yegua-Jackson Aquifer consists of four units as defined in Knox and others (2007). These are, from youngest to oldest, the Upper Jackson Unit, the Lower Jackson Unit, the Upper Yegua Unit, and the Lower Yegua Unit. The groundwater availability model developed for the Yegua-Jackson Aquifer consists of five layers, with layers 2 through 5 representing the downdip portion of the four units making up the aquifer and layer 1 representing the entire outcrop area of all four units in the aquifer as well as the younger sediments that overlie the downdip portion of the aquifer.

The Texas Water Code codified the requirement for generation of a State Water Plan that allows for the development, management, and conservation of water resources and the preparation and response to drought, while maintaining sufficient water available for the citizens of Texas (TWDB, 2007). Senate Bill 1 and subsequent legislation directed the TWDB to coordinate regional water planning with a process based upon public participation. Also, as a result of Senate Bill 1, the approach to water planning in the state of Texas has shifted from a water-demand based allocation approach to an availability-based approach.

Groundwater models provide a tool to estimate groundwater availability for various water use strategies and to determine the cumulative effects of increased water use and drought. A groundwater model is a numerical representation of the aquifer system capable of simulating historical conditions and predicting future aquifer conditions. Inherent to the groundwater model are a set of equations that are developed and applied to describe the primary or dominant physical processes considered to be controlling groundwater flow in the aquifer system.

Groundwater models are essential to performing complex analyses and in making informed predictions and related decisions (Anderson and Woessner, 1992).

Development of groundwater availability models for the major and minor Texas aquifers is integral to the state water planning process. The purpose of the groundwater availability model program is to provide a tool that can be used to develop reliable and timely information on groundwater availability for the citizens of Texas and to ensure adequate supplies or recognize inadequate supplies over a 50-year planning period. The groundwater availability models also serve as an integral part of the process of determining managed available groundwater based on desired future conditions, as required by House Bill 1763. The Yegua-Jackson Aquifer groundwater availability model will thus serve as a critical tool for groundwater planning in the state.

The groundwater availability model for the Yegua-Jackson Aquifer was developed using a modeling protocol that is standard to the groundwater modeling industry. This protocol includes: (1) the development of a conceptual model for groundwater flow in the aquifer, including defining physical limits and properties, (2) model design, (3) model calibration, (4) sensitivity analysis, and (5) reporting. The conceptual model is a conceptual description of the physical processes governing groundwater flow in the aquifer system. Available data and reports for the model area were reviewed in the conceptual model development stage. Model design is the process used to translate the conceptual model into a physical model, which in this case is a numerical model of groundwater flow. This involves organizing and distributing model parameters, developing a model grid and model boundary conditions, and determining the model integration time scale. Model calibration is the process of modifying model parameters so that observed field measurements (e.g., water levels in wells) can be reproduced. The model was calibrated to pre-development conditions representing, as closely as possible, conditions in the aquifer prior to significant development and to transient aquifer conditions focused primarily on the time period from January 1980 through December 1997. Sensitivity analyses were performed on both the pre-development and transient models to offer insight on the uniqueness of the model and the impact of uncertainty in model parameter estimates.

Consistent with state water planning policy, the groundwater availability model for the Yegua-Jackson Aquifer was developed with the support of stakeholders through stakeholder advisory forums. The purpose of the groundwater availability models is to provide a tool for Regional Water Planning Groups, Groundwater Conservation Districts, River Authorities, and state planners for evaluating groundwater availability and to support the development of water management strategies and drought planning. The Yegua-Jackson Aquifer groundwater availability model will provide a tool for use in assessing water-planning strategies.

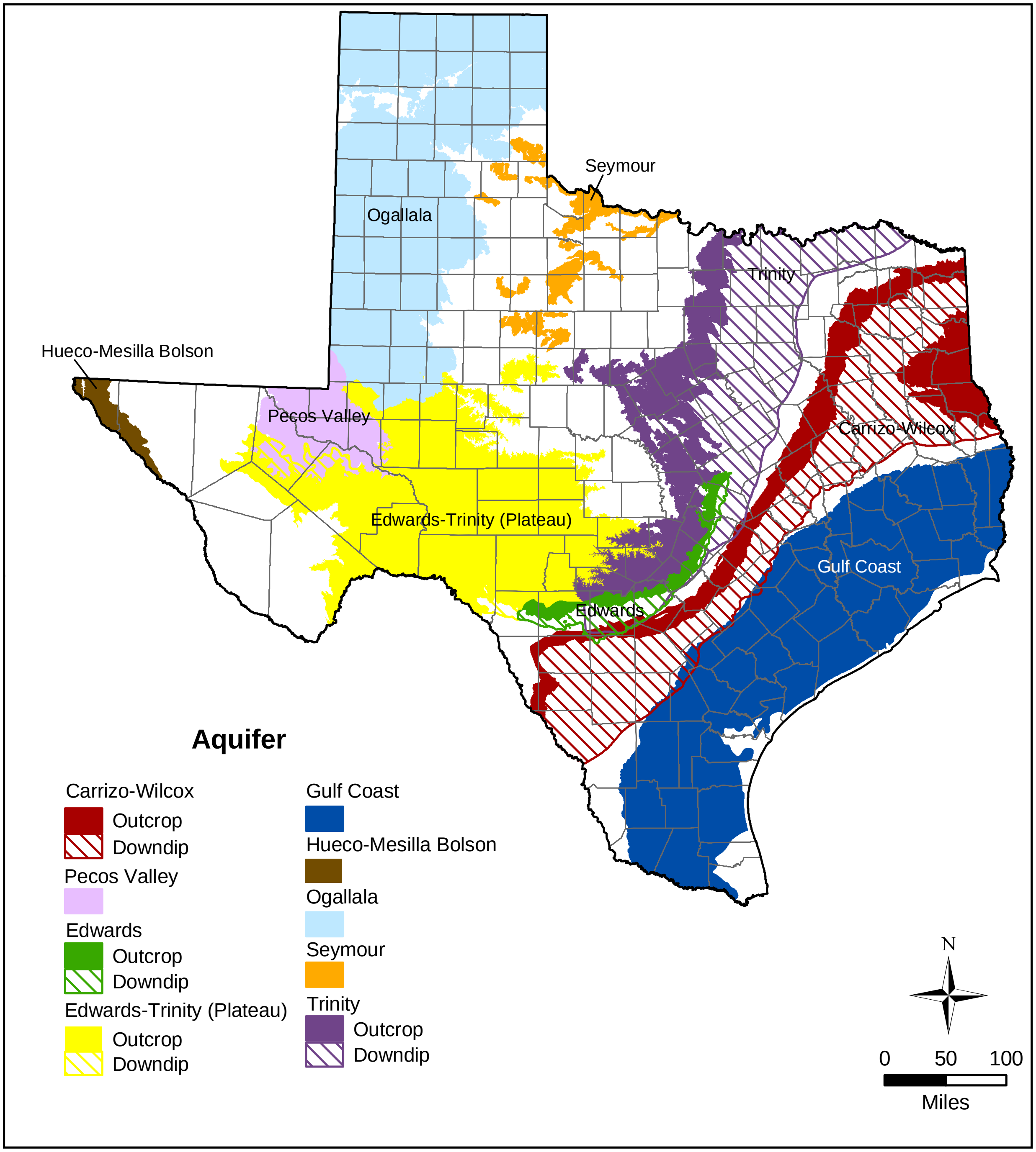


Figure 1.0.1 Locations of major aquifers in Texas (TWDB, 2007).

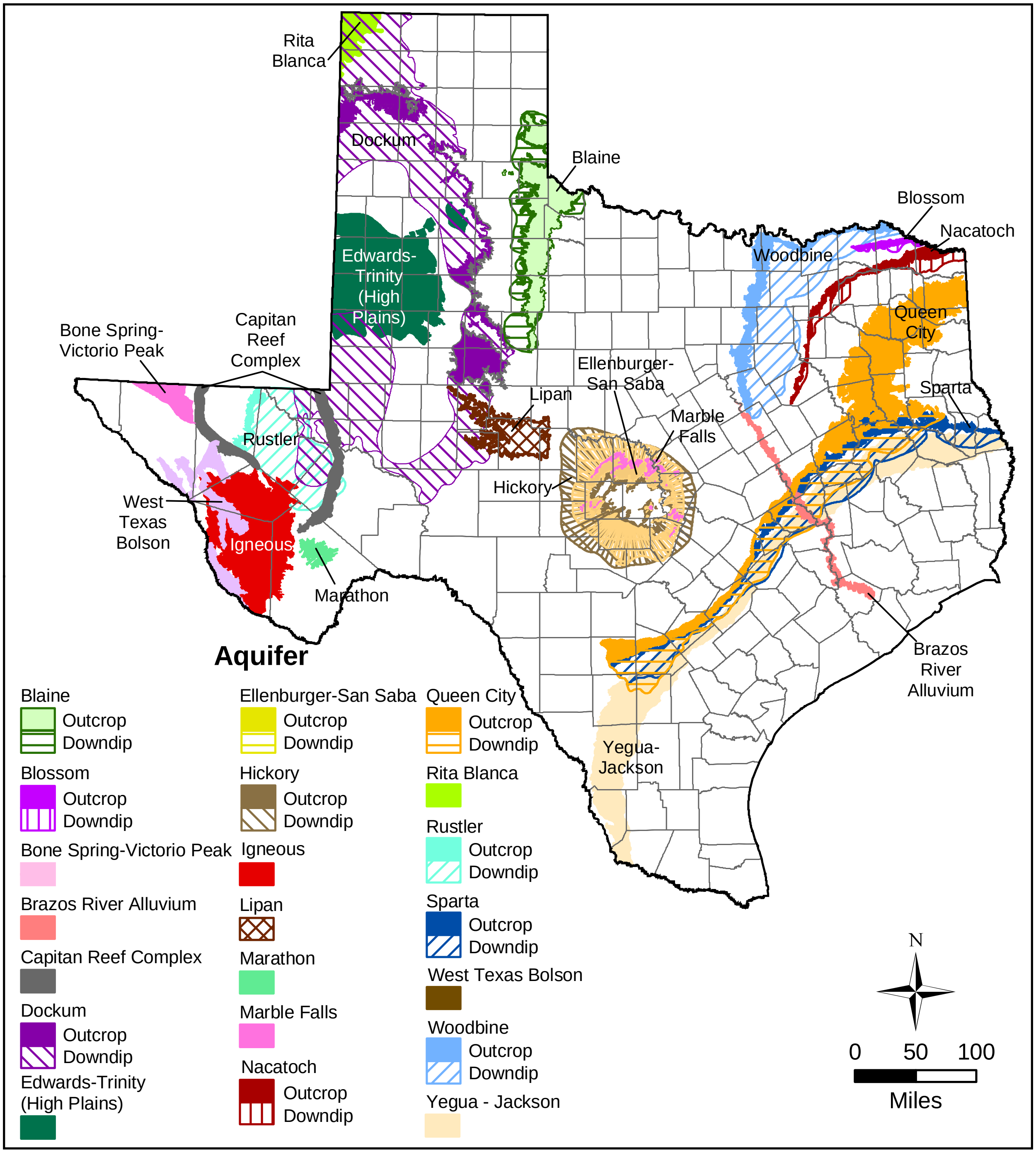


Figure 1.0.2 Locations of minor aquifers in Texas (TWDB, 2007).

2.0 Study Area

The Yegua-Jackson Aquifer exists predominantly in the outcrop or near-outcrop areas of the Yegua Formation and Jackson Group. In Texas, this outcrop area stretches in a relatively thin band approximately parallel to the coastline, from Starr County in the Rio Grande Valley to Sabine County in East Texas. The width of this outcrop varies from less than 10 miles in Gonzales County to nearly 40 miles in LaSalle County, with an area of approximately 11,000 square miles (Preston, 2006).

The location of the active model area is shown in Figure 2.0.1. The outcrop and downdip portions of the active model boundary for the Yegua-Jackson Aquifer groundwater availability model are shown in Figure 2.0.2. The study area is coincident with the active model boundary. Groundwater model boundaries are typically defined on the basis of surface or groundwater hydrologic boundaries. The boundary on the updip side of the aquifer (away from the coast) corresponds to the contact between the Yegua Formation and the Cook Mountain Formation. The boundary to the southwest corresponds to the Rio Grande. The boundary to the northeast corresponds to the Sabine River and Toledo Bend Reservoir. The downdip boundary was defined based on the extent of the data that was used to create the Yegua-Jackson Aquifer structural surfaces (Knox and others, 2007). The downdip boundary extends well beyond the fresh or slightly saline portions of the aquifer. This allows the inclusion of portions of the aquifer that do not produce fresh or slightly saline water, but may be used in conjunction with desalination at some future date.

Figure 2.0.3 shows the counties, roadways, cities, and towns in and near the study area. All or part of 53 Texas counties are included in the study area. The locations of rivers, streams, lakes, and reservoirs in or near the study area are shown on Figure 2.0.4.

Figures 2.0.5 and 2.0.6 show the surface outcrop and downdip subcrop of the major and minor aquifers, respectively, in Texas that intersect the study area. Major aquifers located in the study area include portions of the Carrizo-Wilcox Aquifer and the Gulf Coast Aquifer. In addition to the Yegua-Jackson Aquifer, minor aquifers located in the study area include portions of the Queen City, Sparta, and Brazos River Alluvium aquifers.

The Yegua-Jackson Aquifer encompasses part of eight Texas Regional Water Planning Groups (Figure 2.0.7). From north to south they are (1) the East Texas Regional Water Planning Group (Region I), (2) the Region H Regional Water Planning Group, (3) the Brazos Regional Water Planning Group (Region G), (4) the Lower Colorado Regional Water Planning Group (Region K), (5) the Lavaca Regional Water Planning Group (Region P), (6) the South Central Texas Regional Water Planning Group (Region L), (7) the Coastal Bend Regional Water Planning Group (Region N), and (8) the Rio Grande Regional Water Planning Group (Region M). The aquifer includes all or part of 26 Groundwater Conservation Districts in Texas (Figure 2.0.8) as listed in Table 2.0.1. The aquifer intersects portions of Texas Groundwater Management Areas 11 through 16 (Figure 2.0.9). The aquifer intersects 12 Texas river authorities, which are summarized in Table 2.0.2. The boundaries for the river authorities are shown in Figure 2.0.10.

There are 16 major river basins that intersect the Yegua-Jackson Aquifer (Figure 2.0.11). Climate is the major control on flow in rivers and streams. The primary climatic factors are precipitation and evapotranspiration. In general, flow in rivers in the far southwestern portion of the study area is episodic with extended periods of low flow, or no flow conditions. Some of these rivers tend to lose water to the underlying formations, as discussed in Section 4.5.1. In contrast, rivers and streams in the central and eastern portions of the study area are perennial and tend to gain flow from the underlying sediments. Table 2.0.3 provides a listing of the river basins in the study area along with some characteristics of the primary basins, including the river length in Texas, the river basin area in Texas, and the number of major reservoirs within the river basin in Texas.

Table 2.0.1 Texas Groundwater Conservation Districts intersecting the Yegua-Jackson Aquifer groundwater availability model study area.

Bee GCD	Lost Pines GCD
Bluebonnet GCD	Lower Trinity GCD
Brazos Valley GCD	McMullen GCD
Coastal Bend GCD	Mid-East Texas GCD
Colorado County GCD	Pecan Valley GCD
Evergreen UWCD	Pineywoods GCD
Fayette County GCD	Post Oak Savannah GCD
Fort Bend Subsidence District	San Patricio County GCD
Goliad County GCD	Southeast Texas GCD
Gonzales County UWCD	Starr County GCD
Harris-Galveston Subsidence District	Texana GCD
Live Oak UWCD	Victoria County GCD
Lone Star GCD	Wintergarden GCD

GCD = Groundwater Conservation District
UWCD = Underground Water Conservation District

Table 2.0.2 Texas River Authorities intersecting the Yegua-Jackson Aquifer groundwater availability model study area.

Angelina-Neches River Authority	North Harris County RWA
Brazos River Authority	Nueces River Authority
Guadalupe-Blanco River Authority	Sabine River Authority
Lavaca-Navidad River Authority	San Antonio River Authority
Lower Colorado River Authority	San Jacinto River Authority
Lower Neches Valley Authority	Trinity River Authority

Table 2.0.3 River basins intersecting the Yegua-Jackson Aquifer groundwater availability model study area (Bureau of Economic Geology, 1996a).

River Basin	Texas River Length (miles)	Texas River Basin Drainage Area (square miles)	Number of Major Reservoirs in Texas
Brazos	840	42,800	19
Brazos-Colorado			
Colorado	600	39,893	11
Guadalupe	250	6,070	2
Lavaca	74	2,309	1
Lavaca-Guadalupe			
Neches	416	10,011	4
Nueces	315	16,950	2
Nueces-Rio Grande			
Rio Grande	1,250	48,259	3
Sabine	360	7,426	2
San Antonio			
San Antonio-Nueces			
San Jacinto	70	5,600	2
San Jacinto-Brazos			
Trinity	550	17696	14

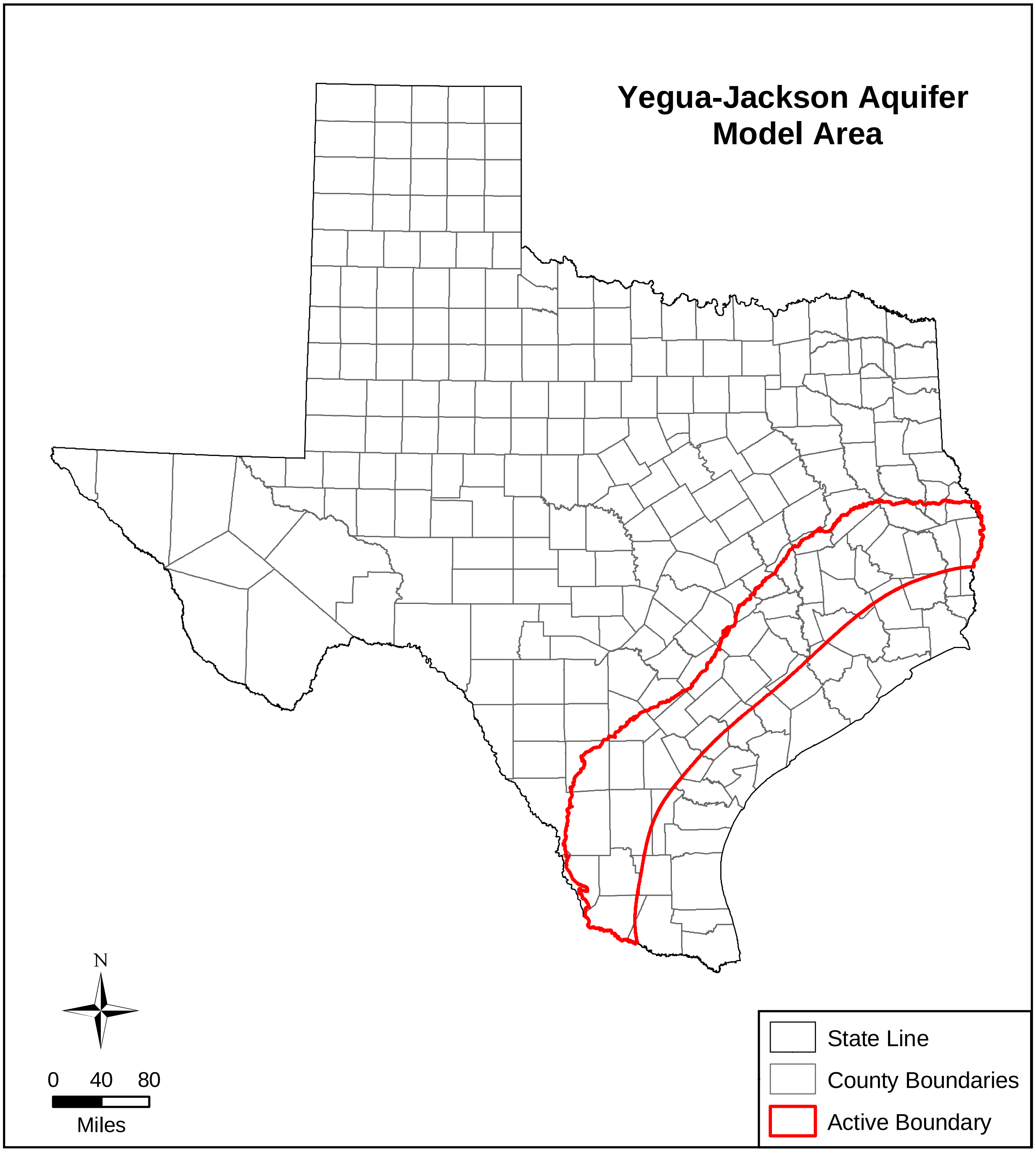


Figure 2.0.1 Study area for the Yegua-Jackson Aquifer groundwater availability model.

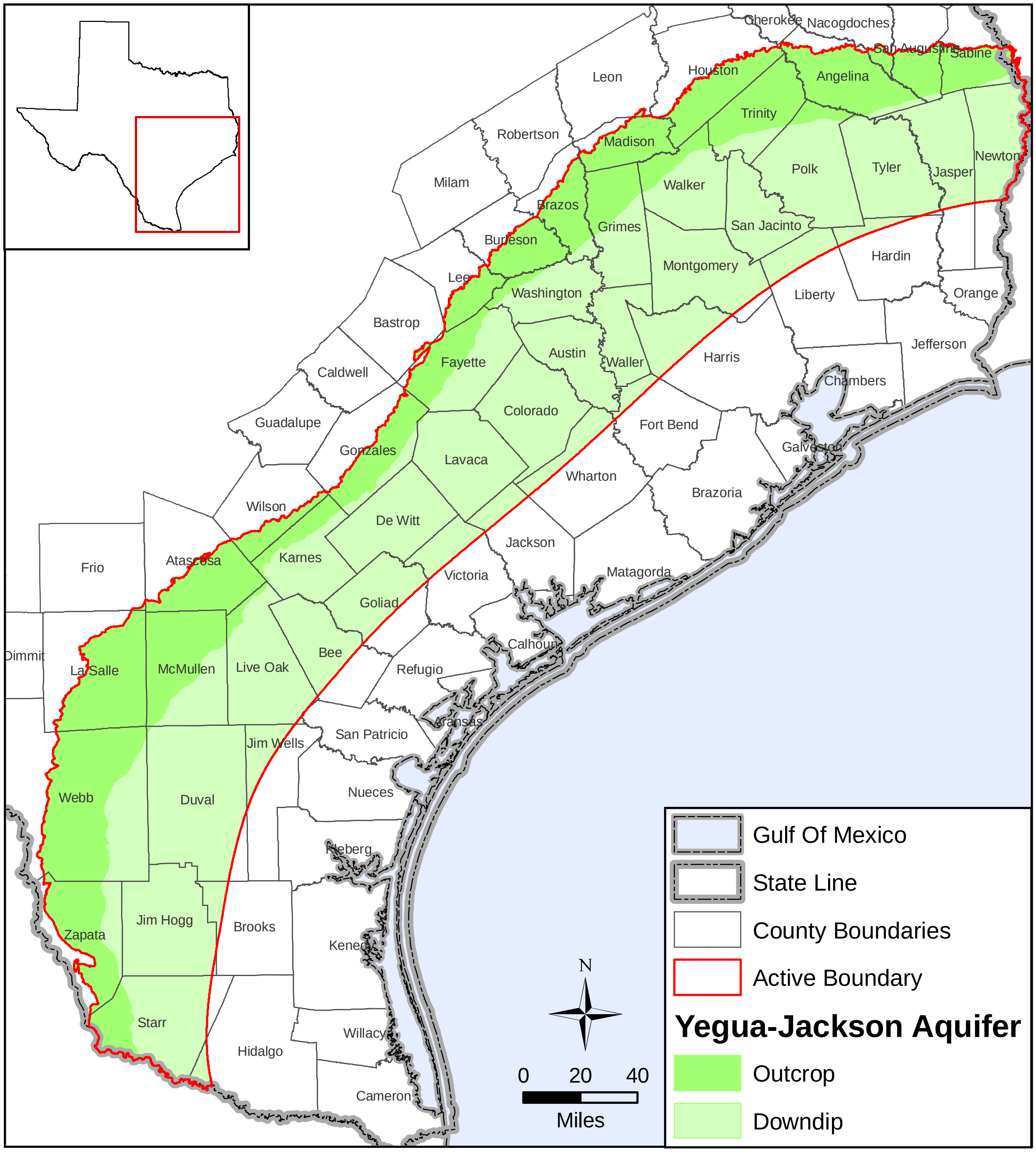


Figure 2.0.2 Active model boundary for the Yegua-Jackson Aquifer groundwater availability model (after Knox and others, 2007).

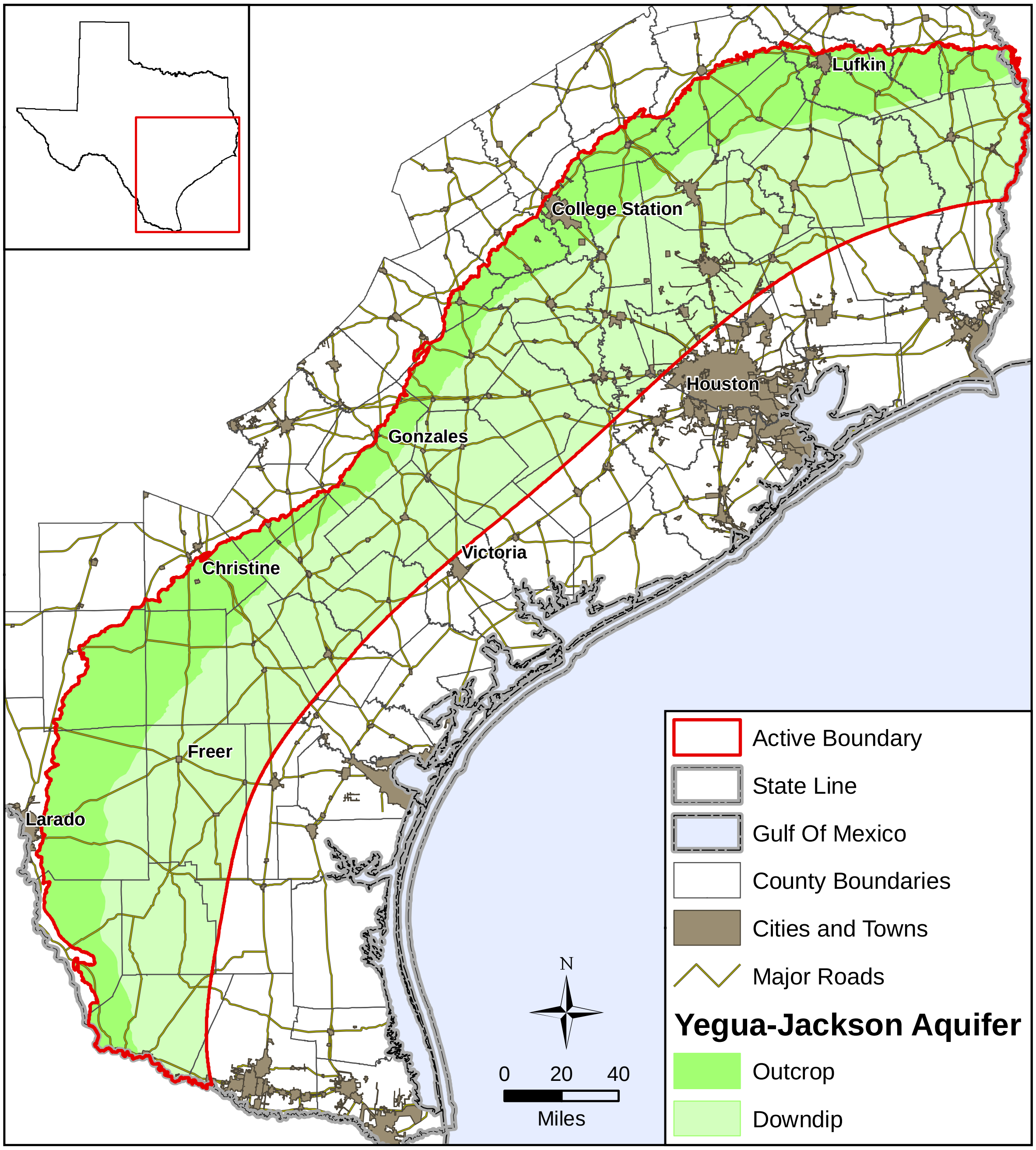


Figure 2.0.3 Cities and major roadways in or near the study area.

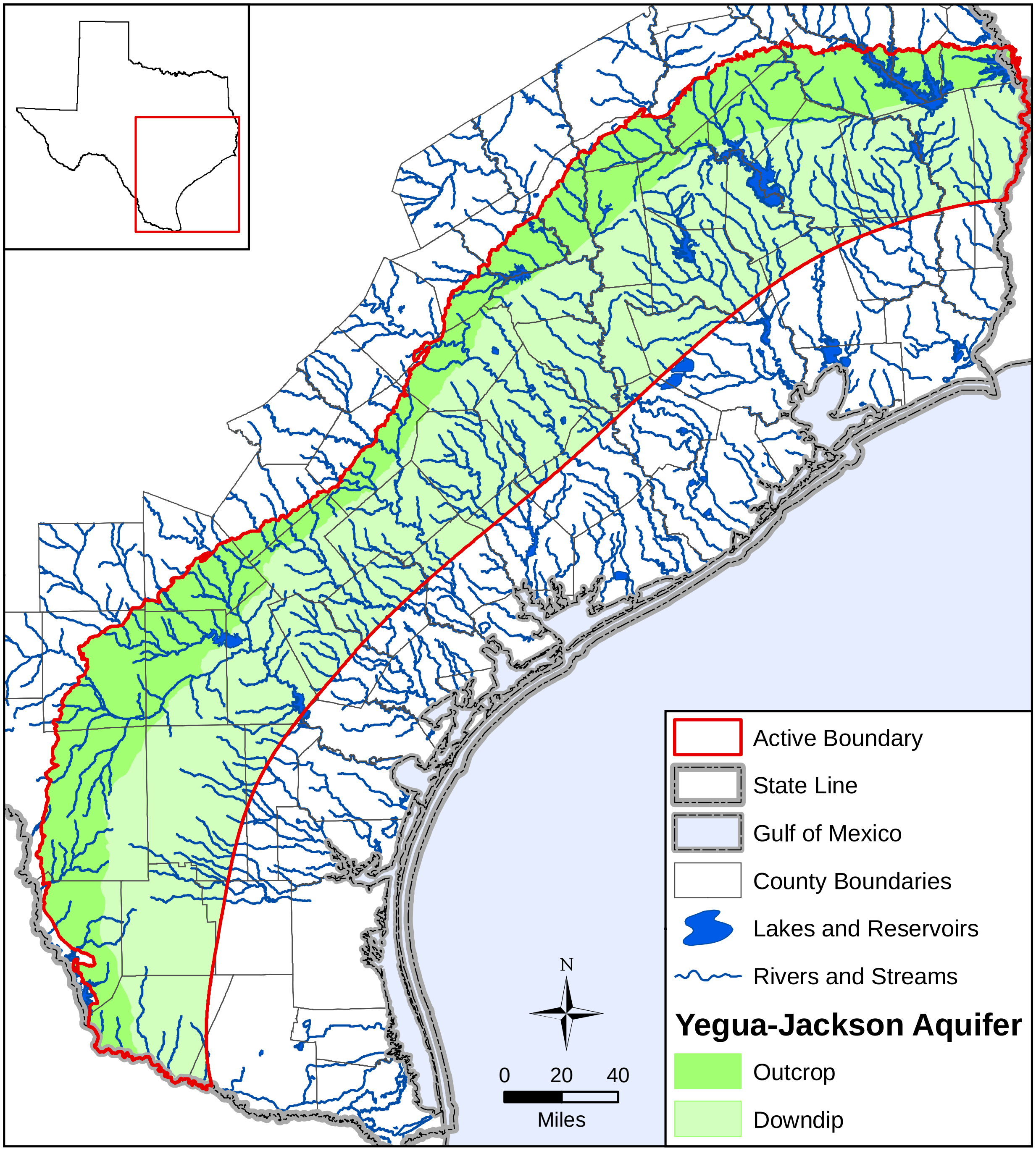


Figure 2.0.4 Lakes and rivers in or near the study area (TWDB, 2007).

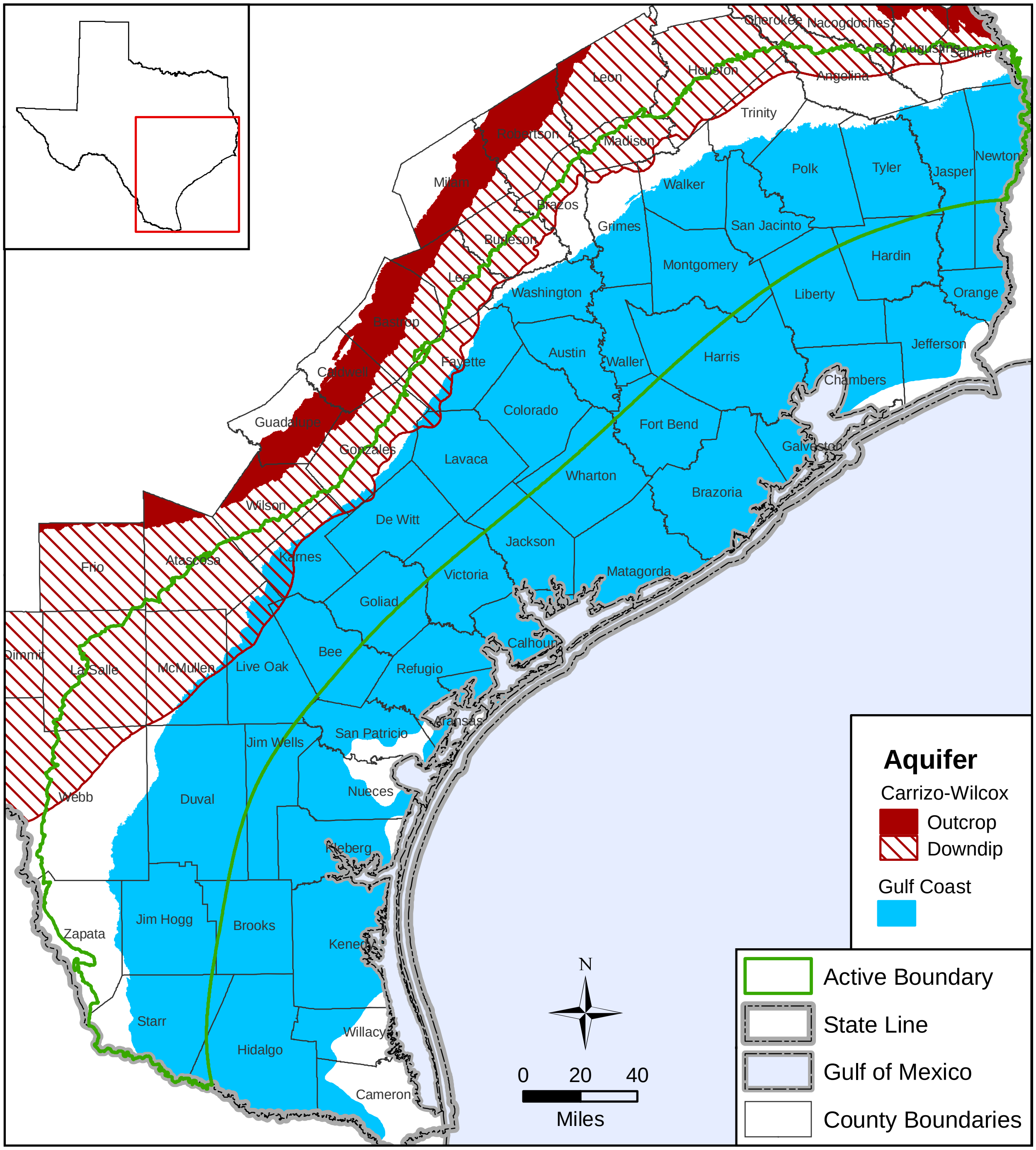


Figure 2.0.5 Major aquifers intersecting the study area (TWDB, 2007).

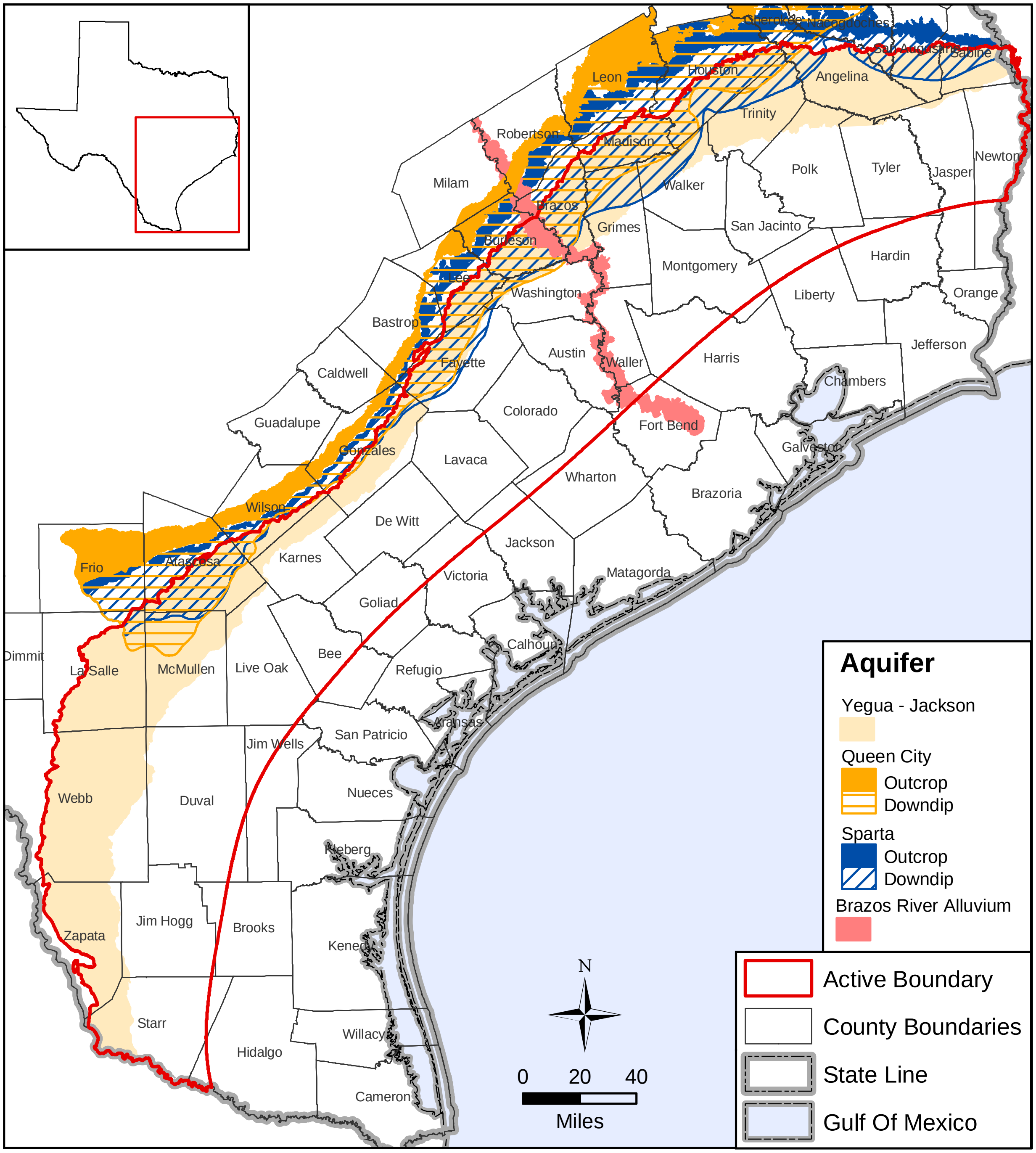


Figure 2.0.6 Minor aquifers intersecting the study area (TWDB, 2007).

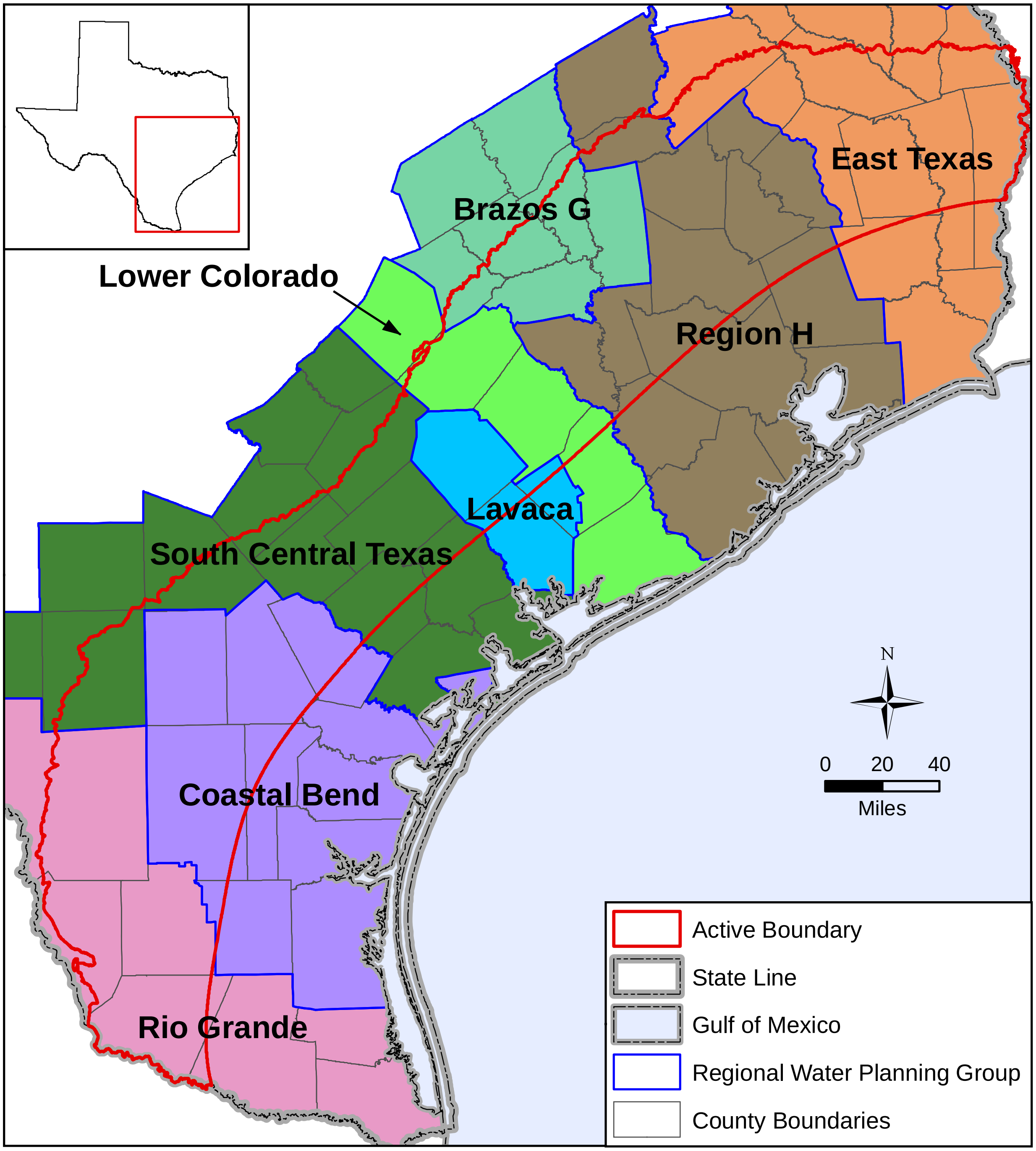
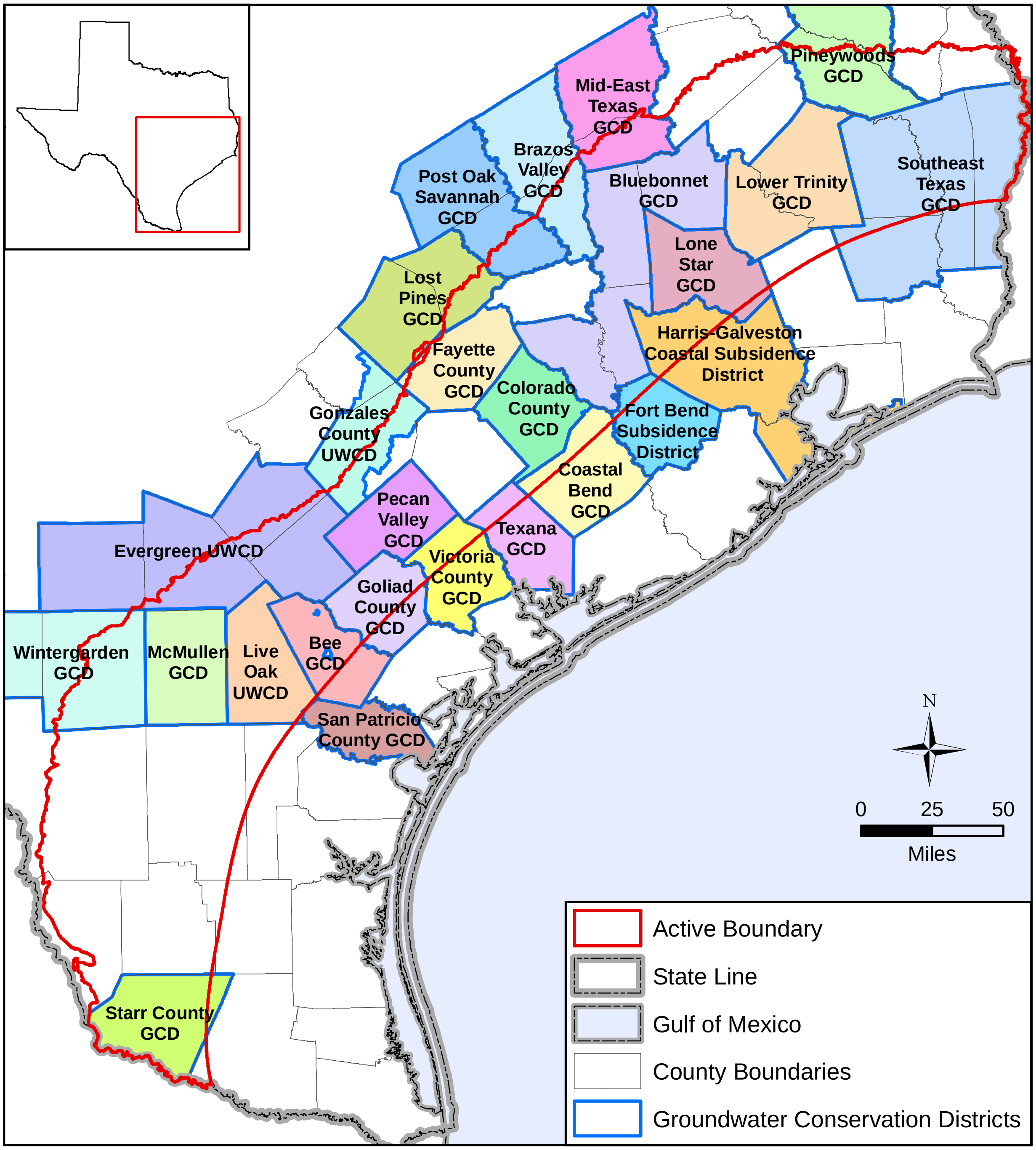


Figure 2.0.7 Regional Water Planning Groups in the study area (TWDB, 2008a).



GCD = Groundwater Conservation District
UWCD = Underground Water Conservation District

Figure 2.0.8 Groundwater Conservation Districts in the study area (TWDB, 2008a).

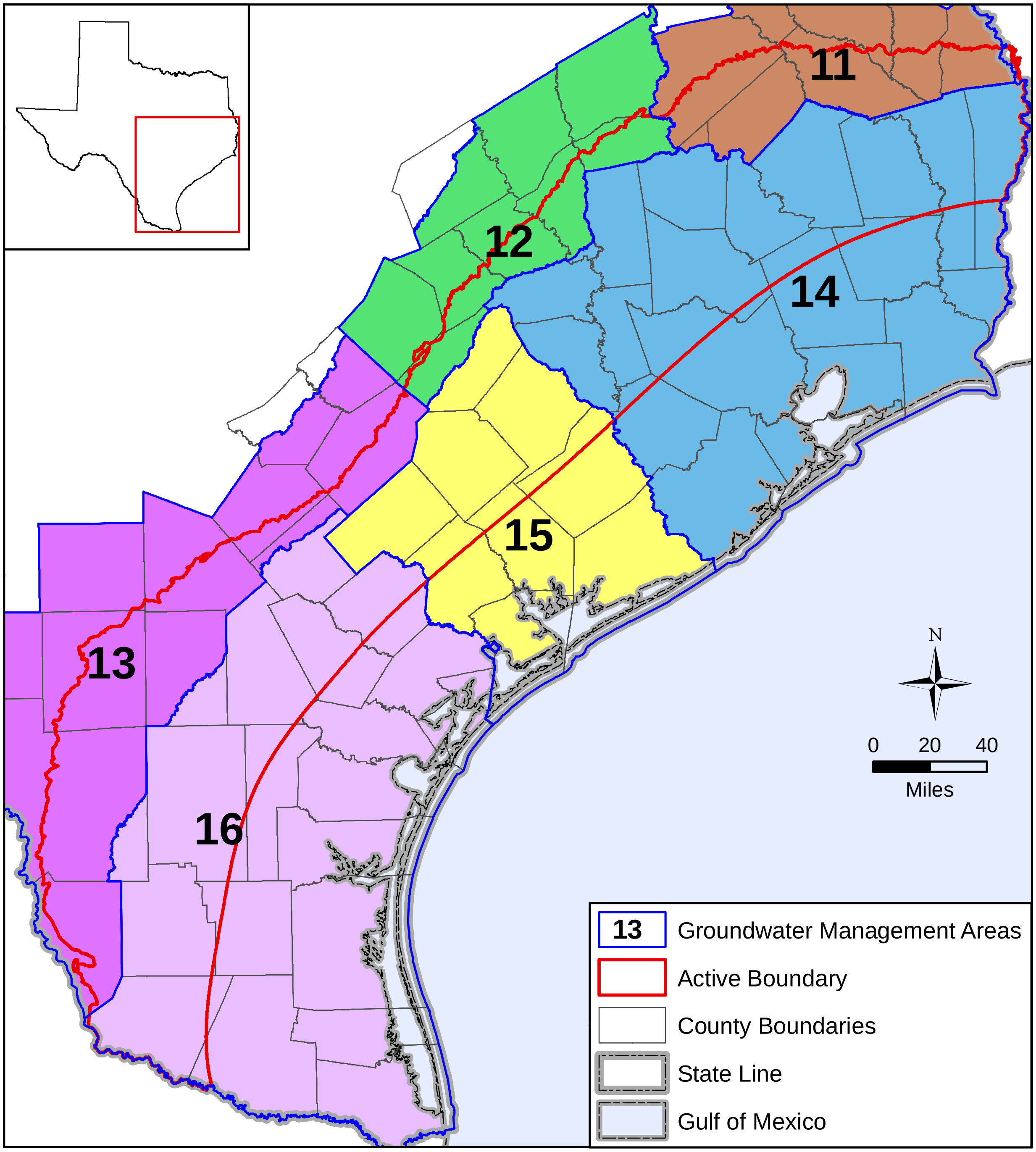


Figure 2.0.9 Locations of Texas Groundwater Management Areas in the study area (TWDB, 2008a).

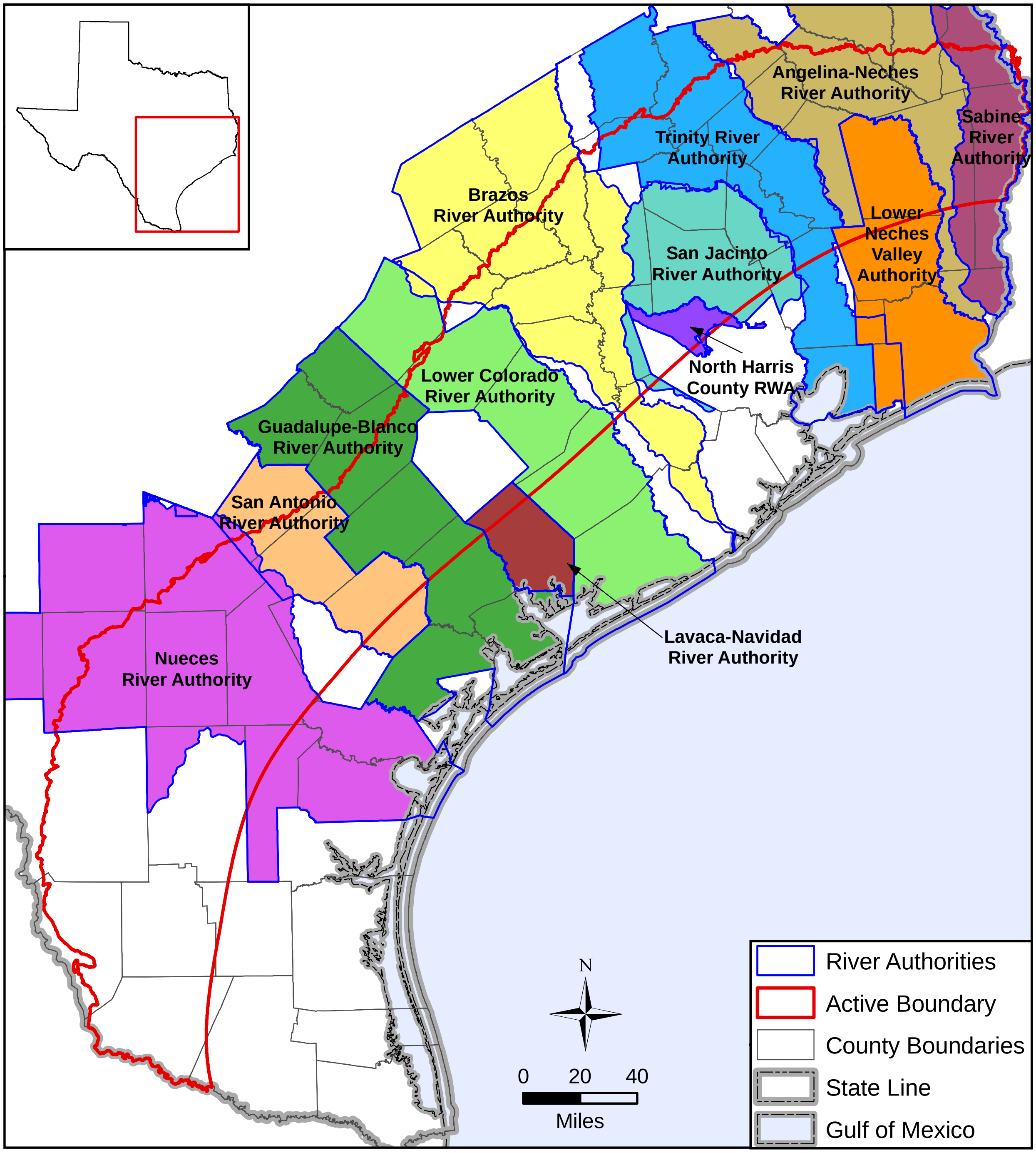


Figure 2.0.10 River Authorities in the study area (TWDB, 2008a).

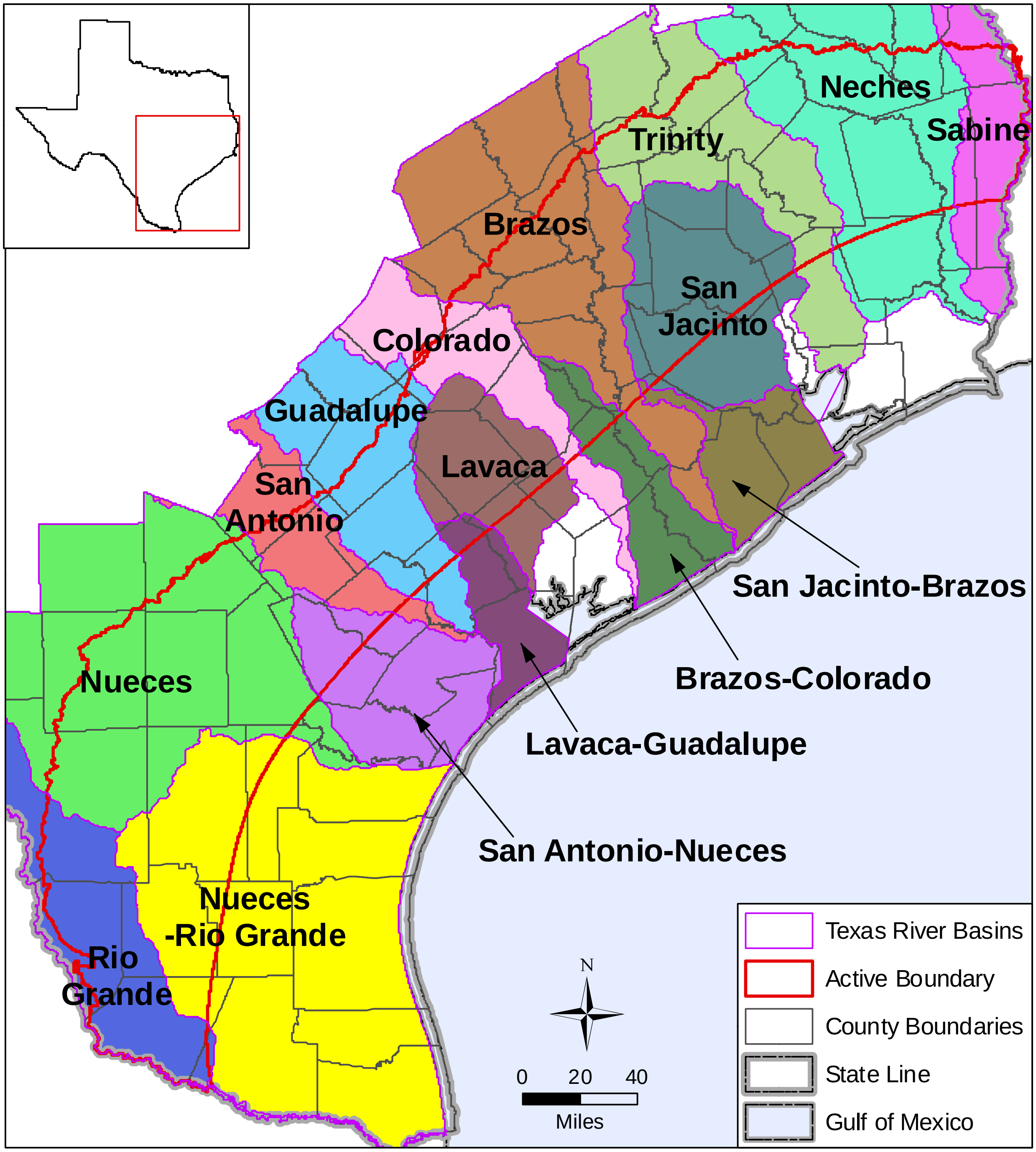


Figure 2.0.11 Major river basins in the study area (TWDB, 2008a).

2.1 Physiography and Climate

The study area is located in the Interior Coastal Plains subprovince of the Gulf Coastal Plains physiographic province (Wermund, 1996). Figure 2.1.1 shows the physiographic provinces in the study area. The Gulf Coastal Plains physiographic province of Texas is subdivided into the Coastal Prairies, the Interior Coastal Plains, and the Blackland Prairies (lies to the northwest and is not shown in the figure). The Coastal Prairies subprovince is generally south of the study area between the study area and the Gulf of Mexico. The Interior Coastal Plains are comprised of alternating sequences of unconsolidated sands and clays. The Yegua-Jackson Aquifer outcrop lies completely in the Interior Coastal Plains. The sands tend to be more resistant to erosion than the clay rich soils and, as a result, the province is characterized as having sand ridges paralleling the coast.

Figure 2.1.2 provides a topographic map of the study area. Generally, the surface elevation decreases from northwest to southeast towards the Gulf across the study area. The largest local contrast in topography occurs in Webb County, where a ridge in the southeastern portion of the county occurs at approximately 900 feet, ranging down to 300 feet at the lower elevations. The drainage features of the major rivers can be clearly seen in the topography in much of the study area, although the variation decreases as the terrain flattens near the surface expression of the downdip boundary.

The climate in the study area is classified as Subtropical (or Modified Marine climate) (Figure 2.1.3). Onshore flow of air from the Gulf of Mexico causes the marine climate. Distinctions in the climate occur based on the moisture content of the maritime air. Air from the Gulf decreases in moisture content from east to west as it travels across the state. Intrusion of continental air into the maritime air occurs seasonally and also affects the moisture content of the air (Larkin and Bomar, 1983). In the study area, the Subtropical classification is subdivided based on this moisture content. The subdivisions Humid (the northeastern and central area), Subhumid (southwestern area) and Steppe (southernmost area) are applied. Subtropical Humid climate is most noted for warm summers; Subtropical Subhumid climate is characterized by hot summers and dry winters; Subtropical Steppe climate is typified by semi-arid to arid conditions. The average annual temperature in the study area ranges from a high of 76 degrees Fahrenheit in the south to a low of 64 degrees Fahrenheit in the north based on the period from 1971 to 2000 (Figure 2.1.4).

The Parameter-elevation Regressions on Independent Slopes Model (PRISM) precipitation dataset developed and presented online by the Oregon Climate Service at Oregon State University provides a distribution of average annual precipitation across the study area based on the period from 1971 to 2000 (Figure 2.1.5). Generally, the average annual precipitation decreases from the northeast to the southwest and from a high of 62 inches at the northeastern boundary to a low of 20 inches in the southwest.

Precipitation data are available at over 168 Texas stations within the study area (Figure 2.1.6) from as early as 1899 through the present. Measurement of precipitation at most gages began in the 1940s. In general, measurements are not continuous on a month-by-month or year-by-year basis for the gages. Examples of the historical variation in precipitation at a few selected gages are shown in Figure 2.1.7. Figure 2.1.8 shows long-term average monthly variation in precipitation at selected gages. Precipitation peaks in late spring to early summer, and again in early fall.

Average annual lake evaporation in the study area ranges from a high of 66 inches per year to a low of 44 inches per year (TWDB, 2009), as shown in Figure 2.1.9. The evaporation rates in the southwestern region of the study area significantly exceed the average annual rainfall, with deficits (when the evaporation exceeds precipitation) approaching 45 inches per year. In the northeast portion of the study area, evaporation rates are approximately similar or slightly less than average annual rainfall rates. Monthly variations in lake surface evaporation are shown in Figure 2.1.10 for six locations in the study area. These values represent the average of the monthly lake surface evaporation data from January 1954 through December 2004.
Figure 2.1.10 shows that average lake evaporation peaks in July.

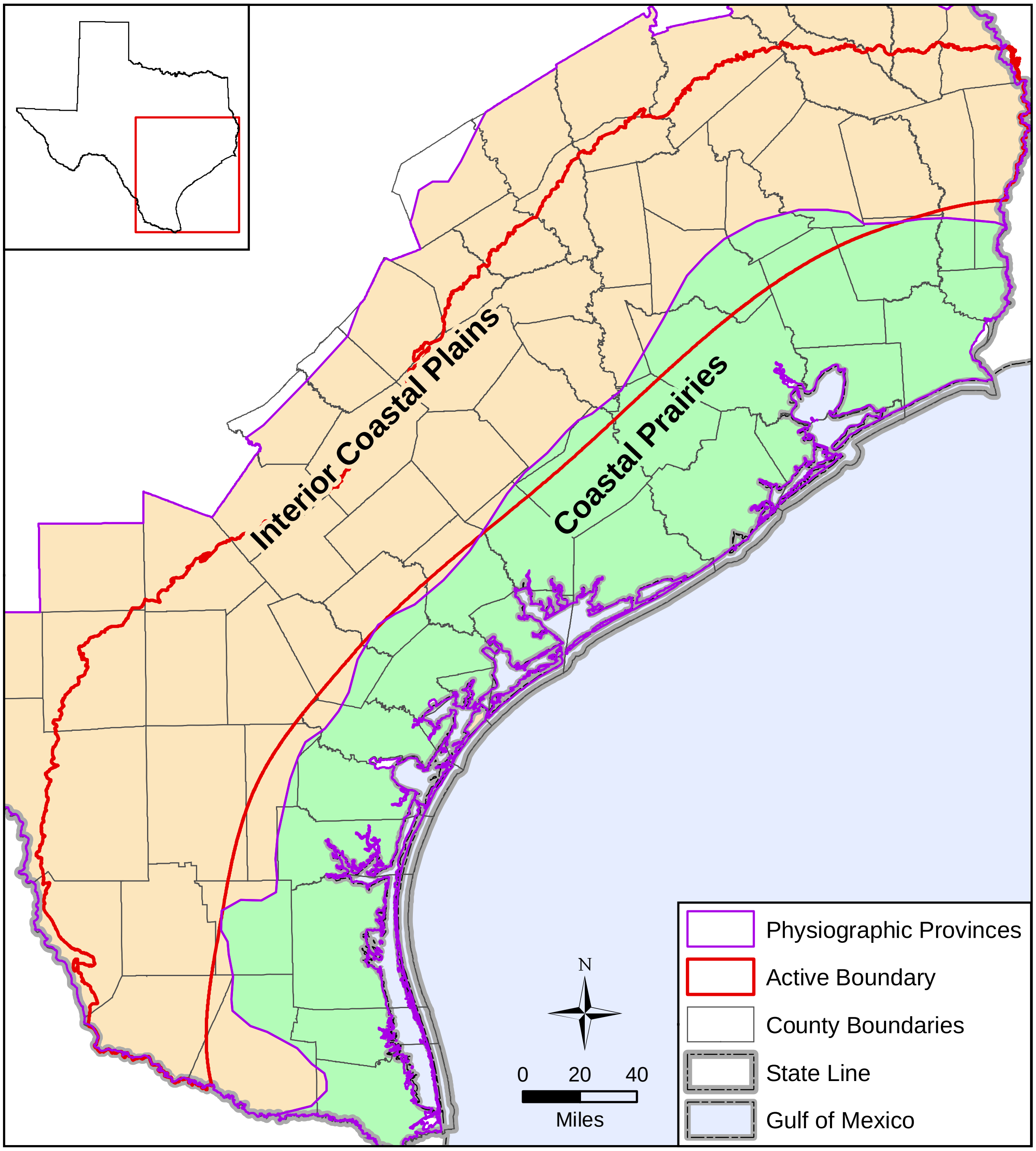


Figure 2.1.1 Physiographic provinces in the study area (modified from Bureau of Economic Geology, 1996b).

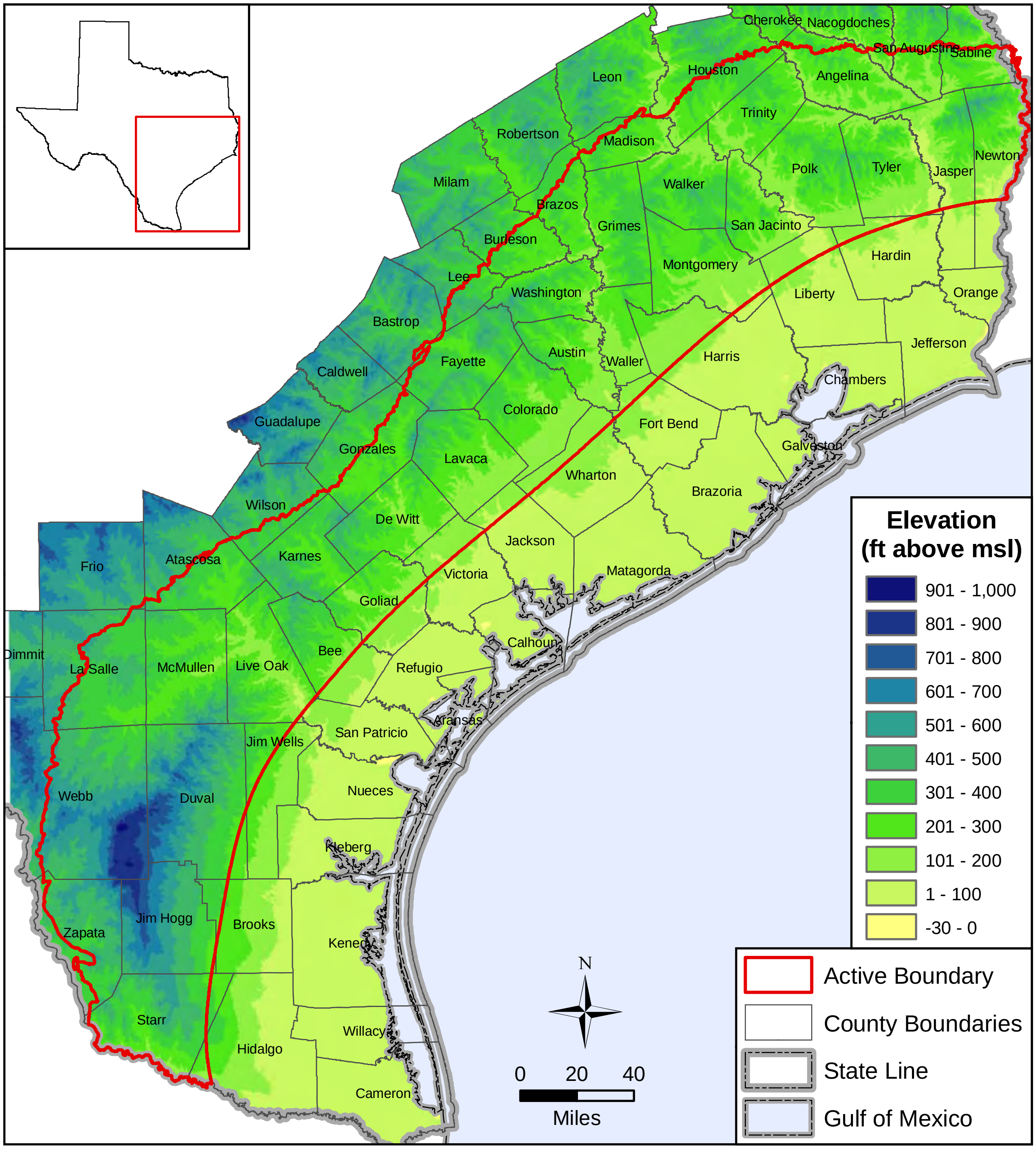


Figure 2.1.2 Topographic map (in feet above mean sea level) for the study area (USGS, 2007).

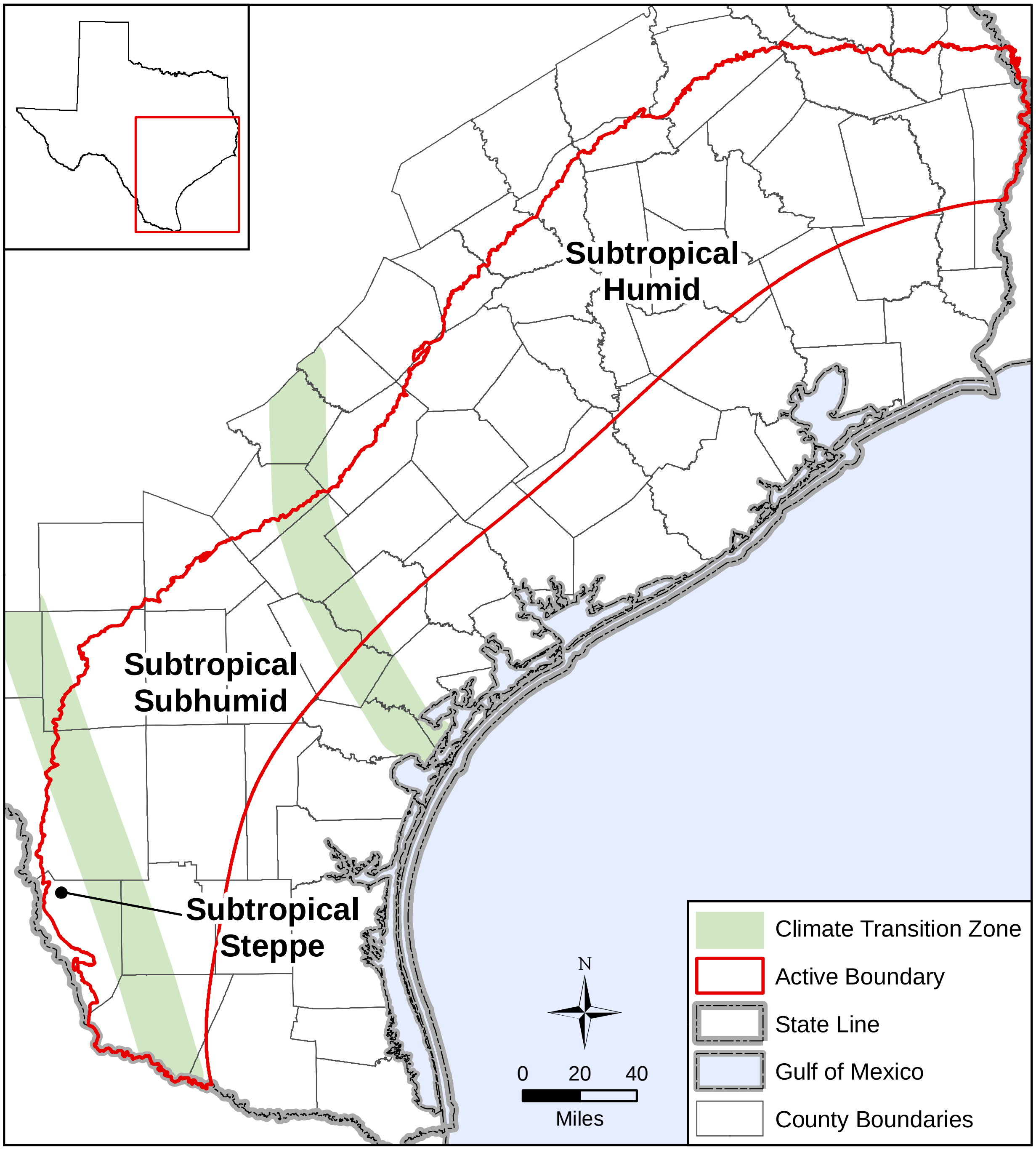


Figure 2.1.3 Climate classifications of the study area (modified from Larkin and Bomar, 1983).

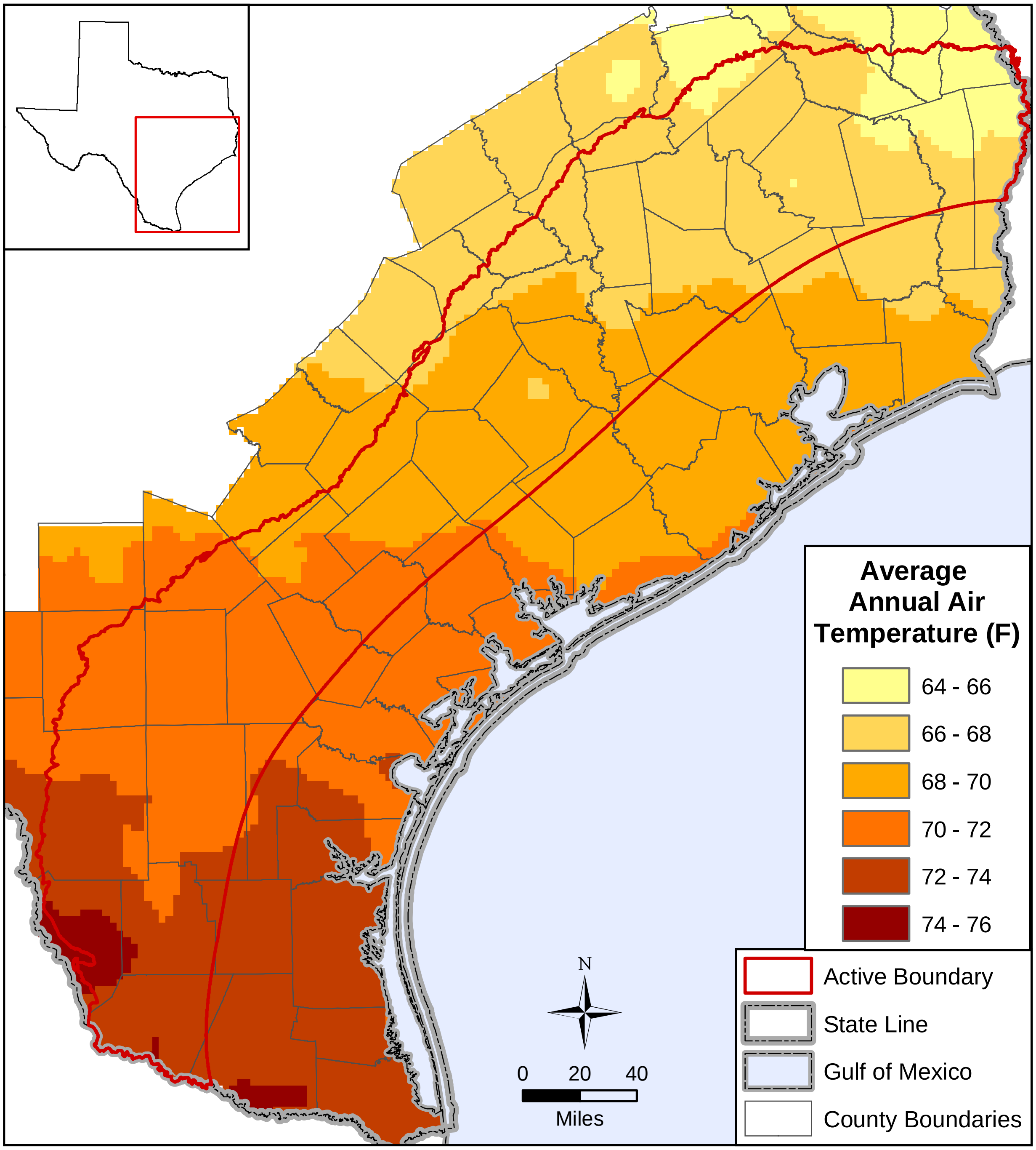


Figure 2.1.4 **Average annual air temperature (in degrees Fahrenheit) of the study area for the time period 1971 to 2000 (modified from Narasimhan and others, 2005).**

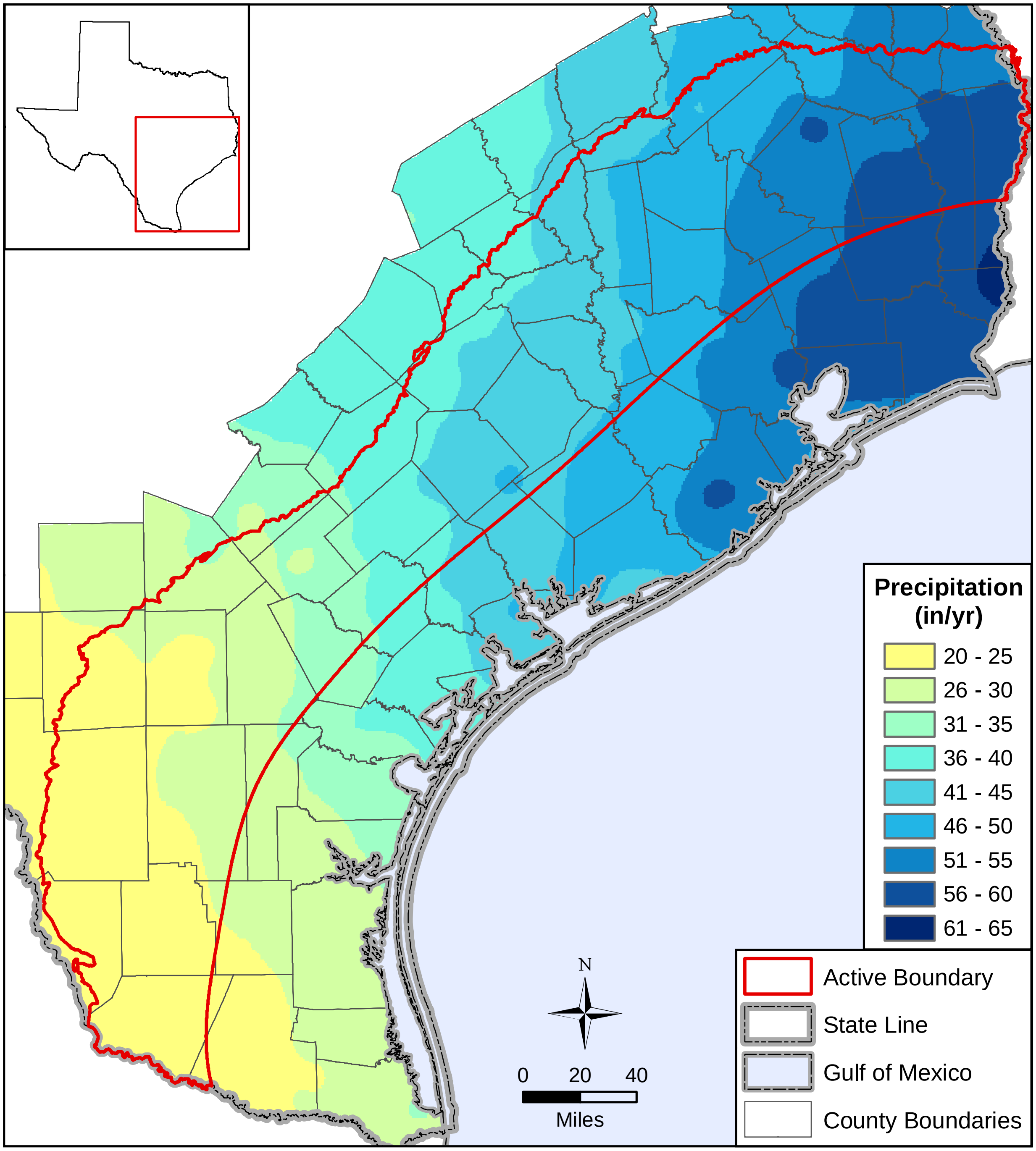


Figure 2.1.5 Average annual precipitation (in inches per year) over the study area for the time period 1971 to 2001 (Oregon Climate Service, Oregon State University, 2008).

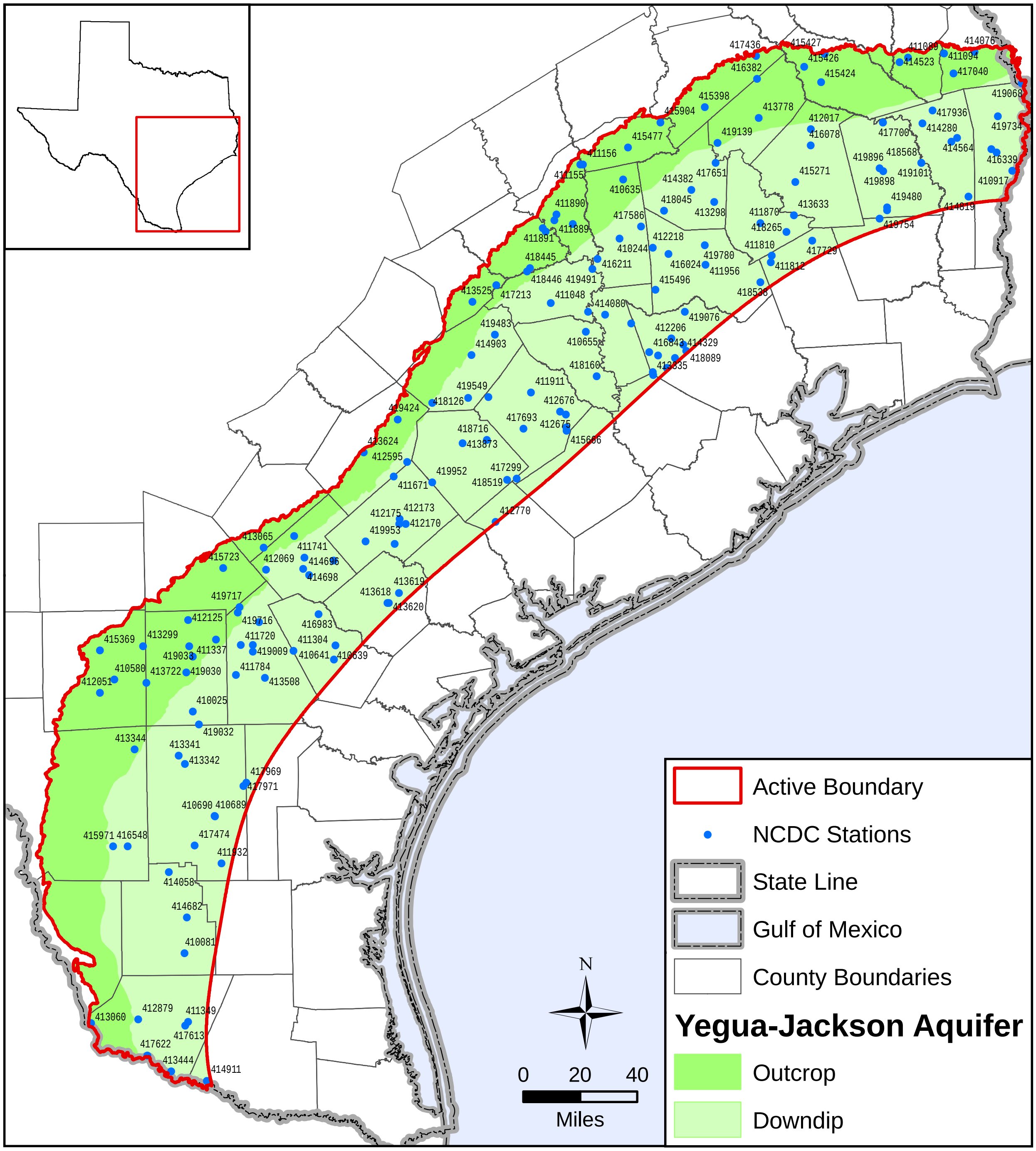


Figure 2.1.6 Location of precipitation gages in the study area (National Climate Data Center, 2008).

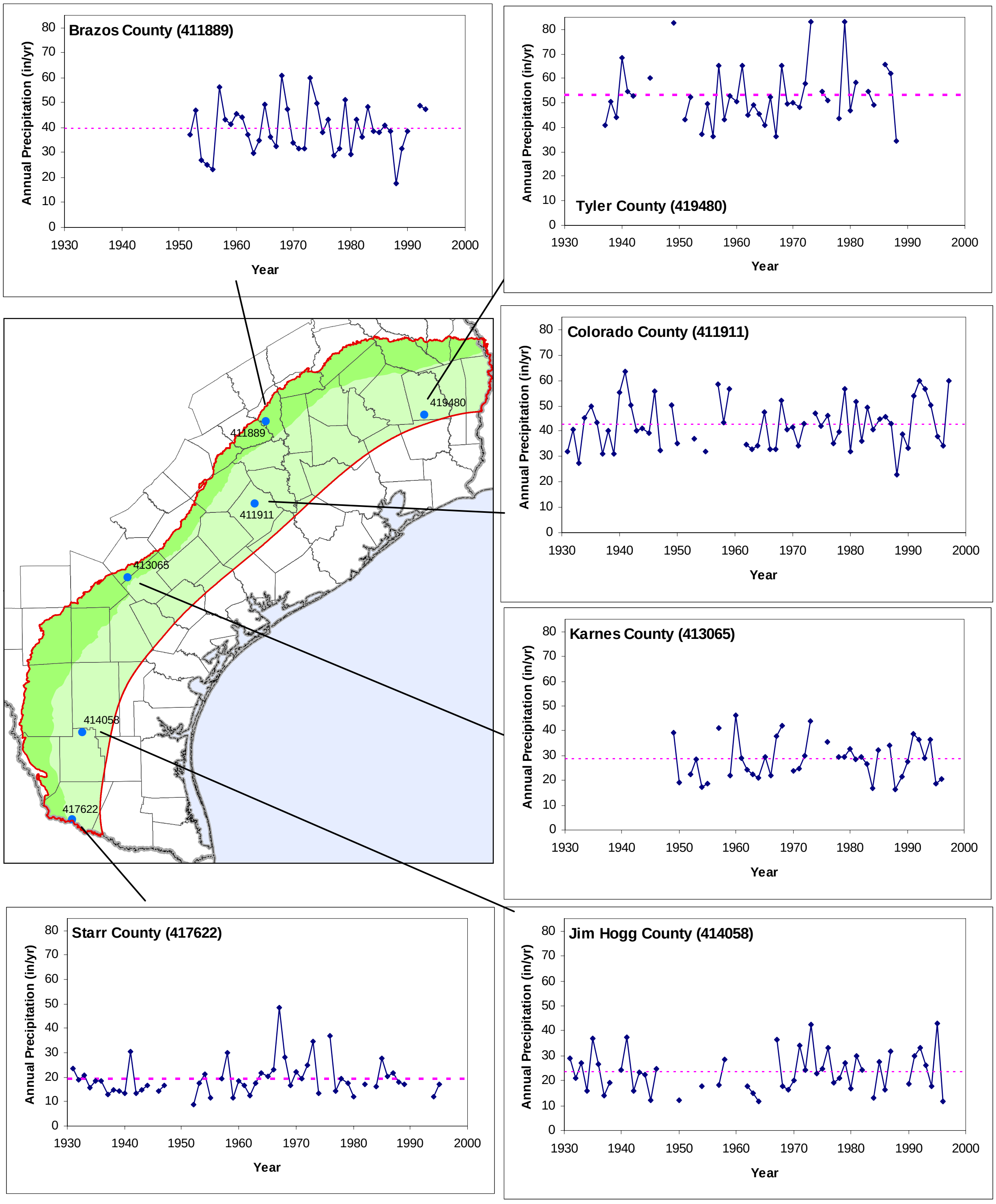


Figure 2.1.7 Selected time series of annual precipitation (in inches per year) in the study area. A discontinuous line indicates a break in the data. The dashed red line represents the mean annual precipitation.

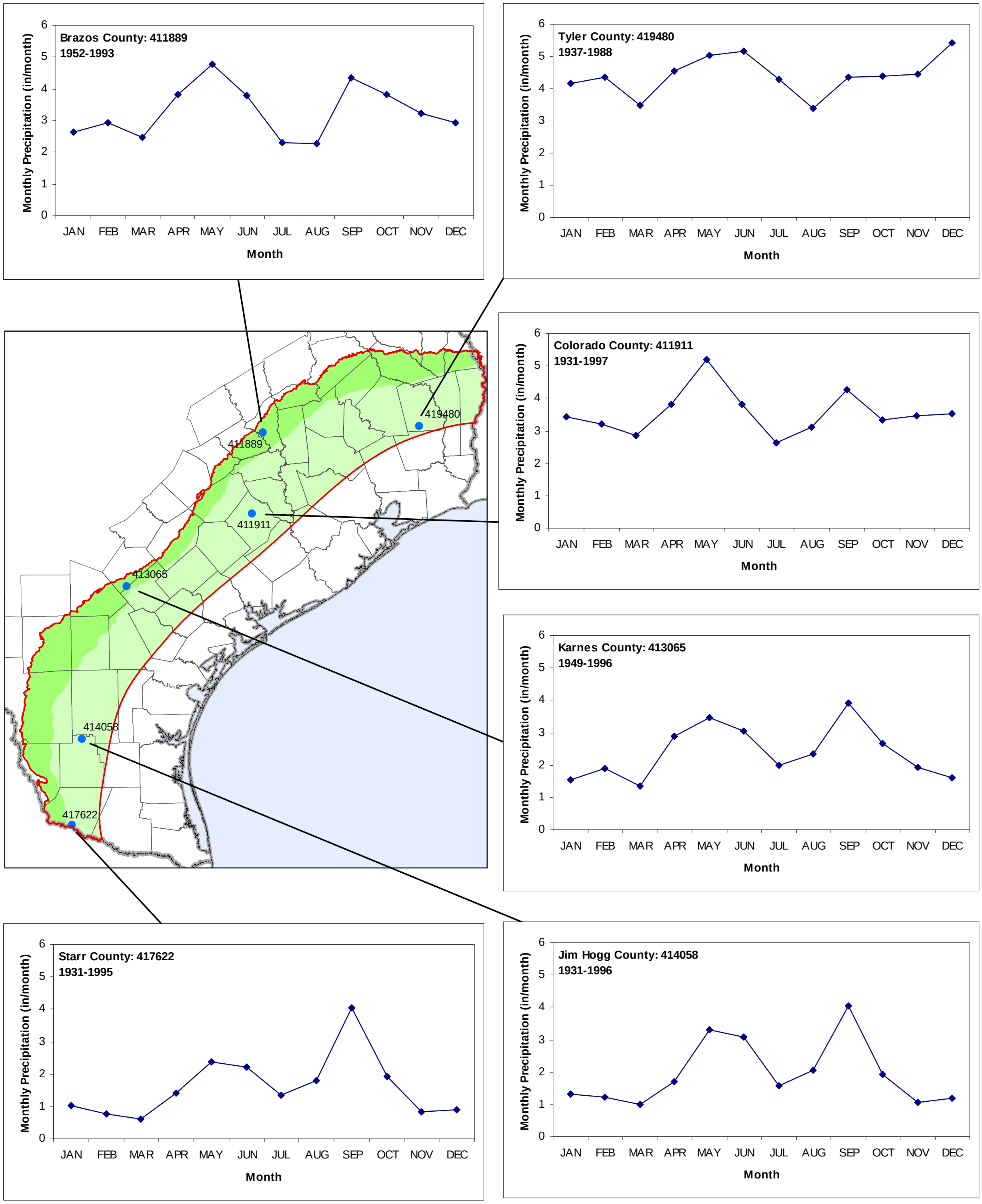


Figure 2.1.8 Selected time series of monthly precipitation (in inches per month) in the study area.

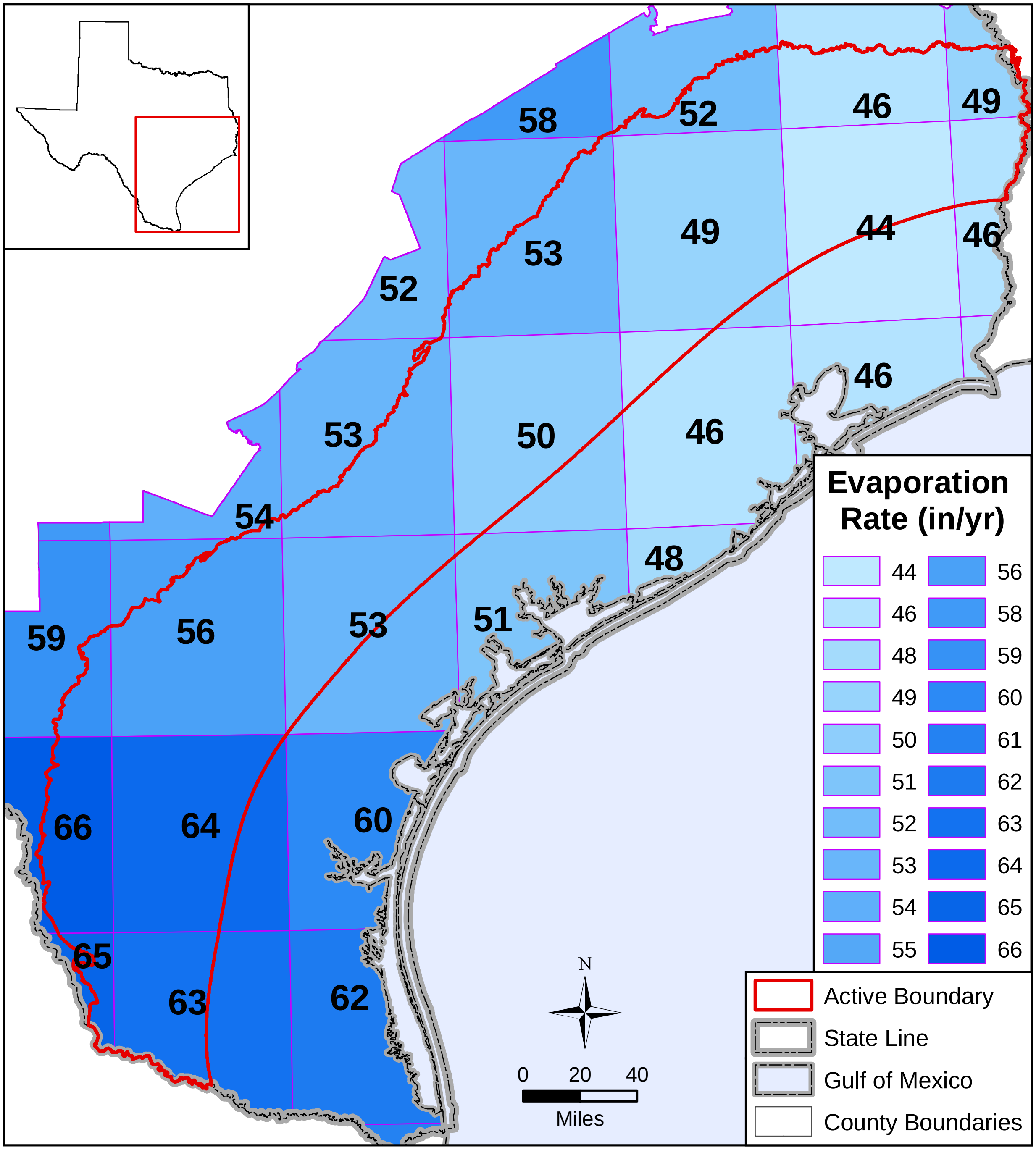


Figure 2.1.9 Average annual lake evaporation rate (in inches per year) over the study area (TWDB, 2009a).

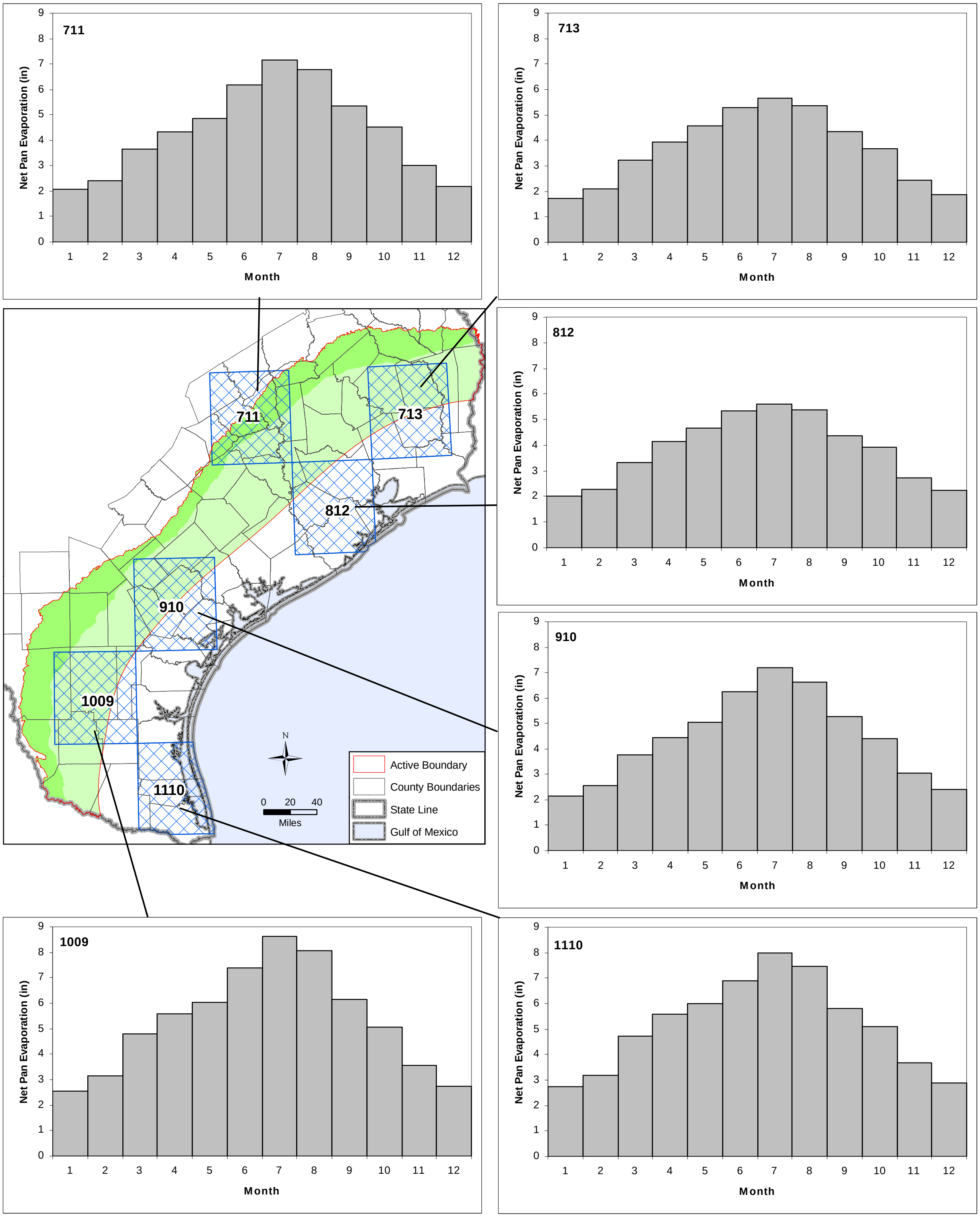


Figure 2.1.10 Average monthly lake evaporation rates (in inches) at selected locations in the study area (TWDB, 2009a).

2.2 Geology

The alternating sand- and clay-rich Yegua-Jackson Aquifer interval includes the Middle Eocene Upper Claiborne Group (Yegua and Cook Mountain formations) and the overlying Upper Eocene to Oligocene Jackson Group (Caddell, Wellborn, Manning, and Whitsett formations). These units dip toward the modern coastline and were deposited as part of the progressive filling of the Gulf of Mexico basin by sand, silt, and clay carried from the mountains of northern Mexico and the Rocky Mountains, as well as from other areas of Texas and the western part of the North American continental interior. These sediments, deposited in rivers and deltas, and even farther offshore, create a gradual down-warping (subsidence) of the Earth's crust along the edges of the basin. Thus, sediments of the Yegua-Jackson Aquifer interval dip more steeply toward the gulf than the current land surface. Additionally, because sediment deposition has outpaced the slow subsidence, the current shoreline has built farther toward the center of the Gulf of Mexico than the position of the shoreline that existed during Yegua-Jackson Aquifer deposition.

The following discussion of the major structural features in and near the study area (Figure 2.2.1) was taken from Knox and others (2007). Yegua-Jackson Aquifer deposition was focused in the Houston and Rio Grande Embayments, where downwarping of the crust by tectonic forces was greatest. The northwest-southeast trending San Marcos Arch represents a long-standing tectonically uplifted area in Central Texas and acts to separate the Houston and Rio Grande Embayments. To the west and south of the Yegua-Jackson Aquifer outcrop lay the Del Rio Fold Belt and the Picachos Arch, which are associated with tectonic compression in northeastern Mexico, possibly before, during, and after Yegua-Jackson Aquifer deposition. During the early phases of the development of the Gulf of Mexico basin, salt was deposited in layers because the basin was small and lacked good circulation with the open ocean. As a result, evaporation exceeded water influx over many millions of years. Salt was generally deposited south and east of the Balcones escarpment trend and areas of especially thick salt accumulation occurred in the Rio Grande and Houston Embayments. Basinward sliding of this salt layer may have localized affects on Yegua-Jackson Aquifer deposition and post-deposition structure. A less obvious tectonic feature that might slightly impact Yegua-Jackson Aquifer structure is a series of northwest-trending transfer faults, which are strike-slip faults in basement rocks beneath the

Tertiary sediments, that are known from offshore Texas that were initiated during the opening of the Gulf of Mexico. These transfer faults appear to have influenced salt tectonics in the Gulf of Mexico (Huh and others, 1996) and may have had minor lateral movement throughout the Tertiary.

A geologic map of the Yegua-Jackson Aquifer interval is provided in Figure 2.2.2a,b. The Yegua-Jackson Aquifer exists predominantly in the outcrop or near-outcrop areas of the Yegua Formation and Jackson Group. In Texas, this outcrop area stretches in a relatively thin band approximately parallel to the coastline, from Starr County in the Rio Grande Valley to Sabine County in East Texas, and is thus bracketed by the Rio Grande to the south, and the Toledo Bend Reservoir (along the Sabine River) to the east. The width of this outcrop varies from less than 10 miles in Gonzales County to nearly 40 miles in La Salle County, with an area of approximately 11,000 square miles.

Figure 2.2.3 provides a generalized stratigraphic section of the Yegua-Jackson Aquifer. The Yegua Formation overlies the Cook Mountain Formation and is uppermost in the Middle Eocene Upper Claiborne Group. This group is overlain by the Upper Eocene to Oligocene Jackson Group, as shown in Figure 2.2.3. In Texas, the Jackson Group consists of the Whitsett, Manning, Wellborn, and Caddell formations (or their analogues). The Yegua-Jackson Aquifer interval continues across the Sabine River into Louisiana, where the Yegua Formation is called the Cockfield Formation, and the Jackson Group is undifferentiated.

The Yegua-Jackson Aquifer interval is overlain in outcrop by an interval variously mapped as the Catahoula Formation and Frio Formation (Figure 2.2.2a,b). This interval varies laterally from clay-rich to locally sand-rich and, in South Texas, contains tuff and volcaniclastic conglomerates. Over much of the aquifer area and in the subsurface, this interval includes the Oligocene-age Vicksburg and overlying Frio formations, which reflect later pulses of sandy sediment influx into the Gulf of Mexico basin. In East Texas, Anders (1967) states that it is not possible to separate the overlying Vicksburg sediments. Thus, in eastern counties, the Vicksburg is mapped with the Jackson (Figure 2.2.2a).

Below the Yegua-Jackson Aquifer interval in outcrop is a generally shaly interval mapped as the Cook Mountain Formation of the upper Claiborne Group or as the Laredo Formation (Barnes, 1992). In the subsurface, the study interval is underlain by the shale-rich Cook Mountain Formation and, beneath that, the sand-rich Sparta Formation of the Lower Claiborne Group. The Cook Mountain Formation thins in the updip direction, almost pinching out before reaching outcrop in some locations.

The thickness of the total Yegua-Jackson Aquifer interval ranges from less than 1,800 feet over the San Marcos Arch in Central Texas to more than 3,000 feet in the Houston and Rio Grande depositional basins of east and south Texas, respectively. Structural dips vary from about 20 to 360 feet per mile (Preston, 2006), with the greater dips generally occurring in the downdip regions and across the San Marcos Arch. The Yegua-Jackson Aquifer tends to be limited to the outcrop or shallow subcrop based upon potable water quality standards (Preston, 2006). However, the geologic formations comprising this aquifer extend to significant depths with some freshwater sands occurring within the aquifer subcrop (Knox and others, 2007). Figure 2.2.4 shows a generalized dip-oriented structural cross-section of the Yegua-Jackson Aquifer in east Texas within the Houston Embayment (after Knox and others, 2007). In general, the dip and the thickness of the Yegua Formation and Jackson Group increase with depth and towards the basin. Figure 2.2.5 shows a generalized dip-oriented structural cross-section of the Yegua-Jackson Aquifer in south-central Texas in the vicinity of the San Marcos Arch. Dips are steep in this region through a depth of approximately 3,000 feet below sea level where a general flattening dip occurs (after Knox and others, 2007). Thickening of the geologic section parallel to strike, which is apparent in each cross-section, is indicative of deposition occurring as the basin was subsiding.

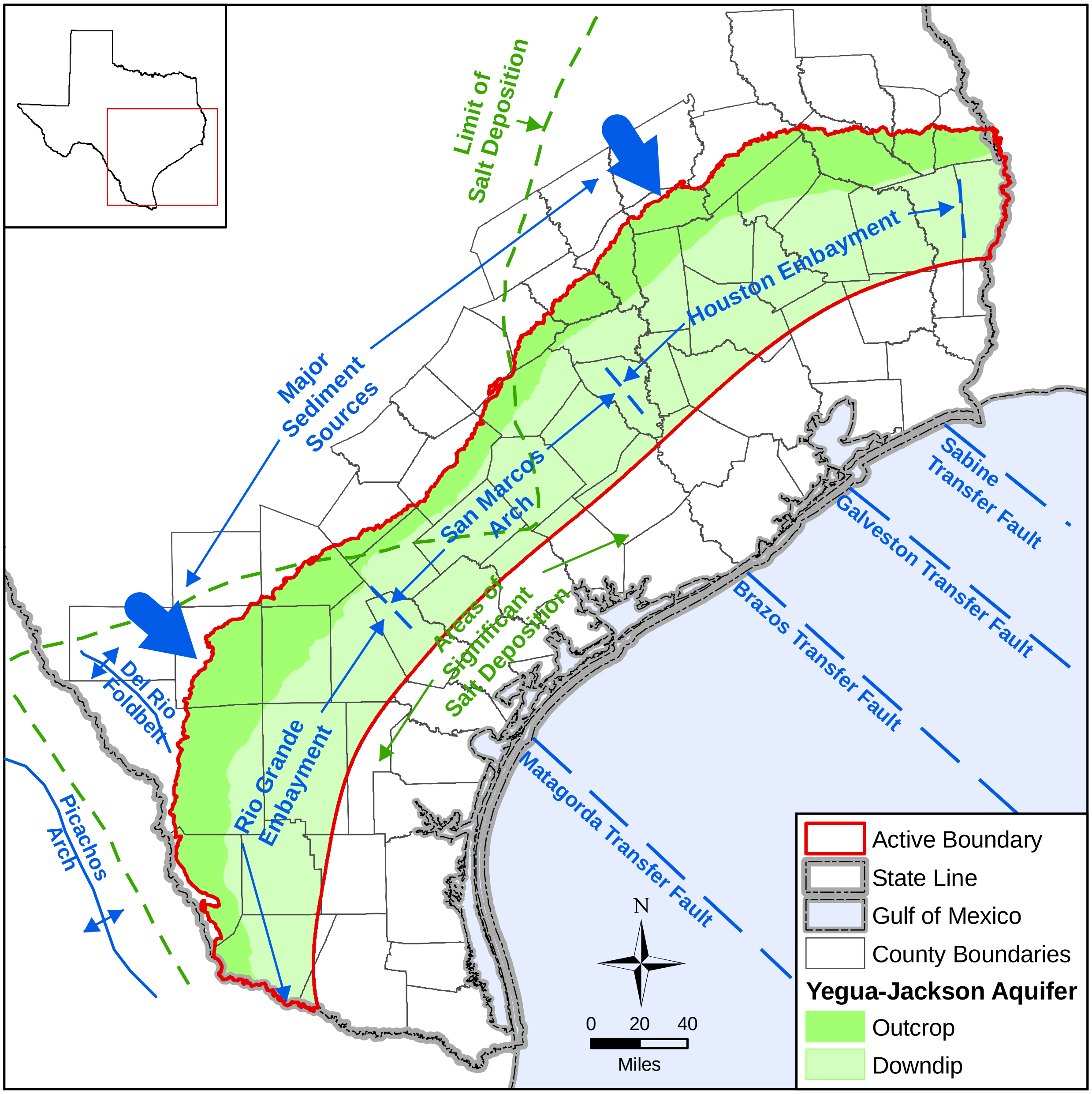


Figure 2.2.1 Major structural features in and near the study area (from Knox and others, 2007).

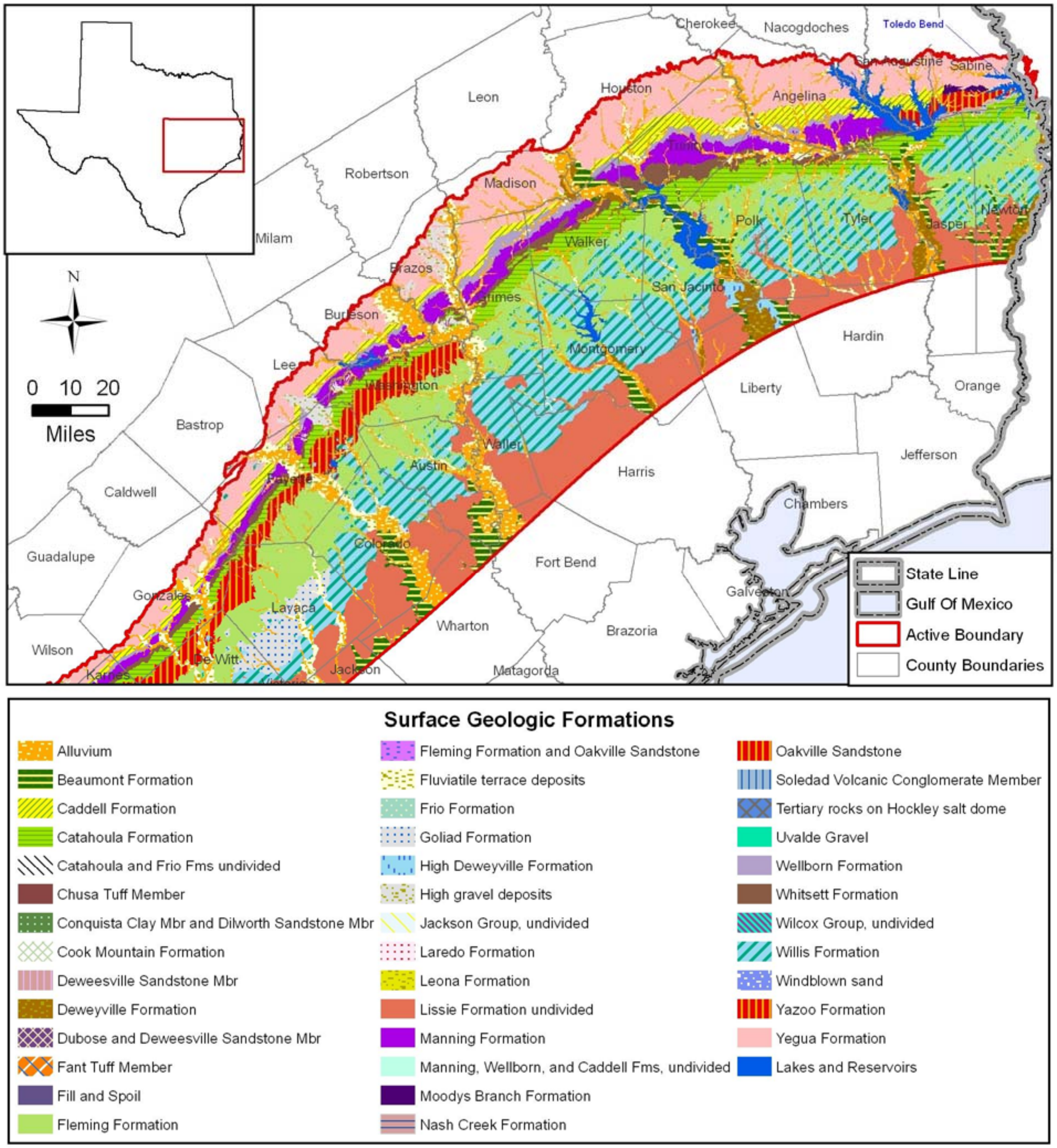


Figure 2.2.2.a Surface geology of the northern portion of the study area (modified from Barnes, all years).

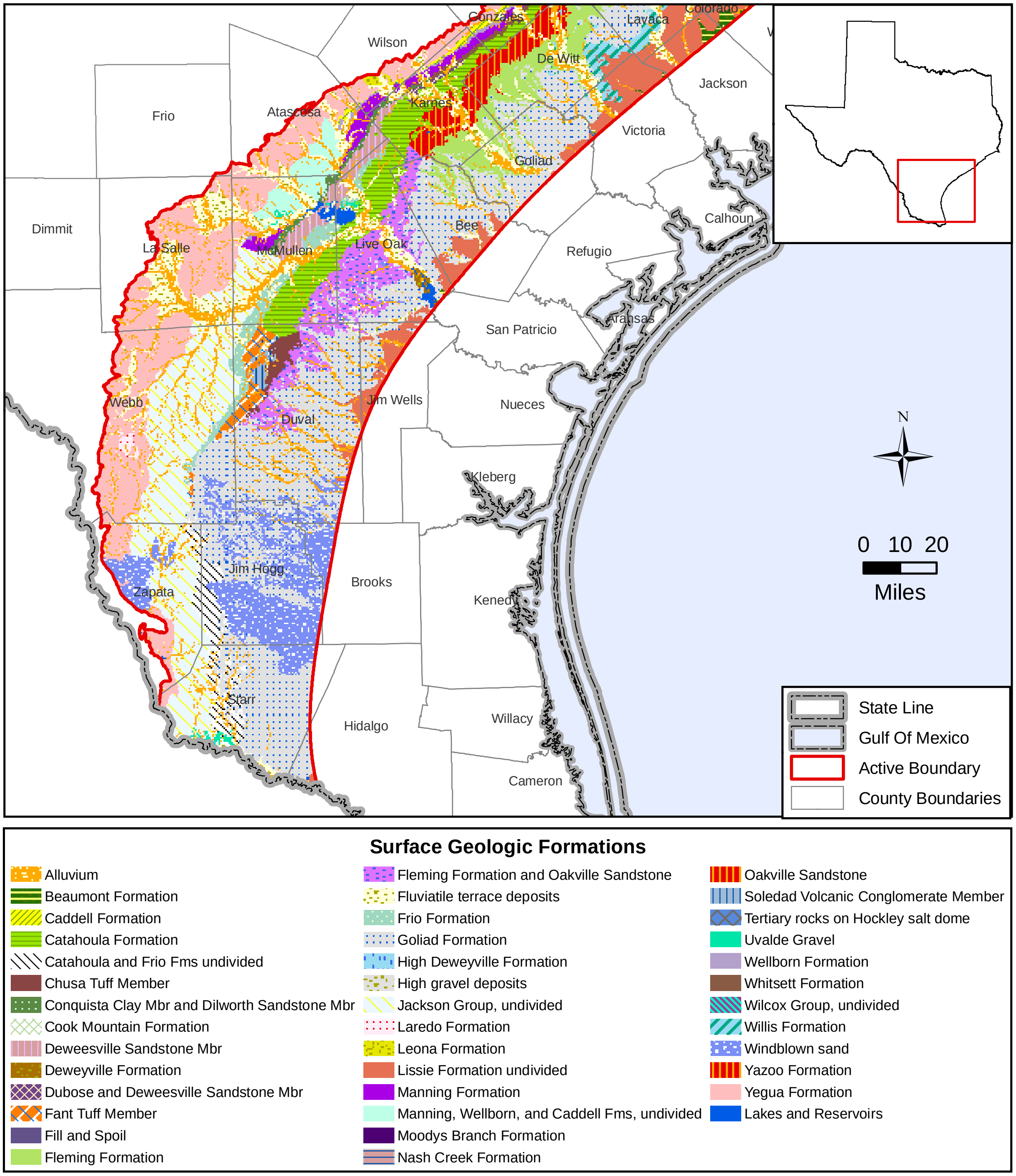


Figure 2.2.2.b Surface geology of the southern portion of the study area (modified from Barnes, all years).

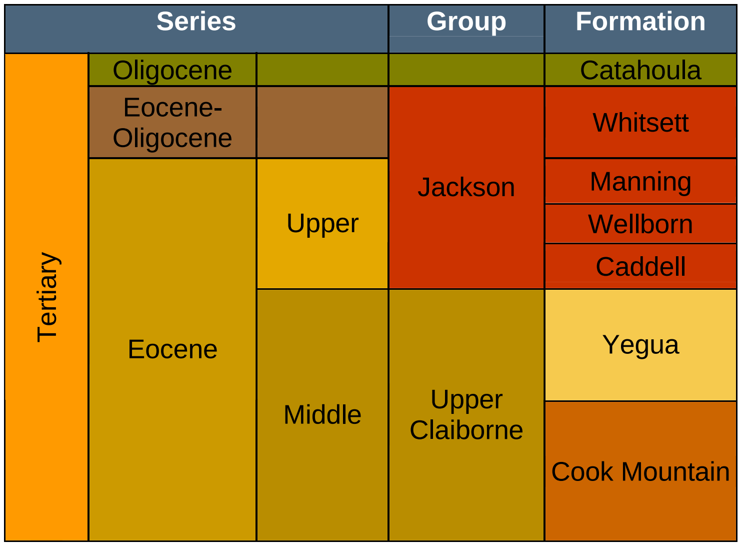


Figure 2.2.3 Generalized stratigraphic section of the Jackson and Upper Claiborne groups in Texas (after Preston, 2006; Knox and others, 2007).

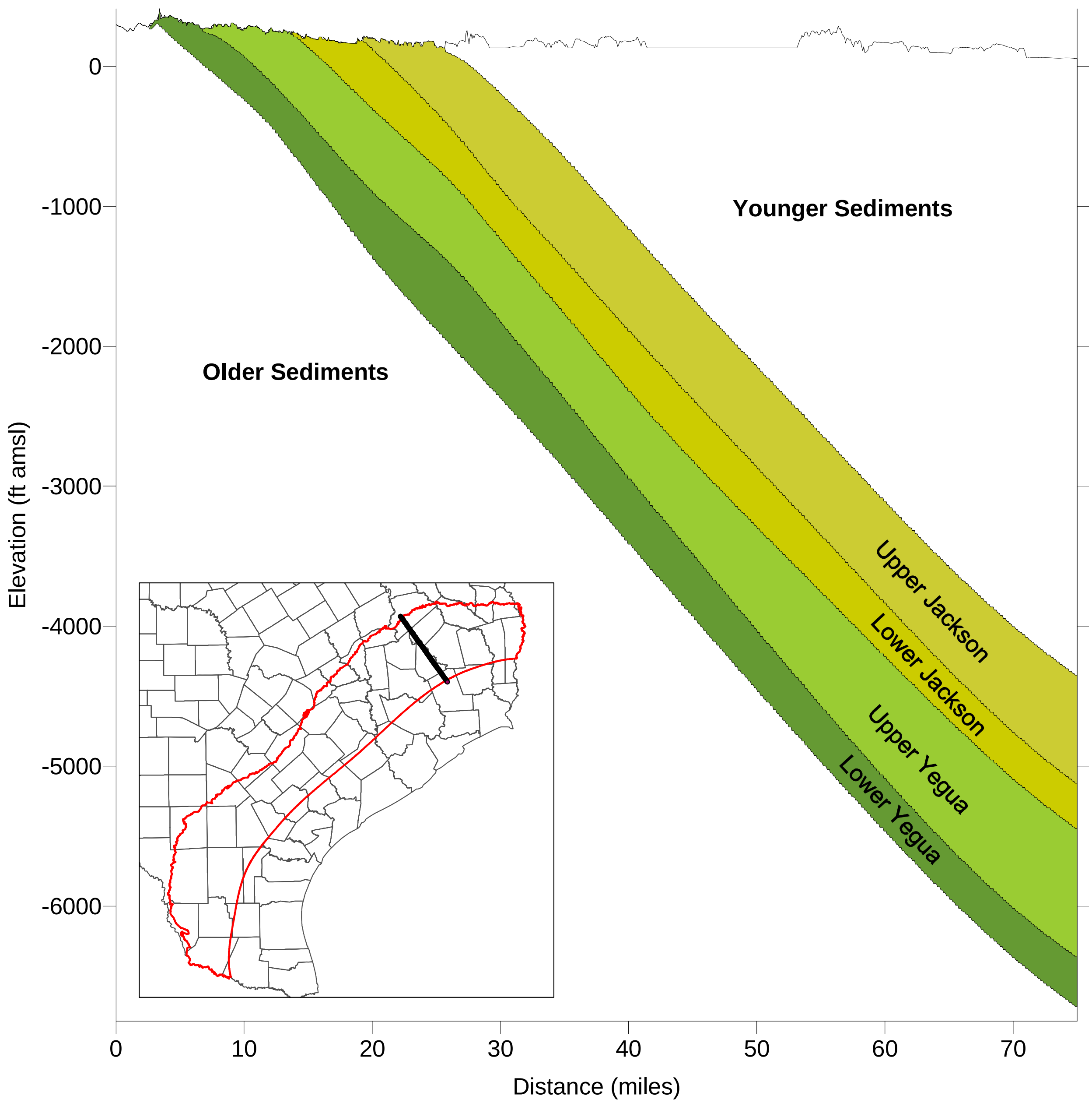


Figure 2.2.4 Generalized structural cross-section in east Texas near the center of the Houston Embayment (after Knox and others, 2007).

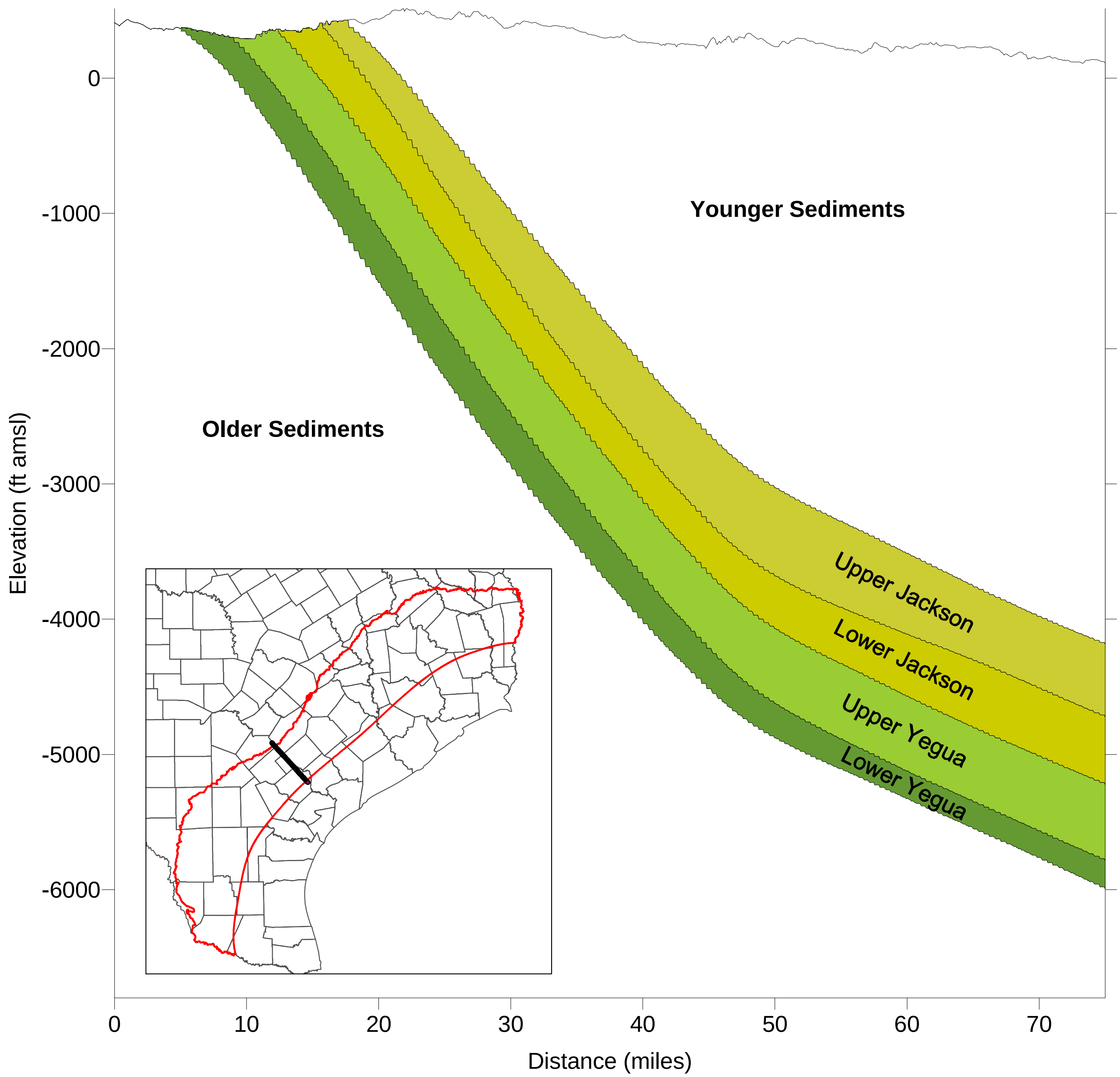


Figure 2.2.5 **Generalized structural cross-section in south-central Texas over the San Marcos Arch (after Knox and others, 2007).**

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3.0 Previous Investigations

An abundant body of previous work exists for the Yegua-Jackson Aquifer interval because of its extensive resources of oil, gas, coal, and uranium. Geologic investigations extend from initial and broad stratigraphic investigations in the 19th century to modern-day detailed subsurface structural, chronostratigraphic, micropaleontologic, and depositional analyses. An extensive review of previous geologic work was completed as part of the TWDB-sponsored study that produced the Yegua-Jackson Aquifer structure (Knox and others, 2007). Rather than repeating this review of the previous geologic investigations, the reader is directed to Section 3 of that document. The Yegua-Jackson Aquifer structure was developed specifically to support the development of the Yegua-Jackson Aquifer groundwater availability model, documented herein.

Early outcrop geology and stratigraphy for the Yegua Formation and Jackson Group was established by Renick (1926, 1936) and by Sellards and others (1932). The economic importance of oil, gas, coal, and uranium resources spurred investigations from the early 1960's through about 1990 (Fisher, 1963; Fisher and others, 1970; Eargle, 1972; Quick and others, 1977; Galloway and others, 1979; Kaiser and others, 1980; Jackson and Garner, 1982; Ewing, 1986; and Galloway and others, 1991). These works established, on the basis of outcrop and subsurface detailed investigations, the general structure, stratigraphy, depositional systems, and lithologic distribution of the Yegua Formation and Jackson Group.

Also during this period, the United States Geological Survey and the TWDB carried out joint studies of the water resources of the Yegua-Jackson Aquifer in many counties, especially those in the southeast Texas part of the aquifer (Winslow, 1950; Dale, 1952; Anders and Baker, 1961; Thompson, 1966; Rogers, 1967; Wesselman, 1967; Tarver, 1968 a,b; Guyton and Associates, 1970; Baker and others, 1974). These subsurface studies added knowledge regarding the distribution of fresh and slightly saline water in the aquifer and groundwater geochemistry.

Yegua-Jackson Aquifer outcrop distribution was identified and compiled by the Bureau of Economic Geology, The University of Texas at Austin, at a 1:250,000 scale during the 1970's, 1980's, and 1990's under the direction of Virgil Barnes (Barnes, 1974a, 1974b, 1976a, 1976b, 1976c, 1992). The Yegua and Cook Mountain/Laredo formations were mapped across the state.

Over a large area of outcrop belt, the main formations of the Jackson Group (Caddell, Wellborn, Manning, and Whitsett) were mapped individually, including some local unit names such as the Yazoo shale and the Nash Draw sand.

Studies from the early 1990's to present have been prompted by the discovery of the downdip Yegua Formation oil and gas trend and have employed the technologies of sequence stratigraphy, three dimensional seismic, and organic geochemistry (Sneider, 1992; Goings and Smosna, 1994; Ewing, 1994; Yuliantoro, 1995; Meckel and Galloway, 1996; Swenson, 1997; Ewing and Vincent, 1997; Thomas, 1999; Routh and others, 1999; Galloway and others, 2000; and Fang, 2000). These works have produced a refined chronostratigraphic understanding of the Yegua-Jackson Aquifer interval that stands in some contrast to the lithostratigraphic-dominated understanding evident in outcrop mapping and in studies from the 1960's, 1970's, and 1980's.

From a hydrogeologic perspective, there has been very little work done in the Yegua-Jackson Aquifer, especially studies at a scale larger than an individual county (Preston, 2006). Anders (1967) has some estimates of the transmissivity of the Yegua Formation in eastern Texas. Payne (1970) studied the Yegua Formation in Texas (and the corresponding Cockfield Formation of Louisiana and Mississippi). He provided some generic conceptual information about the hydrogeology of the Yegua Formation as a whole. However, due to lack of data in Texas, he produced hydrogeologic interpretations only for Louisiana and Mississippi. Beyond these two larger scale studies, county-scale reports provide the most information about the Yegua-Jackson Aquifer. The available county reports are listed in Table 3.0.1. In the current study, the county reports were used extensively when conceptualizing recharge-discharge, developing the pre-1980 pumping datasets, and analyzing water quality.

There have been several groundwater models in the region that have included the Yegua Formation or Jackson Group, although none of the models placed more than secondary emphasis on them. The earliest models were super-regional models developed by the United States Geological Survey as part of their national Regional Aquifer System Analysis Project. These studies included aquifers from the Midway Formation through the Gulf Coast Aquifer system. In all cases, the stratigraphic conceptualization was similar. The Jackson Group was lumped with the Vicksburg Formation as the Vicksburg-Jackson confining unit. Confining units were not considered to have horizontal flow and, thus, the Jackson Group was not actually modeled as an aquifer. The lower portion of the Yegua Formation was modeled as part of the Upper-Claiborne Aquifer.

Ryder (1988) and Ryder and Ardis (1991) modeled the system from the southwest in Texas to the border between Texas and Arkansas, as shown in Figure 3.0.1 The research code developed by Kuiper (1985) was used to develop the models. Ryder (1988) documented a steady-state calibration of the predevelopment conditions. Ryder (1988) reported that the model objectives were to define the hydrogeologic framework and hydraulic characteristics of the Texas coastal plain aquifer systems, delineate the extent of freshwater and density of saline water in the various hydrogeologic units, and describe the regional groundwater flow system. Ryder and Ardis (1991) extended the work performed by Ryder (1988) and created another model of the coastal plain aquifers in Texas, again using the research code developed by Kuiper (1985). The model was calibrated to both steady-state, predevelopment conditions and transient conditions from 1910 to 1982. In addition, transient predictive simulations were performed using the calibrated model.

Williamson and others (1990) and Williamson and Grubb (2001) contained a larger active area that also included portions of Arkansas, Louisiana, Mississippi, Alabama, Tennessee, Kentucky, and Illinois, as shown in Figure 3.0.1. Similar to Ryder (1988), they used the research code developed by Kuiper (1985) as the basis for the models. The Williamson and others (1990) model consisted of a steady-state calibration to predevelopment conditions, a steady-state calibration to 1980 water-level data, and transient simulations from 1935 to 1980. The model objectives were "to help in the development of quantitative appraisals of the major ground-water systems of the United States, and to analyze and develop an understanding of the ground-water flow system on a regional scale, and to develop predictive capabilities that will contribute to effective management of the system". Williamson and Grubb (2001) extended the earlier efforts and included modeling of density dependent flow to better characterize effects of salinity on groundwater movement in the aquifers..

In 1998, LBG-Guyton Associates and HDR Engineering, Inc. developed a groundwater model with a focus on the interaction between surface water and groundwater in the Wintergarden area

(LBG-Guyton & HDR, 1998). The model was an extension of the Klemt and others (1976) Carrizo model and modeled from the base of the Wilcox through the Yegua Formation. The Yegua Formation was lumped together with the Weches, Sparta, and Cook Mountain formations to form the “younger units” in the model. This combination makes extraction of meaningful results for the Yegua Formation impossible.

Table 3.0.1 Summary of county reports for the study area.

County	Report Number	Citation
Angelina	TWDB, R110	W.F. Guyton & Associates (1970)
Atascosa	USGS, WSP676	Lonsdale (1935)
	USGS, WSP1079-C	Sundstrom and Follett (1950)
	TWDB, R32	Alexander and White (1966)
Bastrop	TWDB, R109	Follett (1970)
Brazos	TWDB, R185	Follett (1974)
Burleson	TWDB, R185	Follett (1974)
Duval	TWDB, R181	Shafer (1974)
	USGS, WSP776	Sayre (1937)
Fayette	TWDB, R56	Rogers(1967)
Frio	USGS, WSP676	Lonsdale (1935)
	TWDB, R32	Alexander and White (1966)
Gonzales	TWDB, R4	Shafer (1965)
Grimes	TWDB, R186	Baker and others (1974)
Houston	TWDB, R18	Tarver (1966)
Jasper	TWDB, R59	Wesselman (1967)
Karnes	TWDB, B6007	Anders (1960)
La Salle	TWDB, B6520	Harris (1965)
Lavaca	TWDB, R270	Loskot and others (1982)
Lee	TWDB, R20	Thompson (1966)
Leon	TWDB, B6513	Peckham (1965)
Live Oak	TWDB, B6105	Anders and Baker (1961)
McMullen	TWDB, B6520	Harris (1965)
Nacogdoches	TWDB, R110	W.F. Guyton & Associates (1970)
	TWDB, R327	Preston and Moore (1991)
Newton	TWDB, R59	Wesselman (1967)
Polk	TWDB, R82	Tarver (1968a)
Sabine	TWDB, R37	Anders (1967)
San Augustine	TWDB, R37	Anders (1967)
Starr	TWDB, B5209	Dale (1952)
Tyler	TWDB, R74	Tarver (1968b)
Walker	TWDB, B5003	Winslow (1950)
Washington	TWDB, R162	Sandeen (1972)
Webb	TWDB, LP209	Adidas (1991)
	USGS, WSP778	Lonsdale and Day (1937)
Wilson	TWDB, B5710	Anders (1957)

USGS = United States Geological Survey
R = Report
WSP = Water Supply Paper
B = Bulletin
LP = Limited Publication

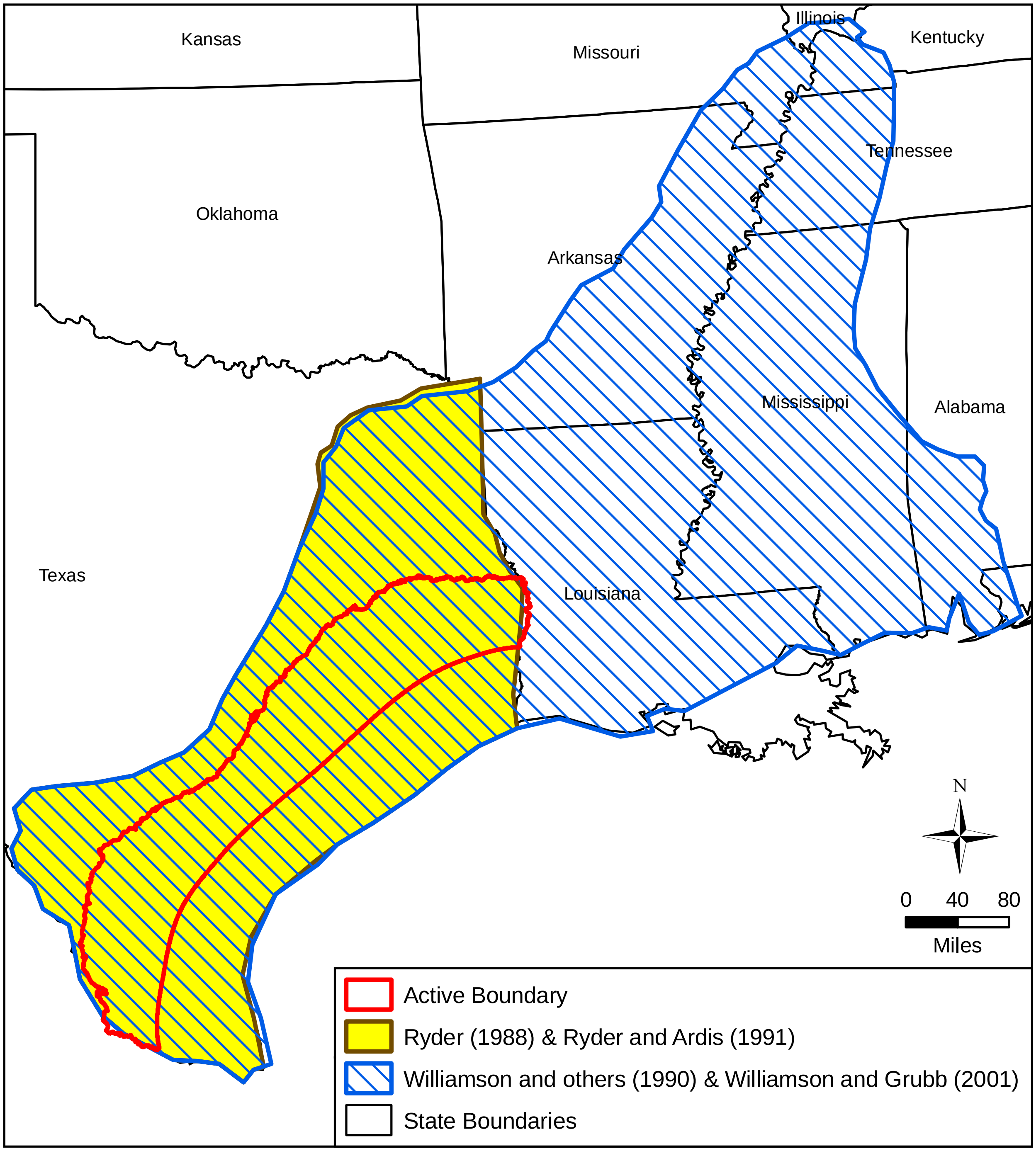

Figure 3.0.1 Location of boundaries for previous modeling studies.

4.0 Hydrogeologic Setting

This section details the data compilation and analyses used to support development of the conceptual model for the Yegua-Jackson Aquifer. This information, in total, is referred to as the hydrogeologic setting and includes a discussion of the hydrostratigraphy, structure, water levels, recharge, surface water-aquifer interaction, discharge, hydraulic properties, and water quality of the aquifer.

4.1 Lithology and Hydrostratigraphy

Groundwater occurs within the Yegua Formation and the formations comprising the Jackson Group (Preston, 2006). Preston (2006) reports that the majority of the potable groundwater within the Yegua-Jackson Aquifer occurs, as might be expected, within the sand units of the aquifer. The productivity of these sands is related to their depositional environments with the more significant amounts of water occurring within areas of more extensive fluvial channel sands and thick deltaic sands. Therefore, the more productive portions of the aquifer are found within the ancestral fluvial trends of the ancestral rivers such as the Trinity, Colorado, and Brazos (Jackson and Garner, 1982). Therefore, to understand the significant hydrostratigraphy and the occurrence of potable groundwater within the aquifer requires an understanding of the lithology of the formations comprising the aquifer and how they vary geographically.

The lithology of geologic units comprising the Yegua-Jackson Aquifer can be generalized as interbedded sand, silt, and clay. The following lithologic descriptions of geologic units of interest were synthesized from the Geologic Atlas of Texas (Barnes, 1968a, 1968b, 1974a, 1974b, 1974c, 1975, 1976a, 1976b, and 1976c) and county resource reports from the United States Geological Survey and TWDB (in order from eastern counties to southern counties: Anders, 1967; Guyton and Associates, 1970; Tarver, 1966; Baker and others, 1974; Follett, 1974; Thompson, 1966; Rogers, 1967; Anders, 1957; Anders and Baker, 1961; and Harris, 1965).

Sediments of the Upper Claiborne Group (see Figure 2.2.3) include the Cook Mountain and Yegua formations. The Cook Mountain Formation is a shale-dominated interval between the often sand-dominated Sparta and Yegua formations. In parts of east Texas, the Cook Mountain Formation contains the Spiller Sand (Tarver, 1966; Follet, 1974; and Thompson, 1966), which is a fine- to medium-grain-sized lignitic crossbedded argillaceous sandstone up to 100 feet thick containing interbeds of chocolate-brown clay. In south Texas, time-equivalent sediments are mapped as the Laredo Formation (Barnes, 1976b and 1976c). Sandstone is abundant in the Laredo Formation, with thick, glauconitic, micaceous, ferruginous, crossbedded very-fine- to fine-grained sandstone beds predominating. Interbedded brown shales contain marine megafossils and limestone concretions.

The Yegua Formation is described as a gray to brown sandstone and dark brown to gray shale with minor interbedded lignites. The sandstones are fine- to medium-grained and variously contain bentonite, carbonaceous debris, fossil wood, glauconite, gypsum/selenite, and calcareous cement. Sandstone beds may form low hills which, in some areas, are discontinuous (Anders, 1967; Follet, 1974; and Thompson, 1966), and in some areas can be traced for many miles (Anders, 1967). In the outcrop, the base of the Yegua Formation is identified as the first significant sand above the Cook Mountain Formation (Tarver, 1966) or as the stratigraphically lowest location where sandstone predominates over shale (Thompson, 1966). The Yegua Formation varies from 400 feet to over 1,000 feet in thickness at the outcrop, being thinnest in east Texas.

Sediments of the Jackson Group include, from oldest to youngest, the Caddell, Wellborn, Manning, and Whitsett formations (see Figure 2.2.3). These units are mapped separately in east and central Texas but grouped as one unit in south Texas (Barnes, 1992). Additionally, formation names vary locally and some units are further divided. In east Texas, the Caddell Formation laterally transitions eastward to the Moody’s Branch Formation, the eastward equivalent of a combined Wellborn and Manning formations is the Yazoo Formation, and the Whitsett Formation transitions to the Nash Creek Formation to the east (Barnes, 1968b). In southern-central Texas, from southern Wilson County to central Duval County (Geologic Atlas of Texas Sheets Seguin, Crystal City-Eagle Pass, and Beeville-Bay City), the Whitsett Formation is divided into an upper unit, containing the Dubose Member above and the Deweesville Sandstone Member below, and a lower unit containing the Conquista Clay Member above the

Dilworth Sandstone Member below. The lateral equivalents of the Jackson Group are shown in Figure 4.1.1.

In general terms, the Jackson Group is described as a variously sand- or clay-dominated succession, with sand content being greatest in south Texas. It contains some lignites, marine fossils, glauconite, and marl beds. It is often bentonitic, with ash and tuff content appearing to increase from east Texas to south Texas. Total Jackson Group thickness varies from a low of 310 feet in east Texas to a maximum of 875 feet in south-central Texas, thinning again to 360 feet in south Texas (Barnes, 1968a, 1968b, 1974a, 1974b, 1974c, 1975, 1976a, 1976b, and 1976c).

Where individual members are described, the Caddell Formation is a clay or siltstone with sandstone (Barnes, 1968a, 1968b, 1974a, 1974b, and 1974c). The laterally equivalent Moody's Branch of east Texas is a glauconitic marl with abundant marine fossils. The Caddell Formation is generally approximately 50 to 150 feet thick.

The Wellborn Formation is a very fine- to coarse-grained sandstone and minor clay, with sand grain size being greatest in south Texas. It is lignitic, containing fossil leaf and wood pieces, can be glauconitic, and contains marine megafossils. It can be massive to crossbedded and variably bentonitic or tuffaceous, locally being silica-cemented and forming resistive ridges. The Wellborn Formation is generally 150 feet thick, but thins to less than 50 feet in east Texas.

The Manning Formation is generally described as a chocolate brown lignitic clay with lesser sandstone, bentonite, and tuff. However, in east Texas sandstone predominates (Barnes, 1968a, and 1968b). Clays are bentonitic to lignitic, with some thin beds of marine megafossils. Sandstones are laminated to massive to crossbedded, lignitic, and bentonitic to tuffaceous. Sandstones are light yellow-gray, forming resistant ridges. In east Texas, the Yazoo Formation is laterally equivalent to both the Wellborn and Manning formations and is a sandy clay with interbeds of silt and glauconitic sand containing marine megafossils. The Manning Formation is 250 to 350 feet thick, but thins to about 200 feet in east Texas.

The Whitsett Formation is generally described as a fine- to medium-grained sandstone that is tuffaceous, lignitic, argillaceous, and locally silica-cemented. It can be massive or crossbedded, contains abundant fossil wood, and is light to dark gray, weathering to dark gray. The lateral equivalent of the Whitsett Formation in east Texas, the Nash Creek Formation, is a bentonitic brownish to pale greenish gray clay with interbeds of fine-grained light gray sand. In south-central Texas, the Whitsett Formation is divided into four members (Barnes, 1974a, 1974b, 1974c, and 1975). From oldest to youngest, these are the Dilworth Sandstone Member, Conguista Clay Member, Deweesville Sandstone Member, and the Dubose Clay Member. Sandstone members can be massive to crossbedded, tuffaceous, and heavily bored by *Ophiomorpha*. The Whitsett Formation and included members are approximately 200 feet thick in south-central Texas but thin eastward, becoming 60 feet thick or less in far east Texas.

In east Texas, the Oligocene-age Vicksburg Formation overlies the Jackson Group and is not separated from it in mapping (Anders, 1967). The Vicksburg Formation includes a lower unit of fine-to medium-grained sandstone and interbedded silt and clay and an upper unit of clay with interbedded silt and sand. This unit as likely mapped in east Texas as part of the Whitsett Formation, but the Vicksburg Formation thickness is unknown because it cannot be distinguished from the Whitsett Formation.

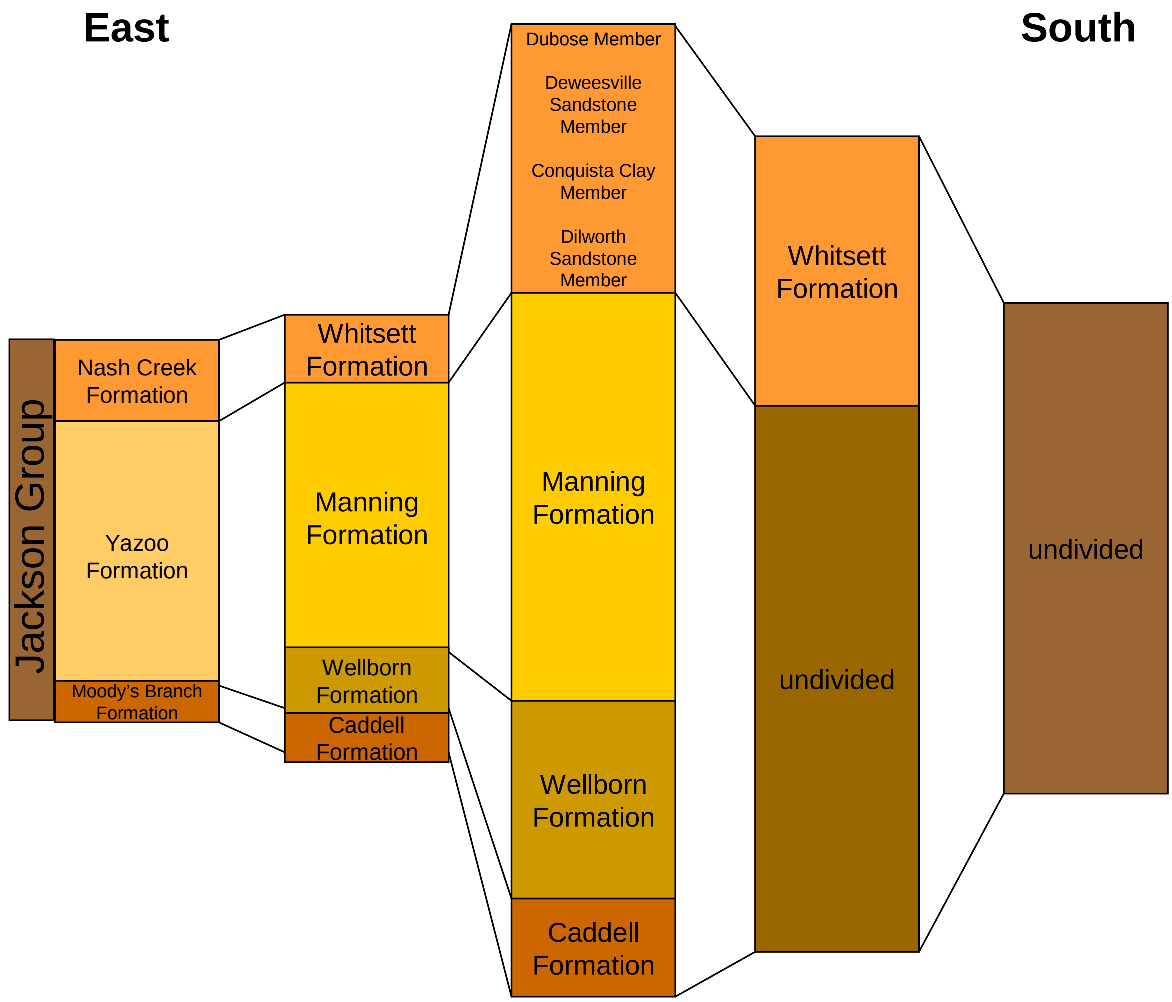

Figure 4.1.1 Lateral equivalents of the Jackson Group.

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4.2 Structure

The discussion of structure begins with a discussion regarding the structural setting. This discussion is followed by a summary of the structure development study funded by the TWDB and completed by Knox and others (2007). In two regions of the State, inconsistencies with surface geological interpretations were encountered in Knox and others (2007). It was recommended in Knox and others (2007) that these inconsistencies be resolved prior to model development. As part of the conceptual model development for the Yegua-Jackson Aquifer, these issues were revisited and a discussion of the findings are provided within this section. Finally, this section provides the Yegua-Jackson Aquifer structure surfaces, net sand maps, and maps of the dominant depositional environment present during deposition for each of the units.

4.2.1 Structural Setting

The alternating sand- and clay-rich Yegua-Jackson Aquifer intervals dip toward the modern coastline and are part of the progressive filling of the Gulf of Mexico basin by sand, silt, and clay carried from the mountains of northern Mexico and the Rocky Mountains, as well as from other areas of Texas and the western part of the North American continental interior. These sediments, deposited in rivers and deltas, and even farther offshore, create a gradual down-warping (subsidence) of the Earth's crust along the edges of the basin. Thus, sediments of the Yegua-Jackson Aquifer interval dip more steeply toward the gulf than the current land surface. Additionally, because sediment deposition has outpaced the slow subsidence, the current shoreline has built farther toward the center of the Gulf of Mexico than the position of the shoreline that existed during Yegua-Jackson Aquifer deposition.

Yegua-Jackson Aquifer deposition was focused in the Houston and Rio Grande Embayments (see Figure 2.2.1), where downwarping of the crust by tectonic forces was greatest. The northwest-southeast trending San Marcos Arch (see Figure 2.2.1) represents a long-standing tectonically uplifted area in central Texas and acts to separate the Houston and Rio Grande embayments. To the west and south of the Yegua-Jackson Aquifer outcrop lie the Del Rio and Picachos foldbelts (see Figure 2.2.1), which are associated with tectonic compression in northeastern Mexico, possibly before, during, and after Yegua-Jackson Aquifer deposition.

During the early phases of the development of the Gulf of Mexico basin, salt was deposited in layers because the basin was small and did not have good circulation with the open ocean. As a result, evaporation exceeded water influx over many millions of years. Salt was generally deposited south and east of the Balcones Escarpment trend and areas of especially thick salt accumulation occurred in the Rio Grande and Houston embayments (see Figure 2.2.1). Basinward sliding of this salt layer may have localized affects on Yegua-Jackson Aquifer deposition and post-deposition structure. A less obvious tectonic feature that might slightly impact Yegua-Jackson Aquifer structure is a series of northwest-trending transfer faults, which are strike-slip faults in basement rocks beneath the Tertiary sediments, that are known from offshore Texas that were initiated during the opening of the Gulf of Mexico (see Figure 2.2.1). These transfer faults appear to have influenced salt tectonics in the Gulf of Mexico (Huh and others, 1996) and may have had minor lateral movement throughout the Tertiary.

4.2.2 Structure of the Yegua-Jackson Aquifer

The TWDB funded a study to develop the structure for the Yegua-Jackson Aquifer which is documented in Knox and others (2007). The approach used in Knox and others (2007) used a chronostratigraphic framework that was developed for the Yegua-Jackson Aquifer spanning its entire extent in Texas. The use of a chronostratigraphic approach to mapping provides a consistent depositional framework for the geologic intervals comprising the aquifer. The dominant controls on aquifer framework in terms of fluid flow characteristics result from the distribution of sedimentary processes, both geographically and through geologic time. Estimating aquifer framework and heterogeneity on the basis of outcrop and limited subsurface data requires a predictive approach founded on an understanding of the activities that built the aquifer.

Unlike lithostratigraphic correlation, which relies on lithologic changes to subdivide sedimentary intervals, chronostratigraphic correlation relies on recognition of depositional surfaces formed at critical times in a depositional cycle. At these relatively brief periods of time, broad areas of the coast are undergoing similar depositional processes. At sea-level highstand times, deposition of fine-grained deposits (future aquitards) cover a large portion of the sand-rich sediments deposited during the last lowstand (future aquifer). These highstand times are represented by maximum flooding surfaces, and their associated fine-grained deposits are especially useful in defining aquifer framework because they often have a characteristic signature on geophysical logs from wellbores. Thus, these deposits can be traced across a regional extent in the subsurface. The intervals above and below these fine-grained deposits are sand-rich packages deposited under a common set of conditions, including positions of major sediment input. Predictive methods for evaluating the geographic distribution of sand-rich areas within the package can then be applied. These predictive methods are based on observations of modern depositional processes and systems such as rivers and deltas. These methods rely on the commonality of depositional conditions within the time frame of the package, and the location and style of sand-rich deposition will vary from package to package.

The general chronostratigraphic correlation approach used in Knox and others (2007) is based upon the correlation of maximum flooding surfaces within fine-grained highstand deposits as defined in geophysical well logs arranged in dip-oriented cross sections, connecting low-resistivity markers in downdip shale sections with shales or abrupt-based sands in updip sandy and silty intervals.

Correlation was based upon the use of geophysical logs from 250 wells. These wells were used to develop a grid of 30 dip-oriented cross sections and three strike-oriented cross sections for correlation purposes (Figure 4.2.1). Dip sections extend from the Yegua-Jackson Aquifer outcrop area downdip (southeast) more than 50 miles and to depths exceeding 6,000 feet subsea to allow a more complete stratigraphic analysis. Strike sections extend between the Mexico and Louisiana borders. Two sections roughly parallel the outcrop and, depending on their location, show either mostly the Jackson Group interval or mostly the Yegua Formation interval. A third strike section was created from selected wells such that coverage of both intervals was optimized.

Four major chronostratigraphic units (third-order genetic units) were defined for the Yegua-Jackson Aquifer. These include, from the bottom upward, the Lower Yegua, Upper Yegua, Lower Jackson, and Upper Jackson units, which each span one to two million years of deposition (third-order genetic units) and are of appropriate scale for regional groundwater availability modeling (generally 400 to 800 feet thick, thickening in the downdip direction). Each of the four major chronostratigraphic units is bounded above and below by time-synchronous maximum flooding surfaces dominated in the sedimentary record by fine-grained (clay-rich) deposition. Such surfaces and the associated fine-grained sediments impede vertical fluid flow, forming low-flow units (aquitards) within the aquifer. Maximum flooding surfaces also bound laterally contiguous sand-rich sediments, which form high-flow units within the aquifer.

These four aquifer chronostratigraphic units are comprised of 15 or more finer units that are of fourth-order scale, each spanning a period of 100,000 to 400,000 years. These minor sequence stratigraphic units represent finer-scale (fourth-order) genetic units that are also bounded by maximum flooding surfaces. Knox and others (2007) used the four chronostratigraphic units as the basis for defining four operational aquifer layers within the Yegua-Jackson Aquifer; the Lower Yegua Layer, the Upper Yegua Layer, the Lower Jackson Layer, and the Upper Jackson Layer. Of these four aquifer layers, only the Lower Yegua Layer differs from its chronostratigraphic unit equivalent. This is because the base of the chronostratigraphically defined Lower Yegua Unit occurs at or below the lithostratigraphically defined base of the Lower Yegua Unit. Thus, the chronostratigraphic base of the Lower Yegua Unit crops out farther inland (north and west) than the base of the Yegua-Jackson Aquifer. The chronostratigraphic surface represents a maximum flooding surface between the Sparta and Yegua formations depositional cycles and commonly occurs within the shale of the Cook Mountain Formation. To address this issue, the base of the Lower Yegua Layer, which comprises the base of the Yegua-Jackson Aquifer, was defined by Knox and others (2007) to occur at the first significant freshwater sand and was tied to the base in the Yegua Formation outcrop boundary.

Five types of maps were developed and documented in Knox and others (2007) for the four aquifer layers. These are a structure map, an isopach map, a sand thickness map, a sand percent map, and a depositional facies map. These maps provide the necessary framework for future groundwater availability model development.

Revisions to the Structure

The Knox and others (2007) study documented two issues related to the Yegua-Jackson Aquifer structure that were considered unresolved.

- In south Texas, the interval between the chronostratigraphically defined base of the Lower Yegua Unit and the lithostratigraphically defined base of the Yegua-Jackson Aquifer was found to contain significant sands potentially bearing potable water. These sands were excluded from Knox and others (2007). Further analysis has indicated that the exclusion of these sands results in minor differences, so the base of the Yegua-Jackson Aquifer from Knox and others (2007) remained unchanged in the current report.

- Knox and others (2007) provided evidence that the Vicksburg Formation, as mapped by Barnes (1968a, 1968b, 1974a, 1974b, 1974c, 1975, 1976a, 1976b, 1976c, and 1992), was part of the Jackson Group from approximately the Brazos River eastward and mapped as part of the Catahoula Formation and lateral equivalents from the Brazos River southward. In the current study, additional work was completed in an effort to resolve these apparent stratigraphic inconsistencies. The following discussion details these efforts.

The original TWDB Yegua-Jackson Aquifer outcrop boundary is based on Barnes (1992), and is referred to as the Barnes (1992) boundary. A slightly modified boundary was proposed in Knox and others (2007), which is referred to as the Knox and others (2007) boundary. The boundary that is the result of the new analysis in this current study is referred to as the “current boundary”. These three boundaries are illustrated in Figure 4.2.2.

The Barnes (1992) boundaries were based on surface mapping, which can be difficult when surface exposures are poor and where lithologic differences between adjacent units are minimal. Subsurface correlation using well log response can reliably track the same chronostratigraphic (time-equivalent) surface across the entire aquifer area, and can thus group the sediments that fit the regional definition of a given aquifer. The boundary revisions in the current work were primarily based on additional well control that was acquired between the Knox and others (2007) study and the current study. The limitation of the subsurface correlation approach is that it lacks sufficient resolution near the outcrop to draw as detailed an outcrop boundary as can be achieved in careful surface mapping. Many of the boundaries determined by this study from projection of subsurface correlations do not have the complexities of a planar surface interacting with surface topography. Because of this limitation, we explored several techniques beyond subsurface correlation of well log response for refining the coarse location estimates. These techniques were:

1. Comparison of outcrop maps and suspected outcrop boundaries with environmental facies mapped by the Bureau of Economic Geology (Jackson and Garner, 1982);
2. Comparison of the above-mentioned environmental facies with LANDSAT imaging;
3. Analysis of formation dips at outcrop to more accurately constrain projections from the shallowest well control in the subsurface to the land surface; and
4. Qualitative comparison of environmental facies polygons to slope and aspect data from a Digital Elevation Model.

Of these techniques, only the use of environmental facies maps was combined successfully with the results from the new well logs to further refine the boundary locations. The following sections discuss the new well control and the use of environmental facies maps to refine the boundaries for the current study. Although some of the other techniques listed above showed promise, their results were not used in the final product, and a detailed discussion is beyond the scope of the current work.

Additional Well Control

A total of 42 new wells were added in the two areas where the aquifer boundary was in question. The areas include an eastern area stretching from Washington County eastward to the Louisiana border (Figure 4.2.3) and a southern area stretching from Starr County to McMullen County (Figure 4.2.4). The addition of these wells increased subsurface control along the aquifer boundary and more accurately constrained the outcrop position of the stratigraphic boundary mapped in the subsurface. The positions of the wells range from downdip of the boundary, across the boundary, to areas as far north of the boundary as the outcrop of the base of the Jackson Group. Because it was sometimes difficult to find available logs in a timely fashion, some compromises were made between ideal well locations and log availability.

Using the new well data, the outcrop location of the aquifer boundary was estimated by:

1. assuming a constant dip between the last well to encounter the boundary in the subsurface and the next-nearest well updip, regardless of the orientation between wells with respect to strike and dip (method is proportional to well distance, irrespective of true or apparent dip),

2. assuming a constant thickness for the Upper Jackson Unit,

3. assuming that elevation differences between the two wells were substantially less than the thickness of the Upper Jackson Unit, and

4. assuming that the surface profile approximates a straight line between the two wells.

The distance between the two wells was partitioned on the basis of the depth of the boundary in the downdip well and the projected height of the boundary above ground in the updip well. For example, if the boundary occurred at 200 feet below ground surface in the downdip well and was estimated to be at 300 feet above ground in the updip well, the outcrop location was interpreted to occur two-fifths of the way from the downdip well toward the updip well (Figure 4.2.5). The elevation above ground in the updip well was estimated by adding the thickness of the Upper Jackson Unit to the well depth at which the base of the Upper Jackson Unit was encountered in the updip well.

The addition of well control points reduced well distances and, consequently, decreased errors introduced by assuming constant dips between wells, constant thickness of the Upper Jackson Unit, and the assumption of a minimal elevation difference between the two wells and along the path between those wells. In some cases, wells were available that had log data to within 100 feet of the ground surface, allowing very accurate estimates of outcrop locations. Some of the added wells occurred very near the boundary outcrop, allowing a very high level of accuracy in placement of the outcrop location. Dip cross sections 4 and 22 (Figures 4.2.5 and 4.2.6, respectively) show examples of the projection of the contacts from the subsurface to the surface.

Environmental Facies

Jackson and Garner (1982) mapped environmental facies in the eastern extent of the Yegua-Jackson Aquifer outcrop belt. They defined facies regions on the basis of surface lithology, relief, slope, and vegetation. Their more than 30 unit types were simplified into four basic facies and the boundaries of those facies digitized for mapping. These facies consist of sand, sand with clay, clay with sand, and clay. These facies often appear in groups or bands that roughly parallel the aquifer boundary, reflecting dominant lithologies in each of the four layers as they come to outcrop. These bands are, in places, interrupted by Quaternary river valley sediments or major lakes. An example can be seen in the area of the junction of the Navasota River, the Brazos River, and East Yegua Creek, at the southeastern tip of Brazos County (Figure 4.2.7). A sandy trend from the south becomes obscured below the Quaternary alluvium and is not clear for about 10 miles along strike. An area between the Brazos and Navasota rivers shows a mix of lithologies. North of the river junction, two sand trends can be seen. Those who mapped the surface geology interpreted the southeastern most trend as the continuation of the sand trend from the south. Subsurface correlations match much better with the northwestern most of the northern sand trends. This may account for some of the difference between Jackson Group boundaries in Barnes (1992) and the current boundaries.

The outcrop boundaries of these bands of lithology were interpreted, in many cases, as the surface expression of layer boundaries. Note that because these layer boundaries are often dominated by more easily eroded clay, relatively straight reaches of some rivers that paralleled the outcrop trend were also considered to be suggestive of layer boundaries when lithology information was scarce.

Using this approach, in conjunction with additional well control, significantly clarified layer boundaries in the eastern end of the study area. Unfortunately, no similar map data were available for other parts of the aquifer.

Final Boundary Revisions

In the eastern area, differences between the Barnes (1992) boundary and the current boundary are small, generally 1 to 5 miles. The current boundary lies to the north of the Barnes (1992) boundary. The additional well control also allowed an improvement in accuracy from the Knox and others (2007) boundaries. As shown in Figure 4.2.3, the outcrop location of the base of the Upper Jackson Unit was further refined because of the additional well data.

In the southern area, differences between the Barnes (1992) boundary and the current boundary are greater in some places, ranging from 2 to 10 miles. The differences are small along much of the length of the revised region, as shown in Figure 4.2.4. An increase in the difference occurs in two areas where Barnes (1992) boundaries departed eastward from the outcrop trend, then abruptly angled back to the west to rejoin that trend. As with the eastern area, improvements were made to the outcrop location of the base of the Upper Jackson Unit.

Aquifer Structure Contour and Net Sand Maps

As discussed in the introduction to this subsection, a chronostratigraphic framework was created for the Yegua-Jackson Aquifer on the basis of micropaleontologic information and the three-dimensional distribution of maximum flooding surfaces interpreted from well logs (Knox and others, 2007). The four major subdivisions of the Yegua-Jackson Aquifer are at a scale appropriate to regional numerical groundwater flow modeling. Previous work cited in Knox and others (2007) suggests that both the Yegua Formation and Jackson Group intervals span a depositional period of about 2 to 3 million years, suggesting that the four major layers identified span roughly one million years each. These are categorized as third-order depositional cycles; the controls on which are not well understood. It is known that these longer cycles can be influenced by variations in the rate of basin subsidence and sediment supply, as well as tectonically driven changes in global sea level. However, periodicities of these factors are not well quantified.

The following provides a description of each of the four units of the Yegua-Jackson Aquifer and provides structure contour and isopach maps for each. Structure contours are generally smooth and follow the directional trends of the outcrop belt. Cross sections of the interpreted structure (Knox and others, 2007) demonstrate that boundaries closely parallel one another except in far downdip parts of the study area where thickening results in divergence.

Lower Yegua Unit

The basal boundary of the Yegua-Jackson Aquifer (Figure 4.2.8) is also the basal boundary of the deepest aquifer layer, the Lower Yegua Unit. This surface extends from the northern outcrop boundary of the aquifer (base of the Yegua Formation in Barnes, 1992) to the base of the first significant sand (greater than 20 feet thick) above the Cook Mountain Formation in the subsurface. The upper boundary of the Lower Yegua Unit (Figure 4.2.9) is a maximum flooding surface that marks a regional change in sand distribution. It is commonly reflected in logs as a low-resistivity marker above a trend of upward fining or upward thinning sands or as a pronounced low resistivity marker within a shaly interval of tens to one hundred or more feet thick. The Lower Yegua Unit ranges in thickness from less than 500 feet near the updip limit of well control to more than 1,100 feet in middip to downdip parts of the study area (Figure 4.2.10). Sand deposition prograded gradually from landward (updip) areas to seaward (downdip areas), such that sand is present near the base of the unit in the outcrop area but overlies a progressively thicker blanket of shale in the downdip direction. Conversely, the upper part of the unit is most shale-dominated in the updip area, with sand becoming increasingly common toward the top of the unit farther downdip. In a strike orientation, sandy deposition was mostly pervasive in the Houston and Rio Grande embayments and least concentrated over the San Marcos Arch.

Upper Yegua Unit

The boundary between the Yegua Formation and Jackson Group intervals is expressed in well logs as a low-resistivity shale, commonly above a 100-foot thick or thicker shaly section containing thin interbedded sands of upward-decreasing thickness. The elevation of the top of the Upper Yegua Unit is shown in Figure 4.2.11. The Upper Yegua Unit varies in thickness from less than 500 feet at the updip limit of well control up to more than 1,200 feet at the downdip study edge (Figure 4.2.12). Sand deposition is most prevalent in the middip to downdip parts of the study area. Shales in the updip area may contain thin (5 feet) to thick (50 feet) upward-fining sand interbeds. Downdip shales commonly occur in the upper part of the unit, may be several hundred feet thick, and may contain thin (less than 10 feet thick) isolated sand interbeds. In a strike orientation, sandy deposition is significant in the Houston Embayment and in a part of the San Marcos Arch, but is pervasive in the Rio Grande Embayment.

Lower Jackson Unit

The upper boundary of the Lower Jackson Unit is a maximum flooding surface that commonly lies above a 100-foot thick or thicker upward-fining silty shale and below a 100-foot thick or thicker sandy to silty shale. The boundary is often expressed in logs as a low-resistivity marker overlain by an abrupt-based silt of slightly higher resistivity than the underlying section. The elevation of the top of the Lower Jackson Unit is shown in Figure 4.2.13. The Lower Jackson Unit ranges in thickness from less than 400 feet at the updip limit of well control to nearly 600 feet at the downdip edge of the study area (Figure 4.2.14). Sand is a minority lithology in the Lower Jackson Unit and occurs primarily in the lower part of the unit, rarely in updip areas and more commonly in middip areas. In strike orientation, sand deposition was minor in the Houston Embayment, almost nonexistent over the San Marcos Arch, and common in the Rio Grande Embayment.

Upper Jackson Unit

The top of the Jackson Group is taken here as a maximum flooding surface below an upward-coarsening interval containing thick (20 to 50 feet thick or more) abrupt-based sandstones suggestive of fluvial incision surfaces. In the subsurface, the Jackson Group is overlain by the Vicksburg Formation (Coleman, 1990). In the outcrop, the Jackson Group is considered to be overlain by the Catahoula Formation, which is a combination of the Vicksburg and Frio formations (Galloway, 1990) dominated by thick fluvial sands and gravels. In well logs, the top of the Upper Jackson Unit is marked by low-resistivity shale above an upward fining shale commonly exceeding 100 feet in thickness and often several hundred feet thick and is overlain by an upward coarsening silty shale or abrupt-based sand. The elevation of the top of the Upper Jackson Unit is shown in Figure 4.2.15. The Upper Jackson Unit varies in thickness from less than 500 feet at the updip limit of well control to more than 1,000 feet at the downdip study edge (Figure 4.2.16). Shale dominates this interval, with thin sands (most less than 30 feet thick) occurring in the middle or upper parts of the unit. In strike orientation, sands are uncommon in the Houston Embayment, more common over the San Marcos Arch, and are roughly equal to shales in abundance in the Rio Grande Embayment.

Net Sand Maps

The Yegua-Jackson Aquifer is composed of interbedded sand, silt, and clay. Sand-rich intervals form the high-conductivity framework of the aquifer and the percent of interbedded fine-grained material is critical to numerical modeling for apportioning hydrologic properties across model grid cells. Net sand thickness maps have been prepared for each of the four aquifer layers. Net sand maps for the Lower Yegua Unit through the Upper Jackson Unit are shown in

Figures 4.2.17 through 4.2.20. Net sand thickness of the Lower Yegua Unit (Figure 4.2.17) exceeds 400 feet in small areas, and is greater than 100 feet across three-quarters of the study area. Absence of sand occurs rarely in the outcrop area, but is more broadly distributed downdip at the southeast edge of the central and southern parts of the study area. Net sand thickness in the Upper Yegua Unit (Figure 4.2.18) exceeds 400 feet in small areas, and is greater than 100 feet across approximately one-half of the study area. Absence of sand occurs rarely in the outcrop area, but is more widespread at the southeast edge of the central and southern parts of the study area. Net sand thickness of the Lower Jackson Unit (Figure 4.2.19) ranges from almost 300 feet to essentially zero feet in much of the downdip (southeast) extent of the study area. Thickest sand accumulations occur in the south-central and southern part of the study area. The net sand thickness of the Upper Jackson Unit (Figure 4.2.20) ranges from over 300 feet in a several locations to zero feet in isolated or downdip areas in the south-central and northeastern parts of the study area. The distribution of net sand in the Yegua-Jackson Aquifer is greatly influenced by the depositional environment and fluvial axes present during deposition. The next section will provide an interpretation of the depositional environments present within the four units interpreted for the Yegua-Jackson Aquifer.

Depositional Environments

Depositional facies for each unit are discussed in the following sections, in the order in which they were deposited (Lower Yegua through Upper Jackson). For a complete discussion of the interpretive methods used, please refer to Knox and others (2007).

Lower Yegua Unit

The interpreted facies map for the Lower Yegua Unit is shown in Figure 4.2.21. Updip sand-rich intervals dominated by upward-fining sands are interpreted as dip-oriented fluvial deposits. Intervening areas of less than 100 feet of sand are marginal to these fluvial axes and are considered floodplain deposits, even though these areas may contain some individual upward-fining fluvial sand bodies. Sand-rich regions across the middle of the study area that are dominated by upward coarsening or blocky sand bodies are interpreted as deltaic facies fed by updip fluvial systems. In the northern and southern part of the study area, these deltas prograde out to the shelf-edge position as interpreted by Galloway and others (1983). Areas between the fluvial deposits and the shelf edge that contain less than 100 feet of net sand are interpreted as delta margin deposits. The area downdip of the shelf edge is dominated by shale, but a sandy interval in a well in south Texas exhibits an upward-fining sand body approximately 100 feet thick. This suggests that sandy sediment bypassed the delta and was carried by channels across the slope.

Upper Yegua Unit

The interpreted facies map for the Upper Yegua Unit is shown in Figure 4.2.22. As in the Lower Yegua Unit, updip regions are interpreted as fluvial axes separated by floodplain deposits (defined as having less than 100 feet of net sand). Sand-rich regions across the middle of the study area are interpreted as deltaic deposits fed by the updip fluvial systems. Deltaic centers in the southern part of the study area are likely more wave-dominated as suggested by strike alignment and the dominance of blocky sand bodies. Thick sand accumulations at the shelf edge containing blocky sands or interbedded sand and shale are interpreted as shelf-edge deltas. These were constructed as deltas built to the shelf edge and received sustained volumes of sediment, resulting in thick layers of sand as delta progradation was slowed by having to fill increasing depths of water on the slope. It is extremely likely, assuming the shelf-edge position is accurate, that abundant sand bypassed deltas near the shelf edge and was deposited on, and carried across, the slope.

Lower Jackson Unit

The interpreted facies map for the Lower Jackson Unit is shown in Figure 4.2.23. As in the Yegua units, updip regions are interpreted as fluvial axes separated by floodplain deposits (defined as having less than 50 feet of net sand). Sand-rich regions across the middle of the study area are interpreted as deltaic deposits fed by the updip fluvial systems. Areas between fluvial and deltaic settings but containing less than 50 feet of net sand and dominated by thin upward-coarsening sands were interpreted as delta margins. Areas downdip of deltaic regions and containing between zero and 50 feet of net sand are interpreted as distal deltaic facies. Deltaic centers in the southern part of the study area have been interpreted by Fisher and others (1970) as being more wave-dominated deltas, or even strandplain/barrier bar systems, as suggested by strike alignment and the dominance of blocky sand bodies. A similar interpretation is made here, and it is noted that more strike-aligned sandbodies result in a decrease of sand in the outcrop direction. Downdip shale-dominated intervals are more abundant in the Lower Jackson Unit than in either of the Yegua units, indicating a significantly higher relative sea level, possibly related to decreased sediment supply. Thick sand accumulations at the shelf edge containing blocky sands or interbedded sand and shale are again interpreted as shelf-edge deltas, which feed sand down across the slope in narrow dip-oriented channels.

Upper Jackson Unit

The interpreted facies map for the Upper Jackson Unit is shown in Figure 4.2.24. As in the Yegua units, updip regions are interpreted as fluvial axes separated by floodplain deposits (defined as having less than 50 feet of net sand). Sand-rich regions across the middle of the study area are interpreted as deltaic deposits fed by the updip fluvial systems. Areas between fluvial and deltaic settings but containing less than 50 feet of net sand and dominated by thin upward-coarsening sands are interpreted as delta margins. Areas downdip of deltaic regions and containing from less than 50 feet of net sand to zero sand are interpreted as distal deltaic facies. Areas updip of the shelf edge having no sand are mapped as ‘shelf’ facies.

Deltaic centers in the southern part of the study area, as in the Lower Jackson Unit, appear strongly wave-influenced, especially compared to deltas in the northern part of the study area in which patterns of thick sands are more dip-oriented and which are likely more fluvially dominated. Downdip shale-dominated intervals are less abundant in the Upper Jackson Unit than in the Lower Jackson Unit. This reinvigorated progradation (although still weaker than the Lower Yegua Unit) indicates a lower relative sea level, possibly related to increased sediment supply. Thick sand accumulations at the shelf edge containing blocky sands or interbedded sand and shale are again interpreted as shelf-edge deltas, which feed sand down across the slope in narrow dip-oriented channels. However, in the Upper Jackson Unit, the southern wave-dominated delta has built to, or past, the shelf edge, creating a strike-aligned shelf-edge sand body.

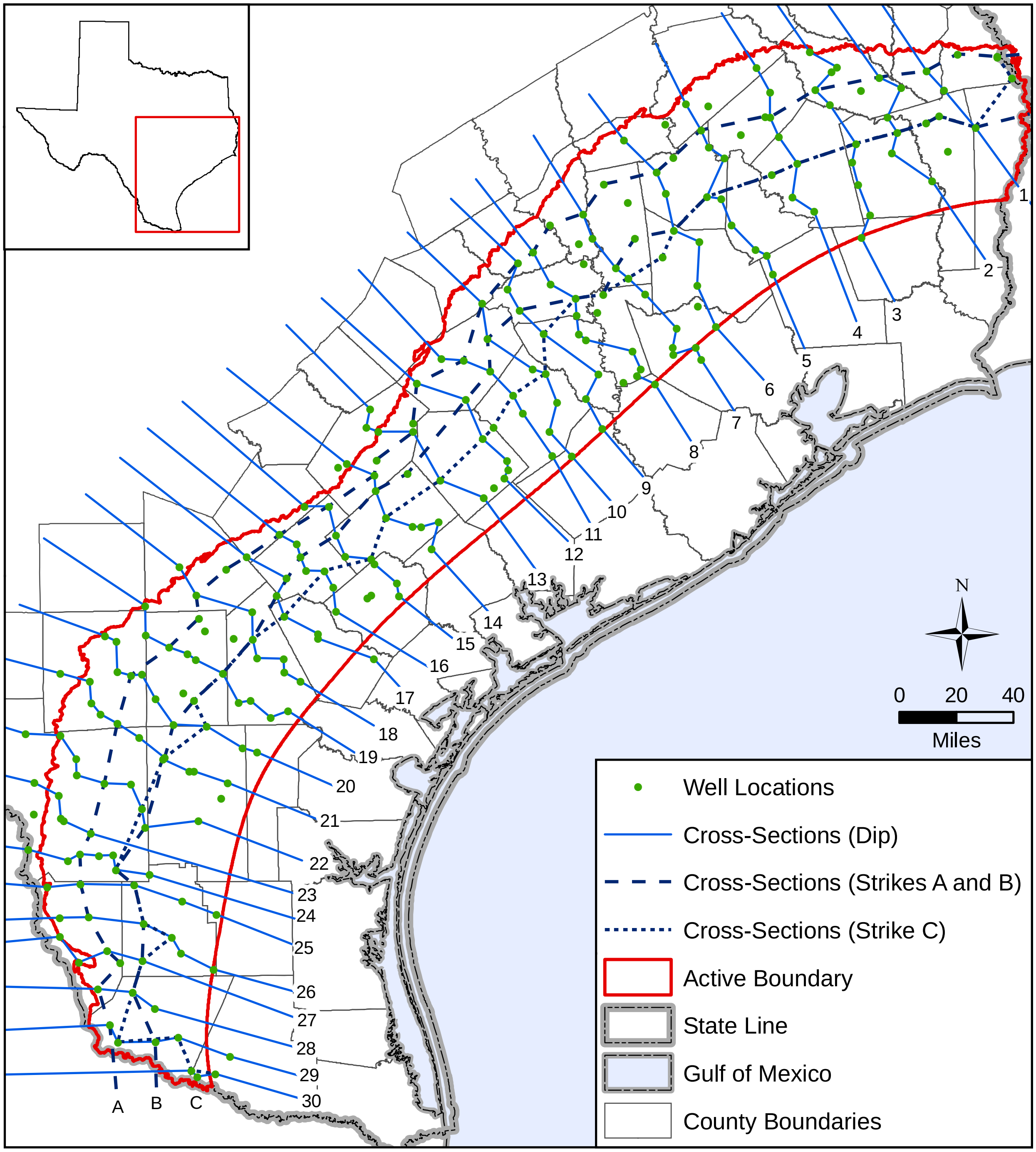

Figure 4.2.1 Stratigraphic correlation basemap with cross section lines (after Knox and others, 2007).

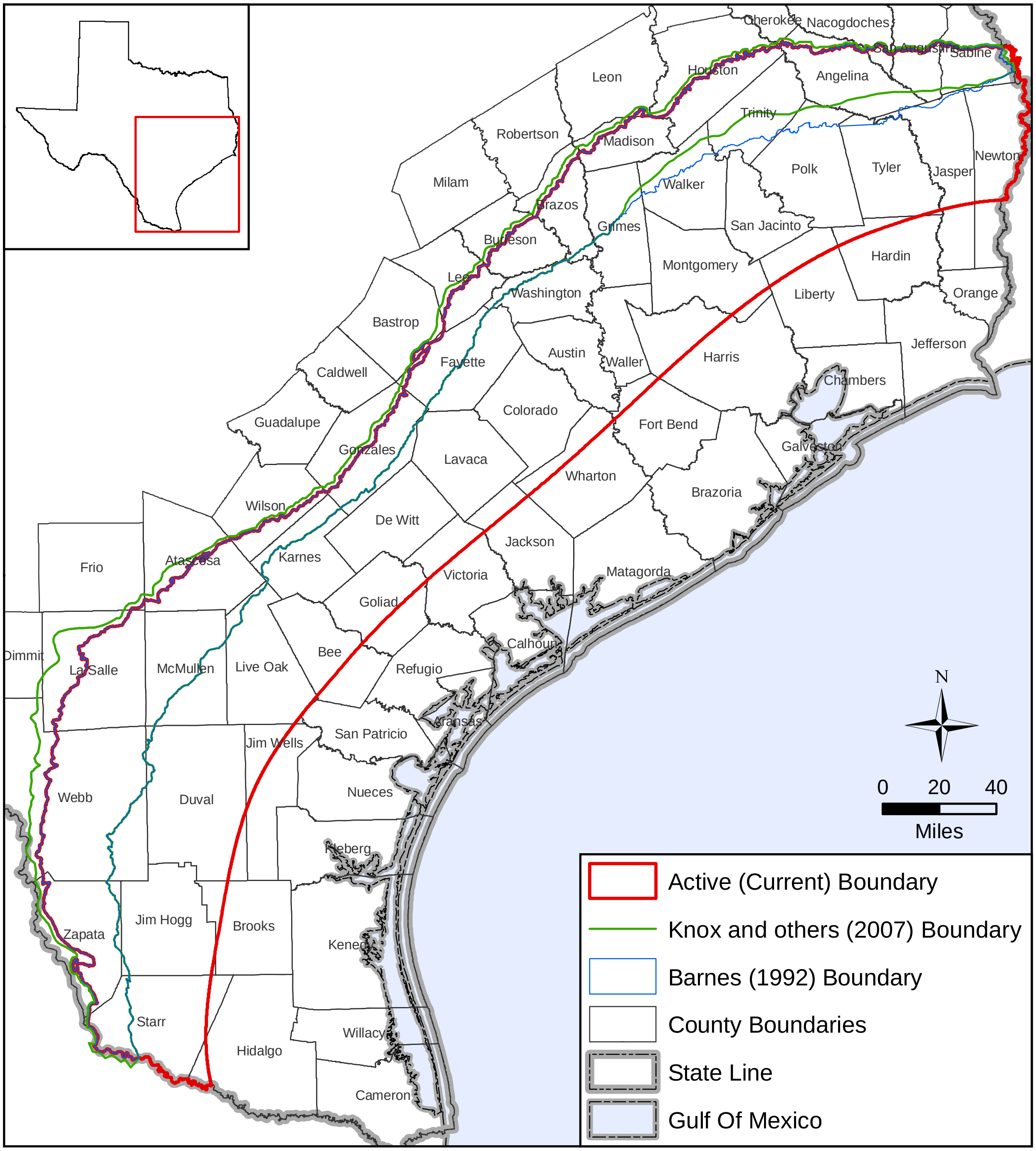

Figure 4.2.2 Barnes (1992) boundary, Knox and others (2007) boundary, and current boundary for the Yegua-Jackson Aquifer.

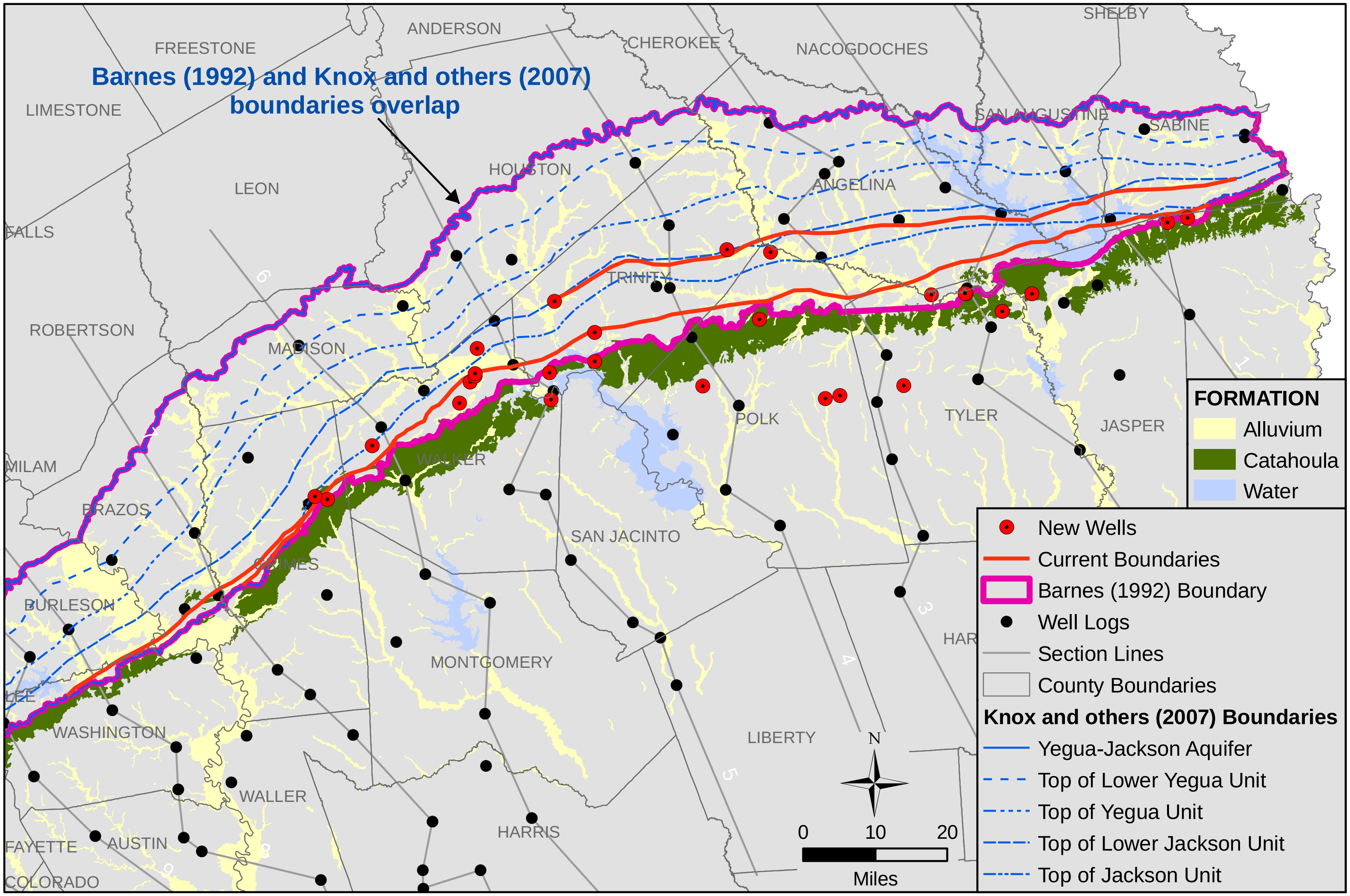

Figure 4.2.3 Location of wells and boundary modifications for the northern region of the Yegua-Jackson Aquifer.

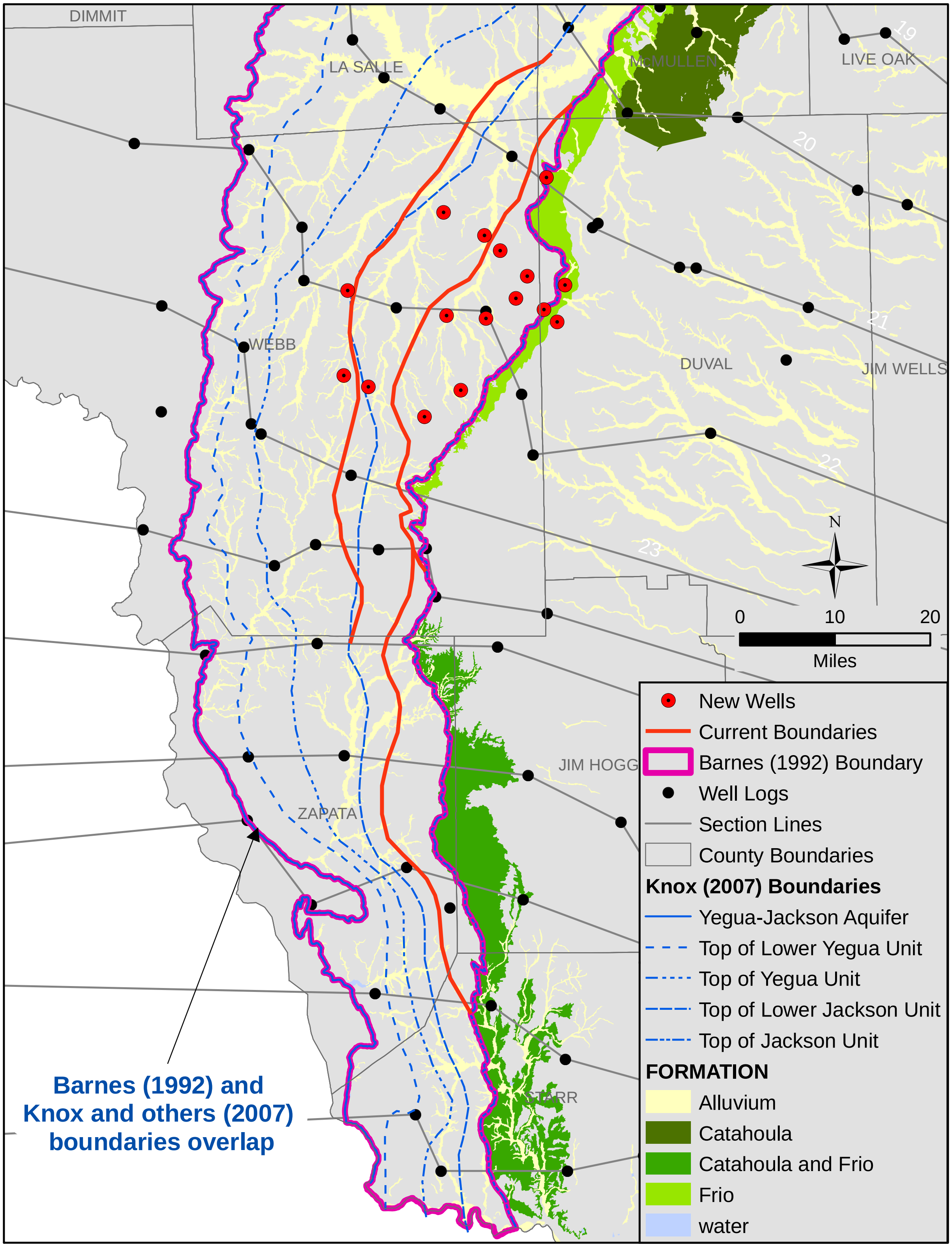

Figure 4.2.4 Location of wells and boundary modifications for the southern region of the Yegua-Jackson Aquifer.

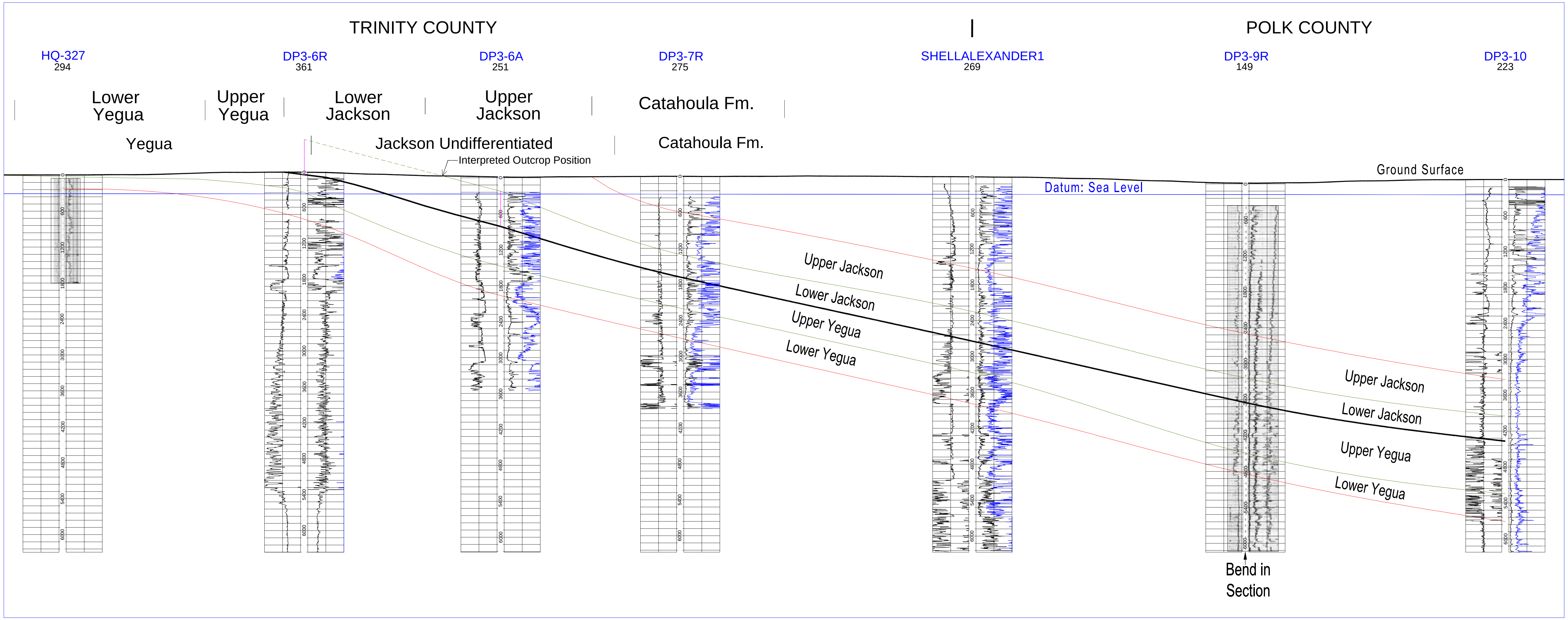

Figure 4.2.5 Modified dip section 4 with method of determining outcrop locations illustrated.

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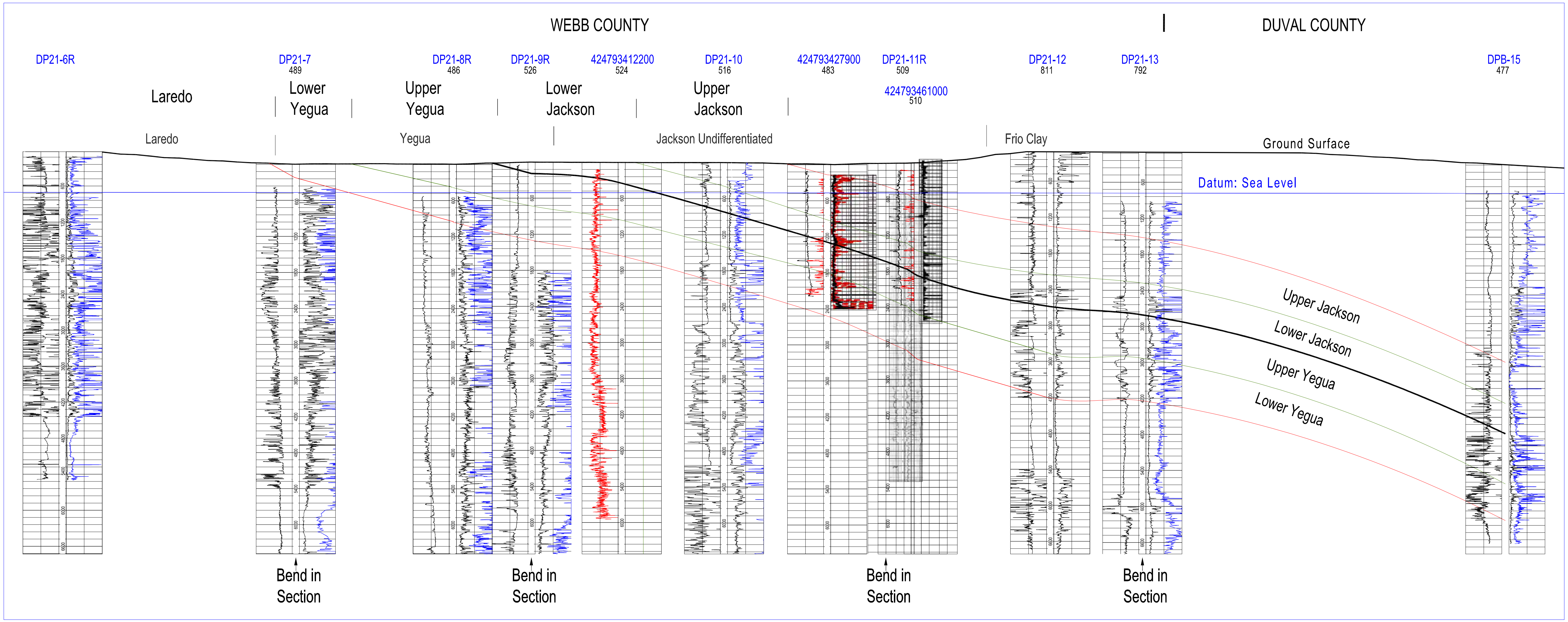

Figure 4.2.6 Modified dip section 22.

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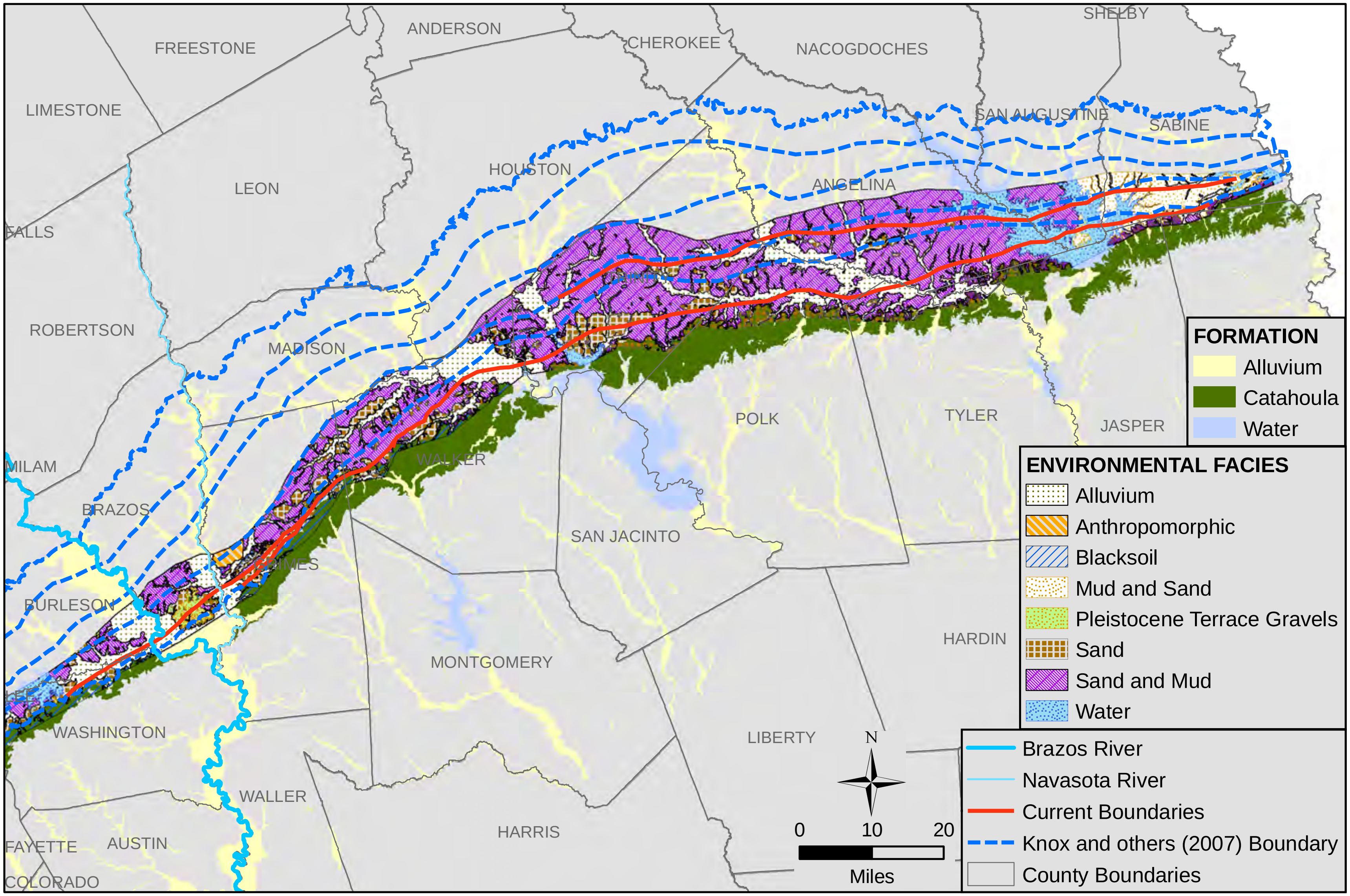


Figure 4.2.7 Environmental facies plotted with new outcrop boundaries.

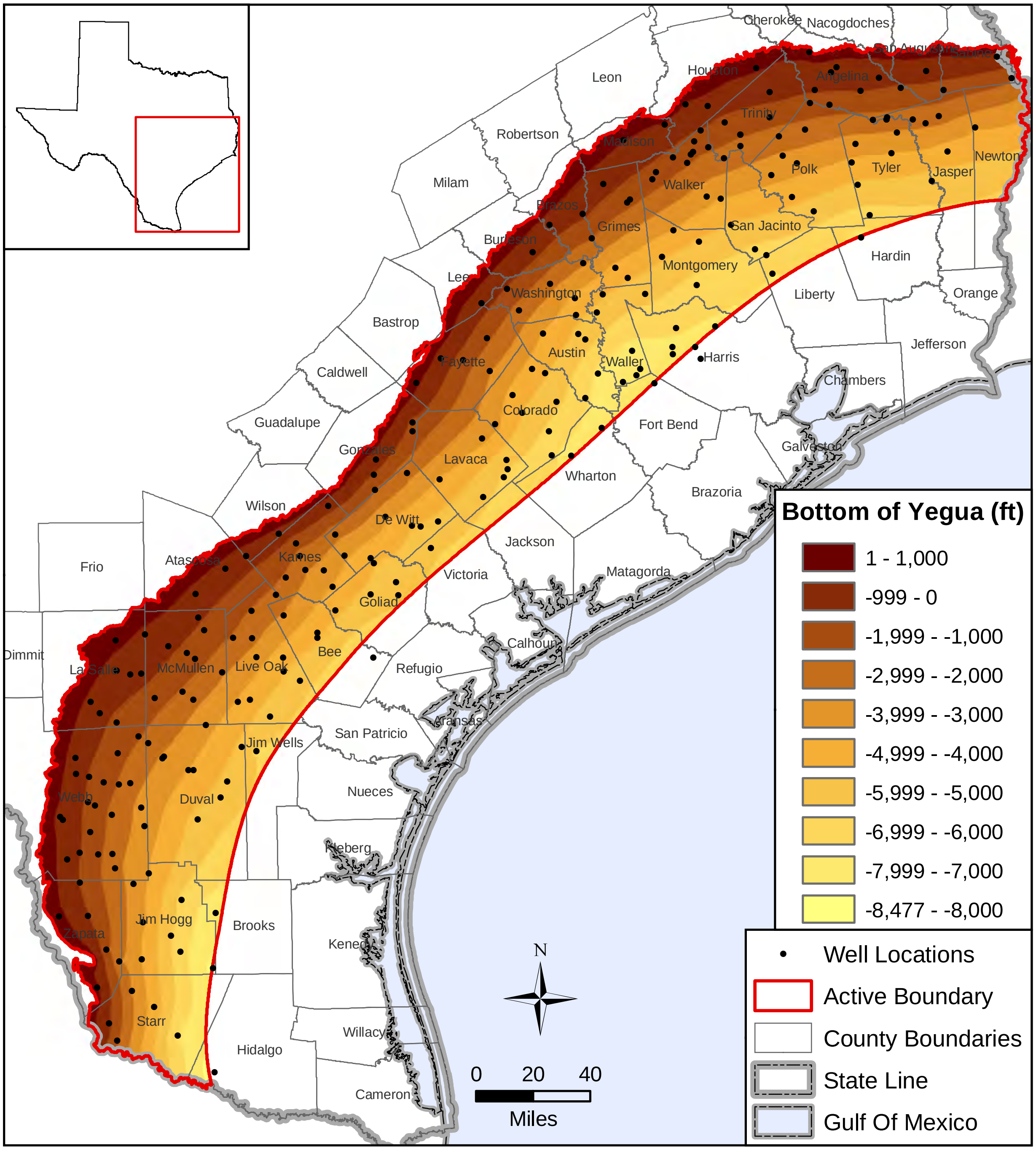


Figure 4.2.8 Base of Yegua-Jackson Aquifer in feet above mean sea level (Knox and others, 2007).

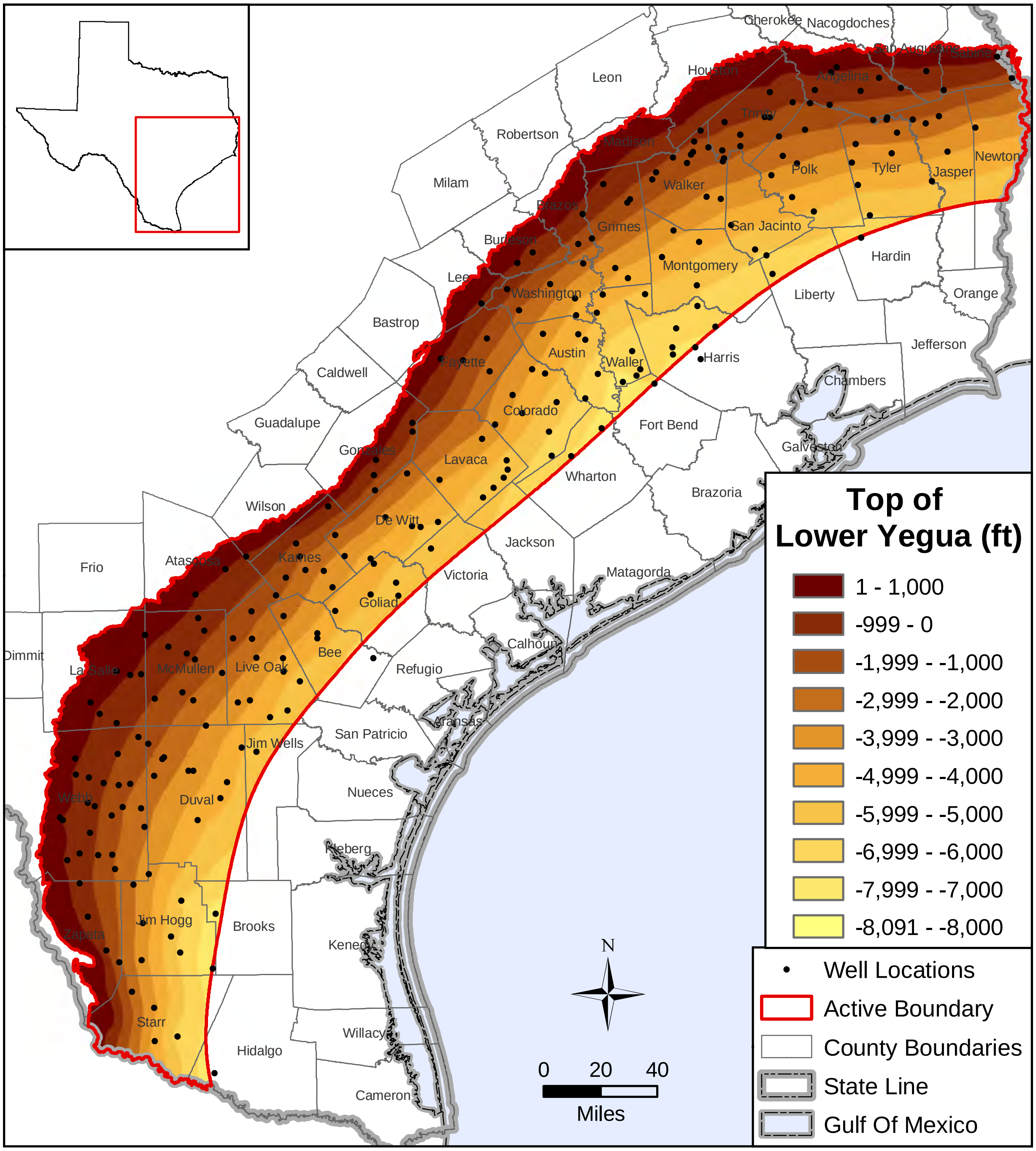


Figure 4.2.9 Top of Lower Yegua Unit in feet above mean sea level (Knox and others, 2007).

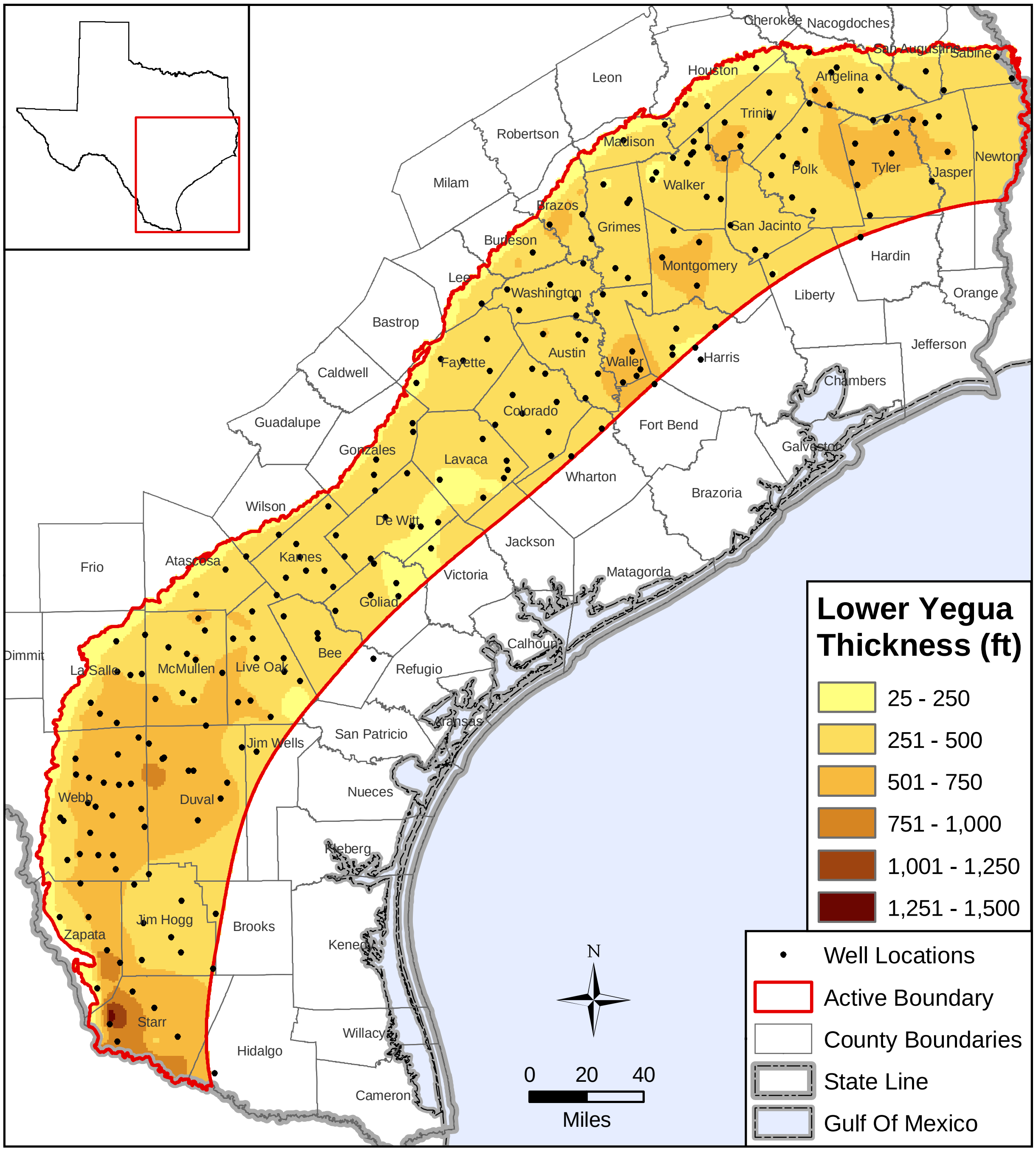


Figure 4.2.10 Thickness of Lower Yegua Unit in feet (Knox and others, 2007).

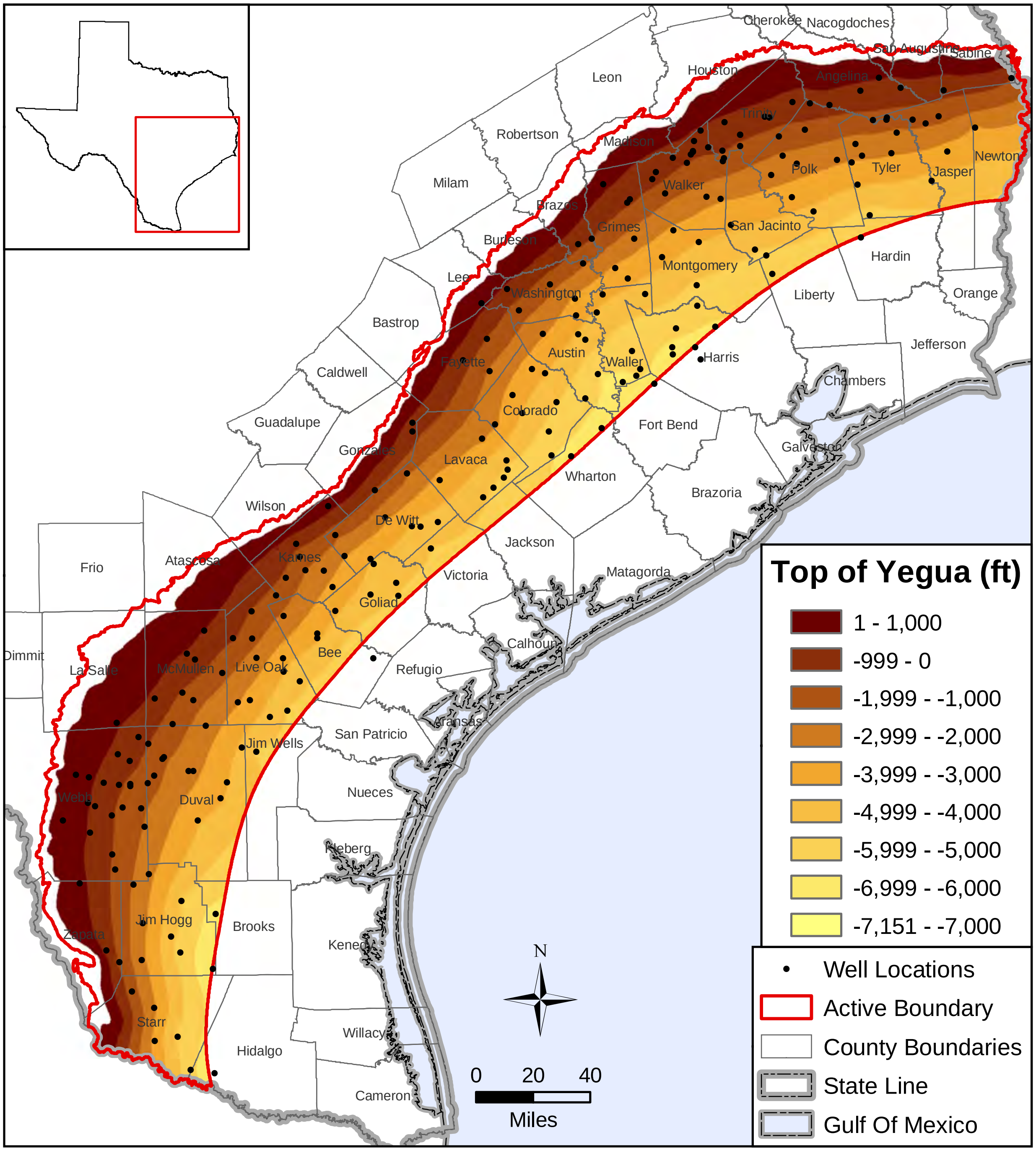


Figure 4.2.11 Top of Upper Yegua Unit in feet above mean sea level (Knox and others, 2007).

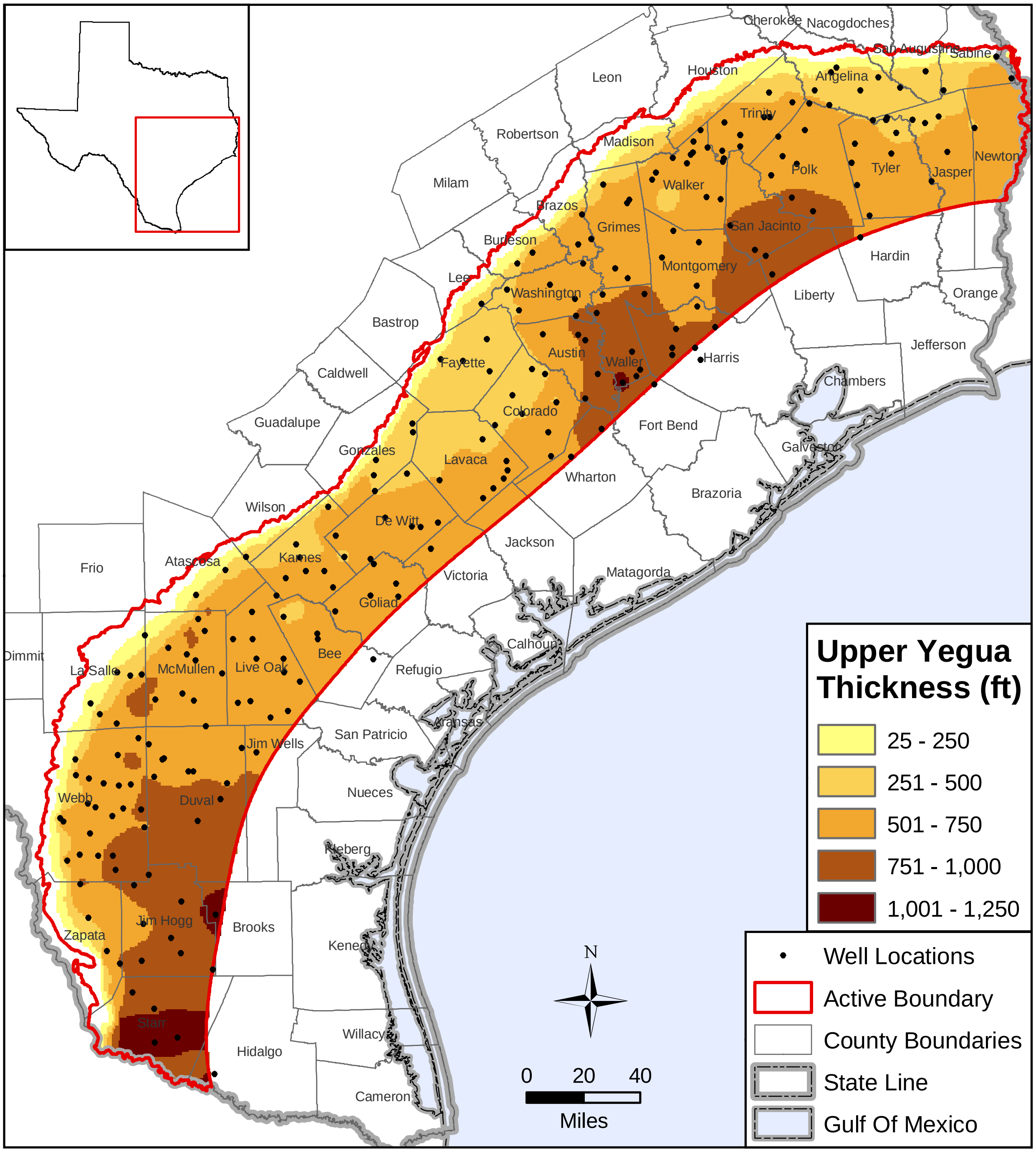


Figure 4.2.12 Thickness of Upper Yegua Unit in feet (Knox and others, 2007).

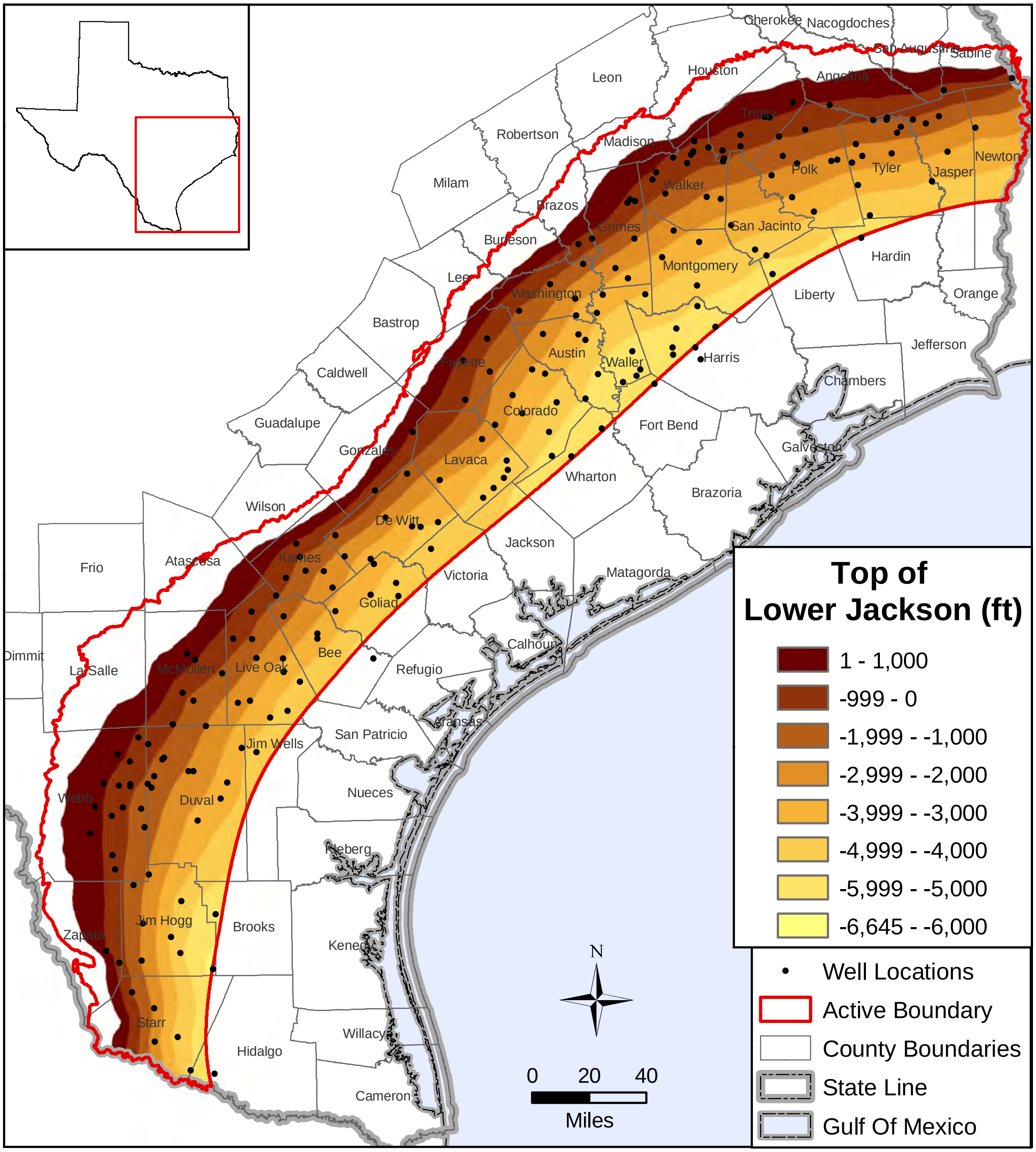


Figure 4.2.13 Top of Lower Jackson Unit in feet above mean sea level (Knox and others, 2007).

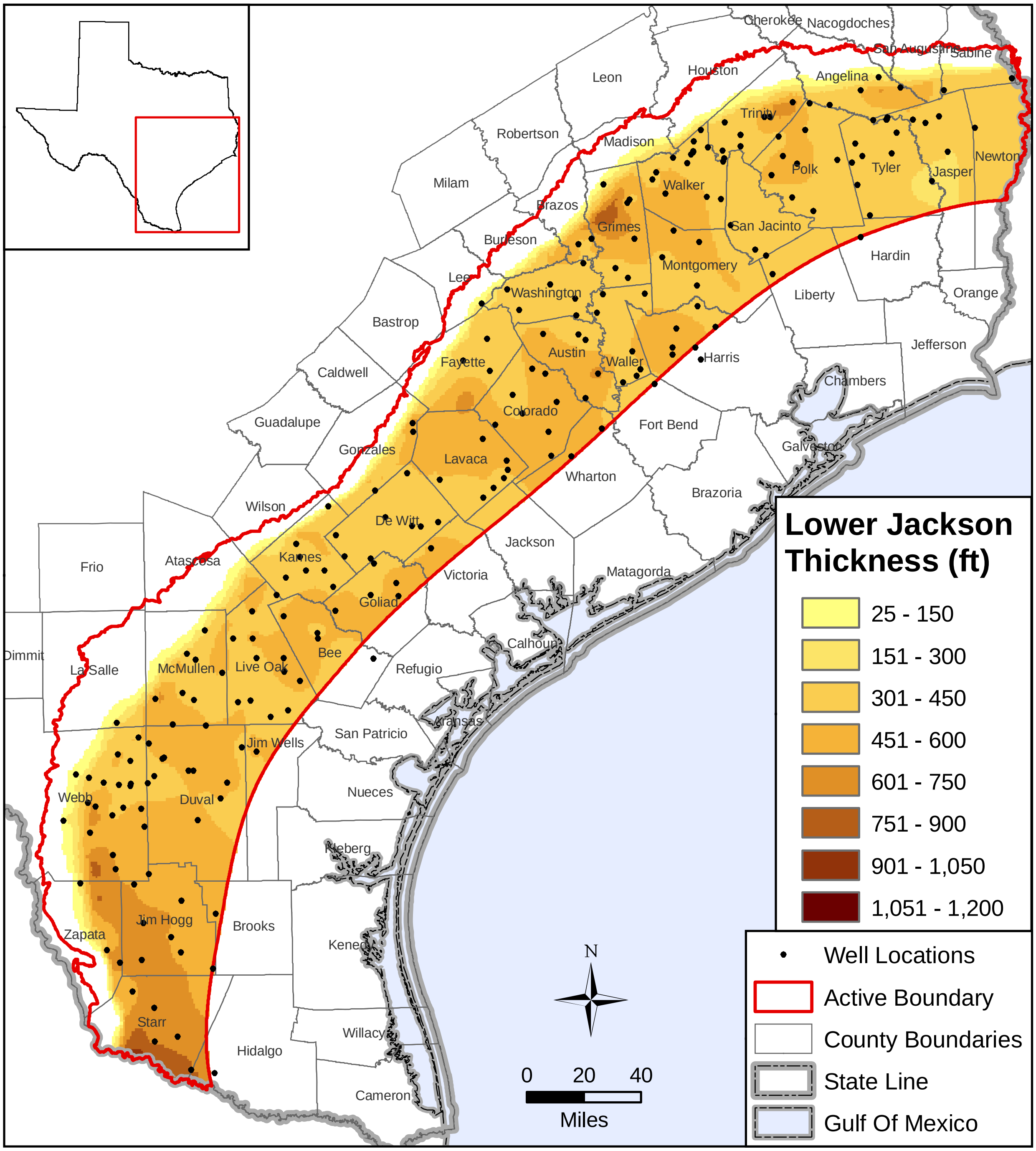


Figure 4.2.14 Thickness of Lower Jackson Unit in feet (Knox and others, 2007).

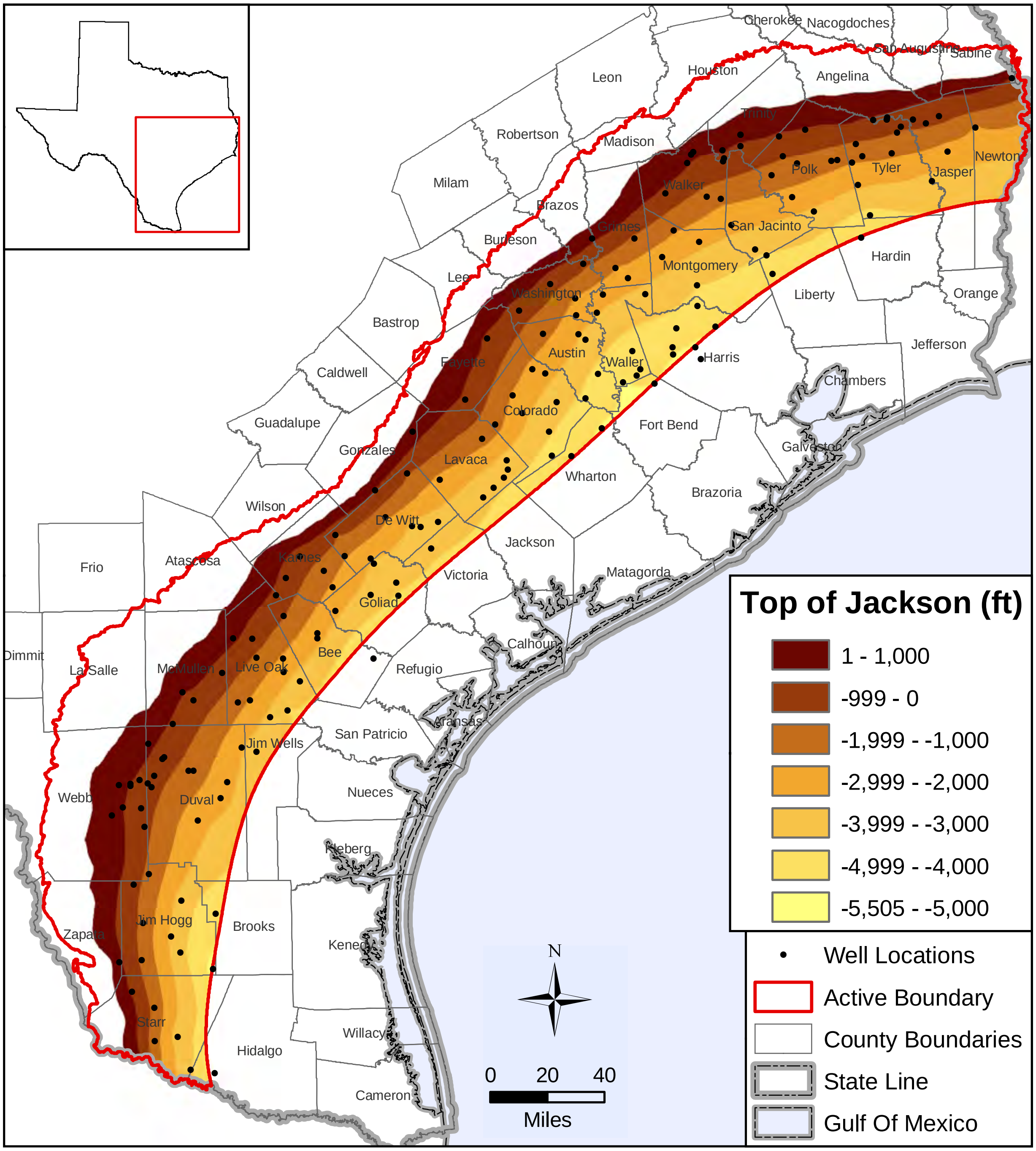


Figure 4.2.15 Top of Upper Jackson Unit in feet above mean sea level (Knox and others, 2007).

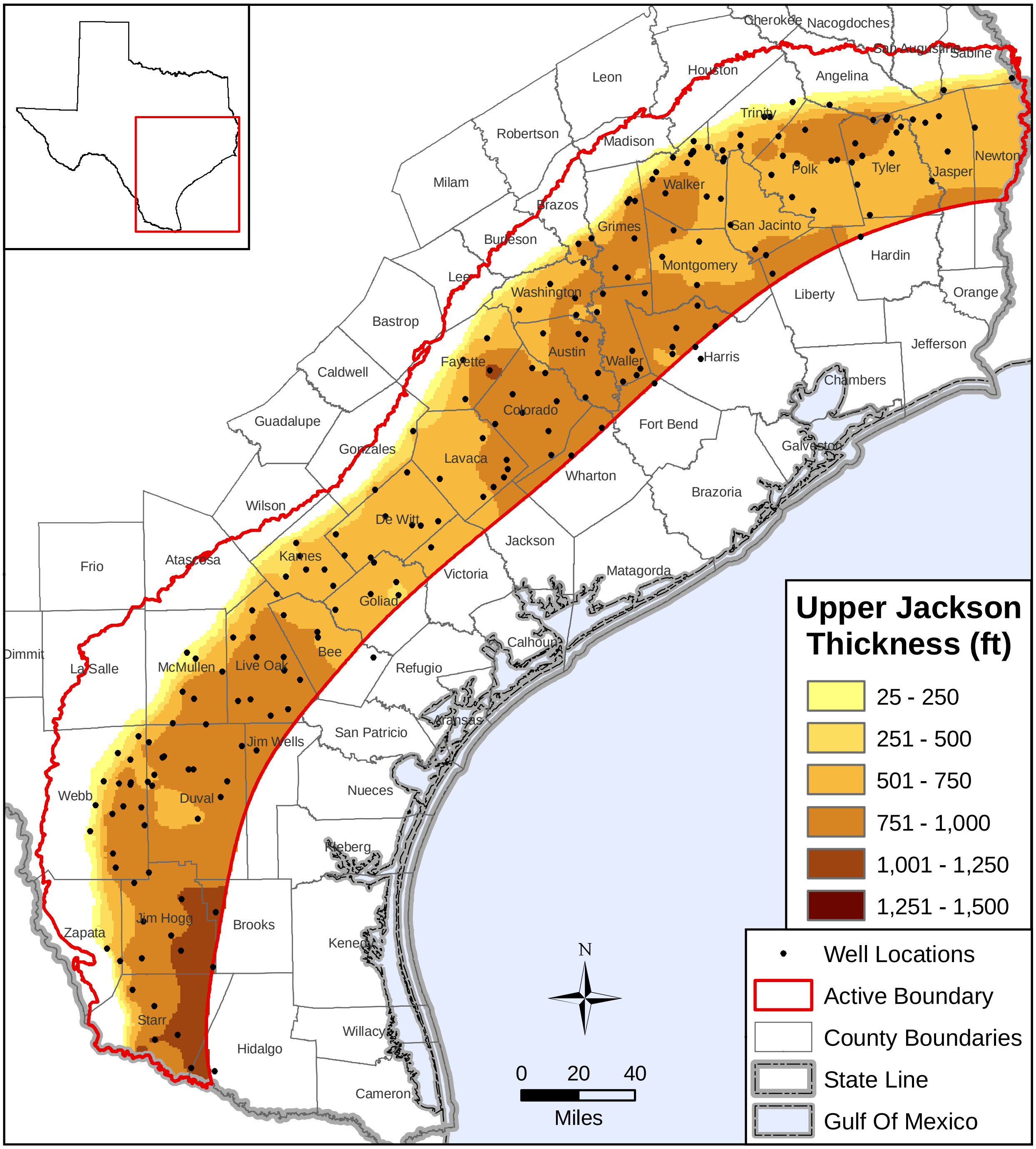


Figure 4.2.16 Thickness of Upper Jackson Unit in feet (Knox and others, 2007).

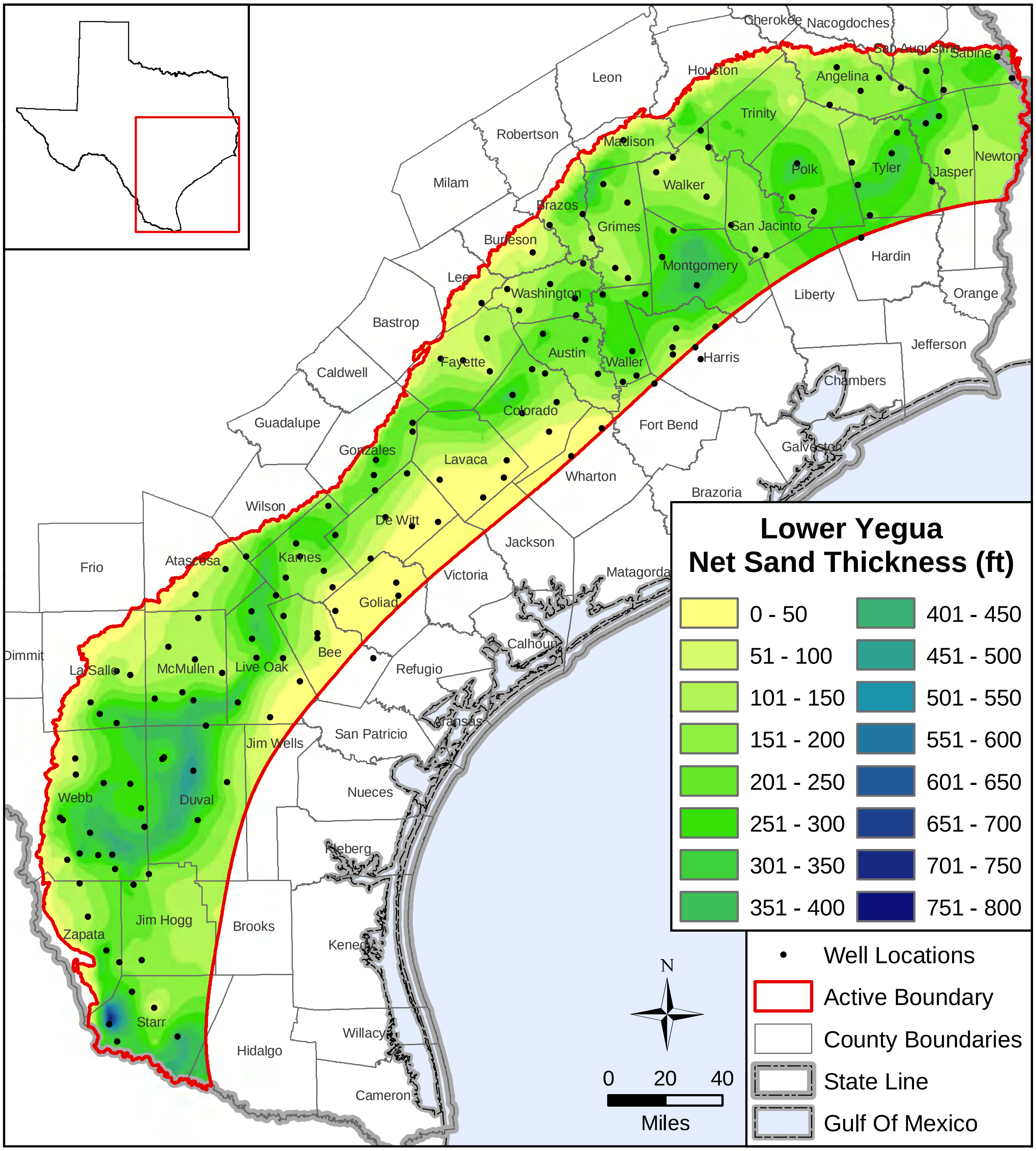


Figure 4.2.17 Net sand thickness of Lower Yegua Unit in feet (Knox and others, 2007).

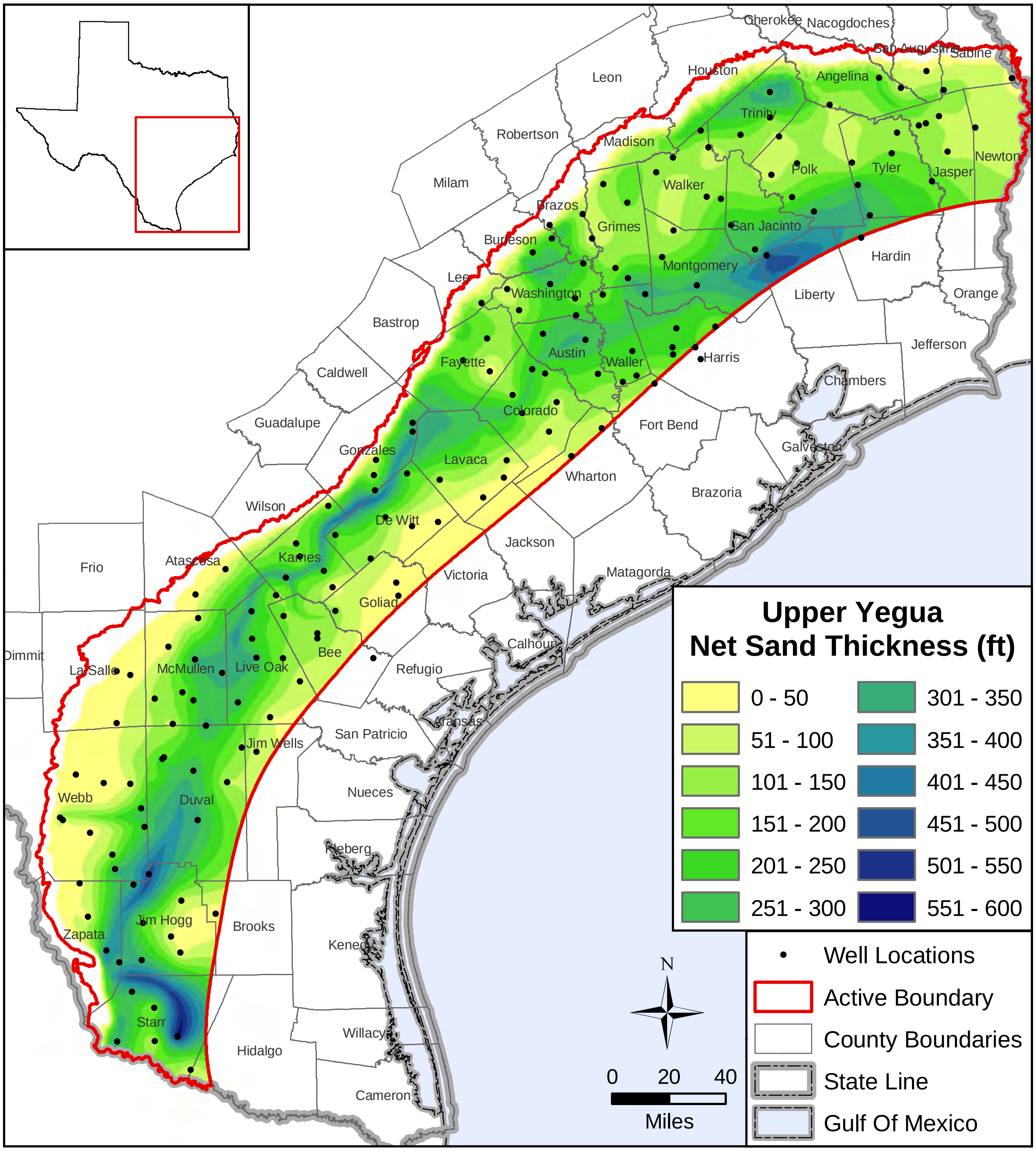


Figure 4.2.18 Net sand thickness of Upper Yegua Unit in feet (Knox and others, 2007).

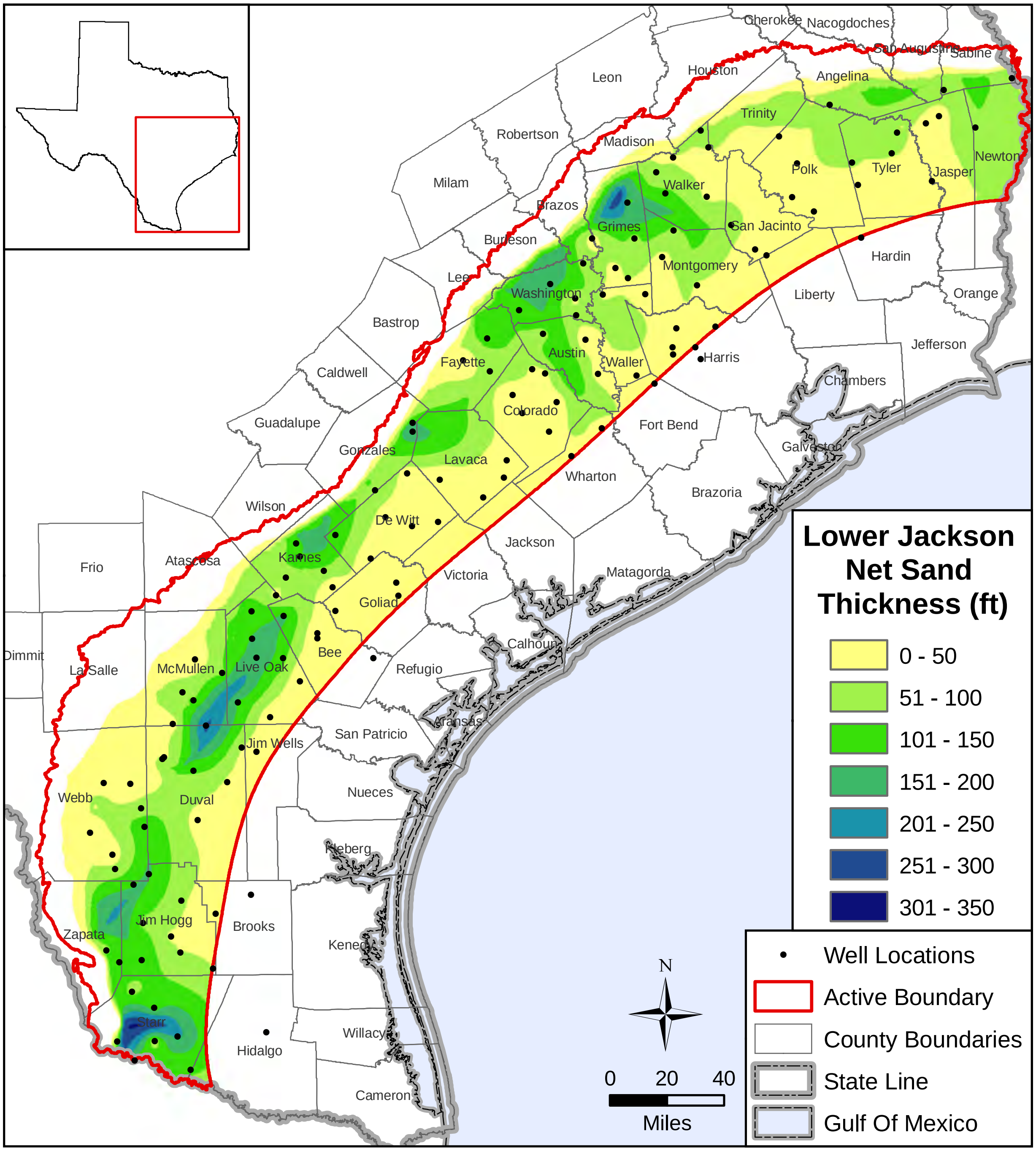


Figure 4.2.19 Net sand thickness of Lower Jackson Unit in feet (Knox and others, 2007).

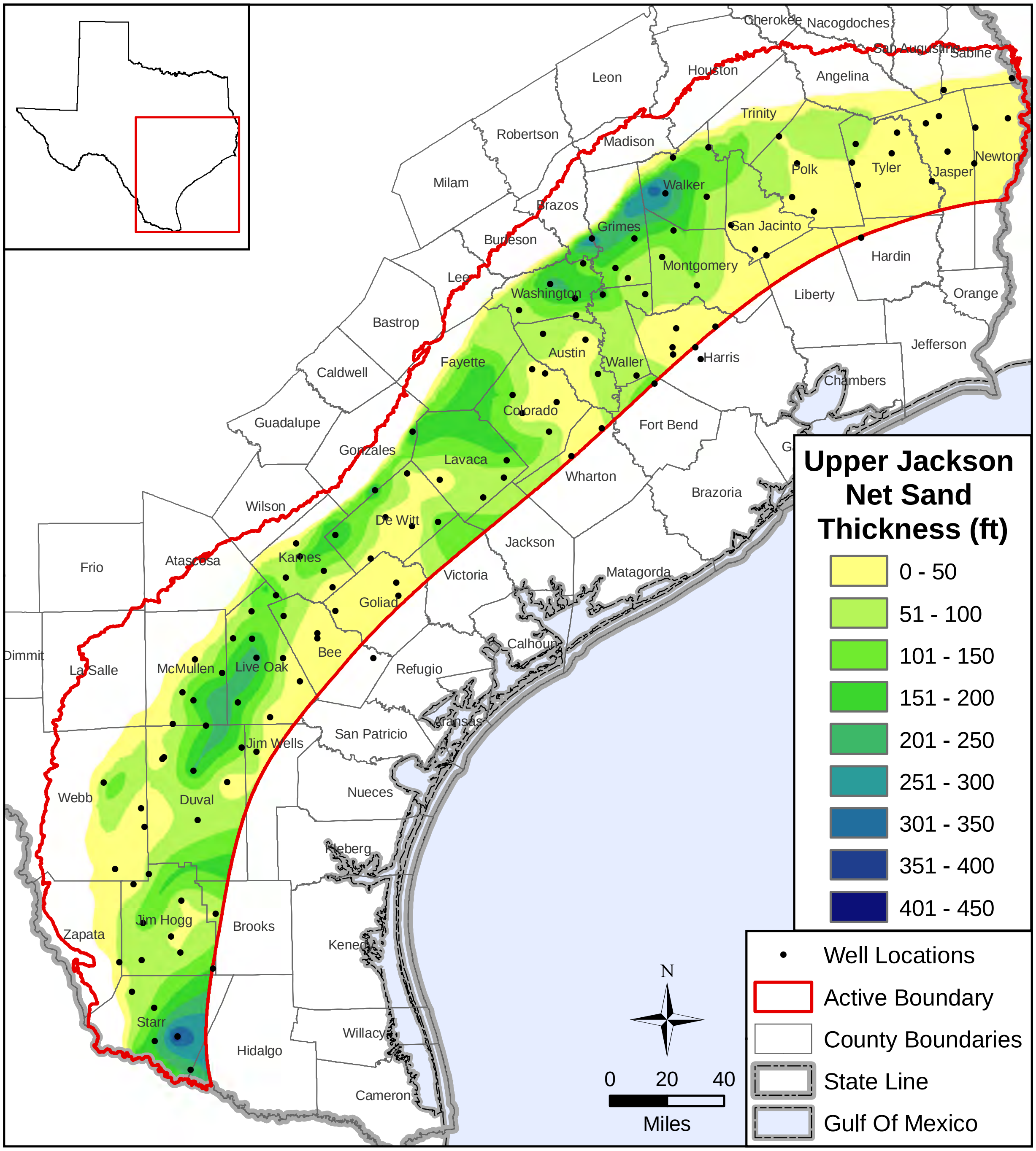


Figure 4.2.20 Net sand thickness of Upper Jackson Unit in feet (Knox and others, 2007).

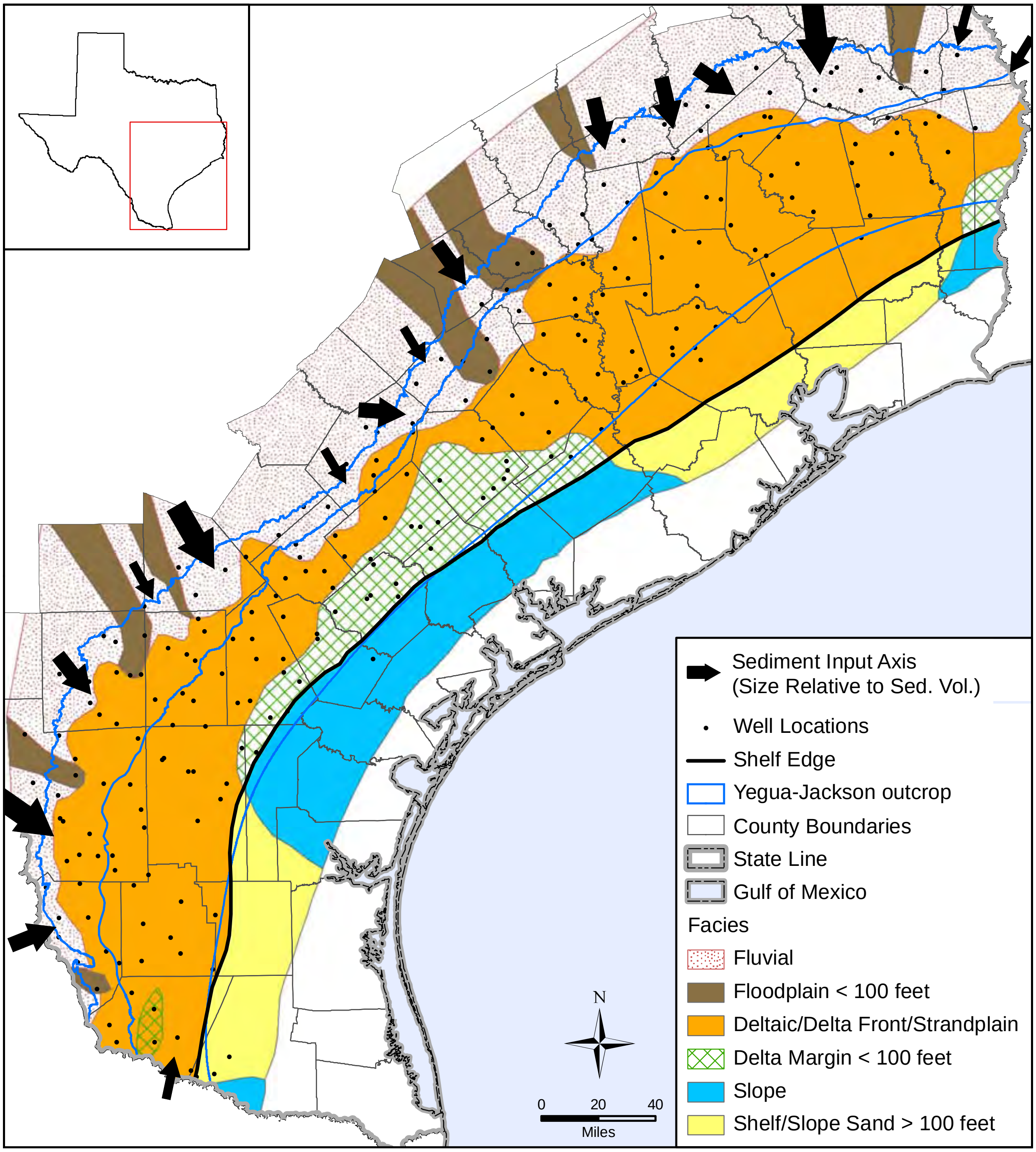


Figure 4.2.21 Lower Yegua Unit depositional facies map (Knox and others, 2007).

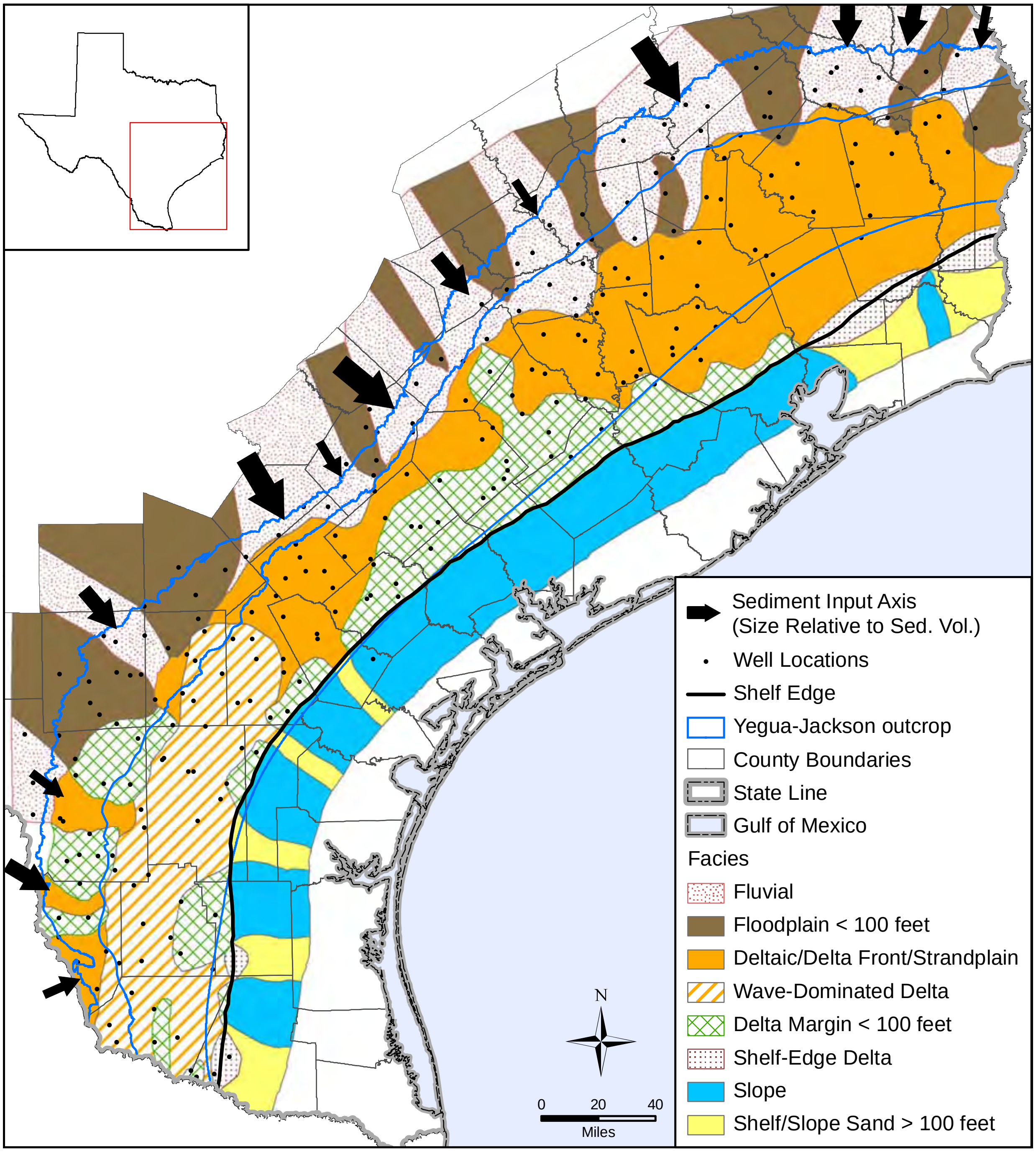


Figure 4.2.22 Upper Yegua Unit depositional facies map (Knox and others, 2007).

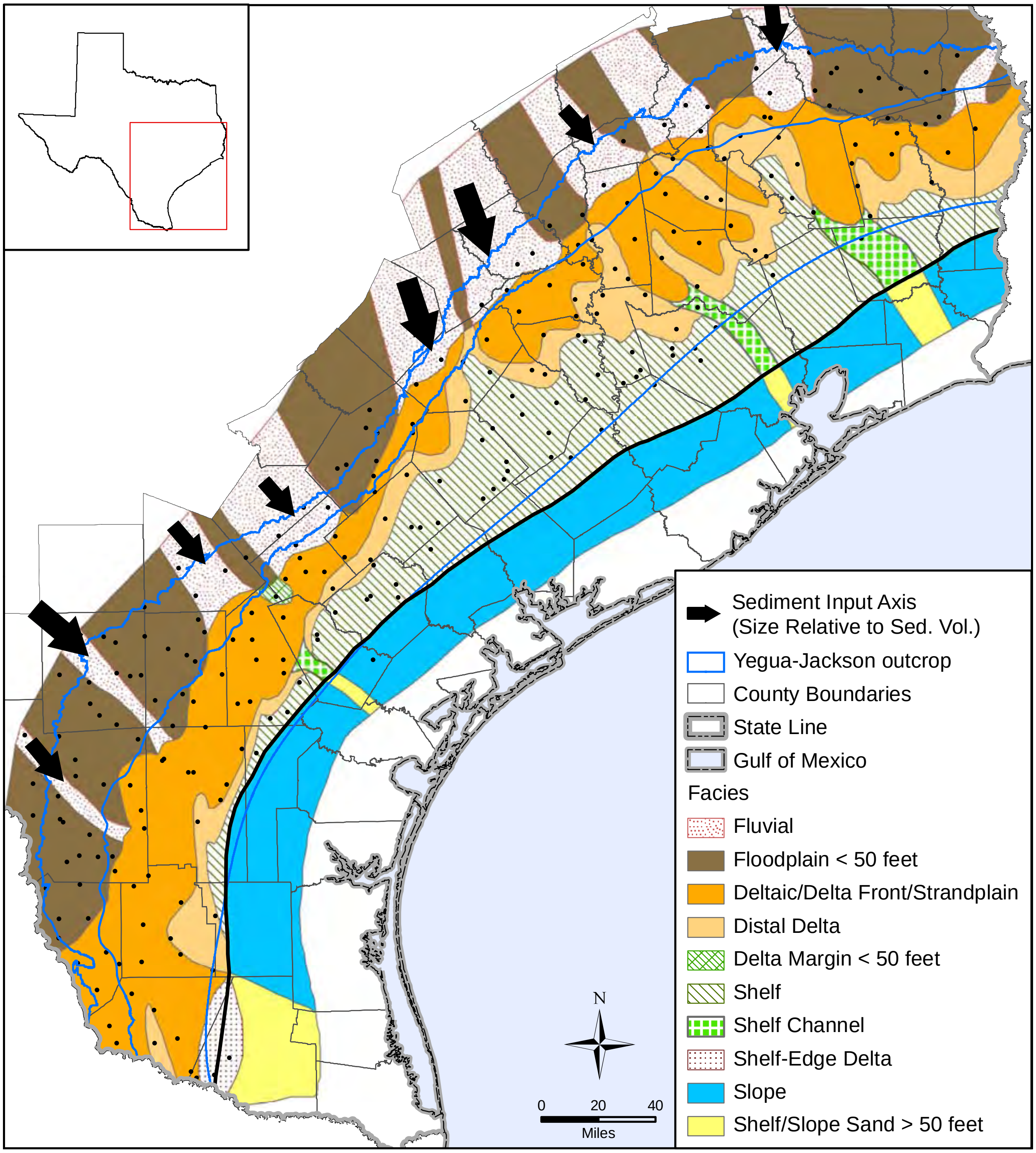


Figure 4.2.23 Lower Jackson Unit depositional facies map (Knox and others, 2007).

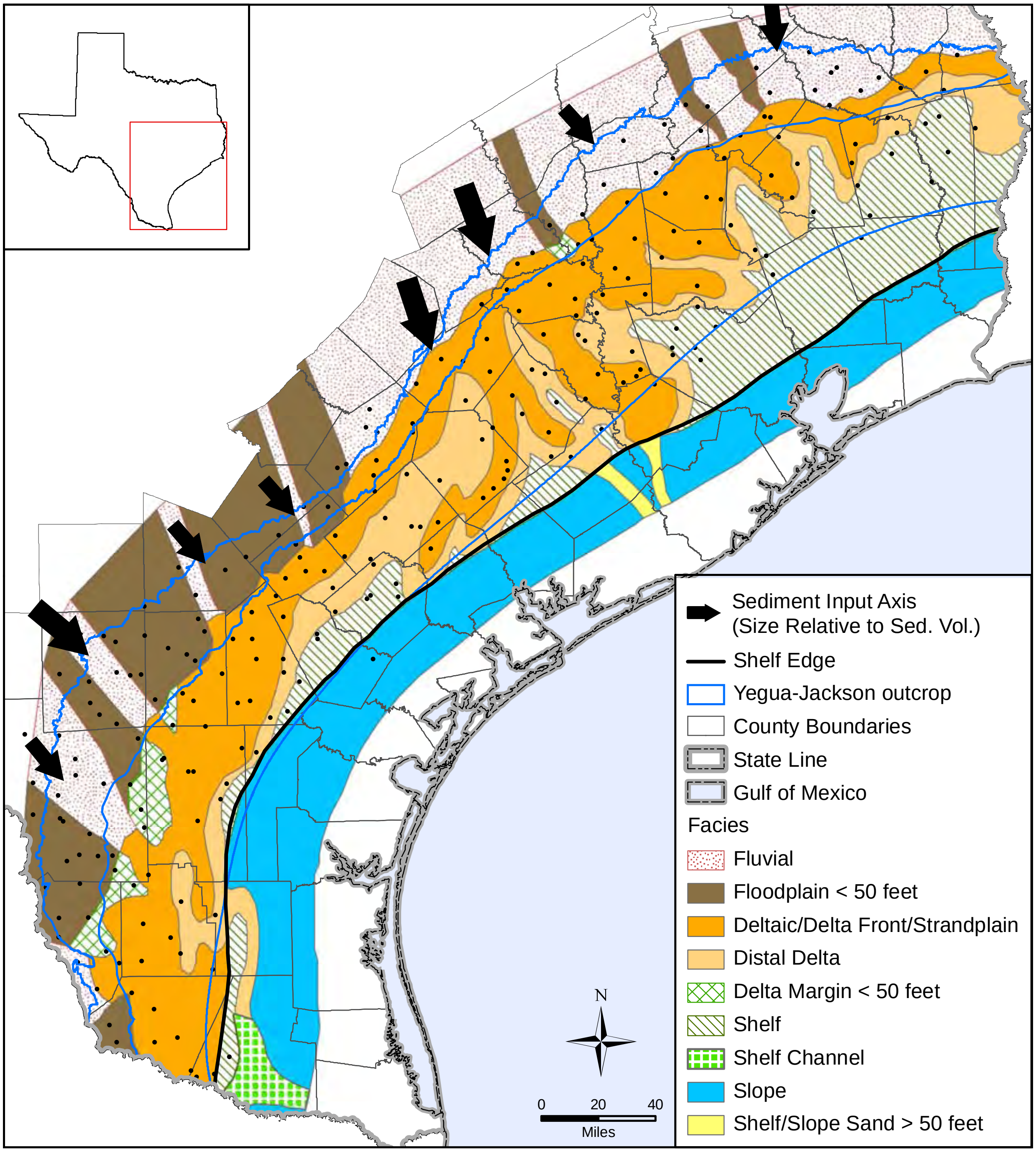


Figure 4.2.24 Upper Jackson Unit depositional facies map (Knox and others, 2007).

4.3 Water Levels and Regional Groundwater Flow

Water-level data for the Jackson Group and Yegua Formation were obtained from the TWDB website (TWDB, 2008b) in the groundwater database. Water-level data were available for these two units through the United States Geological Survey (United States Geological Survey, 2008a), but were found to be a subset of the TWDB data, with the exception of a single measurement that was not used.

The groundwater availability model for the Yegua-Jackson Aquifer separates both the Jackson Group and Yegua Formation into upper and lower units for a total of four model layers. In order to evaluate the water-level data with respect to each model layer, the layer into which the wells are completed was determined. This was done using the completion interval, screened or open hole interval(s), or the total depth when the completion interval was unknown. Completion intervals were obtained from the TWDB website (TWDB, 2008b) and from drillers' logs. These intervals were compared to the top and bottom elevations of the upper and lower units of the Jackson Group and upper and lower units of the Yegua Formation as given in Knox and others (2007) to determine the layer(s) into which the wells were completed. In several cases, the location determined through this process was inconsistent with the aquifer code given for the well on the TWDB website (TWDB, 2008b). For example, the comparison of completion interval to structural tops and bottoms might indicate a well is completed in the Lower Jackson Unit, but the aquifer code for the well indicates it is completed into the Yegua Formation. In these instances, the unit determined based on the comparison of completion interval and structural tops and bottoms was used rather than the aquifer code. In addition, the completion interval for several wells fell either above the top of the Upper Jackson Unit or below the base of the Lower Yegua Unit. Those wells were not used in evaluating water-level data for the Yegua-Jackson Aquifer. A specific unit could be determined for 91 percent of the wells with a known completion interval.

For wells where a completion interval could not be found, the total depth was used in an effort to determine into which unit the wells were completed. The following summarizes how the total depth was used to assign a unit to each well.

- If a well had an aquifer code indicating it was completed into the Jackson Group and the total depth fell within the structure for the Upper Jackson Unit, it was assigned to the Upper Jackson Unit.
- If a well had an aquifer code indicating it was completed into the Jackson Group, the total depth fell within the structure for the Lower Jackson Unit, and the Upper Jackson Unit was missing at the well location, the well was assigned to the Lower Jackson Unit.
- If a well had an aquifer code indicating it was completed into the Jackson Group, the total depth fell within the structure for the Lower Jackson Unit, and the Upper Jackson Unit was present at the well location, the unit into which the well was completed could not be conclusively determined and the well was not used.
- If a well had an aquifer code indicating it was completed into the Yegua Formation and the total depth fell within the structure for the Upper Yegua Unit, it was assigned to the Upper Yegua Unit.
- If a well had an aquifer code indicating it was completed into the Yegua Formation, the total depth fell within the structure for the Lower Yegua Unit or below the bottom of the Lower Yegua Unit, and the Upper Yegua Unit was missing at the well location, the well was assigned to the Lower Yegua Unit.
- If a well had an aquifer code indicating it was completed into the Yegua Formation, the total depth fell within the structure for the Lower Yegua Unit or below the bottom of the Lower Yegua Unit, and the Upper Yegua Unit was present at the well location, the unit into which the well was completed could not be conclusively determined and the well was not used.
- If the total depth fell above the top of the Upper Jackson Unit, the well was not used.
- If the total depth fell below the bottom of the Lower Yegua Unit, and the Lower Jackson Unit, Upper Jackson Unit, and/or Upper Yegua Unit were present at the well location, the unit into which the well was completed could not be conclusively determined and the well was not used.

- If the layer into which the total depth fell was inconsistent with the aquifer code (i.e., total depth located in Lower Yegua Unit but aquifer code indicates Jackson Group), the unit into which the well was completed could not be conclusively determined and the well was not used.

A specific unit could be assigned for 65 percent of the wells that did not have a completion interval by using the total depth. The results of the evaluation of model layer for each well are provided in Appendix A.

The following evaluation of water-level data for the Yegua-Jackson Aquifer used only those wells for which a specific unit could be determined. Figure 4.3.1 shows the location of wells with water-level data by unit and Table 4.3.1 summarizes the number of wells per county by unit. Note that counties and units having no wells with water-level data are left blank in Table 4.3.1. About the same number of wells are completed into the Upper Jackson Unit, Upper Yegua Unit, and Lower Yegua Unit, with significantly fewer wells completed into the Lower Jackson Unit. Wells with water-level data are almost exclusively limited to the outcrop area of the Yegua-Jackson Aquifer. In addition, several counties in which the outcrop is located have few wells (i.e., Atascosa, Houston, LaSalle, Lee, Madison, McMullen, Nacogdoches, Walker, Webb, and Wilson counties). The number of water-level measurements per county and unit is summarized in Table 4.3.2. In this table, counties and units having no water-level data are left blank. The fewest number of measurements are available for the Lower Jackson Unit and the greatest number are available for the Upper Yegua Unit.

A check was conducted to determine whether eliminating some wells that could not be assigned to a specific unit contributed to the low number of wells and water-level measurements in some counties. This check indicated that the majority of wells eliminated are located in counties with a large number of wells and measurements, so eliminating them has little impact on the evaluation of water-level data for the Yegua-Jackson Aquifer. For the few unused wells that are located in counties with few data, their water-level measurements are predominately from the 1950s and 1960s, which is a period of time that does not contribute to the understanding of water levels under pre-development conditions or conditions during the model calibration period.

The number of water-level measurements by year is summarized in Figure 4.3.2. Several water-level measurements are available prior to 1950 in all four units, with one as early as 1911 and 1912 in the Upper and Lower Yegua units, respectively. The distribution of water-level measurements by year varies for the four units. The greatest number of measurements is available in 1956 for the Upper Jackson Unit, in 1989 for the Lower Jackson Unit and Upper Yegua Unit, and in 1988 for the Lower Yegua Unit.

4.3.1 Regional Groundwater Flow

Groundwater in the Yegua-Jackson Aquifer is under water-table conditions in the shallow outcrop areas and under confined conditions in the deeper, dipping sediments. In some confined areas, artesian pressures in the aquifer were originally sufficient to drive water above ground surface. Groundwater flow in the Yegua-Jackson Aquifer is influenced by the topography in the outcrop areas. In general, groundwater flows from the topographically high areas along drainage divides to the topographically low areas in creeks and rivers.

In the confined portion of the aquifer, groundwater moves horizontally along the dip of the aquifer and vertically across formations, assuming no influence from pumpage. In general, the dip of the aquifer and land surface is toward the Gulf of Mexico, resulting in groundwater flow in the southward direction in Sabine, Newton, San Augustine, Jasper, Nacogdoches, Angelina, and Tyler counties, in the eastward direction in Webb, Duval, Zapata, Jim Hogg, and Starr counties, and in the southeasterly direction in the remaining counties.

4.3.2 Pre-Development Conditions

Pre-development conditions are defined as those existing when aquifer recharge is balanced by natural aquifer discharge. For the Yegua-Jackson Aquifer, this occurred prior to significant disturbances of natural groundwater flow due to artificial discharge via pumping. Pumping for rural domestic, livestock, and public supply purposes appears to have begun as early as 1900 in some counties (see Section 4.6.2). This pumping, however, was relatively small and likely did not result in significant drawdown of the aquifer. The water-level data for each aquifer layer prior to 1950 were assumed to be representative of pre-development conditions. These data were not sufficient to generate contour maps, but are posted in Figures 4.3.3, 4.3.4, 4.3.5, and 4.3.6 for the Upper Jackson Unit, Lower Jackson Unit, Upper Yegua Unit, and Lower Yegua Unit, respectively. The water-level elevations on these figures indicate large differences over relatively short distances in places in the outcrop area. This is predominantly due to the variation in topography resulting from the numerous rivers and streams that cross the outcrop. Table 4.3.3 summarizes the pre-development data presented on these figures. These data were used as calibration targets for the pre-development model.

4.3.3 Water-Level Elevations for Transient Model Calibration

Transient model calibration considers the time period from January 1, 1980 to December 31, 1997. Water-level data obtained from the TWDB website (TWDB, 2008b) were used to look at water-level elevations for the four units in the Yegua-Jackson Aquifer for the start of model calibration (January 1980), the middle of model calibration (January 1990), and the end of model calibration (December 1997). These water-level elevations were used to aid in assessing the transient model's ability to represent observed conditions.

Water-level data are not available at regular time intervals in every well. Therefore, the coverage of water-level data for a particular month or even a year is very sparse. Since the amount of water-level data available for the three times of interest are not sufficient to evaluate water-level elevations, data for the year of interest and for two years prior to and two years after the year of interest were used. If a well had only one water-level measurement during that time, that measurement was used. If a well had several water-level measurements during that time, the average of the water levels was used.

For each layer in the Yegua-Jackson Aquifer, the updip to downdip extent of wells having water-level data for the start, middle, and end of model calibration is very narrow and it was not possible to generate meaningful water-level elevation contours. Therefore, the water-level elevations for these three time periods are shown as posted values on figures. Figures 4.3.7 through 4.3.10 show the water-level elevations in the Upper Jackson Unit, Lower Jackson Unit, Upper Yegua Unit, and Lower Yegua Unit, respectively, at the start of model calibration (January 1980). Figures 4.3.11 through 4.3.14 show the water-level elevations in the Upper Jackson Unit, Lower Jackson Unit, Upper Yegua Unit, and Lower Yegua Unit, respectively, at the middle of model calibration (January 1990). Figures 4.3.15 through 4.3.18 show the water-level elevations in the Upper Jackson Unit, Lower Jackson Unit, Upper Yegua Unit, and Lower Yegua Unit, respectively, at the end of model calibration (December 1997).

A comparison of water levels at the start, middle, and end of model calibration is difficult based solely on the posted values on Figures 4.3.7 through 4.3.18. Table 4.3.4 presents the water-level elevations for wells having data for at least two of these three times for all four layers of the Yegua-Jackson Aquifer. This table also provides an indication of the trend in the water level and the magnitude of any observed increases or decreases over all or a portion of the model calibration time period. The information in Table 4.3.4 is also plotted on Figures 4.3.19 through 4.3.22 for the Upper Jackson Unit, Lower Jackson Unit, Upper Yegua Unit, and Lower Yegua Unit, respectively. The site numbers used to identify wells on these figures are included in Table 4.3.4. Some sites in these figures are identified as having a less than 2-foot change in water level, which indicates that any increase or decrease in water level in the well was less than 2 feet.

Figure 4.3.19 shows that water levels in the Upper Jackson Unit either increased or changed less than 2 feet between 1980 and 1997, with the exception of one downdip well in Fayette County that showed a decrease of over 50 feet during this time period. Figure 4.3.20 shows that water levels in the Lower Jackson Unit increased in Angelina County; changed less than 2 feet in Burleson and Trinity counties; decreased or changed less than 2 feet in Grimes County; and increased at one well and decreased at two wells in Fayette County during the 1980 to 1997 time period. Figure 4.3.21 shows that water levels in the Upper Yegua Unit decreased in Sabine and Madison counties; increased in three wells and decreased in three wells in Angelina County; increased in some wells, decreased in some wells, and changed less than 2 feet in some wells in Trinity and Fayette counties; decreased in some wells and changed less than 2 feet in other wells in Lee and Grimes counties; and increased in Karnes County during the 1980 to 1997 time period. Figure 4.3.22 shows that water levels in the Lower Yegua Unit decreased in Angelina and Lee counties; changed less than 2 feet in Madison, Grimes, and Fayette counties; increased in some wells and decreased in other wells in Sabine County; and changed less than 2 feet in some wells, increased in some wells, and decreased in some wells in Zapata County during the 1980 to 1997 time period. Based on the data shown in Figures 4.3.19 through 4.3.22, decreases of over 50 feet were observed in the Upper Jackson Unit in Fayette County and in the Upper Yegua Unit in Sabine and Angelina counties. Water levels in all four layers have either changed less than 2 feet or decreased in Grimes County. In the eastern portion of the aquifer from Trinity to Sabine counties, water levels in the Upper and Lower Jackson units increased while water levels in the Upper and Lower Yegua units predominately decreased.

A comparison of water levels for pre-development conditions in the aquifer and conditions during the period for the transient model calibration was also conducted. Unfortunately, data for this comparison is very limited. No wells in the Upper and Lower Jackson units have water-level measurements during both the pre-development period and the transient calibration period. One well in the Upper Yegua Unit and three wells in the Lower Yegua Unit have water-level measurements during both periods. Those data are summarized in Table 4.3.5. For the well completed into the Upper Yegua Unit, the water-level elevation during the pre-development period, measured in 1937, is lower than that observed in 1980, 1990, and 1997 by 4, 9, and 10 feet, respectively. Based on these measurements, it appears that the water level in this well has continually risen over time. The water-level elevation during the pre-development period is lower than that observed during the transient calibration period for two of the wells completed into the Lower Yegua Unit and higher for one well. The difference in water-level elevation between pre-development conditions, based on a measurement in 1948, and 1980 is 50 feet for well 59-08-904 located in Madison County. This indicates a 50-foot rise in water level in this well between 1948 and 1980. The magnitude of this rise suggests the possibility that the 1948 water level measured in the well is not really representative of pre-development conditions. For well 86-16-701 located in Zapata County and completed into the Lower Yegua Unit, the pre-development water level, measured in 1940, is about 20 feet lower than the water level measured in 1980. The water level under pre-development conditions is about 4 feet higher than the water level in 1980 in well 37-48-303 located in Sabine County and completed into the Lower Yegua Unit.

4.3.4 Cross-Formational Flow

An exercise was conducted to investigate cross-formational flow between the four units in the Yegua-Jackson Aquifer. At several places, wells completed separately into two of the units in the aquifer share a similar ground-surface location. The wells at these locations were used to assess upward or downward hydraulic gradients indicative of cross-formational flow between the units.

The top two plots in Figure 4.3.23 show water-level elevations in the Upper Jackson Unit and Lower Jackson Unit at two locations. From the limited data available at these two locations, the gradient was upward from the Lower Jackson Unit to the Upper Jackson Unit in Karnes County in the 1950s and the gradient was downward from the Upper Jackson Unit to the Lower Jackson Unit in Washington County in the late 1960s.

Figure 4.3.24 shows water-level elevations in the Lower Jackson Unit and Upper Yegua Unit at four locations. These data indicate a downward gradient from the Lower Jackson Unit to the Upper Yegua Unit in Angelina and Sabine counties in the late 1980s and mid-1960s, respectively, and little gradient between the two units in Grimes and Burleson counties in about 1970.

A comparison of water-levels in the upper and Lower Yegua Unit at one location is also shown in the bottom plot in Figure 4.3.23. This comparison indicates an upward gradient from the Lower Yegua Unit to the Upper Yegua Unit in Sabine County prior to 1950.

An exercise was also conducted to investigate cross-formational flow between the Upper Jackson Unit and the overlying Catahoula Formation, between the Lower Yegua Unit and the underlying Cook Mountain Formation, and between the Lower Yegua Unit and underlying Sparta Formation through the Cook Mountain Formation.

Figure 4.3.25 shows water-level elevations in the Catahoula Formation and the Upper Jackson Unit at five locations. At the locations in Polk, Washington, and Fayette counties, a downward gradient from the Catahoula Formation to the Upper Jackson Unit is indicated by available water-level data. At the location in Brazos County, an upward gradient from the Upper Jackson Unit to the overlying Catahoula Formation is indicated.

A comparison between water-level elevations in the Lower Yegua Unit and the underlying Cook Mountain Formation at four locations, all in Brazos County, are shown in Figure 4.3.26. At three of the locations, the data indicates a downward gradient from the Lower Yegua Unit to the

Cook Mountain Formation in the 1960s. At the other location, however, the data indicate an upward gradient from the Cook Mountain Formation to the Upper Yegua Unit also during the 1960s.

The Lower Yegua Unit is separated from the underlying Sparta Formation by the Cook Mountain Formation. Water-level elevations in the Lower Yegua Unit and Sparta Formation were compared to evaluate the gradient between these to units and the potential for flow across the Cook Mountain Formation. At all three locations with data (Figure 4.3.27), the water-level elevations in the Lower Yegua Unit are higher than those in the Sparta Formation, indicating the potential for downward flow.

This investigation of the potential for cross formation flow within the units of the Yegua-Jackson Aquifer and from the aquifer to overlying and underlying units is very limited for several reasons. First, completion data for wells in the Yegua-Jackson Aquifer are limited, resulting in uncertainty in the determination of whether the wells are completed into the Upper Jackson Unit, Lower Jackson Unit, Upper Yegua Unit, and Lower Yegua Unit. Second, only one measurement is available in each unit for most locations used for the comparisons. Any error in those measurements or impact of pumping in the well or near the well on the measurement could impact conclusions.

4.3.5 Transient Water Levels

Transient water-level data are used to calibrate the transient model. Figure 4.3.28 shows the locations of the 77 wells for which transient water-level data, defined as five or more water-level measurements, are available for the Yegua-Jackson Aquifer based on data found in the TWDB Groundwater Database (TWDB, 2008b). Of those wells, 17 are completed into the Upper Jackson Unit, 10 are completed into the Lower Jackson Unit, 25 are completed into the Upper Yegua Unit, 20 are completed into the Lower Yegua Unit, one is completed into both the Upper and Lower Jackson units, one is completed into both the Lower Jackson Unit and Upper Yegua Unit, and three are completed into both the Upper and Lower Yegua units. Table 4.3.6 summarizes the wells with transient water-level data, the year of the first and last water-level measurement, and the total number of water-level measurements. For about three-quarters of these wells, transient water-level data are available during the model calibration period from January 1980 through December 1997.

Figures 4.3.29 through 4.3.35 contain hydrograph plots of the transient water-level data for selected wells. Data for wells with long-term water-level records were selected for these plots. Most of these hydrographs are plotted with a 100-foot elevation range on the y-axis. In some cases, the difference in water-level elevation was greater than 100 feet and the y-axis was expanded. In all cases, the interval between grid lines on the y-axis is 10 feet.

Figure 4.3.29 shows water-level elevations with an increasing or stable trend in five wells completed into the Upper Jackson Unit. The increases are about 5 to 10 feet, with the exception of the well in Trinity County that shows an increase of about 70 feet between about 1990 and 2008. Note that two of these wells are located in the outcrop and three are located right on the edge of the outcrop. Figure 4.3.30 shows water-level elevations with fluctuating or decreasing trends in four wells completed into the Upper Jackson Unit. The decreases are about 30 feet in Trinity County and over 80 feet in Fayette County. Note that both these wells with large decreases, as well as the well in Walker County with a fluctuating trend, are located in the downdip portion of the Upper Jackson Unit.

Figure 4.3.31 shows water-level elevations in five wells located in the Lower Jackson Unit. The water levels show a stable trend in one well, an increasing trend in two wells, a decreasing trend in one well, and a fluctuation trend in one well. The magnitude of the increases ranges from about 5 to 15 feet and the magnitude of the decrease is about 20 feet. The well with the fluctuating trend shows large fluctuations on the order of about 10 to 130 feet. It is unknown whether these fluctuations are due to pumping conditions or to conditions in the aquifer. All water-level data from the TWDB Groundwater Database (TWDB, 2008b) labeled as not publishable, having a remark indicating a questionable measurement, or one affected by pumping were removed. However, if the measurement was questionable or taken when affected by pumping and no remark was recorded, that measurement would be included in the data presented here. Note that the well in Grimes County with the decreasing trend is located in the outcrop of the Lower Jackson Unit and the only well located in the downdip area (well 60-05-301 in Trinity County) shows a slight increasing trend in water levels.

Figure 4.3.32 shows water-level elevations with increasing or decreasing then increasing trends in five wells completed into the Upper Yegua Unit. The magnitudes of the increases are small; ranging from about 10 to 15 feet. For the two wells with a decreasing then increasing trend in water levels, the magnitude of the decrease ranges from about 30 to 70 feet and the magnitude of the increase ranges from about 10 to 45 feet. The switch from a decreasing trend to an increasing trend occurred in about 1990 for the well in Angelina County and in about 2000 for the well in Grimes County. The well in Fayette County with the slightly increasing trend in water levels, as well as the well in Grimes County, is located in the downdip portion of the Upper Yegua Unit. The other three wells on this figure are located at the edge of the outcrop. Figure 4.3.33 shows water-level elevations with a decreasing trend in four wells completed in the Upper Yegua Unit. The magnitude of the observed decreases ranges from about 20 to 100 feet. The well in Angelina County is located in the downdip portion of the Upper Yegua Unit and the other three wells are located in the outcrop.

Figure 4.3.34 shows water-level elevations with increasing or decreasing trends in five wells completed into the Lower Yegua Unit. All five of these wells are located in the outcrop area. A large decrease of about 120 feet is observed in the well in Angelina County. The magnitude of the increases ranges from about 10 to 20 feet. Figure 4.3.35 shows water-level elevations with stable or fluctuating trends for five wells completed into the Lower Yegua Unit. All of these wells are located in the outcrop area, except for well 36-41-702 in Sabine County.

Based on the available transient data, the following summaries can be made. The observed increases in water levels generally range from about 10 to 20 feet for all units in the Yegua-Jackson Aquifer. The only exception is the large increase of about 70 feet observed in a well completed into the Upper Jackson Unit. Large declines in water level have been observed in the Upper Jackson Unit and in the Upper and Lower Yegua units. The absence of observed decreases in the Lower Jackson Unit could be due to no declining water levels in that layer or the lack of data for wells completed into that layer. The largest declines in water levels are observed in the downdip portion of the Upper Jackson Unit in Fayette County and in the Upper and Lower Yegua units in Angelina County. Due to an overall lack of data in the four units of the Yegua-Jackson Aquifer, no strong conclusions can be made regarding areas of water-level declines in the aquifer.

An attempt was made to analyze the transient water-level data for the Upper Jackson Unit, Lower Jackson Unit, Upper Yegua Unit, and Lower Yegua Unit with respect to seasonal fluctuations. This analysis could not be performed, however, because measurements of water levels at a frequency sufficient for evaluation of seasonal changes were not taken in any well completed in any unit in the Yegua-Jackson Aquifer.

Table 4.3.1 Number of wells with water-level data completed in the Yegua-Jackson Aquifer by county.

County	Number of Wells with Water-Level Data				
	Upper Jackson Unit	Lower Jackson Unit	Upper Yegua Unit	Lower Yegua Unit	Total[(1)]
Angelina	15	14	47	42	118
Atascosa	3		2		5
Austin					
Bastrop					
Bee					
Brazos	6	6	14	63	89
Brooks					
Burleson	7	7	27	20	60
Colorado					
DeWitt					
Duval					
Fayette	32	15	32	9	85
Fort Bend					
Goliad					
Gonzales	6	4	5	4	19
Grimes	17	7	17	2	43
Hardin					
Harris					
Hidalgo					
Houston			2	1	3
Jackson					
Jasper					
Jim Hogg					
Jim Wells					
Karnes	23	7	15		45
LaSalle			1	3	3
Lavaca					
Lee			3	1	3
Leon					
Liberty					
Live Oak	17				17
Madison			3	3	6
McMullen	8		1		9
Montgomery					
Nacogdoches				2	2
Newton					
Polk	31		1		32
Sabine	9	5	15	16	44
San Augustine			5	5	10
San Jacinto					
Starr	11		6	8	25
Trinity	11	3	12	1	26
Tyler					
Victoria					
Walker	7	1			8
Waller					
Washington	21	5			26
Webb			5	2	7
Wharton					
Wilson		1			1
Zapata	1			16	17
Total	226	75	213	198	712

[(1)]May be less than sum of wells completed into each layer, because some wells are completed into more than one layer.

Table 4.3.2 Number of water-level measurements in the Yegua-Jackson Aquifer by county.

County	Number of Water-Level Measurements				
	Upper Jackson Unit	Lower Jackson Unit	Upper Yegua Unit	Lower Yegua Unit	Total[(1)]
Angelina	60	39	142	83	324
Atascosa	3		2		5
Austin					
Bastrop					
Bee					
Brazos	6	6	15	67	94
Brooks					
Burleson	7	35	31	24	96
Colorado					
DeWitt					
Duval					
Fayette	99	72	134	19	284
Fort Bend					
Goliad					
Gonzales	6	6	13	5	30
Grimes	74	83	106	20	274
Hardin					
Harris					
Hidalgo					
Houston			5	1	6
Jackson					
Jasper					
Jim Hogg					
Jim Wells					
Karnes	28	9	54		91
LaSalle			1	3	3
Lavaca					
Lee			97	33	97
Leon					
Liberty					
Live Oak	18				18
Madison			34	48	82
McMullen	9		1		10
Montgomery					
Nacogdoches				2	2
Newton					
Polk	77		1		78
Sabine	24	5	55	140	201
San Augustine			5	5	10
San Jacinto					
Starr	35		6	8	49
Trinity	66	68	93	1	227
Tyler					
Victoria					
Walker	43	1			44
Waller					
Washington	22	13			35
Webb			7	2	9
Wharton					
Wilson		1			1
Zapata	1			134	135
Total	578	338	802	595	2205

[(1)]May be less than sum of wells completed into each layer, because some wells are completed into more than one layer.

Table 4.3.3 Target values for calibration of the pre-development model.

State Well Number	County	Measurement Date	Observed Water-Level Elevation (feet)
Upper Jackson Unit			
3751901	Angelina	6/1/1937	213.1
3761203	Angelina	4/15/1937	186.5
7823203	Atascosa	11/30/1928	337.8
5950908	Fayette	7/29/1942	314.6
5958204	Fayette	11/30/1924	364.0
5958303	Fayette	11/30/1924	309.0
5958704	Fayette	7/20/1942	343.0
6601610	Fayette	11/30/1919	261.5
6601806	Fayette	11/30/1917	259.0
6601902	Fayette	12/21/1946	204.0
6602103	Fayette	11/30/1921	330.0
6609106	Fayette	7/3/1942	319.5
6716803	Fayette	11/30/1941	333.0
6716904	Fayette	11/30/1947	385.0
6723608	Fayette	10/9/1942	374.6
6724105	Fayette	11/30/1940	354.0
6724205	Fayette	10/13/1942	425.1
6758403	Karnes	12/16/1936	275.7
7808803	Karnes	10/19/1936	350.9
7901302	Karnes	11/13/1936	265.7
7901401	Karnes	10/8/1936	264.7
3758101	Polk	5/16/1947	247.0
3758303	Polk	6/26/1947	214.9
6101101	Polk	4/30/1946	210.0
3651302	Sabine	6/8/1942	161.0
3651408	Sabine	5/31/1942	193.4
6003802	Walker	9/8/1948	162.7
6005101	Walker	9/16/1948	148.5
5944706	Washington	11/11/1942	259.4
5944804	Washington	11/11/1942	240.4
5944902	Washington	11/11/1942	325.0
5951202	Washington	11/12/1942	301.4
Lower Jackson Unit			
5944104	Burleson	6/1/1937	248.4
5944201	Burleson	5/16/1947	197.8
5944303	Burleson	6/26/1947	189.0
5958102	Fayette	4/15/1937	336.4
6601105	Fayette	11/11/1942	249.1
6708905	Fayette	11/11/1942	357.3
6723508	Fayette	7/29/1942	335.0
6009803	Grimes	11/11/1942	255.0
6758301	Karnes	11/12/1942	292.1
6758305	Karnes	11/30/1924	293.8
6758402	Karnes	11/30/1924	278.4
3649111	Sabine	6/8/1942	224.5
3861704	Walker	5/31/1942	272.3
Upper Yegua Unit			
3742703	Angelina	6/1/1937	256.9
3743402	Angelina	5/16/1947	252.2
3743602	Angelina	6/26/1947	308.0
3744803	Angelina	4/15/1937	209.8
3750605	Angelina	7/29/1942	135.0

Table 4.3.3, continued

State Well Number	County	Measurement Date	Observed Water-Level Elevation (feet)
Upper Yegua Unit (continued)			
3751102	Angelina	11/12/1942	271.1
3751301	Angelina	11/30/1924	235.0
3752203	Angelina	11/30/1924	250.0
3753102	Angelina	7/20/1942	173.0
7814202	Atascosa	11/13/1936	261.0
5936301	Burleson	9/16/1948	232.5
5936706	Burleson	4/30/1946	260.9
5936903	Burleson	11/30/1919	241.7
5937110	Burleson	11/30/1917	224.2
5943204	Burleson	12/21/1946	312.0
6708504	Fayette	11/30/1921	270.0
6715604	Fayette	7/3/1942	364.8
6716101	Fayette	11/30/1941	314.9
6723306	Fayette	11/30/1947	287.7
6737501	Gonzales	10/9/1942	261.9
6744301	Gonzales	11/30/1940	223.0
5916801	Grimes	9/8/1948	230.2
6750903	Karnes	10/13/1942	285.7
6751403	Karnes	12/16/1936	280.5
6757503	Karnes	10/19/1936	298.8
6758101	Karnes	11/30/1928	266.0
3643702	Sabine	6/8/1942	165.2
3649104	Sabine	5/31/1942	120.2
3748606	Sabine	11/11/1942	302.9
3747903	San Augustine	11/11/1942	164.9
3748401	San Augustine	11/11/1942	192.2
8640601	Starr	10/8/1936	278.7
Lower Yegua Unit			
3734803	Angelina	6/1/1937	367.8
3742601	Angelina	5/16/1947	225.0
3743101	Angelina	6/26/1947	298.0
3743302	Angelina	4/15/1937	341.3
5930202	Brazos	9/8/1948	175.0
5928904	Burleson	7/20/1942	211.0
5935304	Burleson	9/16/1948	268.9
5935803	Burleson	4/30/1946	313.9
5864904	Fayette	11/30/1924	300.3
6715305	Fayette	11/30/1919	302.0
6737402	Gonzales	11/30/1917	266.0
5908904	Madison	11/30/1924	197.0
3746402	Nacogdoches	11/11/1942	181.8
3641206	Sabine	6/8/1942	296.1
3649106	Sabine	5/31/1942	182.0
3748303	Sabine	11/12/1942	351.3
3746301	San Augustine	11/11/1942	199.7
3747602	San Augustine	11/11/1942	213.2
3748202	San Augustine	7/29/1942	236.9
8632801	Starr	7/3/1942	185.5
8530102	Webb	12/21/1946	461.0
8616701	Zapata	11/30/1921	268.0

Table 4.3.4 Comparison of average 1980, 1990, and 1997 water-level elevations.

State Well Number	County	Site Number on Figures	Average 1980 Water-Level Elevation (feet)	Average 1990 Water-Level Elevation (feet)	Average 1997 Water-Level Elevation (feet)	Trend	Magnitude of Increase (feet)	Magnitude of Decrease (feet)
Upper Jackson Unit								
3760201	Angelina	1	255.6	268.7	273.2	increase	17.6	
5958301	Fayette	2	337.0	338.8	338.6	increase-decrease	1.8	0.2
6617614	Fayette	3	212.0	182.2	157.7	decrease		54.3
6724401	Fayette	4	343.1	343.7	345.6	increase	2.6	
5932701	Grimes	5	193.0	193.0	192.5	stable-decrease		0.4
6017201	Grimes	6	309.2	309.4	308.7	increase-decrease	0.3	0.8
3757702	Polk	7	221.6	221.7	222.7	increase	1.2	
3649706	Sabine	8	171.2	173.3		increase	2.1	
3862801	Trinity	9	188.4	186.5	207.7	decrease-increase	21.2	1.8
6006801	Trinity	10	81.4	89.5	87.8	increase-decrease	8.1	1.7
6019302	Walker	11	295.1	302.3	297.6	increase-decrease	7.2	4.7
Lower Jackson Unit								
3753904	Angelina	12	103.4	113.4	125.6	increase	22.3	
5937611	Burleson	13	210.9	208.6	211.0	decrease-increase	2.4	2.3
6724101	Fayette	14	359.1	370.2	357.1	increase-decrease	11.1	13.1
6724401	Fayette	15	343.1	343.7	345.6	increase	2.6	
6724413	Fayette	16	362.0		354.5	decrease		7.5
5924702	Grimes	17	210.7	206.0	199.8	decrease		10.8
5924703	Grimes	18	197.0	207.7	196.0	increase-decrease	10.7	11.7
6010402	Grimes	19	205.9	202.8		decrease		3.1
3862302	Trinity	20	218.2	218.8	219.7	increase	1.5	
6005301	Trinity	21	130.8	131.1	132.0	increase	1.2	
Upper Yegua Unit								
3743902	Angelina	22	248.6	246.4	244.7	decrease		3.9
3745903	Angelina	23	135.0	140.1		increase	5.1	
3750303	Angelina	24	50.1	22.8	54.8	decrease-increase	31.9	27.3
3751204	Angelina	25		152.2	100.0	decrease		52.2
3751302	Angelina	26	212.0	198.9		decrease		13.1
3751403	Angelina	27	59.7	75.4	68.9	increase-decrease	15.7	6.5
5957701	Fayette	28	254.5	251.1	250.6	decrease		3.8
5957804	Fayette	29		254.7	255.3	increase	0.6	
5957906	Fayette	30	268.5	269.5	271.8	increase	3.3	
6601407	Fayette	31	267.4	265.6		decrease		1.8
5916804	Grimes	32	244.1	239.3	235.3	decrease		8.8
5924404	Grimes	33	223.1	210.8	205.1	decrease		18.0

Table 4.3.4, continued

State Well Number	County	Site Number on Figures	Average 1980 Water-Level Elevation (feet)	Average 1990 Water-Level Elevation (feet)	Average 1997 Water-Level Elevation (feet)	Trend	Magnitude of Increase (feet)	Magnitude of Decrease (feet)
Upper Yegua Unit (continued)								
6009502	Grimes	34	215.7	214.8		decrease		1.0
6750903	Karnes	35	289.7	294.8	296.0	increase	6.3	
5950401	Lee	36	333.6	326.5	319.5	decrease		14.1
5951102	Lee	37	275.6	275.7	274.2	increase-decrease	0.1	1.5
5957201	Lee	38	329.1	328.9	329.3	decrease-increase	0.3	0.1
6003102	Madison	39	187.6	185.1	180.7	decrease		6.9
3641707	Sabine	40	107.8	80.5	51.4	decrease		56.4
3741703	Trinity	41	187.0		174.8	decrease		12.2
3855403	Trinity	42	301.1	303.1	306.5	increase	5.4	
3856501	Trinity	43	301.5	298.8	302.9	decrease-increase	4.1	2.8
Lower Yegua Unit								
3742602	Angelina	44		108.3	103.7	decrease		4.6
3742606	Angelina	45	250.0	214.5		decrease		35.6
3743306	Angelina	46	257.0	245.9		decrease		11.1
3744703	Angelina	47	145.0	125.0		decrease		20.0
3744804	Angelina	48	63.0	16.3		decrease		46.7
5957804	Fayette	49		254.7	255.3	increase	0.6	
5915602	Grimes	50	241.7	247.4	242.4	increase-decrease	5.7	5.1
5950401	Lee	51	333.6	326.5	319.5	decrease		14.1
5908903	Madison	52	263.6	263.9	262.4	increase-decrease	0.3	1.5
5908904	Madison	53	247.4	246.3		decrease		1.1
3641205	Sabine	54	244.6	247.8	249.0	increase	4.3	
3641702	Sabine	55	150.3	138.4	139.9	decrease-increase	1.5	12.0
3641707	Sabine	56	107.8	80.5	51.4	decrease		56.4
3642401	Sabine	57	232.8	238.0	240.9	increase	8.1	
8615604	Zapata	58	316.8	317.1	317.6	increase	0.8	
8616402	Zapata	59		314.2	311.2	decrease		3.0
8616403	Zapata	60	279.6	266.9		decrease		12.8
8616501	Zapata	61	282.9	270.9	283.9	decrease-increase	13.0	12.0
8616705	Zapata	62	283.2	282.3	276.9	decrease		6.3
8616707	Zapata	63		277.9	271.4	decrease		6.5
8624503	Zapata	64	208.5	219.6		increase	11.1	

Table 4.3.5 Comparison of water-level elevations for the pre-development and transient calibration periods.

State Well Number	County	Pre-Development Water-Level Elevation (feet)	Average 1980 Water-Level Elevation (feet)	Average 1990 Water-Level Elevation (feet)	Average 1997 Water-Level Elevation (feet)
Upper Yegua Unit					
6750903	Karnes	285.7	289.7	294.8	296.0
Lower Yegua Unit					
5908904	Madison	197.0	247.4	246.3	
3748303	Sabine	351.3	347.8		
8616701	Zapata	268.0	287.6		

Table 4.3.6 Summary of transient water-level data for wells completed into the Yegua-Jackson Aquifer.

State Well Number	County	Aquifer Layer	Date of First Water-Level Measurement	Date of Last Water-Level Measurement	Number of Water-Level Measurements
3753906	Angelina	Upper Jackson Unit	1973	1982	7
3760201	Angelina	Upper Jackson Unit	1977	2007	36
5958301	Fayette	Upper Jackson Unit	1965	2008	29
6617614	Fayette	Upper Jackson Unit	1980	2007	11
5932701	Grimes	Upper Jackson Unit	1972	2006	21
6017201	Grimes	Upper Jackson Unit	1970	2007	35
3757701	Polk	Upper Jackson Unit	1966	1975	5
3757702	Polk	Upper Jackson Unit	1966	2008	34
3758501	Polk	Upper Jackson Unit	1947	1960	8
3649706	Sabine	Upper Jackson Unit	1971	1989	16
8717401	Starr	Upper Jackson Unit	1950	1962	9
8725802	Starr	Upper Jackson Unit	1950	1962	10
8733502	Starr	Upper Jackson Unit	1950	1959	8
3862801	Trinity	Upper Jackson Unit	1969	2008	35
6006801	Trinity	Upper Jackson Unit	1970	1995	17
6003803	Walker	Upper Jackson Unit	1972	1982	7
6019302	Walker	Upper Jackson Unit	1974	2007	30
6724401	Fayette	Upper and Lower Jackson Unit	1965	2000	28
3753904	Angelina	Lower Jackson Unit	1971	2007	18
5937611	Burleson	Lower Jackson Unit	1966	2008	29
6716202	Fayette	Lower Jackson Unit	1965	1984	14
6724101	Fayette	Lower Jackson Unit	1977	1997	16
5924702	Grimes	Lower Jackson Unit	1970	2007	34
5924703	Grimes	Lower Jackson Unit	1980	2007	22
6010402	Grimes	Lower Jackson Unit	1970	1989	16
3862302	Trinity	Lower Jackson Unit	1969	2008	35
6005301	Trinity	Lower Jackson Unit	1969	2008	32
5944601	Washington	Lower Jackson Unit	1968	1978	9
5924402	Grimes	Lower Jackson Unit and Upper Yegua Unit	1970	1978	8
3743902	Angelina	Upper Yegua Unit	1967	2007	36
3750303	Angelina	Upper Yegua Unit	1967	1995	16
3751204	Angelina	Upper Yegua Unit	1965	1998	5
3751403	Angelina	Upper Yegua Unit	1967	2007	25
5957701	Fayette	Upper Yegua Unit	1965	2008	28
5957905	Fayette	Upper Yegua Unit	1965	1981	15
5957906	Fayette	Upper Yegua Unit	1965	2007	29
6601407	Fayette	Upper Yegua Unit	1977	1994	14
6716501	Fayette	Upper Yegua Unit	1977	1986	9
6737501	Gonzales	Upper Yegua Unit	1938	1969	9
5916801	Grimes	Upper Yegua Unit	1942	1970	7
5916804	Grimes	Upper Yegua Unit	1959	2007	34
5924404	Grimes	Upper Yegua Unit	1978	2007	21
6009502	Grimes	Upper Yegua Unit	1970	1989	18
6750903	Karnes	Upper Yegua Unit	1937	2008	33
5951102	Lee	Upper Yegua Unit	1964	2008	34
5957201	Lee	Upper Yegua Unit	1973	2008	30
6003102	Madison	Upper Yegua Unit	1973	2007	28
6003501	Madison	Upper Yegua Unit	1971	1983	5
3649402	Sabine	Upper Yegua Unit	1971	1977	7
3650307	Sabine	Upper Yegua Unit	1971	1984	11

Table 4.3.6, continued

State Well Number	County	Aquifer Layer	Date of First Water-Level Measurement	Date of Last Water-Level Measurement	Number of Water-Level Measurements
3749102	Trinity	Upper Yegua Unit	1965	1985	14
3855403	Trinity	Upper Yegua Unit	1963	2008	37
3856501	Trinity	Upper Yegua Unit	1960	1995	23
3856502	Trinity	Upper Yegua Unit	1970	1976	7
5957804	Fayette	Upper Yegua Unit	1974	1997	11
5950401	Lee	Upper and Lower Yegua Unit	2007	2006	33
3641707	Sabine	Upper and Lower Yegua Unit	1968	2007	23
3742303	Angelina	Lower Yegua Unit	1937	1940	8
3744801	Angelina	Lower Yegua Unit	1959	1989	4
5915602	Grimes	Lower Yegua Unit	1970	1996	19
5908903	Madison	Lower Yegua Unit	1968	2007	31
5908904	Madison	Lower Yegua Unit	1948	1993	16
3641205	Sabine	Lower Yegua Unit	1963	1996	25
3641702	Sabine	Lower Yegua Unit	1965	2007	32
3642401	Sabine	Lower Yegua Unit	1964	2007	35
3748303	Sabine	Lower Yegua Unit	1942	1982	13
8615604	Zapata	Lower Yegua Unit	1973	1995	23
8615902	Zapata	Lower Yegua Unit	1961	2004	7
8616402	Zapata	Lower Yegua Unit	1961	1995	10
8616403	Zapata	Lower Yegua Unit	1961	1990	16
8616501	Zapata	Lower Yegua Unit	1961	1995	21
8616701	Zapata	Lower Yegua Unit	1940	1983	12
8616705	Zapata	Lower Yegua Unit	1961	2002	21
8616707	Zapata	Lower Yegua Unit	1986	1995	8
8624502	Zapata	Lower Yegua Unit	1961	1974	5
8624503	Zapata	Lower Yegua Unit	1971	1988	5
3742602	Angelina	Lower Yegua Unit	1963	1995	13

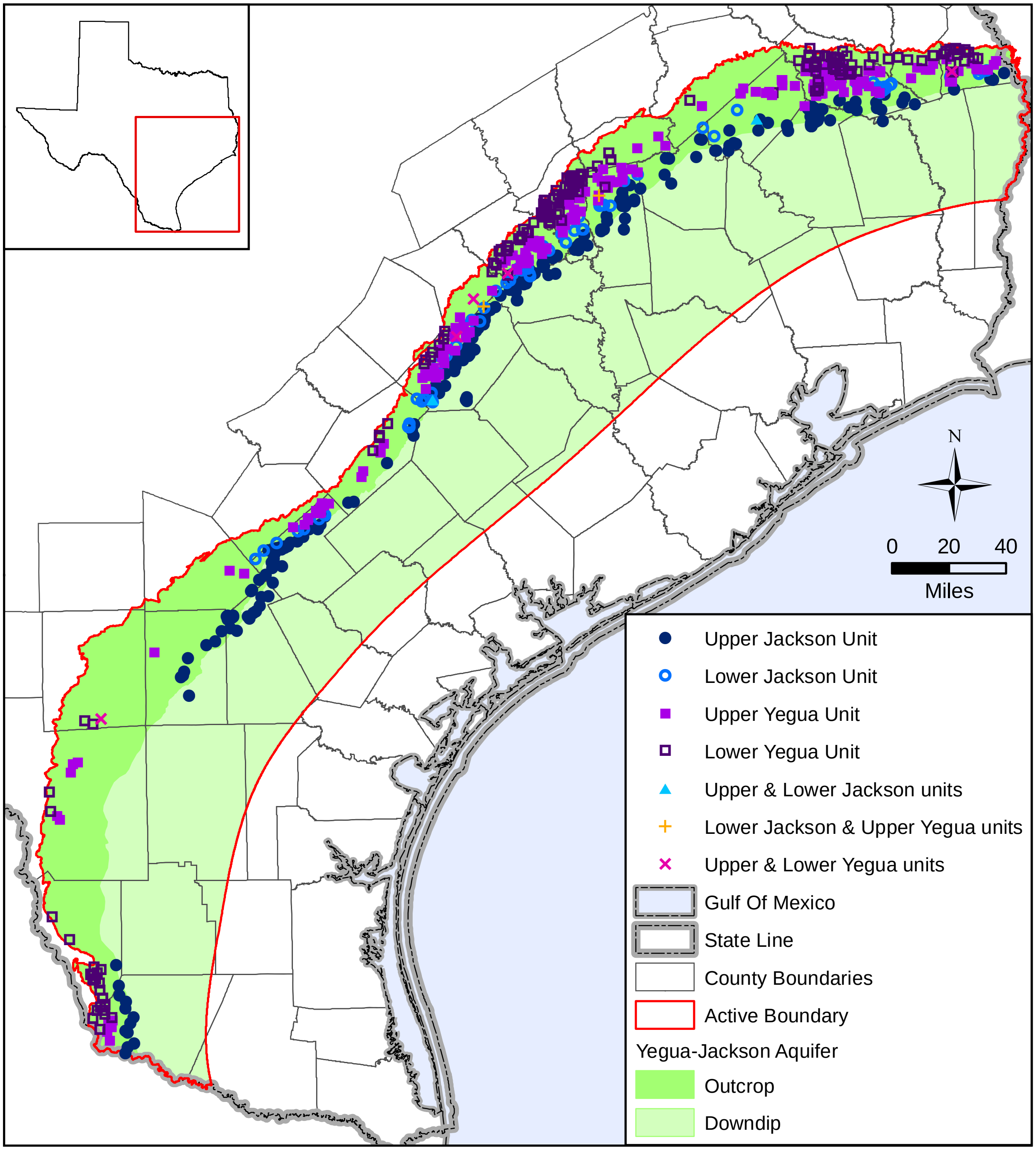


Figure 4.3.1 Water-level measurement locations for the Yegua-Jackson Aquifer.

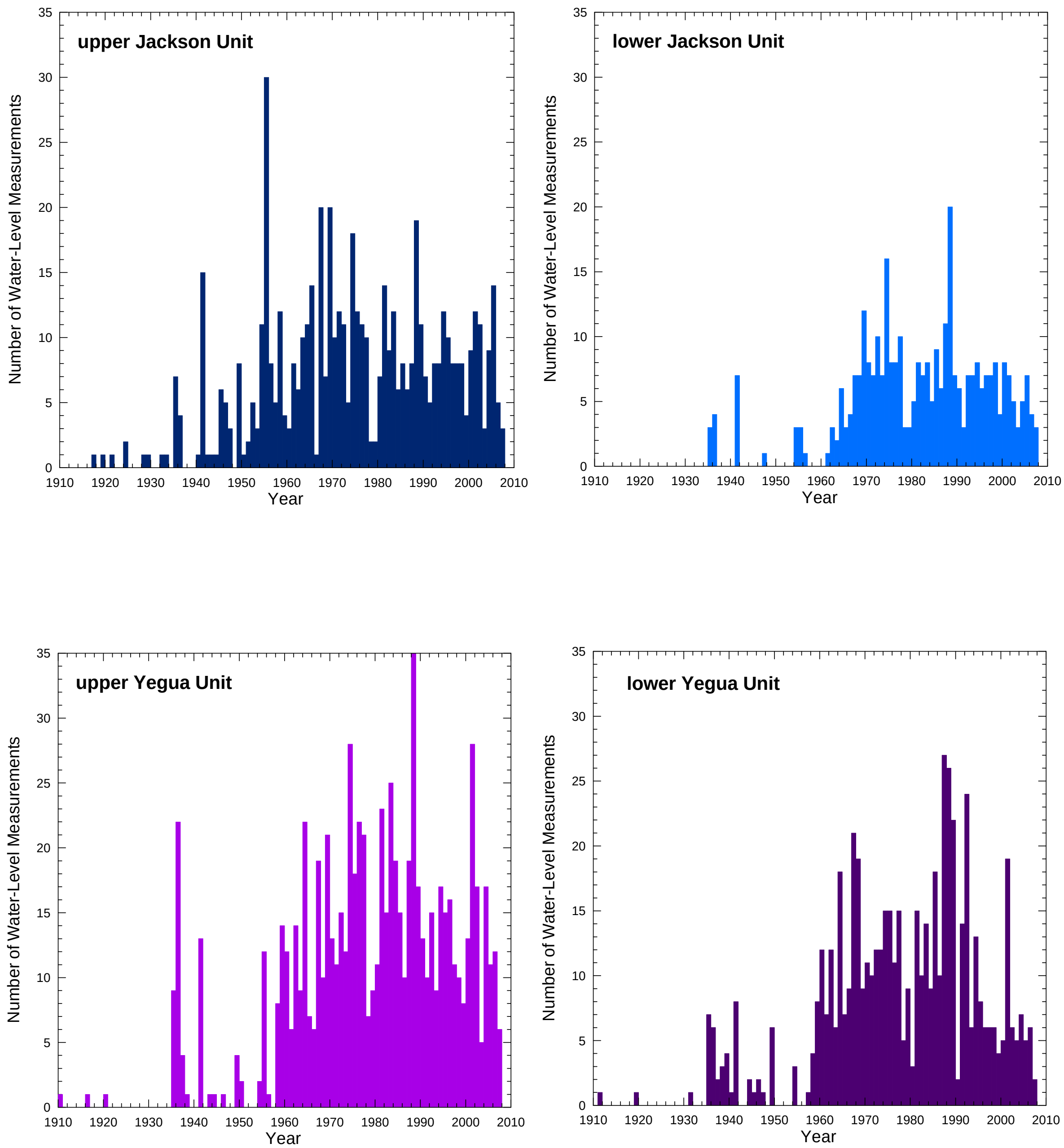


Figure 4.3.2 Temporal distribution of water-level measurements in the Yegua-Jackson Aquifer.

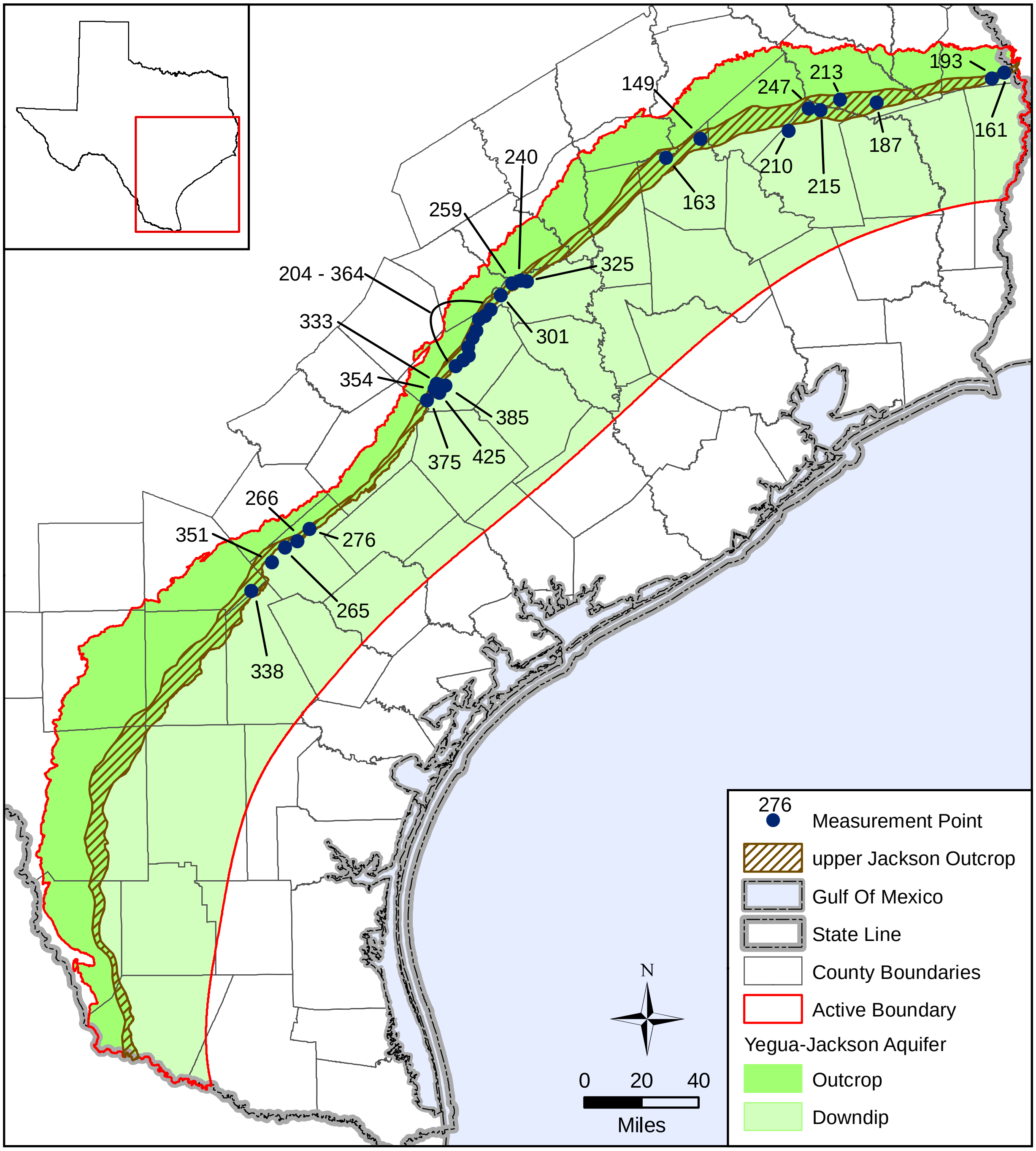


Figure 4.3.3 Estimated pre-development water-level elevations in feet for the Upper Jackson Unit of the Yegua-Jackson Aquifer.

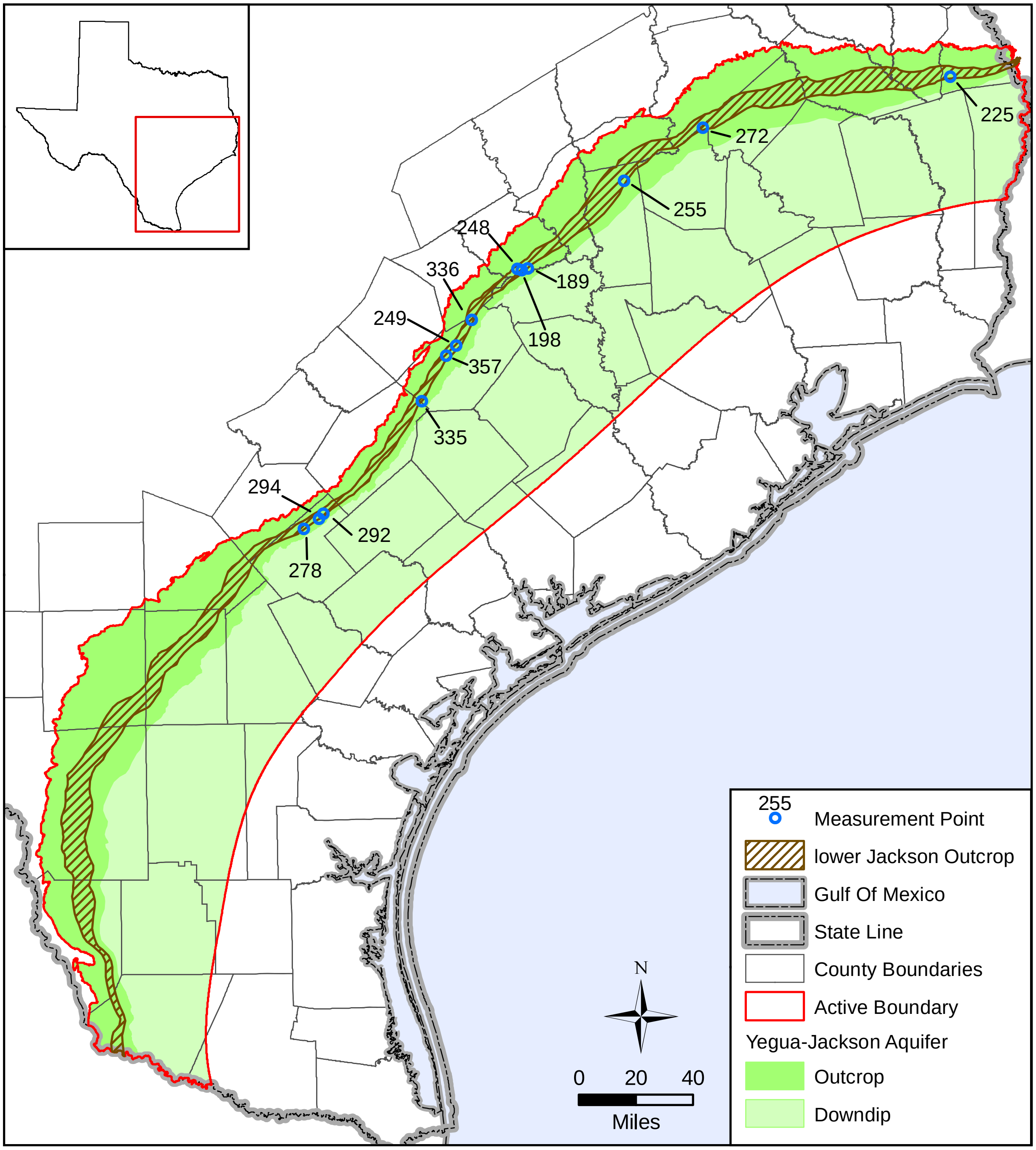


Figure 4.3.4 Estimated pre-development water-level elevations in feet for the Lower Jackson Unit of the Yegua-Jackson Aquifer.

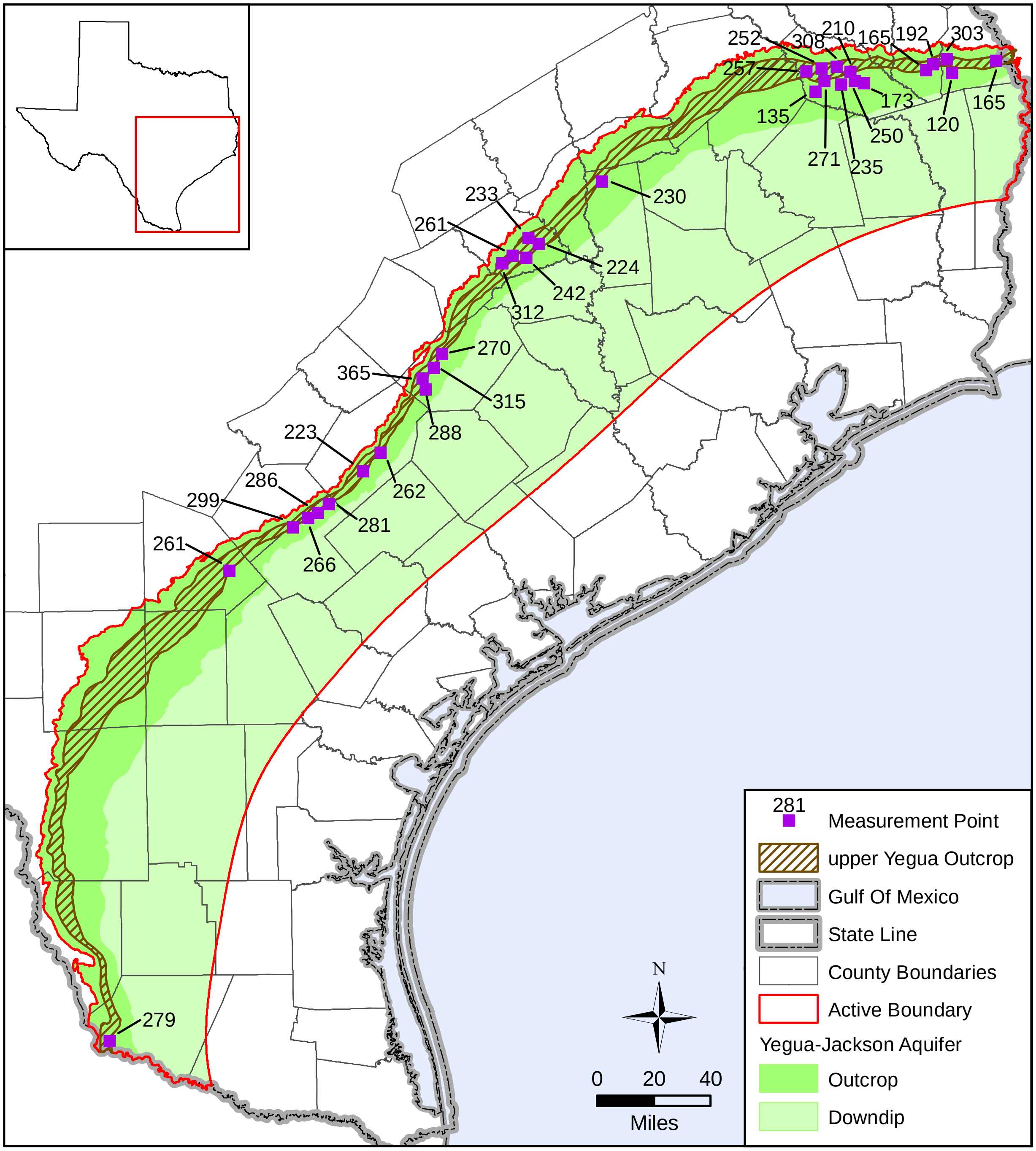


Figure 4.3.5 Estimated pre-development water-level elevations in feet for the Upper Yegua Unit of the Yegua-Jackson Aquifer.

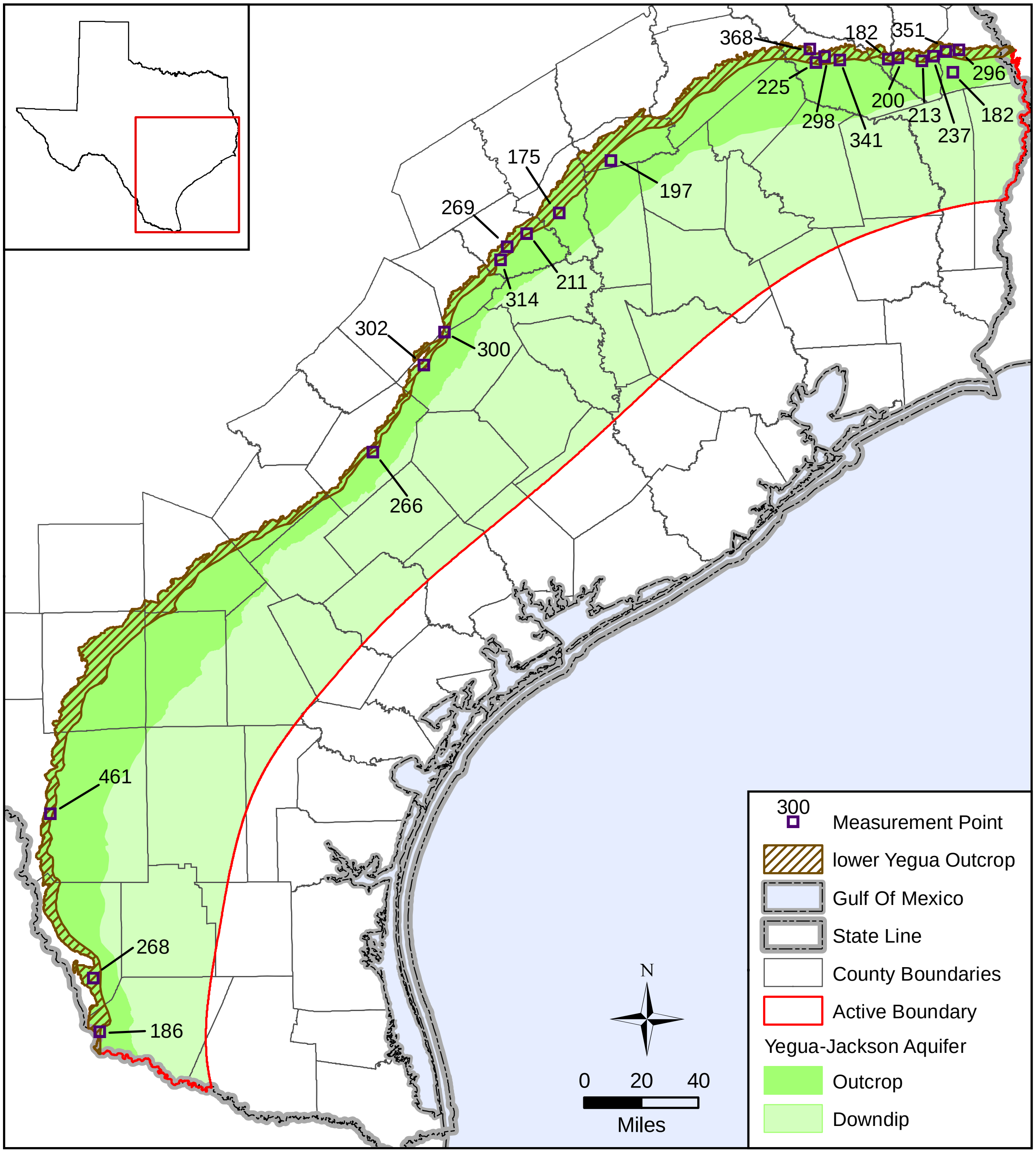


Figure 4.3.6 Estimated pre-development water-level elevations in feet for the Lower Yegua Unit of the Yegua-Jackson Aquifer.

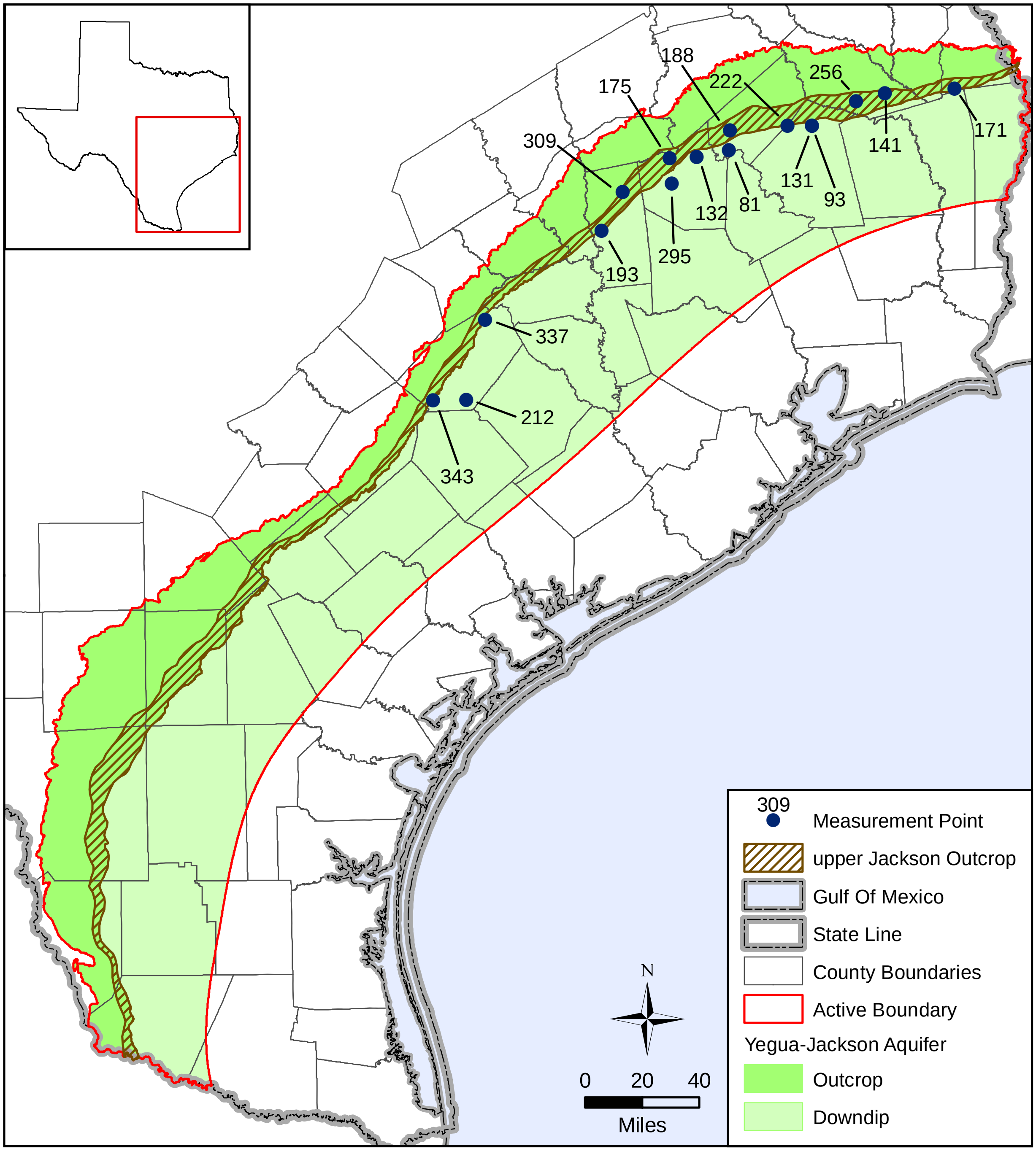


Figure 4.3.7 Estimated water-level elevations in feet for the Upper Jackson Unit of the Yegua-Jackson Aquifer at the start of model calibration (January, 1980).

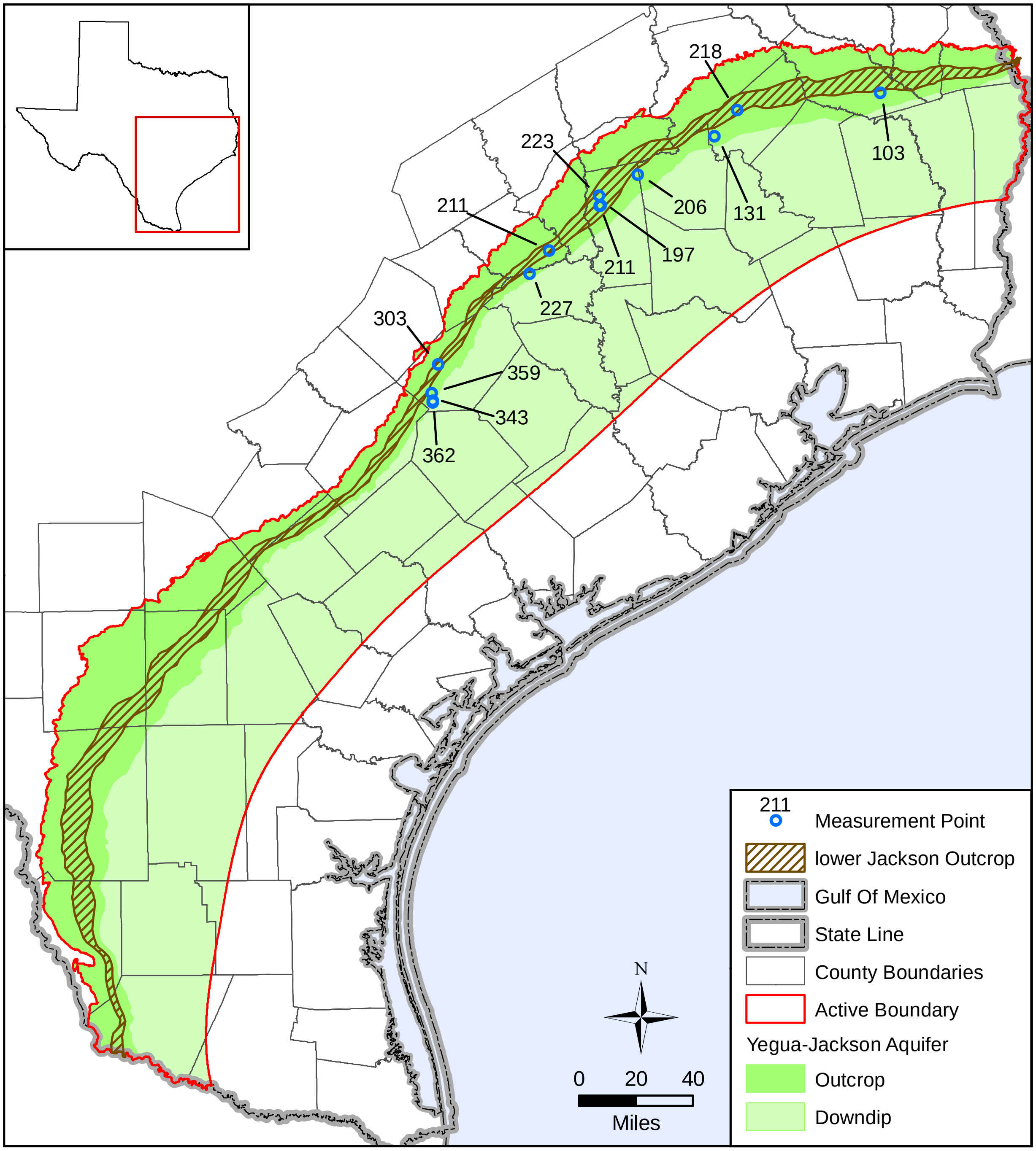


Figure 4.3.8 Estimated water-level elevations in feet for the Lower Jackson Unit of the Yegua-Jackson Aquifer at the start of model calibration (January, 1980).

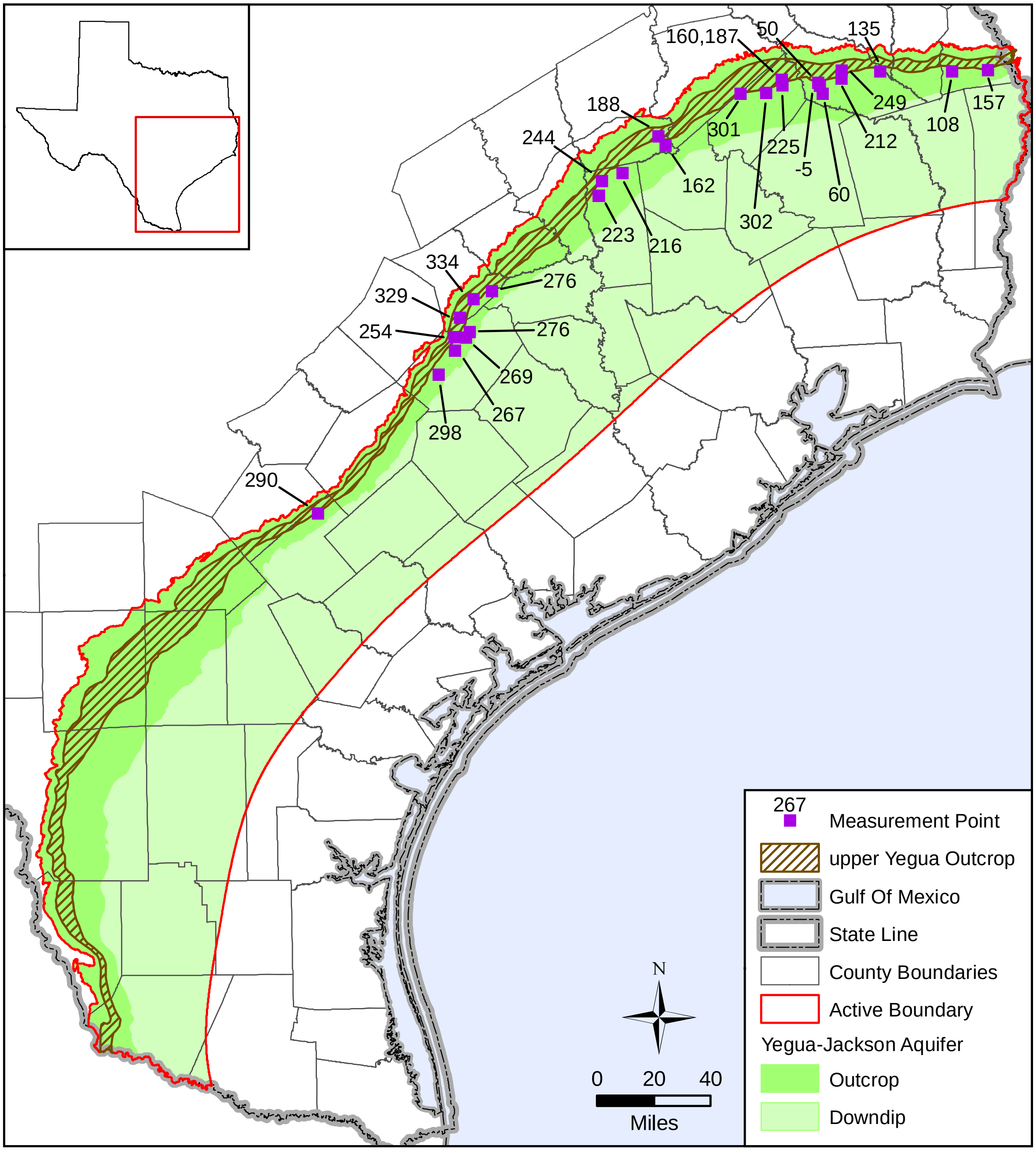


Figure 4.3.9 Estimated water-level elevations in feet for the Upper Yegua Unit of the Yegua-Jackson Aquifer at the start of model calibration (January, 1980).

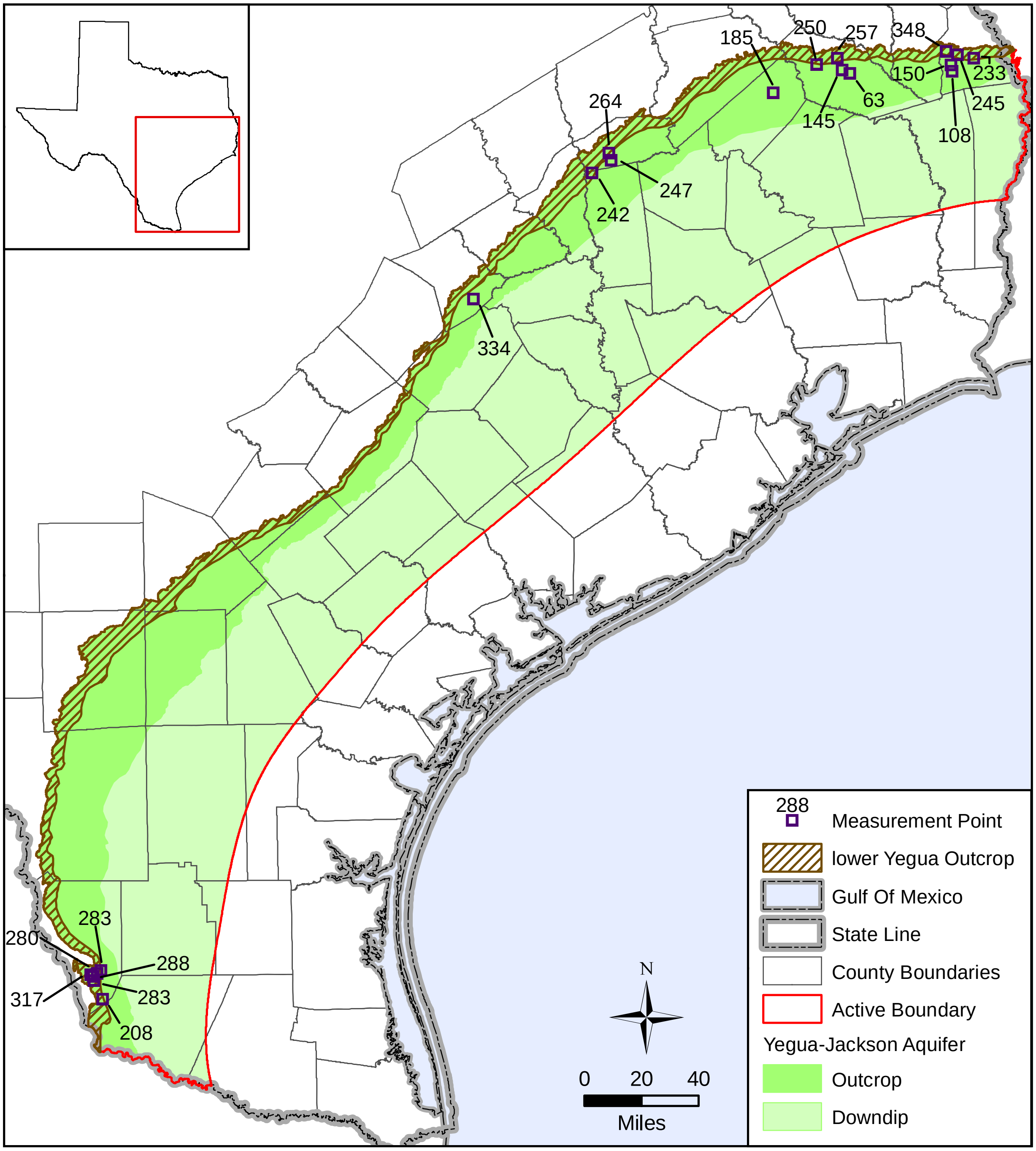


Figure 4.3.10 Estimated water-level elevations in feet for the Lower Yegua Unit of the Yegua-Jackson Aquifer at the start of model calibration (January, 1980).

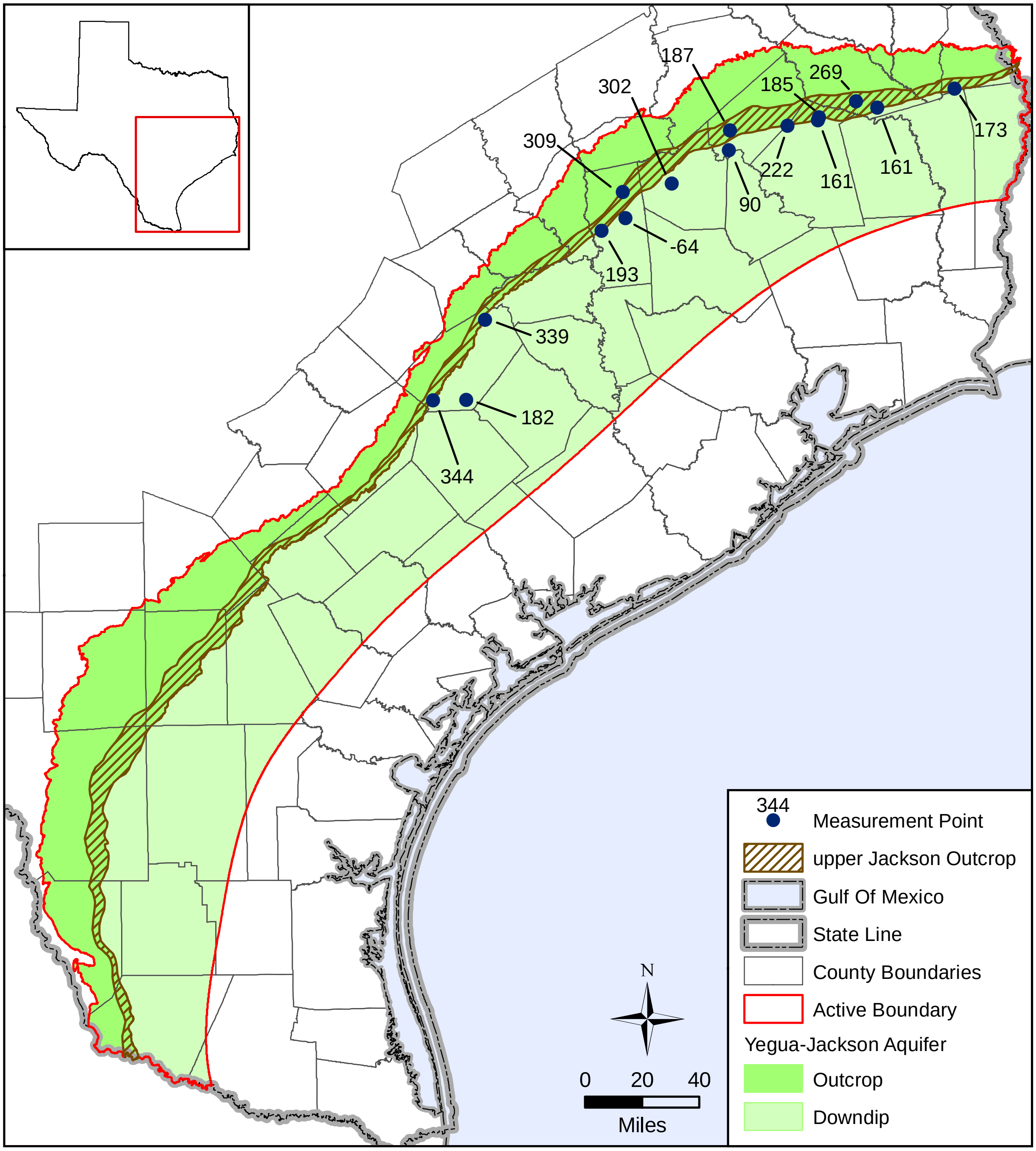


Figure 4.3.11 Estimated water-level elevations in feet for the Upper Jackson Unit of the Yegua-Jackson Aquifer at the middle of model calibration (January, 1990).

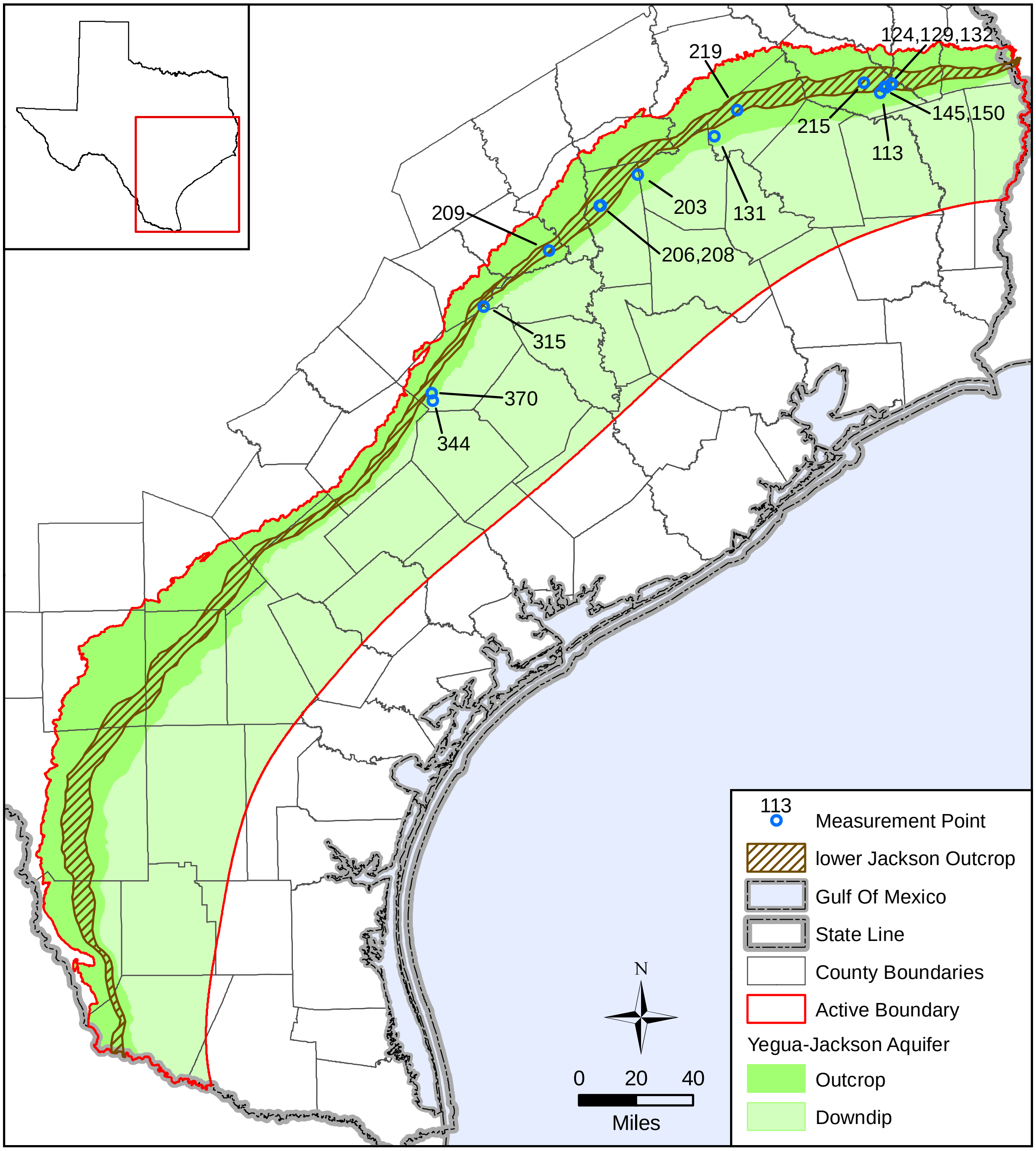


Figure 4.3.12 Estimated water-level elevations in feet for the Lower Jackson Unit of the Yegua-Jackson Aquifer at the middle of model calibration (January, 1990).

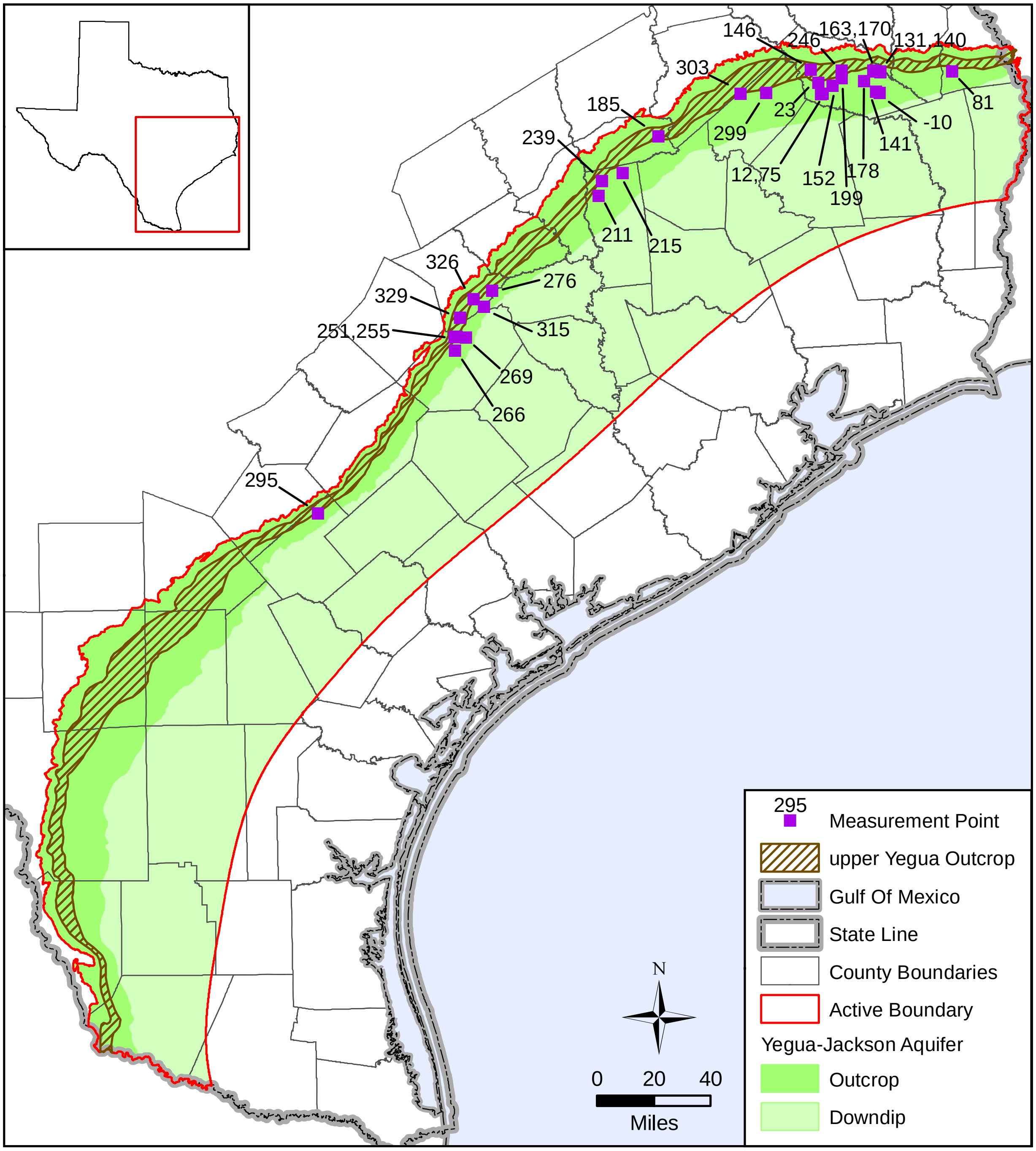


Figure 4.3.13 Estimated water-level elevations in feet for the Upper Yegua Unit of the Yegua-Jackson Aquifer at the middle of model calibration (January, 1990).

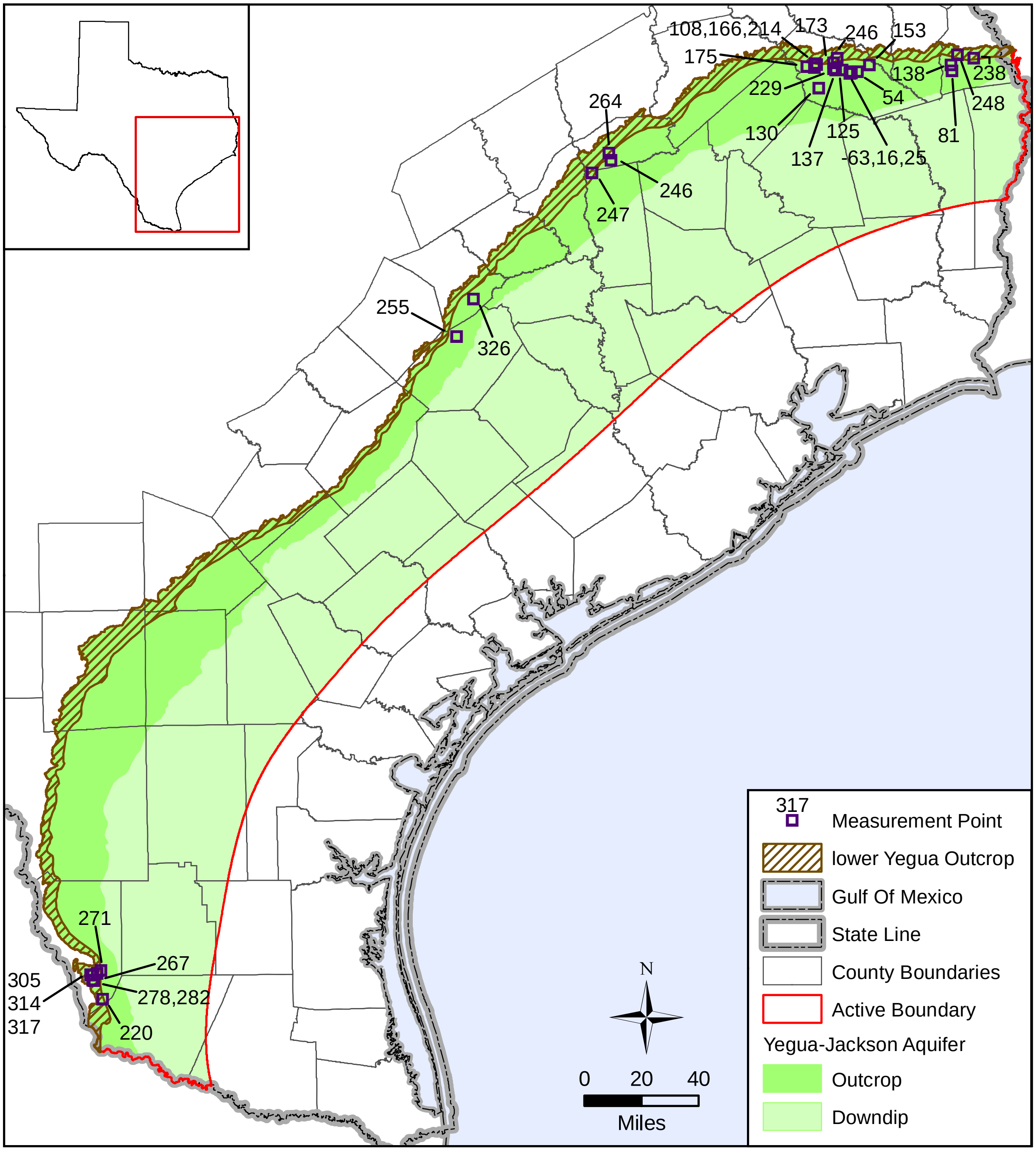


Figure 4.3.14 Estimated water-level elevations in feet for the Lower Yegua Unit of the Yegua-Jackson Aquifer at the middle of model calibration (January, 1990).

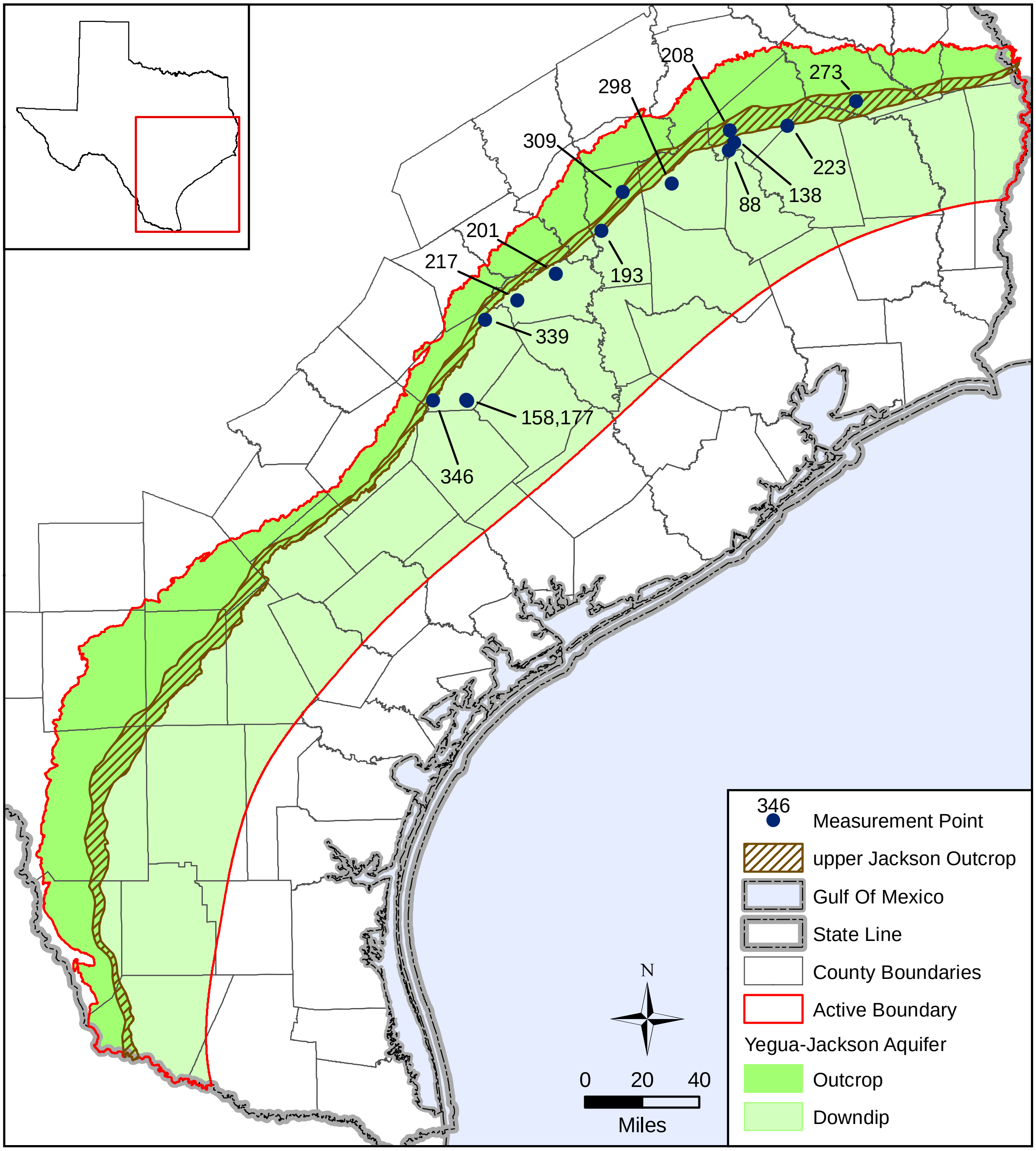


Figure 4.3.15 Estimated water-level elevations in feet for the Upper Jackson Unit of the Yegua-Jackson Aquifer at the end of model calibration (December, 1997).

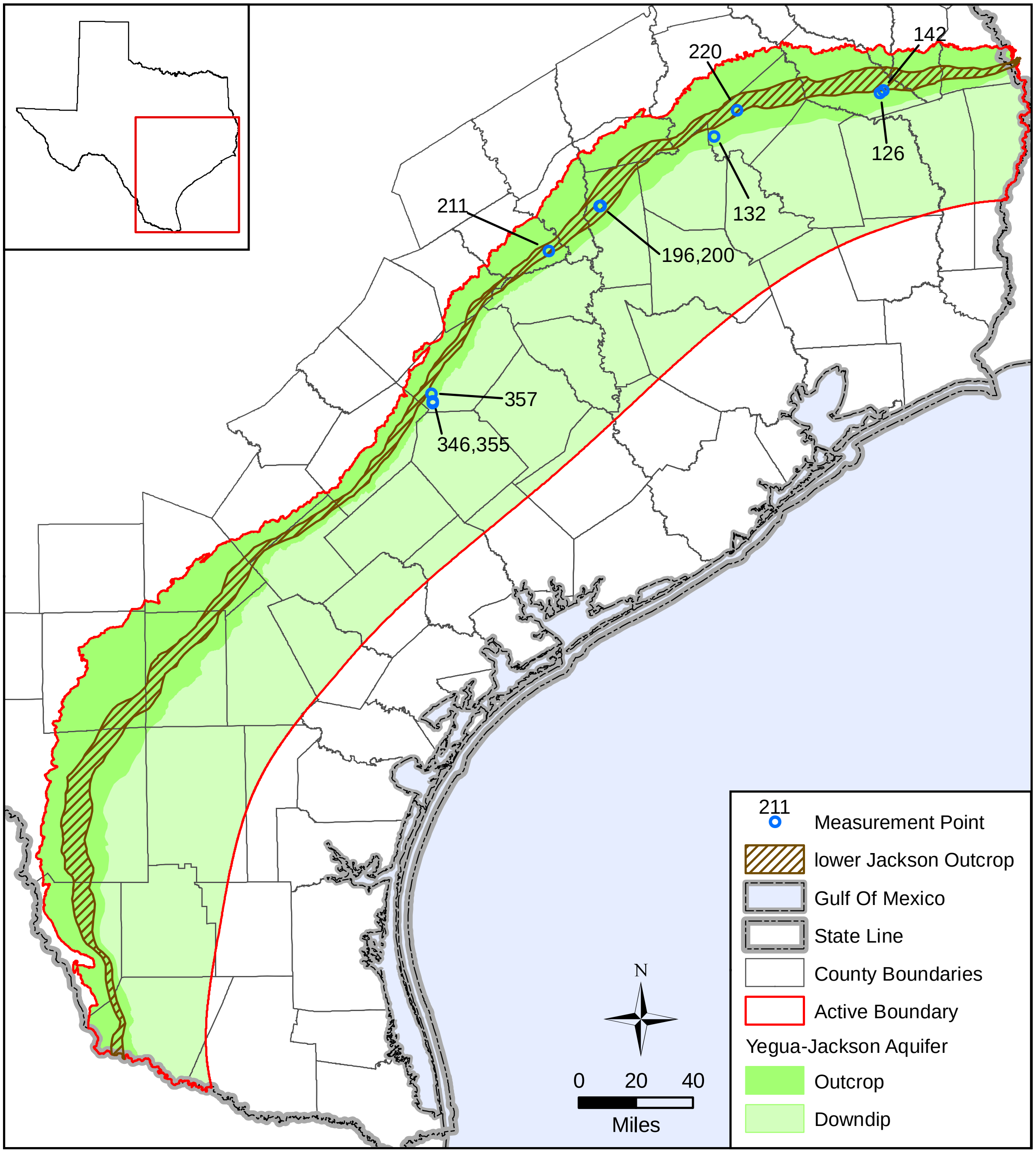


Figure 4.3.16 Estimated water-level elevations in feet for the Lower Jackson Unit of the Yegua-Jackson Aquifer at the end of model calibration (December, 1997).

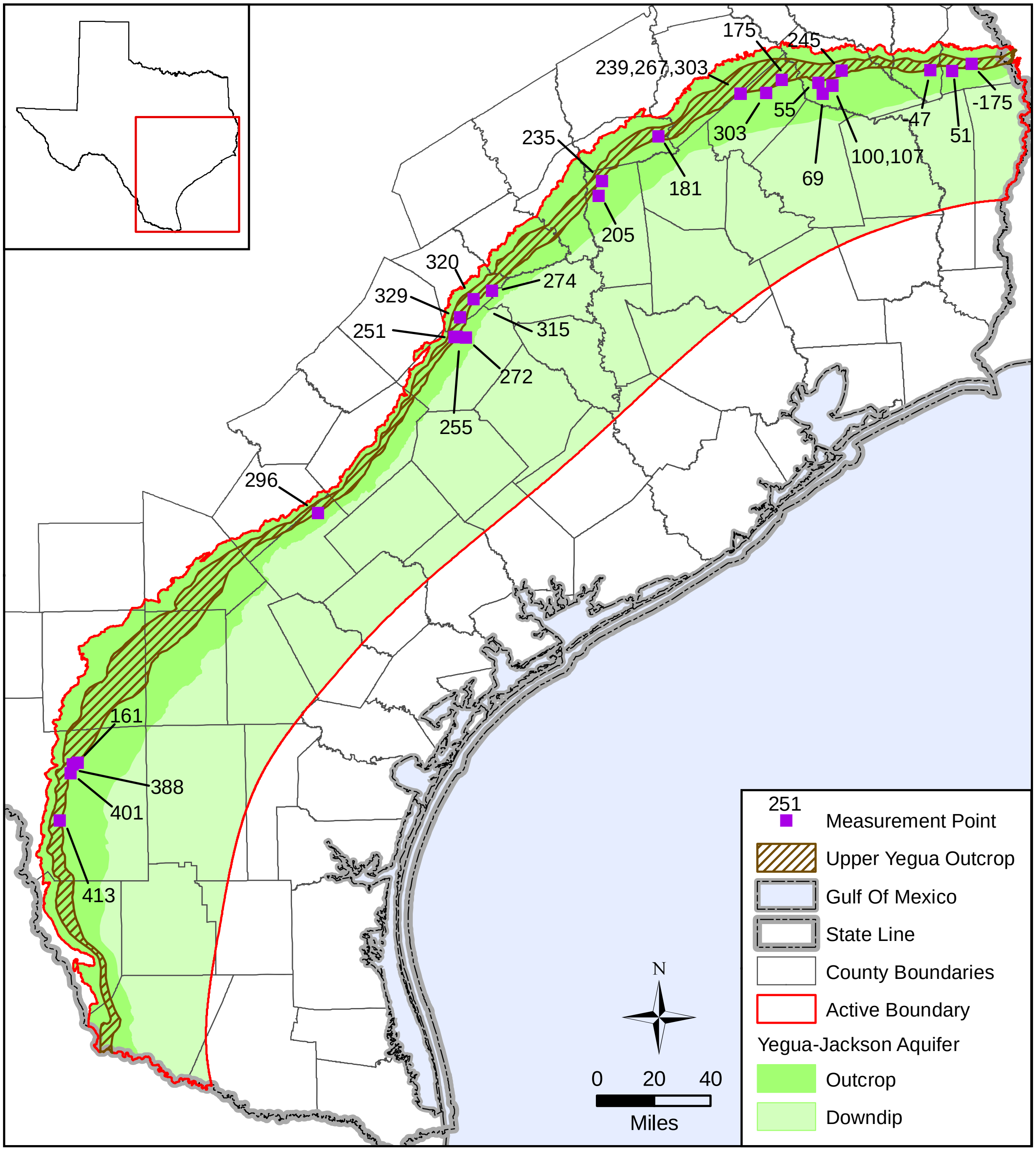


Figure 4.3.17 Estimated water-level elevations in feet for the Upper Yegua Unit of the Yegua-Jackson Aquifer at the end of model calibration (December, 1997).

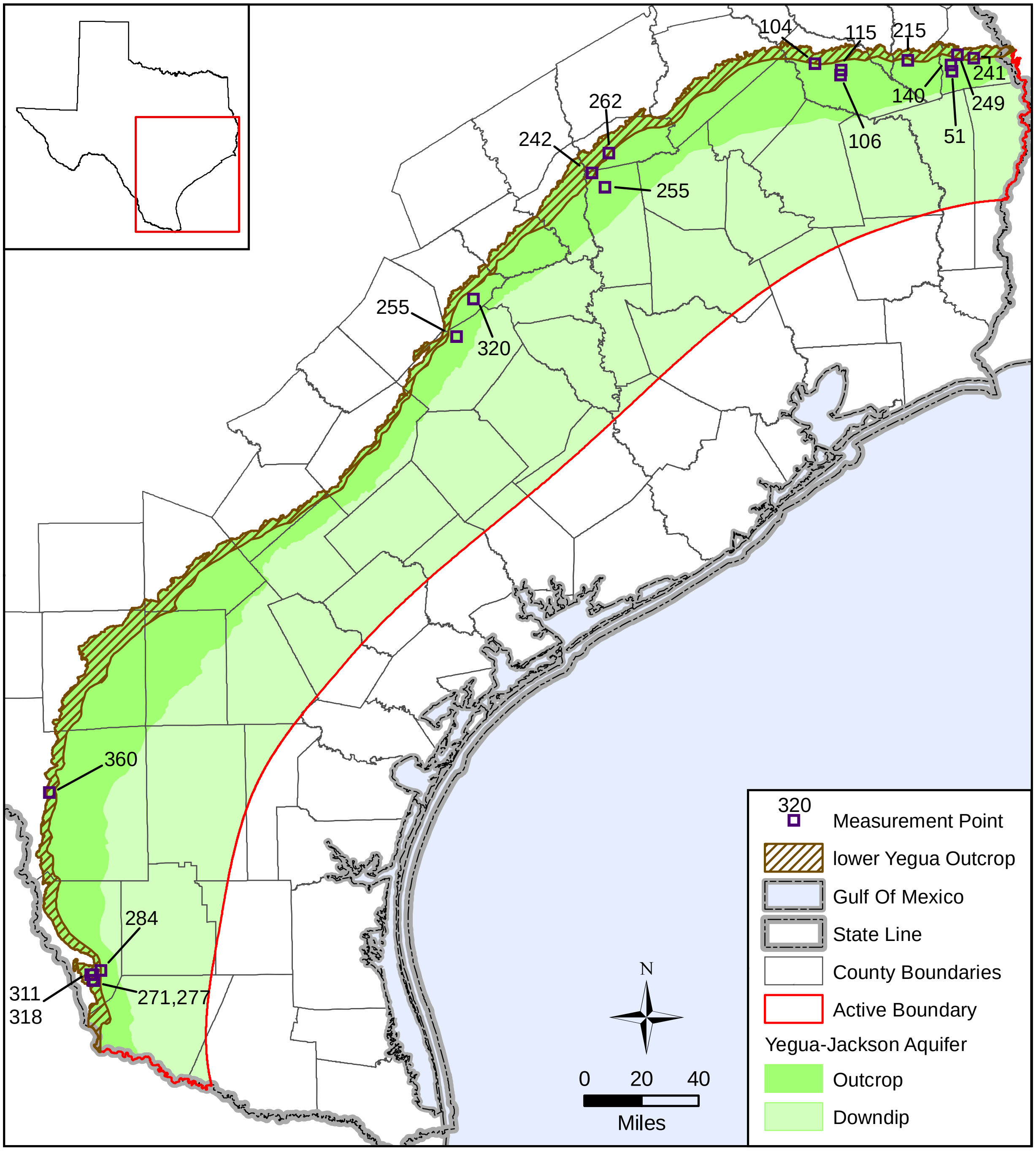


Figure 4.3.18 Estimated water-level elevations in feet for the Lower Yegua Unit of the Yegua-Jackson Aquifer at the end of model calibration (December, 1997).

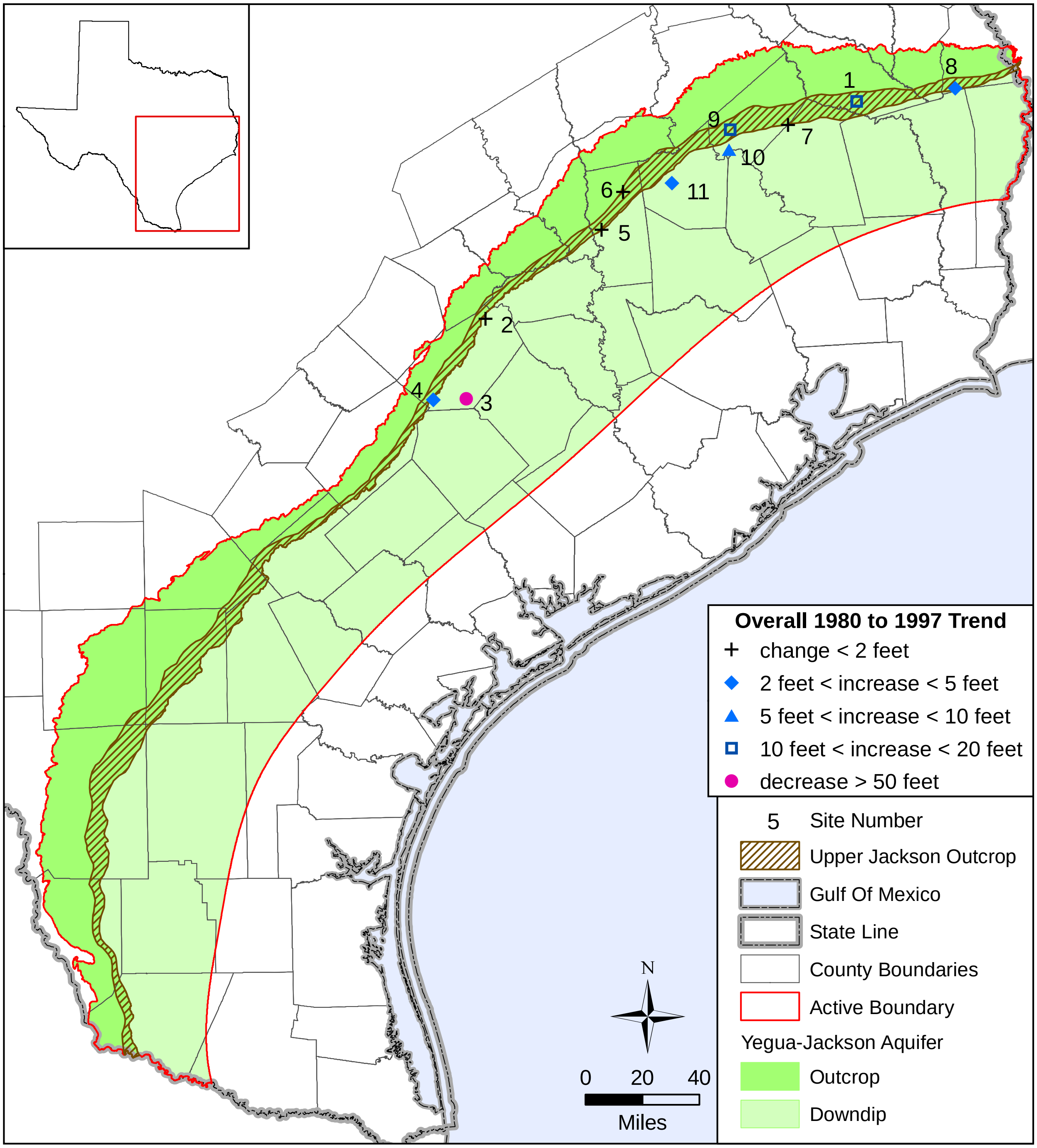


Figure 4.3.19 Overall 1980 to 1997 trend in estimated water-level elevations in the Upper Jackson Unit of the Yegua-Jackson Aquifer.

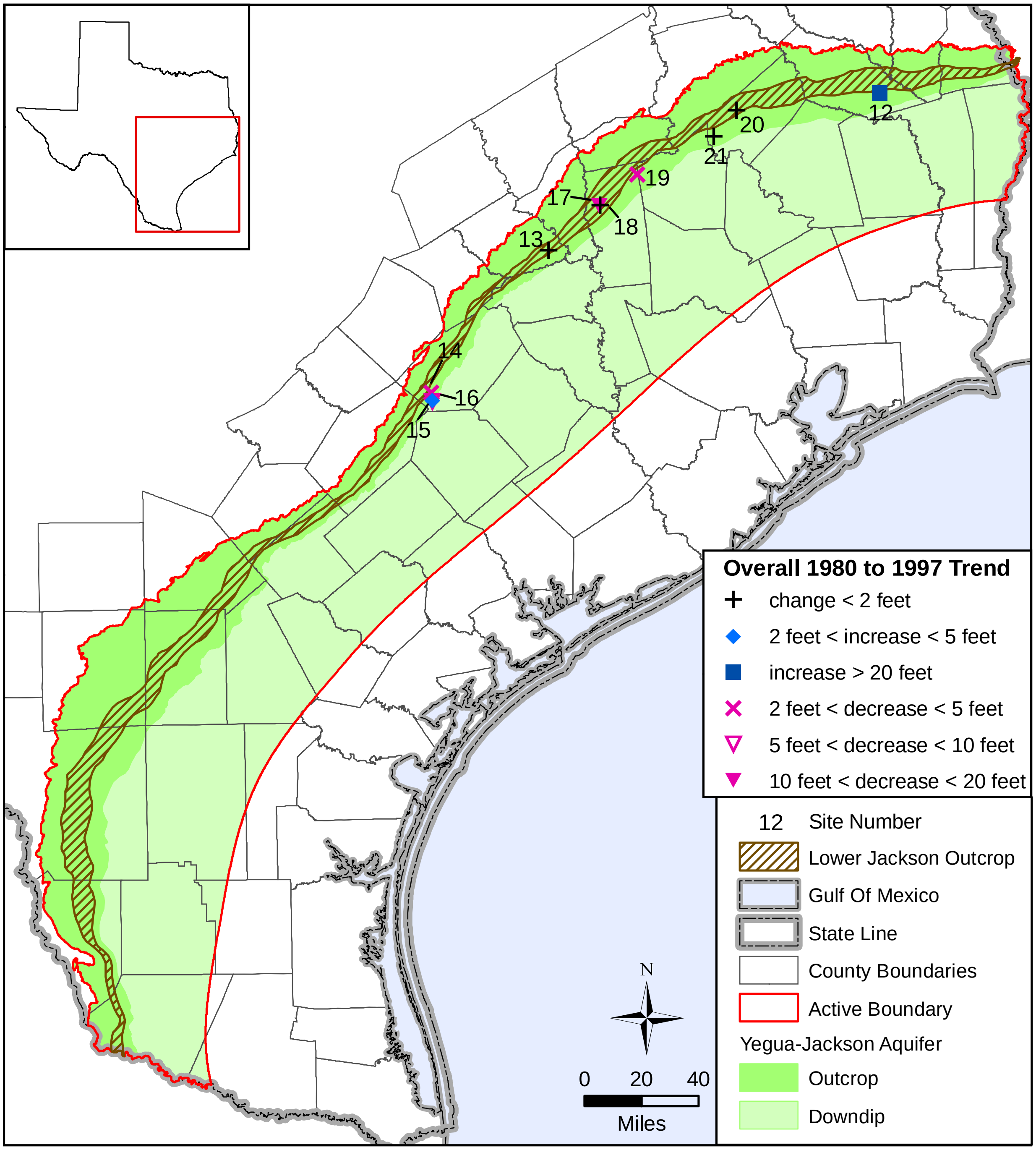


Figure 4.3.20 Overall 1980 to 1997 trend in estimated water-level elevations in the Lower Jackson Unit of the Yegua-Jackson Aquifer.

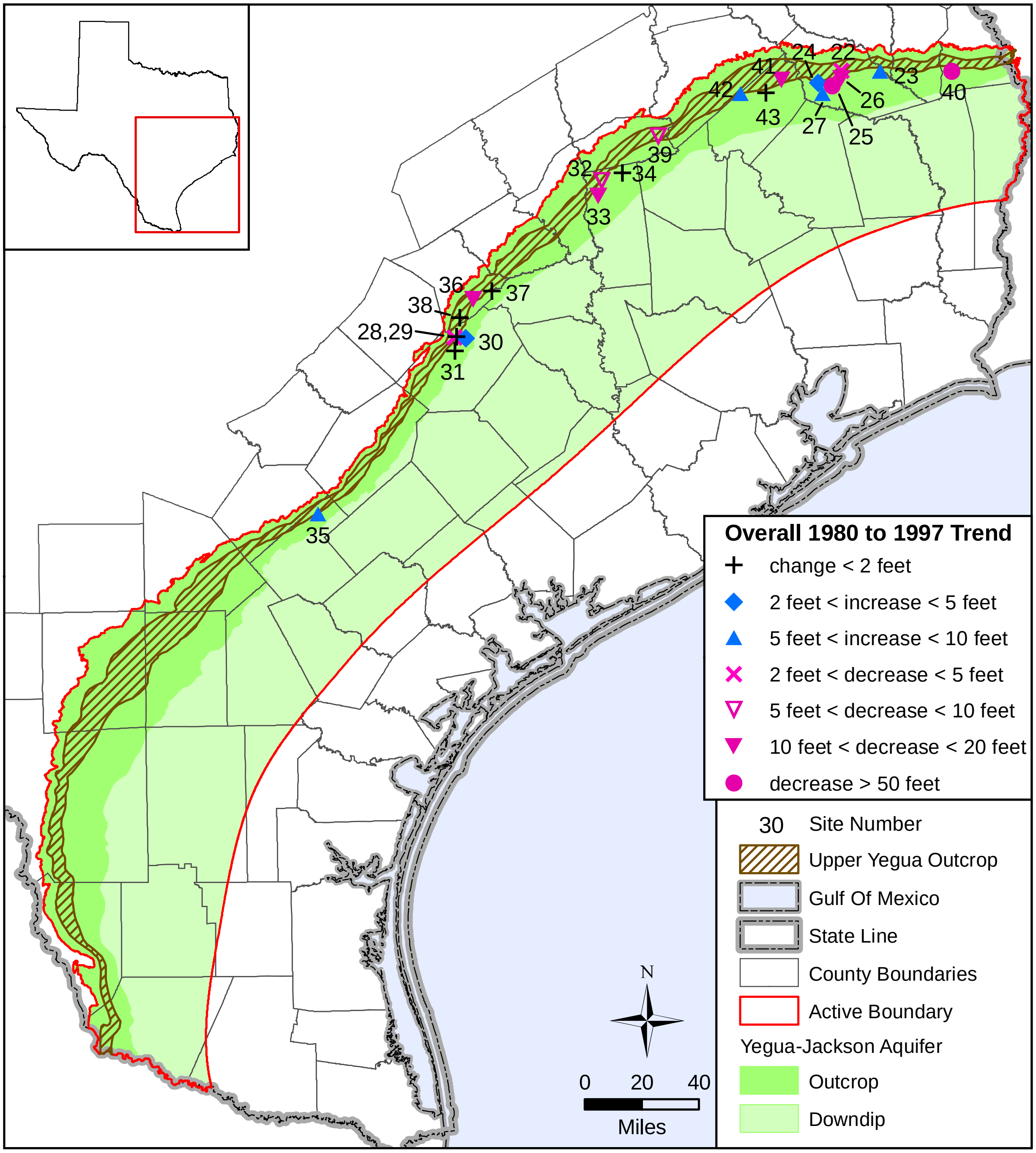


Figure 4.3.21 Overall 1980 to 1997 trend in estimated water-level elevations in the Upper Yegua Unit of the Yegua-Jackson Aquifer.

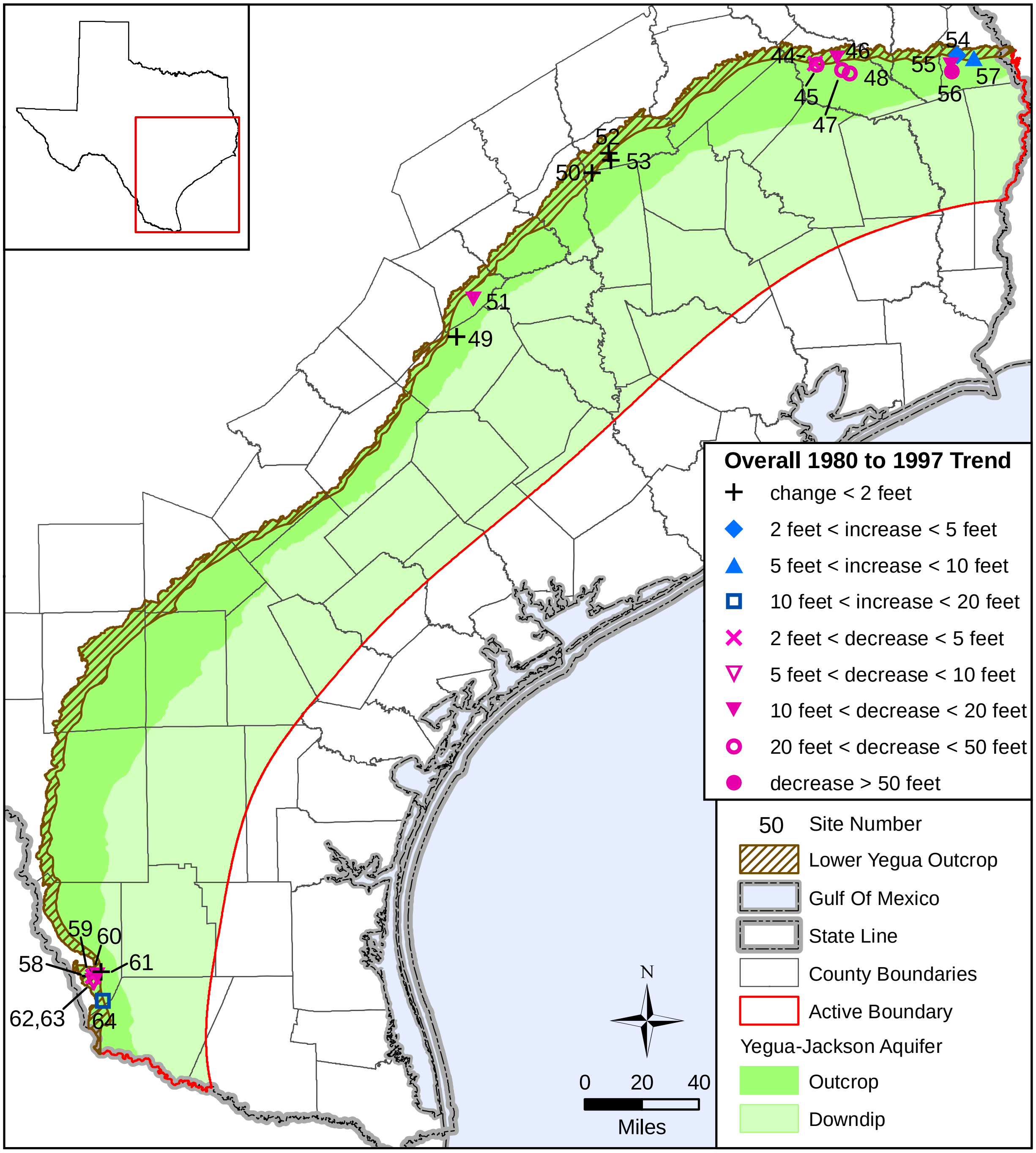


Figure 4.3.22 Overall 1980 to 1997 trend in estimated water-level elevations in the Lower Yegua Unit of the Yegua-Jackson Aquifer.

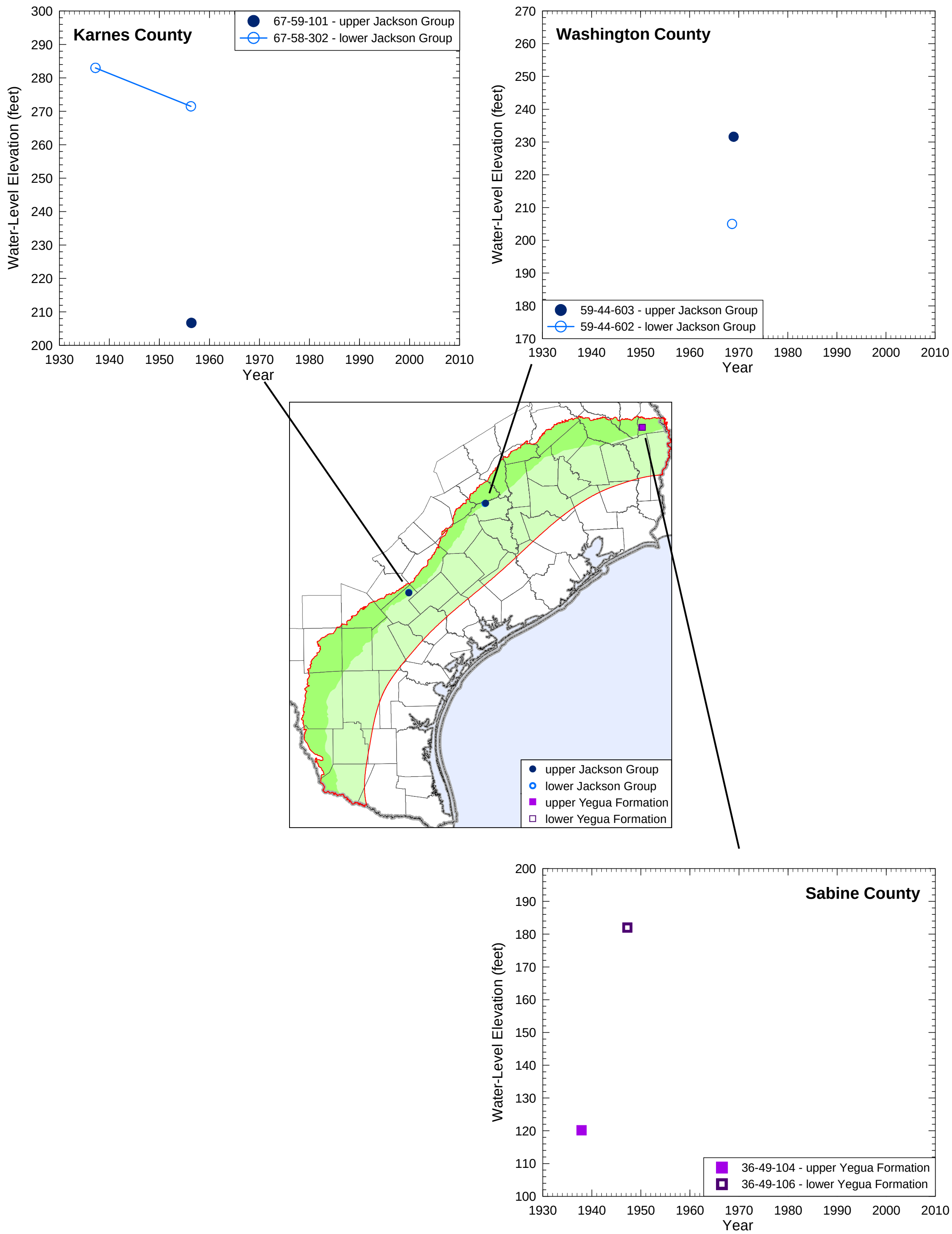


Figure 4.3.23 Comparison of water-level elevations in the Upper Jackson Unit and the Lower Jackson Unit of the Yegua-Jackson Aquifer and comparison of water-level elevations in the Upper Yegua Unit and the Lower Yegua Unit of the Yegua-Jackson Aquifer.

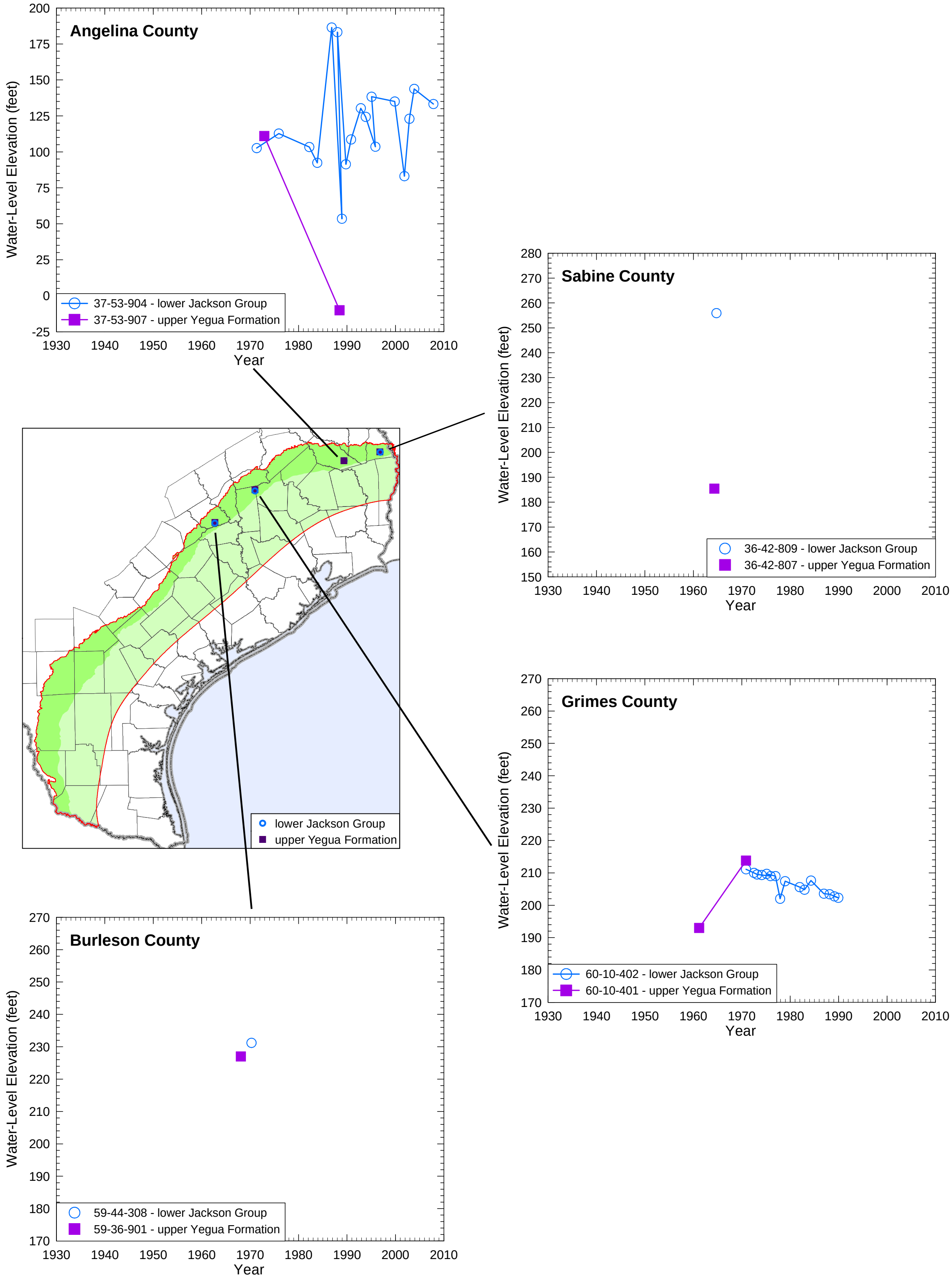


Figure 4.3.24 Comparison of water-level elevations in the Lower Jackson Unit and Upper Yegua Unit of the Yegua-Jackson Aquifer.

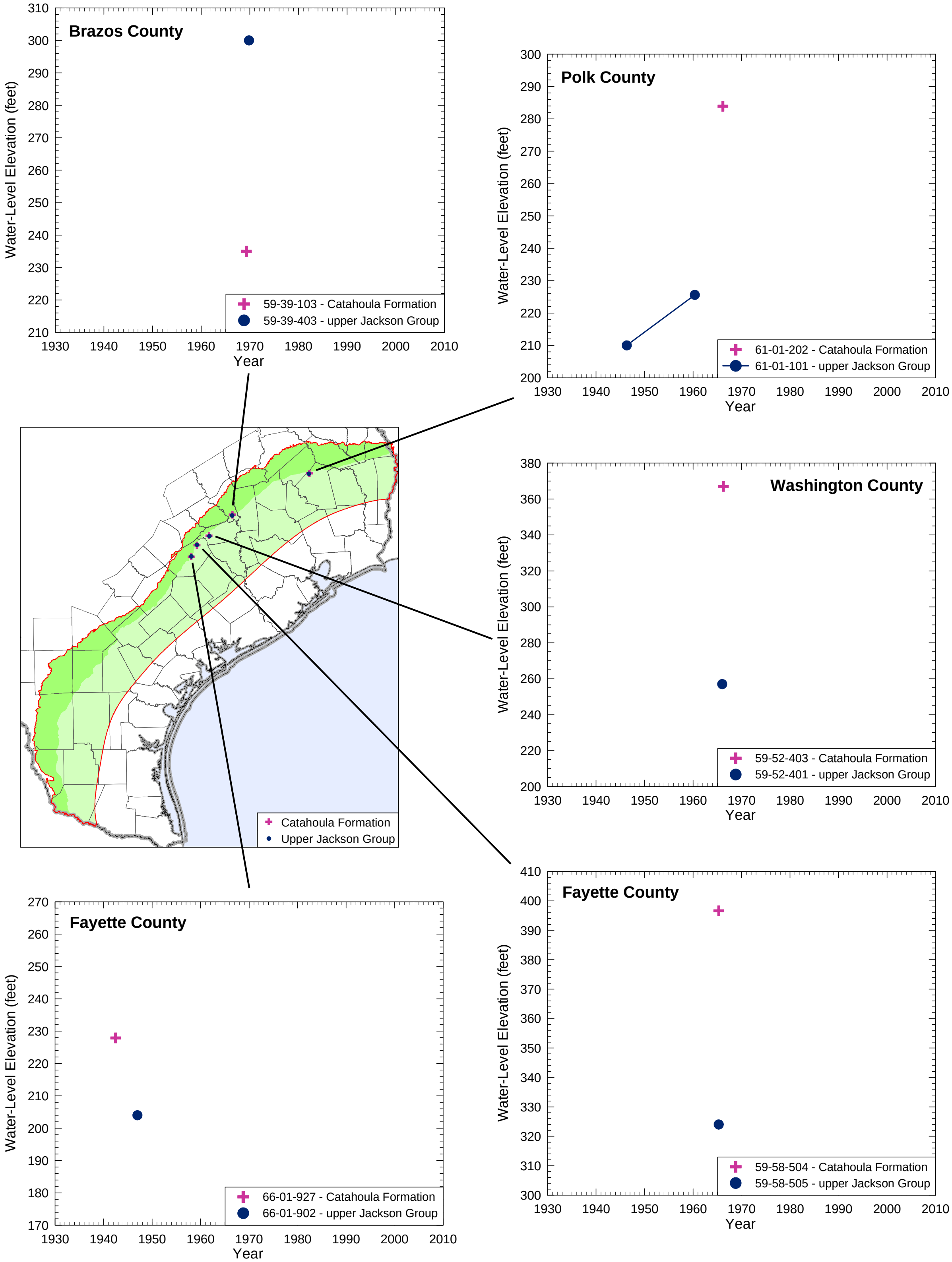


Figure 4.3.25 Comparison of water-level elevations in the Upper Jackson Unit of the Yegua-Jackson Aquifer and the overlying Catahoula Formation.

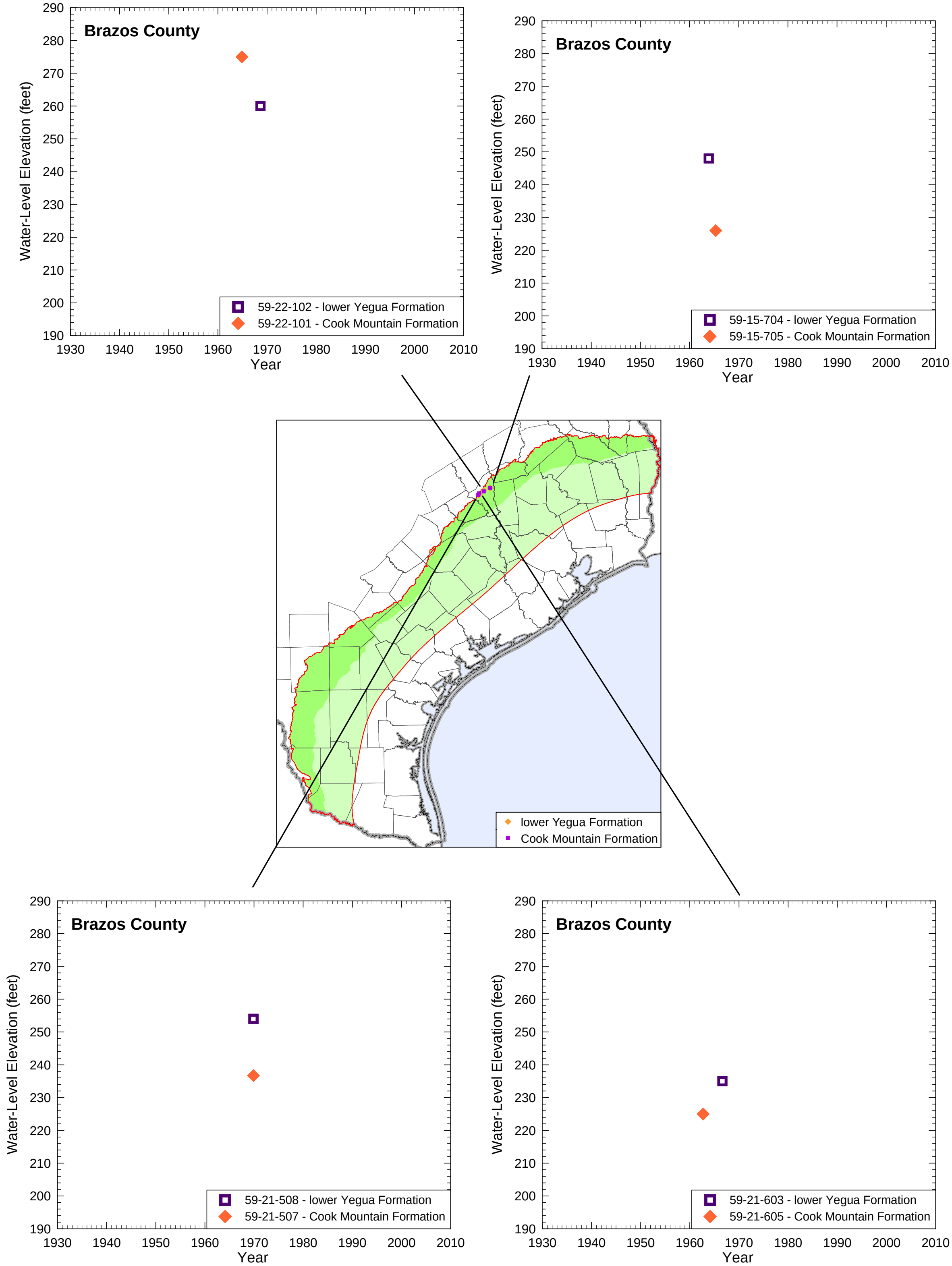


Figure 4.3.26 Comparison of water-level elevations in the Lower Yegua Unit of the Yegua-Jackson Aquifer and the underlying Cook Mountain Formation.

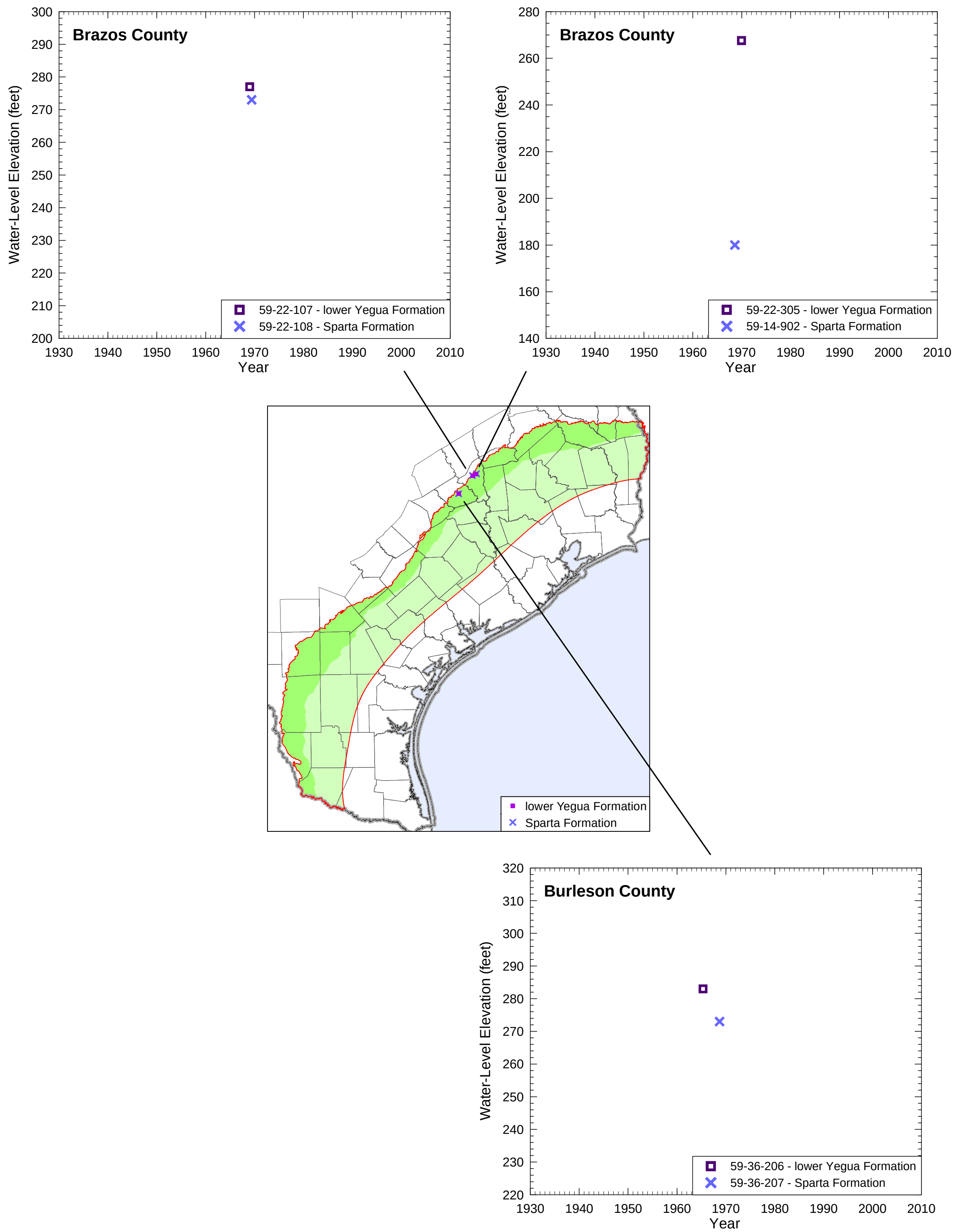


Figure 4.3.27 Comparison of water-level elevations in the Lower Yegua Unit of the Yegua-Jackson Aquifer and the underlying Sparta Formation.

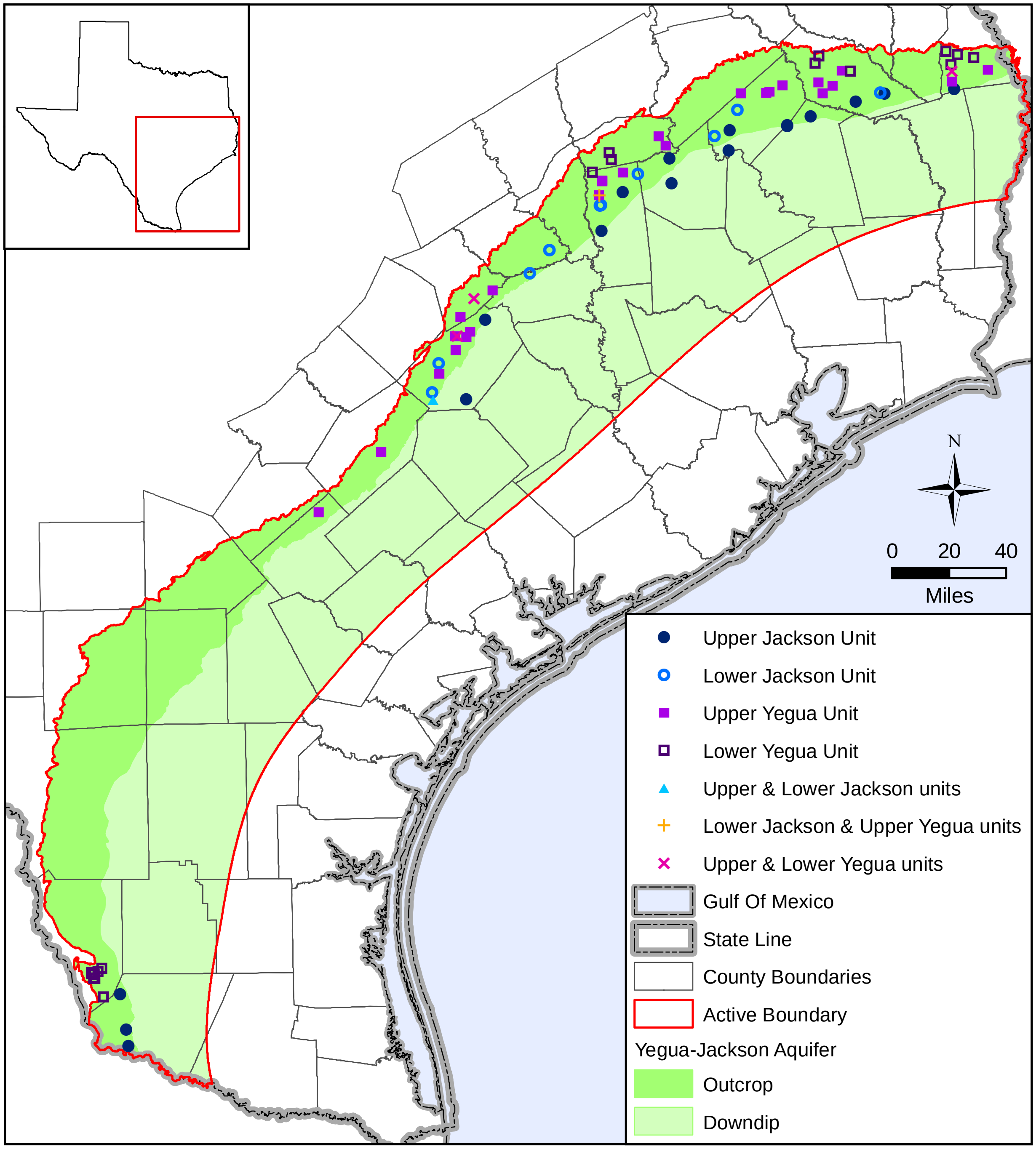


Figure 4.3.28 Locations of wells completed into the Yegua-Jackson Aquifer having transient water-level data.

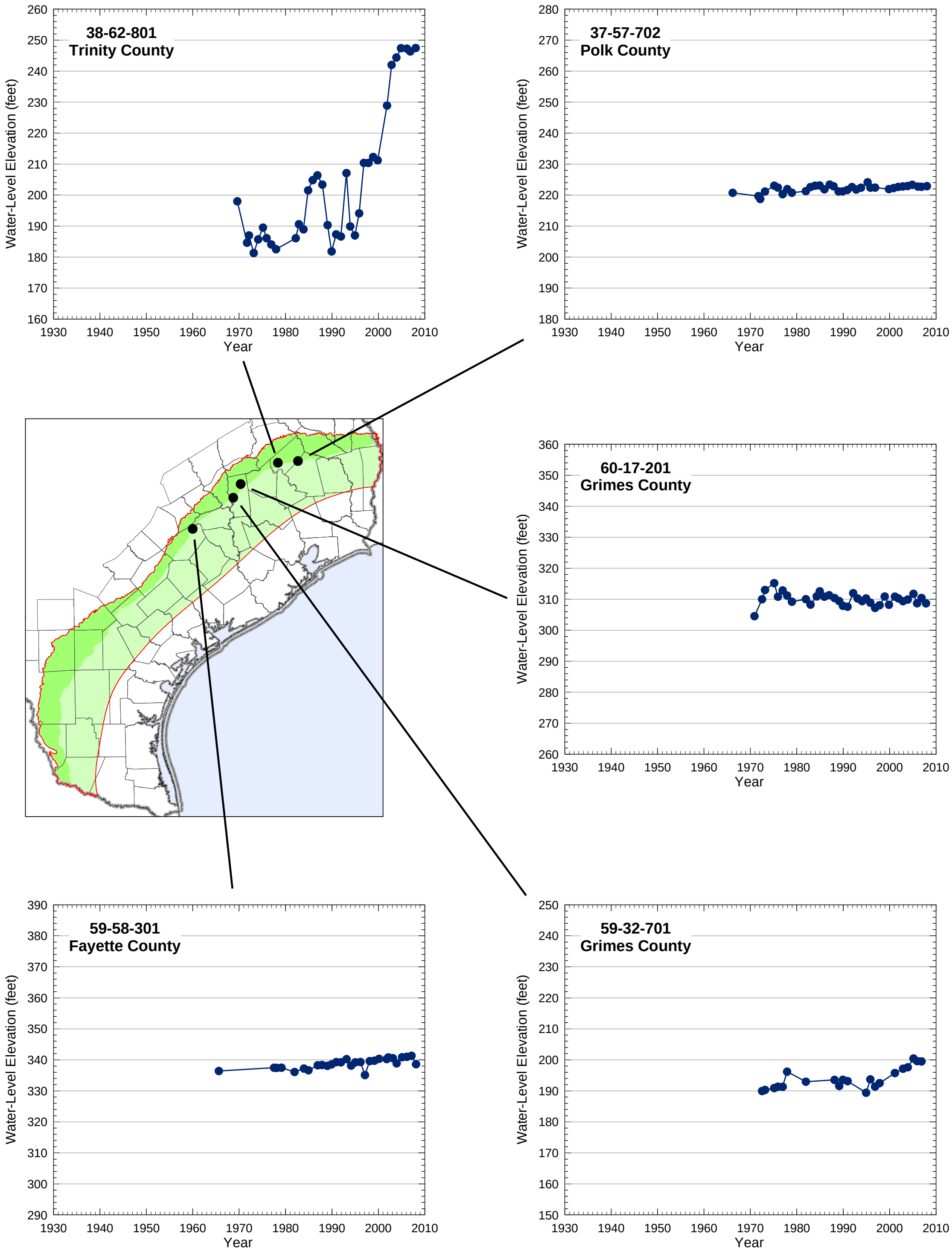


Figure 4.3.29 Hydrographs of transient water-level data with increasing or stable trends for wells completed into the Upper Jackson Unit of the Yegua-Jackson Aquifer.

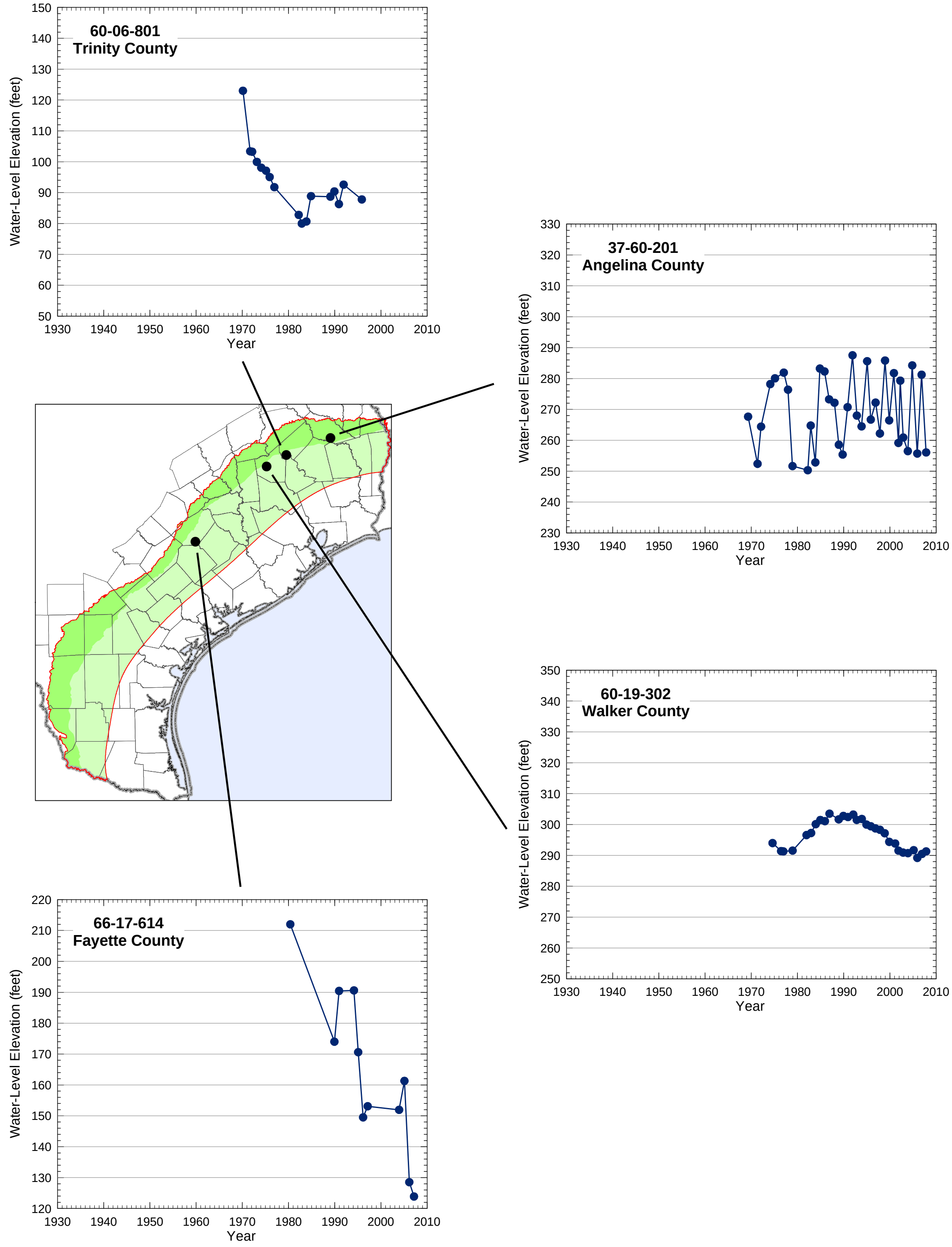


Figure 4.3.30 Hydrographs of transient water-level data with decreasing or fluctuating trends for wells completed into the Upper Jackson Unit of the Yegua-Jackson Aquifer.

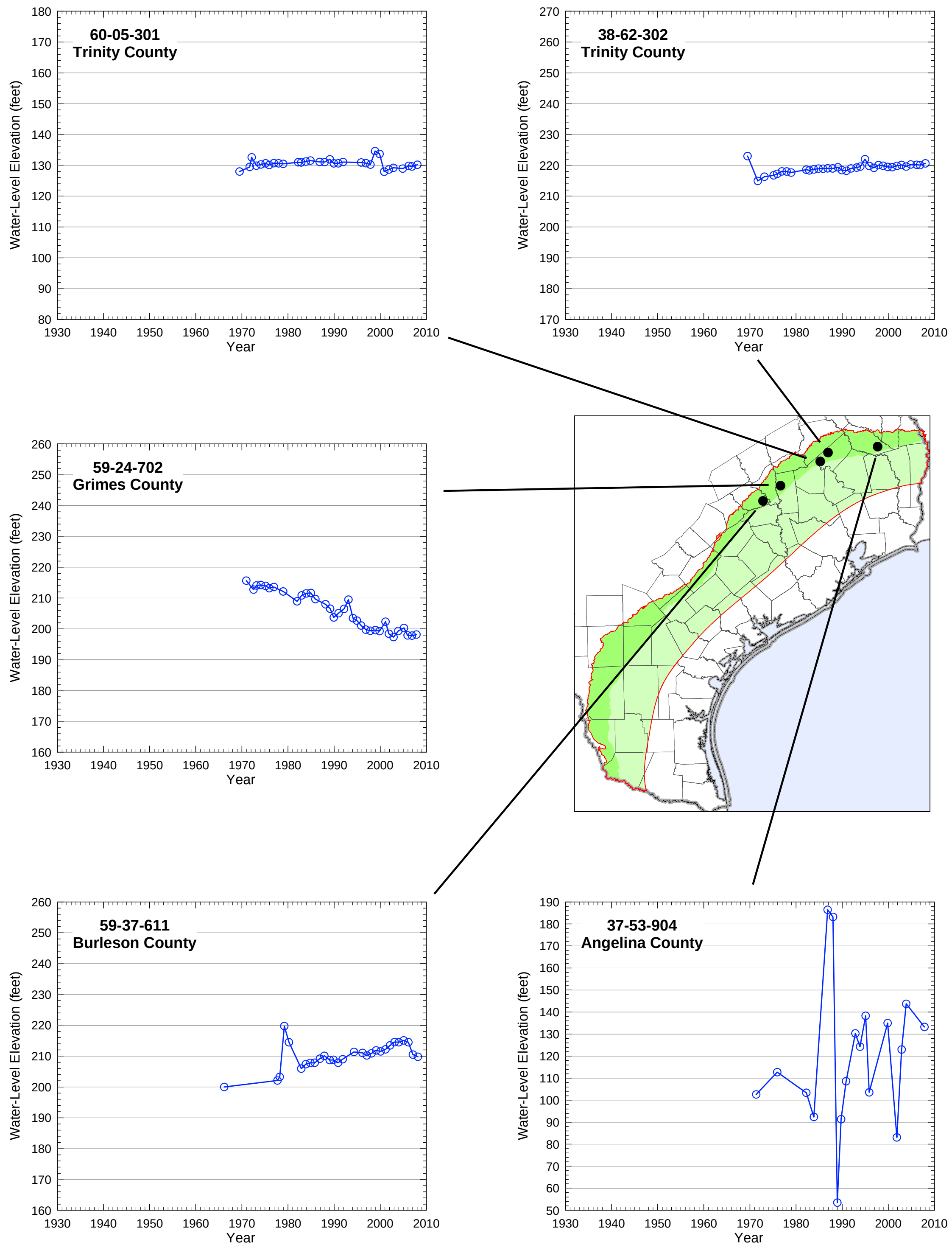


Figure 4.3.31 Hydrographs of transient water-level data for wells completed into the Lower Jackson Unit of the Yegua-Jackson Aquifer.

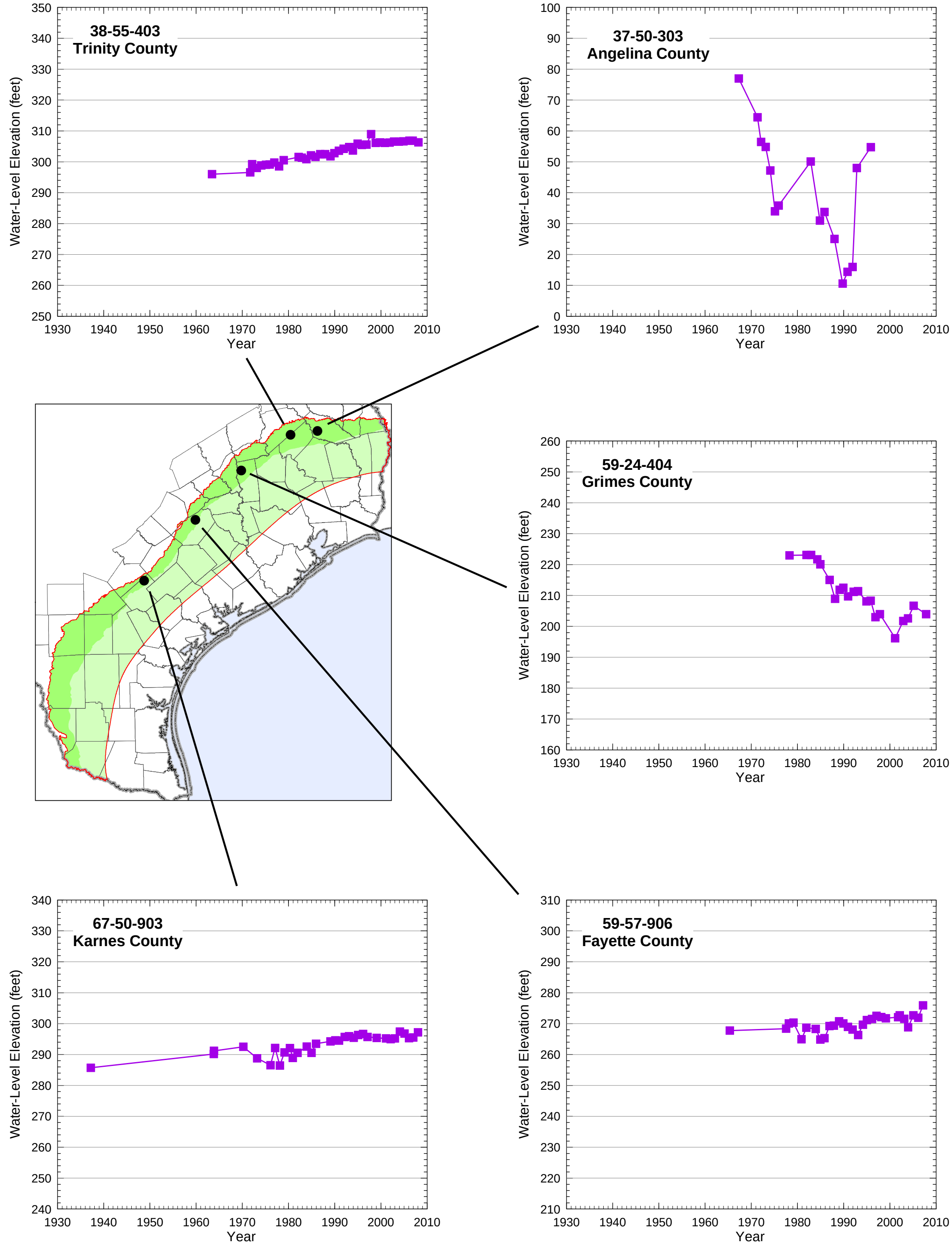


Figure 4.3.32 Hydrographs of transient water-level data with increasing or decreasing then increasing trends for wells completed into the Upper Yegua Unit of the Yegua-Jackson Aquifer.

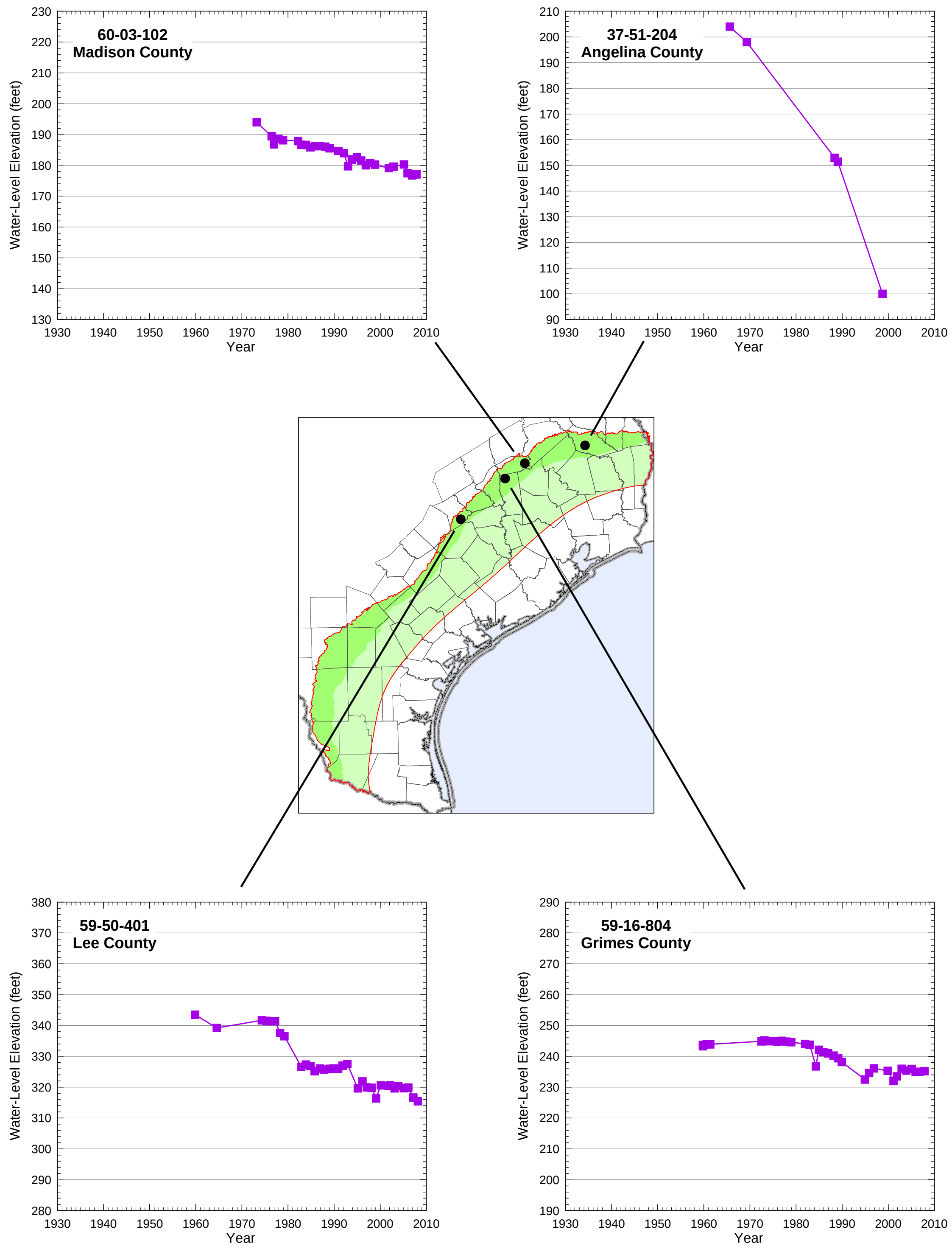


Figure 4.3.33 Hydrographs of transient water-level data with a decreasing trend for wells completed into the Upper Yegua Unit of the Yegua-Jackson Aquifer.

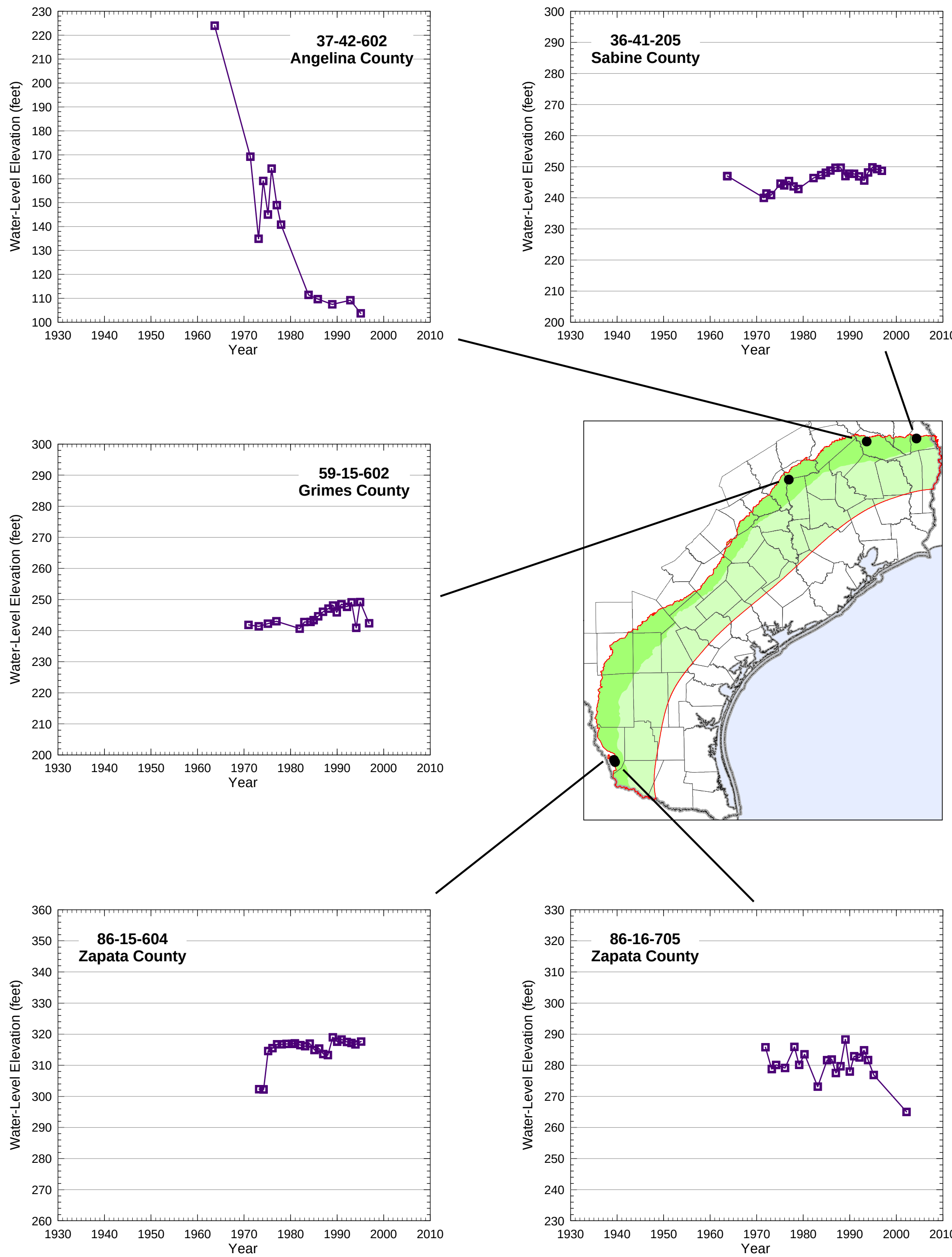


Figure 4.3.34 Hydrographs of transient water-level data with increasing or decreasing trends for wells completed into the Lower Yegua Unit of the Yegua-Jackson Aquifer.

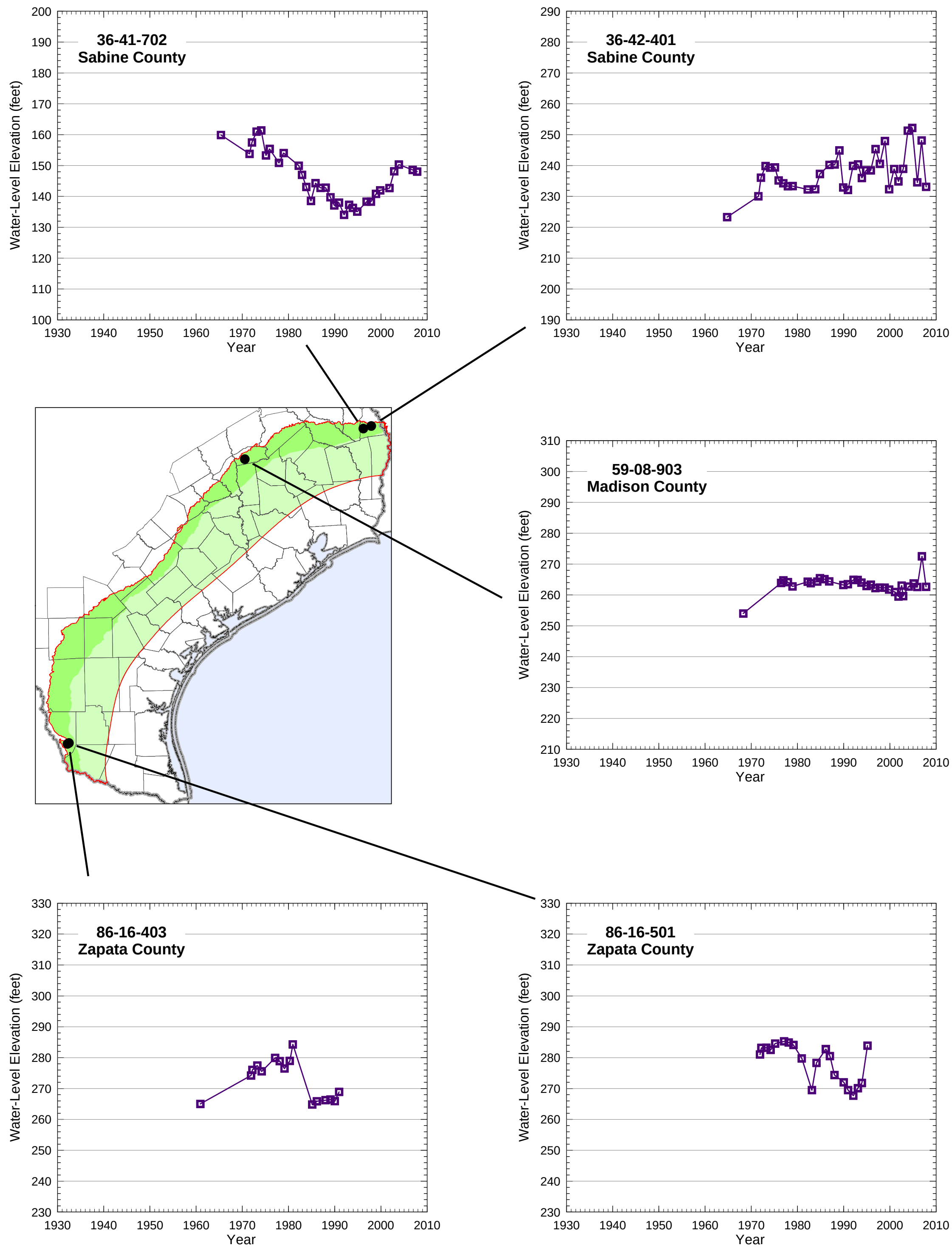


Figure 4.3.35 Hydrographs of transient water-level data with stable or fluctuating trends for wells completed into the Lower Yegua Unit of the Yegua-Jackson Aquifer.

4.4 Recharge

This section discusses the conceptual framework describing groundwater recharge in the Yegua-Jackson Aquifer. This discussion is followed by the conceptual approach for estimating average recharge and for distributing recharge spatially and temporally in the Yegua-Jackson Aquifer outcrop. Implementation of recharge in the numerical model is described in Section 6.3.4

4.4.1 Conceptual Basics

Recharge can be defined as water that is made available at the water-table surface, together with the associated flow away from the water table within the saturated zone (Freeze, 1969). Recharge is a complex function of the rate and volume of precipitation, soil type, water level, soil moisture, topography, and evapotranspiration (Freeze, 1969). Potential sources for recharge include precipitation, irrigation subsurface return flow, and stream or reservoir leakage. Precipitation and irrigation return flow are generally considered to be diffuse sources of recharge, while stream or reservoir leakage are considered to be focused sources of recharge. For the Yegua-Jackson Aquifer, we expect rivers to be predominantly losing in the far southwest and gaining in the central to northeast portion of the aquifer outcrop, with a transition area between the two regions where losing and gaining conditions are dependent on recent climate.

Man-made reservoirs provide the potential for focused recharge in the model area in the aquifer outcrop. However, the reservoirs that significantly intersect the Yegua-Jackson Aquifer outcrop are in the more humid northeast region, where gaining conditions are expected. Even in the drier regions, because reservoirs are necessarily located in topographically low areas, we would expect that most of the recharge associated with reservoirs would represent shallow recharge subject to evapotranspiration and discharge to wetlands and streams.

During a rainfall event (or irrigation event), some of the water may run off to small streams and surface features and some of the water infiltrates the soil (a small fraction of the water that infiltrates the soil may become interflow, but this process is neglected as inconsequential in this discussion.) Much of the infiltrating water evaporates while still near the surface or is taken up by vegetation in the vadose zone (vadose zone evapotranspiration). If enough water infiltrates to satisfy the moisture deficit of the soil and the vegetation in the vadose zone, then the remaining water will continue to percolate downward to the water table. Water that reaches the water table is considered recharge.

The groundwater system in the outcrop can often act as a classic topographically-driven recharge/discharge system, where recharge primarily occurs in the areas of higher elevation, and discharge occurs in the areas of lower elevation through streams, seeps, and groundwater evapotranspiration. The recharge to the water table that discharges relatively quickly in the surficial groundwater system does not have a significant impact on the deeper, confined aquifer system. Conceptually, recharge can be divided into two types, “shallow” recharge which discharges relatively quickly through baseflow and other surficial discharge components (such as groundwater evapotranspiration, springs, and seeps), and “deep” recharge which moves into the confined system and exits through cross-formational flow or pumping after aquifer development. Of the former, the portion of recharge that exits through surficial discharge components is sometimes termed “rejected recharge”. This discharging water has the potential to be captured by pumping, if the water table is lowered enough to reverse the gradients driving flow towards the natural discharge points.

Figure 4.4.1 is a flow balance diagram depicting how precipitation partitions into the various components described above, under predevelopment conditions (i.e., no pumping). The values in Figure 4.4.1 represent estimates for an average precipitation of 40 inches per year over the Yegua-Jackson Aquifer outcrop. This would be similar to what might occur in Fayette County, in the central region of the outcrop.

This conceptualization would be valid moving to the northeast, with the magnitude of the numbers for the shallow system increasing. In the far southwestern region of the Yegua-Jackson Aquifer outcrop, where streams are not typically gaining, the local discharge component would be close to zero, and may even be negative, where streams recharge the aquifer. In addition, deep recharge may also be reduced in these areas. In the following sections, we will discuss how similar values were estimated over the entire model region, including the analysis of deep and shallow recharge (along with runoff). Note that in Figure 4.4.1, evapotranspiration is assumed to be the difference between precipitation and the sum of recharge and runoff, and regional discharge is assumed to be equivalent to deep recharge.

4.4.2 Average Recharge

Deep Recharge

Recharge in Texas aquifers has been studied by many investigators. Scanlon and others (2003) provides a summary of the studies for the major aquifers in Texas, which does not include the Yegua-Jackson Aquifer. Only two previous estimates of average recharge could be found for the Yegua-Jackson Aquifer: one for Grimes County (Baker and others, 1974) and one for Sabine and San Augustine counties (Anders, 1967). These estimates were based on a simple application of Darcy's law, where the approximate gradient and transmissivity at the location where the aquifer subcrops were used to estimate the volume of water flowing downdip. In the case of Grimes County, the estimates for the Yegua Formation and Jackson Group were 3,400 acre-feet per year and 2,500 acre-feet per year, respectively. For outcrop areas of approximately 280 square miles and 250 square miles, an equivalent outcrop flux of 0.23 inches per year for the Yegua Formation and 0.18 inches per year for the Jackson Group were estimated. In the case of Sabine and San Augustine counties, a total of 11,800 acre-feet per year was estimated for the Yegua Formation. Given an outcrop area of approximately 279 square miles, this translates to 0.79 inches per year of outcrop flux. These two estimates of deep recharge are in the central and northeastern portions of the Yegua-Jackson Aquifer outcrop and are in places where overall transmissivity is adequate for development. In areas such as Atascosa County, poor water quality in the outcrop indicates that less deep recharge occurs, likely due to a combination of lower transmissivity and less rainfall. So the estimates of about 0.2 to 0.8 inches per year of deep recharge may be reasonable for those areas of the Yegua-Jackson Aquifer outcrop where transmissivity is adequate, and rainfall is sufficient to keep the water table near the surface.

Shallow Recharge

For the current study, baseflow separation analyses were completed on several gages with subwatersheds (the catchment area above the gage) that intersected the Yegua-Jackson Aquifer outcrop. These baseflow separation analyses are described in Section 4.5.1. Baseflow can be used as a surrogate measure of shallow recharge, if we assume that most of the shallow recharge discharges through baseflow. In reality, some portion of shallow recharge will discharge through seeps and groundwater evapotranspiration. So the baseflow estimates should be considered minimum shallow recharge estimates. The minimum recharge flux rate is determined by dividing the baseflow rate by the subwatershed area (the catchment area above the gage). Table 4.4.1 shows the results of the hydrograph separation analysis expressed in terms of an average flux. As noted previously, the constraints imposed by the hydrograph separation technique results in a small set of potentially valid gages. These gages are on rivers and streams that vary widely in their basic characteristics of subwatershed area and overall flow. The smaller streams which are typically in higher topographic regions than the larger rivers, would be expected to have less baseflow than the larger streams and, thus, estimates of flux would vary accordingly. In addition, many of the gages selected as potentially valid for hydrograph separation are in the southwest portion of the model area, where streams may be intermittent and not have significant baseflow.

The “fraction non-zero” field in Table 4.4.1 reports the fraction of days where a positive flow rate was recorded. This included the gages where flow at an upstream gage was subtracted from the downstream gage to determine the impact over the outcrop between the gages. So, for example, although gage 8038500 in the Angelina River shows a fraction of 0.96, this does not mean that the river was dry 4 percent of the time, but rather that the measurement at the upstream gage met or exceeded the measurement at the downstream gage 4 percent of the time. In general, we would expect that those gages that show positive flow a large fraction of the time would provide the best estimates of baseflow. These gages will naturally be in the central and northeastern regions of the outcrop, where precipitation is highest. The median baseflow from Table 4.4.1 is 0.34 inches per year while the average is 0.60 inches per year.

Figure 4.4.2 shows a plot of the baseflow index, which is the average baseflow divided by the average total flow at a particular gage, versus the subwatershed area that drains to the gage. A clear increasing trend of baseflow index with increasing area is evident. As noted earlier, the larger rivers with larger areas will typically have higher baseflow, since they are incised deeper and wider relative to the surrounding topography. Figure 4.4.2 shows only those gages where flow was positive for over 75 percent of the days recorded. Figure 4.4.3 shows the same plot for those gages where flow was positive for less than 75 percent of the days recorded. The trend is less evident in this plot, which supports the suggestion of decreasing baseflow contribution for gages on streams with inconsistent flow. The area weighted average baseflow for the gages shown in Figure 4.4.2 is 0.8 inches per year. The range goes from 0.12 inches per year for a small creek feeding into the San Antonio River to 1.5 inches per year for the Angelina River.

Considerable difficulty lies in estimating how much shallow recharge would exceed the baseflow estimates due to other sources of discharge, such as groundwater evapotranspiration. There are no known estimates of groundwater evapotranspiration based on field measurements in the general region (Scanlon and others, 2005). In Texas groundwater availability models along the coast, groundwater evapotranspiration has been simulated to be as low as 3 percent to as high as 48 percent of the total discharge water budget (Scanlon and others, 2005). Our conceptual approach to groundwater evapotranspiration is detailed in Section 4.6.1.

4.4.3 Precipitation

In the previous section, we introduced the concept of using baseflow estimates as a minimum estimate of shallow recharge. In this section, we discuss how baseflow can provide a basis for deriving a relationship between shallow recharge and precipitation. With this relationship, an estimate of how recharge would vary temporally under particular climatic conditions can be made.

In the previous section, the areas of the subwatersheds were determined based on the United States Geological Survey estimate of gage area. For this analysis, the actual boundaries of the subwatersheds were required. The "batch subwatershed delineation" tool in ArcHydro Tools (Maidment, 2002) was used to determine the boundaries of the subwatersheds associated with each gage, based on the 30 meter Digital Elevation Model. These boundaries are shown in Figure 4.4.4.

We estimated monthly precipitation for each subwatershed by intersecting the boundary of the subwatershed with monthly precipitation grids from the Parameter-elevation Regression on Independent Slopes Model precipitation dataset. We then summed the daily baseflow values for each month, so that we had monthly total baseflow estimates along with corresponding monthly precipitation and evapotranspiration estimates for each subwatershed.

Subregional groundwater flow (even in shallow systems) is typically not a process that happens on short time scales. So we would not expect much correlation between precipitation and baseflow even on a monthly timescale, and found little correlation during the course of the analyses. Because the measurement of baseflow integrates recharge from flow paths with widely varying lengths, the baseflow response will not occur at a single time. The best we could do was to perform the analysis on an average timescale that captures the response time of the majority of the flow paths. Because the Yegua-Jackson Aquifer groundwater model was developed with stress periods of one year, our objective was to predict annual average baseflow, based on a 12-month precipitation average that leads the baseflow by some number of months. This annual average should allow all of the smaller temporal effects on baseflow, such as bank storage, to be integrated within the time window. Also, note that the annual averaging aggregates any effects of in-year seasonal variations.

To estimate a best predictive model, we performed regressions of annual average baseflow versus a 12-month average precipitation, with a time lag (baseflow lagging precipitation) varying from zero to ten months. Note that in the regressions, our response variable was the logarithm of baseflow while the predictor was untransformed precipitation, since annual average baseflow is approximately lognormally distributed, while annual precipitation is approximately normally distributed. After performing the regressions for each of the lag times, we then took the regression model with the best fit based on the coefficient of determination and noted the corresponding lag. Of the 17 gage data sets considered, two were eliminated due to lack of data (i.e., only about 2 to 3 years of data were available, which were insufficient for an annual regression). Of the regressions on the remaining gage data, eight resulted in a coefficient of determination greater than 0.5. A summary of the results for those gages is shown in Table 4.4.2.

Figures 4.4.5 and 4.4.6 show plots of baseflow versus precipitation and the corresponding linear trendlines. Taking a simple median of the slopes and intercepts shown in Table 4.4.2 results in a slope of 0.032 and an intercept of -1.78. Our objective in the analysis was to produce a single equation describing the relationship for the entire outcrop, since creating multiple equations would be needlessly complex given the overall uncertainty in the base data. Using the median coefficients, and adding an offset for deep recharge (the estimates ranged from 0.2 to 0.8 for Grimes and Angelina counties, as noted in Section 4.4.2) yields:

$$\text{Recharge} = 10^{(0.032*\text{precipitation}-1.78)+(\text{deep recharge})} \qquad (4.4.1)$$

The results of this equation predicted over the expected range of annual precipitation are shown in Figure 4.4.7, where deep recharge is set at 0.2 inches per year, the low end of the range. The equation is only valid over the given range of precipitation. At 40 inches per year precipitation, similar to that in Fayette County in the central portion of the Yegua-Jackson Aquifer outcrop, the shallow recharge is about 0.35 inches per year, which is similar to the median shallow recharge determined from the long-term hydrograph separation studies (see Section 4.5.1). Note that the minimum recharge is approximately equal to the average deep recharge, and the maximum recharge does not exceed the maximum observed annual baseflow of approximately 3.0 inches per year.

Conceptually, Equation 4.4.1 describes a relationship where, for low precipitation years, recharge is mostly deep, with very little shallow recharge resulting in baseflow. As precipitation increases, shallow recharge increases, slowly at first, and faster at higher values of precipitation. Therefore, some minimum amount of precipitation is required before significant shallow recharge begins to occur.

Although this relationship was derived from temporal data, it also provides a convenient way of distributing recharge spatially, for a long-term average precipitation distribution. This would be appropriate for the predevelopment model, where precipitation and recharge do not vary temporally, but will vary spatially. For the model region, long-term average precipitation varies from approximately 15 to 60 inches per year, which would produce a long-term average recharge of approximately 0.25 to 1.7 inches per year over the model domain, based only on precipitation. Figure 4.4.8 shows an example of this distribution of recharge. Other considerations, such as topography, will provide for further distribution of recharge spatially, as described in the following sections.

4.4.4 Irrigation Return Flow

Irrigation return flow can be a significant source of recharge, depending on the concentration of irrigation activities and the type of crops being grown. For example, a crop that requires constant flooding, such as rice, will provide more groundwater return flow than a crop that is irrigated more intermittently, such as corn (rice is not an important crop in the region of the Yegua-Jackson Aquifer outcrop). In general, current good agricultural management practices for most crops include balancing irrigation application with plant evapotranspiration requirements (e.g., Allen and others, 1998), so that the amount of water that moves beyond the root zone to the water table below is minimized. Thus, a large amount of irrigation would be required to yield significant potential return flow.

Irrigation pumping in the Yegua-Jackson Aquifer is basically limited to four counties: Angelina, Brazos, Burleson, and Fayette. The maximum irrigation pumping for any year in a particular county was Fayette, at 159 acre-feet per year for 1980. Given the small magnitude of the pumping rates, irrigation return flow from pumping of the Yegua-Jackson Aquifer is not expected to add significantly to recharge. Irrigation pumping from other aquifers, such as from the Carrizo-Wilcox Aquifer in the Wintergarden area, occurs primarily outside of the Yegua-Jackson Aquifer outcrop.

Counties with significant surface water use for irrigation in the Yegua-Jackson Aquifer outcrop include Starr and Webb counties. The major source of surface water in those counties is the Rio Grande. In Webb County, the Rio Grande does not intersect the Yegua-Jackson Aquifer outcrop, so irrigation near the river would not return to the Yegua-Jackson Aquifer. According to the Texas Gap Analysis Program vegetation coverage (Parker and others, 2003), the majority of farmland in Starr County is southeast of the Yegua-Jackson Aquifer outcrop so, again, return flow should not recharge the aquifer.

Based on these observations of groundwater and surface water irrigation in the Yegua-Jackson Aquifer outcrop, irrigation return flow is not expected to make a significant contribution to recharge in the Yegua-Jackson Aquifer.

4.4.5 Topography

Investigators have determined that recharge is affected by topography with higher values of recharge occurring in highlands relative to lowlands which are more likely associated with discharge (Meyboom, 1966; Toth, 1966). Freeze (1971) concluded from modeling studies that the unsaturated zone delivers greater flow rates when the saturated zone is under higher gradients. These higher saturated zone gradients will typically exist in the topographically elevated areas. The effects of topography on the flow system and the potential for recharge are also noted in the Carrizo-Wilcox Aquifer in east Texas by Fogg and Kreitler (1982). Our objective was to develop a topographic scale factor that could be applied to the precipitation based recharge estimates to increase recharge in local highlands and decrease recharge in lowlands, while conserving the overall average recharge rate.

We developed a grid that reflected the relative topography in a given area by taking a 5-mile neighborhood average of the Digital Elevation Model and subtracting this from the original Digital Elevation Model. Because the neighborhood average Digital Elevation Model is locally smoothed (i.e., the highs are lower and the lows are higher), the difference between the two grids represents a local topographic indicator. Figure 4.4.9 shows the estimated areas of recharge and discharge based on topography.

4.4.6 Surface Soils

Soil properties can have a significant influence on recharge because of their impact on runoff, infiltration, and even evapotranspiration. Sandy soils will typically accept more infiltration for a given precipitation event than will clayey soils. Also, clayey soils will tend to retain water, allowing more time for evapotranspiration by vegetation.

The Soil Survey Geographical Database from the Natural Resource Conservation Service of the United States Department of Agriculture has estimates of soil properties throughout most of Texas. One of the physical properties of the soils estimated in the database is saturated hydraulic conductivity. The Soil Survey Geographical Database provides a spatial coverage of delineated areas, called map units, of soils with similar properties. For each of these map units, there can be up to six soil components, including an estimate of what fraction of the map unit is comprised of each component. In addition, each component can have up to four soil horizons (layers of soil which share common physical characteristics). Each horizon of each component will generally have an associated estimate of saturated hydraulic conductivity, as well as the thickness of that particular horizon.

Because we are interested in an integrated estimate of infiltration capacity, the saturated hydraulic conductivity values from the soil horizons were harmonically averaged (weighted by the thickness of the layers) for each component. An estimate of saturated hydraulic conductivity was made for each map unit by calculating an area-weighted, geometrically averaged value for the integrated component saturated hydraulic conductivity values. Figure 4.4.10a,b shows the estimate of surface soil saturated conductivity in the Yegua-Jackson Aquifer outcrop. A consistently low conductivity can be seen in the southwestern portion of the outcrop, especially through Webb, LaSalle, and McMullen counties (Figure 4.410a). The contrast between the outcrop conductivity and the conductivity of the regions just updip is clear. Through Wilson and Gonzales counties, the conductivity increases slightly, and appears to stay relatively unchanged up to Angelina and the tip of Nacogdoches counties, where conductivity appears slightly higher. Throughout the outcrop, many of the alluvial areas appear as higher conductivity areas. Note that the sharp change in the calculated average soil saturated hydraulic conductivities in McMullen County (Figure 4.4.10a) is a result of lower soil horizon saturated hydraulic conductivity values in the Soil Survey Geographical Database.

Because there is no real evidence of conductivity divisions between the various units of the Yegua-Jackson Aquifer, average recharge will be similar in all of the outcrops, for similar levels of precipitation.

Table 4.4.1 Results of the hydrograph separation analysis expressed in terms of outcrop flux.

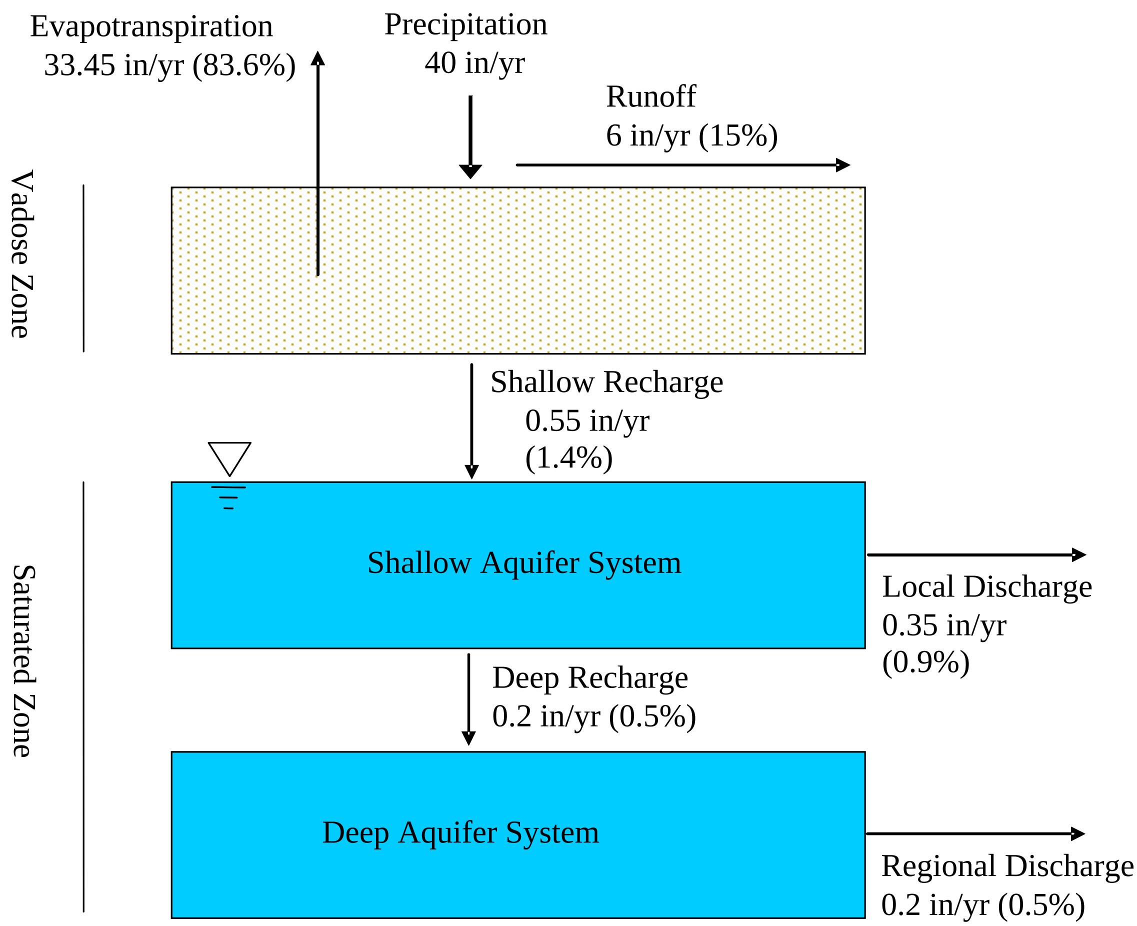
Gage Number	Stream Name	Major River	Baseflow (in/yr)	Area (mi^2)	Fraction non-zero	Baseflow Index
8175000	Sandies Creek	Guadalupe River	0.34	550	1	0.1
8038500		Angelina River	1.50	1300	0.96	0.17
8065800	Bedias Creek	Trinity River	0.64	320	0.95	0.07
8066100	White Rock Creek	Trinity River	0.74	220	0.93	0.1
8111025	Burton Creek	Navasota River	0.42	1.3	0.92	0.015
8174600	Peach Creek	Guadalupe River	0.30	460	0.89	0.057
8110100	Davidson Creek	Brazos River	0.33	200	0.83	0.064
8186500	Ecleto Creek	San Antonio River	0.12	240	0.77	0.055
8033000		Neches River	3.0	780	0.75	0.26
8033300	Piney Creek	Neches River	0.47	79	0.72	0.07
8065700	Caney Creek	Trinity River	0.27	110	0.67	0.036
8194500		Nueces River	0.16	2900	0.64	0.13
8110000	Yegua Creek	Brazos River	0.97	770	0.61	0.21
8206600		Frio River	0.1	1100	0.57	0.073
8208000		Atascosa River	0.11	640	0.56	0.063
8194200	San Casimiro Creek	Nueces River	0.026	470	0.44	0.018

in/yr = inches per year
mi^2 = square miles

Table 4.4.2 Summary of baseflow regression analyses.

Gage	Lag (months)	Slope	Intercept	R^2
8194500	1	0.108	-3.42	0.59
8175000	3	0.033	-1.73	0.59
8174600	5	0.046	-2.49	0.69
8110100	4	0.030	-1.79	0.59
8110000	6	0.047	-2.72	0.50
8066100	3	0.031	-1.54	0.63
8065800	3	0.032	-1.76	0.60
8038500	1	0.019	-0.77	0.60

R^2 = coefficient of determination



in/yr = inches per year
% = percent

Figure 4.4.1 Block diagram of precipitation partitioning into various components of the hydrologic system. Flux rates are examples of what might occur in the model area.

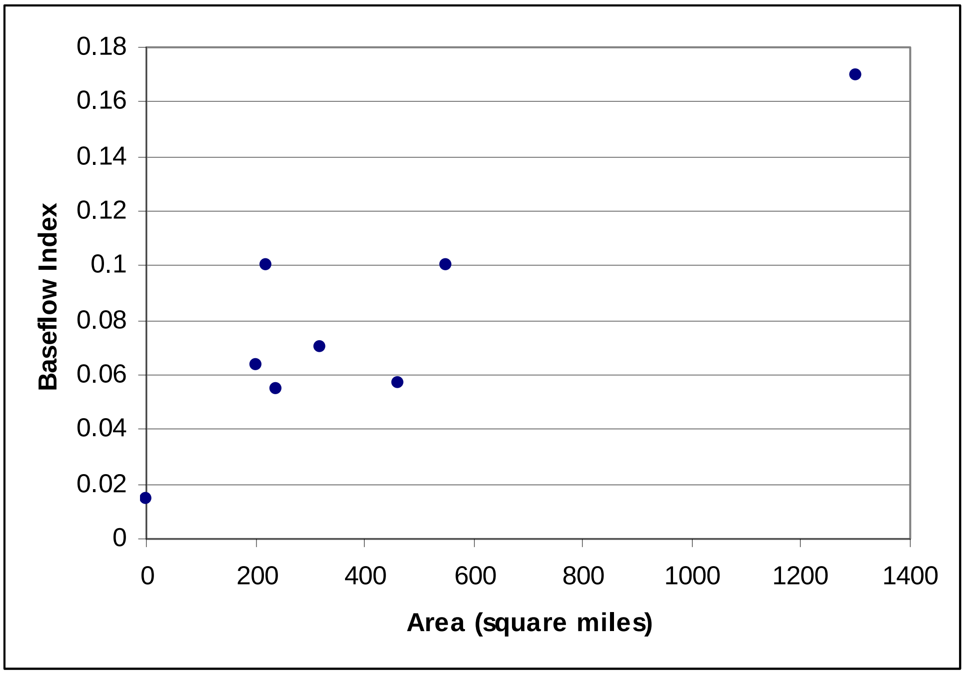


Figure 4.4.2 **Plot of baseflow index versus subwatershed area for gages where positive flow fraction exceeded 75 percent.**

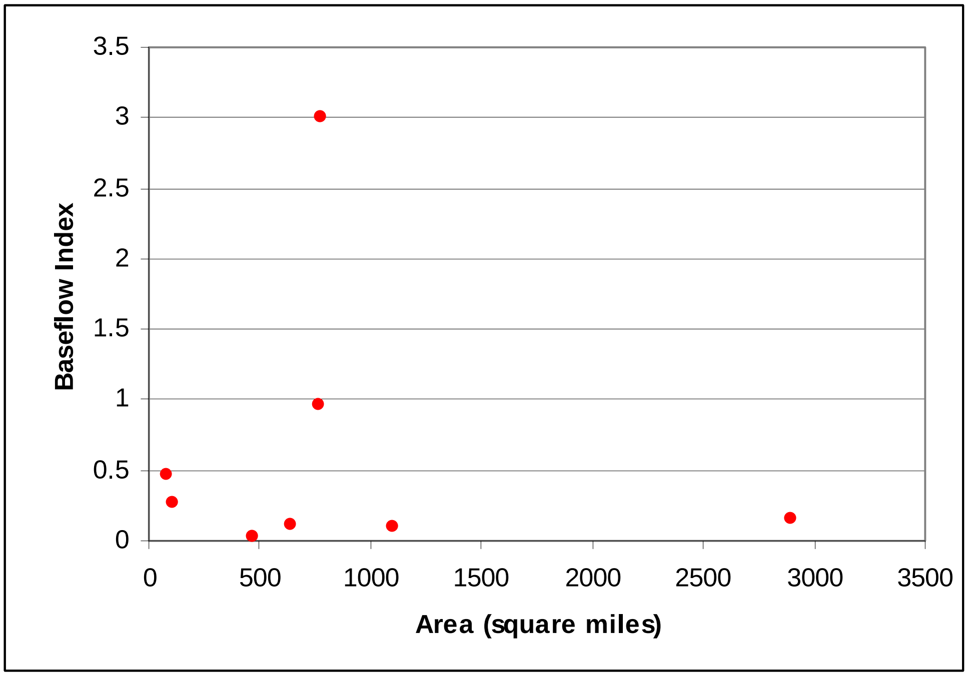


Figure 4.4.3 **Plot of baseflow index versus subwatershed area for gages where positive flow fraction was less than 75 percent.**

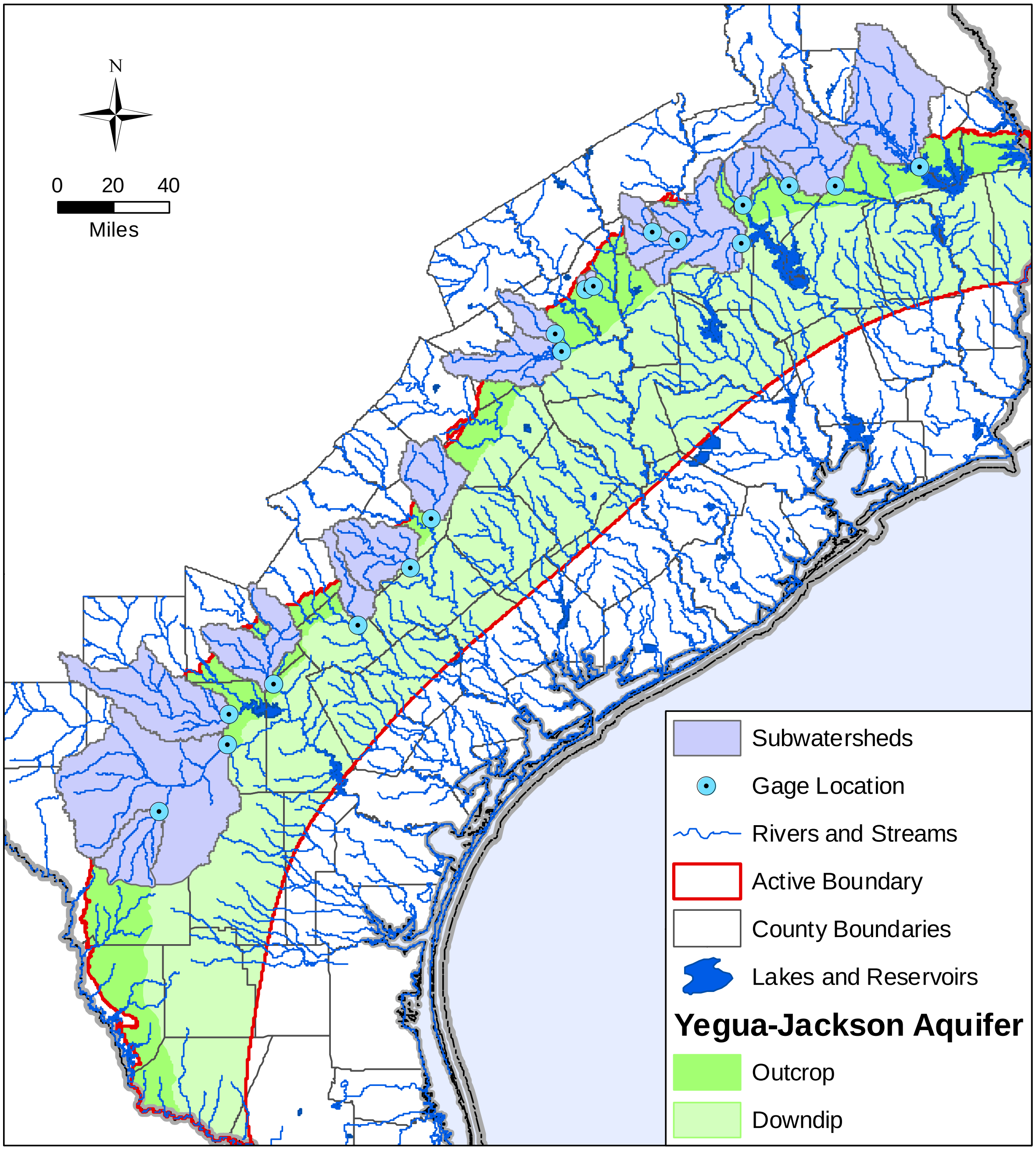


Figure 4.4.4 Location of subwatershed areas for the gages used in precipitation versus baseflow analysis.

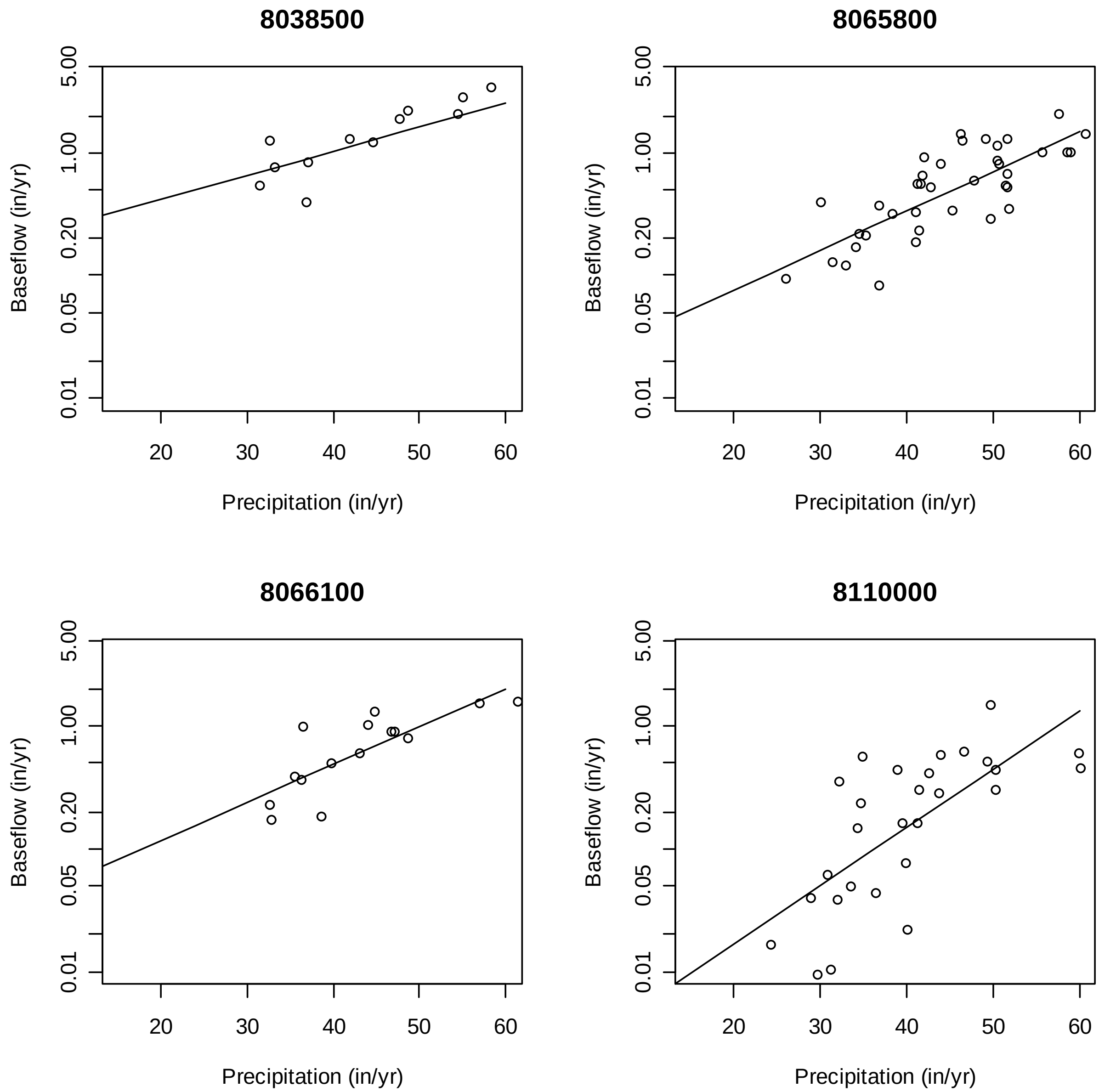


Figure 4.4.5 Plots of annual baseflow in inches per year versus precipitation in inches per year along with regression trendlines.

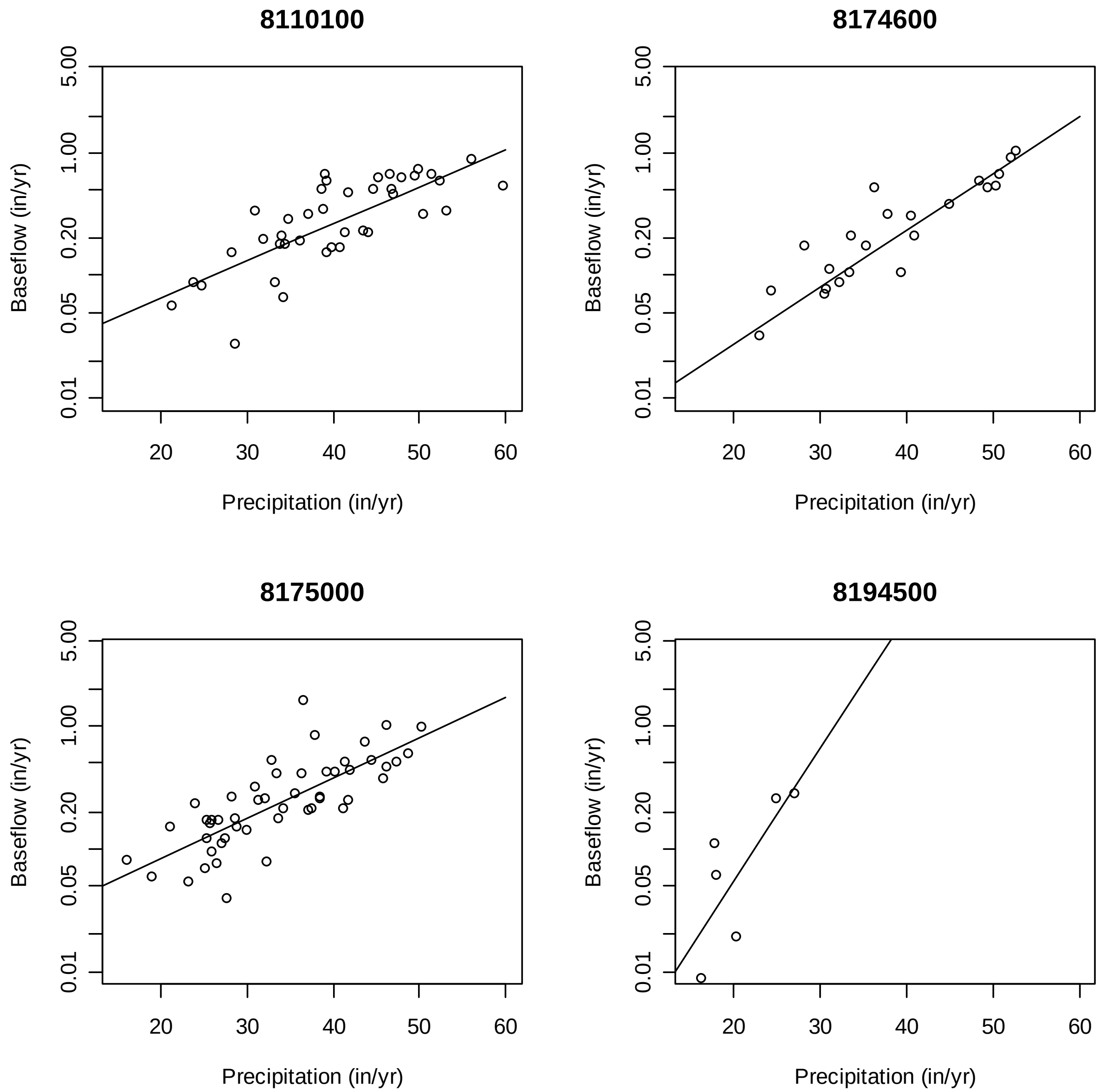


Figure 4.4.6 Plots of annual baseflow in inches per year versus precipitation in inches per year along with regression trendlines.

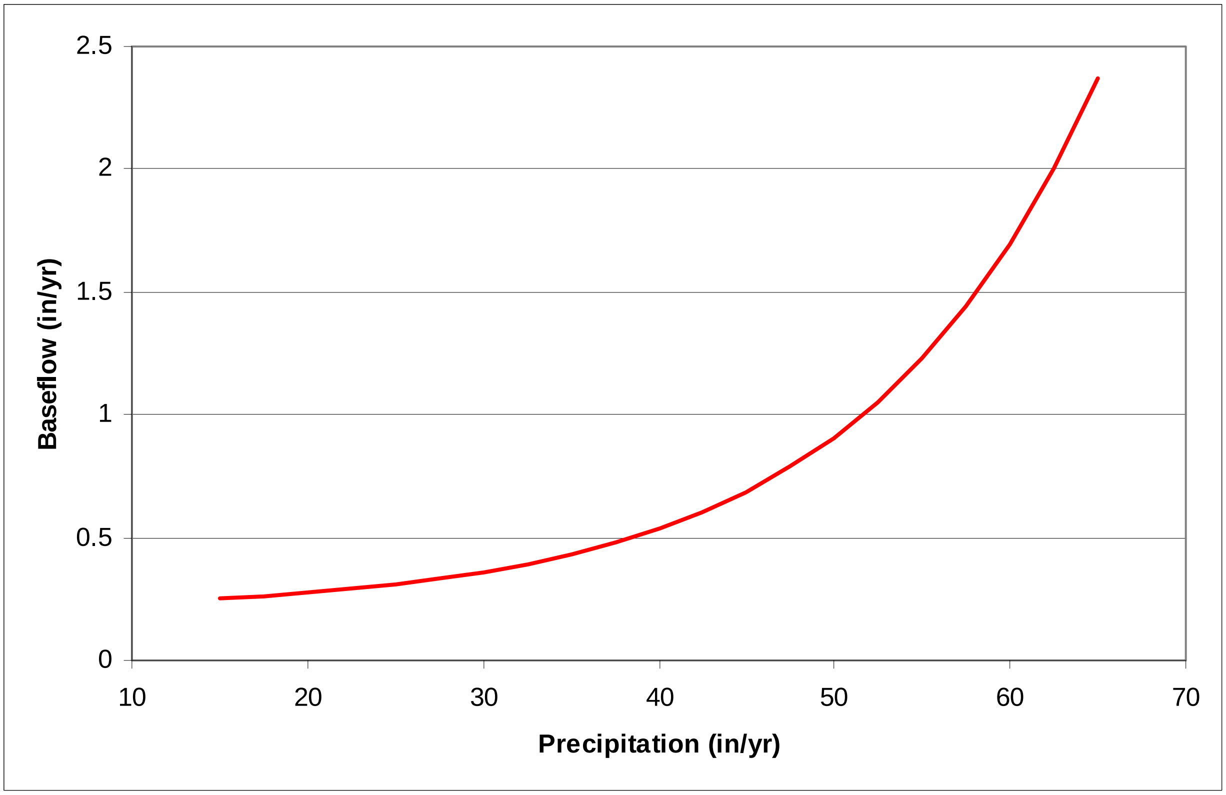


Figure 4.4.7 Theoretical variation of annual average baseflow in inches per year with annual average precipitation in inches per year based on regressions.

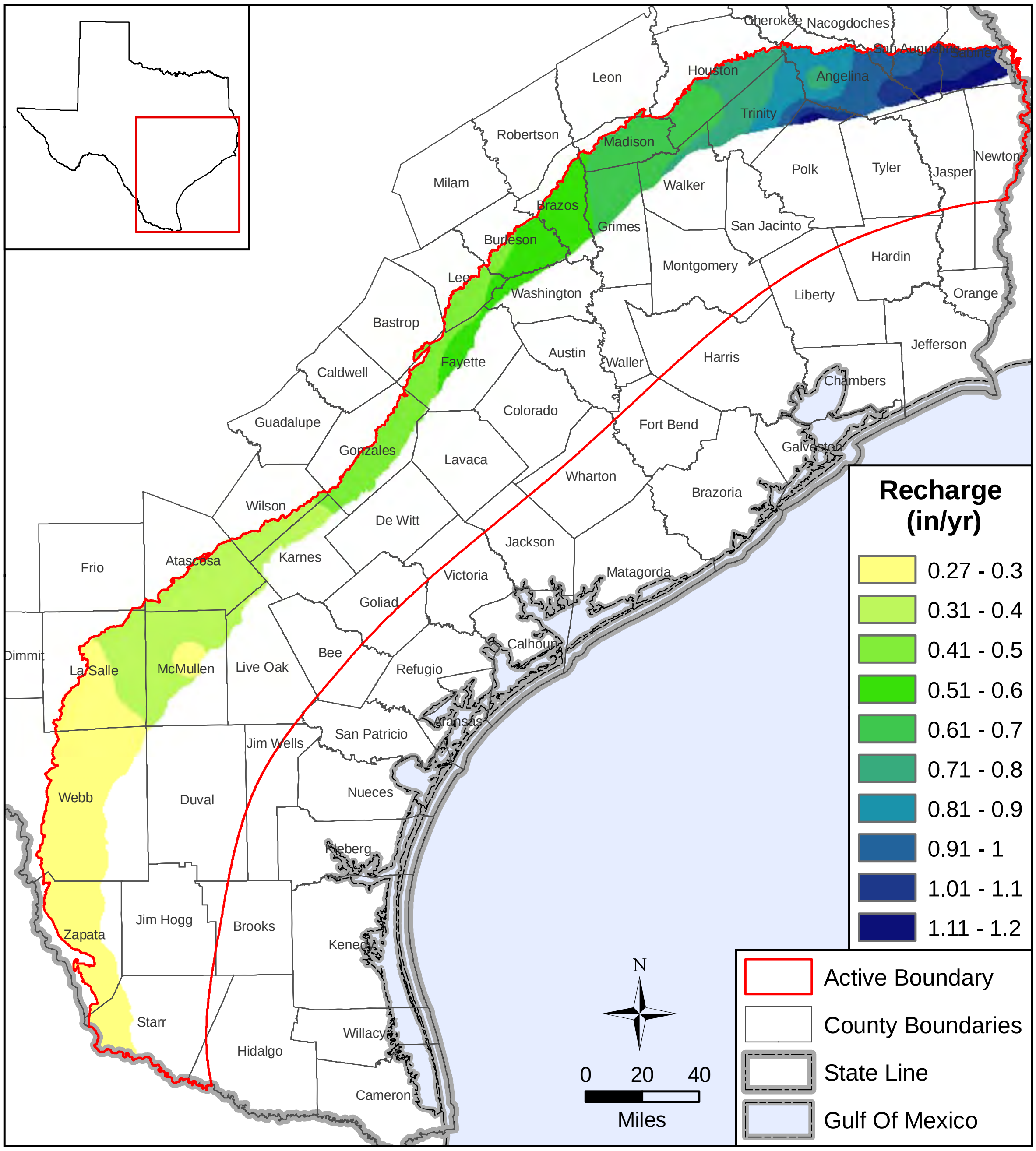


Figure 4.4.8 Estimated recharge distribution based on long-term average precipitation (1970 to 2000).

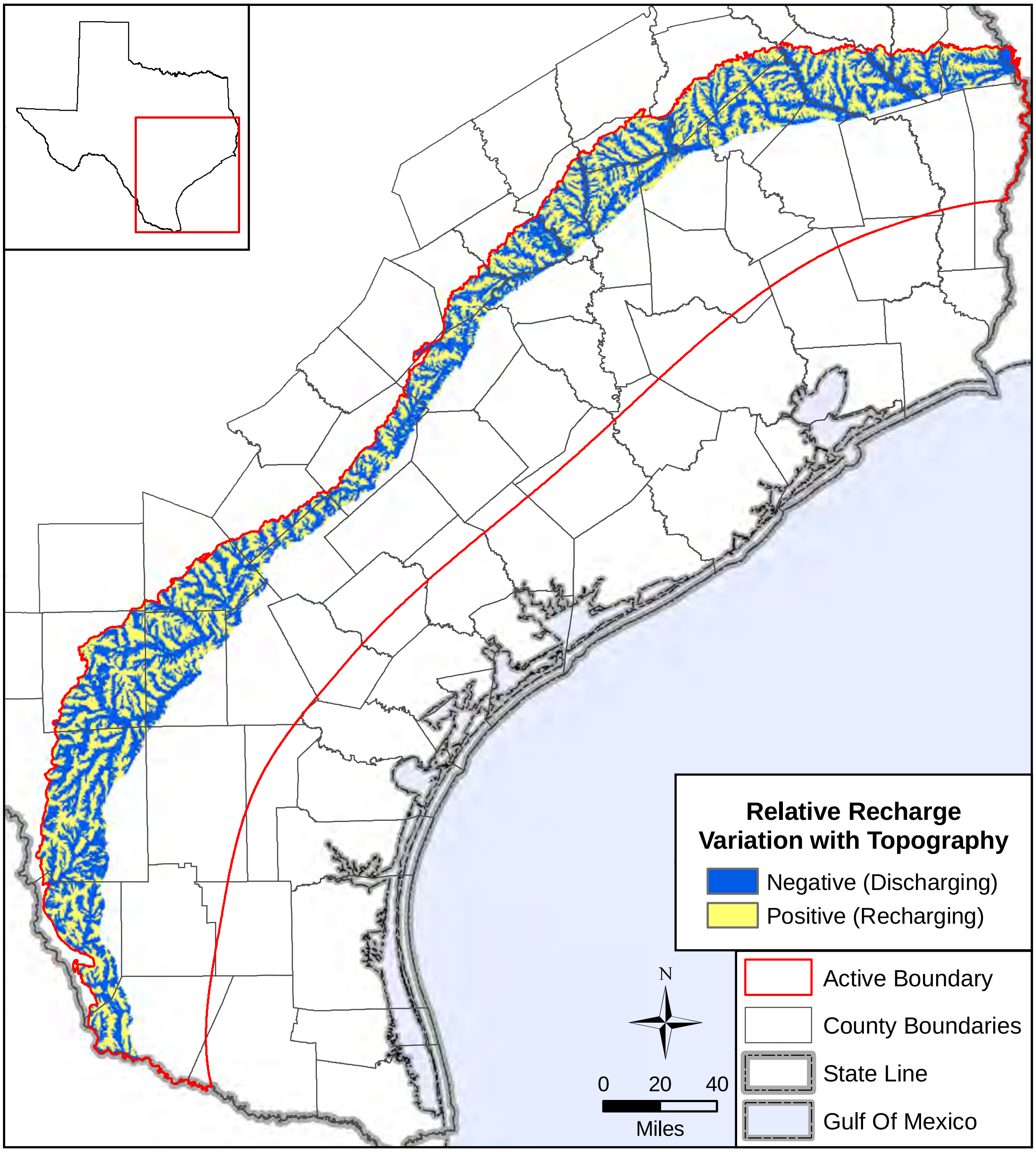
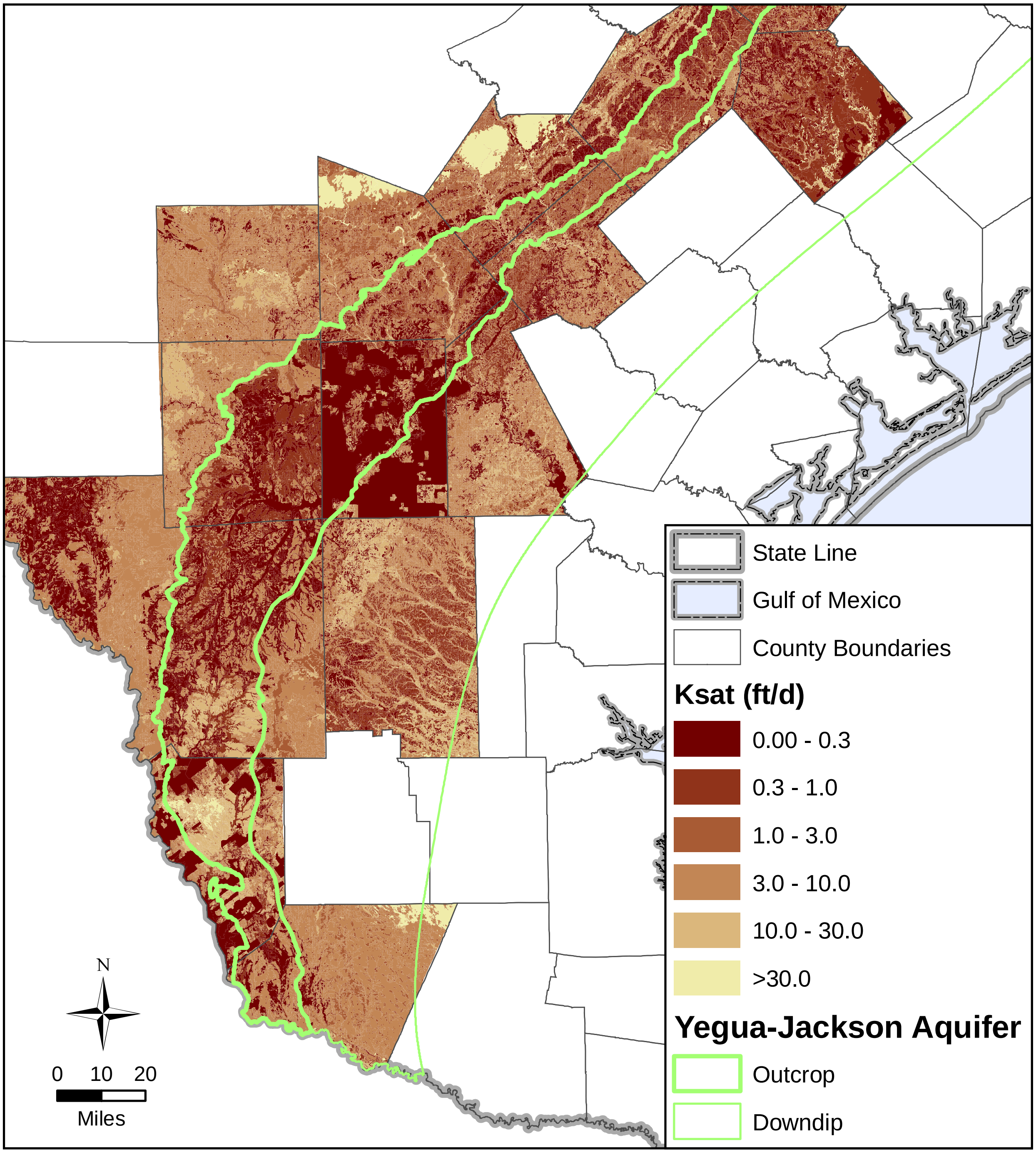
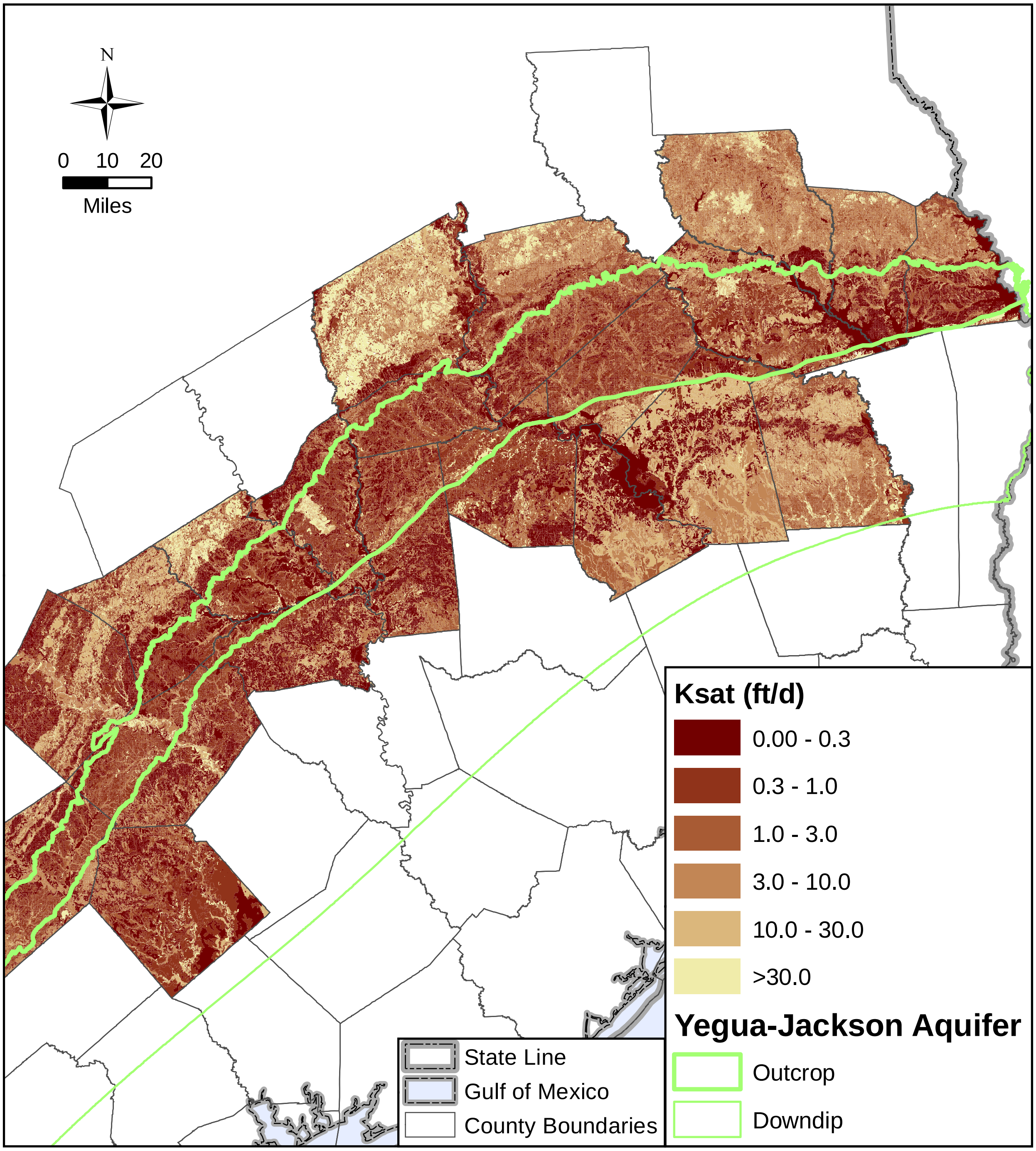


Figure 4.4.9 Relative variation of recharge with topography.



Ksat = saturated hydraulic conductivity

Figure 4.4.10a Averaged saturated soil conductivity in feet per day based on analysis of the Soil Survey Geographical data for the southwestern portion of the study area.



Ksat = saturated hydraulic conductivity

Figure 4.4.10b Averaged saturated soil conductivity in feet per day based on analysis of the Soil Survey Geographical data for the northeastern portion of the study area.

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4.5 Rivers, Streams, Springs, and Lakes

The interaction between groundwater and surface water can occur at the locations of rivers, streams, springs, and lakes. Interaction occurs primarily where the surface water body intersects an aquifer outcrop. Rivers and streams can either lose water to the underlying aquifer, resulting in aquifer recharge, or gain water from the underlying aquifer, resulting in aquifer discharge. Discharge from an aquifer also occurs where the water table intersects the ground surface at springs or seeps. Lakes, like rivers and streams, may provide a potential site of focused recharge when the water table is below the elevation of the lake, or may gain water from the aquifer when the water table is above the elevation of the lake.

Because the interaction between surface water and groundwater occurs where the aquifer is unconfined, the following discussion is limited to those surface water features that intersect the Yegua-Jackson Aquifer outcrop. Implementation of surface water features in the numerical model is described in Section 6.3.3.

4.5.1 Rivers and Streams

For a groundwater model, rivers and streams are primarily relevant as points of recharge or discharge to the unconfined portion of the aquifer. Their other characteristics, such as the magnitude and timing of flows, are less important, except as secondary indicators of stream-aquifer interaction. The first part of this section provides general background about the streams that intersect the outcrop area, in terms of their location and typical flows, and serves as a foundation for the conceptualization of stream-aquifer interaction. The section then continues with an attempt to quantify some of the stream losses and gains through literature values and new analyses.

Background

Nine major rivers intersect the outcrop of the Yegua-Jackson Aquifer. From southwest to northeast, they are the Rio Grande, Nueces, San Antonio, Guadalupe, Colorado, Brazos, Trinity, Neches, and Sabine rivers. The location of these rivers is shown in Figure 4.5.1. There are also many smaller streams that intersect the outcrop area (see Figure 2.0.4). Approximately

29 United States Geological Survey gages are in or near the outcrop area that have reported daily streamflow, although many are not currently being monitored. The locations of these gages are shown in Figure 4.5.2a,b, along with examples of historical streamflow for selected gages. Table 4.5.1 shows estimates of long term average flow in the major rivers measured in or near the outcrop. The first estimate is from the United States Environmental Protection Agency River Reach file, using the mean flow attribute from the river segment that exits the outcrop. The second estimate is an arithmetic average of all of the annual flows from the nearest United States Geological Survey gage. The two sources compare favorably, with the exception of the United States Environmental Protection Agency River Reach file estimate for the Rio Grande, which appears to be at least an order of magnitude too large.

Figure 4.5.3 shows flow duration curves for all available daily historical data from several of the gages reported in Table 4.5.1. Flow duration curves track exceedance probabilities for daily mean flow at the gages and, thus, provide insight into the range of flows that occur at a given gage in a river. The gage locations range from the drier regions in the southwest to the more humid area in the central portion of the area of interest. Figure 4.5.3 shows that the overall flow gains in magnitude and consistency moving from the southwest (Nueces) to the central portion (San Antonio and Colorado rivers). Further east, the Trinity River has larger magnitude flows than the Colorado River 70 to 80 percent of the days. The curve for the Nueces River indicates that negligible flow occurs for about 40 percent of the reported days. These flow duration curves are consistent with the general conceptualization of surface water and groundwater interaction across the Yegua-Jackson Aquifer outcrop. Rivers in drier regions without a significant baseflow component, such as the Nueces River, are less likely to have consistent flows of a significant magnitude.

In the southwest, rivers are typically losing, where the water level in the aquifer is below the river stage and, thus, river water recharges the aquifer. Moving to the more central and eastern regions, rivers are typically gaining, where the water level in the aquifer is above the river stage, and groundwater flows into the stream as baseflow. Where the transition occurs from losing to gaining is not well-defined in the literature. The Harris (1965) report for La Salle and McMullen counties, which contain the Nueces River, indicates that the only apparent natural discharge is evaporated from the soil by plants. The Anders (1960) report for Karnes County, which contains the San Antonio River, indicates that groundwater moves towards streams, but little baseflow is observed. The report for Fayette County (Rogers, 1967) discusses discharge to streams in a qualitative fashion. From these reports, the rivers would appear to be transitioning from losing to gaining in the region of the San Antonio and Guadalupe rivers.

The previous discussion outlined the general conceptualization of interaction between groundwater and streams with support from flow duration curves and local reports. The following sections will discuss quantitative estimates of surface water and groundwater interaction. The most common estimation techniques for quantifying this interaction are gain-loss studies (typically based on measurements made in periods of low flow) and hydrograph separation studies. Gain-loss studies can indicate gaining and losing segments of a stream, and are not dependent on the occurrence of baseflow. Hydrograph separation requires the upstream (or only) gage to measure flow in a segment that is experiencing baseflow.

Existing Studies

The most comprehensive analysis of gain-loss studies in Texas was completed by Slade and others (2002). This compilation contains the results of 366 gain/loss studies conducted since 1918 that included 249 individual stream reaches throughout Texas. Figure 4.5.4 shows the location of the Slade and others (2002) studies that intersected the Yegua-Jackson Aquifer outcrop, and the average gain or loss per river mile for each of the rivers. According to these studies, the only river that is losing is the Atascosa River. The Nueces River result (slightly gaining) is contrary to our conceptualization of the rivers in this portion of the outcrop as being predominantly losing. Gain-loss studies represent a snapshot of the river at a given time, rather than a long-term average. Examination of the flow duration curve in Figure 4.5.3 shows that the Nueces River has negligible flow a significant portion of the time, so it is unlikely to be a consistently gaining stream.

The United States Geological Society, in cooperation with the San Antonio River Authority, began a study in 2005 to analyze surface water and groundwater interaction in the lower San Antonio River. Four gain-loss surveys were conducted during "periods of relatively steady baseflow" (Ockerman, 2007). Figure 4.5.5 shows the locations of the measurements that most closely spanned the Yegua-Jackson Aquifer outcrop. Table 4.5.2 shows the results from the gain-loss measurements.

The results in Table 4.5.2 indicate that Cibolo Creek does not have significant gains or losses over the outcrop region. The San Antonio River ranged from slightly gaining to slightly losing over the course of the studies, with an overall average gain of 724 acre-feet per year per mile.

As part of a Lower Colorado River Authority and San Antonio River Authority joint water project, Saunders (2006) performed a gain-loss study on the lower Colorado River from Austin to Bay City. Figure 4.5.5 shows the location of the gages used in the study that bracketed the Yegua-Jackson Aquifer outcrop. The measurements indicated that a loss occurred across the outcrop of -22 cubic feet per second. This was the only segment where a loss was measured on the Colorado River, and was noted by the author to be “difficult to explain” given the typical gaining nature of the Colorado River.

A United States Geological Survey study by Turco and others (2007) estimated baseflow (through hydrograph separation) and streamflow gain and loss (through synoptic measurement) on the Brazos River. None of the hydrograph separation studies were made using gages with a predominant catchment area in the Yegua-Jackson Aquifer outcrop, so those studies are not discussed here. Gain-loss measurements were made at four points along the Brazos River where it crosses the Yegua-Jackson Aquifer outcrop. The authors took the (somewhat rare, but commendable) approach of identifying which gains and losses exceeded the potential error in the measurements. One of the estimates for the span across the Yegua-Jackson Aquifer met the criteria. The gain-loss for this estimate was +258 cubic feet per second over 11 river miles, which equates to 17,000 acre-feet per year per mile.

New Hydrograph Separation Analyses

The previous section had references to hydrograph separation as a technique for estimating baseflow. Hydrograph separation is a methodology whereby streamflow hydrograph data is analyzed and surface runoff is partitioned from the stream baseflow component. The basic premise is that in the streamflow hydrograph, sharp peaks will represent surface runoff events, whereas the smooth, constant portion of the streamflow hydrograph represents baseflow. Figure 4.5.6 shows an example of this technique for streamflow gage 817500 on Sandies Creek in southern Gonzales County. The figure shows the order of magnitude changes in overall flow (from 3 to more than 1,000 cubic feet per second) and the relatively steady baseflow component. There are several automated methods available to perform the separation. The hydrograph separation code Base Flow Index (Wahl and Wahl, 1995) was used for the analyses in the current study.

While hydrograph separation is relatively easy to perform, finding appropriate gage data can be difficult. Gages and their corresponding data must meet certain criteria before they can be considered for analysis. The primary criteria considered in the current study are as follows:

1. The gage should be on a stream considered to be primarily gaining.

2. The catchment area for the gage must be primarily in the outcrop of the Yegua-Jackson Aquifer.

3. If the catchment area for the gage extends well upstream of the outcrop of the Yegua-Jackson Aquifer, there must be an upstream gage near the top of the outcrop that can be used to subtract the effects of the upstream area (i.e., the contribution from the catchment area that is not in the Yegua-Jackson Aquifer outcrop).

4. The majority of the catchment area for the gage must be unregulated. If the gage is paired with an upstream gage, the unregulated periods must have a significant overlapping record.

Criteria number four is a difficult one to overcome, since many of the major rivers in Texas are highly regulated. In some cases, analysts attempt to use local knowledge of river management to account for regulation of the river. This is a difficult and time-consuming approach that is not tractable for the current study given the regional nature of the model.

Figure 4.5.7a,b shows the gages (and upstream pairs) that were considered for hydrograph separation as part of the analysis. Table 4.5.3 summarizes these same gages and provides information on the various criteria for rejection or selection.

Table 4.5.3 indicates that gages on primary rivers always require an upstream gage, while those that represent headwaters are smaller streams or creeks. The inclusion of one or two upstream gages increases the potential error in the baseflow calculation, so this must be considered when analyzing the hydrograph separation results. In addition, for those gages that are on intermittent streams, the estimate of baseflow will only be relevant for those durations when the stream has been flowing consistently.

The results of the hydrograph separation analyses are shown in Figure 4.5.8. To convert the total baseflow rate to a per mile rate, river segment lengths were estimated based on the United States Environmental Protection Agency River Reach file coverage. For cases where a paired upstream gage was used, the length was the distance from the upstream gage to the downstream gage. For cases were only headwaters were represented, the length of the primary (highest mean flow) segment was used. Figure 4.5.8 shows that, in general, the gains increase moving from southwest to northeast. Some of the largest gaining rivers eventually became reservoirs (the separation analysis was completed with flow data before impoundment). Those rivers that are most deeply incised and lie in broad topographic lows are likely to have significant gaining interaction with groundwater, and also are well-suited for impoundment.

4.5.2 Springs

Springs are locations where the water table intersects the ground surface. Springs typically occur in topographically low areas in river valleys or in areas of the outcrop where hydrogeologic conditions preferentially reject recharge. Three sources were used to find spring data for the Yegua-Jackson Aquifer: the TWDB well database (TWDB, 2008b) (no natural springs were found), a database of Texas springs compiled by the United States Geological Survey and reported in Heitmuller and Reece (2003), and Brune (2002). Figure 4.5.9 shows the locations of springs in the outcrop of Yegua-Jackson Aquifer. These springs flow from the Yegua Formation, Jackson Group, or Terrace Gravel in the outcrop.

The literature review identified 41 springs or groups of springs in the outcrop of the Yegua-Jackson Aquifer. Of these, two springs do, or at one time did, discharge at a rate greater than 0.22 cubic feet per second (100 gallons per minute). They are located in Fayette and McMullen counties. The available measured spring flow rates range from the springs being dry to a high of 24 cubic feet per second at Wheeler Hole in McMullen County. Brune (2002) states that the water hole at this location was fed by springs from river terrace sand and gravel. The highest discharge was measured in May 1949 and it is considered to be a result of spring flow and seepage. No significant springs or seeps existed in 1979.

Throughout much of the state, including the study area, spring flows have shown a general decline over time. Most information regarding spring declines for minor springs is anecdotal and undocumented. Table 4.5.4 shows that two flow measurements are available for six springs, while most have one or zero measurements. The six springs with two measurements show declining flow over time. The flow from five springs has stopped and the springs have become dry.

4.5.3 Lakes and Reservoirs

There are no natural lakes in the study area. However, seven reservoirs intersect the outcrop of the Yegua-Jackson Aquifer. Table 4.5.5 lists the names, owners, surface area, and year impounded for these reservoirs in the study area. Figure 4.5.10 shows the locations of the reservoirs and the historical lake stage elevations for three of the reservoirs are shown in Figure 4.5.11. The water level time series for Sam Rayburn Reservoir (1966 to 2007) shows elevation fluctuations from about 135 to 174 feet above mean sea level with an average value of about 161 feet above mean sea level. The water level time series for Somerville Lake (1967 to 2007) shows elevation fluctuations from about 210 to 258 feet above mean sea level with an average value of about 238 feet above mean sea level. From 1969 to 2007, the elevation of Somerville Lake stayed fairly constant except in 1992 when the elevation rose briefly to 258 feet above mean sea level. The water level time series for Choke Canyon Reservoir (1982 to 2008) shows elevation fluctuations from about 156 to 221 feet above mean sea level with an average value of about 203 feet above mean sea level. The elevation of Choke Canyon Reservoir increased from about 156 to 220 feet from 1984 to 1987, decreased to 192 feet in 1997, and then went back to 220 feet in 2002.

Table 4.5.1 Estimates of long-term average flow in the major rivers where they exit the outcrop.

River Name	RF1 Average Flow (cfs)	Gage Number	Average Gaged Flow (cfs)
Rio Grande	80,500	IBWC08-4647.00	3,500
Nueces River	500	08194500	400
San Antonio River	550	08183500	500
Guadalupe River	1,300	08173900	2,200
Colorado River	2,200	08160400	2,800
Brazos River	4,600	08110200	5,200
Trinity River	6,200	08066000	6,300
Neches River	1,800	08033000	1,600
Sabine River	6,000	08024400	5,000

RF1 = United States Environmental Protection Agency River Reach file
cfs = cubic feet per second

Table 4.5.2 Gains and losses from the Ockerman (2007) study.

River	Gains and Losses (cfs)				Average (cfs)	Segment Length (mi)	Average Gain/Loss (AFY/mi)
	Study 1	Study 2	Study 3	Study 4			
San Antonio River	-30	+3	+43	+40	+14	14	724
Cibolo Creek	-1			1	0	8	0

cfs = cubic feet per second
mi = miles
AFY/mi = acre-feet per year per mile

Table 4.5.3 Summary of gages considered for hydrograph separation.

Gage Number	Stream Name	Major River	Upstream Gage	Accept?	Reason for Rejection	Valid Date Span
8194200	San Casimiro Creek	Nueces River	Headwaters	Yes		1963-2000
8194500		Nueces River	8194000	Yes		1944-1949
8206600		Frio River	8205500	Yes		1979-
8207000		Frio River	8206600,8206700	No	No overlap with upstream gages	none
8206700	San Miguel Creek	Frio River	None	No	No upstream gage	
8208000		Atascosa River	8207500	Yes		1951-
8207500		Atascosa River	None	No	No upstream gage	
8183500		San Antonio River	8183200	No	No unregulated data	
8186000	Cibolo Creek	San Antonio River	8185500	No	No overlap with upstream gages	none
8186500	Ecleto Creek	San Antonio River	Headwaters	Yes		
8175000	Sandies Creek	Guadalupe River	Headwaters	Yes		
8174600	Peach Creek	Guadalupe River	Headwaters	Yes		
8160400		Colorado River	8159500	No	No unregulated data	
8110000	Yegua Creek	Brazos River	8109700,8109800	Yes		1963-1966
8110100	Davidson Creek	Brazos River	Headwaters	Yes		1963-2000
8110200		Brazos River	None	No	No upstream gage	
8111025	Burton Creek	Navasota River	Headwaters	Yes		1969-1970
8111050	Hudson Creek	Navasota River	Headwaters	Yes		1969-1970
8111010		Navasota River	8111000	No	No unregulated data	
8111000		Navasota River	8110800	No	No overlap with upstream gage	none
8065700	Caney Creek	Trinity River	Headwaters	Yes		1964-1976
8065800	Bedias Creek	Trinity River	Headwaters	Yes		1968-2000
8066000		Trinity River	8065500	Yes		1940-1953
8066100	White Rock Creek	Trinity River	Headwaters	Yes		1967-1985
8033300	Piney Creek	Neches River	Headwaters	Yes		1962-1989
8033000		Neches River	8032500	Yes		1945-1961
8038500		Angelina River	8037000	Yes		1952-1956
8025360		Sabine River	8024400,8024500	No	No unregulated data	

Table 4.5.4 Summary of springs in the study area.

County	Spring Name/Number	Formation	Max flow (lps)	Max flow (gpm)	Max flow (cfs)	Max flow (AFY)	Date of Max	Min flow (lps)	Min flow (gpm)	Min flow (cfs)	Min flow (AFY)	Date of Min	Number of Measurements	Source
Angelina	37-53-602	Jackson	0.32	**5.00**	0.01	8.07							1	USGS
Angelina	37-53-903	Jackson											0	USGS
Brazos	59-30-801	Jackson	0.25	**4.00**	0.01	6.45	7/1970						1	USGS
Brazos	59-31-601	Jackson											0	USGS
Burleson	59-45-204	Jackson											0	USGS
Burleson	Sulphur Springs	Terrace gravel											0	USGS
Burleson	59-38-707	Terrace gravel											0	USGS
Fayette	Cistern Springs	Yegua	**0.75**	11.88	0.03	19.16	2/1977		**dry**			1979	2	Brune (2002)
Fayette	Primm Springs	Terrace gravel	**30.00**	475.20	1.06	766.50	10/1975	**16.00**	253.44	0.57	408.80	4/1978	2	Brune (2002)
Grimes	Kellum Springs	Jackson	1.58	**25.00**	0.06	40.33							1	USGS
Grimes	Piedmont Springs	Jackson	0.13	**2.00**	0.00	3.23							1	USGS
Grimes	59-32-703	Jackson											0	USGS
Grimes	Black Sulphur Spring	Jackson											0	USGS
Grimes	Gibbons Spring	Jackson											0	USGS
La Salle	Nogate Water Hole	Yegua							**seeps**			1979	1	Brune (2002)
La Salle	Charco Largo Spring	Terrace gravel							**seeps**			1979	1	USGS
Leon	Lick Hill Spring												0	USGS
Live Oak	Bell Seeps	Jackson							**seeps**			1979	1	Brune (2002)
Mc Mullen	Hill side seeps at Dickinson's ranch	Jackson							**seeps**			1979	1	Brune (2002)
Mc Mullen	Seepage at Franklin Ranch	Jackson							**seeps**			1979	1	Brune (2002)
Mc Mullen	Seeps at archeological site on James Donnel's Ranch	Jackson							**dry**			1979	1	Brune (2002)
Mc Mullen	Wheeler hole	Terrace gravel	**680.00**	10,771.20	24.01	17,374.02	3/1949		**dry**			1979	2	Brune (2002)

Table 4.5.4, continued

County	Spring Name/Number	Formation	Max flow (lps)	Max flow (gpm)	Max flow (cfs)	Max flow (AFY)	Date of Max	Min flow (lps)	Min flow (gpm)	Min flow (cfs)	Min flow (AFY)	Date of Min	Number of Measurements	Source
Nacogdoches	Blue Springs	Yegua	**0.18**	2.85	0.01	4.60	1978						1	Brune (2002)
Polk	37-58-304	Jackson	0.06	**1.00**	0.00	1.61							1	USGS
Polk	37-59-401	Jackson	0.32	**5.00**	0.01	8.07	6/1947						1	USGS
San Augustine	37-46-603	Yegua	0.06	**1.00**	0.00	1.61	1942		**dry**			1964	2	USGS
San Augustine	37-54-201	Yegua	0.06	**1.00**	0.00	1.61	1942		**dry**			1964	2	USGS
San Augustine	37-55-401	Jackson											0	USGS
San Augustine	Indian Springs	Yegua	**0.65**	10.30	0.02	16.61	2/1978						1	Brune (2002)
San Augustine	Magnolia Springs	Yegua	**0.05**	0.79	0.00	1.28	1978						1	Brune (2002)
San Augustine	Sulphur Springs (1)	Yegua	**0.08**	1.27	0.00	2.04	1978						1	Brune (2002)
San Augustine	Sulphur Springs (3)	Yegua							**seeps**			1978	1	Brune (2002)
Starr	Agua Verde (geen water) Springs	Jackson		**seeps**			1967		**dry**			1979	2	Brune (2002)
Starr	Springs along Arroyo Laminta	Jackson	**0.12**	1.90	0.00	3.07	12/1976						1	Brune (2002)
Starr	Indian Springs	Terrace gravel	**0.11**	1.74	0.00	2.81	1976						1	Brune (2002)
Trinity	Apple Springs												0	USGS
Webb	El Pato Spring	Yegua							**dry**				1	USGS
Webb	Charco de los Indios (Indian water hole)	Yegua											0	Brune (2002)
Webb	El Patito (Little Duck Spring)	Yegua							**dry**			before 1979	1	Brune (2002)
Webb	San Ygnacio Spring	Yegua							**dry**			before 1979	1	Brune (2002)
Zapata	Charco Redondo Spring	Jackson							**dry**				1	USGS

Note: Bolded information reflects values and text given in the data source.
USGS = United States Geological Survey (Heitmuller & Reece, 2003)
Max = maximum   Min = minimum   lps = liters per second
gpm = gallons per minute   cfs = cubic feet per second   AFY = acre-feet per year

Table 4.5.5 Characteristics of reservoirs in the study area intersecting the Yegua-Jackson Aquifer outcrop.

Reservoir Name	Owner/Controlling Authority	Surface Area (acres)	Date Impounded
Toledo Bend Reservoir	Sabine River Authorities of Texas and Louisiana	200,000	1966
Sam Rayburn Reservoir	US Army Corps of Engineers	114,500	1965
Lake Livingston	Trinity River Authority	93,000	1969
Gibbons Creek Reservoir	Texas Municipal Power Agency	2,770	1981
Somerville Lake	US Army Corps of Engineers	11,630	1967
Choke Canyon Reservoir	City of Corpus Christi	25,670	1982
International Falcon Reservoir	International Boundary and Water Commission	83,654	1953

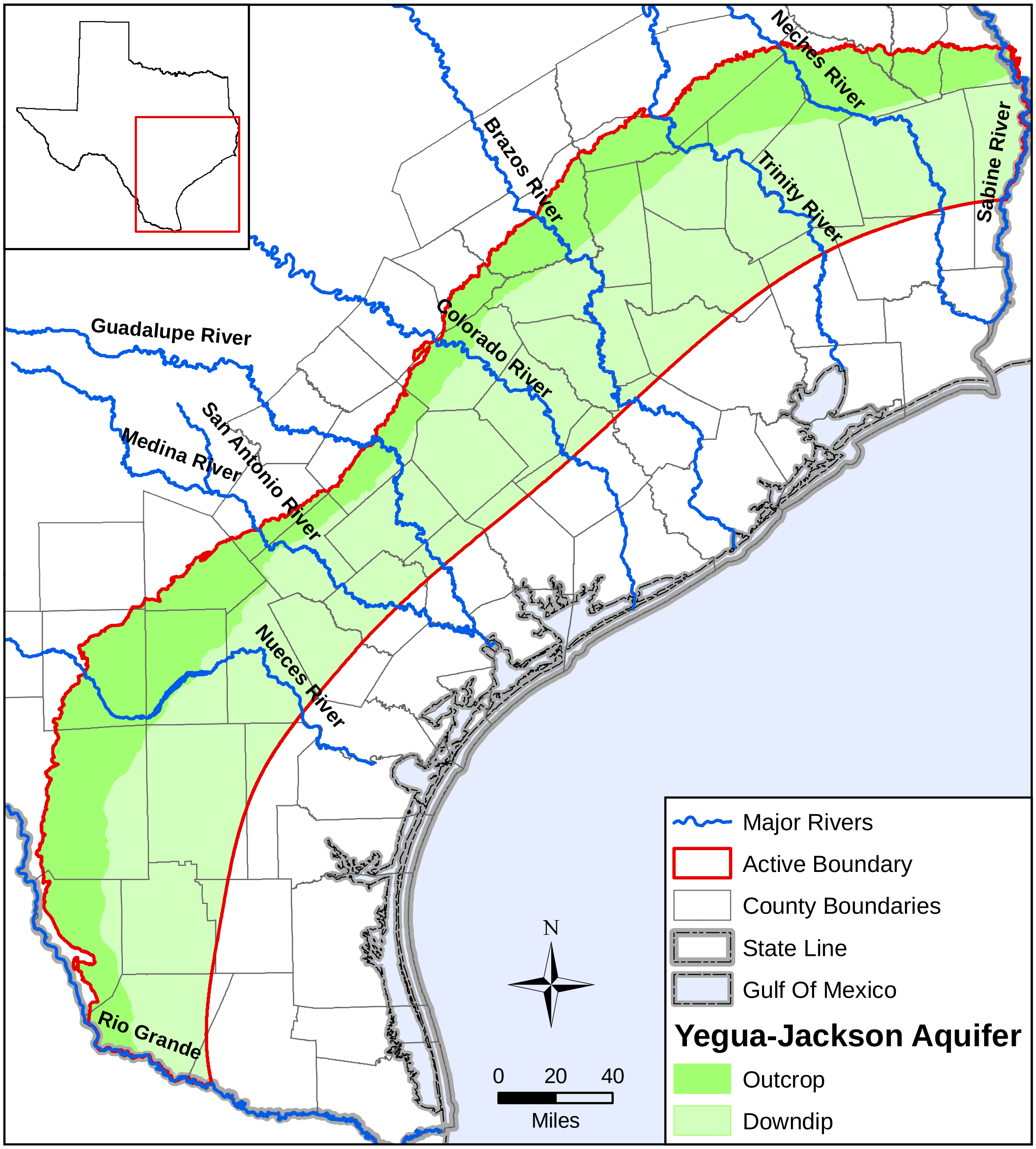
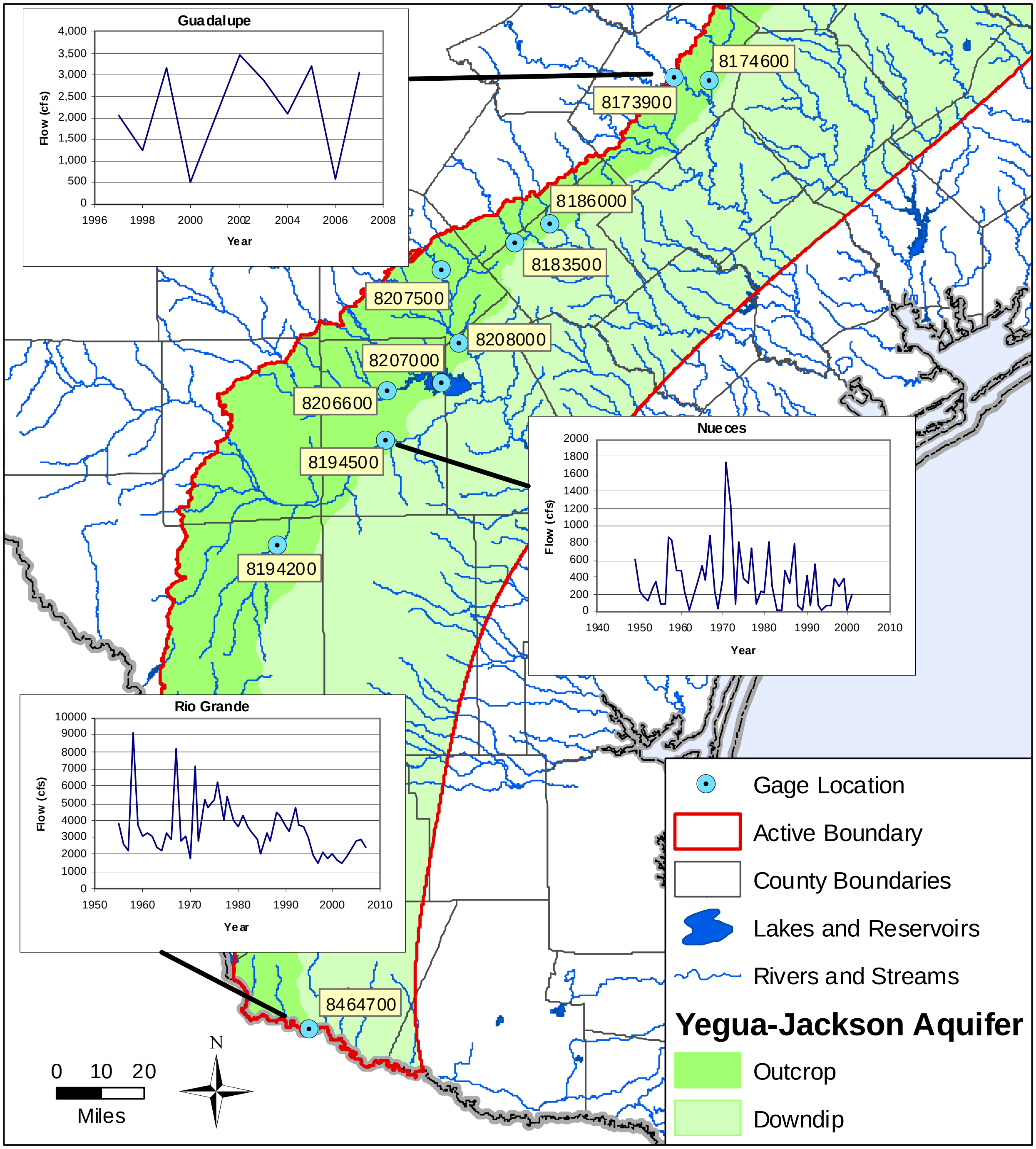
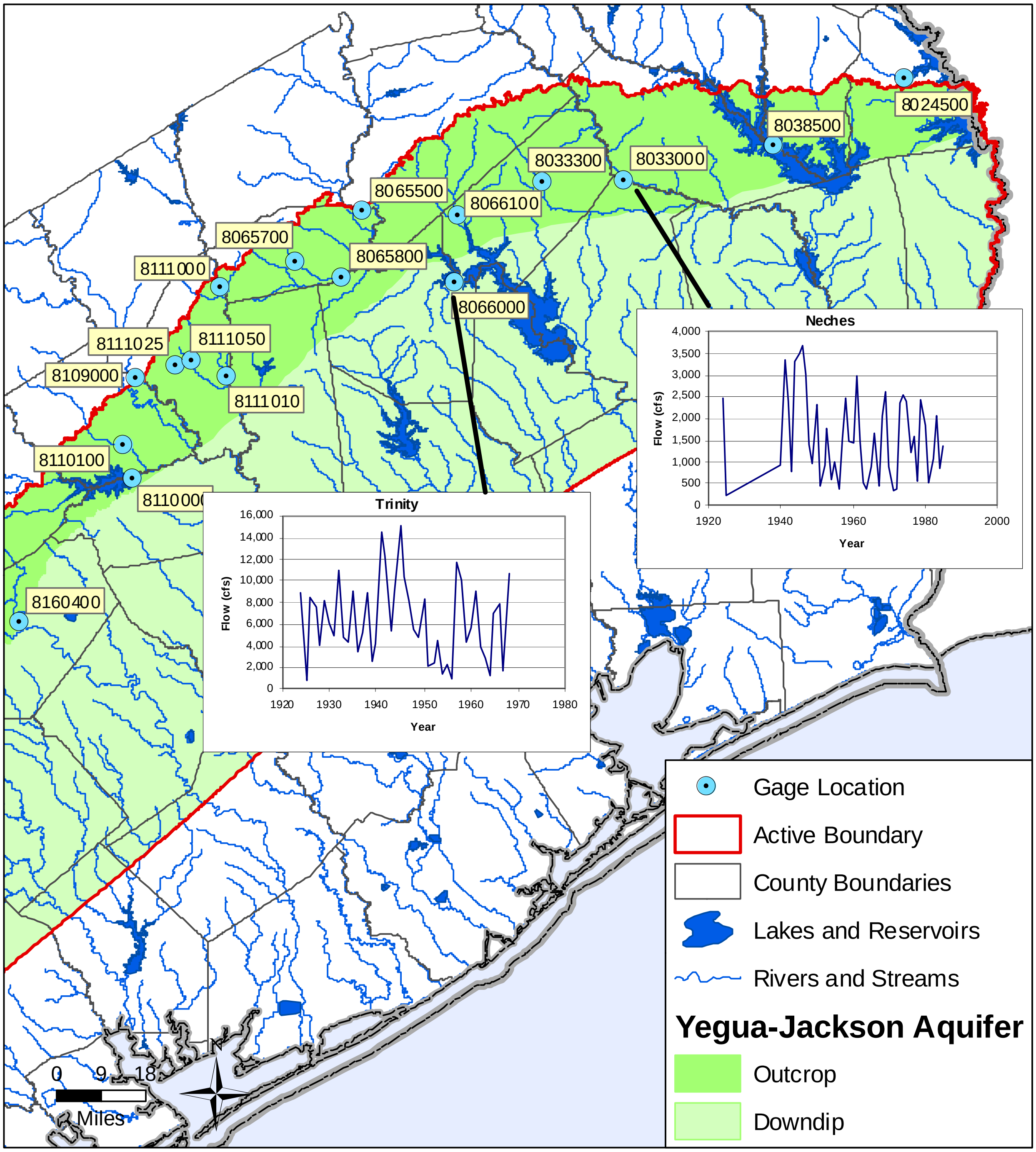


Figure 4.5.1 Major rivers in the study area.



cfs = cubic feet per second

Figure 4.5.2a Stream gages in the southern outcrop with selected streamflow hydrographs.



cfs = cubic feet per second

Figure 4.5.2b Stream gages in the northern outcrop with selected streamflow hydrographs.

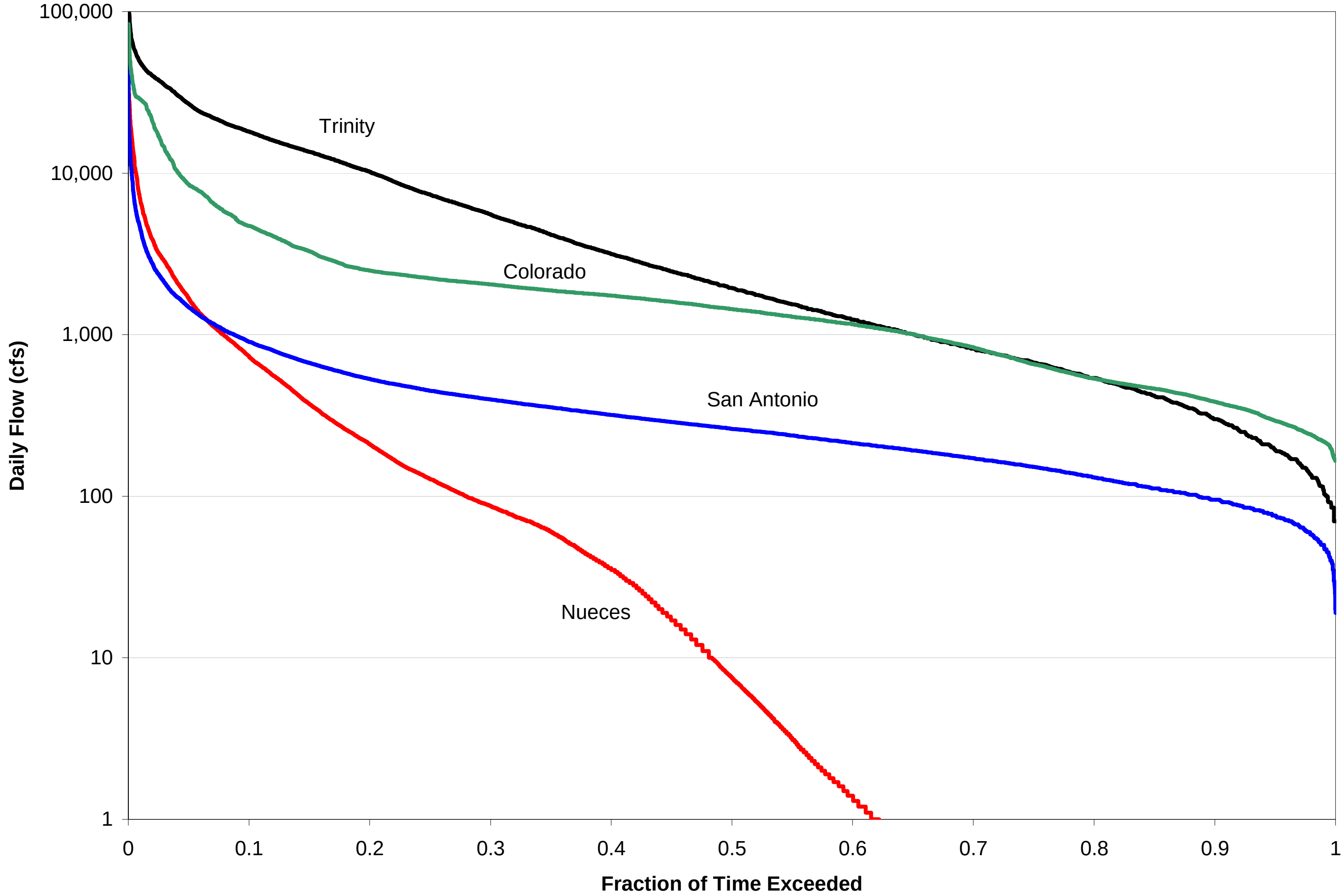


Figure 4.5.3 Flow duration curves for the major rivers in the region. (cfs = cubic feet per second)

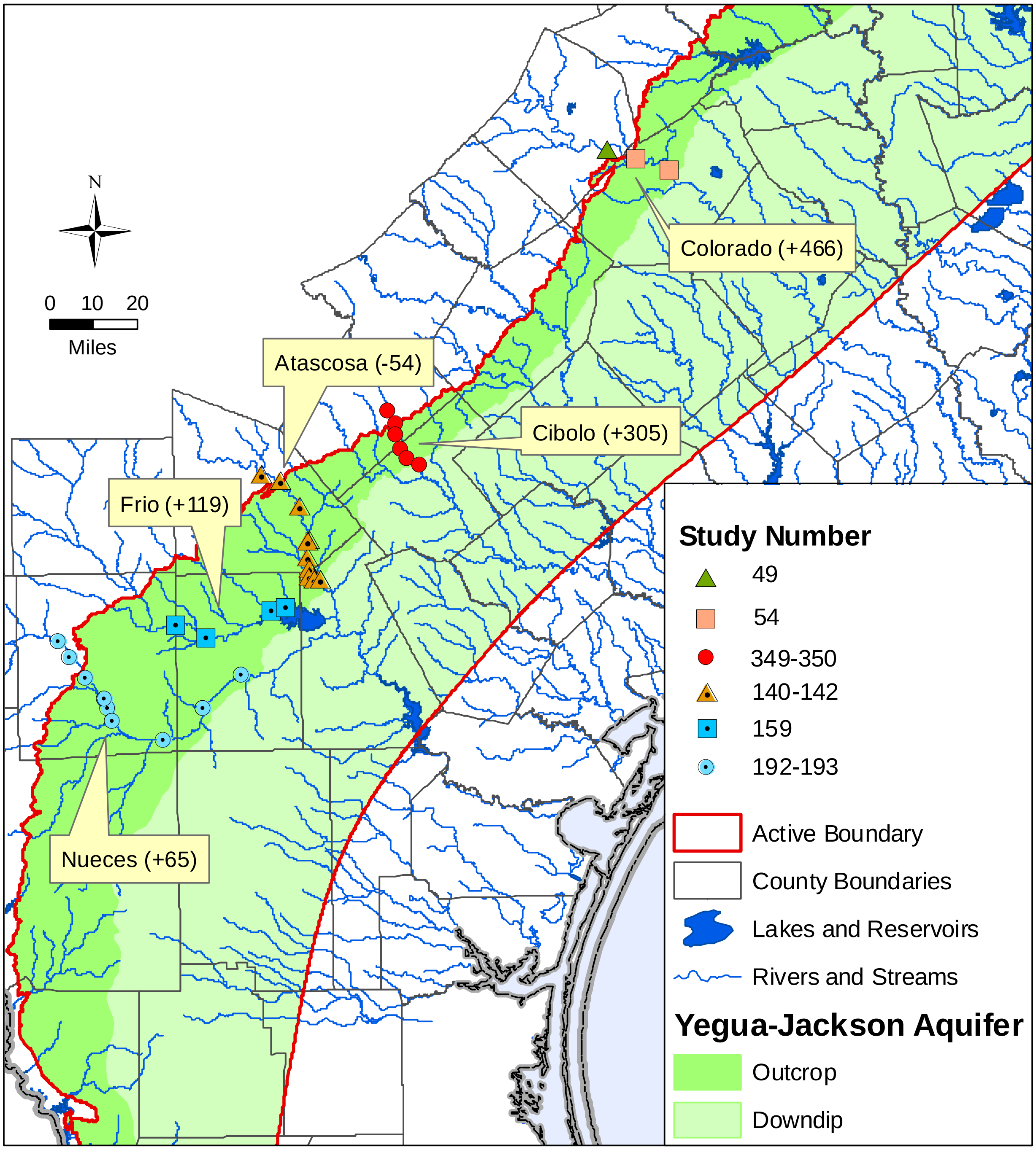


Figure 4.5.4 Location of Slade and others (2002) studies in or near the Yegua-Jackson Aquifer outcrop. The number in parentheses denotes the average gain (+) or loss (-) in acre-feet per mile of river length.

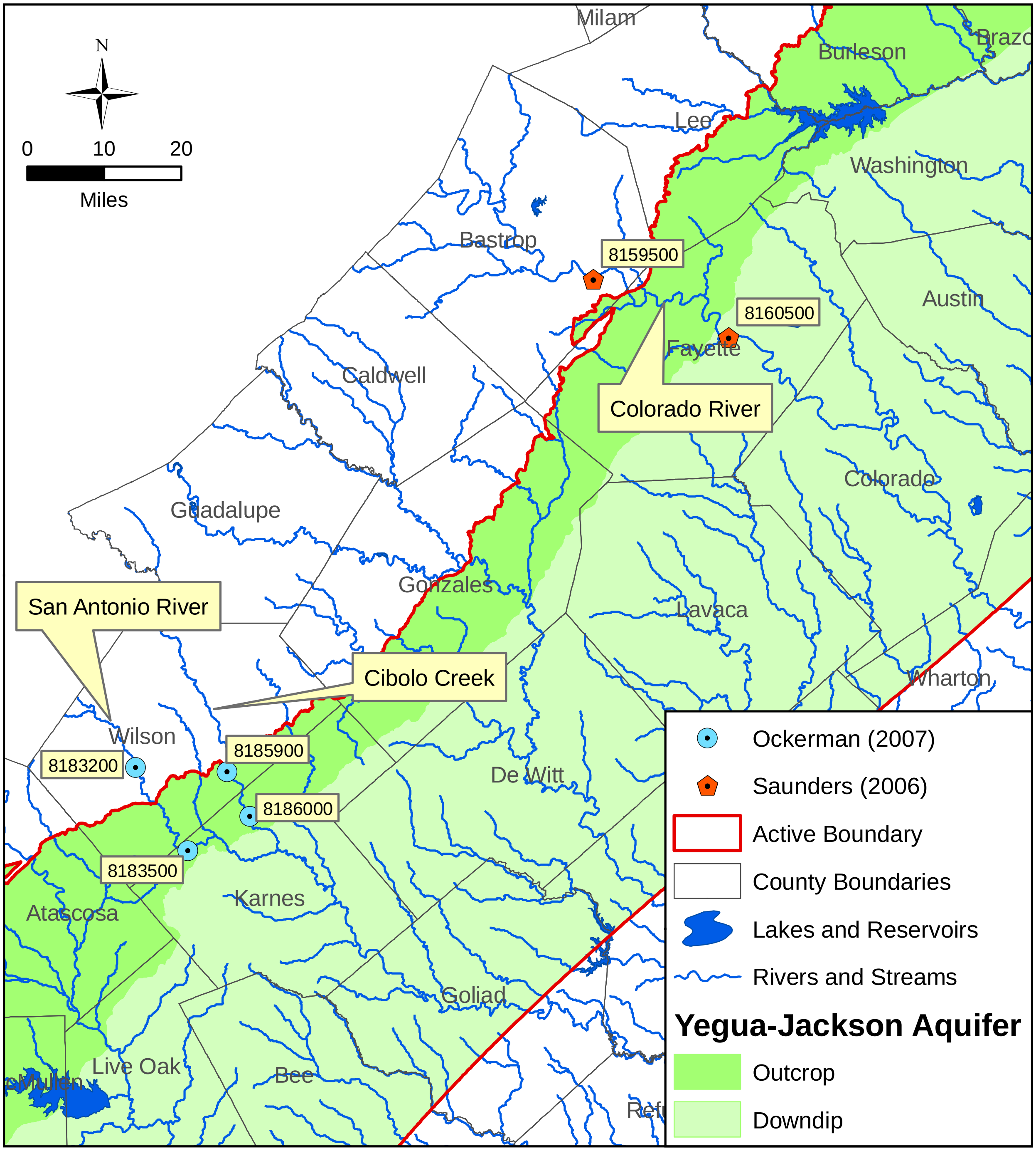
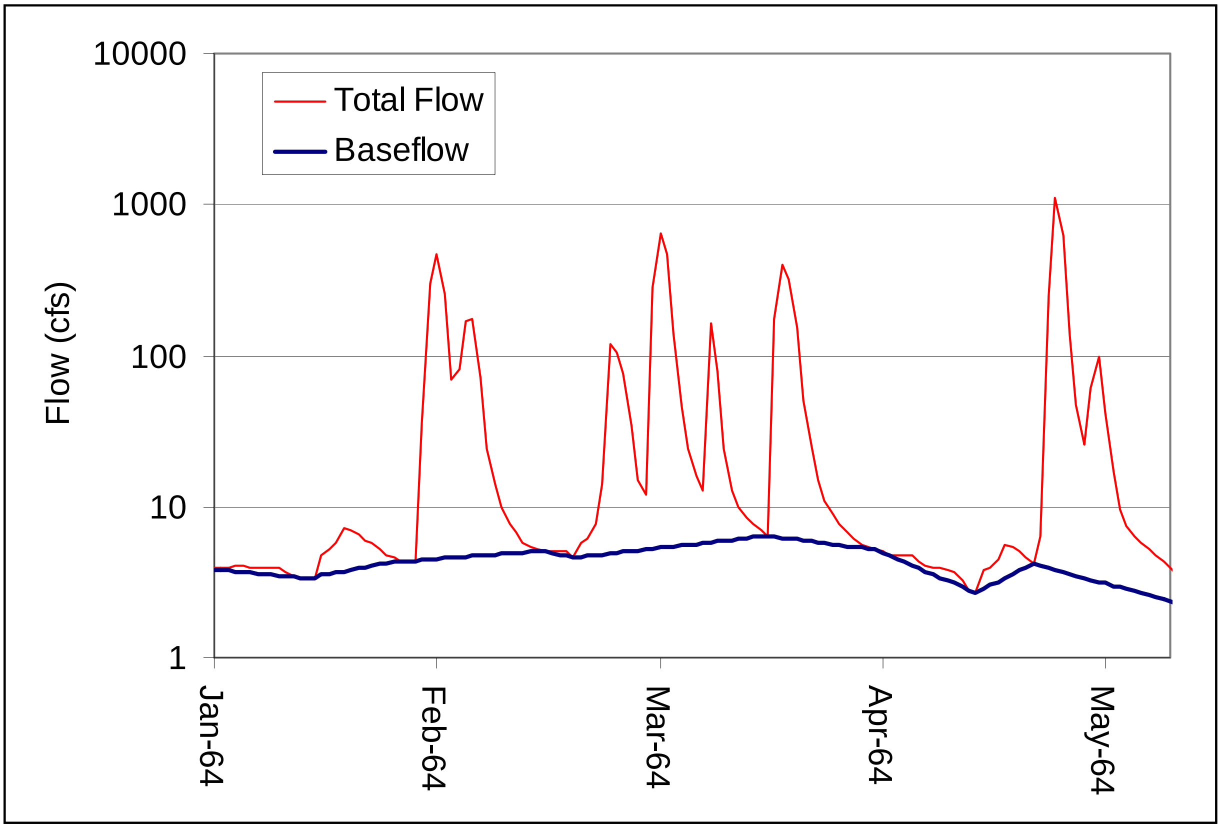


Figure 4.5.5 Location of Ockerman (2007) and Saunders (2006) studies in the San Antonio River Basin and Lower Colorado River Basin near the Yegua-Jackson Aquifer outcrop.



cfs = cubic feet per second

Figure 4.5.6 Example hydrograph separation for United States Geological Survey gage 8175000 on Sandies Creek in southern Gonzales County.

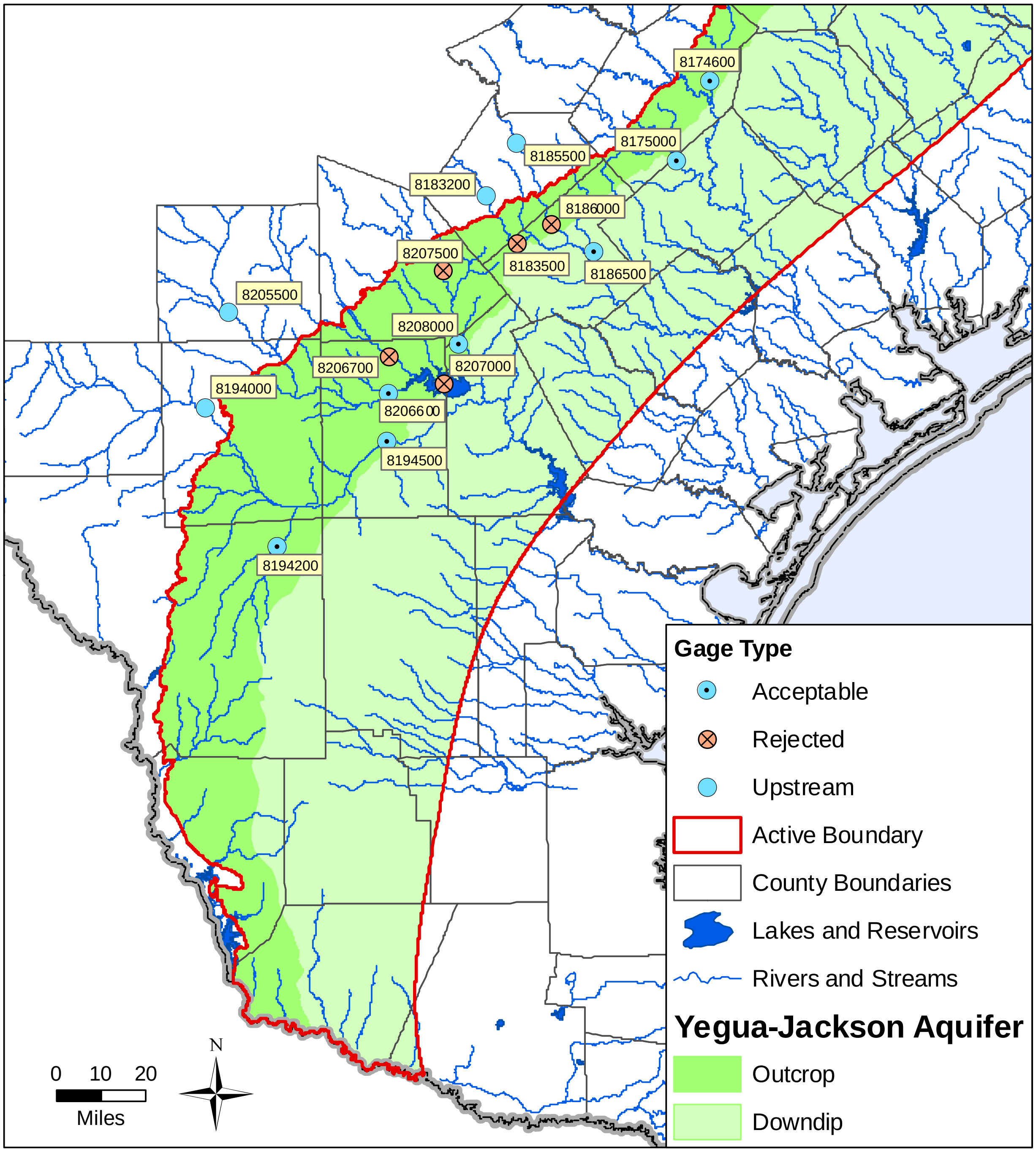


Figure 4.5.7a Locations of potential gages in the southern outcrop used in the hydrograph separation analyses.

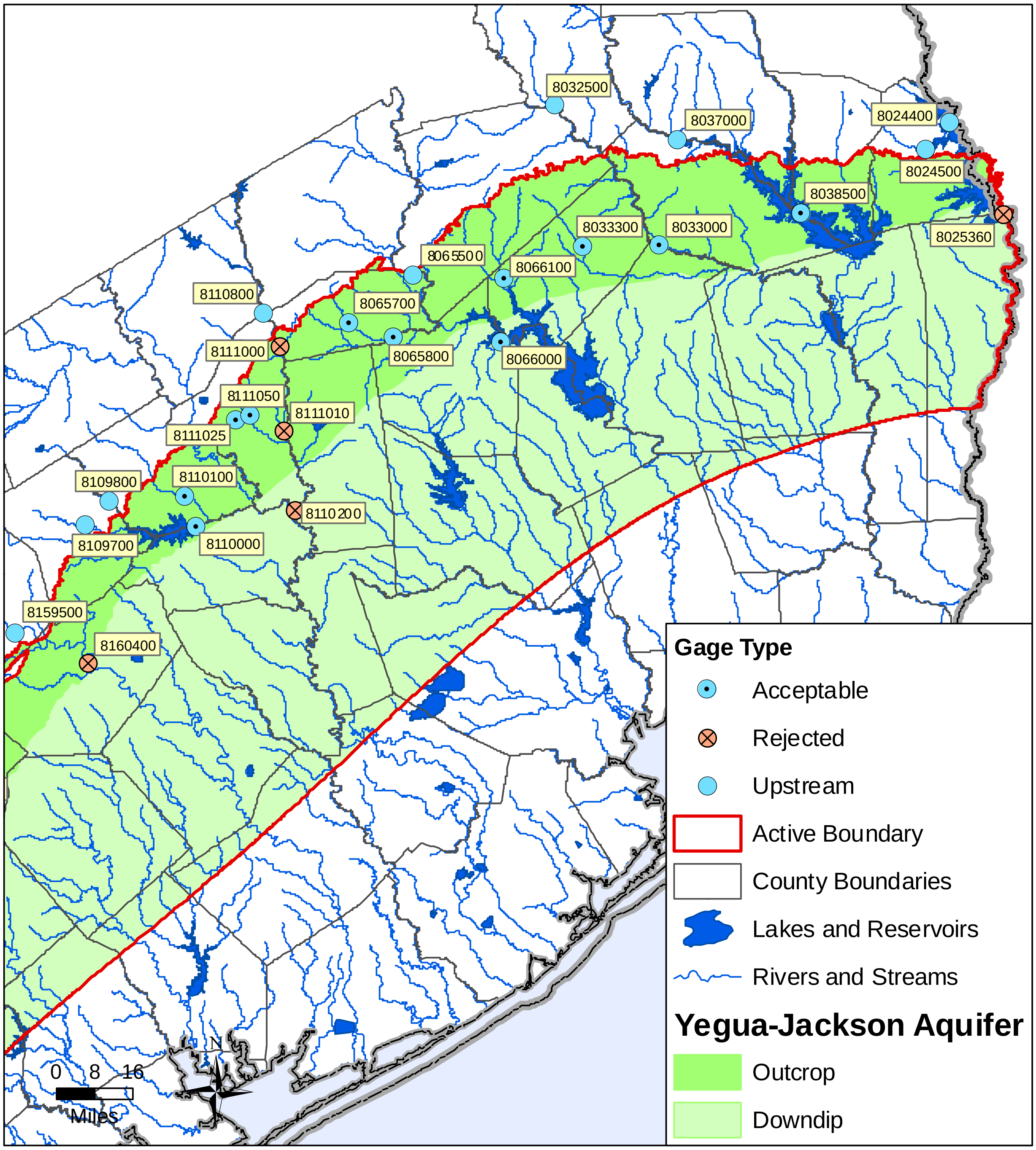
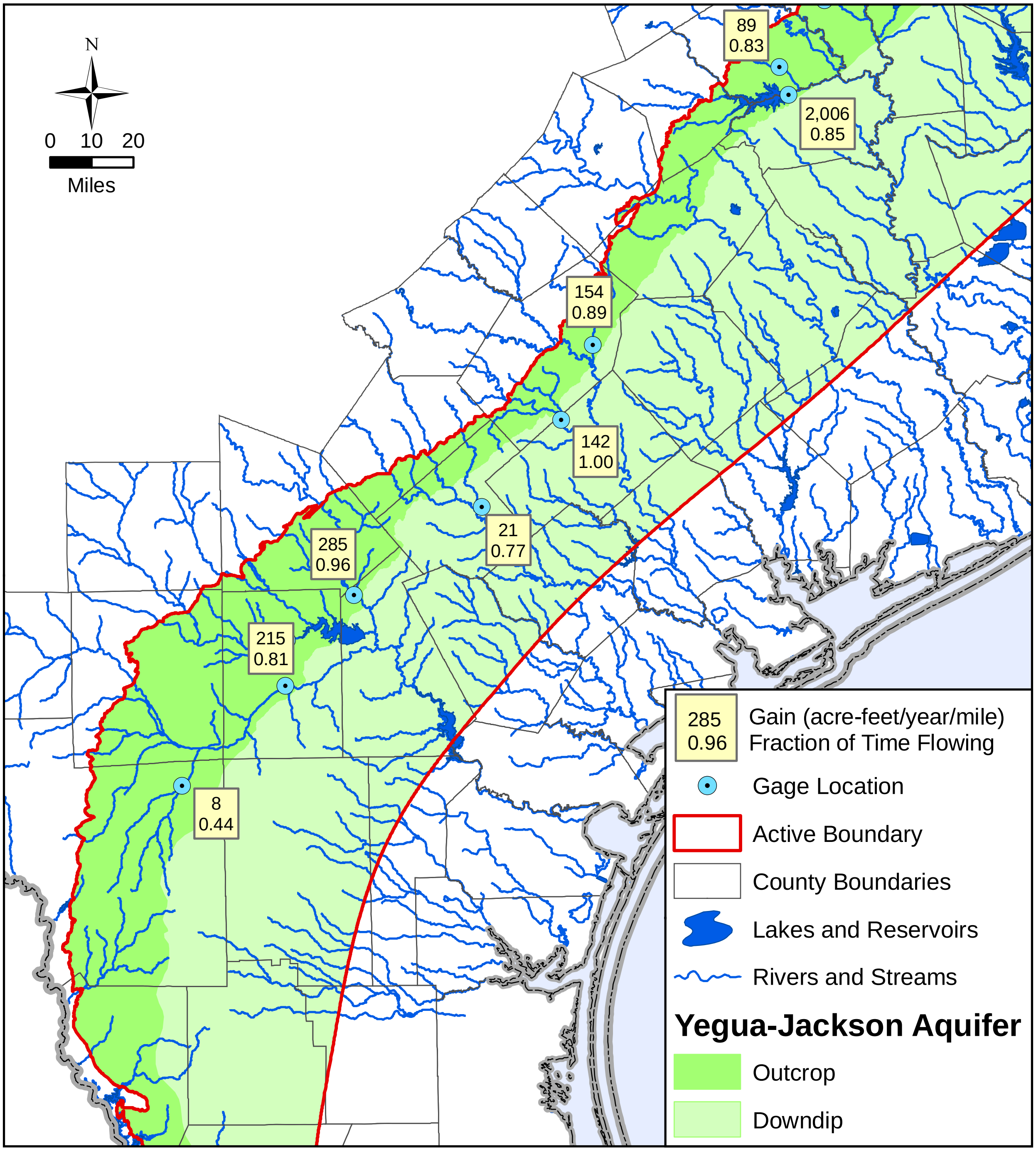
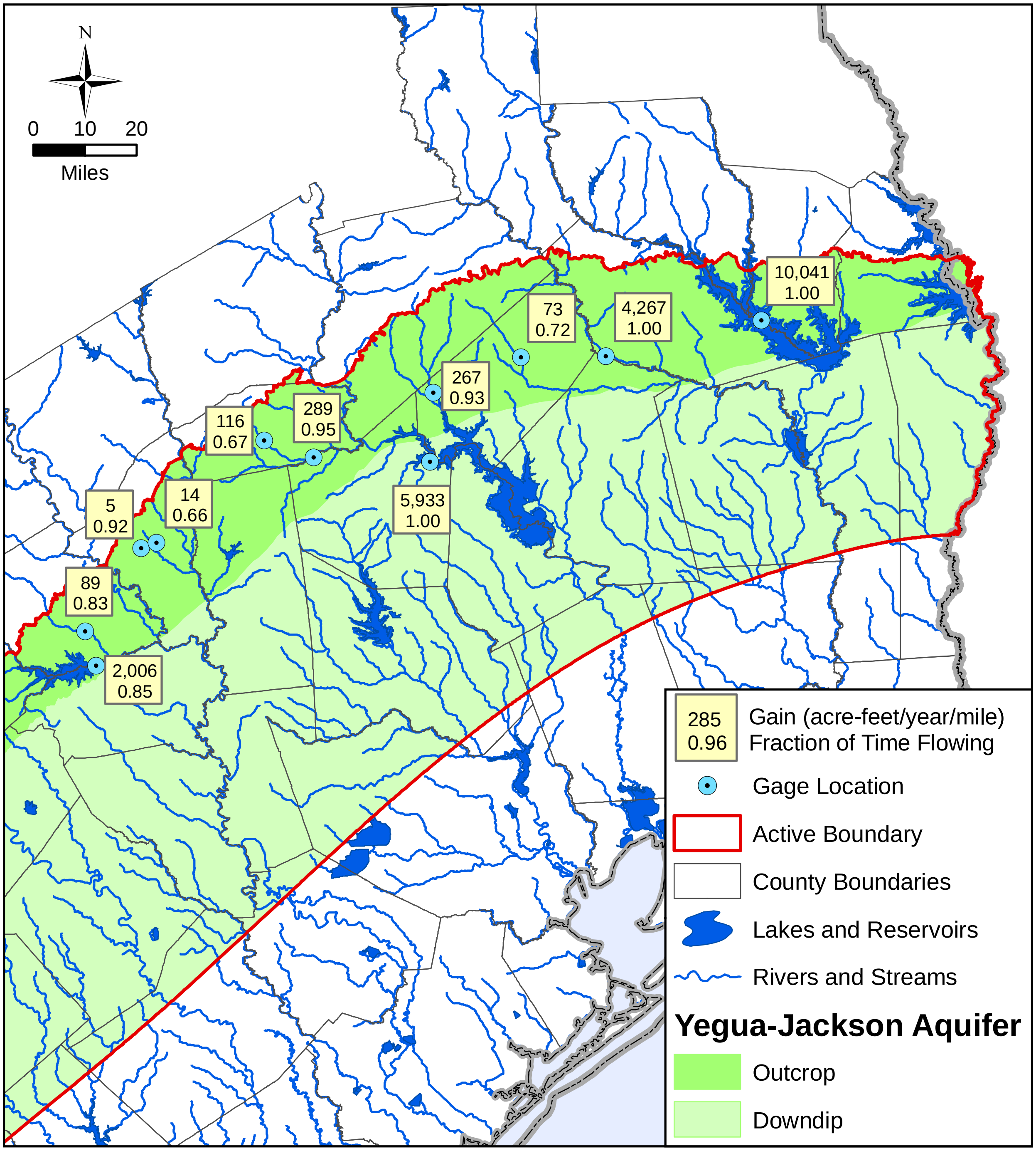


Figure 4.5.7b Locations of potential gages in the northern outcrop used in the hydrograph separation analyses.



acre-feet/year/mile = acre-feet per year per river mile

Figure 4.5.8a Hydrograph separation analyses results for the southern outcrop.



acre-feet/year/mile = acre-feet per year per river mile

Figure 4.5.8b Hydrograph separation analysis results for the northern outcrop.

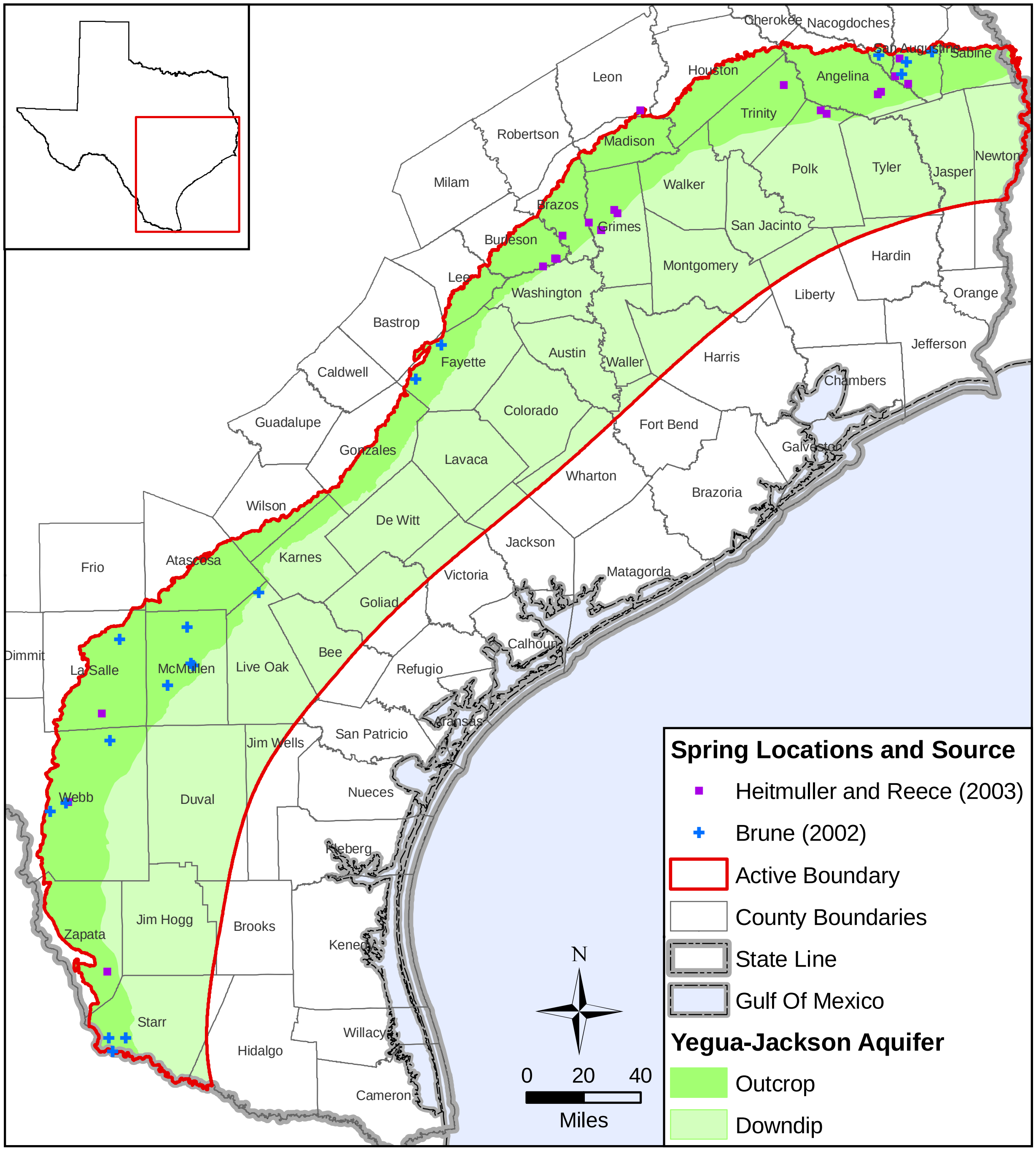


Figure 4.5.9 Location and source of springs located in the Yegua-Jackson Aquifer outcrop.

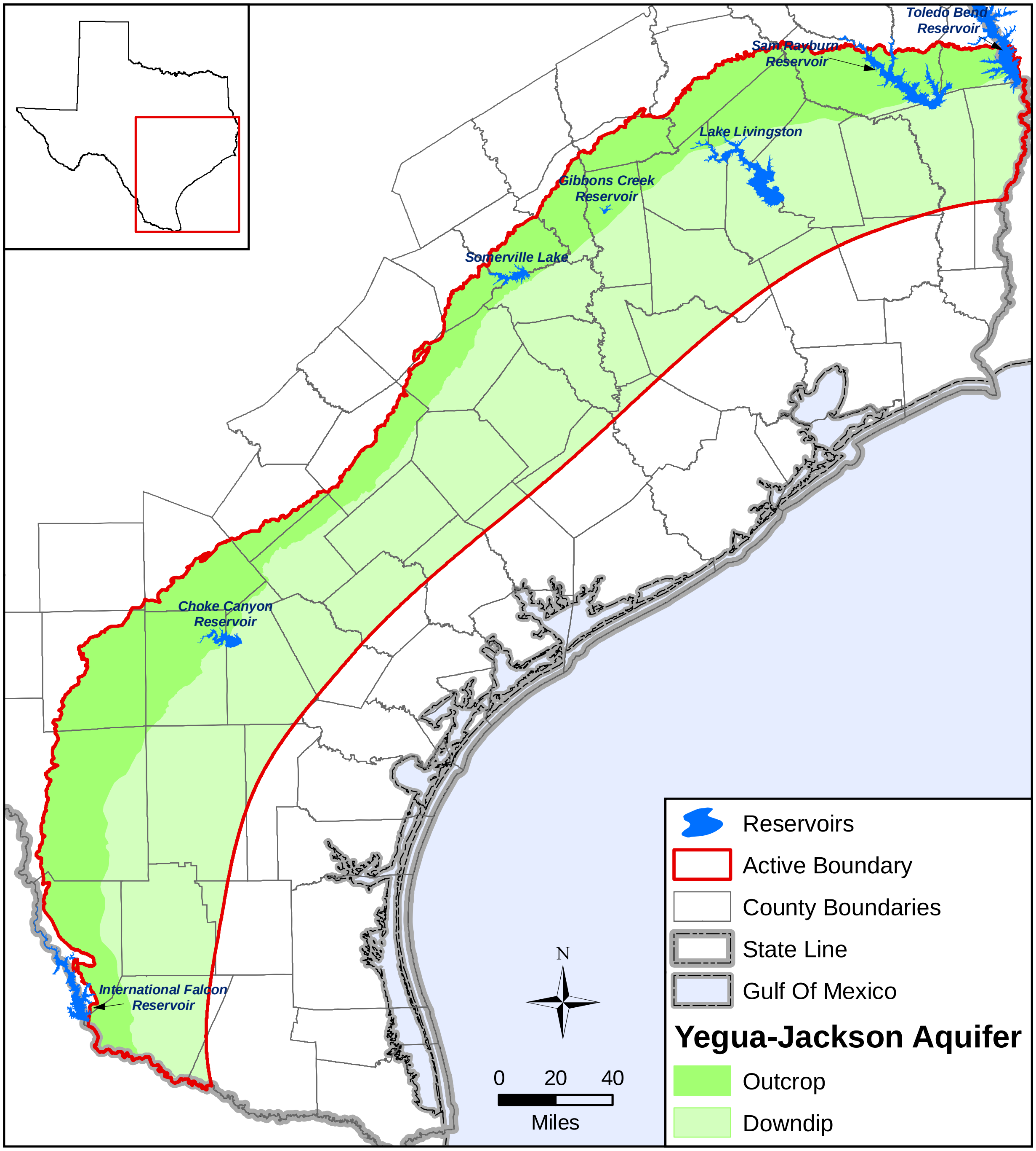


Figure 4.5.10 Reservoirs in the Yegua-Jackson Aquifer outcrop.

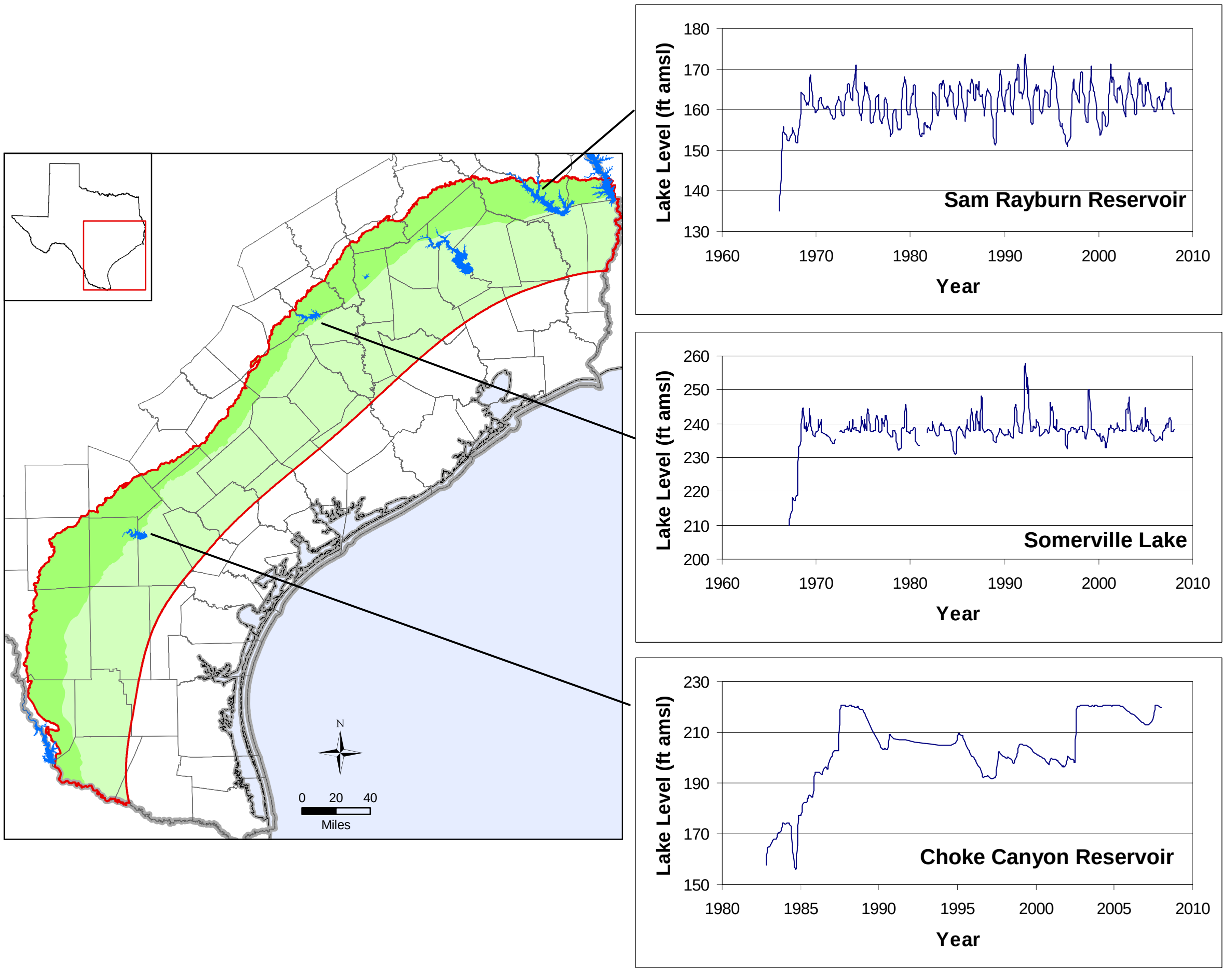


Figure 4.5.11 Water level histories for selected reservoirs in the study area. (ft amsl = feet above mean sea level)

4.6 Aquifer Discharge

Discharge refers to water moving out of the aquifer, by one of several possible processes. The first group of processes discussed in this section are the natural ones, including discharge through streams, springs, evapotranspiration, and cross-formational flow. With the exception of evapotranspiration, these natural processes have been discussed in previous sections. The second important discharge mechanism is through pumping.

4.6.1 Natural Aquifer Discharge

Under predevelopment conditions, without any pumping, aquifer recharge and discharge are balanced. In the typical topographically driven system, percolation of precipitation results in recharge at the water table, which flows from the topographic highs and discharges at the topographic lows through streams, springs, and groundwater evapotranspiration. Water that moves downdip eventually discharges upward through cross-formational flow. In the Yegua-Jackson Aquifer, which is usable primary in the outcrop area, any water moving downdip exits upwater within a short distance, as evidenced by the generally poor downdip water quality.

Discharge through baseflow is discussed in detail in Sections 4.5.1 as well as Sections 4.4.2 and 4.4.3. Discharge through springs is discussed in Section 4.5.2. Cross-formational flow is discussed in detail in Section 4.3.4. Refer to these sections for additional information on these discharge mechanisms. The current section is focused on the remaining natural discharge mechanism, groundwater evapotranspiration.

Evapotranspiration is the combined process of soil water evaporation near the land surface and the uptake in the root zone and subsequent transpiration of water by vegetation. For the purposes of groundwater modeling, we distinguish between two types of evapotranspiration: vadose zone evapotranspiration and groundwater evapotranspiration. Evapotranspiration in the vadose zone captures infiltrating water before it reaches the water table. Groundwater evapotranspiration is plant uptake or surface evaporation of groundwater. Here, our focus will be groundwater evapotranspiration, since it is the type implemented in the groundwater model. Vadose zone evapotranspiration is already accounted for in the recharge estimate.

Groundwater evapotranspiration occurs primarily in riparian buffer strips adjacent to streams (Scanlon and others, 2005). Riparian zones are not specifically mapped in Texas. Two methods can be used for defining the location of groundwater evapotranspiration in the model region. Either we can define some fixed buffer around the streams as riparian areas, or we can assume that the topographically lower areas would be likely regions of groundwater evapotranspiration. In general, we are trying to create the potential for groundwater evapotranspiration in regions where the water table is near ground surface. The approaches will likely produce similar results, and some combination may be necessary if the stream coverage does not have adequate resolution to define all of the discharge areas.

Scanlon and others (2005) summarizes the conceptual approach to groundwater evapotranspiration. In general, if water tables are very near the surface, evapotranspiration will be close to the potential evapotranspiration, assuming there is some type of vegetative cover. Potential evapotranspiration and reference evapotranspiration are terms that are often used interchangeably. Reference evapotranspiration is defined as the evapotranspiration rate from a reference vegetation, often a short grass, that has unlimited available water. Potential evapotranspiration should not be confused with "pan evaporation", which is the rate of water evaporation from an open pan. Potential evapotranspiration can be related to pan evaporation by the use of pan coefficients; however, since potential evaporation can be estimated with basic climate data, we did not use pan evaporation in the calculation of potential evapotranspiration.

When the water table is below ground surface, but still in the main vegetation root zone, evapotranspiration will occur at the unhindered vegetative evapotranspiration rate, ETVmax. This can be estimated by (Scanlon and others, 2005):

$$ETVmax = PET * Kc \qquad (4.6.1)$$

where Kc is the vegetation coefficient and PET is the potential evapotranspiration. Thus, to parameterize groundwater evapotranspiration, we need to estimate three parameters: potential evapotranspiration, vegetation coefficient, and rooting depth. Rooting depth and vegetation coefficient are specific to the type of vegetation, so a necessary prerequisite is some knowledge of the types of vegetation in the riparian areas in the model region. In the following paragraphs we will discuss how we estimated the types of vegetation in the model region, the corresponding vegetation coefficients and rooting depths, and potential evaporation in the area.

Borrelli and others (1998) provide an estimate of long-term potential evapotranspiration in Texas, based on the Penman-Monteith method, as reproduced in Figure 4.6.1. Figure 4.6.1 shows that long-term average potential evapotranspiration ranges from about 51 to 72 inches per year, increasing from east to west. Although evapotranspiration varies considerably with seasons, it does not vary significantly on an annual average basis. For this reason, we may make the assumption that potential evapotranspiration is constant throughout a transient simulation, where annual stress periods are used.

A detailed vegetation map in Texas is available from the Texas Gap (a geographic approach to planning for biological diversity) Analysis Project (Parker and others, 2003). Their estimates are based on a combination of geographic information system (GIS) analysis and ground truthing. Figure 4.6.2 shows an example of the vegetation coverage in Brazos County. The vegetation types are labeled by their broad National Vegetation Classification System categories. The Texas Gap Analysis Project report names several possible subcategories for each main category that provide information on the specific types of vegetation in Texas that might be representative. However, they do not specifically identify riparian vegetation or riparian zones in their analysis.

Figure 4.6.3 shows the frequency for vegetation types in the outcrop. Table 4.6.1 provides a key between the classification number and the vegetation name. The primary vegetation types are classification numbers 4, 7, 8, 21, and 22, which correspond to cropland, rounded-crowned temperate or subpolar needle-leaved evergreen forest (e.g., ponderosa and loblolly pine), extremely xeromorphic deciduous shrubland (e.g., honey mesquite), short-sod temperate or subpolar grassland (e.g., burrograss), and cold-deciduous woodland (e.g., blackjack oak and post oak).

To determine whether different types of vegetation are identified in areas near rivers, we created a coverage of the major rivers (i.e., the rivers listed in Table 4.5.1) including a one-mile riparian buffer, then intersected it with the vegetation coverage. We calculated the frequency of each vegetation type for this subset and compared it to the entire model region, as shown in

Figure 4.6.3. The relative frequency of each vegetation type is very similar, indicating that either markedly atypical vegetation does not occur near streams, or the vegetation coverage does not contain sufficient resolution to discriminate the riparian areas. Lacking higher resolution information, we will assume some buffer around the streams as riparian areas with potential for discharge through groundwater evapotranspiration.

Relevant parameters for groundwater evapotranspiration can be estimated from Scanlon and others (2005), which provides a database of estimates of vegetation coefficient and rooting depths for many types of vegetation. Table 4.6.2 shows estimates for several types relevant to this region.

4.6.2 Aquifer Discharge Through Pumping

Pumping discharge estimates must be developed for both the calibration period (1980 to 1997) and the period before calibration. The following section describes the methodology used in deriving the pumping by county for each of these periods. Implementation of the pumping in the numerical model is discussed in Section 6.3.5.

Calibration Period (1980 to 1997) Pumping

Estimates of groundwater pumping throughout Texas for the transient calibration period (1980 to 1997) are provided by the TWDB as master pumpage tables contained in a pumpage geodatabase. The six water-use categories defined in the TWDB database are municipal, manufacturing, power generation, mining, livestock, and irrigation. Rural domestic pumping, which consists primarily of unreported domestic water use, is estimated based on population density and per capita-usage rates provided by the TWDB.

Each water-use record in the pumping geodatabase carries an aquifer identifier. The TWDB database, however, does not have a unique identifier for the Yegua-Jackson Aquifer. Instead, the Yegua-Jackson Aquifer is categorized with other minor aquifers under the label ‘OTHER AQUIFER’. To estimate pumping, certain assumptions needed to be made as to where “OTHER AQUIFER” would include the Yegua-Jackson Aquifer. Pumping occurs in the Yegua-Jackson Aquifer primarily in and around the outcrop, and very near down-dip regions. Further down-dip, water quality is poor, and the more productive Gulf Coast Aquifer system is typically used.

Figure 4.6.4 shows the counties that were estimated to contain Yegua-Jackson Aquifer pumping. Many of the counties have only a small amount of pumping, due to rural domestic use.

The counties with pumping are: Angelina, Atascosa, Bastrop, Brazos, Burleson, Duval, Fayette, Frio, Gonzales, Grimes, Houston, Karnes, La Salle, Lavaca, Lee, Leon, Live Oak, Madison, McMullen, Nacogdoches, Polk, Sabine, San Augustine, Starr, Trinity, Tyler, Walker, Washington, Webb, Wilson, and Zapata. For each of these counties, pumping under 'OTHER AQUIFER' was assumed to come from the Yegua-Jackson Aquifer and other minor aquifers, the significance of which was decided on a county-by-county basis. County reports (see Section 3.0 for a list of county reports), wherever available, were used to ascribe and apportion pumping to the Yegua-Jackson Aquifer. The methodology for this is described below:

1. For each county, water-bearing formations that were not uniquely identified in the pumping geodatabase were assumed to be part of the 'OTHER AQUIFER' category. Water-bearing properties for the formations as reported in the county reports (see Section 3 for a list of county reports) were used to determine potential candidates for this category. The water-bearing units identified as potentially part of 'OTHER AQUIFER' were: the Yegua-Jackson Aquifer, and the Cook Mountain, Reklaw, and Laredo formations, as well as local alluvial and terrace deposits. In counties where the Yegua-Jackson Aquifer was reported to be yielding more water than the other minor water-bearing formations, a conservative assumption (in terms of use) was made that all the pumping in the 'OTHER AQUIFER' category came from the Yegua-Jackson Aquifer. In addition, for many counties, the Yegua-Jackson Aquifer is the only minor water-bearing formation (in addition to other notable aquifers such as the Sparta, Carrizo-Wilcox, Gulf Coast, etc., that had been explicitly assigned pumping in the geodatabase). For these counties (Atascosa, Fayette, Karnes, Lee, Madison, Polk, Sabine, San Augustine, Walker, Washington, and Nacogdoches), 'OTHER AQUIFER' corresponded directly to the Yegua-Jackson Aquifer. Note that there were some counties that did not have published county reports (La Salle, Lavaca, Leon, Live Oak, McMullen, Trinity, Tyler, Wilson, and Zapata). For these counties, neighboring county reports and spatial coverages of potential minor water-bearing formations were used to ascertain if there were any potential sources other than the Yegua-Jackson Aquifer for that county.

2. The pumping was sub-divided into two types – distributed and localized. Irrigation, livestock, and rural domestic were considered to be distributed pumping, whereas municipal, manufacturing, and mining were considered to be localized pumping. None of the selected counties showed any power generation pumping ascribed to 'OTHER AQUIFER', so this type of pumping was not included.

3. For localized pumping, the main water consumers/suppliers were identified from the TWDB pumping geodatabase. The Texas Commission on Environmental Quality Public Water System database and the TWDB well database (TWDB, 2008b) were then used to determine whether the Yegua-Jackson Aquifer is the groundwater source for the municipal, manufacturing, or mining supply. In cases where no information was available from either the Texas Commission on Environmental Quality or the TWDB database, suppliers that were within the Yegua-Jackson Aquifer outcrop were assumed to be drawing their water from the aquifer.

4. Rural domestic pumping was calculated based on United States census block population density (Figure 4.6.5a,b) in non-urban areas within the Yegua-Jackson Aquifer outcrop. The TWDB has provided a polygon feature class of census blocks, based on the 1990 United States census, and a table of factors for converting rural population density into annual groundwater use. Urban areas with a municipal water supply were excluded from the rural population calculations and the rural domestic groundwater pumpage. In addition, certain census blocks were not classified as either rural or municipal water supply. A decision was made to include some of these census blocks in areas that did not have any municipal supply wells, public water supplies, or surface water sources in the vicinity.

5. For distributed pumping for irrigation and livestock purposes, the number of wells in the TWDB wells database (TWDB, 2008b) was not large enough to make any statistically-significant decisions on the proportion of pumping coming from the Yegua-Jackson Aquifer. For this reason, pumping for each minor water-bearing formation was assumed to be directly proportional to the area of its outcrop in the county. Thus, total pumping under 'OTHER AQUIFER' was prorated to the Yegua-Jackson Aquifer based on the

ratio of its outcrop area to the total outcrop area of minor water-bearing formations in a given county. For counties with no other minor aquifers, all of the pumping was attributed to the Yegua-Jackson Aquifer.

Based on this investigation, master tables for each category were updated to show pumpage of Yegua-Jackson Aquifer only.

Pre-1980 Pumping

Detailed pumping data are not available prior to the calibration period. An estimated pumping history was generated using a combination of various sources to account for groundwater withdrawals that occurred before 1980. Due to the poor temporal resolution of available information, average pumping was estimated over 10 year periods for each of the selected counties prior to 1980.

The sources of information utilized to estimate pre-1980 pumping were: the TWDB wells database (TWDB, 2008b), published reports for counties intersecting the Yegua-Jackson Aquifer outcrop, and the 1981 Inventory of Irrigation in Texas (TWDB, 1981). The TWDB wells database was used primarily to identify the earliest period when a particular type of pumping began in the Yegua-Jackson Aquifer for a given county. The TWDB wells database also provided information for historical suppliers/consumers of groundwater (prior to 1980). In most cases, pumping in the Yegua-Jackson Aquifer started as early as the 1900's (mostly for rural domestic and livestock purposes). For this reason, 1900 to 1910 was taken as the earliest decade of record for pre-1980 pumping.

The irrigation report provides irrigation related groundwater pumping for the years 1958, 1964, 1969, 1974, and 1979. The county reports typically reported total pumping (sometimes broken into different kinds of pumping) for a few years in the 1960's. Some county reports also displayed historical pumping from the 1940's to the late 1960's and, in these cases, these data were also utilized to estimate pre-1980 pumping. Once all the data were collected from different sources (i.e., the irrigation pumping values from the irrigation report and the county-based pumping from the county reports), pre-1980 pumping scenarios were developed for each kind of pumping for each county as follows:

1. If a particular type of pumping did not exist (was zero in the TWDB pumping geodatabase) for the Yegua-Jackson Aquifer in the calibration period, then it was ignored in the pre-1980 period. For example, if a county has no reported municipal pumping from the Yegua-Jackson Aquifer in the span of 1980 to 1997, it was assumed that pre-1980 municipal pumping was insignificant and could be ignored in the pre-calibration period.

2. The irrigation report and the county reports typically give the total pumping for the entire county, without breaking it up for different aquifers. For either report type, it was necessary to consider apportioning part of the pumping to the Yegua-Jackson Aquifer. To do this, the average ratio of the 1980 to 1997 Yegua-Jackson Aquifer pumping to the total pumping (of a given pumping type) in the county was calculated. This ratio was assumed to be the same for the pre-calibration period and was used to apportion a part of the reported pumping to the Yegua-Jackson Aquifer. Some county reports (e.g., the one for Angelina and Nacogdoches counties by Guyton & Associates, 1970), however, gave the total pumping as well as pumping from major aquifers in the county. In such cases, the difference between these two numbers was assumed to belong to the 'OTHER AQUIFER' category, and a methodology similar to the one used for the calibration period (based on the ratio of outcropping areas and groundwater source for localized pumping) was used to apportion the pumping to the Yegua-Jackson Aquifer.

3. In many cases, county reports combined two or more different kinds of pumping (typically rural domestic and livestock were combined together). Once the proportion of the combined pumping for the Yegua-Jackson Aquifer was calculated, it was split into individual types of pumping based on the average 1980 to 1997 ratio of a particular type of pumping to the combined pumping. For example, consider a county report that provides the total combined rural domestic and livestock pumping for a given year. First, the total rural domestic and livestock pumping for the Yegua-Jackson Aquifer was calculated based on the average 1980 to 1997 ratio of Yegua-Jackson Aquifer rural domestic and livestock pumping to total rural domestic and livestock pumping for that county. Next, the Yegua-Jackson Aquifer rural domestic and livestock pumping was separated into rural domestic and livestock pumping by using the average 1980 to 1997

ratio of Yegua Jackson Aquifer rural domestic pumping to Yegua-Jackson Aquifer rural domestic and livestock pumping and the average 1980 to 1997 ratio of Yegua-Jackson Aquifer livestock pumping to Yegua-Jackson Aquifer rural domestic and livestock pumping.

4. Once this analysis was completed, Yegua-Jackson Aquifer pumping of different types was collated for all the reported years. The next step was to generate average pumping estimates for the 10 year periods from 1900 to 1980. For this, all the data points within a given decade were averaged. If only one data point was available for a particular decade, it was assumed to be a representative number for that period. Next, the TWDB wells database was used to estimate the earliest pumping well for a certain kind of pumping in the county. The decade before this period was given a value of zero pumping. Finally, the average pumping (of a certain kind) in the 1980 to 1989 decade was calculated from the calibration period pumping estimates (discussed in the previous section). The pumping for intermediate decades that did not have any reported data was then interpolated between all these pumping estimates. For example, in Lee County, rural domestic pumping estimates were available for 1943, and 1955 to 1963. The earliest rural domestic well in the TWDB well database was in the 1920s. Thus, rural domestic pumping was assumed to be zero in the 1910 to 1919 decade; the 1943 value was assumed to be representative for 1940 to 1949; 1955 to 1959 values were averaged to give the 1950 to 1959 average pumping, 1960 to 1963 values were averaged to give the 1960 to 1969 average. The ‘missing’ decades that needed to be filled in were 1920 to 1929, 1930 to 1939, and 1970 to 1979. For 1920 to 1929 and 1930 to 1939, the average was linearly interpolated between zero for 1910 to 1919 and the 1940 to 1949 average. For 1970 to 1979, the average was linearly interpolated between the 1960 to 1969 and the 1980 to 1989 average values. The final result is a decadal pumping history for rural domestic pumping from 1900 to 1979 for Lee County.

5. A minor adjustment needed to be made when pumping was reported for the early 1980’s but then decreased to zero in the late 1980’s. This always happened for localized types of pumping (municipal, manufacturing, and mining) and most probably represented cases where pumping from the Yegua-Jackson Aquifer either stopped due to the closure of a

water supplier or industry, or pumping switched from the Yegua-Jackson Aquifer to another aquifer. In such cases, the average values for the 1980 to 1989 period were based on the non-zero pumping values, so that there was no impact of the pumping stoppage on pre-1980 interpolated estimates.

Pumping Results

The results from the analysis of pumping in the Yegua-Jackson Aquifer are summarized by use category in Tables 4.6.3 to 4.6.8. Figure 4.6.6 provides a bar chart of total pumping by category for the Yegua-Jackson Aquifer. Pumping histories by use for each of the thirty counties are shown in Figures 4.6.7 to 4.6.36. Each graph shows the different types of pumping for each year, as well as the total pumping for the county. In cases where the county has only a single type of pumping (typically rural-domestic), the total is not shown since it is identical to the magnitude of the single type. The period between 1900 and 1980 has a step-like pumping curve, due to the decadal estimates. Rural domestic and livestock are the largest pumping types in most cases. We will only discuss the counties that are exceptions to the dominance of rural domestic pumping.

Figure 4.6.7 shows the pumping curves for Angelina County, which has the highest total pumping from the Yegua-Jackson Aquifer. Rural domestic pumping is the most significant category by 1997, although municipal and manufacturing are also important. Figure 4.6.25 shows the pumping curves for Nacogdoches County. Livestock pumping is similar in magnitude to rural domestic for Nacogdoches County. Figure 4.6.26 shows the pumping curves for Polk County. For Polk County, manufacturing and municipal pumping are the most important categories. The pumping in Sabine County, shown in Figure 4.6.27, has significant contributions from municipal and manufacturing, while San Augustine County, shown in Figure 4.6.28, is dominated by livestock pumping. Starr County has a similar trend, as shown in Figure 4.6.29, where total pumping is nearly identical to livestock pumping. Pumping in Trinity County, shown in Figure 4.6.30, shows a clear spike in municipal pumping from 1980 to 1983 that drops off completely in 1984. Of the remaining counties, all are dominated by rural domestic pumping, with the exception of Webb and Zapata counties, where they are dominated by livestock use.

Table 4.6.1 Vegetation classifications for Gap (a geographic approach to planning for biological diversity) dataset.

Vegetation Name	Classification Number
Water	1
Bare Soil	2
Cropland (irrigated, row, herbaceous, etc.)	4
Urban Area	5
Rounded-Crowned Temperate or Subpolar Needle-Leaved Evergreen Forest	7
Extremely Xeromorphic Deciduous Shrubland	8
Lowland Mixed Evergreen - Drought Deciduous Shrubland	10
Medium-Tall Bunch Temperate or Subpolar Grassland	13
Semipermanently Flooded Temperate or Subpolar Grassland	17
Temporarily Flooded Cold-Deciduous Woodland	20
Short Sod Temperate or Subpolar Grassland	21
Cold-Deciduous Woodland	22
Round-Crowned Temperate or Subpolar Needle-Leaved Evergreen Woodland	29
Temperate Broad-Leaved Evergreen Woodland	33
Dunes with Sparse Herbaceous Vegetation	37
Mixed Broad-Leaved Evergreen - Cold-Deciduous Woodland	47
Lowland or Submontane Cold-Deciduous Forest	51
Medium-Tall Sod Temperate or Subpolar Grassland	56
Temporarily Flooded Cold-Deciduous Forest	63

Table 4.6.2 Estimates of vegetation coefficient and rooting depth for several vegetation types in the region.

Vegetation Type	Potential Evapotranspiration	Rooting Depth (feet)
Mesquite	0.54	6 to50
Grassland	0.70	2.
Pine	0.53	7.
Post Oak	0.5*	5.*
Cropland	0.6*	1.

*estimated from analogs

Table 4.6.3 Municipal pumping (acre-feet per year) by decade from 1900 to 1979 and yearly from 1980 to 1997.

Year	County			
	Angelina	Sabine	Trinity	Total Municipal
1900-1909	0	12	20	32
1910-1919	120	24	39	183
1920-1929	180	36	59	275
1930-1939	241	48	78	367
1940-1949	481	61	98	640
1950-1959	601	73	117	791
1960-1969	842	254	137	1,233
1970-1979	978	226	156	1,360
1980	1,114	211	562	1,887
1981	1,037	204	574	1,815
1982	1,038	188	621	1,847
1983	1,081	168	0	1,249
1984	1,126	192	0	1,318
1985	1,186	192	0	1,378
1986	1,185	175	0	1,360
1987	1,289	191	0	1,480
1988	1,316	227	0	1,543
1989	1,418	235	0	1,653
1990	1,379	234	0	1,613
1991	1,406	227	112	1,745
1992	1,459	180	203	1,842
1993	1,503	189	27	1,719
1994	1,441	181	33	1,655
1995	1,414	197	18	1,629
1996	1,456	207	67	1,730
1997	1,406	198	430	2,034

Table 4.6.4 Manufacturing pumping (acre-feet per year) by decade from 1900 to 1979 and yearly from 1980 to 1997.

Year	County									
	Angelina	Fayette	Gonzales	Grimes	Karnes	Polk	Sabine	Trinity	Walker	Total Manufacturing
1900-1909	0	0	0	0	0	0	0	0	0	0
1910-1919	0	0	0	0	0	0	0	0	0	0
1920-1929	0	0	0	0	0	0	10	0	0	10
1930-1939	102	0	0	0	0	0	10	0	0	112
1940-1949	768	0	0	0	0	45	10	0	0	823
1950-1959	1,331	0	0	0	0	89	10	0	0	1,430
1960-1969	1,536	0	0	0	0	134	10	0	0	1,680
1970-1979	1,145	5	16	58	3	376	172	0	0	1,775
1980	631	0	8	110	0	647	140	0	0	1,536
1981	941	0	0	129	37	406	133	0	0	1,646
1982	753	0	0	59	31	662	158	0	0	1,663
1983	776	0	134	12	0	629	346	0	0	1,897
1984	748	0	166	66	0	620	433	0	0	2,033
1985	723	0	11	83	0	649	417	0	0	1,883
1986	715	0	0	95	0	642	420	0	0	1,872
1987	730	0	0	206	0	640	457	0	7	2,040
1988	789	0	0	219	0	640	418	0	6	2,072
1989	739	0	0	173	0	632	432	0	7	1,983
1990	760	0	0	174	0	597	374	0	5	1,910
1991	777	0	0	82	0	538	364	0	5	1,766
1992	792	0	0	70	0	568	401	0	6	1,837
1993	775	0	0	85	0	558	455	0	8	1,881
1994	754	0	0	132	0	530	513	0	0	1,929
1995	741	0	0	122	0	221	451	0	0	1,535
1996	756	0	0	135	0	247	368	0	0	1,506
1997	687	0	0	0	0	375	374	0	0	1,436

Table 4.6.5 Irrigation pumping (acre-feet per year) by decade from 1900 to 1979 and yearly from 1980 to 1997.

Year	County									
	Angelina	Bastrop	Brazos	Burleson	Fayette	Gonzales	Houston	Lee	Trinity	Total Irrigation
1900-1909	0	0	0	0	0	0	0	0	0	0
1910-1919	0	0	0	0	0	0	0	0	0	0
1920-1929	0	0	0	0	0	0	0	0	0	0
1930-1939	0	0	0	0	0	0	0	0	0	0
1940-1949	0	0	0	0	0	0	0	0	0	0
1950-1959	0	0	105	98	49	0	0	0	0	252
1960-1969	1	0	112	133	96	0	0	0	0	342
1970-1979	174	0	39	85	68	0	0	0	0	366
1980	191	1	30	56	159	0	0	0	0	437
1981	191	0	42	61	127	0	0	0	0	421
1982	191	0	53	66	94	0	0	0	0	404
1983	191	0	65	70	62	0	0	0	0	388
1984	191	0	76	75	29	0	0	0	0	371
1985	153	0	65	62	45	0	0	2	0	327
1986	136	0	66	53	41	0	1	3	0	300
1987	136	0	63	62	59	0	0	3	0	323
1988	136	0	92	48	62	0	1	3	50	392
1989	0	0	51	49	61	0	0	15	3	179
1990	0	0	79	65	19	0	0	8	4	175
1991	0	0	43	76	19	0	0	8	4	150
1992	0	0	30	57	14	0	0	6	4	111
1993	30	0	47	45	47	0	0	8	3	180
1994	30	0	0	0	10	7	0	0	3	50
1995	30	0	0	0	9	9	0	0	3	51
1996	30	0	0	0	9	13	0	0	3	55
1997	30	0	0	0	9	6	0	0	3	48

Table 4.6.6 Livestock pumping (acre-feet per year) by decade from 1900 to 1979 and yearly from 1980 to 1997.

Year	County										
	Angelina	Bastrop	Brazos	Burleson	Fayette	Grimes	Houston	Lee	Madison	Nacogdoches	Polk
1900-1909	0	0	15	0	72	3	13	0	0	0	1
1910-1919	0	0	29	8	82	6	26	0	0	15	2
1920-1929	1	0	44	17	92	9	40	45	0	31	4
1930-1939	1	1	59	25	103	12	53	91	0	46	5
1940-1949	2	1	73	34	113	15	66	136	43	62	6
1950-1959	3	1	88	42	123	26	79	163	86	77	7
1960-1969	4	1	94	45	133	25	85	148	129	93	8
1970-1979	52	3	267	114	77	179	134	132	172	67	13
1980	70	5	237	214	30	341	153	128	204	51	21
1981	89	5	316	204	27	348	166	125	211	50	21
1982	108	5	396	194	24	355	180	123	218	48	21
1983	127	5	475	183	21	362	194	120	225	47	20
1984	146	5	554	173	18	369	207	117	232	45	20
1985	95	5	511	183	16	314	210	105	224	33	17
1986	85	4	512	170	17	317	156	105	208	35	11
1987	88	5	475	162	17	324	179	111	208	33	14
1988	100	5	494	170	17	319	189	115	218	32	15
1989	88	5	436	168	17	281	192	113	198	35	13
1990	87	5	436	165	18	320	196	112	199	41	13
1991	88	5	445	168	18	322	200	114	203	41	13
1992	124	5	421	205	23	358	196	137	251	41	10
1993	122	5	398	237	22	342	186	150	236	42	11
1994	100	5	322	226	22	307	200	149	205	46	14
1995	100	5	340	223	21	374	181	154	218	41	16
1996	91	6	491	270	17	339	181	139	323	55	16
1997	89	4	360	266	19	301	159	128	201	38	16

Table 4.6.6, continued

Year	County								
	Sabine	San Augustine	Starr	Trinity	Walker	Washington	Webb	Zapata	Total Livestock
1900-1909	2	5	8	22	0	0	0	0	141
1910-1919	5	10	15	44	0	0	6	0	248
1920-1929	7	15	23	66	0	0	12	0	406
1930-1939	9	21	31	88	0	3	17	0	565
1940-1949	11	26	38	110	17	6	23	13	795
1950-1959	14	31	46	132	34	9	29	26	1,016
1960-1969	16	36	54	153	50	11	35	40	1,160
1970-1979	29	64	61	175	67	14	41	53	1,714
1980	42	101	72	136	79	19	50	59	2,012
1981	42	97	72	158	82	19	48	63	2,143
1982	41	93	73	180	85	18	46	67	2,275
1983	41	89	73	202	88	18	44	71	2,405
1984	40	85	73	224	91	17	43	75	2,534
1985	36	77	74	224	81	17	43	67	2,332
1986	38	87	67	224	93	16	46	65	2,256
1987	46	94	60	210	79	15	48	63	2,231
1988	47	97	62	222	86	16	50	66	2,320
1989	48	99	65	193	76	16	49	65	2,157
1990	53	110	63	191	75	16	48	64	2,212
1991	54	113	75	195	77	16	49	66	2,262
1992	47	120	69	234	58	15	26	36	2,376
1993	49	121	70	214	51	14	23	30	2,323
1994	18	40	59	180	61	15	29	41	2,039
1995	14	44	71	180	65	14	31	41	2,133
1996	13	38	97	174	64	17	43	41	2,415
1997	29	69	54	187	76	12	28	41	2,077

Table 4.6.7 Rural domestic pumping (acre-feet per year) by decade from 1900 to 1979 and yearly from 1980 to 1997.

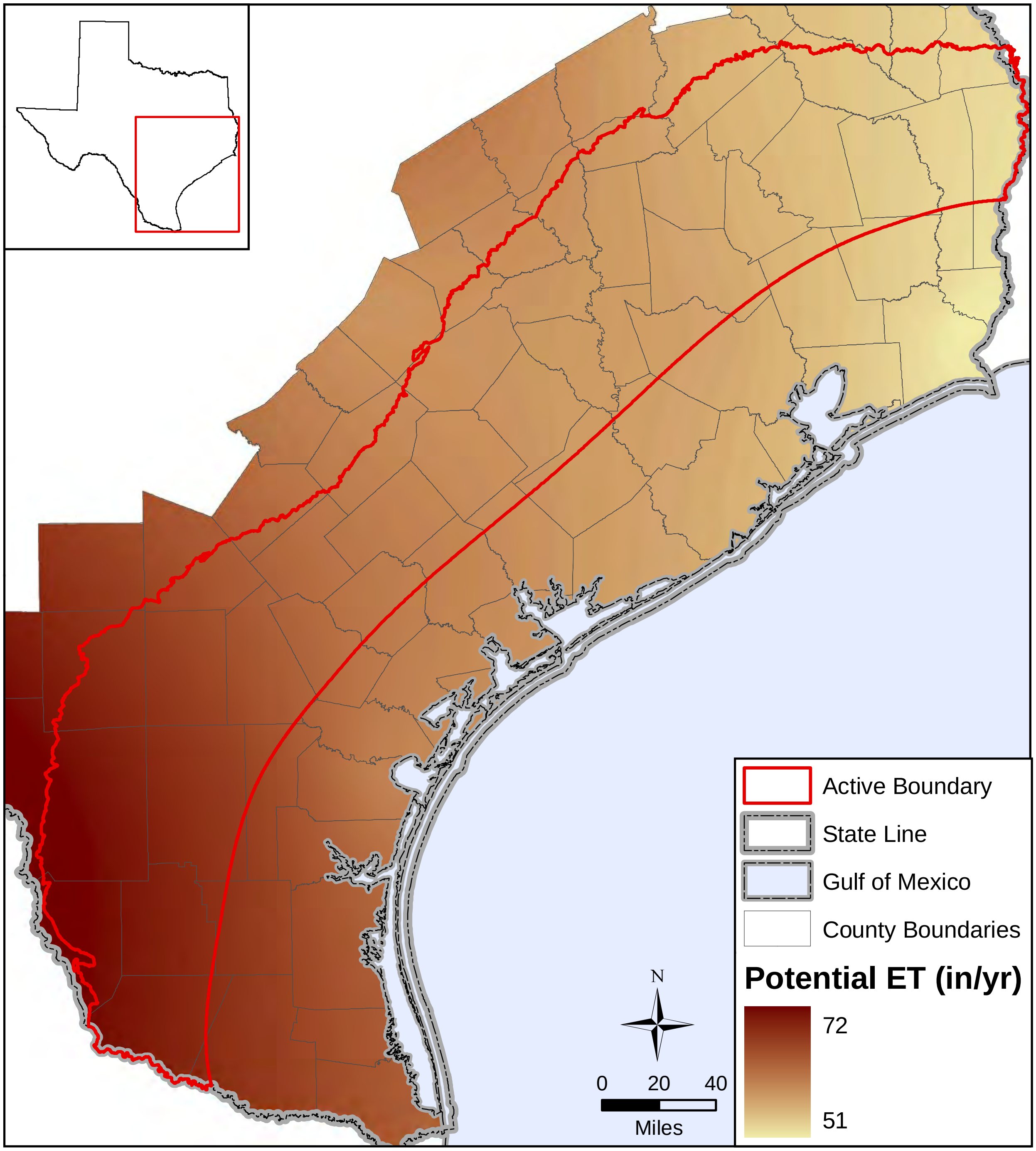
Year	County										
	Angelina	Atascosa	Bastrop	Brazos	Burleson	Fayette	Frio	Gonzales	Grimes	Houston	Karnes
1900-1909	0	18	0	37	0	69	0	91	3	48	20
1910-1919	0	36	1	74	19	78	0	182	7	96	41
1920-1929	20	55	2	112	38	87	0	273	10	144	61
1930-1939	40	73	2	149	57	95	0	364	14	192	82
1940-1949	60	91	3	186	75	104	0	455	17	241	102
1950-1959	80	109	4	223	94	113	0	547	29	289	123
1960-1969	100	128	5	237	100	236	0	638	28	310	143
1970-1979	1,335	146	9	600	262	302	0	393	201	490	163
1980	2,471	150	11	848	404	348	0	144	256	682	191
1981	2,493	153	12	874	408	351	0	141	266	679	189
1982	2,515	156	12	899	413	353	0	142	276	676	188
1983	2,539	159	13	925	417	355	0	126	286	673	186
1984	2,561	163	13	950	421	358	0	125	295	670	185
1985	2,583	166	14	976	426	360	0	136	305	668	183
1986	2,605	169	15	1,002	430	362	0	146	315	665	181
1987	2,626	172	15	1,027	434	365	0	171	325	662	180
1988	2,648	176	16	1,053	438	367	0	177	335	659	178
1989	2,670	179	16	1,078	443	369	0	167	345	656	177
1990	2,692	182	17	1,104	447	372	0	186	355	654	175
1991	2,731	187	18	1,132	457	375	0	178	364	659	179
1992	2,771	192	19	1,160	466	378	0	157	373	665	183
1993	2,810	197	20	1,188	475	381	0	186	382	670	188
1994	2,849	202	21	1,216	484	384	0	192	390	676	192
1995	2,889	206	21	1,242	494	387	0	192	399	681	196
1996	2,928	211	22	1,270	503	391	0	207	408	687	200
1997	2,967	216	23	1,298	512	394	0	240	417	692	204

Table 4.6.7, continued

Year	County										
	La Salle	Lavaca	Lee	Leon	Live Oak	McMullen	Madison	Nacogdoches	Polk	Sabine	San Augustine
1900-1909	0	2	0	0	1	9	0	0	5	25	3
1910-1919	4	4	0	0	2	17	0	20	10	50	5
1920-1929	8	7	85	2	4	26	0	39	14	75	8
1930-1939	13	9	171	3	5	35	0	59	19	100	10
1940-1949	17	11	256	5	6	43	160	78	24	125	13
1950-1959	21	13	307	6	7	52	321	98	29	150	15
1960-1969	25	15	279	8	8	61	481	117	34	175	18
1970-1979	30	17	337	10	10	69	641	83	45	294	32
1980	35	20	366	10	12	77	792	43	51	395	50
1981	34	20	372	10	13	77	794	42	52	399	30
1982	34	20	379	11	13	77	796	43	53	403	43
1983	34	20	385	11	12	77	798	47	55	407	43
1984	34	20	392	11	12	78	800	48	56	411	47
1985	34	20	398	11	12	78	802	50	57	415	52
1986	34	20	404	12	12	78	804	53	58	420	51
1987	33	20	410	12	7	79	806	51	60	423	52
1988	33	20	417	12	7	79	809	50	61	427	50
1989	33	19	423	13	8	79	811	55	62	432	51
1990	33	19	430	13	8	79	813	53	64	436	52
1991	33	20	439	13	8	80	828	56	66	439	43
1992	34	20	448	14	10	80	843	56	68	444	42
1993	34	20	458	14	9	80	858	59	70	448	46
1994	34	20	467	14	10	81	873	58	72	451	39
1995	35	20	476	14	9	81	888	61	75	456	50
1996	35	20	486	15	12	81	903	56	77	460	46
1997	36	20	495	15	11	82	917	66	79	463	49

Table 4.6.7, continued

Year	County							
	Starr	Trinity	Tyler	Walker	Washington	Webb	Wilson	Total Rural Domestic
1900-1909	0	56	1	0	11	0	27	426
1910-1919	0	111	1	0	22	0	54	834
1920-1929	0	167	2	0	33	0	80	1,352
1930-1939	0	223	2	22	45	0	107	1,891
1940-1949	0	279	3	43	56	1	134	2,588
1950-1959	0	334	3	65	67	1	161	3,261
1960-1969	0	390	4	86	78	1	188	3,893
1970-1979	0	446	5	108	89	1	215	6,333
1980	0	458	5	118	93	1	208	8,239
1981	0	468	5	120	94	1	216	8,313
1982	0	477	5	123	96	1	223	8,427
1983	0	487	5	125	98	1	231	8,515
1984	0	496	5	128	100	2	238	8,619
1985	0	506	5	130	101	2	245	8,735
1986	0	516	5	133	103	1	252	8,846
1987	1	526	5	136	105	1	260	8,964
1988	0	535	5	138	107	1	267	9,065
1989	0	545	5	141	108	1	274	9,160
1990	0	555	5	143	110	1	282	9,280
1991	1	566	5	146	112	1	294	9,430
1992	1	577	5	149	114	1	306	9,576
1993	1	588	6	152	115	1	318	9,774
1994	1	600	6	155	117	0	330	9,934
1995	1	224	6	158	119	0	342	9,722
1996	1	101	6	161	121	0	354	9,762
1997	1	202	6	165	122	0	367	10,059



ET = evapotranspiration

Figure 4.6.1 Potential evapotranspiration in inches per year across the model region.

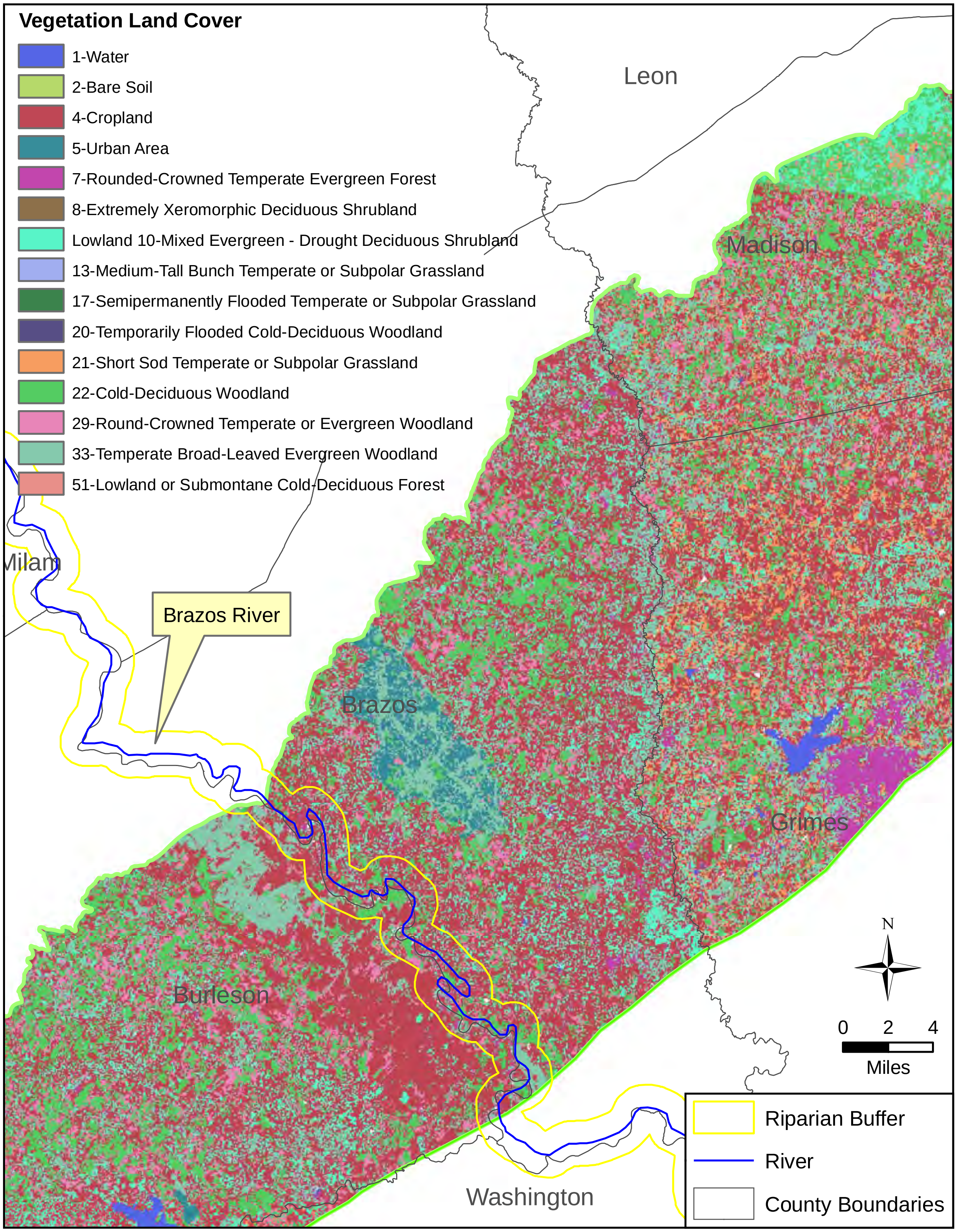


Figure 4.6.2 Example of Gap (a geographic approach to planning for biological diversity) vegetation coverage and quarter-mile riparian buffer.

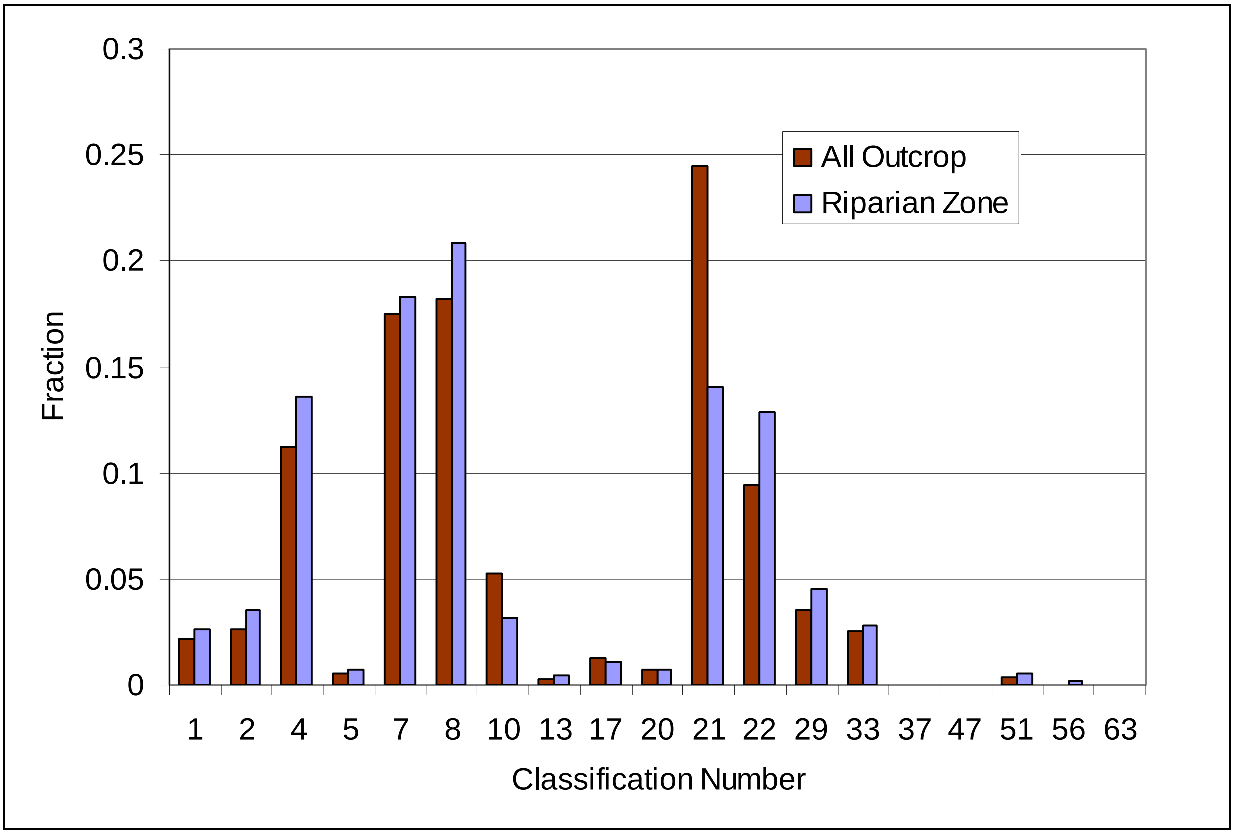


Figure 4.6.3 Frequency of vegetation types in the overall outcrop and in the riparian zones.

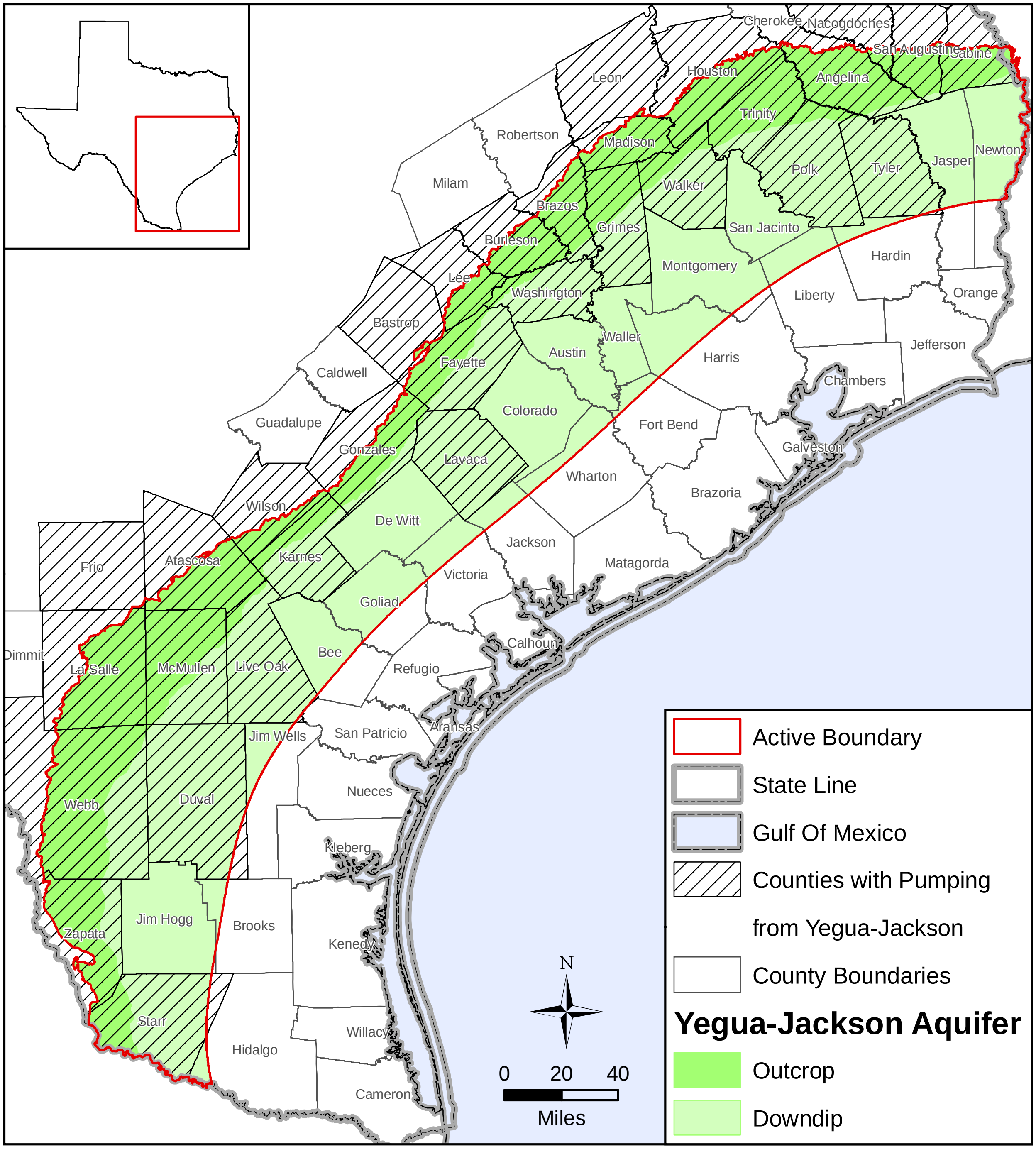


Figure 4.6.4 Counties with pumping in the Yegua-Jackson Aquifer.

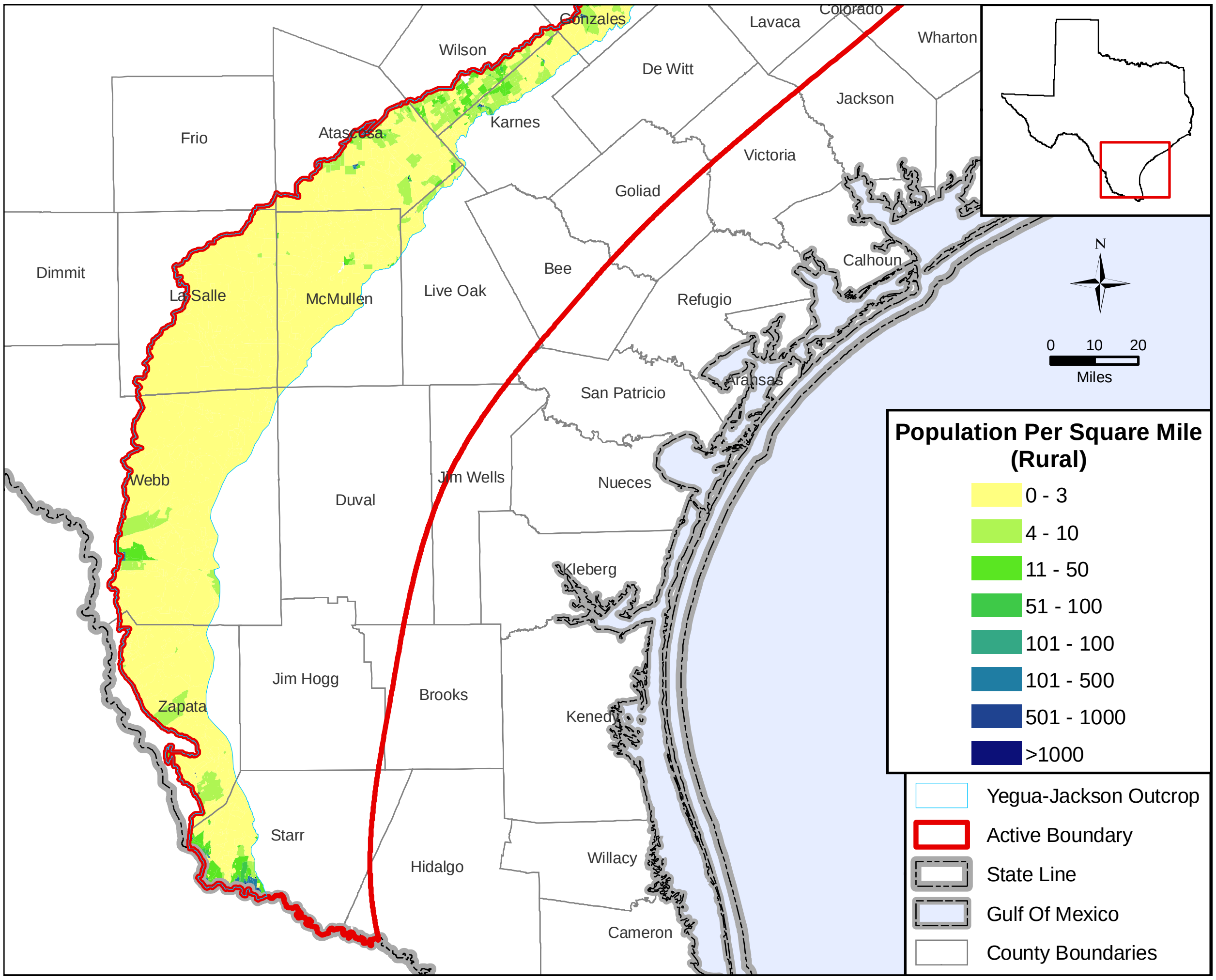


Figure 4.6.5a Population density for rural population within the southern Yegua-Jackson Aquifer outcrop.

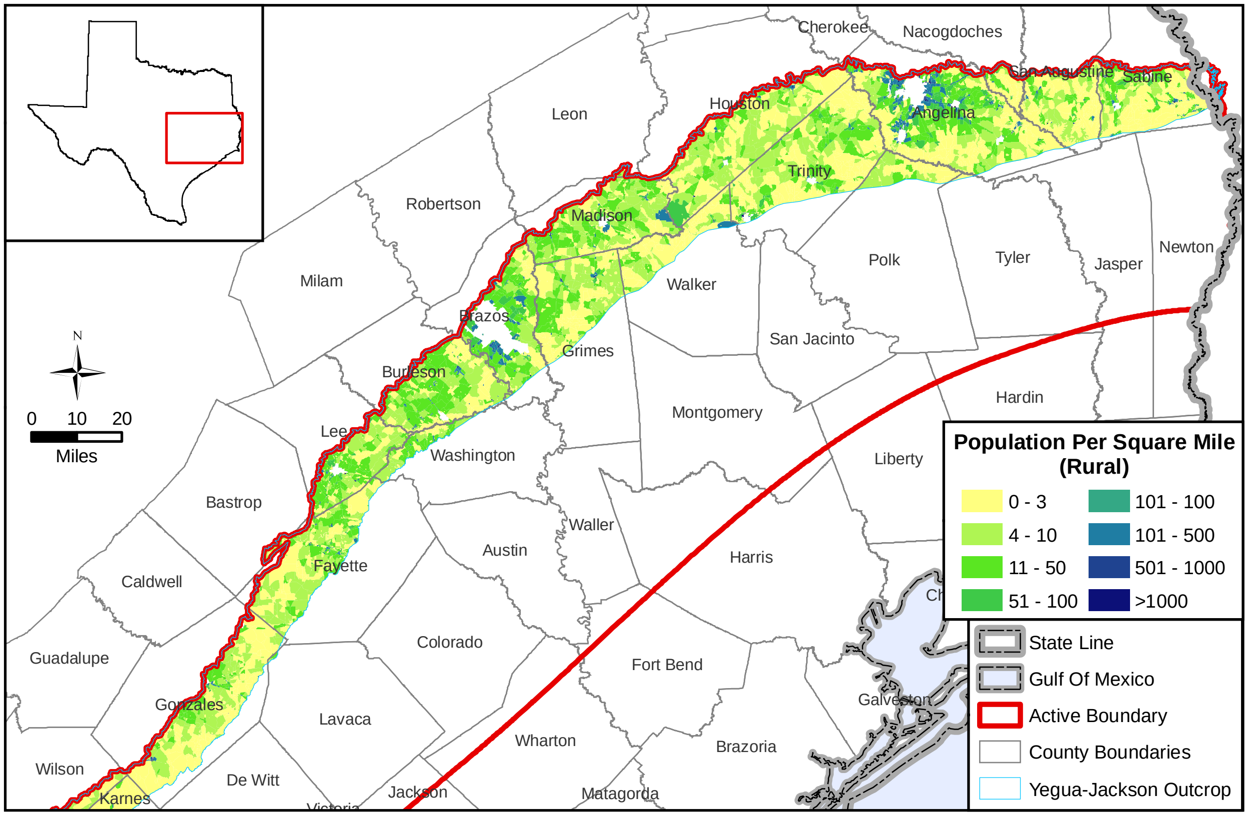


Figure 4.6.5b Population density for rural population within the northern Yegua-Jackson Aquifer outcrop.

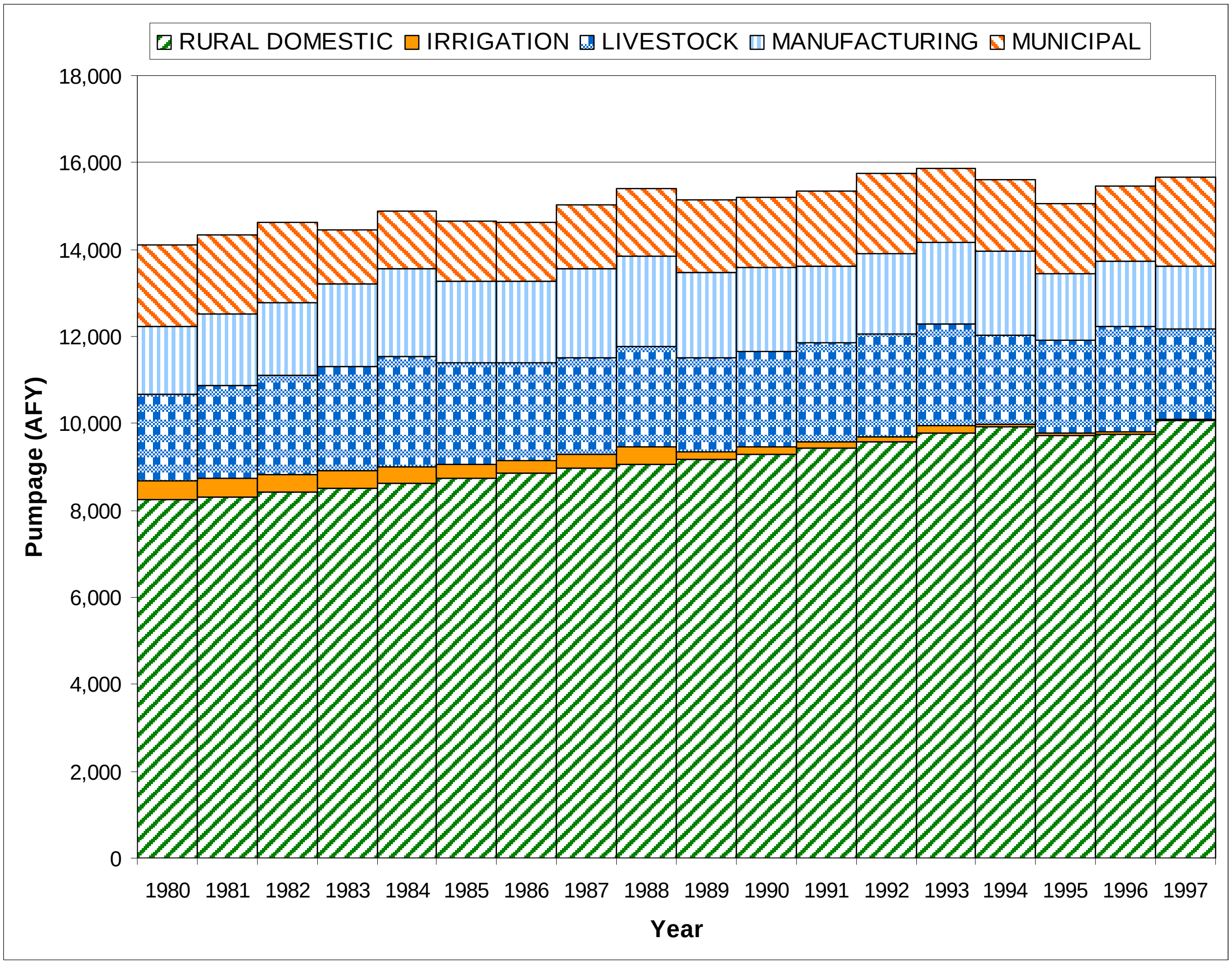


Figure 4.6.6 Total pumpage for the Yegua-Jackson Aquifer in acre-feet per year by category.

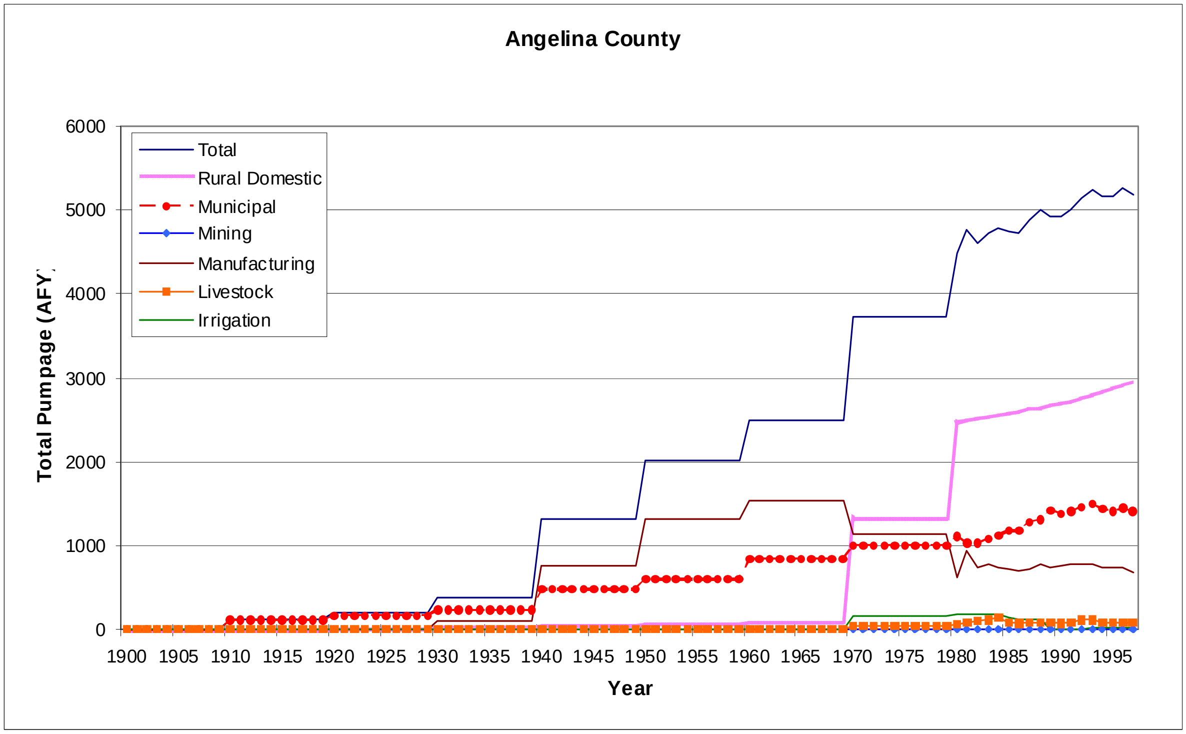


Figure 4.6.7 Total groundwater withdrawals in acre-feet per year for Angelina County by category for 1900 through 1997.

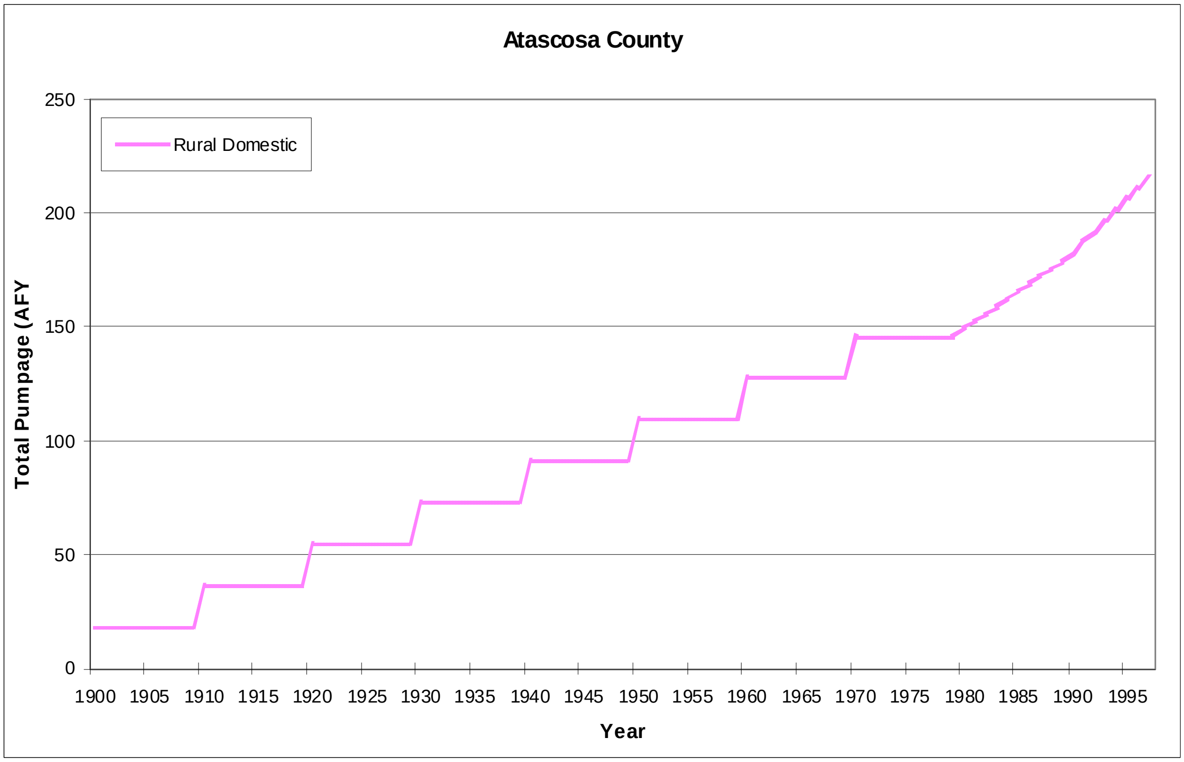


Figure 4.6.8 Total groundwater withdrawals in acre-feet per year for Atascosa County by category for 1900 through 1997.

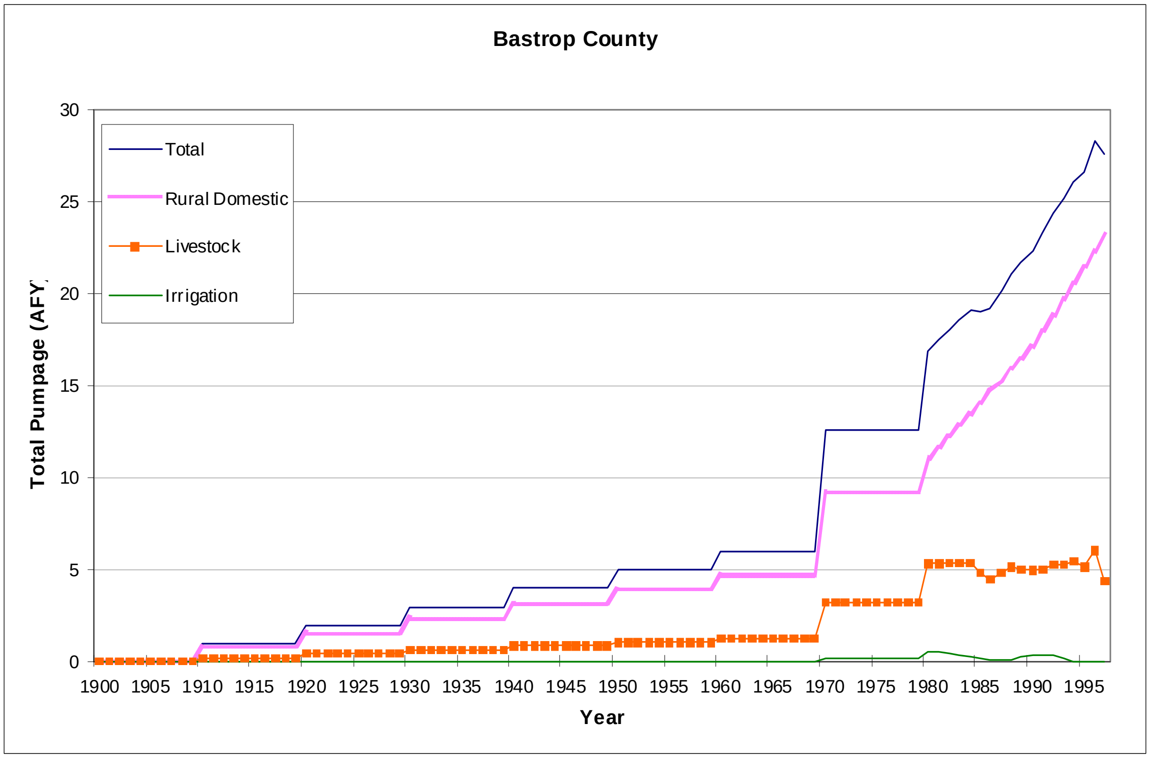


Figure 4.6.9 Total groundwater withdrawals in acre-feet per year for Bastrop County by category for 1900 through 1997.

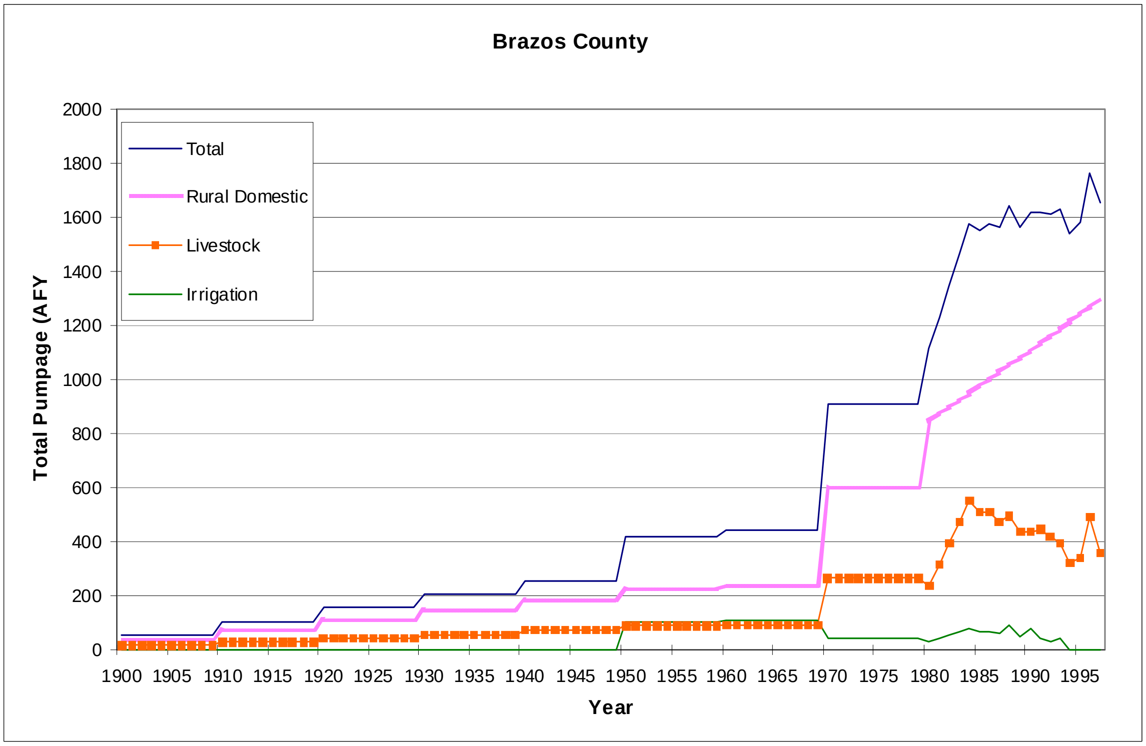


Figure 4.6.10 Total groundwater withdrawals in acre-feet per year for Brazos County by category for 1900 through 1997.

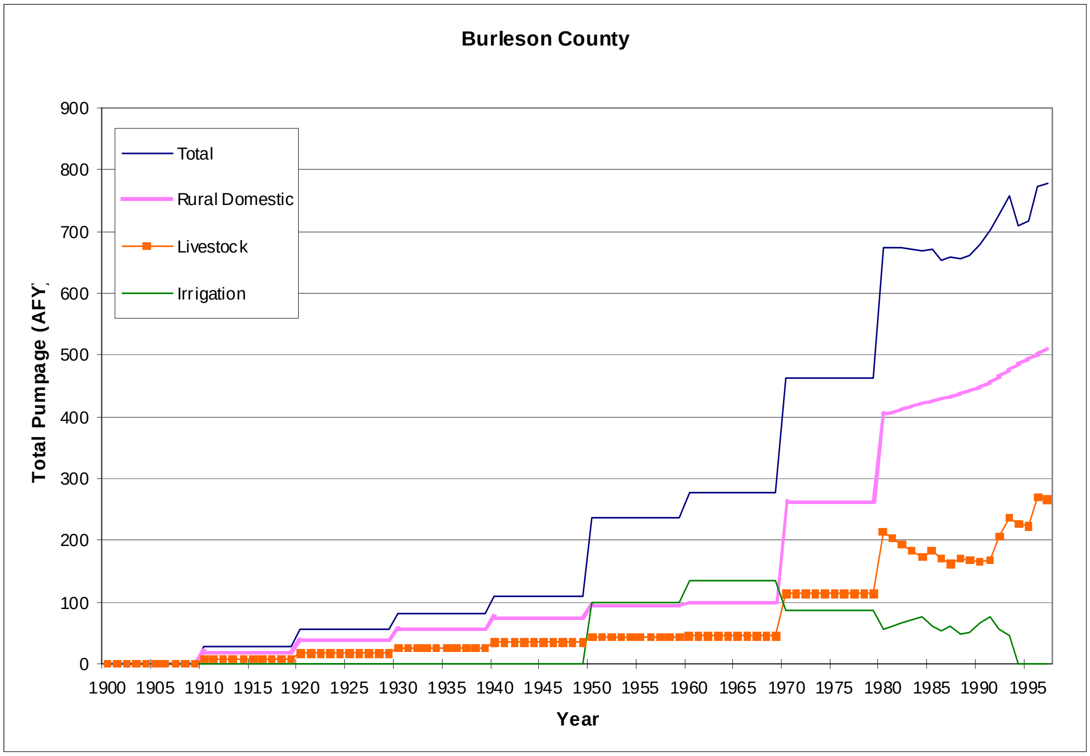


Figure 4.6.11 Total groundwater withdrawals in acre-feet per year for Burleson County by category for 1900 through 1997.

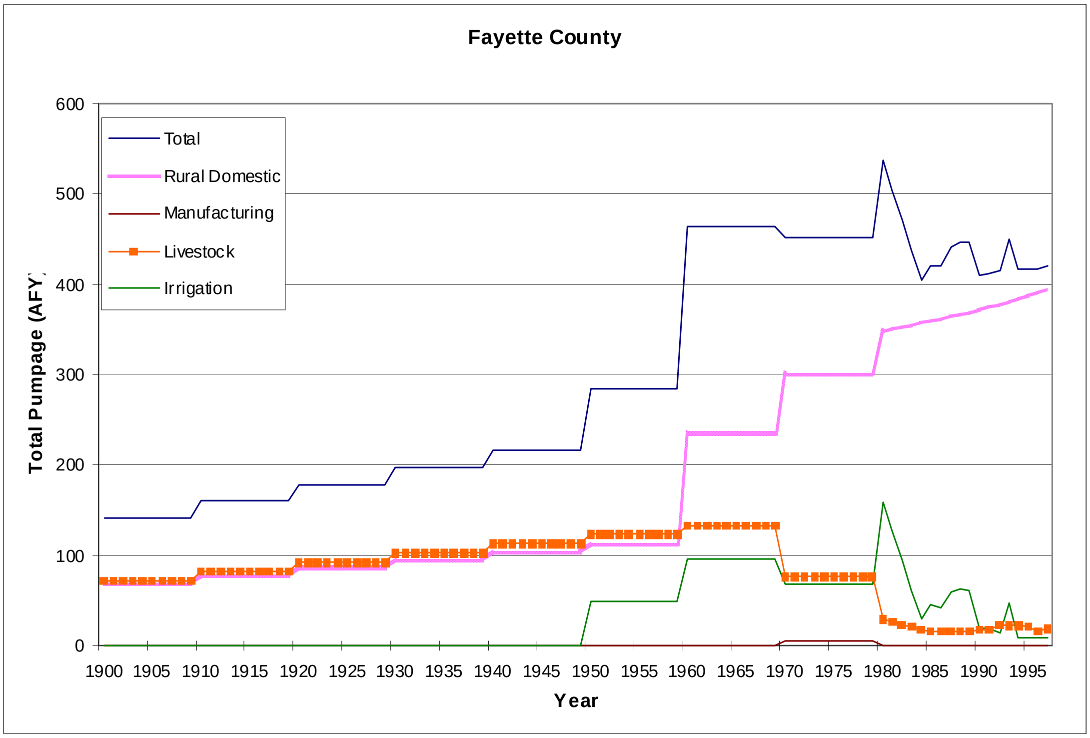


Figure 4.6.12 Total groundwater withdrawals in acre-feet per year for Fayette County by category for 1900 through 1997.

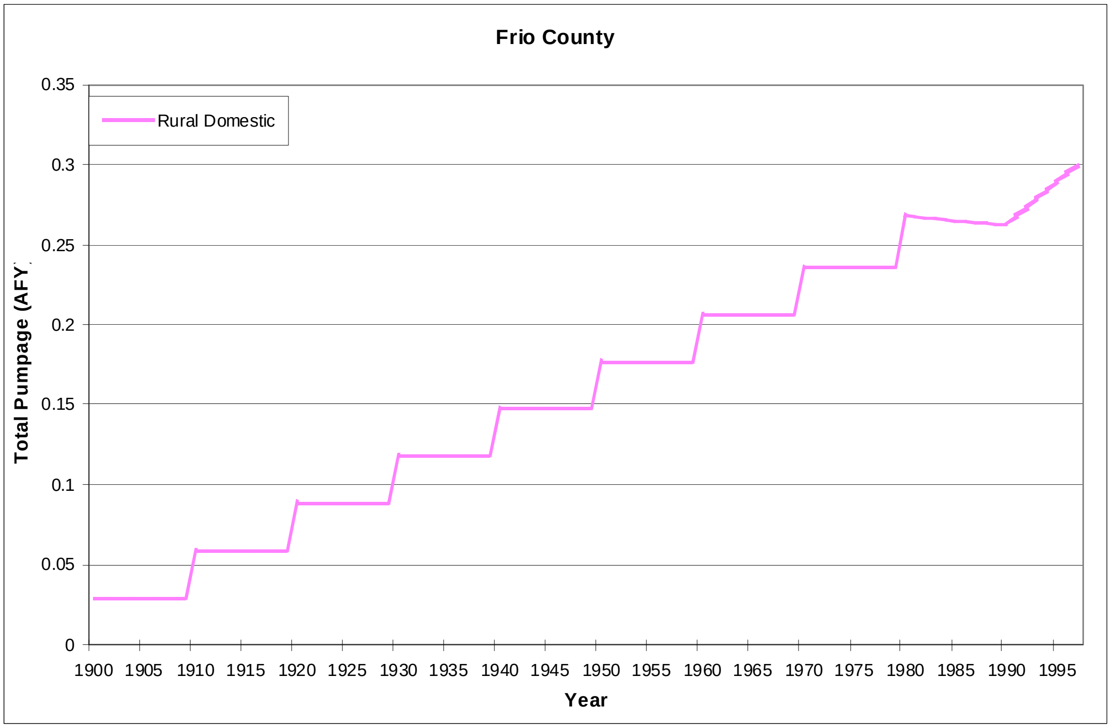


Figure 4.6.13 Total groundwater withdrawals in acre-feet per year for Frio County by category for 1900 through 1997.

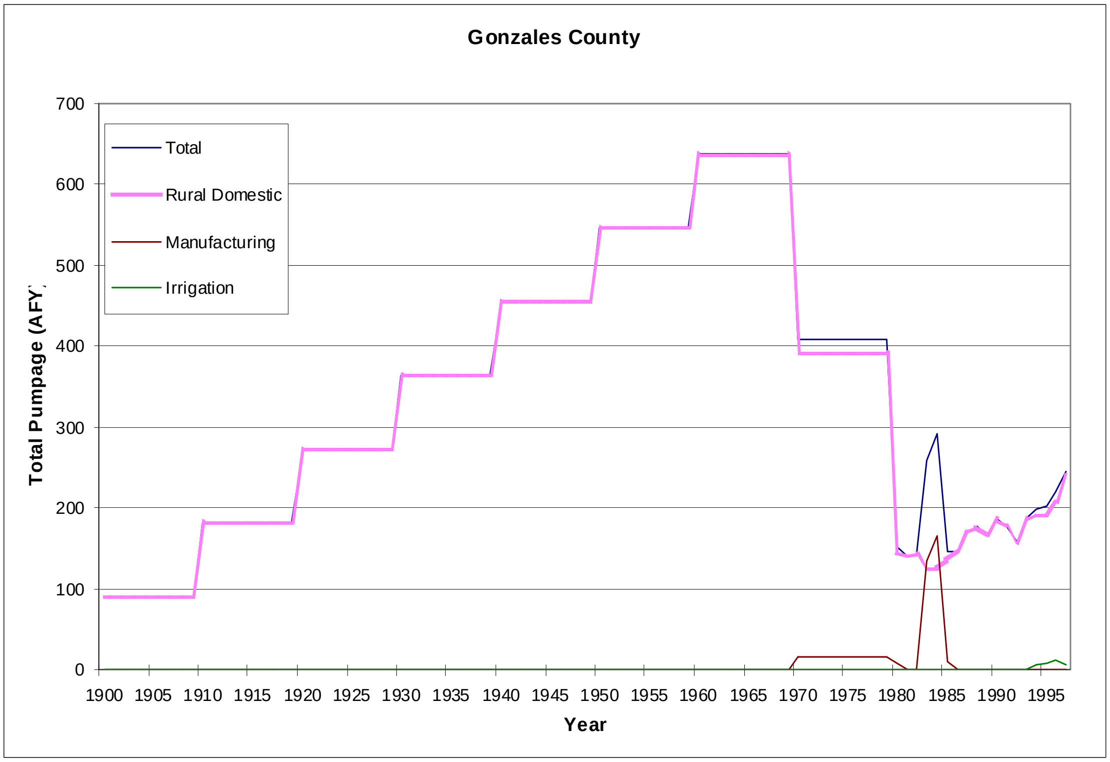


Figure 4.6.14 Total groundwater withdrawals in acre-feet per year for Gonzales County by category for 1900 through 1997.

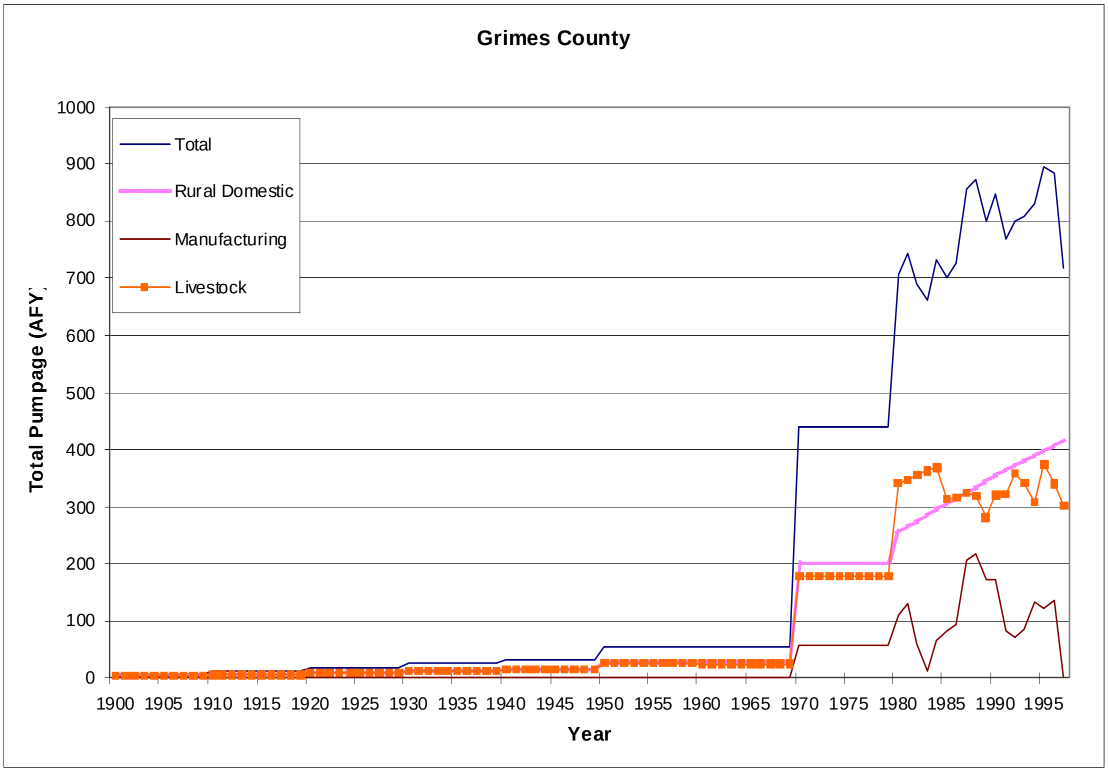


Figure 4.6.15 Total groundwater withdrawals in acre-feet per year for Grimes County by category for 1900 through 1997.

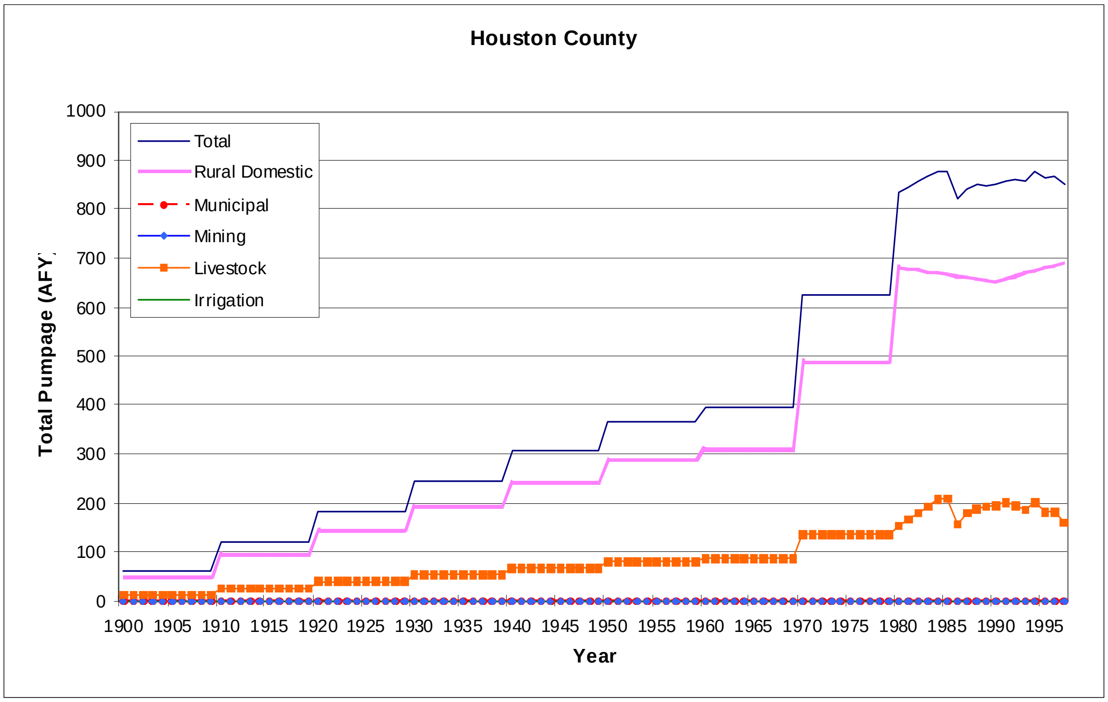


Figure 4.6.16 Total groundwater withdrawals in acre-feet per year for Houston County by category for 1900 through 1997.

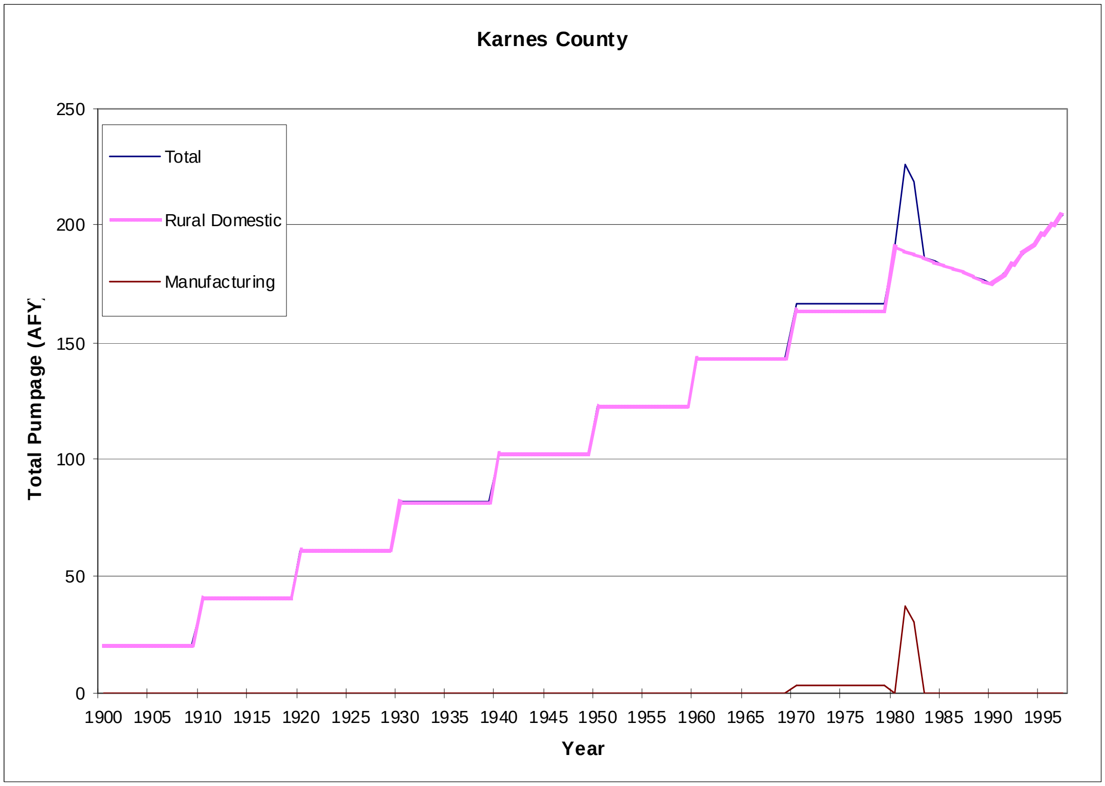


Figure 4.6.17 Total groundwater withdrawals in acre-feet per year for Karnes County by category for 1900 through 1997.

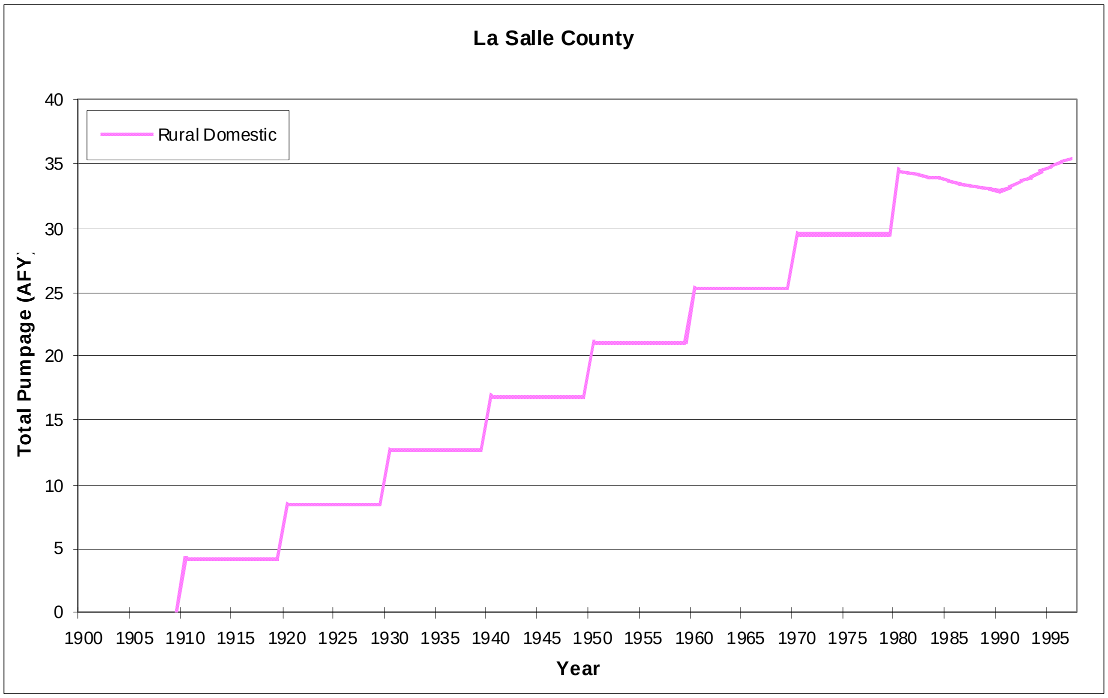


Figure 4.6.18 Total groundwater withdrawals in acre-feet per year for La Salle County by category for 1900 through 1997.

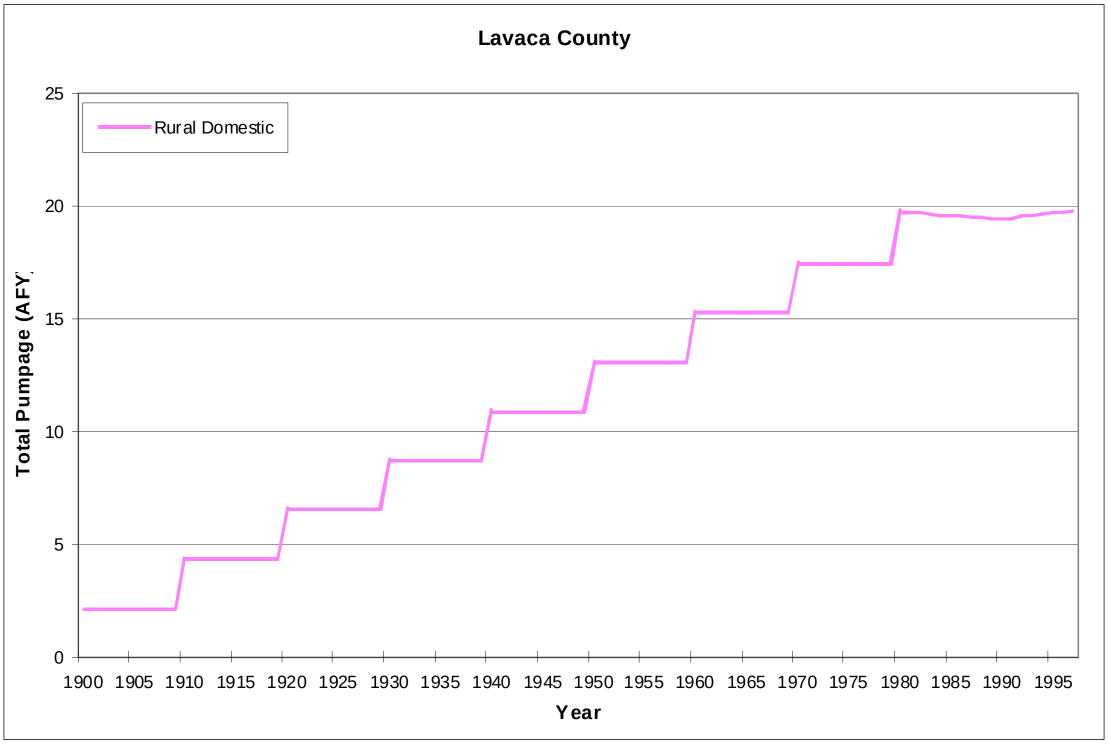


Figure 4.6.19 Total groundwater withdrawals in acre-feet per year for Lavaca County by category for 1900 through 1997.

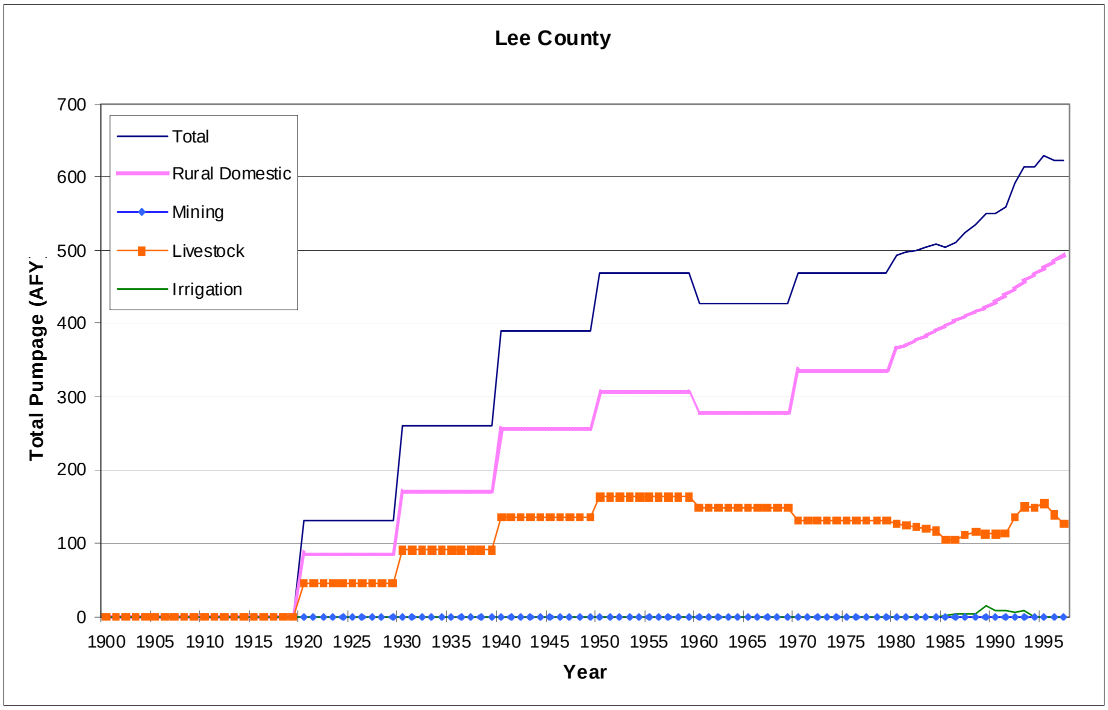


Figure 4.6.20 Total groundwater withdrawals in acre-feet per year for Lee County by category for 1900 through 1997.

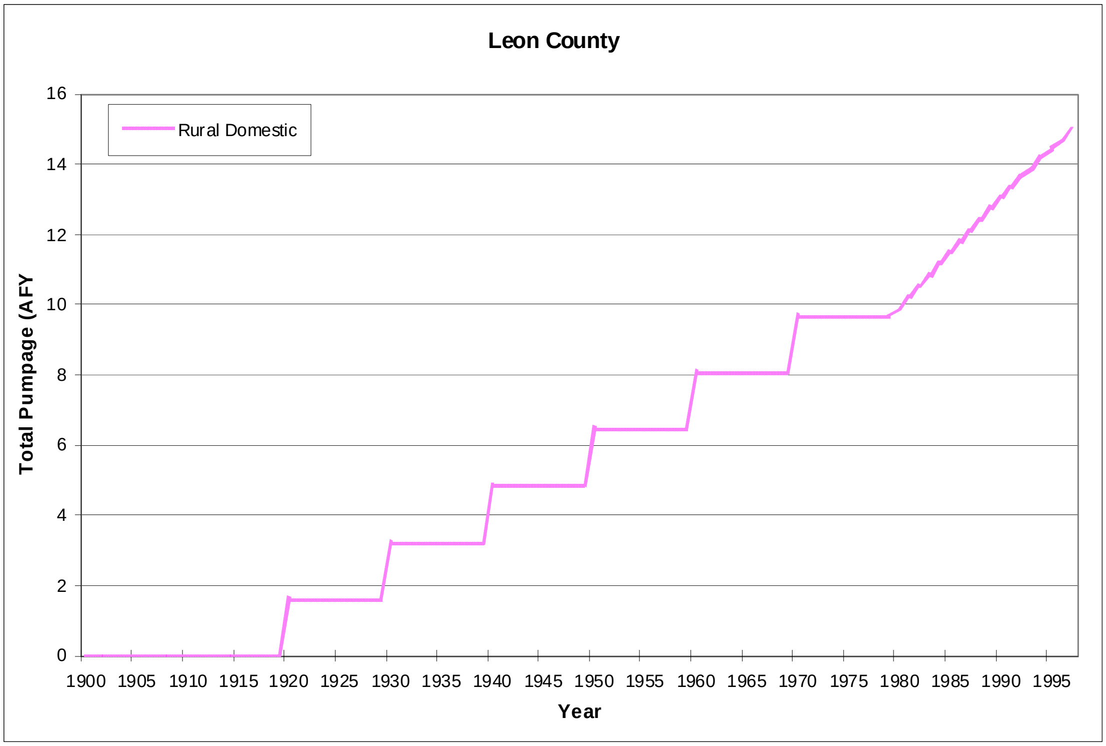


Figure 4.6.21 Total groundwater withdrawals in acre-feet per year for Leon County by category for 1900 through 1997.

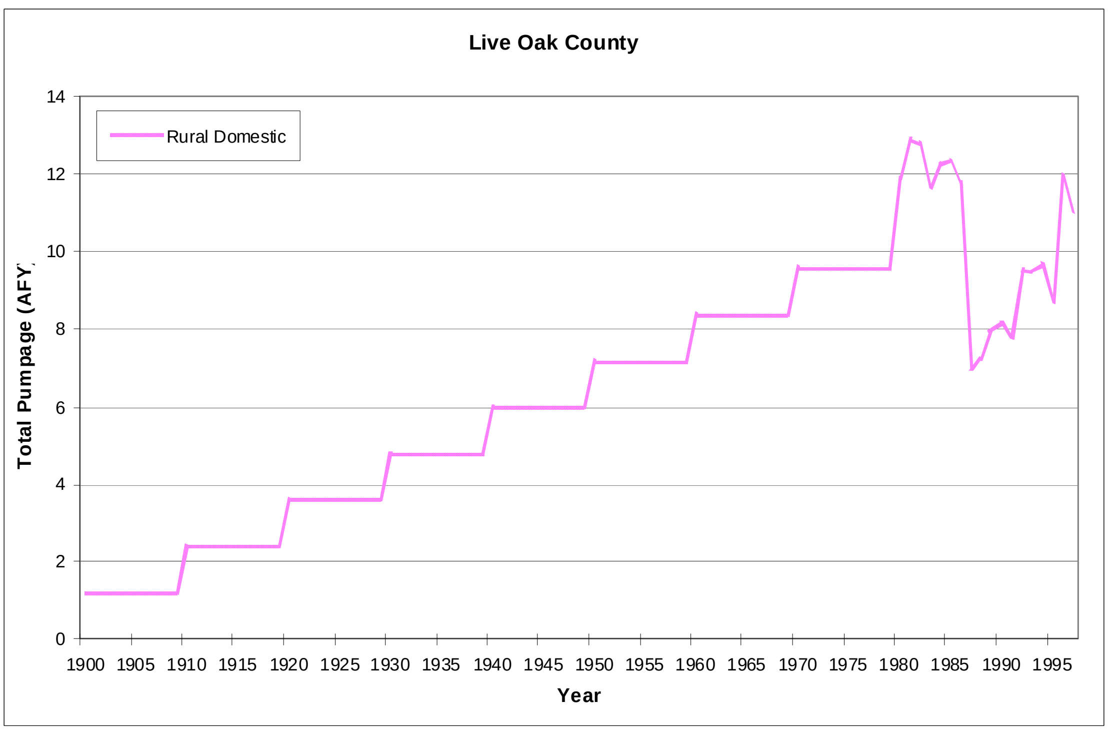


Figure 4.6.22 Total groundwater withdrawals in acre-feet per year for Live Oak County by category for 1900 through 1997.

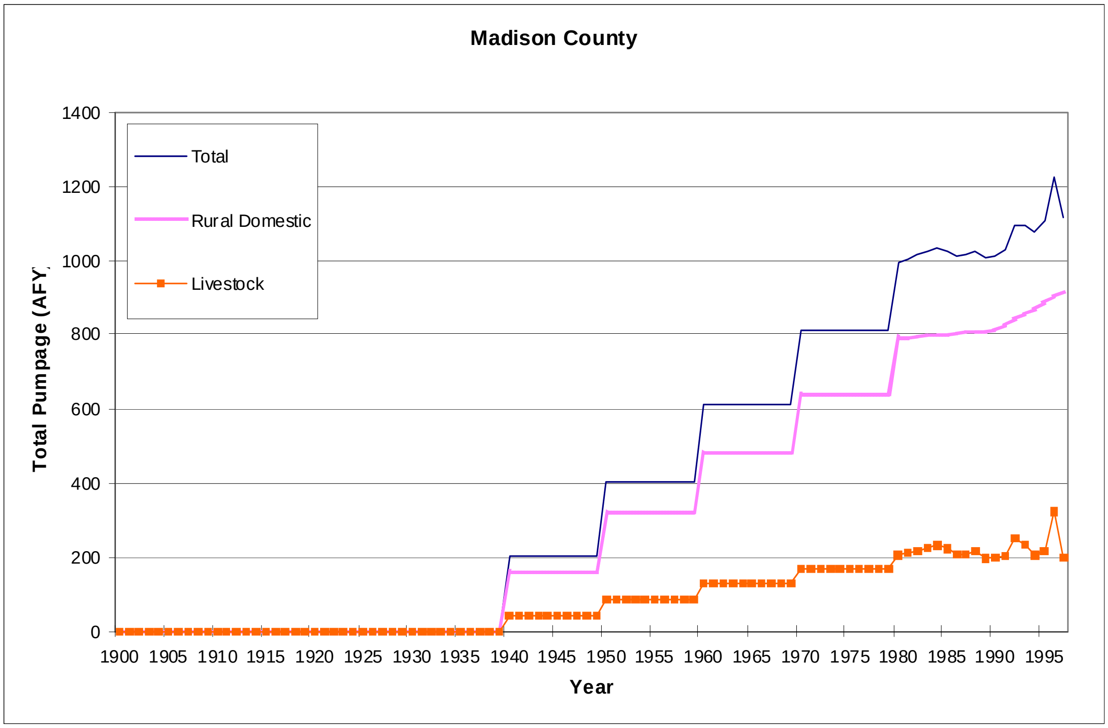


Figure 4.6.23 Total groundwater withdrawals in acre-feet per year for Madison County by category for 1900 through 1997.

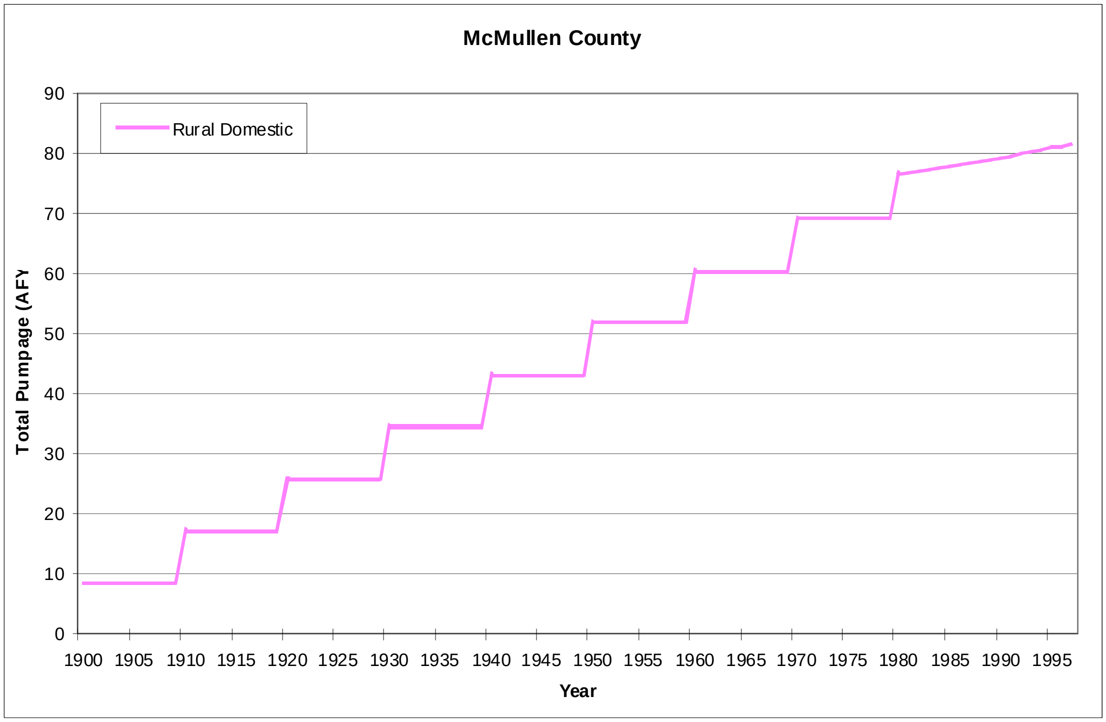


Figure 4.6.24 Total groundwater withdrawals in acre-feet per year for McMullen County by category for 1900 through 1997.

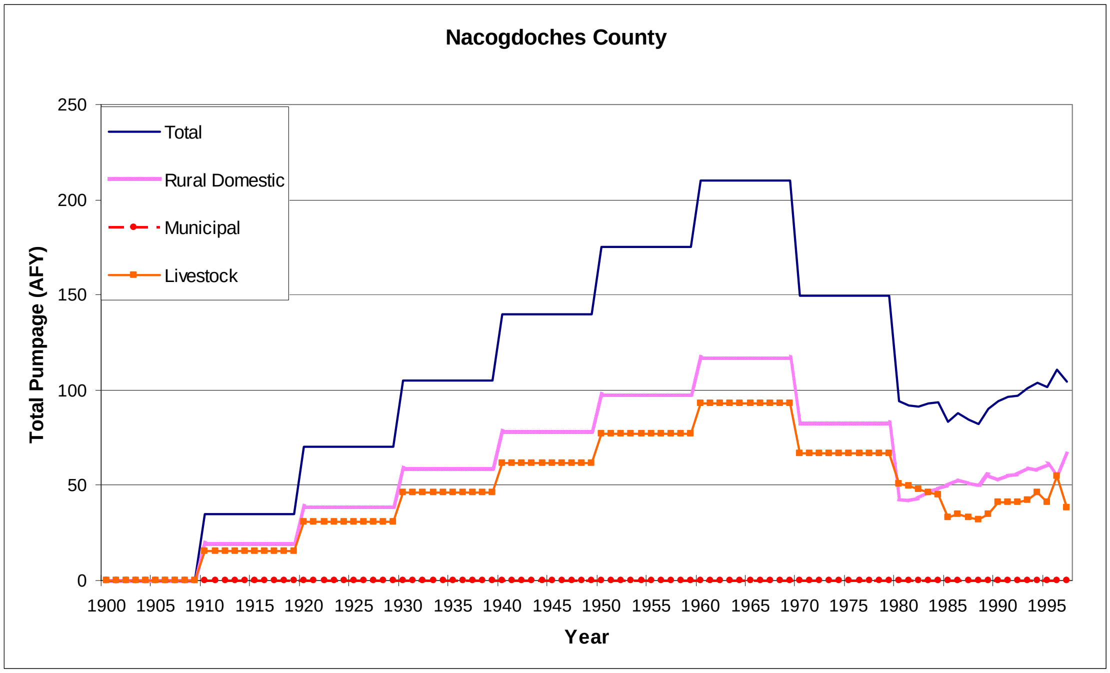


Figure 4.6.25 Total groundwater withdrawals in acre-feet per year for Nacogdoches County by category for 1900 through 1997.

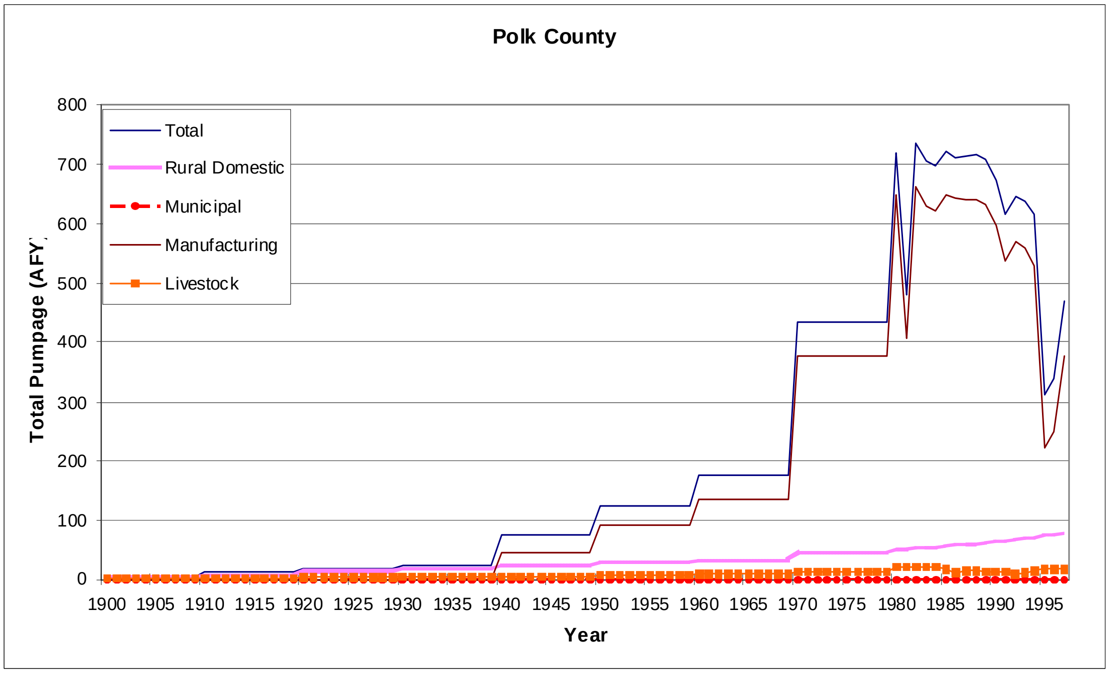


Figure 4.6.26 Total groundwater withdrawals in acre-feet per year for Polk County by category for 1900 through 1997.

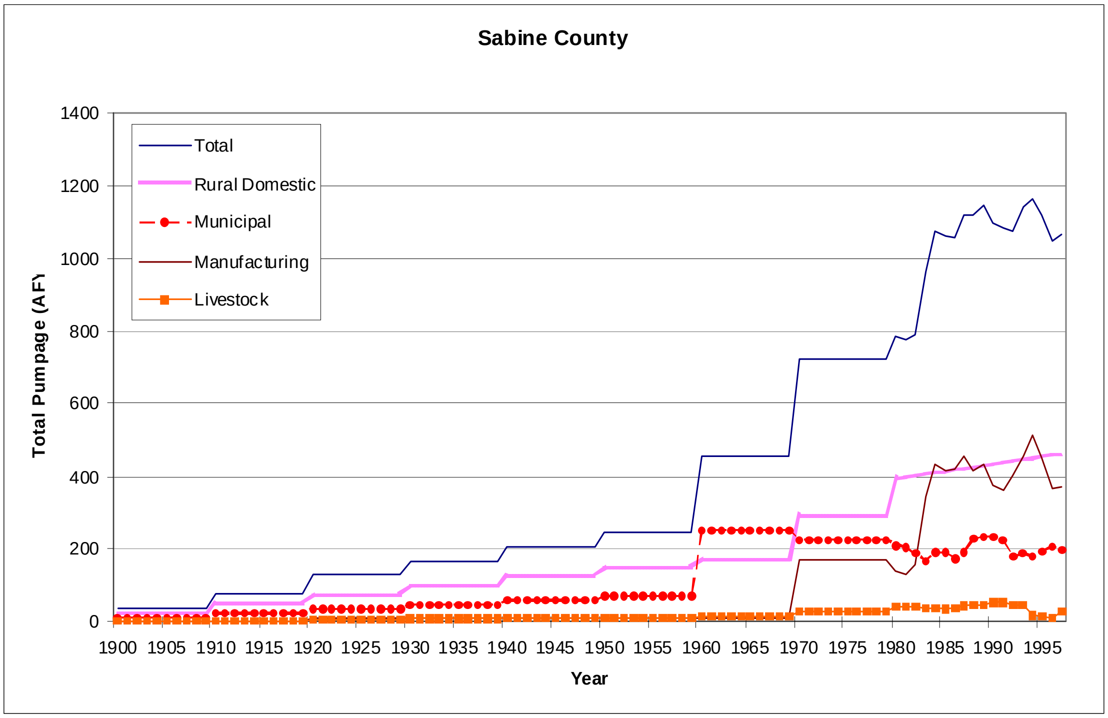


Figure 4.6.27 Total groundwater withdrawals in acre-feet per year for Sabine County by category for 1900 through 1997.

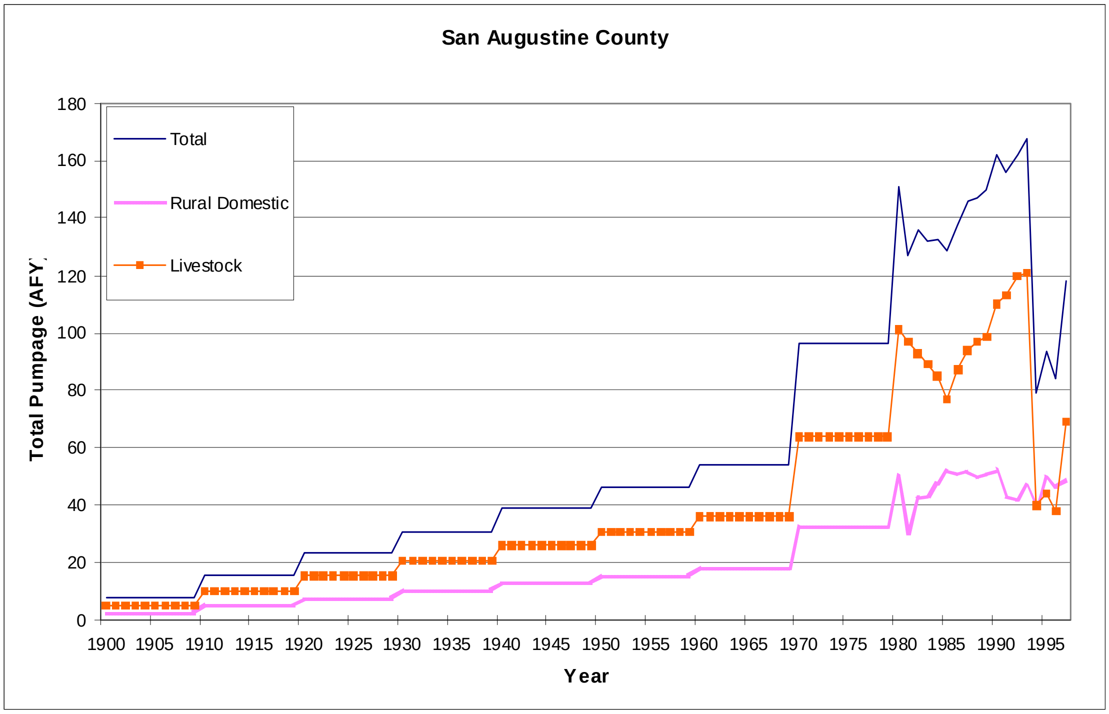


Figure 4.6.28 Total groundwater withdrawals in acre-feet per year for San Augustine County by category for 1900 through 1997.

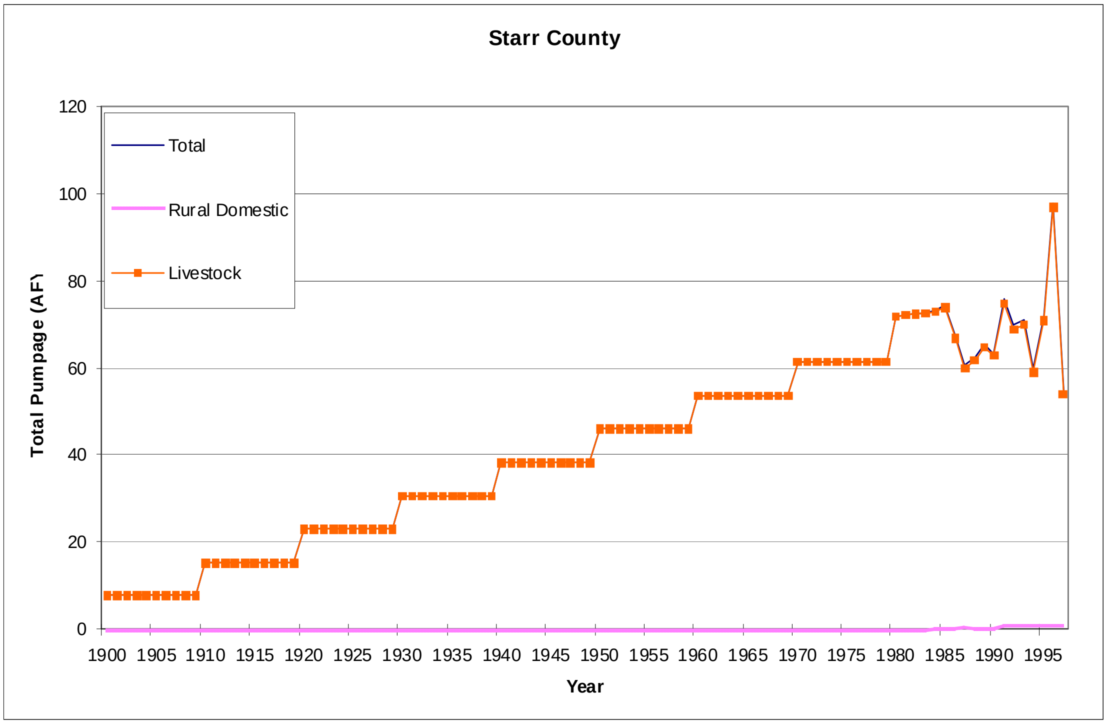


Figure 4.6.29 Total groundwater withdrawals in acre-feet per year for Starr County by category for 1900 through 1997.

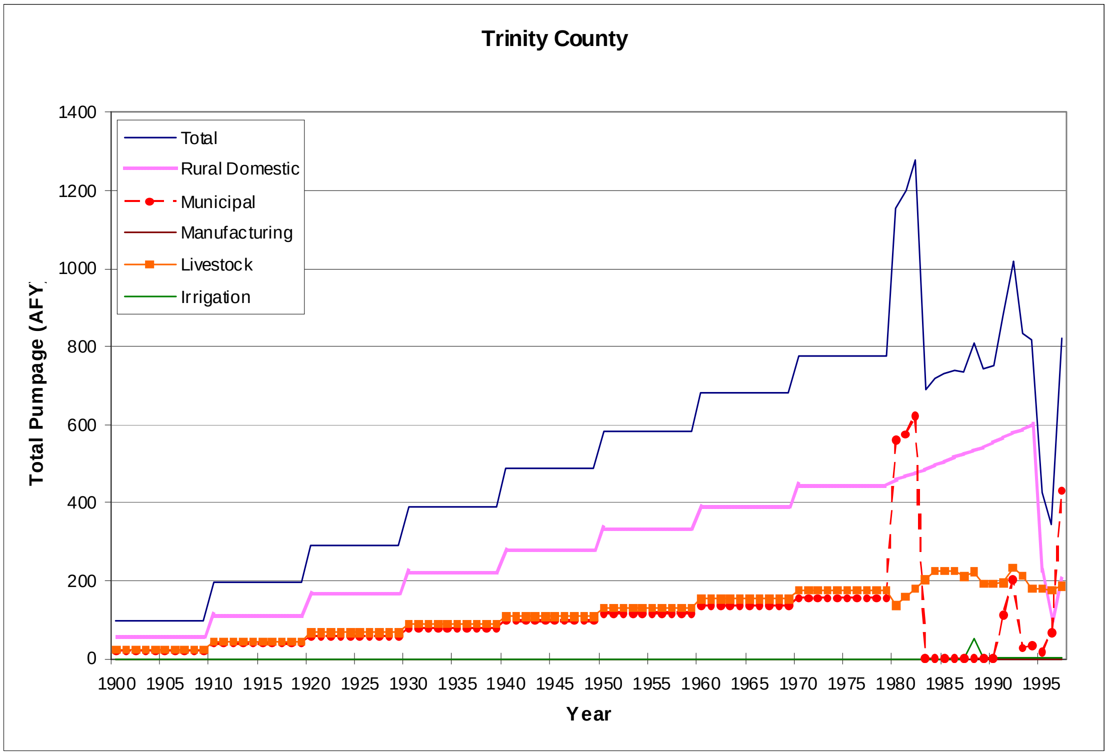


Figure 4.6.30 Total groundwater withdrawals in acre-feet per year for Trinity County by category for 1900 through 1997.

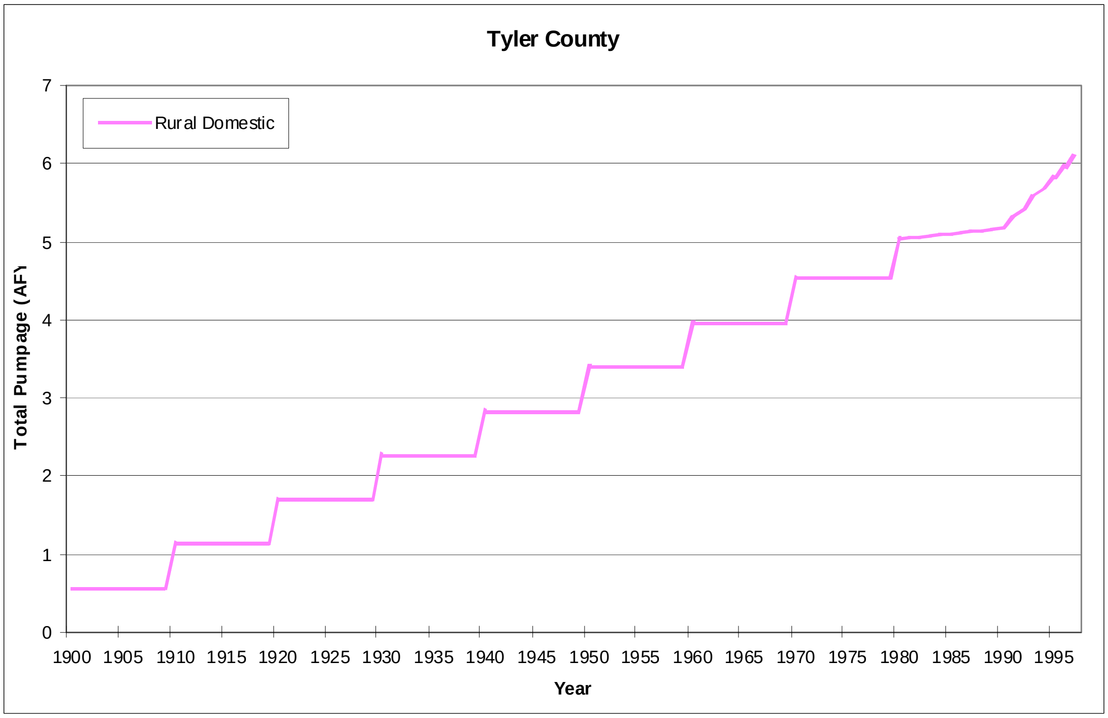


Figure 4.6.31 Total groundwater withdrawals in acre-feet per year for Tyler County by category for 1900 through 1997.

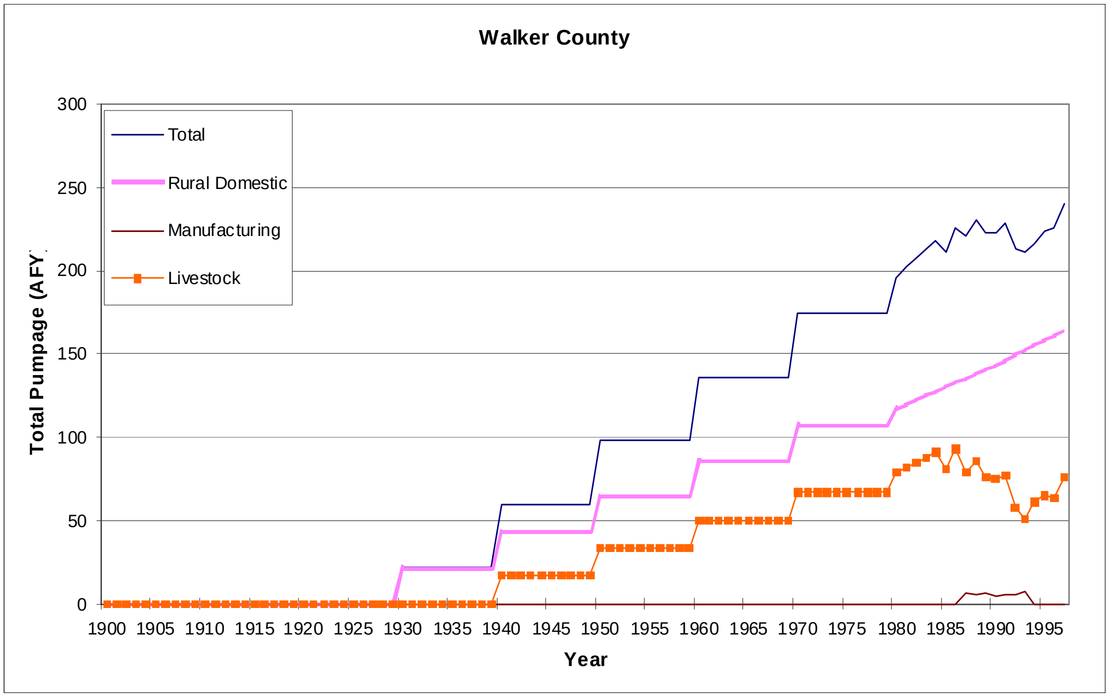


Figure 4.6.32 Total groundwater withdrawals in acre-feet per year for Walker County by category for 1900 through 1997.

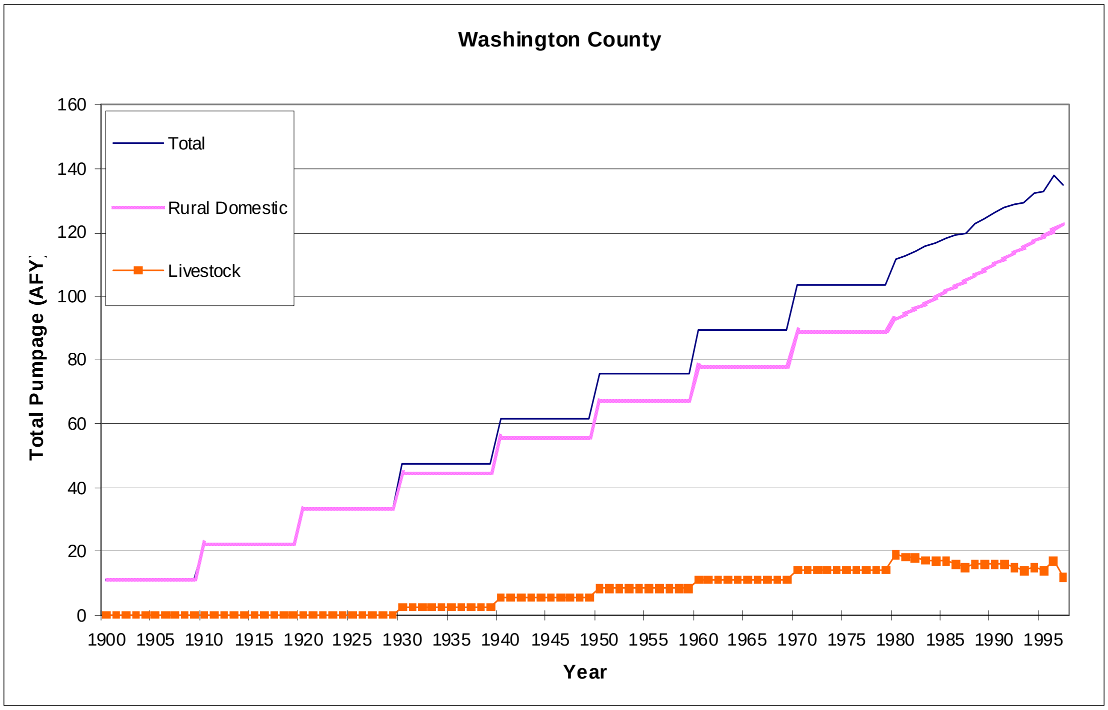


Figure 4.6.33 Total groundwater withdrawals in acre-feet per year for Washington County by category for 1900 through 1997.

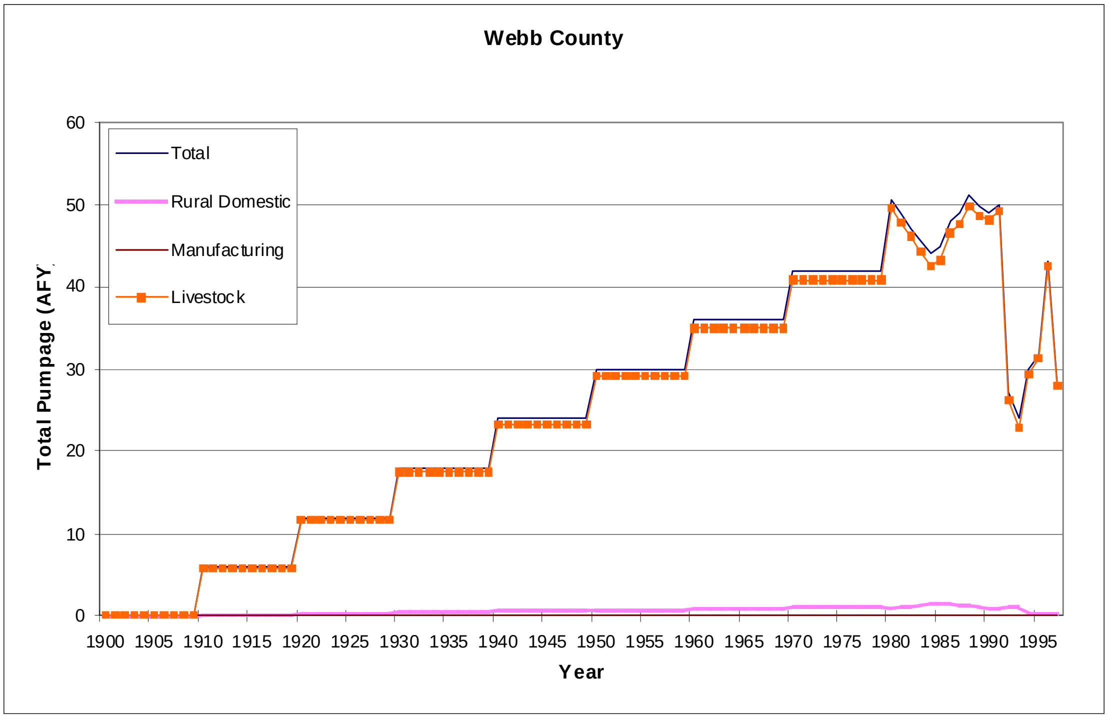


Figure 4.6.34 Total groundwater withdrawals in acre-feet per year for Webb County by category for 1900 through 1997.

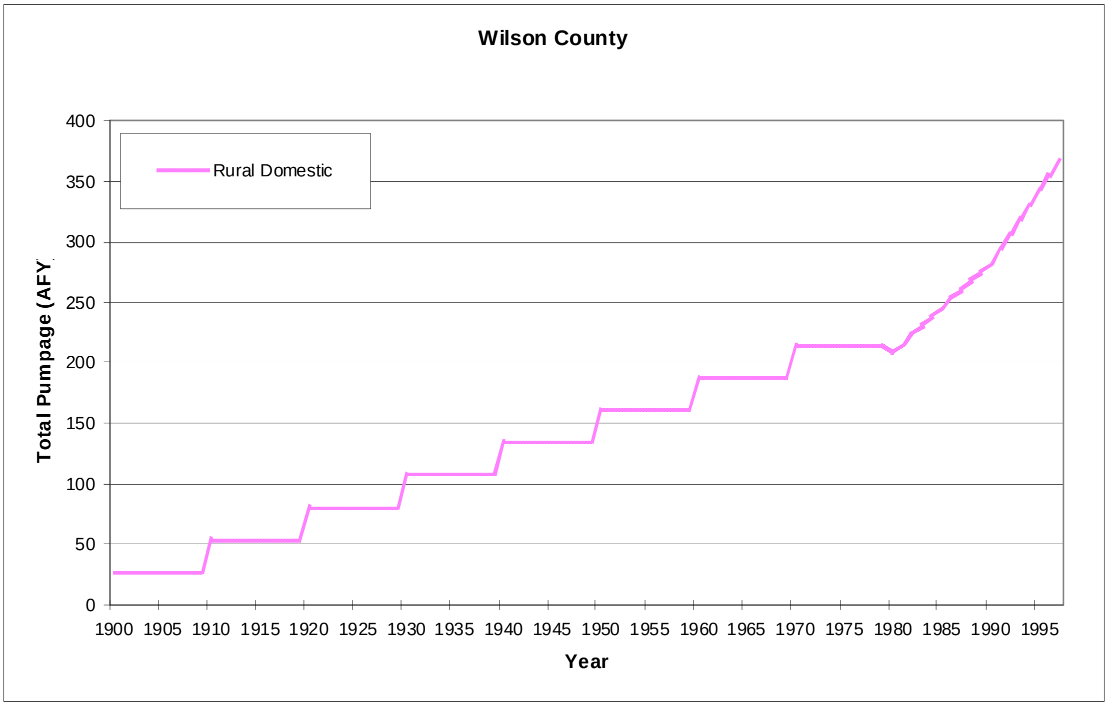


Figure 4.6.35 Total groundwater withdrawals in acre-feet per year for Wilson County by category for 1900 through 1997.

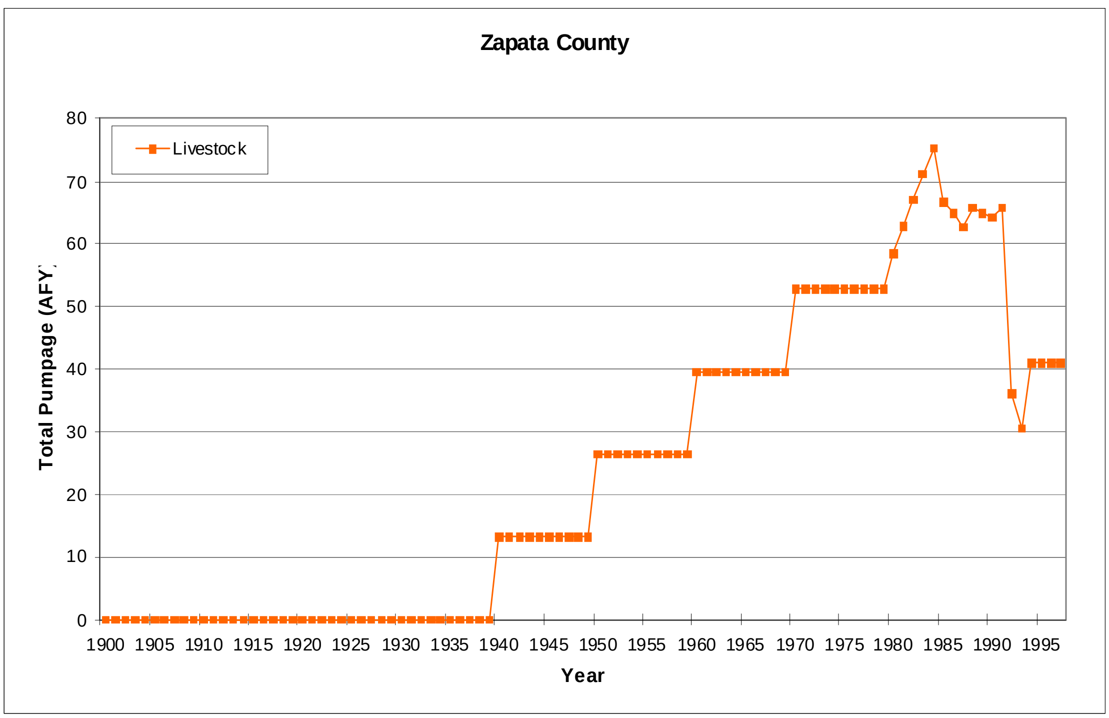


Figure 4.6.36 Total groundwater withdrawals in acre-feet per year for Zapata County by category for 1900 through 1997.

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4.7 Hydraulic Properties

An important part of developing representative aquifer properties for the Yegua-Jackson Aquifer groundwater availability model is a sound conceptual framework for populating and adjusting aquifer properties during model calibration. Without such a framework, the modeler runs the risk of producing a model that adequately matches historical water levels and stream flows at the price of poorly constrained aquifer hydraulic parameters. In order to avoid this outcome, we have assembled aquifer property information and have developed guidelines for generating spatial distributions of properties that are consistent with the purpose of the Yegua-Jackson Aquifer groundwater availability model, the dimensions of the grid cells, and the available information.

4.7.1 Data Sources

Within the Texas groundwater literature and databases, we discovered that there is a limited amount of information available on the Yegua-Jackson Aquifer. For instance, the compilation of aquifer properties by Myers (1969) does not contain a single pumping test for the Yegua-Jackson Aquifer. Because of the scarcity of hydraulic property information in TWDB and United States Geological Survey reports, we investigated other sources of information including the oil/gas literature and the Texas Commission on Environmental Quality databases.

Our efforts at the Texas Commission on Environmental Quality focused on obtaining data from pumping tests performed on public water supply wells. This effort produced over 50 pumping test data sets suitable for detailed analysis. Our efforts in the oil/gas literature focused on subsurface characterization studies concerning permeability values and trends in the Yegua-Jackson Aquifer and similar formations in the Texas Gulf Coast area. Much of this literature describes the spatial variability in the aquifer properties to support the secondary recovery of hydrocarbons.

In addition, we thoroughly reviewed the data and reports produced by the Lower Colorado River Authority-San Antonio Water System Water Project groundwater study. Since 2004, this study has focused on using the analysis of geophysical logs to help develop a regional groundwater model for the Texas Gulf Coast Aquifer.

4.7.2 Comments on the Importance of Dimension and Scale

The Yegua-Jackson Aquifer is comprised of heterogeneous sequences of pinched out and truncated lenticular beds of sands and clays deposited by a wide range of depositional environments that exhibit cyclic periodicity (Knox and others, 2007). For the conceptual model, the hierarchical concept of heterogeneity developed by petroleum geologists and engineers is relevant. These professionals recognize four scales of heterogeneity, which are: microscopic, mesoscopic, macroscopic, and megascopic (Alpay, 1972). Of importance to the development of regional groundwater availability models is capturing the important aspects of the last two measurement scales. Macroscopic heterogeneity is defined by the depositional pattern of lithofacies and subsequent modification during burial. Macroscopic heterogeneity occurs at the scale of a few feet to hundreds of feet and represents processes that can limit hydraulic connectivity between deposits, especially in the vertical dimension. Megascopic heterogeneity is a product of variability across depositional systems and is reflected as fieldwide differences in effective properties at the scale of several thousand feet or more (Tyler and Finley, 1991).

4.7.3 Analysis of Geophysical Log Data

Knox and others (2007) provide the stratigraphic framework for the Yegua-Jackson Aquifer groundwater availability model. Their structural analysis provides the justifications for dividing the Yegua-Jackson Aquifer into four major geologic units that are coincident with the model layers. The geologic units are called, from oldest to youngest, the Lower Yegua Unit, the Upper Yegua Unit, the Lower Jackson Unit, and the Upper Jackson Unit. Each of these units is approximately 400 to 800 feet thick, with thickening occurring in the downdip direction.

A product developed during the structure study that is very useful for analyzing hydraulic properties are the maps of net sand thickness and depositional facies. For many regional groundwater models in Texas, a common practice is to develop transmissivities for each model layer based on the net-sand thickness maps. Thus, the sand thickness maps are used to help characterize megascopic heterogeneity. Within the petroleum industry, a common practice is to use depositional facies maps to superimpose macroscopic heterogeneity onto megascopic heterogeneity. In the following, we discuss additional analyses on the lithology and facies information generated by Knox and others (2007) that guide the development of hydraulic properties.

Depositional Facies

The depositional framework used by Knox and others (2007) is consistent with the general terminology and concepts developed by Fisher and others (1970) for deposits from the top of the Yegua Formation to the base of the Catahoula Formation. For the conceptual model, the general features of the depositional systems are of primary interest.

Knox and others (2007) characterize the depositional setting into three major environments. The fluvial facies are associated with rivers and streams and their floodplains. Deposition by rivers produce blocky sands that tend to be oriented along dip, toward the coastline. The fluvial facies include a large range of depositional energies and, therefore, can include highly heterogeneous sediments. The deltaic facies are associated with the formations of deltas, lagoons, and barrier islands. Deposition tends to be along strike and parallel to the shoreline. Sediments associated with beaches often consist of relatively well sorted moderate and fine-grained sands. The shelf facies are associated with deposition on the continental shelf in relatively deep waters with low energies. Shelf facies include slope, shelf-edge delta, and shelf/slope sands. Deposition tends to be uniform in all directions.

A major focus of study for the petroleum industry is the Yegua-Jackson Barrier/Strandplain Sandstone (Galloway and others, 1983) that extends through the south Texas counties of Zapata, Jim Hogg, Webb, and Duval. This region contains over 300 fields. These sandstones are strongly strike-oriented deposits associated with barrier island complexes that tend to pinch out updip and landward against muddy back-barrier-lagoonal facies. Fisher and others (1970) report individual barrier-bar sandstones that extend 30 to 60 miles in strike length and as much as 20 miles wide. Seni and Choh (1994) report sand bodies elongated along strike with a width of preserved sandstones varying between 5 and 15 miles. West (1963) reports a high degree of lateral uniformity along the strandlines (former shorelines) and that deposit thickness is unrelated to local structural conditions or faults.

Lithology

Numerous studies (Folk, 1980; Carmen, 1939; Lambe and Whitman, 1969; Masch and Denny, 1966; Cade and others, 1994) show that lithology can be a useful and reliable estimator of hydraulic conductivity and other aquifer hydraulic properties. With other factors being equal in a mixture of sands and clays, the hydraulic conductivity of a deposit will increase with increases in the percentage of sand, in the average size of the sand grains, and in the sorting of the deposits.

At the macroscopic scale, an important factor in determining the effective property of an aquifer is both the amount of sand and the connectivity among the different sand bodies (Fogg, 1986; Fogg and Kreitler, 1982). The potential for connectivity among aquifer sand bodies can be shown to be a function of the distribution of their sizes and their orientation. To estimate the size distribution for the sand and clay beds that comprise the Yegua-Jackson Aquifer, we analyzed 150 lithology profiles generated by Knox and others (2007). These profiles provide a continual listing of sand and clay sequences at 0.5-foot intervals. Our analysis involved determining the size of the continuous sand and clay beds for the three major facies groupings in each geologic unit. The parsing of the lithologic profiles is based on the contact information provided by Knox and others (2007). If less than 10 profiles intersected a facies grouping, the results of the analysis are not reported due to an insufficient number of samples.

Results of our analysis are presented in Table 4.7.1 and Figures 4.7.1 through 4.7.3. Table 4.7.1 shows that all four geologic units are relatively sand poor. The highest sand percentage is about 30 percent and occurs in the fluvial deposits in the Upper and Lower Yegua units. Sand percentages of less than 2 percent occur in the shelf deposits in the Upper and Lower Jackson units. Results in Figures 4.7.1 through 4.7.3 show that, throughout the Yegua-Jackson Aquifer, the sand bodies are consistently much smaller than the clay bodies. In fact, over 50 percent of the Yegua-Jackson Aquifer is composed of clay beds that are more than 80 feet thick.

A review of the net-sand thickness maps produced by Knox and others (2007) shows that, despite the average sand content in the geologic units, large areas exist where sand percentages exceed 40 percent and that, in areas of relatively high sand accumulations, the sand percentage is generally between 20 and 40 percent. The lithologic analysis suggests that the hydraulic communication among the sand-rich deposits will typically be limited vertically due to separation by thick clay bodies. Hydraulic connectivity in the lateral directions among the sand bodies will be limited in areas where sand percentages are low and the sand beds are thin.

4.7.4 Analysis of Pumping Tests

The Texas Commission on Environmental Quality maintains a database of public water supply wells. The database includes the well location, well construction specification, and geological logs. For some public water supply wells, there are hardcopies of time drawdown data collected during a pumping test. We collected information from approximately 75 pumping tests from the study area and analyzed the data in an Excel spreadsheet using the Cooper-Jacob straight-line method (Cooper and Jacob, 1946) for fifty of the tests that were found suitable for analysis. After removing several of the tests in wells screened above the Upper Jackson Unit, 41 pumping tests remained, as listed in Table 4.7.2. One of the indicators to evaluate the reliability of the calculated transmissivity value and the validity of the radial flow assumption inherent in the analysis method is whether the drawdown data can be fit to a straight line using linear regression. Figure 4.7.4 shows nine examples of these fits.

Based on the screen interval of each well, the pumping tests were assigned to each of the geologic units. In situations where less than 60 percent of the interval occurred within a single geologic unit, the pumping test was assigned to both intersected units. The hydraulic conductivity is calculated by dividing the transmissivity by the total length of the screened interval. This method is consistent with the approach used by Myers (1969). Table 4.7.3 summaries the hydraulic conductivity values for each geologic unit.

Figures 4.7.5 through 4.7.8 show the location of the pumping tests superimposed on a simplified depositional environments map for each geologic unit. The results show that over 90 percent of the pumping tests in the Upper and Lower Yegua units and in the Upper and Lower Jackson units are located in the fluvial deposits and deltaic deposits, respectively. Despite the potential value of investigating the possible correlation between fluvial and deltaic depositional environments and hydraulic conductivity, this investigation was not pursued because of insufficient data. Among the limitations of the available data is that pumping information for both the fluvial and deltaic deposits does not exist for any of the four chronostratiphic units nor for either the Jackson Group or Yegua Formation. Without an approach to identify and quantify potential differences in the fluvial or deltaic depositional environments that may be unit dependent, we could not provide a credible evaluation that compared the results among the fluvial and deltaic deposits from the different geologic units in the Yegua-Jackson Aquifer.

Figure 4.7.9 shows the relationships between percent sand and hydraulic conductivity. The percent sand is calculated from the driller logs provided in the Texas Commission on Environmental Quality database. For all three data sets, there is evidence that the value of hydraulic conductivity increases with sand content. The relatively low regression coefficients are attributed to inaccuracies in the drillers logs and the wide range of hydraulic properties that the sands and sandy deposits have in the Yegua-Jackson Aquifer. The variability in the sandy materials is particularly important in this analysis because of the relatively small screen lengths. Young and Kelley (2006) discuss the importance of screen length for estimating aquifer properties at the scale of the geologic unit being characterized. For their study of the Gulf Coast Aquifer, they limited their analysis of pumping tests to pumping wells with screens greater than 200 feet. In general, large screen intervals are desired because they provide a better integration of the spatial variability across the vertical interval of a geologic unit than do small screen intervals.

During the analysis of the pumping tests, we estimated the sand percentages at the well locations based on the geophysical log data from Knox and others (2007). This estimate was based on interpolation of sand percentages for the entire geologic unit from the location of the nearest geophysical logs. On average, these sand percentages are approximately one-third the percentages calculated from the driller log information. We can suggest two reasons for this discrepancy. First, well screens are preferentially set by drillers into intervals of high sand content. Second, the analysis method used by Knox and others (2007) to estimate lithology from geophysical logs may consistently under-represent sand percentages compared to driller estimates (i.e., the difference between an electric-log interpretation and a core interpretation).

4.7.5 Reported Values of Hydraulic Conductivity

As part of the literature review for this project, we discovered several reports that provided estimates of hydraulic conductivity useful for our conceptual model. The United States Geological Survey (Payne, 1970) provides an overview of the entire Yegua Formation from Louisiana to the south of Texas. Table 4.7.4 provides the summary information provided by Payne (1970). The hydraulic conductivity values associated with the sand bodies of thicknesses less than 50 feet are consistent with those shown in Tables 4.7.2 and 4.7.3. In addition, the concept that the hydraulic conductivity is a function of the sand body thickness provides some support for our premise that facies type affects the hydraulic properties of the sand.

A search for pumping test reports prepared for public entities resulted in a single report. The report was prepared by LBG-Guyton (2005) for the city of Diboll. That report described a 24-hour pumping test at 326 gallons per minute. The transmissivity of the Yegua Formation was estimated at 2,200 cubic feet per day. Using the method of Myers (1969), we calculate an average hydraulic conductivity of 18 feet per day for the sand formation. Assuming this well intersected the fluvial deposits of the Yegua Formation, the pumping test results are consistent with those shown in Table 4.7.2.

Considerable information exists in the petroleum literature regarding the structure and depositional facies of the Yegua Formation. Because most of these studies involve deposits that occur at depths greater than 2,000 feet, we focused our review of these studies primarily on understanding whether depth of burial affects permeability of sands and, if it does, how to model it. The results of this endeavor are presented in Section 4.7.6.

Among the reports that we found of interest to our conceptual understanding of the deeper Yegua Formation deposits are those of Hamilton (1994), Seni and Choh (1994), and Miller (1989). Hamilton (1994) discusses the discovery and development of the Seventy-Six West well field in northwest Duval County. This well field produces from two sandstones at depths of approximately 1,300 and 1,400 feet. The initial estimated properties for the sandstones are an average porosity of 31 percent and a hydraulic conductivity of 3.3 feet per day (converted from a permeability of 1,200 millidarcies). The permeability unit of millidarcies were converted to hydraulic conductivity in units of feet per day by multiplying millidarcies by 2.74×10^{-3} feet per day. This conversion assumes fresh water at roughly 70 degrees Fahrenheit, where specific gravity is 1.0 and viscosity is 1 centipoise. This conversion factor will vary slightly with changing temperature and dissolved solids concentrations. In this study, literature values of intrinsic permeability are provided along with the estimated values of hydraulic conductivity, since these assumptions about the fluid must be made to convert intrinsic permeability to hydraulic conductivity.

Seni and Choh (1994) provide a summary of the measured permeability of the Loma Novia oil field in Duval County. This field exists at a depth of approximately 3,000 feet and the reservoir sandstones have an average porosity of 32 percent, an average hydraulic conductivity of 2.4 feet per day (906 millidarcies), with a range in hydraulic conductivity between 0.2 feet per day (55 millidarcies) and 16 feet per day (6,000 millidarcies).

Miller (1989) provides a statistical analysis of approximately 1,000 permeability and porosity values for downdip Yegua Formation sandstones that are at depths of approximately 8,000 to 12,000 feet. The cores were obtained from Victoria, Jackson, Wharton, Brazoria, Fort Bend, Jefferson, Hardin, and Newton counties Texas, and Calcasieu Parish, Louisiana. The average porosity is 22 percent and the average hydraulic conductivity is 0.6 feet per day (269 millidarcies). The data supports a log-linear correlation between core porosity and core permeability.

4.7.6 Impact of Depth of Burial on Porosity and Permeability

Although the primary interest in the Yegua-Jackson Aquifer groundwater availability model is to simulate groundwater flow at depths less than 1,000 feet, the simulation of groundwater at these depths and the calibration of the model is affected by the assumptions regarding the aquifer hydraulic properties at much greater depths. The petroleum literature provides overwhelming evidence that sandstone porosities and permeability generally decrease with depth through compaction and cementation. In this section, the primary focus is to provide a generalized formulation of how to represent this decrease with depth.

Evans and others (1997) provide a general approach for how to predict changes in permeability in sandy reservoirs caused by changes in depth of burial. This approach is based on the fact that the size and distribution of pores in the sand matrix control groundwater flow and that increases in the compaction of the sand caused by increases in depth of burial reduces the pore space and, thus, permeability. Loucks and others (1984) provide a comprehensive summary of laboratory tests on cores from 253 wells located in the Gulf Coast to demonstrate a general relationship between a decrease in permeability and porosity with depth. Among their findings is that the sandstone porosity reduction rate remains relatively constant from a depth of a few hundred feet to over 10,000 feet. Table 4.7.5 provides the linear rate at which porosity decreases in the different geological formations in the Texas Gulf Coast that were estimated by Loucks and others (1984). Figure 4.7.10 shows that there is a log-linear relationship between the decrease in porosity and decrease in intrinsic permeability. Intrinsic permeability is plotted instead of hydraulic conductivity because permeability is invariant with the properties of the liquid and hydraulic conductivity is not because the density and viscosity of water will vary with depth, as temperature and dissolved solid concentrations vary.

4.7.7 Conceptual Framework for Aquifer Properties

Based on our review of available literature, little field data is available for interpolation to help establish initial values for the model and to guide the adjustments of the aquifer parameters during model calibration. Because of the lack of field data, our development of initial values for transmissivity, vertical hydraulic conductivity, and storativity are primarily based on the principals and relationships presented in this section.

Transmissivity

The initial transmissivity field was generated based on the following three assumptions:

- Transmissivity can be estimated by multiplying the total amount of sand in a geological unit by the average hydraulic conductivity of the sand in the unit;
- Within a geologic unit, the hydraulic conductivity among different sand bodies will vary and one of the factors that affects this variation is the depositional facies of the sand;
- Hydraulic conductivity decreases as a function of depth.

The net-sand thickness maps used to generate the transmissivity field are based on the 150 lithologic profiles generated by Knox and others (2007). The set of hydraulic conductivity values used to calculate transmissivity are presented in Table 4.7.6. A major assumption in Table 4.7.6 is that fluvial sand bodies have a higher average hydraulic conductivity than do deltaic sand bodies. This assumption is based primarily on the extensive analysis of hydraulic conductivity performed in the Gulf Coast Aquifer by Young and Kelley (2006) and Young and others (2008).

The decrease in hydraulic conductivity with depth is based on the assumption that porosity decreases by approximately 2.2 percent as shown in Table 4.7.5 and the permeability varies as a function of porosity similar to the result in Figure 4.7.10. The combination of these two relationships are combined to produce the results shown in Figure 4.7.11 for sand bodies that have a hydraulic conductivity of 20 feet per day near ground surface.

Figures 4.7.12 thorough 4.7.15 show the initial transmissivity fields generated from the above assumptions. The results show a general decrease in transmissivity down-dip for all geologic units. The highest transmissivity values above 1,000 square feet per day occur in the Upper Yegua Unit across an area that includes Angelina, Trinity, Houston, Madison, Grimes, Brazos, Fayette, Gonzales, and Wilson counties.

Vertical Hydraulic Conductivity

At the very small scale of a few millimeters, the differences between vertical and horizontal hydraulic conductivities may be very small. However, at thicknesses of several hundred feet and greater, the differences between the vertical and horizontal conductivities can be very large because of the large impact that a continuous clay layer can have on vertical flow. Field measurements of vertical hydraulic conductivity are not available at the vertical scale of the thickness of the geologic units that comprise the Yegua-Jackson Aquifer. Because vertical hydraulic conductivity is not measurable at the scale of a typical regional model grid, it is generally a calibrated model parameter.

Our initial values of vertical conductivity are based on the theoretical analysis for determining the effective permeability based on one-dimensional vertical flow through layered media (Freeze and Cherry, 1979). This approach has been used previously to develop groundwater models and several groundwater availability models in Texas (Deeds and others, 2003; Dutton and others, 2003; Young and others, 2008). For one-dimensional flow, the effective hydraulic conductivity is the weighted harmonic mean of the hydraulic conductivity of the different layers. For a two-layer aquifer consisting of a sand layer and a clay layer, the weighted effective hydraulic conductivity is calculated as follows:

$$K_v = B/[(b_s/K_{vs}) + (b_c/K_{vc})] \qquad (4.7.1)$$

where:

K_v	=	effective vertical hydraulic conductivity of deposit;
K_{vs}	=	vertical hydraulic conductivity of sand;
b_s	=	total layer thickness of sand deposits;
K_{vc}	=	horizontal hydraulic conductivity of clay;
b_c	=	total layer thickness of clay deposits; and
B	=	total aquifer thickness.

Our modeling experience has shown that the results generated through application of Equation 4.7.1 are very sensitive to the vertical conductivity of the clay. Our initial application of Equation 4.7.1 is based on the vertical conductivity of 0.0003 feet per day for all clay deposits and 0.02 feet per day for all sand deposits. These values are similar to those used by Young and others (2008) to calibrate a groundwater flow model for the Gulf Coast Aquifer.

Storativity

Storativity is defined as the volume of water that an aquifer releases from storage under a unit decline in hydraulic head (Freeze and Cherry, 1979). For a confined aquifer, the aquifer storativity is equal to the product of specific storage and aquifer thickness. In an unconfined aquifer, the aquifer storativity is equal to the sum of the specific yield and the product of specific storage and aquifer thickness. Specific storage values account for the way changes in the hydraulic pressure change the density of the water and for changes in the arrangement and bulk density of the aquifer matrix. Specific yield values account for the amount of water that drains from the aquifer pores following a drop in the water level.

Our data review did not produce any values of specific yield or storativity for the aquifer. A review of the model calibration results for the regional models for the Gulf Coast aquifers and the Carrizo and Wilcox formations suggests that an approximate value for specific yield is between 0.05 and 0.15. For the initial model simulation, a value of 0.1 was selected for the entire model domain.

As previously discussed in Section 4.7.6, porosity generally decreases as a function of depth. As a result, the value of specific storage should change with depth. Our conceptual model for this relationship is based on the model of Shestakov (2002), who postulated that specific storage, Ss, should vary with depth based on geomechanical considerations as follows:

$$Ss = A / [D + z0] \qquad (4.7.2)$$

In Equation 4.7.2, A and z0 are parameters, and D is depth. Shestakov (2002) showed that A varied in the narrow range between 2×10^{-4} to 10^{-3} per foot for sandy rocks and between 0.003 to 0.03 per foot for clayey rocks. Figure 4.7.16 shows the field data and the model fit from Shestakov (2002). Recently, Young and others (2008) have used a modified version of Equation 4.7.2 to calibrate a regional model of the Gulf Coast Aquifer.

Table 4.7.1 Average sand and clay fractions for the model layers based on the lithology profiles.

Geology Unit	Major Facies Grouping	Number of Lithology Profiles	Fraction Clay	Fraction Sand
Upper Jackson	Fluvial	3	NR	NR
	Delta	72	0.88	0.12
	Shelf	13	1.00	0.00
Lower Jackson	Fluvial	16	0.92	0.08
	Delta	64	0.85	0.15
	Shelf	18	0.98	0.02
Upper Yegua	Fluvial	36	0.72	0.28
	Delta	86	0.78	0.22
	Shelf	1	NR	NR
Lower Yegua	Fluvial	34	0.71	0.29
	Delta	94	0.77	0.23
	Shelf	1	NR	NR

NR - Not Reported

Table 4.7.2 Summary of the Texas Commission on Environmental Quality pumping tests.

Well ID	GAM Coordinates		Screen Information			Geologic Unit	Pumping Test Information				Analysis		
	Easting	Northing	Depth to Top of Screen (ft)	Depth to Bottom of Screen (ft)	Length (ft)		Pumping Rate (gpm)	Total Length of Pumping Test (hr)	Length of Time Period Analyzed (hr)	Data Points	R-Squared	Transmissivity (ft^2/day)	Hydraulic Conductivity (ft/day)
G0030001A	6547997.35	19691213.63	490	601	111	UY	348	3	1	5	0.88	747	6.7
G0030001B	6553538.36	19702945.01	440	520	80	UY	314	11	2	5	0.96	1825	22.8
G0030001C	6555735.06	19704267.83	308	368	60	LJUY	197	281	3	34	0.99	326	5.4
G0030001D	6559098.16	19706719.51	304	406	102	UY	55	3	3	11	0.94	292	2.9
G0030001F	6553475.93	19705976.9	807	953	146	LY	199	36	2	14	0.98	344	2.4
G0030002B	6613378.54	19733723.08	495	690	195	LY	201	46	16	17	0.99	249	1.3
G0030002C	6583025.92	19739713.43	652	726	74	LY	154	26	3	5	0.98	186	2.5
G0030002D	6584854.14	19738783.93	490	580	90	LY	373	29	8	8	0.99	495	5.5
G0030004M	6551771.17	19714512.88	820	875	55	LY	157	23	3	4	0.96	570	10.4
G0030020E	6594356.53	19739185.5	548	608	60	LY	250	36	8	10	0.98	411	6.8
G0260005C	5971412.9	19369652.28	250	320	70	LY	96	24	8	12	0.98	336	4.8
G0260005D	5973576.91	19370567.39	280	349	69	UY	99	24	8	13	0.96	323	4.7
G0260005E	5974512.44	19371576.2	258	346	88	UYLY	99	24	8	13	1.00	339	3.9
G0260012A	6010593.67	19401583.64	650	780	130	LY	75	18	1	11	0.99	98	0.8
G0260033E	5984773.3	19361030.46	556	636	80	UY	150	39	39	36	0.82	1568	19.6
G0750002J	5848979.17	19125195.35	325	380	55	UJ	280	36	36	96	0.96	857	15.6
G0750004I	5901793.31	19125736.07	942	1094	152	UJ	490	24	4	5	1.00	622	4.1
G0750007B	5972884.61	19292958.86	676	758	82	UJ	269	49	1	6	0.88	281	3.4
G0750009B	5904816.8	19204891.82	230	376	146	UJ	400	36	1	14	0.99	560	3.8
G0750017A	5933675.42	19299368.11	306	321	15	UY	92	2	2	3	0.80	149	10.0
G0750017B	5933297.64	19301754.08	210	420	210	UY	96	36	36	98	0.96	276	1.3
G0750017C	5933560.65	19302448.29	280	360	80	LJUY	53	12	0	5	0.93	162	2.0
G0930012E	6191070.07	19535767.76	450	490	40	UY	114	36	36	49	0.91	797	19.9
G1130003C	6345601.9	19670390.89	263	330	67	LY	250	3	3	24	0.99	899	13.4
G1430002C	5825946.94	19084309.77	180	325	145	UJ	209	8	3	7	0.99	393	2.7
G2020002C	6800214.07	19738234.05	492	585	93	UYLY	505	36	8	14	0.97	1828	19.7
G2020070C	6875449.39	19709035.61	443	530	87	UJ	312	36	0	9	0.99	167	1.9

Table 4.7.2, continued

Well ID	GAM Coordinates		Screen Information			Geologic Unit	Pumping Test Information				Analysis		
	Easting	Northing	Depth to Top of Screen (ft)	Depth to Bottom of Screen (ft)	Length (ft)		Pumping Rate (gpm)	Total Length of Pumping Test (hr)	Length of Time Period Analyzed (hr)	Data Points	R-Squared	Transmissivity (ft^2/day)	Hydraulic Conductivity (ft/day)
G2280002C	6361887.39	19589340.5	225	440	215	UJ	245	18	8	9	0.92	278	1.3
G2280002D	6363720.07	19589775.58	254	346	92	UJ	252	36	3	23	0.97	330	3.6
G2280002E	6361888.26	19589340.54	270	365	95	UJ	252	36	5	22	0.93	230	2.4
G2280005B	6468700.55	19696300.64	690	764	74	UJ	120	24	5	6	0.94	879	11.9
G2280006B	6467425.87	19723128.3	341	381	40	UY	35	24	17	18	0.97	438	11.0
G2280006C	6463162.25	19722352.02	380	422	42	UY	50	24	12	13	0.98	103	2.5
G2280007A	6400187.57	19602682.52	268	328	60	UJ	65	7	7	8	0.95	365	6.1
G2280009B	6376243.92	19673348.42	609	845	236	LY	315	23	8	9	0.98	1135	4.8
G2280009D	6407807.16	19695541.06	305	362	57	UY	248	36	13	14	0.99	417	7.3
G2280009E	6374268.79	19673457.8	537	597	60	LY	201	36	36	37	0.98	642	10.7
G2280036B	6530573.15	19668712.78	575	636	61	LJ	90	36	36	53	0.93	736	12.1
G2360010C	6359403.98	19568839.2	620	650	30	UJ	132	20	5	21	0.97	292	9.7
G2390002D	5994973.97	19312639.82	850	900	50	UJ	189	23	2	3	0.98	779	15.6
G2390043F	6042002.05	19352439.94	890	960	70	UJ	150	30	8	39	0.94	732	10.5

Note: UJ = Upper Jackson Unit; LJ = Lower Jackson Unit; UY = Upper Yegua Unit; LY = Lower Yegua Unit; LJUY = both UY and LY.

ft = feet gpm = gallons per minute hr = hours ft^2/day = square feet per day ft/day = feet per day

GAM = groundwater availability model

Table 4.7.3 Summary of the pumping tests for each geologic unit.

Geologic Unit	Number of Tests	Average Depth of Test (feet)	Hydraulic Conductivity (feet per day)				
			Arithmetic Mean	Geometric Mean	Standard Deviation	Minimum Value	Maximum Value
Upper Jackson	14	539	6.6	5.0	5.0	1.3	15.6
Lower Jackson	1	605	12	12	NA	12	12
Upper Yegua	11	408	9.9	7.0	5.0	1.3	22.8
Lower Yegua	11	610	5.8	4.2	7.6	0.8	13.4

Table 4.7.4 Hydraulic conductivity of sand as a function of bed thickness (after Payne, 1970).

Sand Thickness (feet)	Hydraulic Conductivity (feet per day)
15 to 25	11
25 to 50	17
50 to 75	31
75 to 100	36 to 50
100 to 150	53 to 66

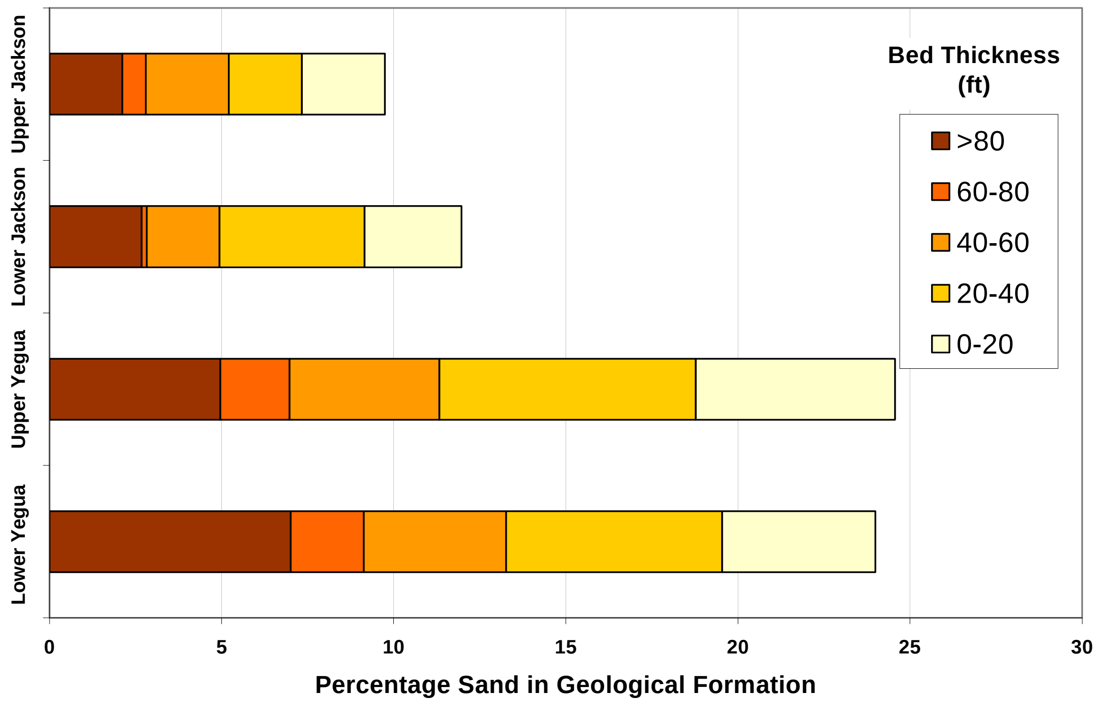
Table 4.7.5 Porosity loss per 1,000 feet of depth of burial for geological formations in the Texas Gulf Coast (from Loucks and others, 1984).

Geological Formations		Porosity Loss per 1,000 feet of depth of burial
Miocene		1.34
Frio	Areas 1-6	1.28
	Areas 1-3	1.48
	Areas 4-6	2.05
Vicksburg		1.32
Jackson/Yegua		2.28
Queen City		1.86
Wilcox		1.51

Table 4.7.6 Set of hydraulic conductivity values for generating an initial transmissivity field.

Geology Unit	Major Facies Groupings	Hydraulic Conductivity (feet per day)	
		Sand	Clay
Upper Jackson	Fluvial	15	0.01 * K sand
	Delta	8	0.01 * K sand
	Shelf	5	0.01 * K sand
Lower Jackson	Fluvial	15	0.01 * K sand
	Delta	8	0.01 * K sand
	Shelf	5	0.01 * K sand
Upper Yegua	Fluvial	20	0.01 * K sand
	Delta	15	0.01 * K sand
	Shelf	5	0.01 * K sand
Lower Yegua	Fluvial	20	0.01 * K sand
	Delta	15	0.01 * K sand
	Shelf	5	0.01 * K sand

K = hydraulic conductivity



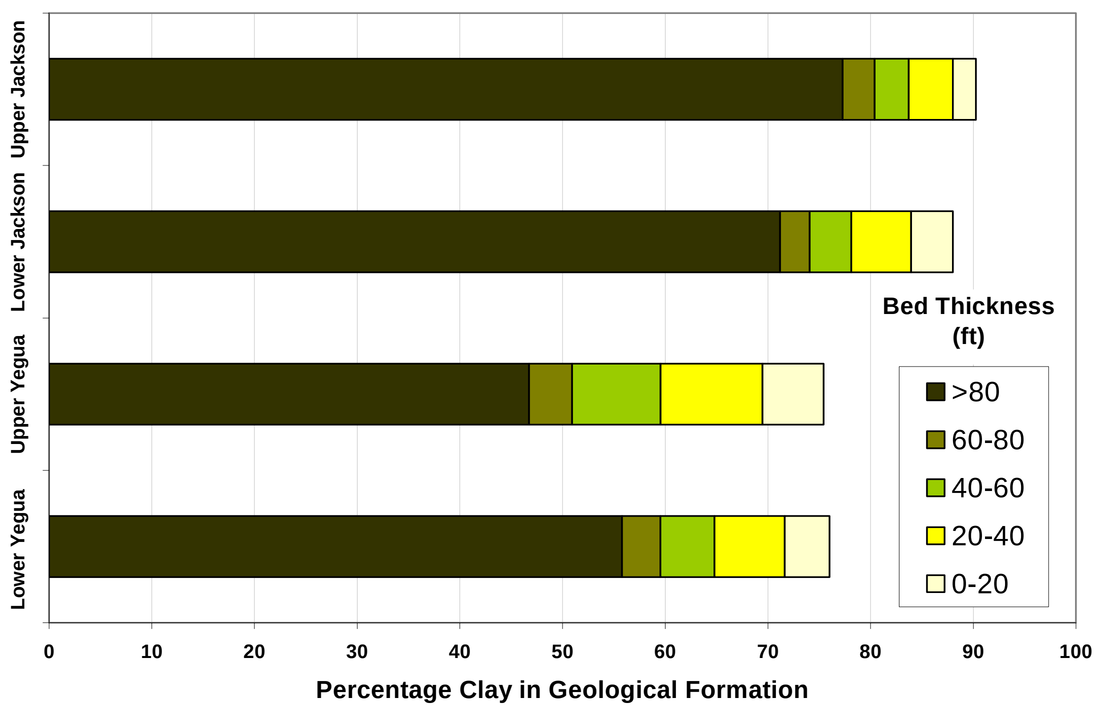


Figure 4.7.1 Thickness in feet of sand and clay beds for the four geologic units that comprise the Yegua-Jackson Aquifer.

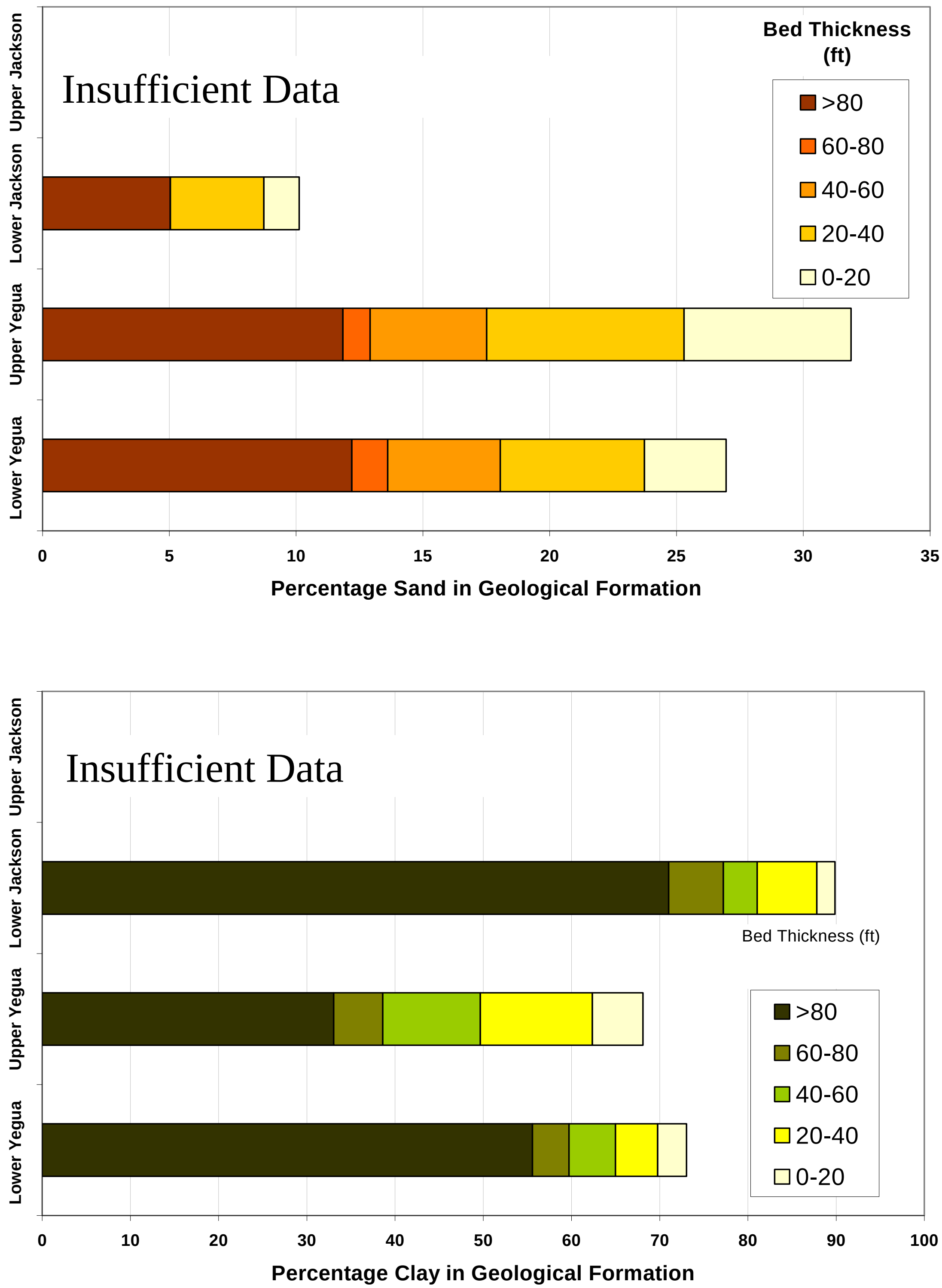


Figure 4.7.2 Thickness in feet of sand and clay beds associated with the fluvial facies of the four geologic units that comprise the Yegua-Jackson Aquifer.

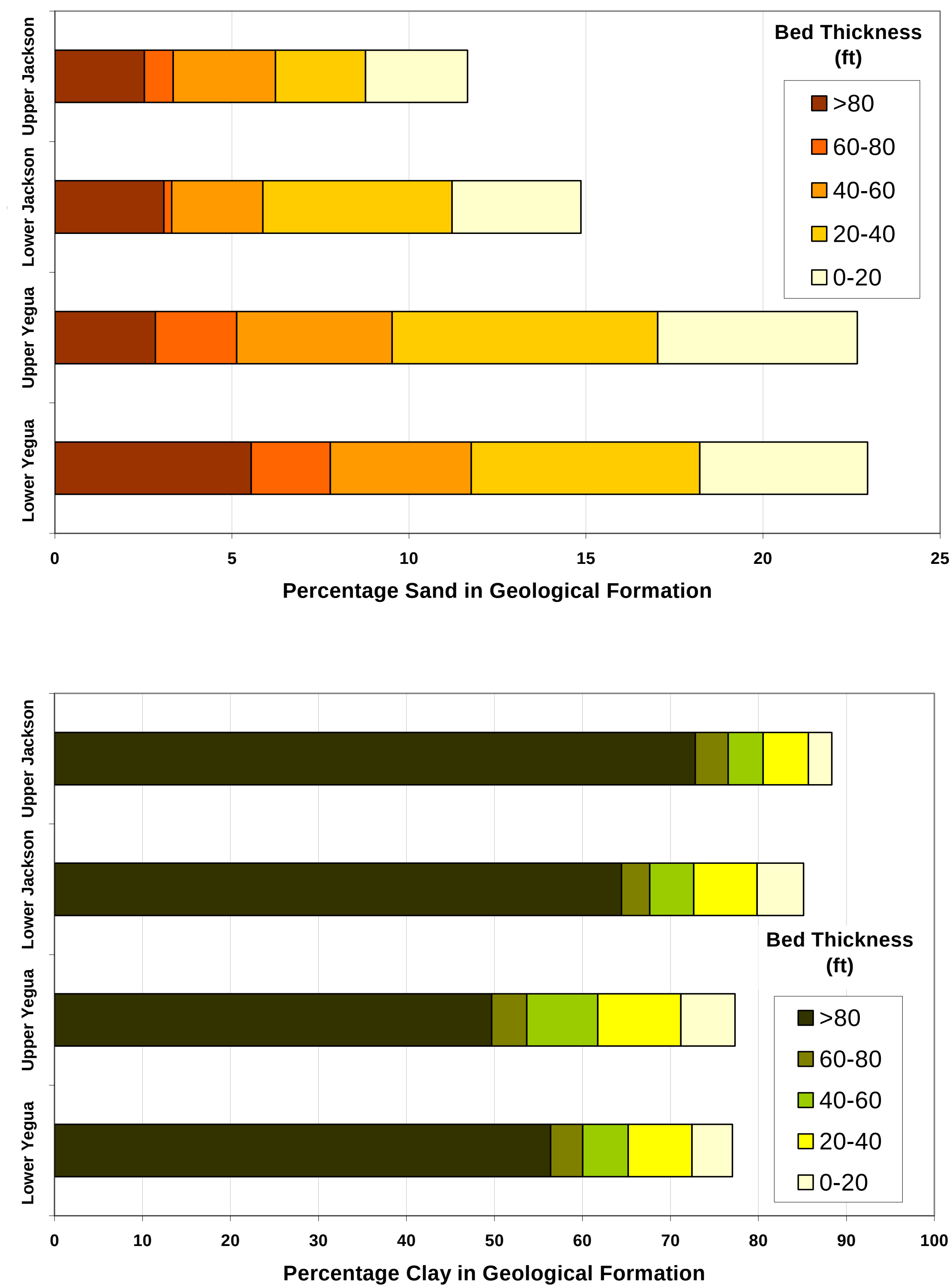
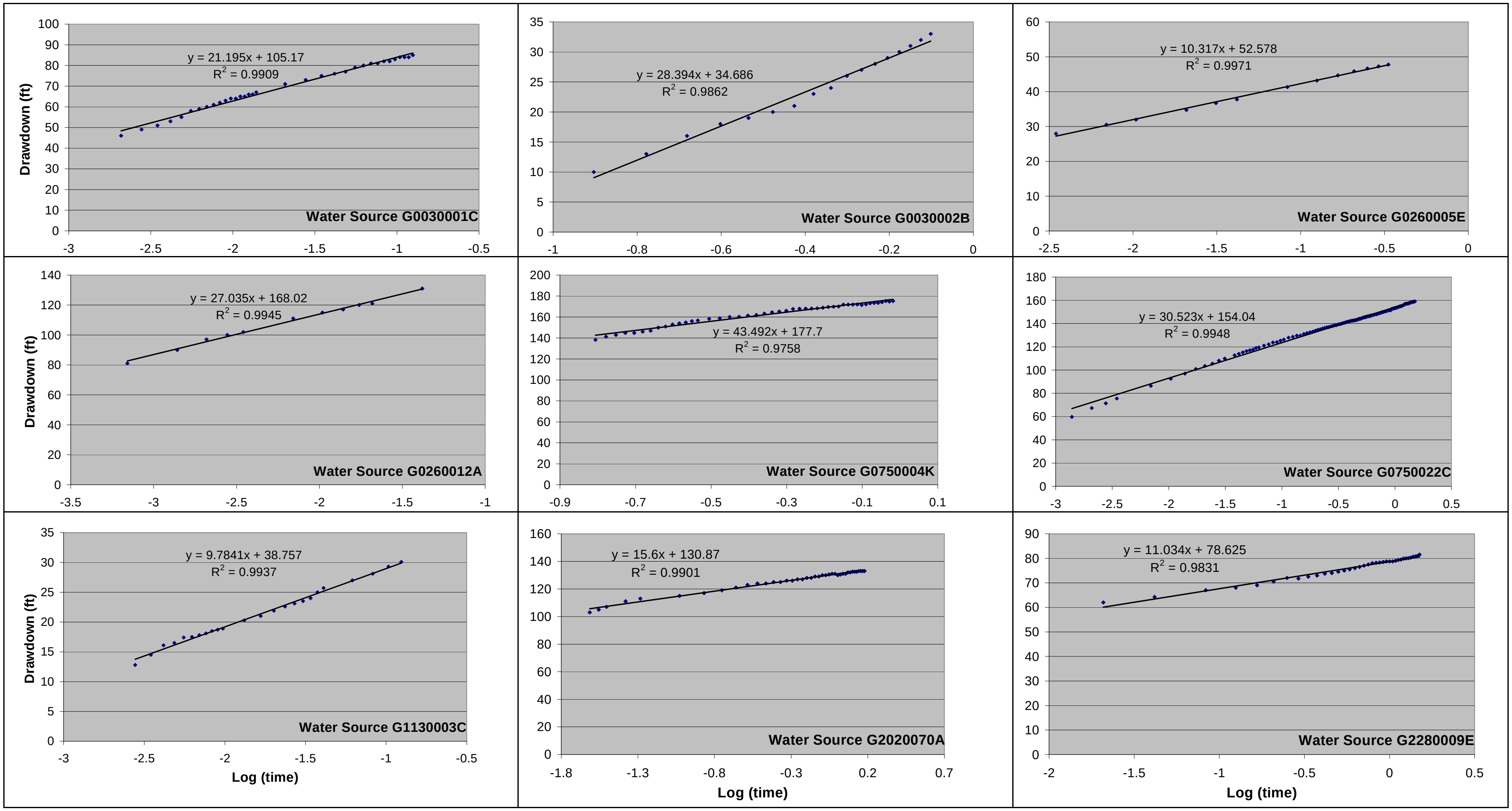


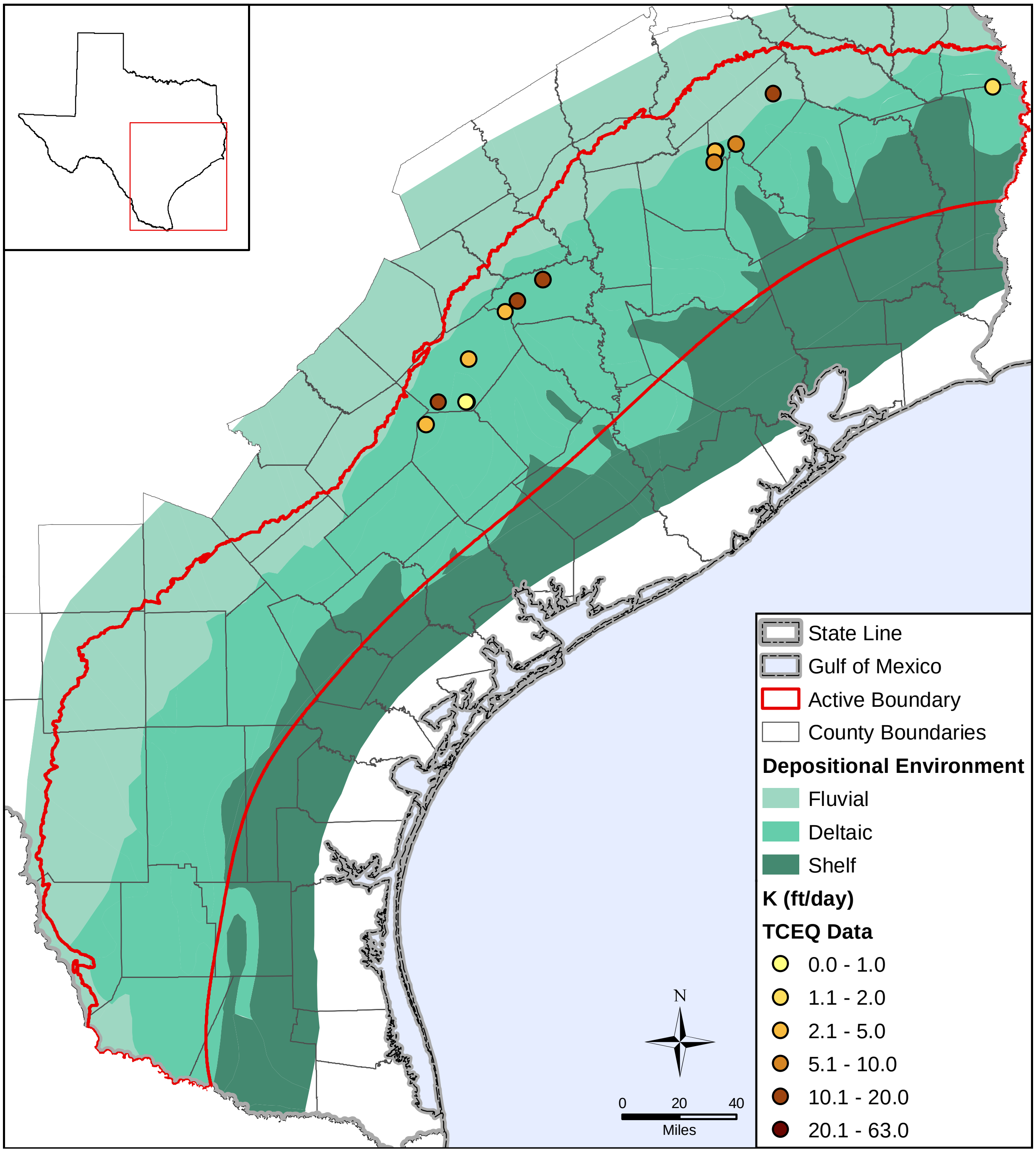
Figure 4.7.3 **Thickness in feet of sand and clay beds associated with the deltaic facies of the four geologic units that comprise the Yegua-Jackson Aquifer.**



ft = feet

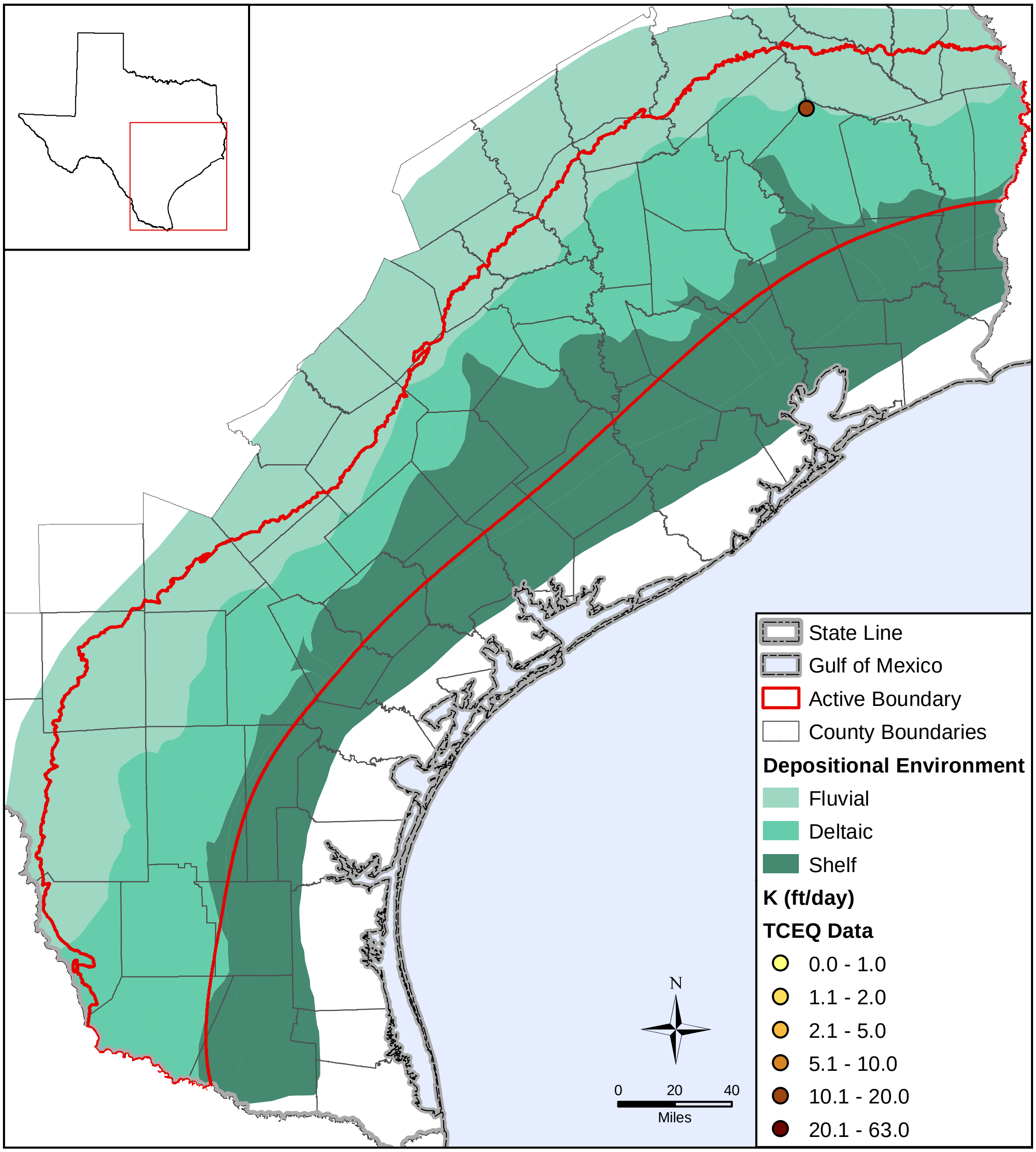
R^2 = coefficient of determination

Figure 4.7.4 Examples of applying the Cooper-Jacob straight-line method to pumping test data collected at the Texas Commission on Environmental Quality Division of Public Water Supply.



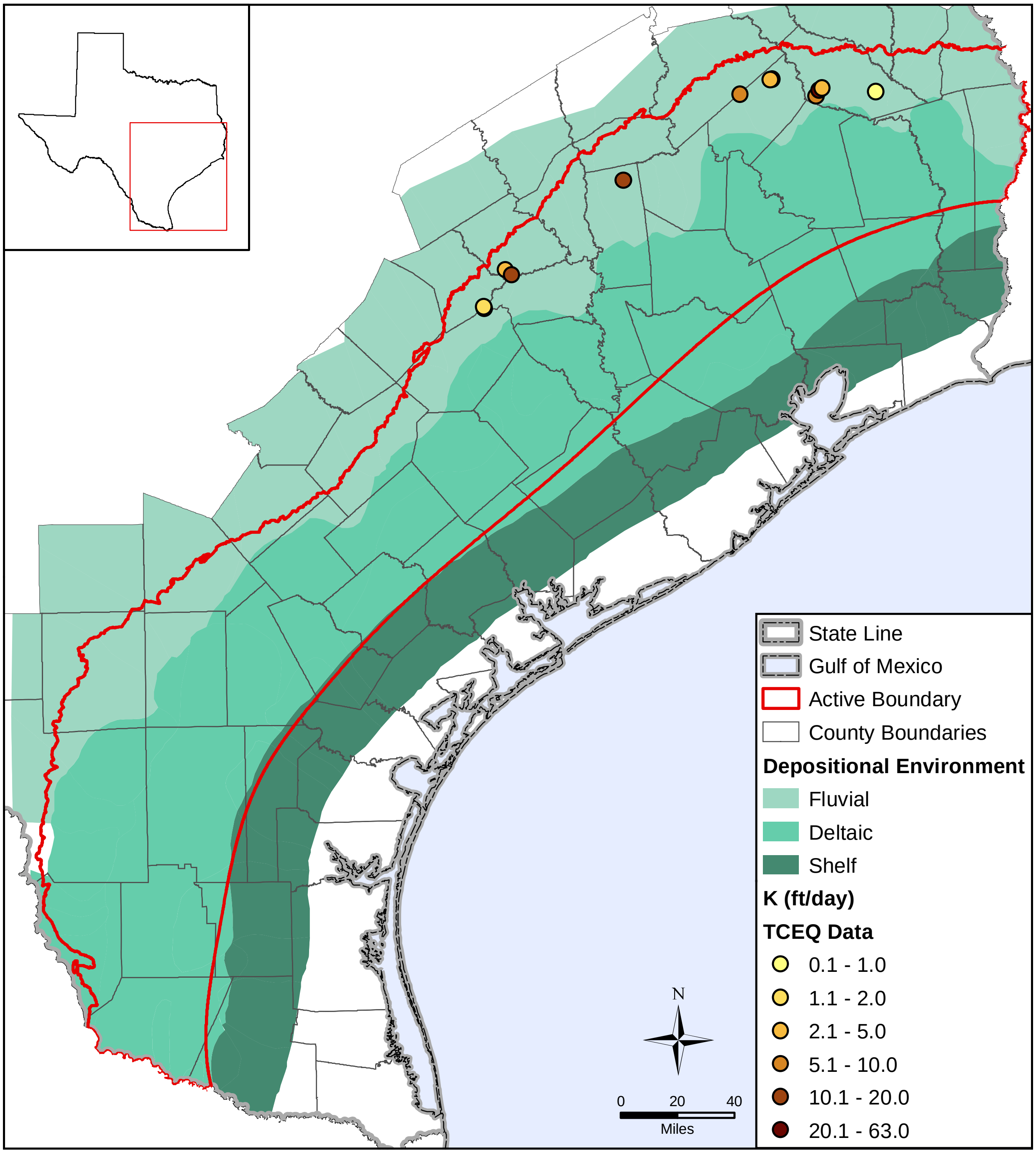
K = hydraulic conductivity
TCEQ = Texas Commission on Environmental Quality

Figure 4.7.5 Location of the depositional environments and hydraulic conductivity measurements in feet per day for the Upper Jackson Unit.



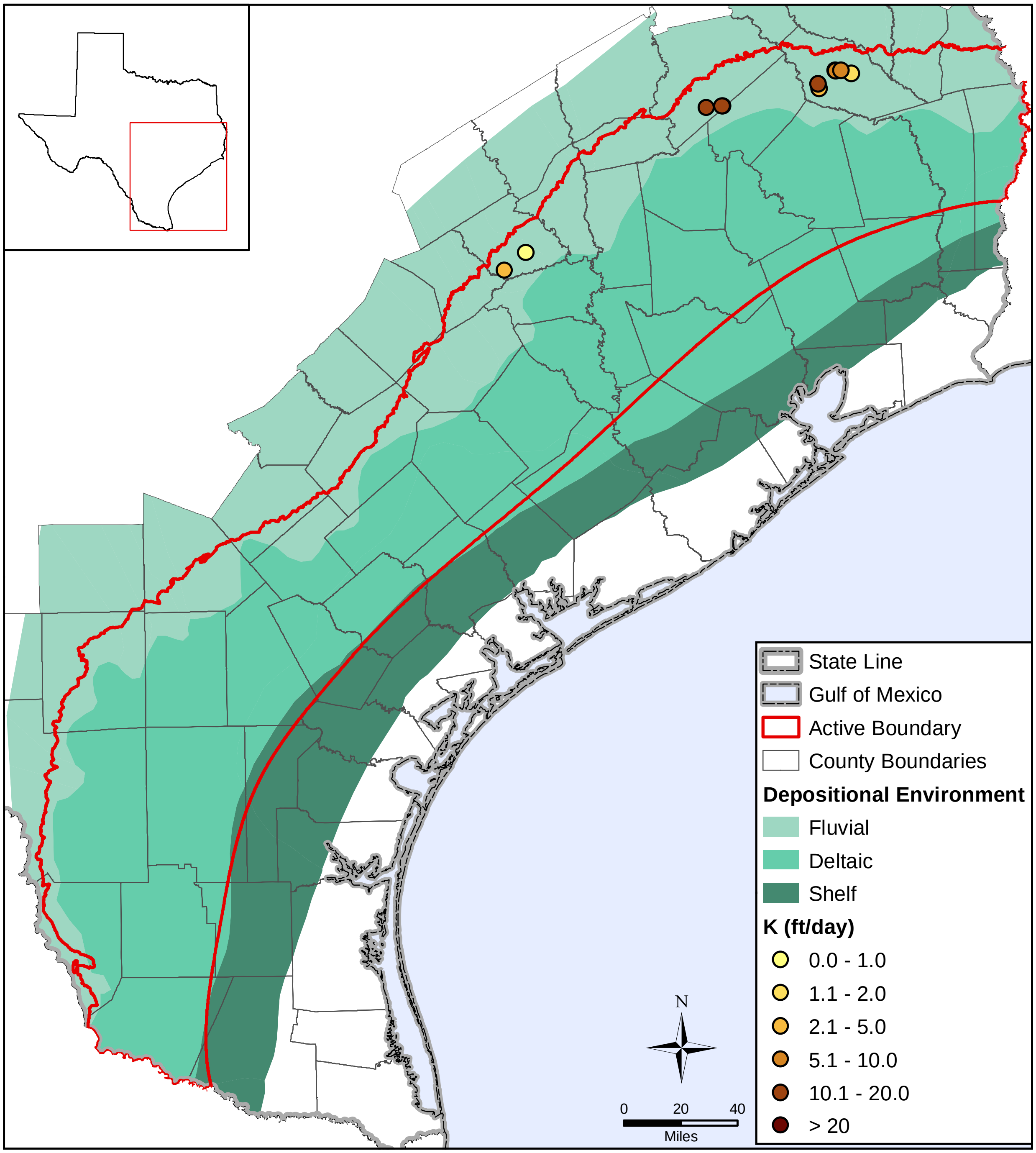
K = hydraulic conductivity
TCEQ = Texas Commission on Environmental Quality

Figure 4.7.6 Location of the depositional environments and hydraulic conductivity measurements in feet per day for the Lower Jackson Unit.



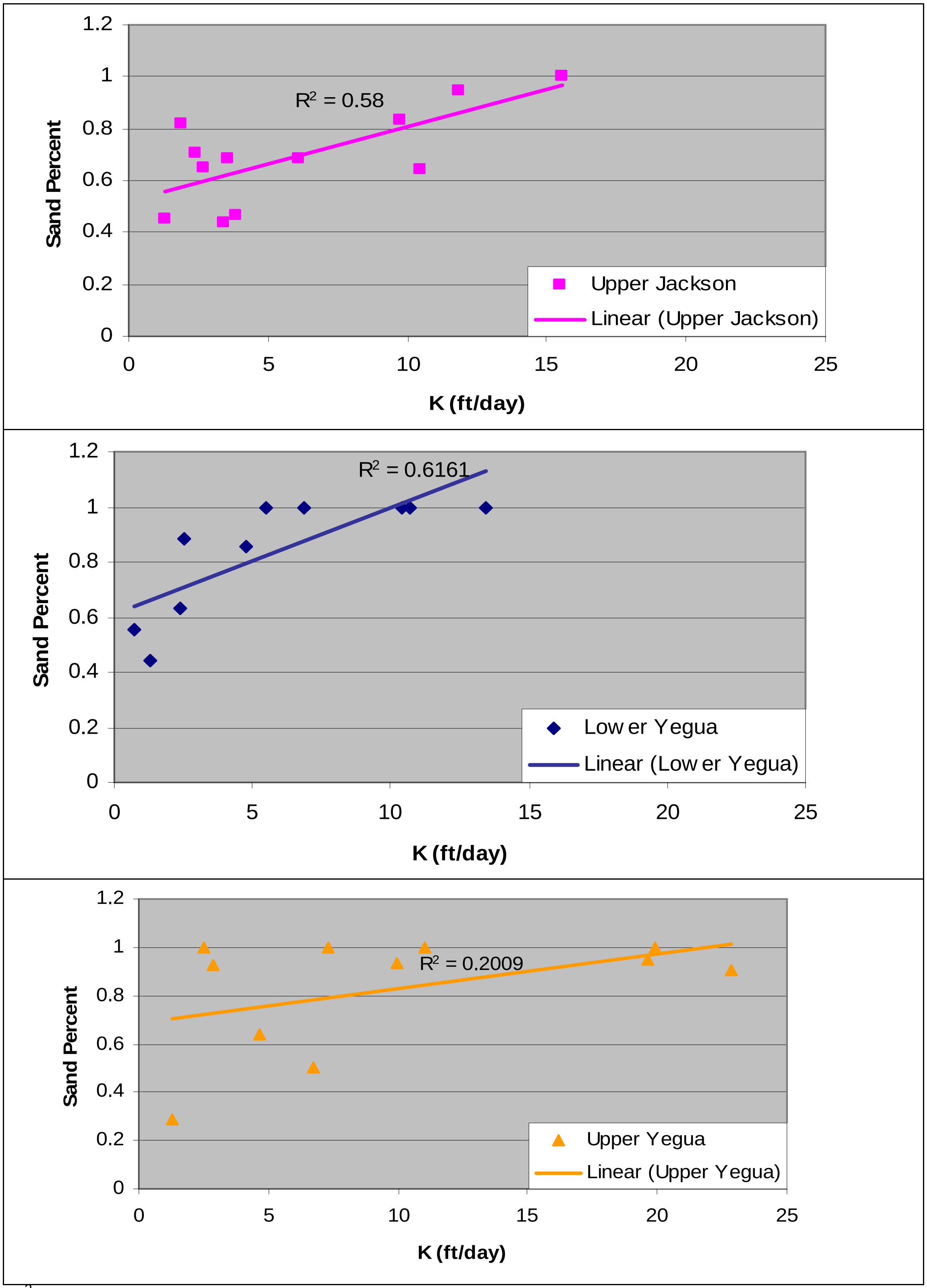
K = hydraulic conductivity
TCEQ = Texas Commission on Environmental Quality

Figure 4.7.7 Location of the depositional environments and hydraulic conductivity measurements in feet per day for the Upper Yegua Unit.



K = hydraulic conductivity
TCEQ = Texas Commission on Environmental Quality

Figure 4.7.8 Location of the depositional environments and hydraulic conductivity measurements in feet per day for the Lower Yegua Unit.



R^2 = coefficient of determination

Figure 4.7.9 Hydraulic conductivity values in feet per day versus sand percentage calculated for the well screened interval based on lithology contained in the driller's log.

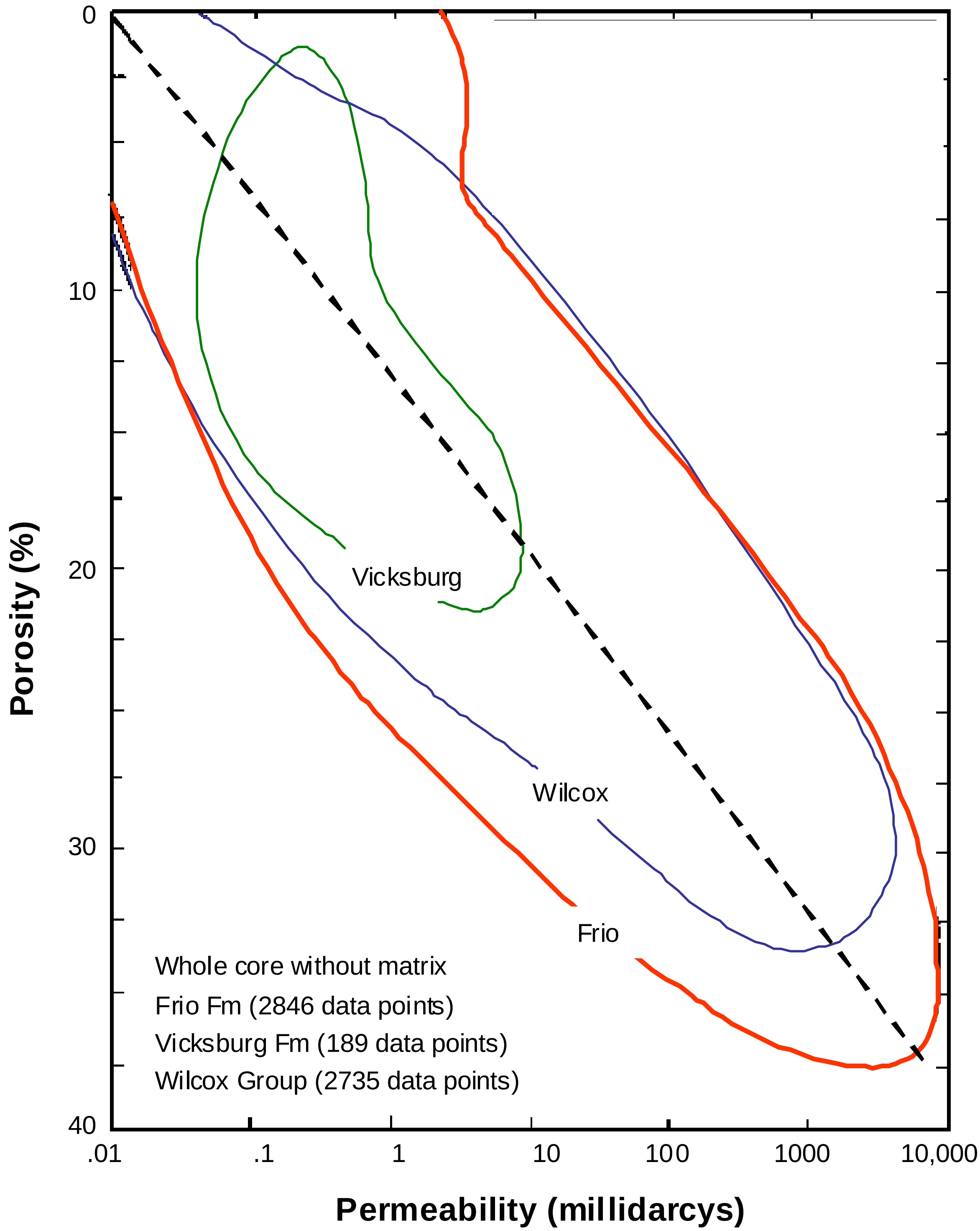


Figure 4.7.10 Measured relationship between porosity in percent and permeability in laboratory cores for geological formations in Texas (modified from Loucks and others, 1984).

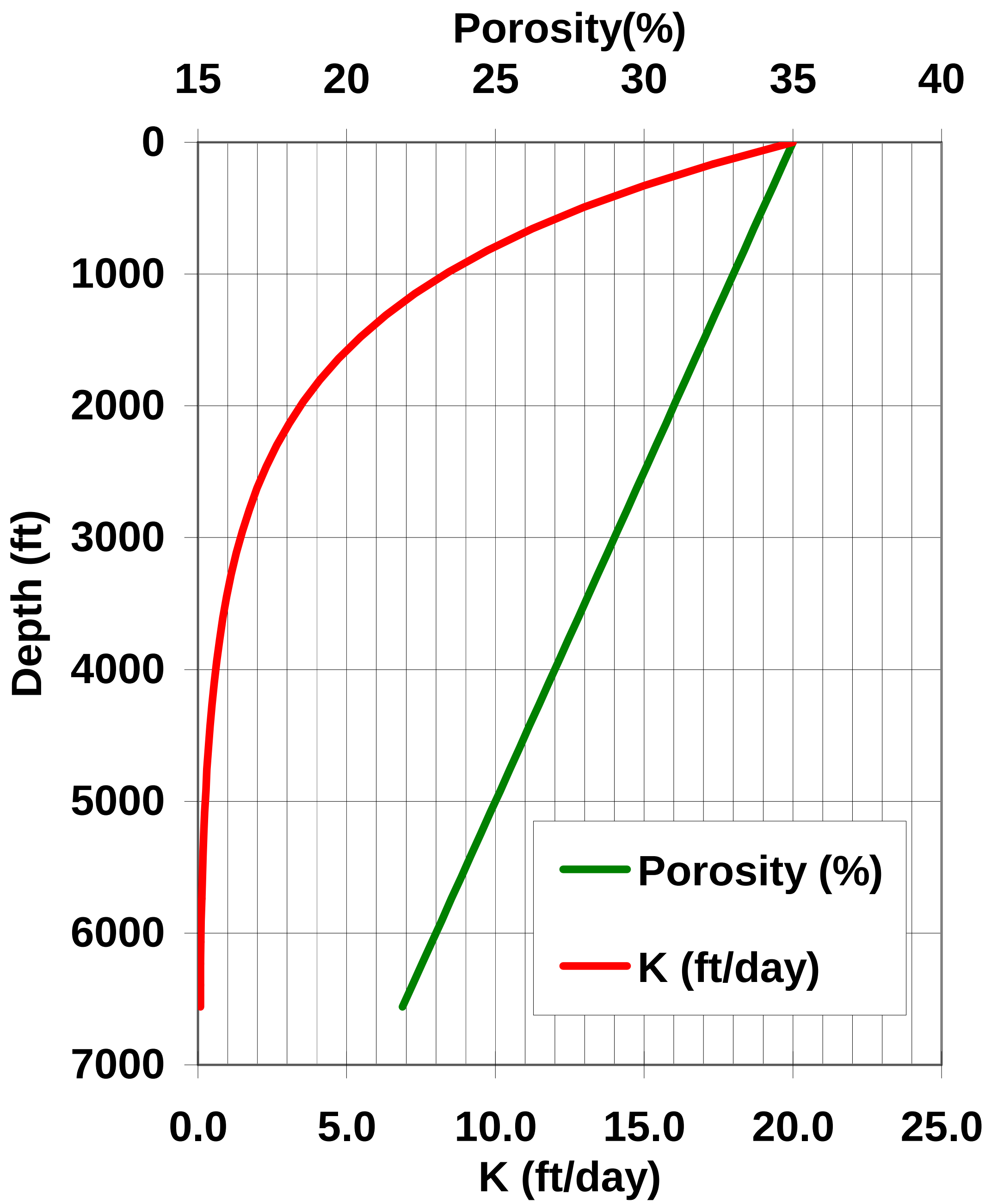


Figure 4.7.11 Proposed relationship of hydraulic conductivity in feet per day and porosity in percent with depth in feet used to develop an initial transmissivity field for model calibration.

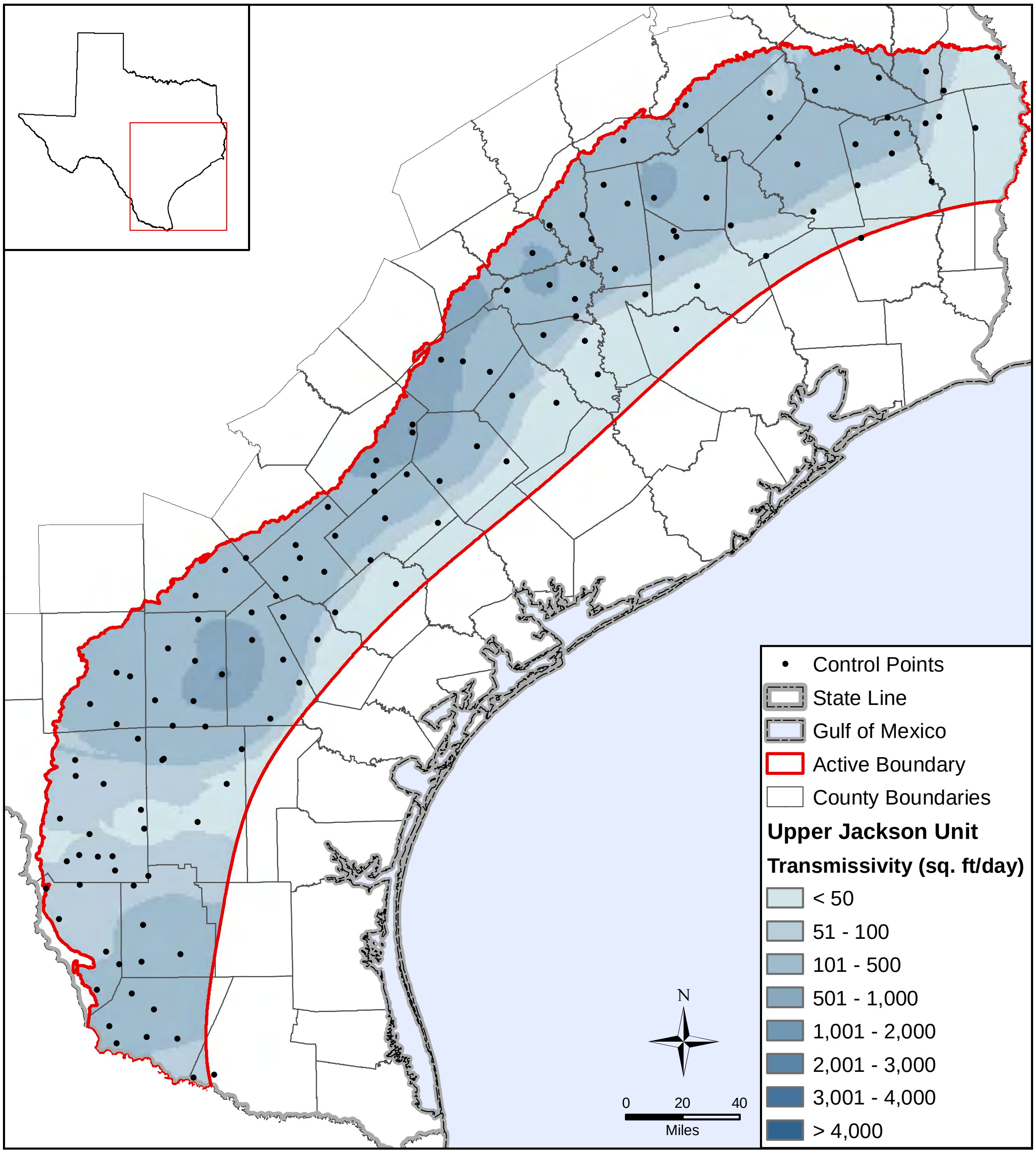


Figure 4.7.12 Initial estimate of the transmissivity field in square feet per day in the Upper Jackson Unit based on the conceptual model.

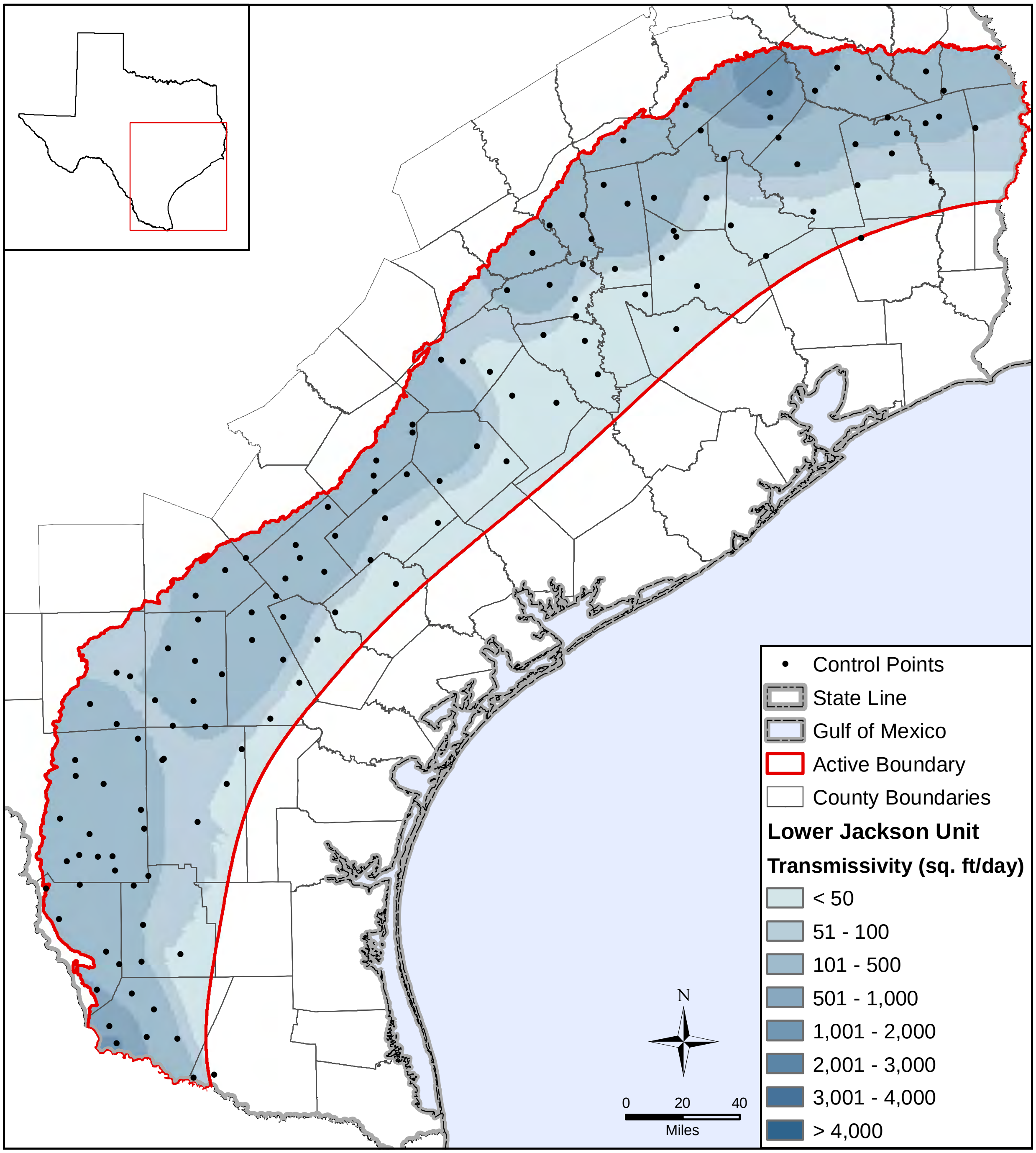


Figure 4.7.13 Initial estimate of the transmissivity field in square feet per day in the Lower Jackson Unit based on the conceptual model.

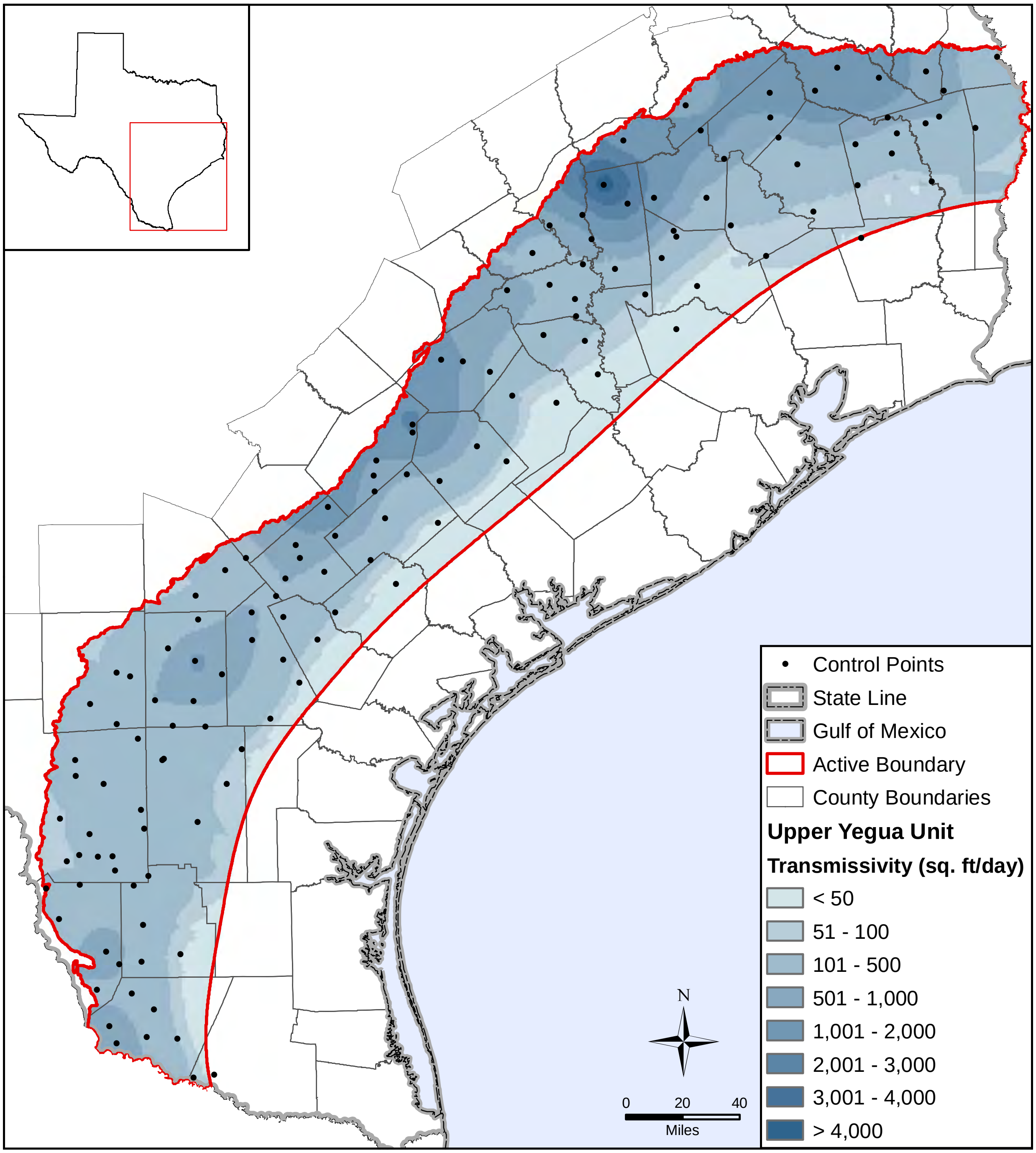


Figure 4.7.14 Initial estimate of the transmissivity field in square feet per day in the Upper Yegua Unit based on the conceptual model.

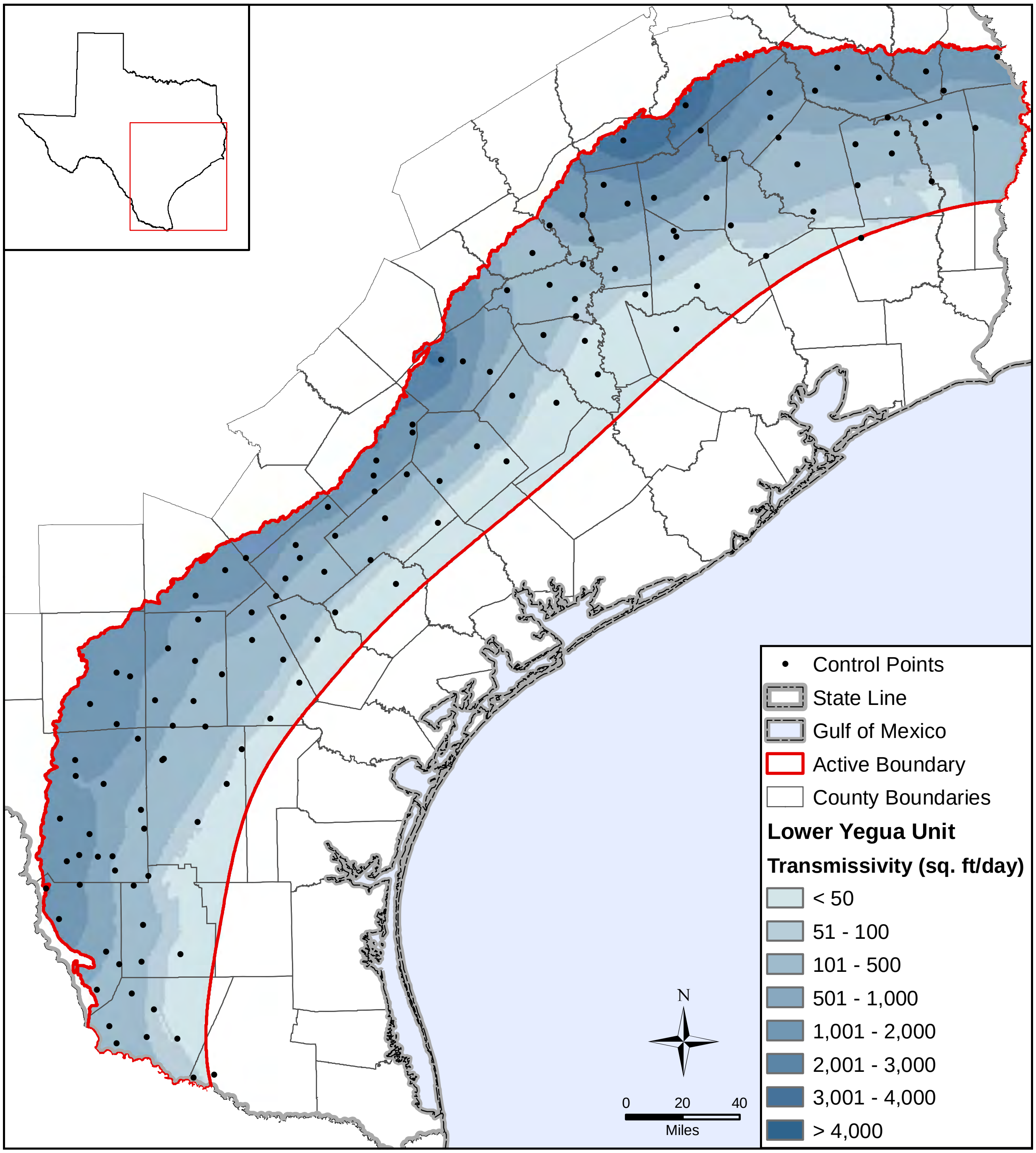


Figure 4.7.15 Initial estimate of the transmissivity field in square feet per day in the Lower Yegua Unit based on the conceptual model.

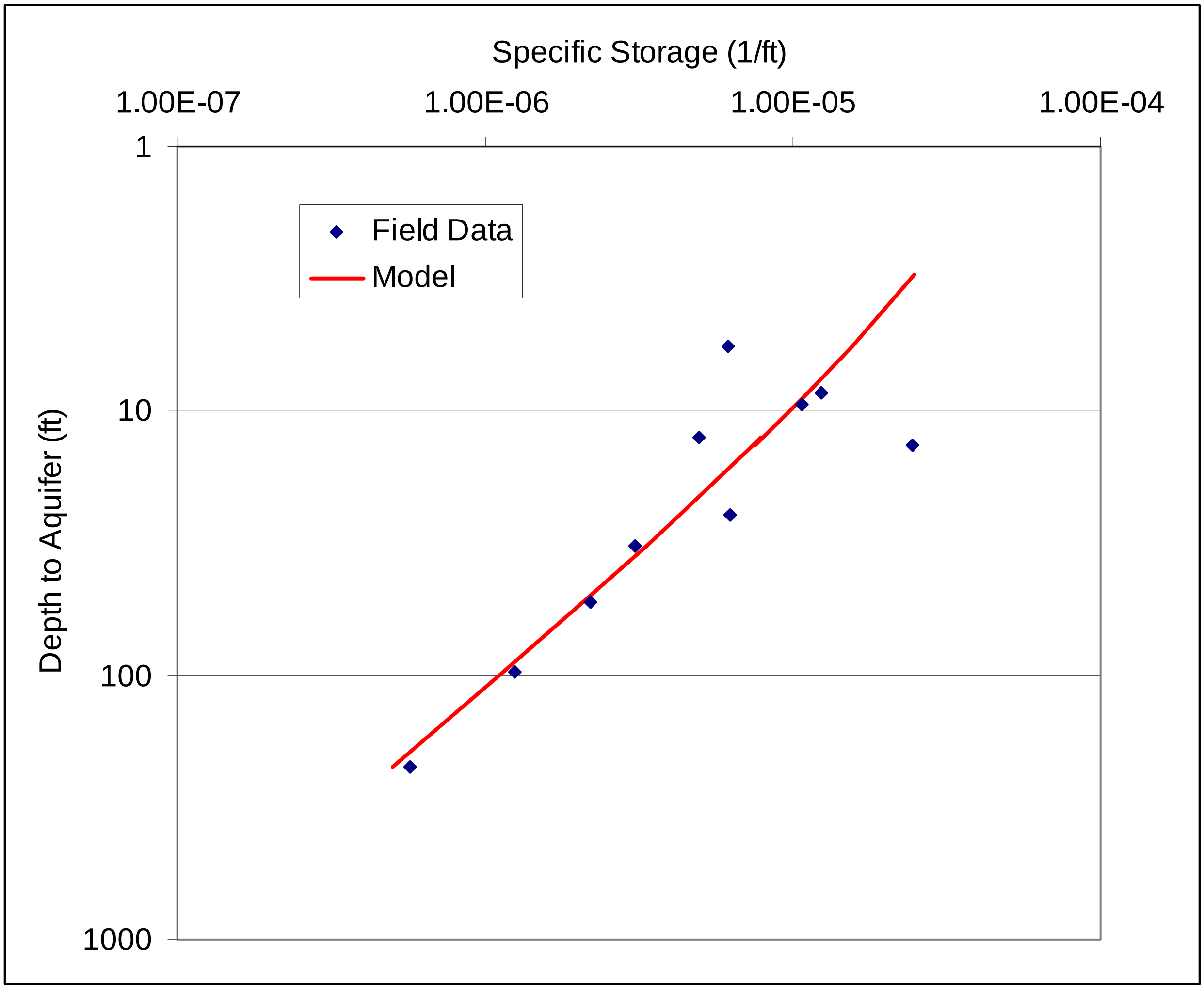


Figure 4.7.16 Field values of specific storage in inverse feet versus depth in feet and the results of the theoretical relationship developed by Shestakov (2002) (modified from Shestakov, 2002).

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4.8 Water Quality

Groundwater quality in the Yegua-Jackson Aquifer is mixed, ranging from good to poor over relatively short distances and depths. The majority of fresh water occurs in or near the outcrop region. In general, concentrations of total dissolved solids increase rapidly moving downdip into the confined portion of the aquifer. Water is typically of higher quality in the central and northeast portions of the aquifer than in regions to the southwest.

The only comprehensive study of water quality in any of the formations that comprise the Yegua-Jackson Aquifer was performed by Pettijohn and others (1988). The study analyzed the temperature and dissolved solids concentrations in the Gulf Coast Aquifer systems, including the Upper Claiborne Aquifer, which is predominantly the Yegua Formation in Texas. A map of total dissolved solids from the study is shown in Figure 4.8.1. This figure shows the increase in total dissolved solids in the confined portion of the aquifer, and the general trend of increasing total dissolved solids in the southwest region.

In the current analysis, groundwater in the Yegua-Jackson Aquifer was evaluated for its quality as a drinking water supply and for irrigation of crops, by comparing the measured chemical and physical properties of the water to screening levels. Water quality measurements were retrieved for the entire available historical record, from 1908 through 2005, from the TWDB groundwater database. Because of the lack of good vertical discrimination in water quality measurements, the upper and lower units of the Yegua Formation were combined for analysis, and the upper and lower units of the Jackson Group were combined for analysis.

4.8.1 Data Sources and Methods of Analysis

Analyses of groundwater samples from 558 and 385 wells were available in the database for the Yegua Formation and Jackson Group, respectively. Among the 849 measurements for Yegua Formation and 536 measurements for Jackson Group, 9 and 8, respectively, were marked as “Sample collected from tank, distribution, or bailed from well. Not indicative of aquifer quality. Data should be used carefully” (Reliability code 01 in TWDB groundwater database). These measurements were considered unreliable and were not used in the water quality analysis.

For the purpose of statistical evaluation and mapping, the most recent sampling event for a given parameter was chosen from each well. The most recent data were used in order to assess the most current status of the quality of groundwater in the Yegua-Jackson Aquifer.

4.8.2 Drinking Water Quality

Screening levels for drinking water supply are based on the maximum contaminant levels established in the Texas Administrative Code (Title 30 Chapter 290). Primary maximum contaminant levels are legally enforceable standards that apply to public water supplies to protect human health from contaminants in drinking water. Secondary maximum contaminant levels are non-enforceable guidelines for drinking water contaminants that may cause aesthetic effects (taste, color, odor, foaming), cosmetic effects (skin or tooth discoloration), and technical effects (corrosivity, expensive water treatment, plumbing fixture staining, scaling, and sediment).

Tables 4.8.1 and 4.8.2 summarize the occurrence and levels of some commonly measured groundwater quality constituents in the Yegua Formation and Jackson Group, respectively. The percentage of samples exceeding the primary or secondary maximum contaminant level is greater than 10 percent in both intervals for pH, chloride, sulfate, total dissolved solids, salinity hazard (specific conductance), and sodium hazard (sodium absorption ratio).

Total dissolved solids is a measure of water salinity, the sum of concentrations of all dissolved ions (such as sodium, calcium, magnesium, potassium, chloride, sulfate, carbonates) plus silica. Some dissolved solids, such as calcium, give water a pleasant taste, but most make water taste salty, bitter, or metallic. Dissolved solids can also increase the corrosiveness of water. Total dissolved solids levels have exceeded the Texas secondary maximum contaminant level in approximately 42 percent of the wells in the Yegua Formation and 46 percent of the wells in the Jackson Group. Figure 4.8.2 shows the total dissolved solids measurements and the interpolated total dissolved solids surface for the combined Yegua-Jackson Aquifer. Similar to Figure 4.8.1, total dissolved solids concentration increases towards the regions in the southwest. The degradation of water quality in deeper sediments is not evident in Figure 4.8.2 because measurements were not available at those depths.

Few long-term measurements of total dissolved solids at particular wells were available. Figure 4.8.3 shows time series for five wells with measurements that span the previous 30 to 40 years. In four of the five series, no real trend is evident, just small oscillations around a flat trend. For well 8616705 in Zapata County, the trend appears to be increasing total dissolved solids, from below 1,300 milligrams per liter in 1960 to over 1,700 milligrams per liter in 2002.

Tables 4.8.1 and 4.8.2 show that concentrations of sulfate, a major component of total dissolved solids, have exceeded secondary maximum contaminant levels in 28 and 34 percent of wells in the Yegua Formation and Jackson Group, respectively. Concentrations of chloride, another major component of total dissolved solids, have exceeded the secondary maximum contaminant level of 300 milligrams per liter in 28 and 40 percent of Yegua Formation and Jackson Group wells, respectively. The locations and concentration ranges for chloride are shown in Figures 4.8.4 and 4.8.5 for the Jackson Group and Yegua Formation, respectively. These figures show that, for the Yegua-Jackson Aquifer, the chloride concentration varies over short distances in an unpredictable fashion. From the few available wells in LaSalle and McMullen counties, chloride concentrations appear to consistently exceed 1,000 milligrams per liter.

High concentrations of nitrate nitrogen can cause serious illness in infants younger than 6 months old. Approximately 2.7 percent and 7.7 percent of wells in the Yegua Formation and Jackson Group, respectively, exceed the primary maximum contaminant level of 10 milligrams per liter as nitrogen. The locations and concentration ranges for nitrate is shown in Figures 4.8.6 and 4.8.7. In the Jackson Group, the locations where nitrate concentrations exceed 10 milligrams per liter appear to cluster in Fayette, Washington, Grimes and Sabine counties. In the Yegua Formation, Fayette, Grimes, Angelina, San Augustine, and Sabine counties show the highest clustering of concentrations exceeding 10 milligrams per liter.

pH is an indicator for acidity or alkalinity. In the Yegua Formation and Jackson Group, the pH values of 12 and 30 percent of wells, respectively, are lower (exceeding for acidity) than the secondary maximum contaminant level of 7.

Fluoride is a naturally-occurring element found in most rocks. At very low concentrations, fluoride is a beneficial nutrient. At a concentration of 1 milligrams per liter, fluoride helps to prevent dental cavities. However, at concentrations above the secondary maximum contaminant level of 2 milligrams per liter, fluoride can stain children's teeth. Approximately 3.3 percent of wells in the Yegua Formation have exceeded this level. At concentrations above the primary maximum contaminant level of 4 milligrams per liter, fluoride can cause a type of bone disease. About 0.5 percent of the wells in the Yegua Formation have fluoride concentrations that exceeded 4 milligrams per liter. None of the wells in the Jackson Group exceeded either the primary or secondary maximum contaminant level for fluoride. Figures 4.8.8 and 4.8.9 show the locations and concentration ranges for fluoride.

In summary, water from the Yegua-Jackson Aquifer is suitable for drinking in many areas, but will be limited in some areas, primarily due to acidity, elevated chloride and sulfate, and for taste reasons due to salinity.

4.8.3 Irrigation Water Quality

The utility of groundwater from the Yegua Formation and Jackson Group for crop irrigation was evaluated based on its salinity hazard, sodium hazard, and concentrations of chloride. The results of this evaluation are presented below.

Saline irrigation waters limit the ability of plants to take up water from soils. Various crops differ in their tolerance of high salinity. Salinity is often measured by the total dissolved solids content or electrical conductivity of the water. The salinity hazard classification system of the United States Salinity Laboratory (1954) indicates that waters with specific conductance over 750 micromhos per centimeter present a high salinity hazard, and those with specific conductance over 2250 micromhos per centimeter present a very high salinity hazard. Of the wells in the Yegua Formation, 81 percent have exhibited a high salinity hazard, and 28 percent of the wells have exhibited a very high salinity hazard. For the Jackson Group, 77 percent of the wells have exhibited a high salinity hazard, and 34 percent of the wells have exhibited a very high salinity hazard. Figures 4.8.10 and 4.8.11 show the locations and ranges for salinity hazard estimates. Both the Jackson Group and Yegua Formation show a consistent mix of measurements above and below the very high salinity hazard standard.

Irrigation water containing large amounts of sodium causes a breakdown in the physical structure of soil such that movement of water and air through the soil is restricted. The sodium hazard was calculated based on the classification system developed by the United States Salinity Laboratory (1954). The sodium absorption ratio is an indication of the sodium hazard to soils. The sodium adsorption ratio is calculated as follows:

$$Sodium\ Adsorption\ Ratio = \frac{Na}{\sqrt{\frac{Ca + Mg}{2}}} \quad (4.8.1)$$

where the sodium (Na), calcium (Ca), and magnesium (Mg) concentrations are expressed in milliequivalents per liter.

Waters with a sodium absorption ratio above 18 are considered to present a high sodium hazard, generally considered unsuitable for continuous use in irrigation. Waters with a sodium absorption ratio above 26 are considered to represent a very high sodium hazard. About 52 percent of the wells in Yegua Formation have exhibited a high sodium hazard, and 37 percent of the wells have exhibited a very high sodium hazard. For the Jackson Group, 30 percent of the wells are considered to represent a high sodium hazard and 17 percent of the wells have exhibited a very high sodium hazard. Figures 4.8.12 and 4.8.13 show the locations and sodium hazard ratings for the Jackson Group and Yegua Formation, respectively. Results are spatially mixed, with few estimates available south of Karnes County.

Most crops cannot tolerate chloride levels above 1000 milligrams per liter for an extended period of time (Tanji, 1990). This level has been exceeded in about 6 percent of wells in the Yegua Formation and 9.8 percent of the wells in the Jackson Group. Plots of chloride concentrations were shown in Figures 4.8.4 and 4.8.5. These figures show locations where the chloride concentration in groundwater in the Yegua Formation and Jackson Group is less than the secondary maximum contaminant level of 300 milligrams per liter, between the secondary maximum contaminant level and 1,000 milligrams per liter, and greater than 1,000 milligrams per liter.

Table 4.8.1 Occurrence and levels of some commonly-measured groundwater quality constituents in the Yegua Formation.

Constituent	Type of Standard	Screening Level	Units	Number of Results	Number of Results Exceeding Screening Level	Percentage of Results Exceeding Screening Level
Fluoride	Primary maximum contaminant level[1]	4	mg/L	364	2	0.5
Nitrate	Primary maximum contaminant level[1]	10	mg/L as N	410	11	2.7
pH	Secondary maximum contaminant level[1] (lower bound)	7	-	439	53	12
Chloride	Secondary maximum contaminant level[1]	300	mg/L	547	155	28
Fluoride	Secondary maximum contaminant level[1]	2	mg/L	364	12	3.3
Sulfate	Secondary maximum contaminant level[1]	300	mg/L	518	144	28
Total Dissolved Solids	Secondary maximum contaminant level[1]	1000	mg/L	451	190	42
Specific Conductance	Irrig. Salinity Hazard - High[2]	750	µmhos/cm	429	347	81
Specific Conductance	Irrig. Salinity Hazard - Very High[2]	2250	µmhos/cm	429	121	28
Sodium Absorption Ratio	Sodium hazard – High[2]	18	-	423	218	52
Sodium Absorption Ratio	Sodium hazard – Very High[2]	26	-	423	157	37
Chloride	Irrig. Hazard[3]	1000	mg/L	547	33	6.0

[1] 30 Texas Administrative Code Chapter 290 Subchapter F
[2] United States Salinity Laboratory (1954)
[3] Tanji (1990)

mg/L = milligrams per liter

µmhos/cm = micromhos per centimeter

Table 4.8.2 Occurrence and levels of some commonly-measured groundwater quality constituents in the Jackson Group.

Constituent	Type of Standard	Screening Level	Units	Number of Results	Number of Results Exceeding Screening Level	Percentage of Results Exceeding Screening Level
Fluoride	Primary maximum contaminant level[1]	4	mg/L	220	0	0
Nitrate	Primary maximum contaminant level[1]	10	mg/L as N	284	22	7.7
pH	Secondary maximum contaminant level[1] (lower bound)	7	-	273	81	30
Chloride	Secondary maximum contaminant level[1]	300	mg/L	378	153	40
Fluoride	Secondary maximum contaminant level[1]	2	mg/L	220	0	0
Sulfate	Secondary maximum contaminant level[1]	300	mg/L	360	124	34
Total Dissolved Solids	Secondary maximum contaminant level[1]	1000	mg/L	326	151	46
Specific Conductance	Irrig. Salinity Hazard - High[2]	750	µmhos/cm	283	218	77
Specific Conductance	Irrig. Salinity Hazard - Very High[2]	2250	µmhos/cm	283	95	34
Sodium Absorption Ratio	Sodium hazard – High[2]	18	-	302	92	30
Sodium Absorption Ratio	Sodium hazard – Very High[2]	26	-	302	51	17
Chloride	Irrig. Hazard[3]	1000	mg/L	378	37	9.8

[1] 30 Texas Administrative Code Chapter 290 Subchapter F
[2] United States Salinity Laboratory (1954)
[3] Tanji (1990)

mg/L = milligrams per liter

µmhos/cm = micromhos per centimeter

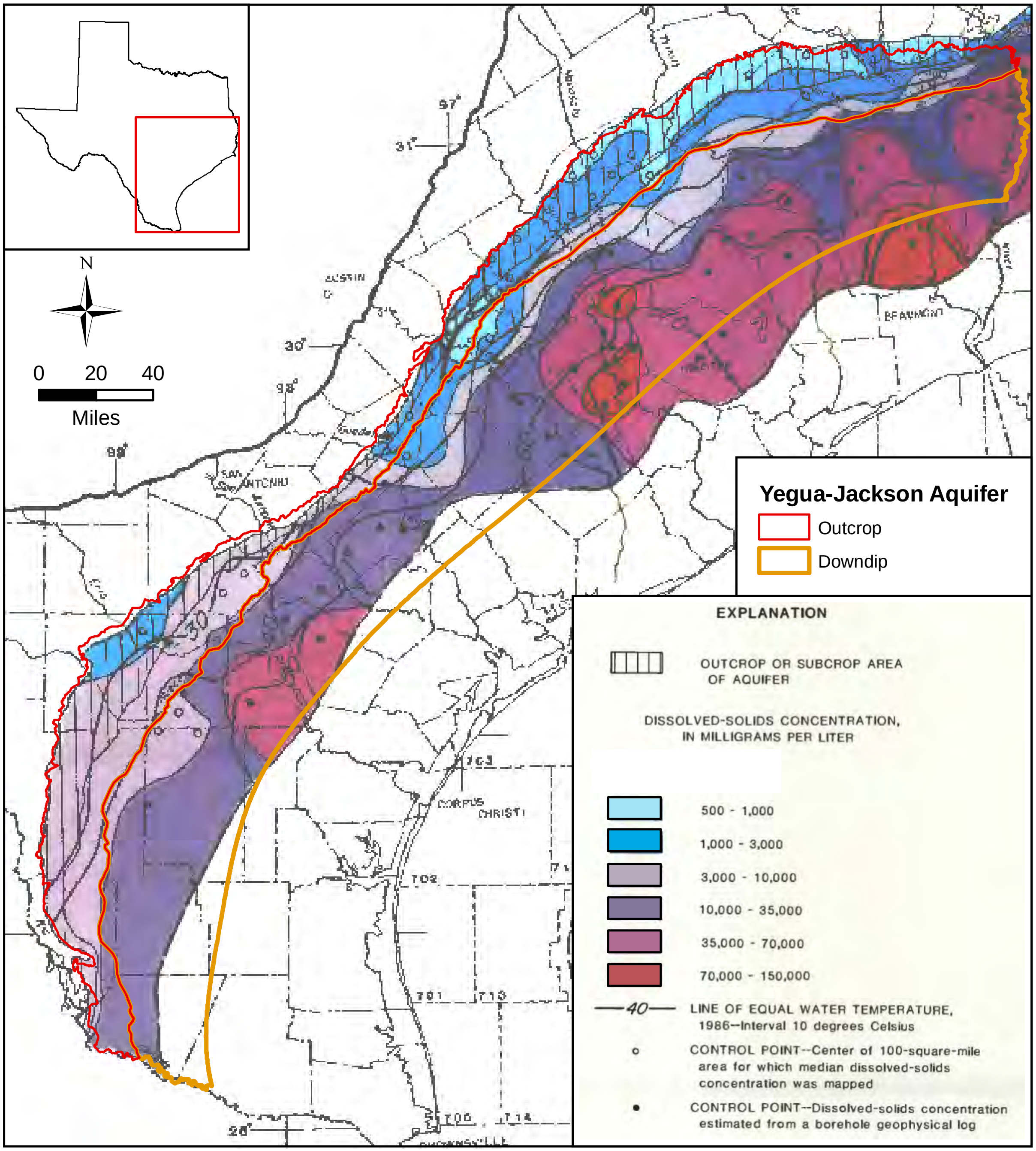

Figure 4.8.1 Map of total dissolved solids concentration for the Yegua Formation from Pettijohn and others (1988).

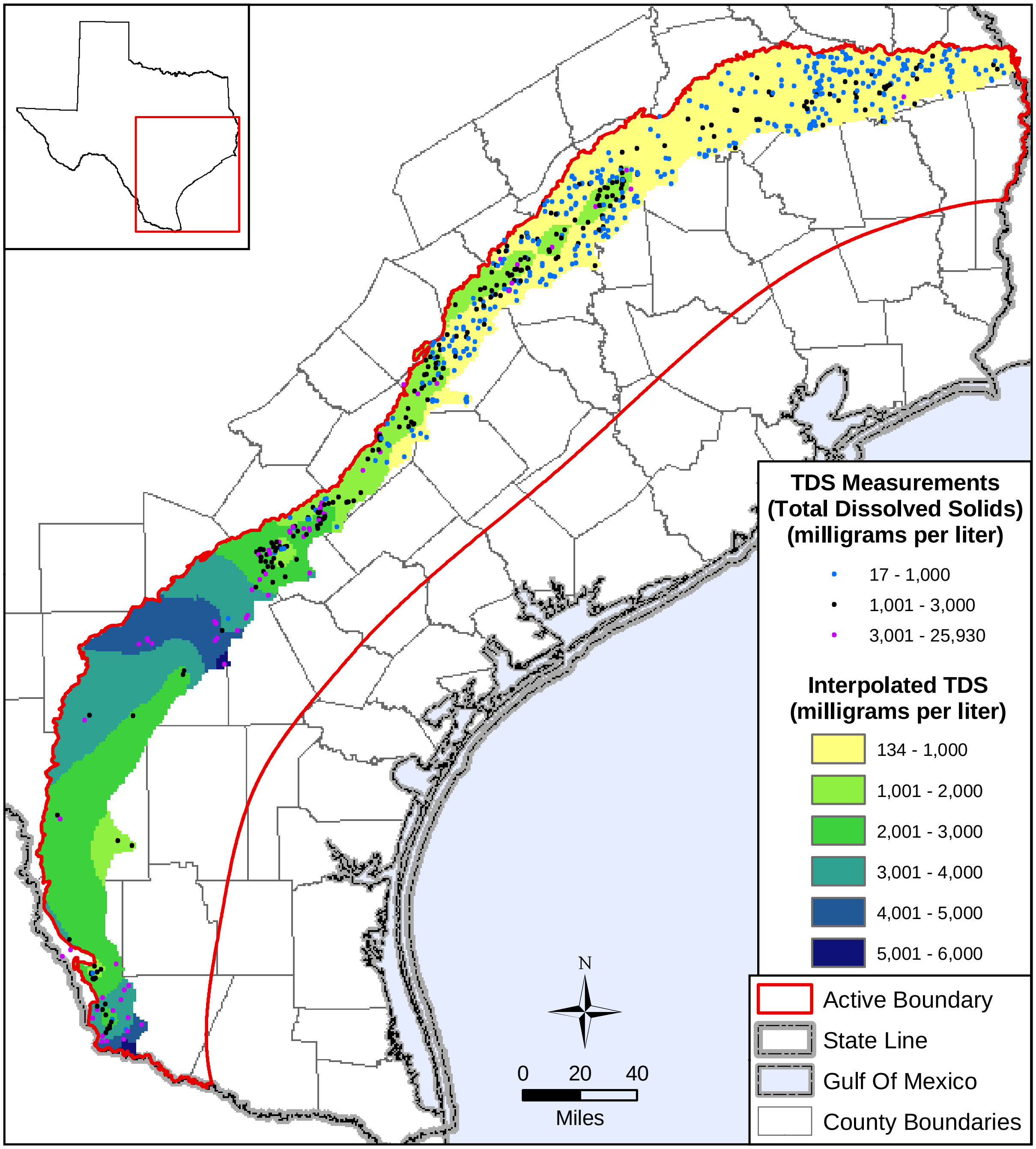

Figure 4.8.2 Total dissolved solids concentration in the Yegua-Jackson Aquifer.

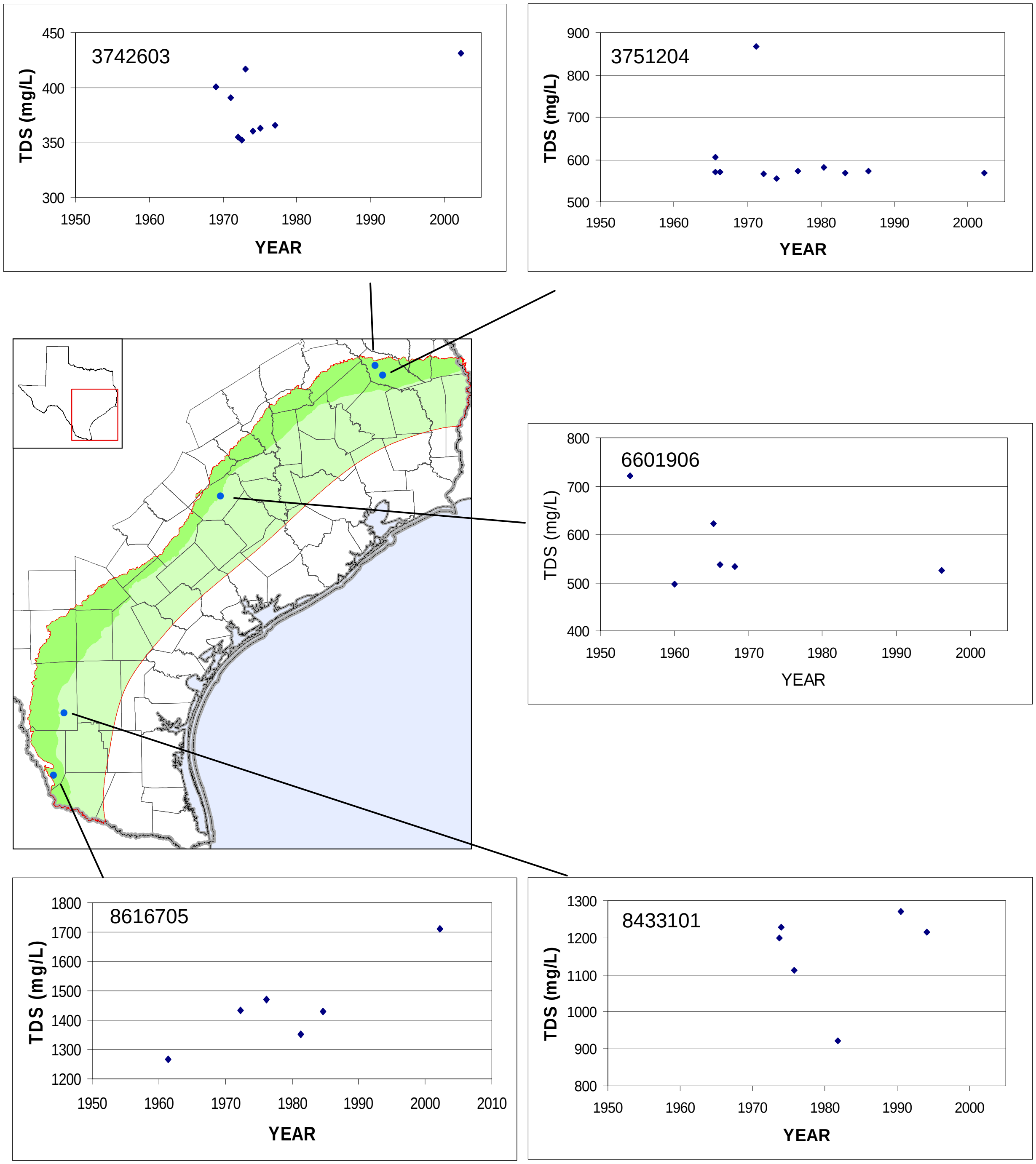

Figure 4.8.3 Time series for total dissolved solids concentration in milligrams per liter in the Yegua-Jackson Aquifer.

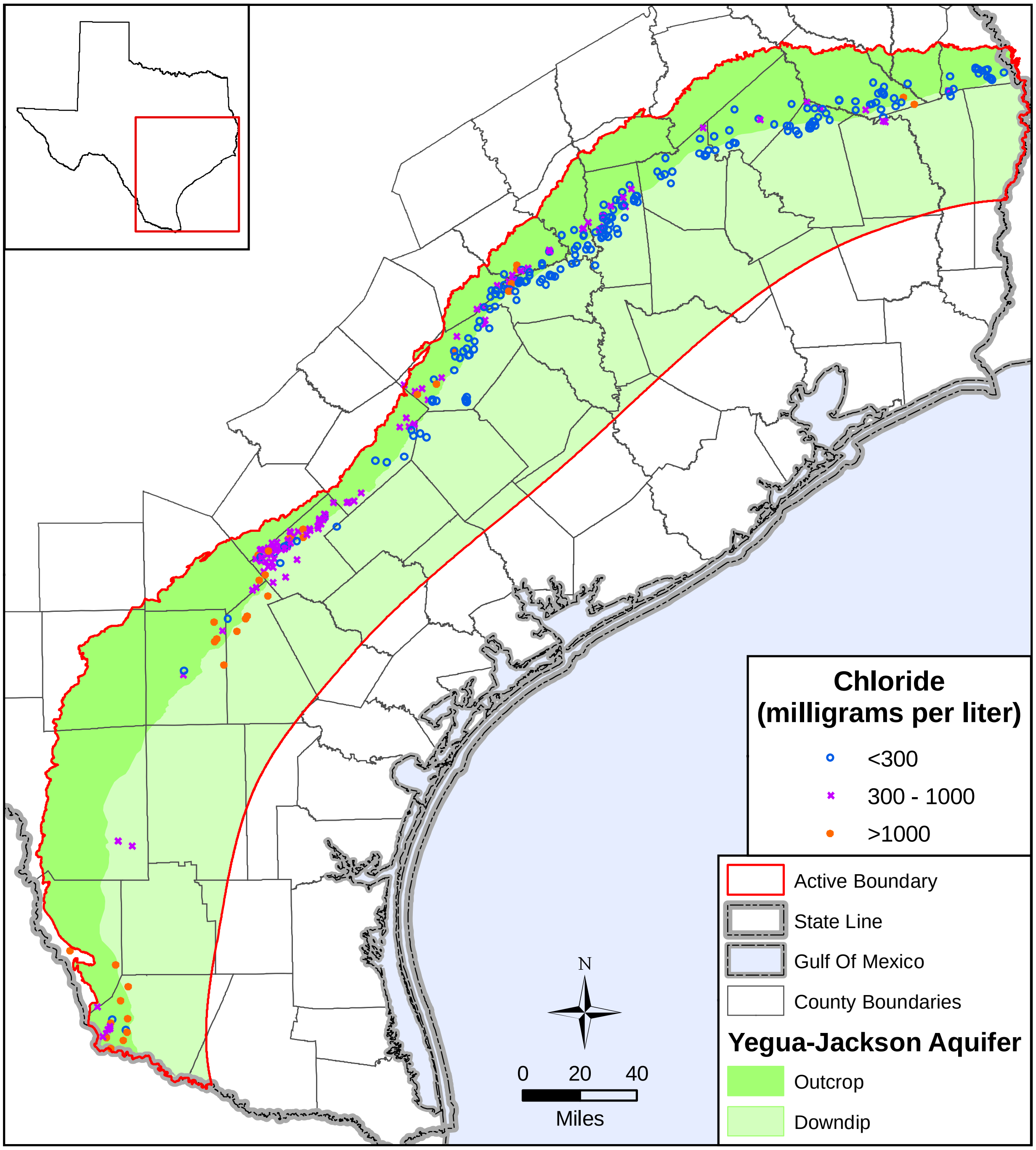

Figure 4.8.4 Chloride concentration in the Jackson Group.

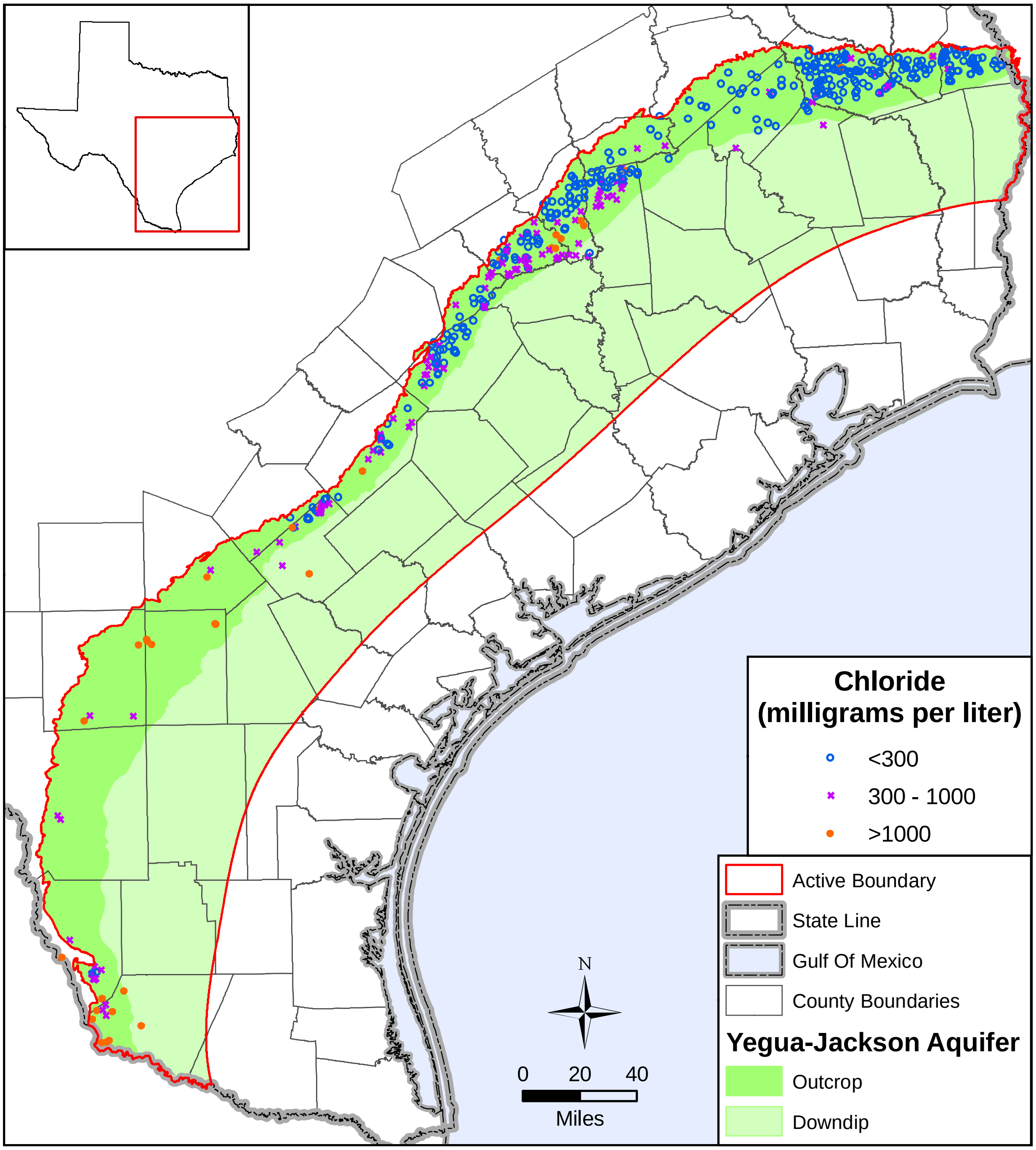

Figure 4.8.5 Chloride concentration in the Yegua Formation.

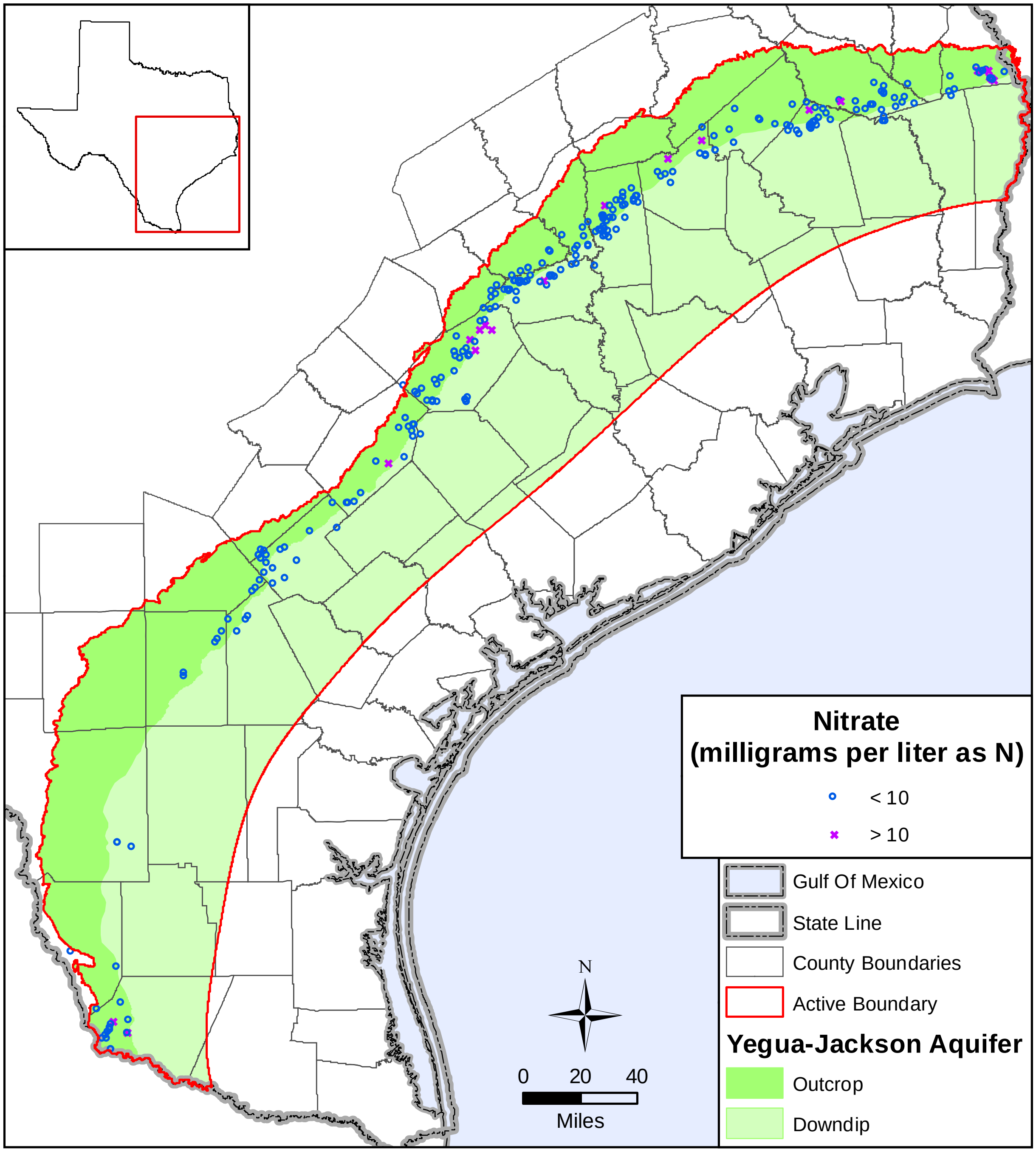

Figure 4.8.6 Nitrate concentration in the Jackson Group.

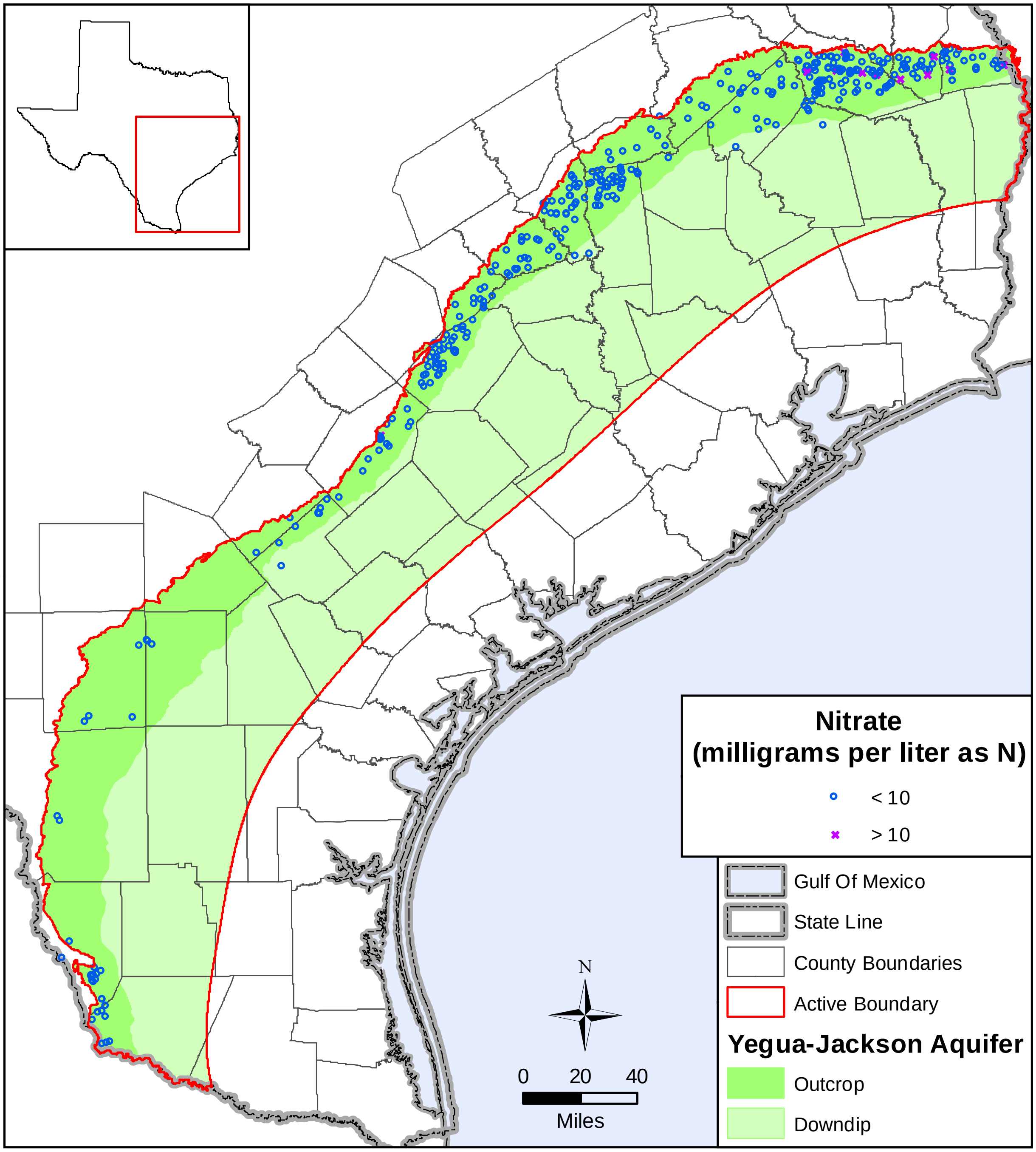

Figure 4.8.7 Nitrate concentration in the Yegua Formation.

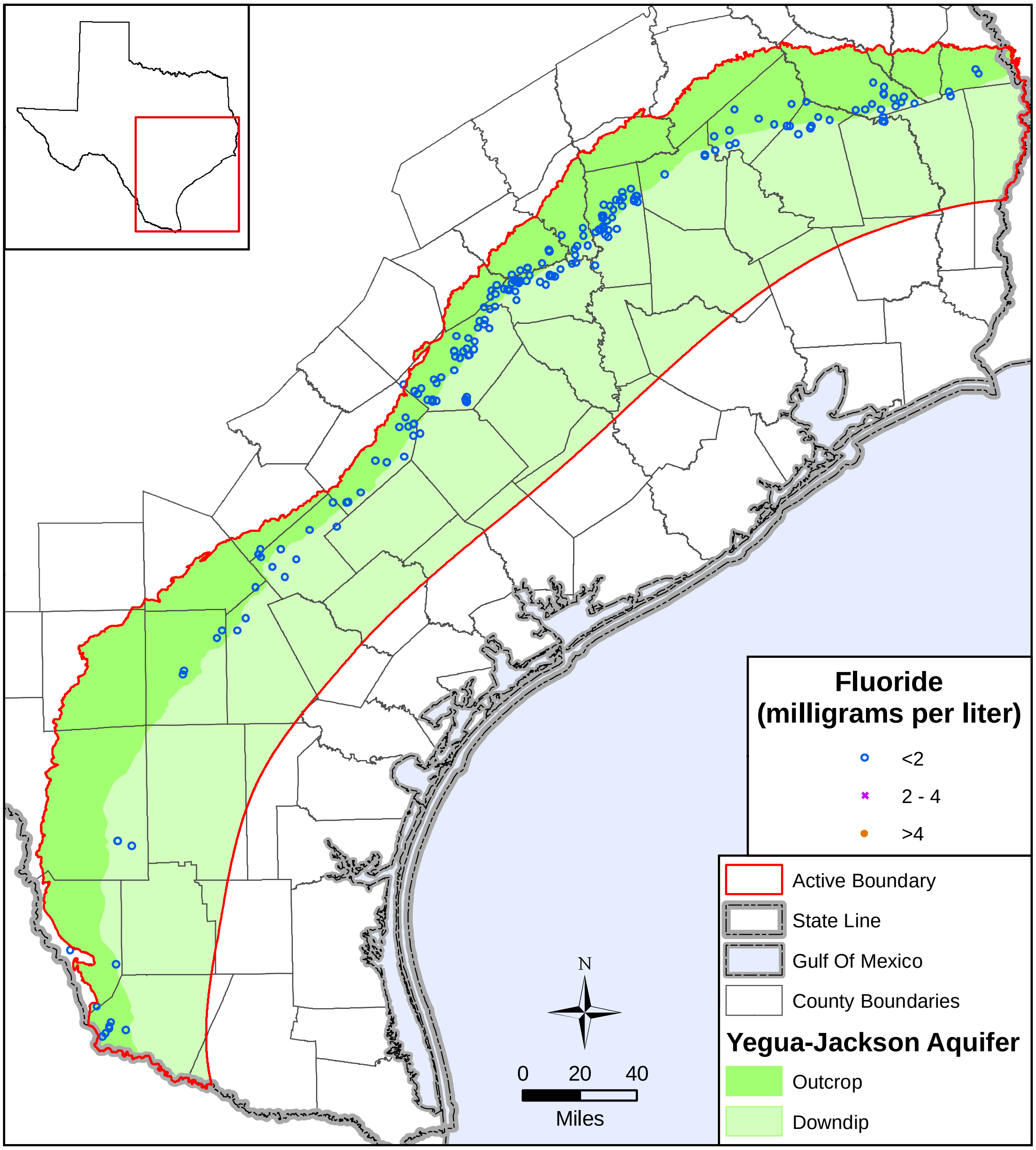

Figure 4.8.8 Fluoride concentration in the Jackson Group.

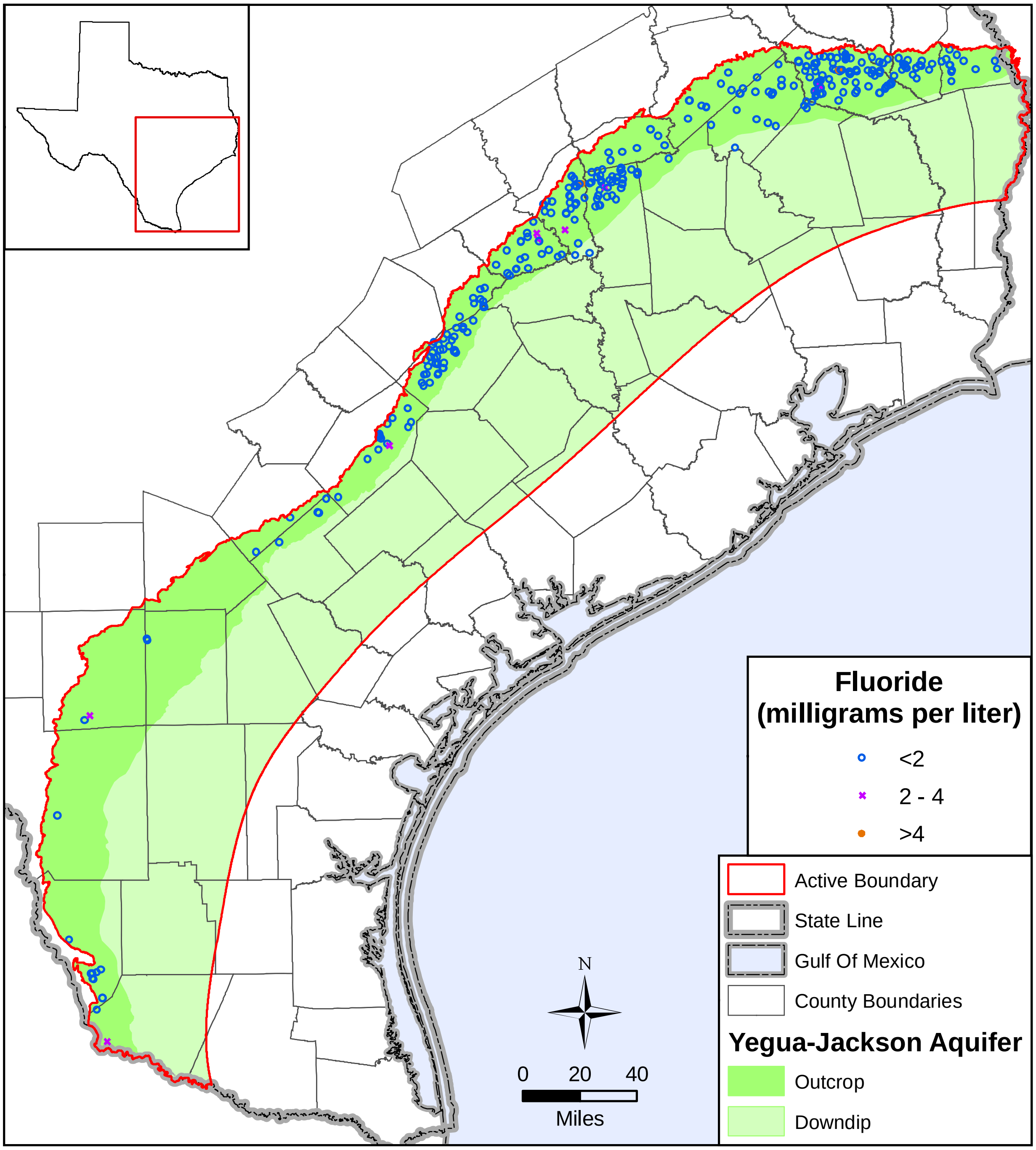

Figure 4.8.9 Fluoride concentration in the Yegua Formation.

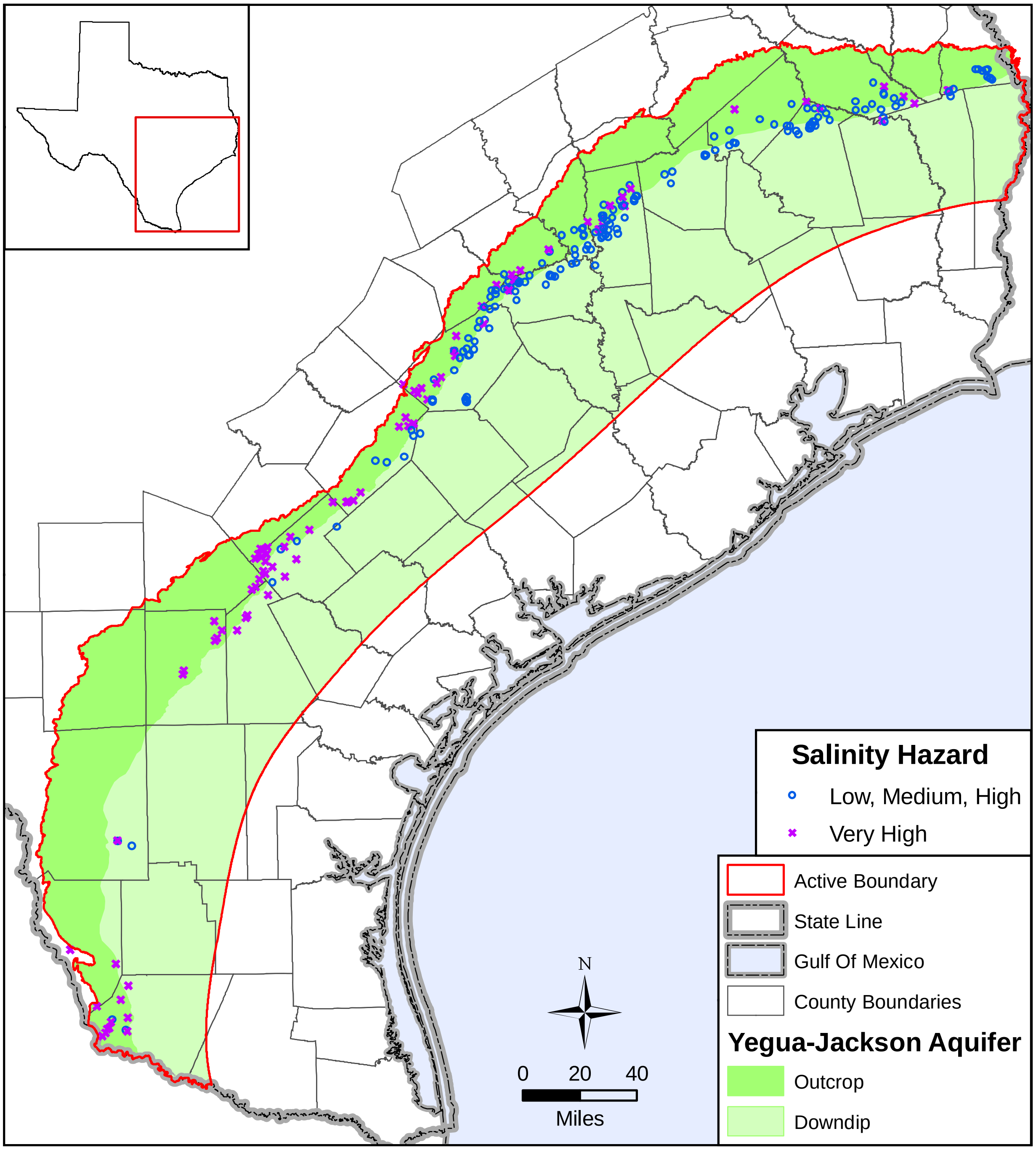

Figure 4.8.10 Salinity hazard in the Jackson Group.

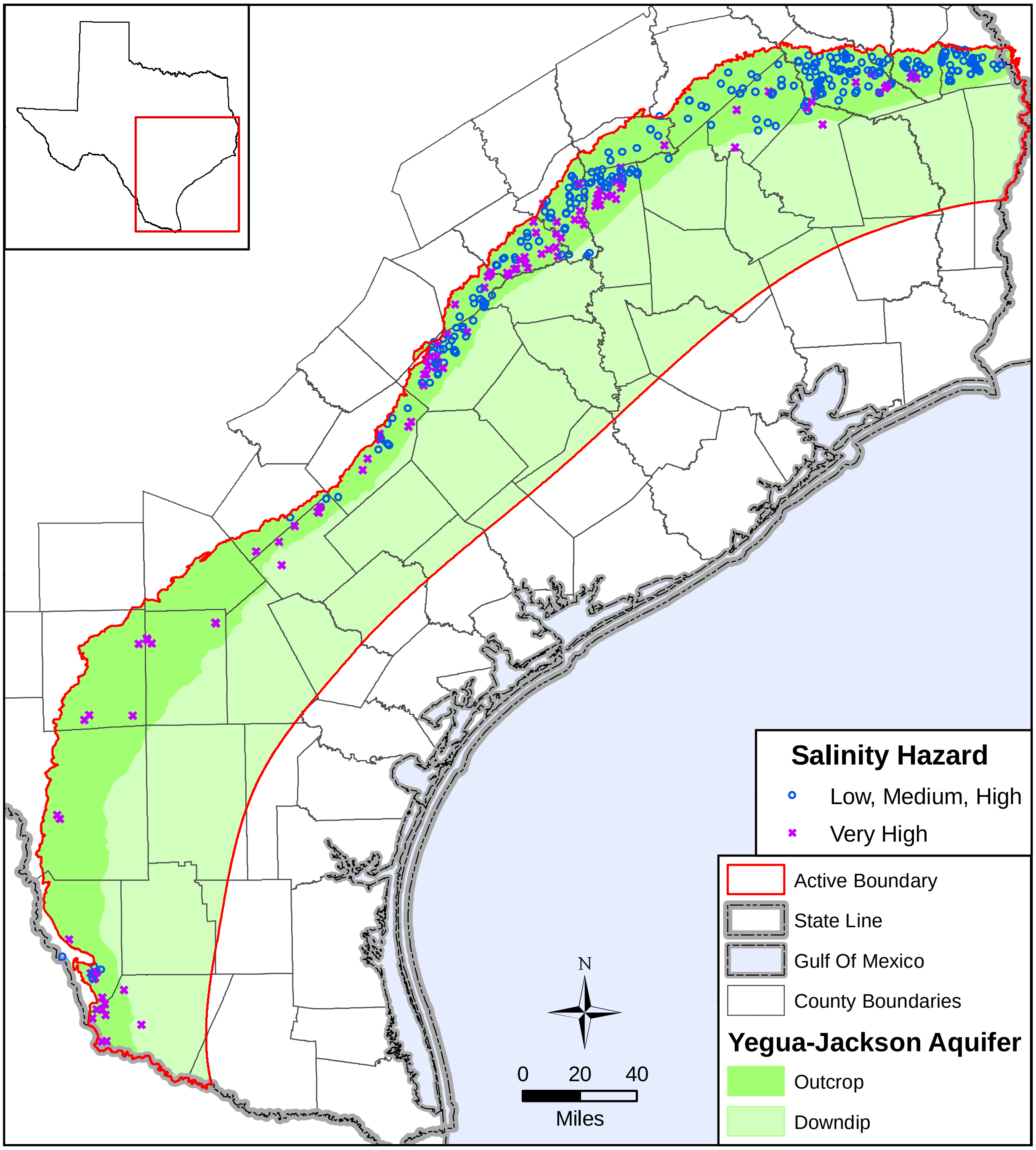

Figure 4.8.11 Salinity hazard in the Yegua Formation.

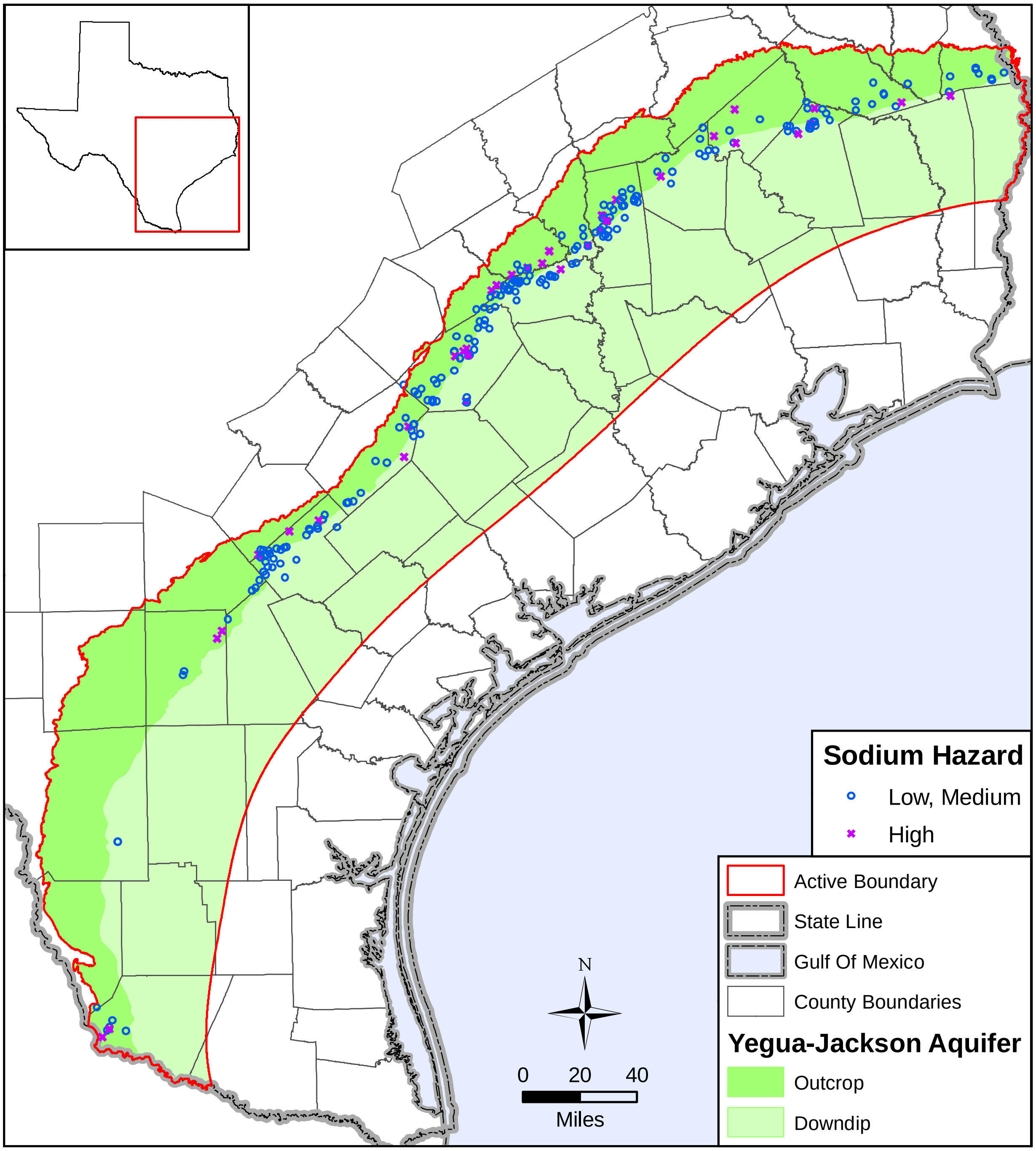

Figure 4.8.12 Sodium hazard in the Jackson Group.

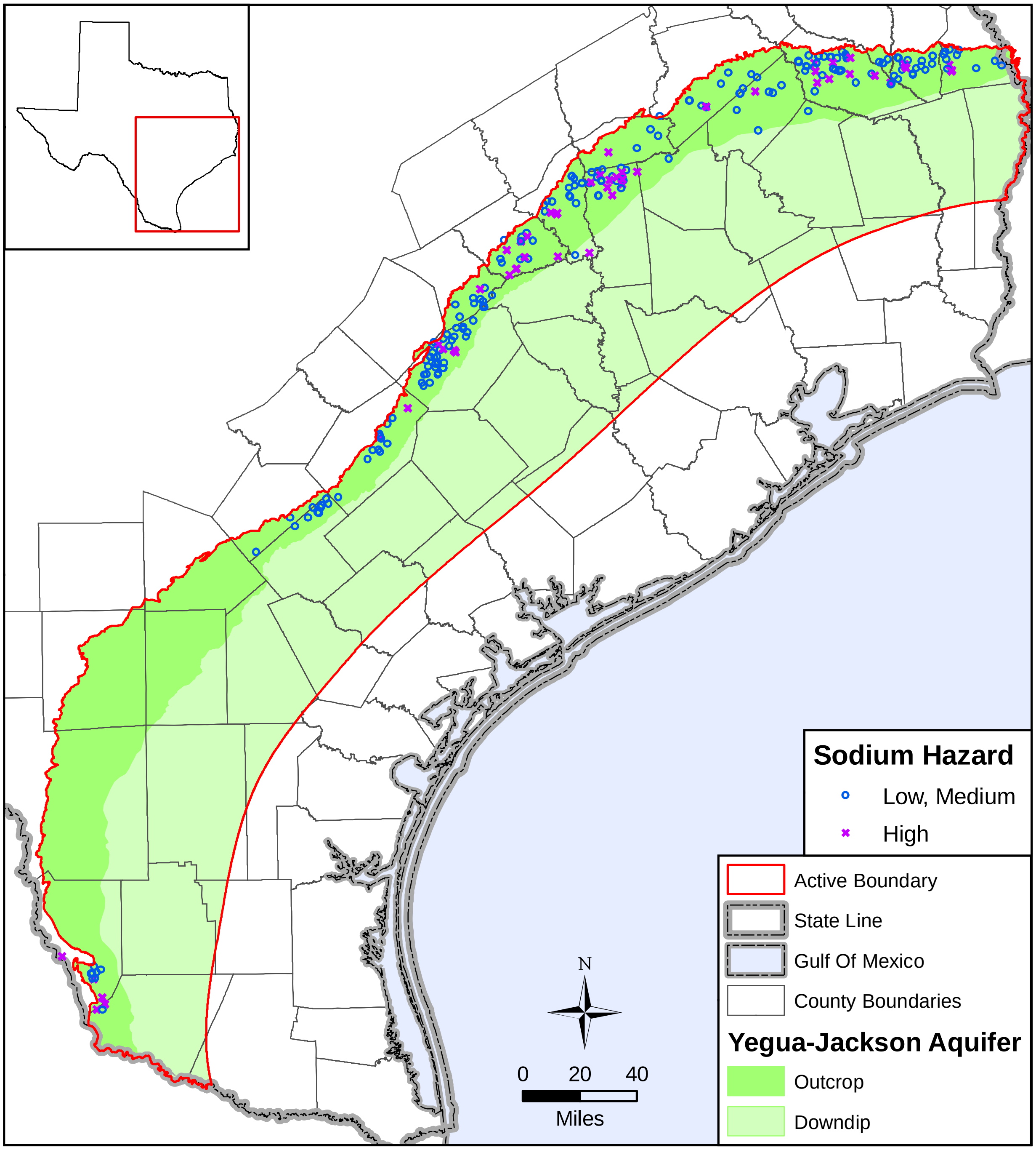

Figure 4.8.13 Sodium hazard in the Yegua Formation.

5.0 Conceptual Model of Groundwater Flow in the Aquifer

The conceptual model for groundwater flow in the Yegua-Jackson Aquifer is based on the hydrogeologic setting, described in Section 4. The conceptual model is a simplified representation of the hydrogeological features which govern groundwater flow in the aquifer. These include the hydrostratigraphy, hydraulic properties, hydraulic boundaries, recharge and natural discharge, and anthropological stresses such as pumping. All of these elements of the conceptual model govern groundwater flow within the aquifer. Each of the elements of our conceptual model is described below.

The schematic diagram in Figure 5.0.1 depicts a simplified conceptual hydrogeologic model of groundwater flow in the Yegua-Jackson Aquifer under predevelopment conditions. For the schematic, pumping is not considered and long-term average aquifer recharge is equal to long-term average discharge. As the aquifer is developed, an additional flow component representing discharge from individual layers would be depicted in Figure 5.0.1 representing pumping of the aquifer.

The conceptual model for the Yegua-Jackson Aquifer defines four units capable of producing groundwater to a well at adequate rates and quality for use. From youngest to oldest, the units are the Upper Jackson Unit, Lower Jackson Unit, Upper Yegua Unit, and Lower Yegua Unit. The Upper Jackson Unit and Lower Jackson Unit are divisions of the Jackson Group, while the Upper Yegua Unit and Lower Yegua Unit are divisions of the Yegua Formation. These units lie conformably in the order shown, and are expected to be hydraulically connected to some extent. The downdip portion of the Upper Jackson, Lower Jackson, Upper Yegua, and Lower Yegua units are represented by model layers 2 through 5, respectively. The entire outcrop area of all four units of the Yegua-Jackson Aquifer is represented by part of model layer 1 (Figure 5.0.1).

Below the Lower Yegua Unit is the Cook Mountain Formation, which serves as an aquitard that separates the Lower Yegua Unit from the Sparta Aquifer. In reality, a small amount of cross-formational flow will occur between the Lower Yegua Unit and the Cook Mountain Formation, but the assumption of a no-flow boundary should have negligible impact on model performance. A wedge of younger sediments lies above the Upper Jackson Unit, the first of which is the

Catahoula Formation. This wedge of sediments is represented by part of model layer 1 as indicated in Figure 5.0.1, and general head boundaries were attached to the layer to simulate the aquifer immediately above, which is the Jasper Aquifer. Under predevelopment conditions, a small amount of interaction occurs between the confined Upper Jackson Unit and the younger sediments, driven by elevation head. However, due to the low overall conductivity of the sediments, this interaction is a minimal part of the overall water budget.

In addition to identifying the hydrostratigraphic layers of the aquifer, the conceptual model also defines the mechanisms of recharge and natural aquifer discharge, as well as groundwater flow through the aquifer. Precipitation falling on the outcrop either runs off as surface water or evaporates at the surface, infiltrates and is lost to evapotranspiration in the vadose zone, or infiltrates into the subsurface and recharges the aquifer. For an average condition in the central region of the Yegua-Jackson Aquifer, we expect about three quarters of the precipitation to be removed via evapotranspiration while most of the remainder runs off as surface water. Only one or two percent of precipitation will become recharge. Recharge from precipitation occurs in the outcrop areas of the Yegua-Jackson Aquifer. We would expect recharge from precipitation to increase from southwest to northeast, as average precipitation increases, and potential evapotranspiration decreases. In the southwest portions of the Yegua-Jackson Aquifer outcrop, where the water table can be below stream stages, some focused recharge will occur from losing streams.

Once infiltrating water becomes recharge, most will discharge through baseflow, spring or seep discharge, or groundwater evapotranspiration. Only a fraction of an inch per year of recharge is estimated to travel downdip in the Yegua-Jackson Aquifer. Under natural conditions, this groundwater is expected to eventually discharge vertically to the layer above. Due to overall low transmissivities and low flux rates, we would expect much of the downdip flowing water to discharge through cross-formational flow within a few miles gulfward of the Upper Jackson Unit/Catahoula Formation contact, prior to reaching the depth where water quality degrades beyond slightly saline.

The concentration of total dissolved solids can be a partial indicator of the relative amount of deep recharge that is occurring in an aquifer. The downdip increase of total dissolved solids along with sodium and chloride concentrations might reflect less displacement of connate water by meteoric water, according to a model developed by Domenico and Robbins (1985). The distribution of total dissolved solids depicted in Figure 4.8.1 shows a trend of decreasing near-downdip water quality from northeast to southwest, with a transition in Gonzales County. This supports the conceptualization of a similar trend of decreasing overall downdip flux across the region. This decrease in downdip flux toward the southwest can be attributed to two factors: less recharge with lower overall water table elevations create less driving gradient and decreased transmissivity due to both smaller sand percents in the Yegua Formation and a larger number of faults nearer to the outcrop (e.g., Figures 4-1 through 4-6 in Knox and others, 2007).

Human activities alter the dynamic equilibrium of the predevelopment flow system through pumping withdrawals, changes in recharge through development and irrigation return flow, and changes in vegetation. Generally, groundwater withdrawals due to pumping have the most significant impact on aquifer hydraulics. The water removed by pumping is supplied through decreased groundwater storage, reduced groundwater discharge, and sometimes increased recharge. Generally, increased recharge as a source of water to pumping wells is negligible compared to decreased groundwater storage and decreased aquifer discharge (Alley and others, 1999). If pumping stays relatively constant, a new steady-state condition will be established. In this new equilibrium, the source of the pumped water will be drawn completely from either decreased discharge (likely) or increased recharge (unlikely). Bredehoeft (2002) terms these two volumes as capture. The sources of discharge which are ultimately captured by pumping include stream baseflow, spring flow, evapotranspiration, and cross-formational flow.

Pumping from the Yegua-Jackson Aquifer has been relatively low in overall magnitude at less than 20,000 acre-feet per year for any given year, to date. However, widespread, low-intensity use has occurred in the outcrop portion of the aquifer. While significant drawdown exists in a few regions, regional water levels reflect relatively stable heads indicative of the limited development. Drawdown is typically localized and in the deeper confined sections, with little evidence of impacts to the shallow water table. Therefore, we expect that stream baseflow, spring flow, evapotranspiration, and cross-formational flow have not been significantly impacted by drawdowns.

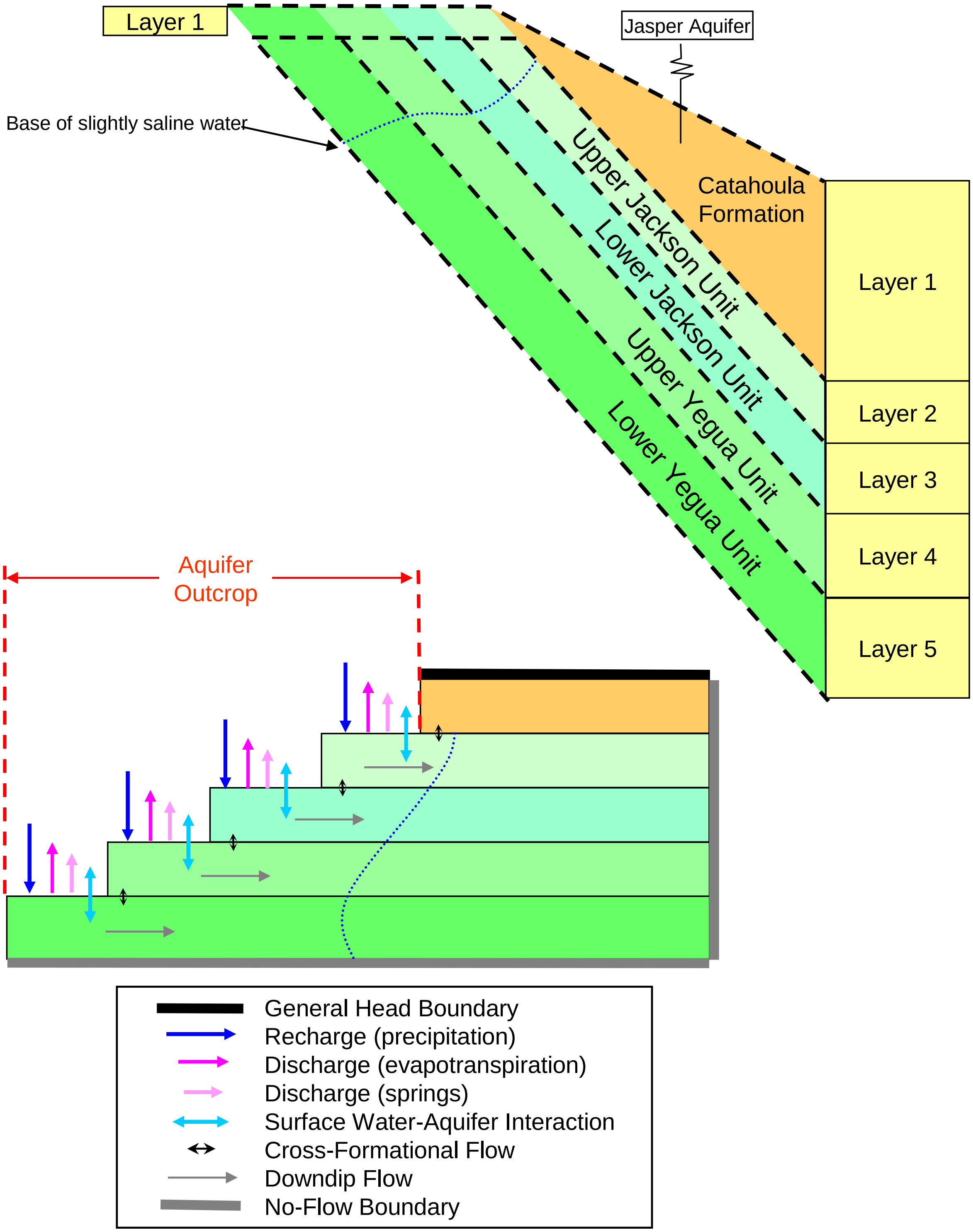

Figure 5.0.1 Conceptual model of groundwater flow for the Yegua-Jackson Aquifer.

6.0 Model Design

Model design represents the process of translating the conceptual model for groundwater flow in the aquifer (Section 5) into a numerical representation which is generally described as the model. The conceptual model for flow defines the processes and attributes required of the code to be used. In addition to selection of the appropriate code, model design includes definition of the model grid and layer structure, the model boundary conditions, and the model hydraulic parameters. Each of these elements of model design and their implementation are described in this section.

6.1 Code and Processor

The code selected for the groundwater availability models developed by or for the TWDB is MODFLOW-2000 (Harbaugh and others, 2000). MODFLOW is a three-dimensional finite-difference groundwater flow code that is supported by enhanced boundary condition packages to handle recharge, evapotranspiration, streams (Prudic, 1988), springs, and reservoirs (Fenske and others, 1996).

The benefits of using MODFLOW for the Yegua-Jackson Aquifer groundwater availability model include: (1) MODFLOW incorporates the necessary physics represented in the conceptual model for flow described in Section 5 of this report; (2) MODFLOW is the most widely accepted groundwater flow code in use today; (3) MODFLOW was written and is supported by the United States Geological Survey and is public domain; (4) MODFLOW is well documented (McDonald and Harbaugh, 1988; Harbaugh and McDonald, 1996; Harbaugh and others, 2000); (5) MODFLOW has a large user group; and (6) there are several mature graphical user interface programs written for use with MODFLOW.

The MODFLOW datasets were developed to be compatible with Groundwater Vistas for Windows Version 5.41 (Rumbaugh and Rumbaugh, 2004). The model was executed on x86 compatible (i.e., Pentium or Athlon) computers equipped with the Windows XP operating system. MODFLOW is not typically a memory-intensive application in its executable form.

However, if any preprocessor (such as Groundwater Vistas) is used for this size and complexity of model, at least 512 megabytes of random access memory (RAM) is recommended.

6.2 Model Layers and Grid

MODFLOW requires a rectilinear grid. For the model of the Yegua-Jackson Aquifer, the grid cells are 1 mile by 1 mile squares throughout the model domain. The model grid origin is located at Texas groundwater availability model coordinate system 17,786,114.1 feet north and 5,353,874.5 feet east with the x-axis oriented 0.78 radians north of east. The model has 475 columns and 142 rows for a total of 67,450 grid cells per layer. Not all of the grid cells in the model are active. Figure 6.2.1 shows the entire model grid and includes an inset with an enlargement of Burleson County to demonstrate the model grid at the county scale. After clipping the layers to their proper dimensions, layer 1 has 31,454 active cells, while layers 2-5 each contain 29,607 active cells. The total number of active grid cells in the model is 149,882.

The Yegua-Jackson Aquifer groundwater availability model is divided into five model layers. Layer 1 represents the shallow portion of the Yegua-Jackson Aquifer in the outcrop and represents the Catahoula Formation gulfward of the Upper Jackson Unit/Catahoula Formation contact. Layers 2 through 5 represent the downdip portions of the Upper Jackson, Lower Jackson, Upper Yegua, and Lower Yegua units, respectively. Figure 6.2.2 shows an example of the vertical discretization of the model grid. Layer 1 represents the shallow portion of all of the units making up the Yegua-Jackson Aquifer, as shown in Figure 6.2.3. Because MODFLOW does not allow vertical flow through inactive cells (inactive cells must be no-flow), intervening 1-foot thick layers were set between model layer 1 and the deeper confined layers as “conduit” cells to provide vertical connection.

The top of layer 1 where it represents the outcrop region was defined by the ground surface as calculated by a quarter mile resampling of the 30-meter digital elevation model. The bottom of layer 1 where it represents the outcrop region was defined based on an estimate of the predevelopment water table elevation, offset deeper by 100 feet. Since the depth to the water table increased to the southwest in the model area, the thickness of layer 1 also increased in the southwest. This approach was used to help ensure that cells in layer 1 did not go dry under predevelopment conditions. Because there is minimal drawdown in the shallow portion of the aquifer, this also resulted in no dry cells in transient conditions. This greatly improves the model stability, but causes the actual bottom of the model grid to be lower than the estimated actual structural bottom of the Lower Yegua in some cells that are very near the Cook Mountain – Lower Yegua contact, especially in the western portion where the water table is deeper. We further discuss the impact of this compromise between model stability and gridding approach in Section 10.

The thickness of layer 1 where it represents the shallow outcrop is typically 200 to 300 feet. Where it represents the Catahoula Formation (and the Yegua-Jackson Aquifer subcrop lies below), the top of layer 1 was defined based on the base of the Jasper Aquifer from the three Gulf Coast Aquifer groundwater availability models (Kasmarek and Robinson, 2004; Chowdhury and others, 2004; Chowdhury and Mace, 2003) and the base of layer 1 was defined as the top of the Upper Jackson Unit (see Figure 4.2.14). The base of model layers 2 through 5 were defined as the base of the Upper Jackson Unit, Lower Jackson Unit, Upper Yegua Unit, and Lower Yegua Unit, respectively.

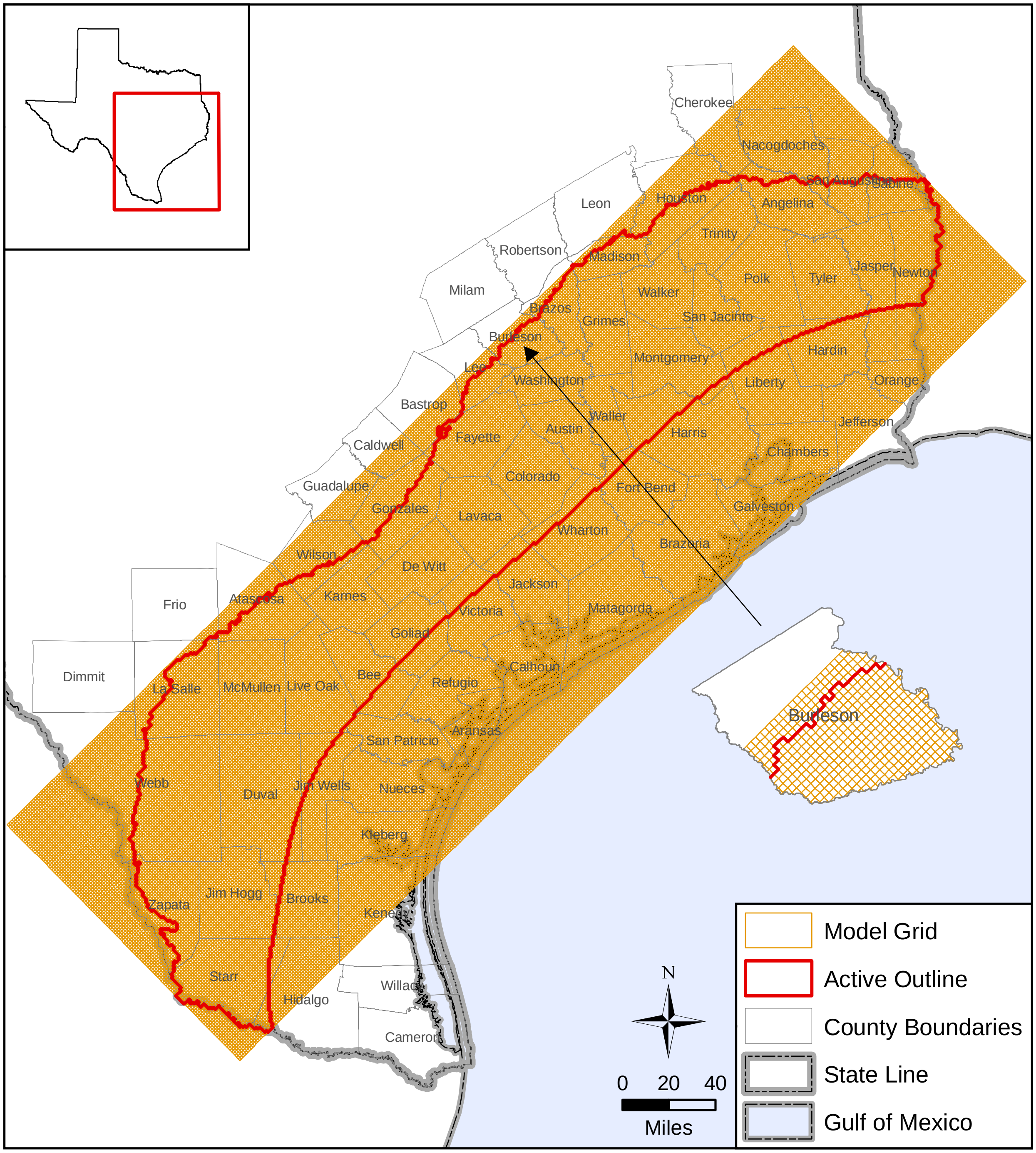

Figure 6.2.1 Model grid for the Yegua-Jackson Aquifer groundwater availability model.

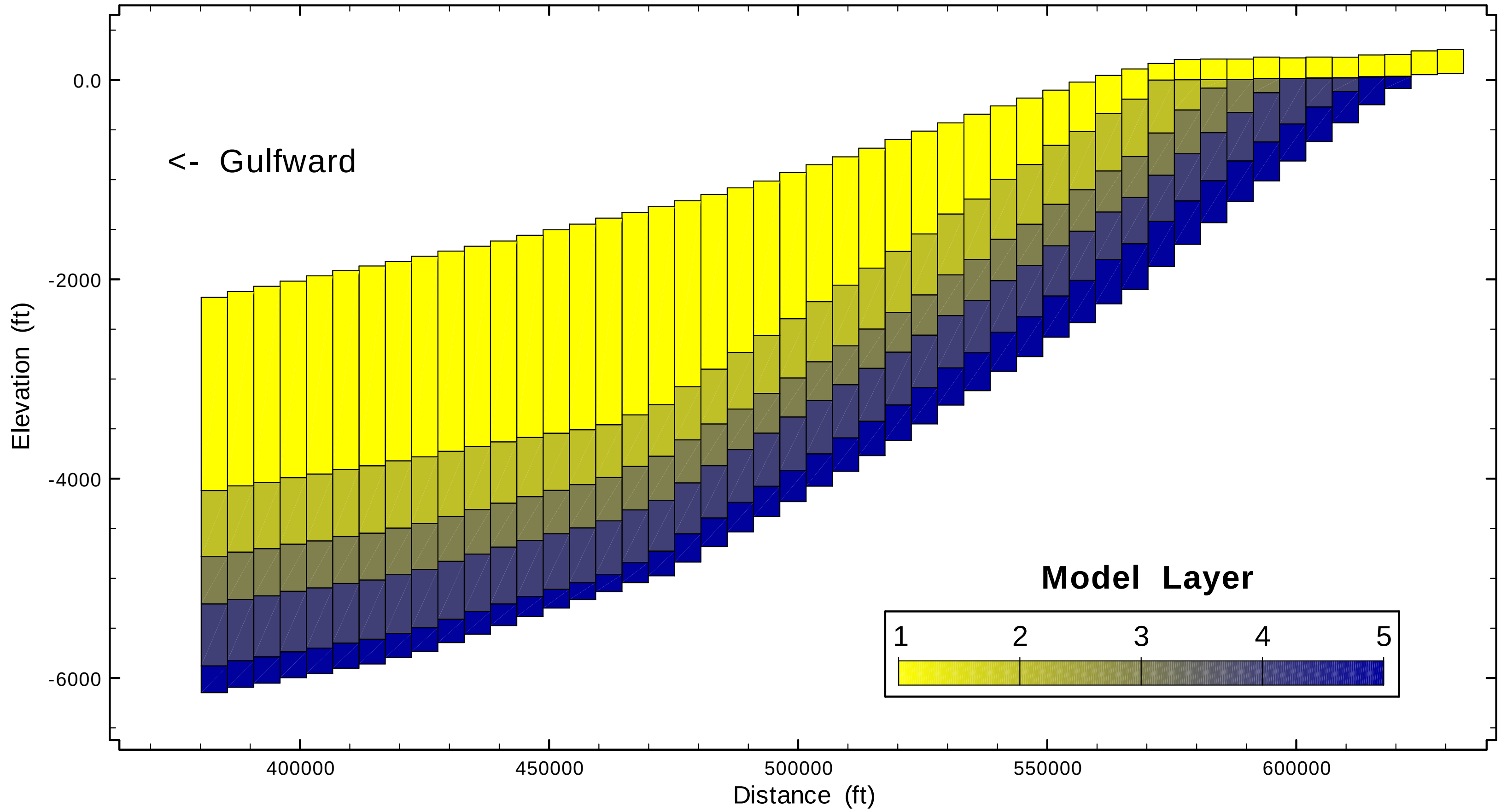

Figure 6.2.2 Example vertical discretization of the model, showing the model layers.

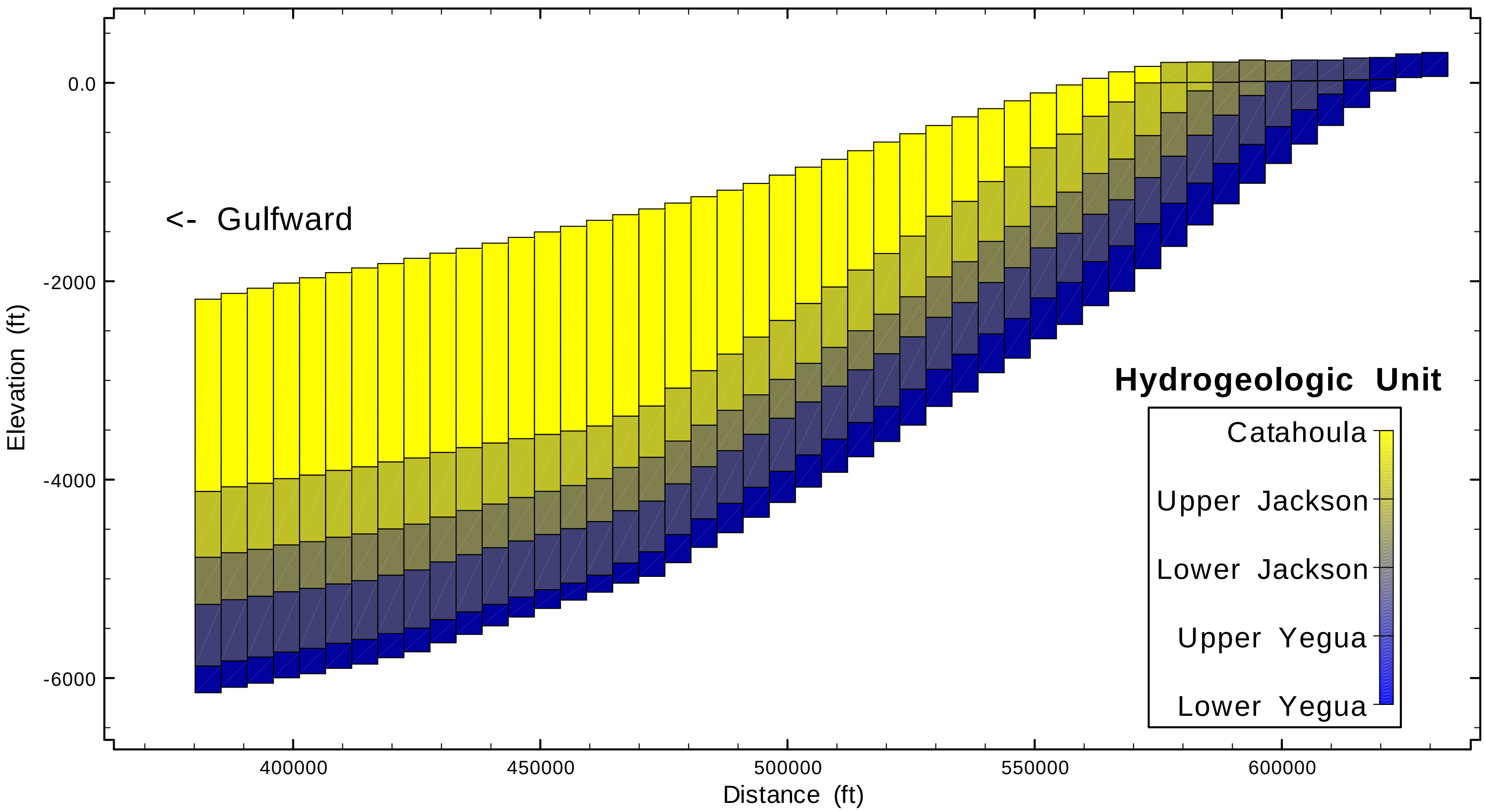

Figure 6.2.3 Example vertical discretization of the model, showing the hydrogeologic units corresponding to the layering.

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6.3 Boundary Condition Implementation

A boundary condition can be defined as a constraint put on the active model grid to characterize the interaction between the active simulation grid domain and the surrounding environment. There are generally three types of boundary conditions: specified head (First Type or Dirichlet), specified flow (Second Type or Neumann), and head-dependent flow (Third Type or Cauchy). The no-flow boundary condition is a special case of the specified flow boundary condition.

Boundaries can be either time independent or time dependent. An example of a time-dependent boundary is a pumping flow boundary (e.g., grid cell with a well) or a reservoir stage elevation. Because many boundaries require time-dependent (transient) specification, the stress periods used by MODFLOW must be specified. A stress period in MODFLOW defines the time period over which boundary and model stresses remain constant. Each stress period may have a number of computational time steps, which are some fraction of the stress period. For the transient model, the stress periods were set at 10 years for 1901 through 1970, 9 years for 1971 to 1979, and 1 year from 1980 through 1997 (Table 6.3.1). Therefore, transient boundaries in the model cannot change over a period of less than 10 years, 9 years, or 1 year in the corresponding stress periods.

Boundaries requiring specification include: lateral and vertical boundaries for each layer, surface-water boundaries, recharge boundaries, and discharge boundaries, including evapotranspiration and pumping. Specified flow (no-flow, Second Type) boundary conditions were assigned to the lateral and lower boundaries and a head-dependent flow (Third Type) was assigned to the portion of the top model layer representing the Catahoula Formation. Surface-water boundaries, including streams, springs (drains), reservoirs, and evapotranspiration, are head-dependent flow boundaries (Third Type). Recharge is a specified flow boundary (Second Type). Pumping discharge is a specified flow boundary (Second Type).

Figures 6.3.1 through 6.3.5 show the active and inactive grid cells for model layers 1 through 5, respectively. In the figures, “conduit cells” refer to those active cells that lie between the shallow layer 1 and the confined deeper layer, as described in Section 6.2. Implementation of the boundary conditions for the Yegua-Jackson Aquifer groundwater availability model is described below. Unless otherwise specified below, the boundary between the active and inactive cells is a no-flow boundary.

6.3.1 Lateral Model Boundary

The lateral model boundaries are primarily defined by the extent of the Yegua-Jackson Aquifer. Beyond the extent of the Yegua-Jackson Aquifer outline, grid cells were set as inactive, creating a de facto no-flow boundary, for the five model layers. The downdip boundary is approximately coincident with the extent of the known structure, and is well beyond any active portion of the aquifer.

6.3.2 Vertical Boundaries

A no-flow boundary was used at the bottom of layer 5, which is the base of the Yegua-Jackson Aquifer. In the portion of layer 1 that represents the Catahoula Formation, the model has a head-dependent flow boundary (Third Type). This general-head boundary represents the overlying Jasper Aquifer. The general head boundary package is able to simulate a head-dependent flow boundary condition, being defined by a head and hydraulic conductance.

The heads for the general head boundary were based on the simulated heads for the Jasper Aquifer extracted from the existing north, central, and south Gulf Coast Aquifer groundwater availability models (Kasmarek and Robinson, 2004; Chowdhury and others, 2004; Chowdhury and Mace, 2003, respectively). For both the steady-state and transient periods of the Yegua-Jackson Aquifer model, the heads were extracted and interpolated from the pre-development or transient hydraulic heads from the model layer representing the Jasper Aquifer in the three Gulf Coast Aquifer models in corresponding stress periods.

The north and central Gulf Coast Aquifer groundwater availability models overlap in a large area, which results in two heads for the Jasper Aquifer, one from each model, in this region. The head for the Jasper Aquifer was assigned the average of the values from the two models across the majority of the overlap region. In order to avoid an abrupt change in Jasper Aquifer heads between the average values in the overlap area and the model values in the remainder of the north and central Gulf Coast Aquifer models, heads for the Jasper Aquifer in a 10-mile wide strip in the northern and southern portions of the overlap area were interpolated by kriging the average values in the overlap region and the model values from the north and central Gulf Coast Aquifer models. This approach is illustrated in Figure 6.3.6. It allowed for a smooth transition in Jasper Aquifer heads between the heads from the north model, the average heads in the central portion of the overlap region, and the heads from the south model.

The central and south Gulf Coast Aquifer models overlap in an area that is less than 10-miles wide. In order to avoid an abrupt change, Jasper Aquifer heads in a 10-mile wide strip centered on the midline of the overlap region were obtained by kriging the values from the central and south models.

In summary, the final head values used for the Jasper Aquifer, from northeast to southwest, consisted of:

- Head values from the north Gulf Coast Aquifer model,
- Kriged head values in a 10-mile wide strip in the northern portion of the region where the north and central Gulf Coast Aquifer models overlap,
- The average of the head values from the north and central Gulf Coast Aquifer models in the central portion of the region where the north and central models overlap,
- Kriged head values in a 10-mile wide strip in the southern portion of the region where the north and central Gulf Coast Aquifer models overlap,
- Head values from the central Gulf Coast Aquifer model,
- Kriged head values in a 10-mile wide strip centered on the midline of the region where the central and south Gulf Coast Aquifer models overlap, and
- Head values from the south Gulf Coast Aquifer model.

The values for the general head boundary in model layer 1 were then assigned as either the head value from the north, central, and south Gulf Coast Aquifer models closest to the center of the Yegua-Jackson Aquifer model grid cell or as the head value extracted from the kriged values at the center of Yegua-Jackson Aquifer model grid cells. The layer 1 general head boundary condition is shown in Figures 6.3.7 through 6.3.9 for the steady-state period, the beginning of the transient calibration period (1980), and the end of the transient calibration period (1997), respectively.

The conductance in the general-head boundary package, which represents the connection between the heads in the boundary condition and the heads calculated by the model, was calculated for each model grid cell as the vertical hydraulic conductivity of the Jasper Aquifer times the model grid cell size (1 square mile) divided by the distance between the midpoint of the Jasper Aquifer and the midpoint of the Catahoula Formation at the location of the grid cell. The vertical hydraulic conductivity for the Jasper Aquifer was initially estimated at 0.001 feet per day, based on the central Gulf Coast Aquifer groundwater availability model (Chowdhury and others, 2004).

6.3.3 Surface Water Implementation

Surface water acts as a head-dependent flow (Third Type) boundary condition for the top boundary of the active model grid cells in the portion of model layer 1 that represents the Yegua-Jackson Aquifer outcrop.

The reservoir package for MODFLOW (Fenske and others, 1996) simulates leakage between a reservoir and an underlying ground-water system as the reservoir area increases and decreases in response to changes in reservoir stage. Seven reservoirs are located within the Yegua-Jackson Aquifer outcrop (see Section 4.5.3). A model grid cell was assigned as a reservoir cell if the area of the reservoir intersecting it exceeded half of the cell size. Six of the seven reservoirs in the Yegua-Jackson Aquifer outcrop were simulated by the MODFLOW reservoir package in model layer 1 (Figure 6.3.10). The International Falcon Reservoir is not present in the model because the only portion of the reservoir on the outcrop has an area less than half the area of a model grid cell.

The stage of each reservoir cell is used to determine if the reservoir boundary is active by comparing it to the land-surface elevation. The historical reservoir stage data were collected from various sources as shown in Table 6.3.2. Yearly average stage from the impounding year was calculated and used in the reservoir package. For years when the stage is not available, an average of all the available data for a specific reservoir was used.

The reservoir package also requires the assignment of a conductivity and thickness for the reservoir bed in order to calculate the hydraulic conductance of the leakage between the reservoir and the ground-water system. Very limited data are available on the bed conductivity and thickness for reservoirs in the Yegua-Jackson Aquifer outcrop. Therefore, values of 0.001 foot per day and 1 foot were initially assumed for the conductivity and thickness, respectively.

The stream package for MODFLOW (Prudic, 1988) is a head-dependent flow boundary condition that offers a first-order approximation of surface water/groundwater interaction. The stream package allows for stream-related discharge during gaining conditions and for stream-related recharge during losing conditions. When pumping affects water levels near stream/aquifer connections, streams may change from gaining to losing or become more strongly losing. The stream package requires designation of segments and reaches. A reach is the smallest division of the stream network and is comprised of an individual grid cell. A segment is a collection of reaches that are contiguous and do not have contributing or diverting tributaries. In MODFLOW, the hydraulic connection (conductance) between the stream and the aquifer must be defined.

INTERA developed a geographical information system (GIS) based method for creating the reach and segment data coverages for MODFLOW. Figure 6.3.11 shows the grid cells in model layer 1 that contain stream reaches in the model domain. These were selected by intersecting the Enhanced River Reach File (Alexander and others, 1999) with the model grid, and then manually adding or removing cells where cells were missed or overly bunched together. Required physical properties of the reaches, including stream width, bed thickness, and roughness, were taken from the Enhanced River Reach File. The hydraulic conductivity used to define the hydraulic conductance between the aquifer and the stream was initially set to 1 foot per day. Stream bed elevation was initially set at the model top cell elevation minus 25 feet.

The stream package also requires specification of a stream flow rate at the starting reach of each headwater segment for each stress period. For both the steady-state condition and the historical period, representative stream gage data are limited for the majority of the stream segments. For both the steady-state and transient simulations, mean flow rates from the Enhanced River Reach File were used to specify the flow rate entering each model headwater segment. The Enhanced

River Reach File contains mean flow rates estimated along the entire stream and coinciding with all of the modeled stream segments.

Spring discharge records were reviewed for application in the Yegua-Jackson Aquifer groundwater availability model as drain boundary conditions (Type 3). Table 4.5.4 summarizes the documented springs in the model domain. Figure 6.3.12 shows the location of the drain cells representing springs in the region.

6.3.4 Implementation of Recharge and Evapotranspiration

Section 4.4 discusses the initial implementation of recharge in the model. The average precipitation for the time period from 1971 through 2000 (Figure 2.1.5) was used to estimate recharge for the steady-state period and the transient periods. Recharge was not varied through time in the transient period.

Recharge may be influenced by topography, as described in Section 4.4.5. This was implemented using a scaled topographic factor, as shown in Figure 4.4.9. The precipitation based recharge was multiplied by the topographic factor, then the recharge distribution was normalized back to the original model-wide average. The recharge distribution was finalized during the steady-state calibration process as discussed in Section 8.

For the simulation of evapotranspiration, the evapotranspiration package was applied to cells neighboring stream cells in the Yegua-Jackson Aquifer outcrop (Figure 6.3.12). Parameters required in the evapotranspiration package include maximum evapotranspiration rate, extinction depth, and elevation of evapotranspiration surface. Following Scanlon and others (2005), the maximum evapotranspiration rate can be estimated by the product of potential evapotranspiration and crop coefficient. The vegetation rooting depth was used as the extinction depth, and the elevation of the top of the model served as the elevation of the evapotranspiration surface. Both vegetation coefficient and rooting depth were adopted from the database in Scanlon and others (2005) according to the land type.

6.3.5 Implementation of Pumping Discharge

Pumping discharge can be a primary stress on the model during the transient period. Pumping discharge is a cell dependent specified flow boundary. The TWDB provides an ArcGIS-based pumpamatic tool to facilitate development of the pumpage data for the model. The pumpamatic master tables, one of the inputs of the pumpamatic tool, contain total pumpage of each supplier for localized pumping categories and of each county-basin for distributed pumping categories. The master tables provided by the TWDB originally categorized the Yegua-Jackson Aquifer with other minor aquifers together as “OTHER AQUIFERS”. Therefore, the first task was to determine the amount of “OTHER AQUIFERS” pumpage to apply to the Yegua-Jackson Aquifer. The processes used to make that determination are described in Section 4.6.2. Based on the results, the master tables for each category were updated to show pumpage for the Yegua-Jackson Aquifer only.

The spatial distribution of pumpage to model grid cells for each category was completed by following the procedures described in the TWDB Pumpamatic Memo (Hamlin and Anaya, 2006). Municipal, manufacturing and mining are the three localized pumping categories for the Yegua-Jackson Aquifer. The master tables from the pumpamatic tool for these categories were linked on key fields to the TWDB groundwater database (TWDB, 2008b) to determine the location, depth, and other detailed information for the wells associated with the records in the master tables. The key field for the master tables is ‘alphanum’ and for the TWDB groundwater database is ‘user_code_econ’. For those master table records where ‘alphanum’ did not find a match in the TWDB groundwater database, supplier information was used to find a match. If that fail to yield a match, an attempt was made to locate wells associated with the supplier using the United States Environmental Protection website or Google Earth.

For some records in the master tables where a match was successfully found in the TWDB groundwater database, the pumping category defined by the master tables did not match the pumping category given in the TWDB groundwater database. In those cases, the information in the TWDB groundwater database was assumed to provide the most up-to-date and precise data, and the associated pumpage record in the master tables was either relocated to the master table associated with the use information in the TWDB groundwater database or removed if the TWDB groundwater database indicated the well was unused. These changes were made based on discussions with TWDB staff. After making these adjustments, all the mining wells were either moved to the manufacturing category or removed from the master tables, leaving only municipal and manufacturing categories for localized pumping for Yegua-Jackson Aquifer.

Determination of the model layer for assignment of localized pumping consisted of comparing the well depth and completion interval, as given in the TWDB groundwater database, to the model layer structure. If the completion interval fell within a single model layer, pumpage for that well was assigned to that layer. When the well depth and completion interval were not available, the vertical layer from a nearby well was assumed.

Irrigation, livestock, and rural domestic pumping were considered to be distributed pumping for the Yegua-Jackson Aquifer. The pumping for these three categories was assigned to the outcrop area of the Yegua Jackson Aquifer only. Vertically, the pumping was assumed to occur in model layer 1 (i.e., the shallow portion of the Yegua-Jackson Aquifer).

Once the pumping was estimated for each of the seven user groups (municipal, manufacturing, livestock, irrigation, and rural domestic), it was summed across all use groups for a give model grid cell (row, column, layer) and a given stress period. This process was repeated for each active grid cell and each stress period in the transient portion of the model.

For pre-1980 pumping, the total pumping for each county and each category was estimated as described in Section 4.6.2. The spatial distribution of pumping for the pre-1980 time period used two ratios. In order to determine how much pumping to assign to each county, the ratio of the average 1980 to 1997 pumping in the county to the average 1980 to 1997 pumping in all counties (i.e., the total pumping) was calculated for each pumping category. In order to determine the amount of pumping to assign to each grid cell within a county, the ratio of the average 1980 to 1997 pumping for that cells to the average 1980 to 1997 pumping for all cells in the county was calculated for each pumping category. For a given pumping category, these two ratios were then used to calculate the pumping for each model grid cells from the total pumping for each model stress period. The pre-1980 pumping from each category was then summed for each model grid cell and model stress period.

Throughout the transient portion of the model, the majority of pumping is from the portion of model layer 1 that represents the outcrop area of the Yegua-Jackson Aquifer. A small amount of localized pumping occurs in the near downdip portion of the model in layers 2 through 5. Figures 6.3.13 through 6.3.15 show the distribution of total pumping in the Yegua-Jackson Aquifer for the beginning of the transient model period (1901 to 1910), the first year of the model calibration period (1980), and the last year of the model calibration period (1997), respectively. The majority of pumpage from the Yegua-Jackson Aquifer in Texas occurs in the outcrop areas in Angelina, Brazos, Burleson, Fayette, Grimes, Houston, Lee, Madison, Trinity, and Washington counties. Of the water pumped from the Yegua-Jackson Aquifer, typically the largest volume per county is used for rural domestic purposes.

Table 6.3.1 Stress periods for the Yegua-Jackson Aquifer groundwater availability model.

Model Stress Period	Inclusive End Year	Stress Period Length (years)	Model Stress Period	Inclusive End Year	Stress Period Length (years)
1	steady-state		15	1985	1
2	1910	10	16	1986	1
3	1920	10	17	1987	1
4	1930	10	18	1988	1
5	1940	10	19	1989	1
6	1950	10	20	1990	1
7	1960	10	21	1991	1
8	1970	10	22	1992	1
9	1979	9	23	1993	1
10	1980	1	24	1994	1
11	1981	1	25	1995	1
12	1982	1	26	1996	1
13	1983	1	27	1997	1
14	1984	1			

Table 6.3.2 Sources of historical reservoir stage data.

Reservoir Name	Data Source
Toledo Bend Reservoir	United States Geological Survey (2008b)
Sam Rayburn Reservoir	United States Army Corps of Engineers (2008)
Lake Livingston	United States Geological Survey (2008b)
Gibbons Creek Reservoir	Texas Parks and Wildlife (2008)
Somerville Lake	United States Army Corps of Engineers (2008)
Choke Canyon Reservoir	Nueces River Authority (2008)

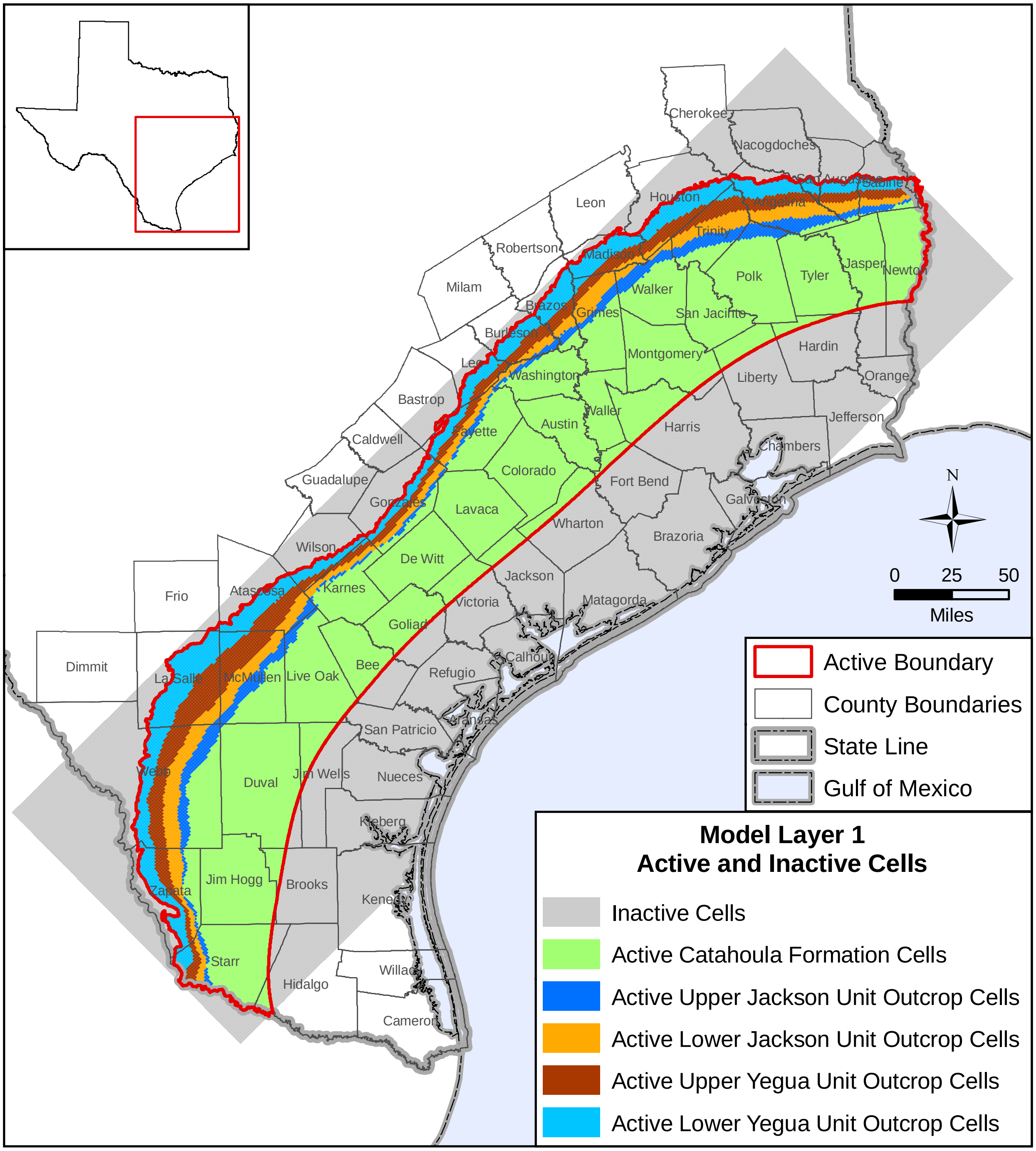


Figure 6.3.1 Layer 1 active/inactive model grid cells.

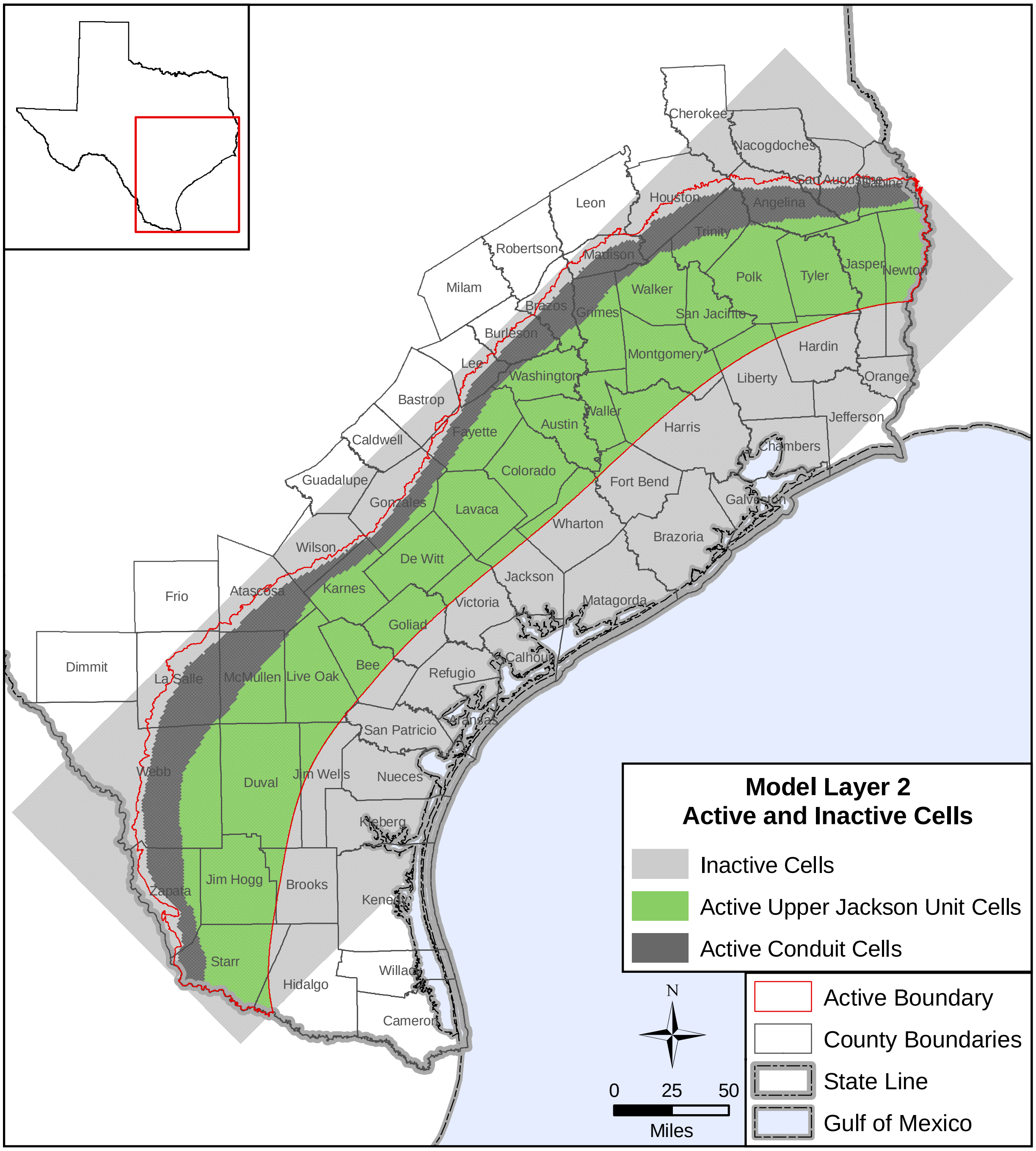


Figure 6.3.2 **Layer 2 active/inactive model grid cells.**

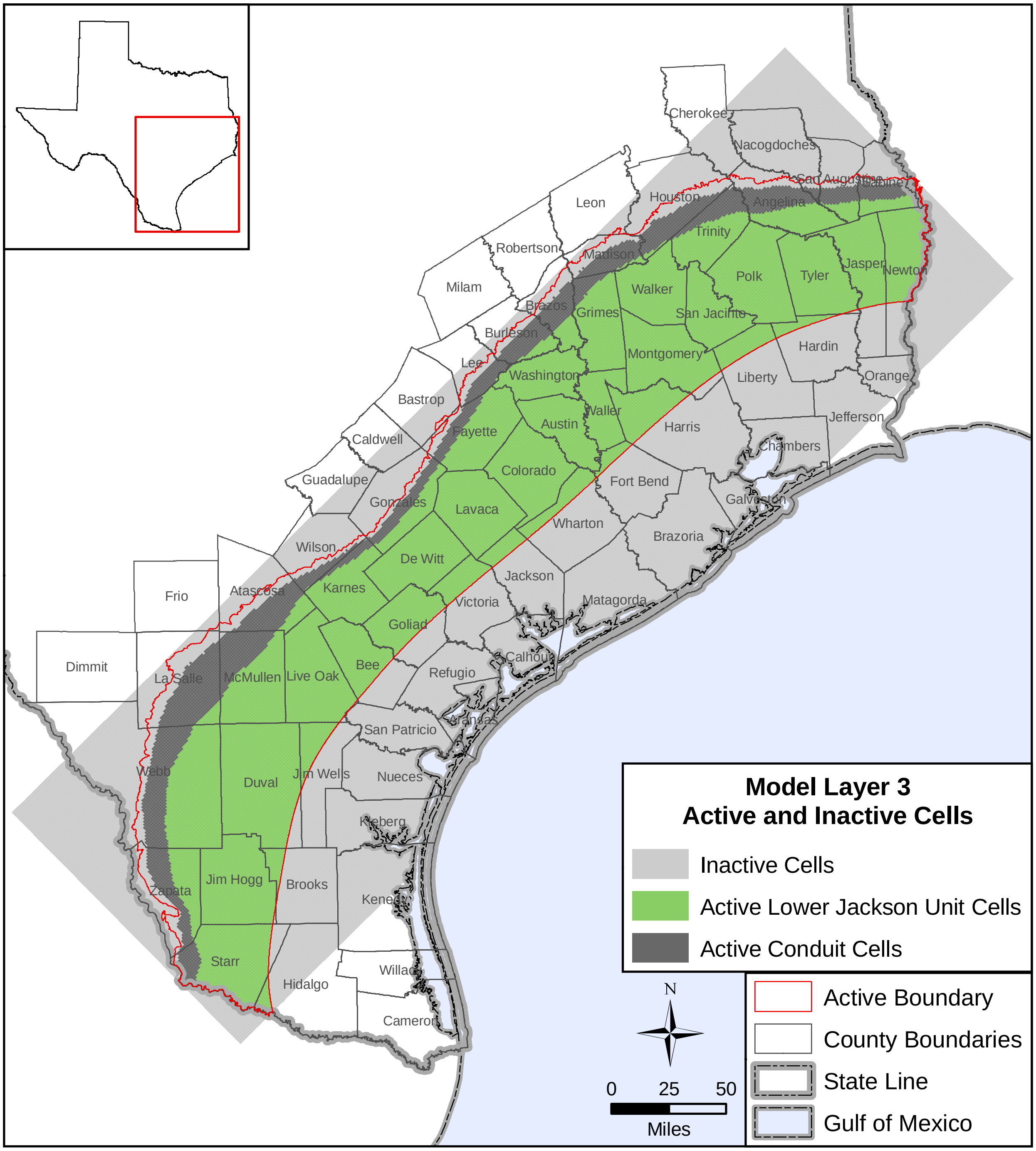


Figure 6.3.3 Layer 3 active/inactive model grid cells.

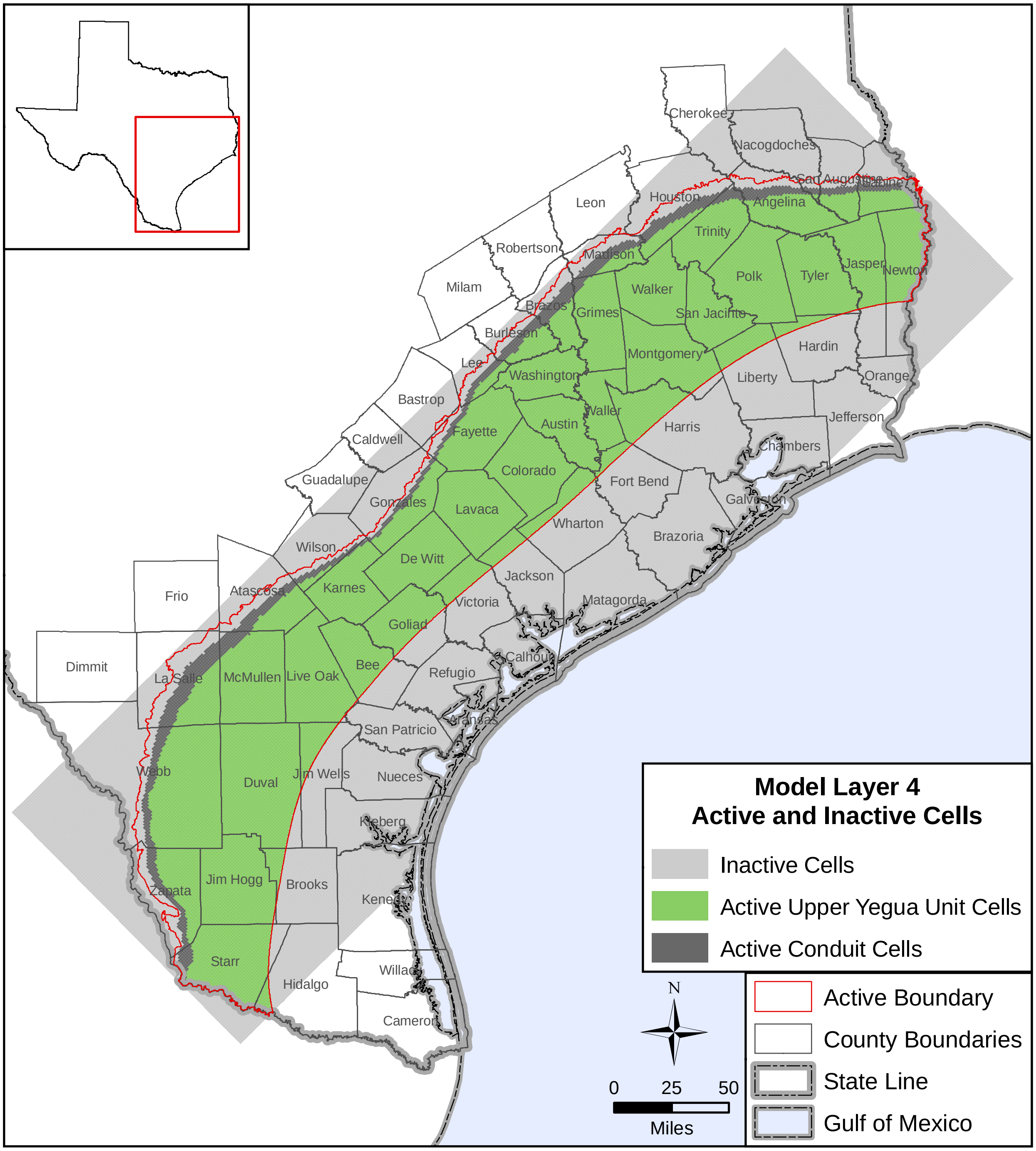


Figure 6.3.4 Layer 4 active/inactive model grid cells.

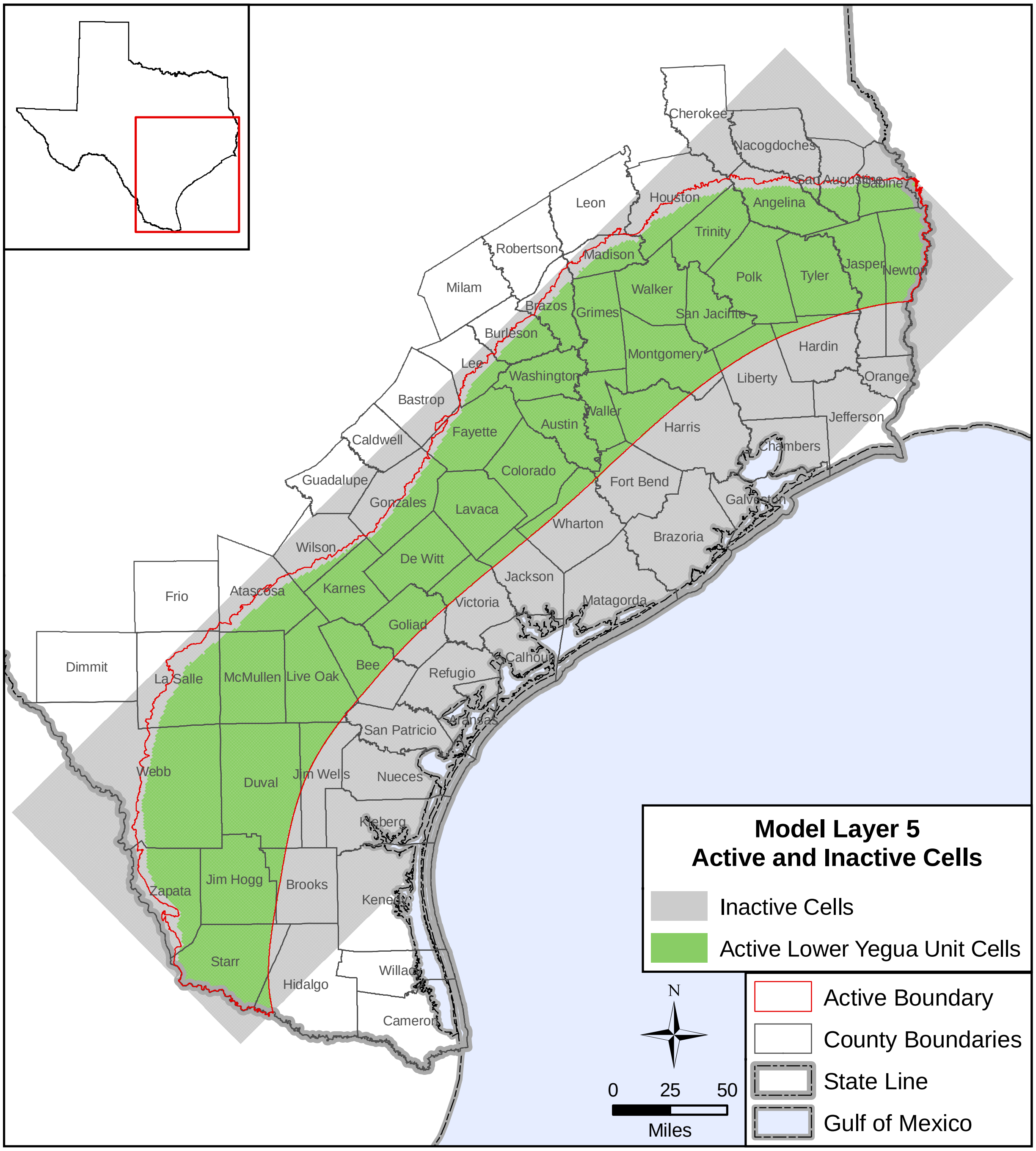
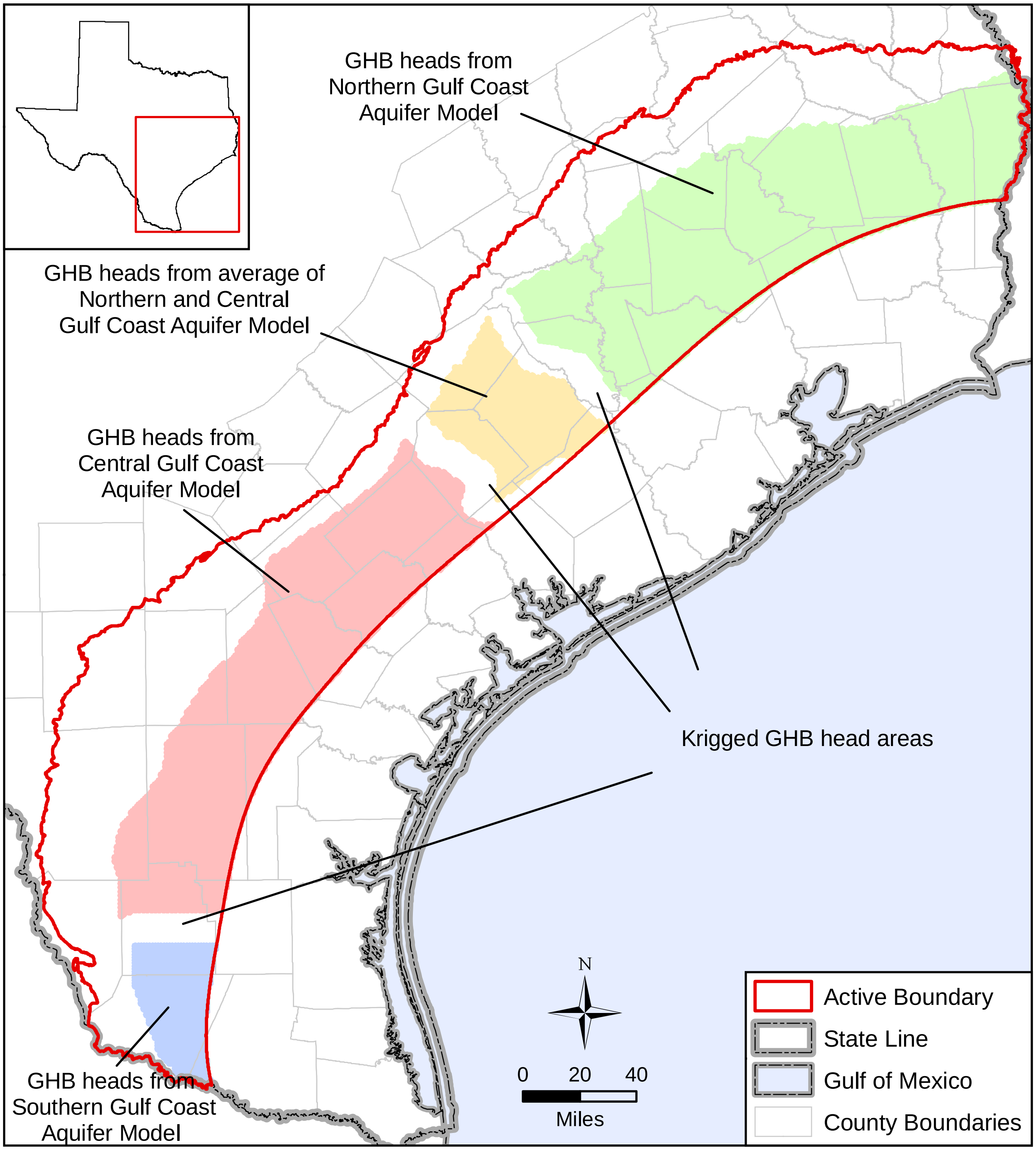


Figure 6.3.5 Layer 5 active/inactive model grid cells.



GHB = general head boundary

Figure 6.3.6 Schematic illustration of Jasper Aquifer head values used to develop the general head boundary conditions for the portion of model layer 1 that represents the Catahoula Formation.

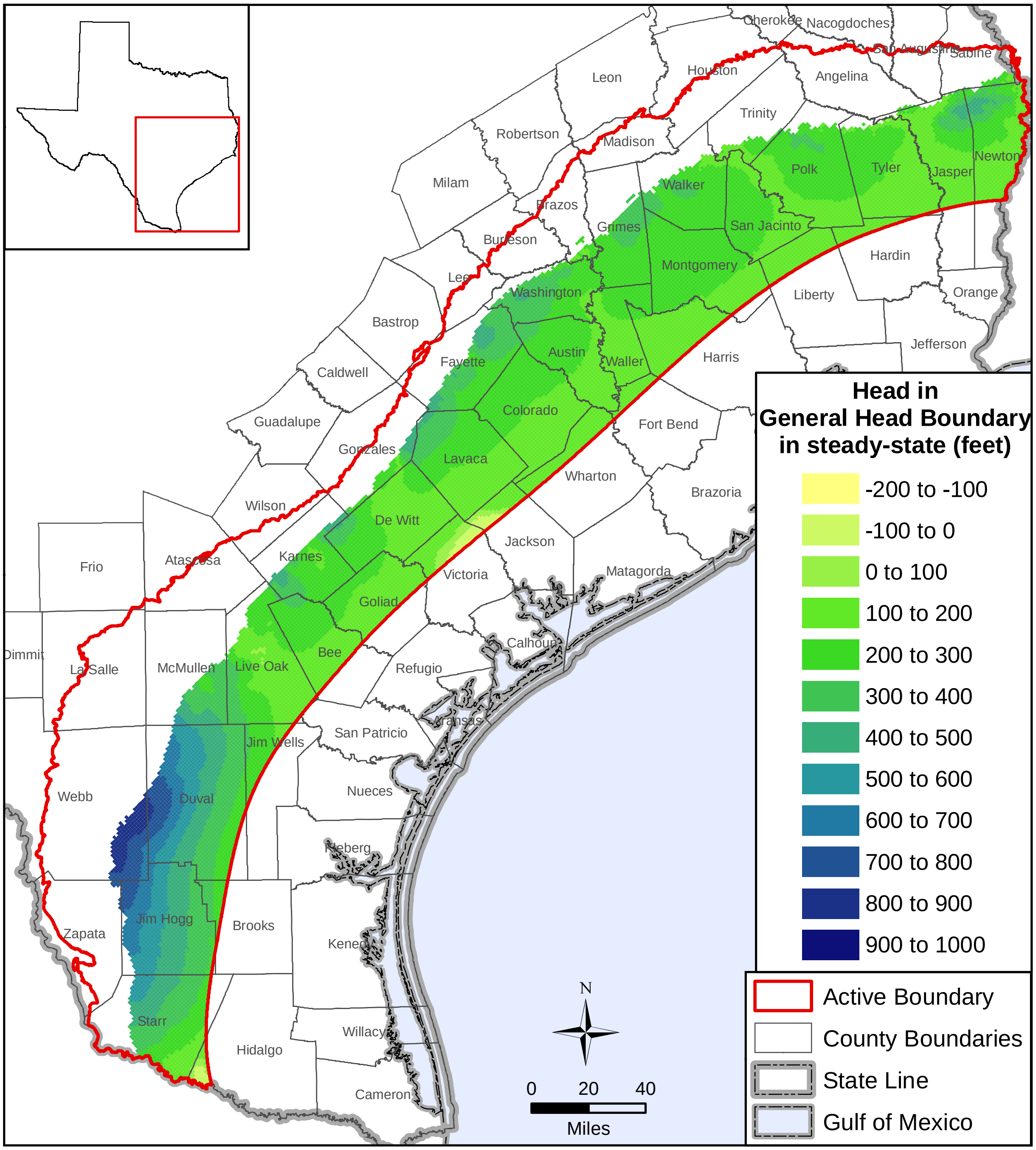


Figure 6.3.7 Layer 1 general head boundary condition for steady-state model calibration.

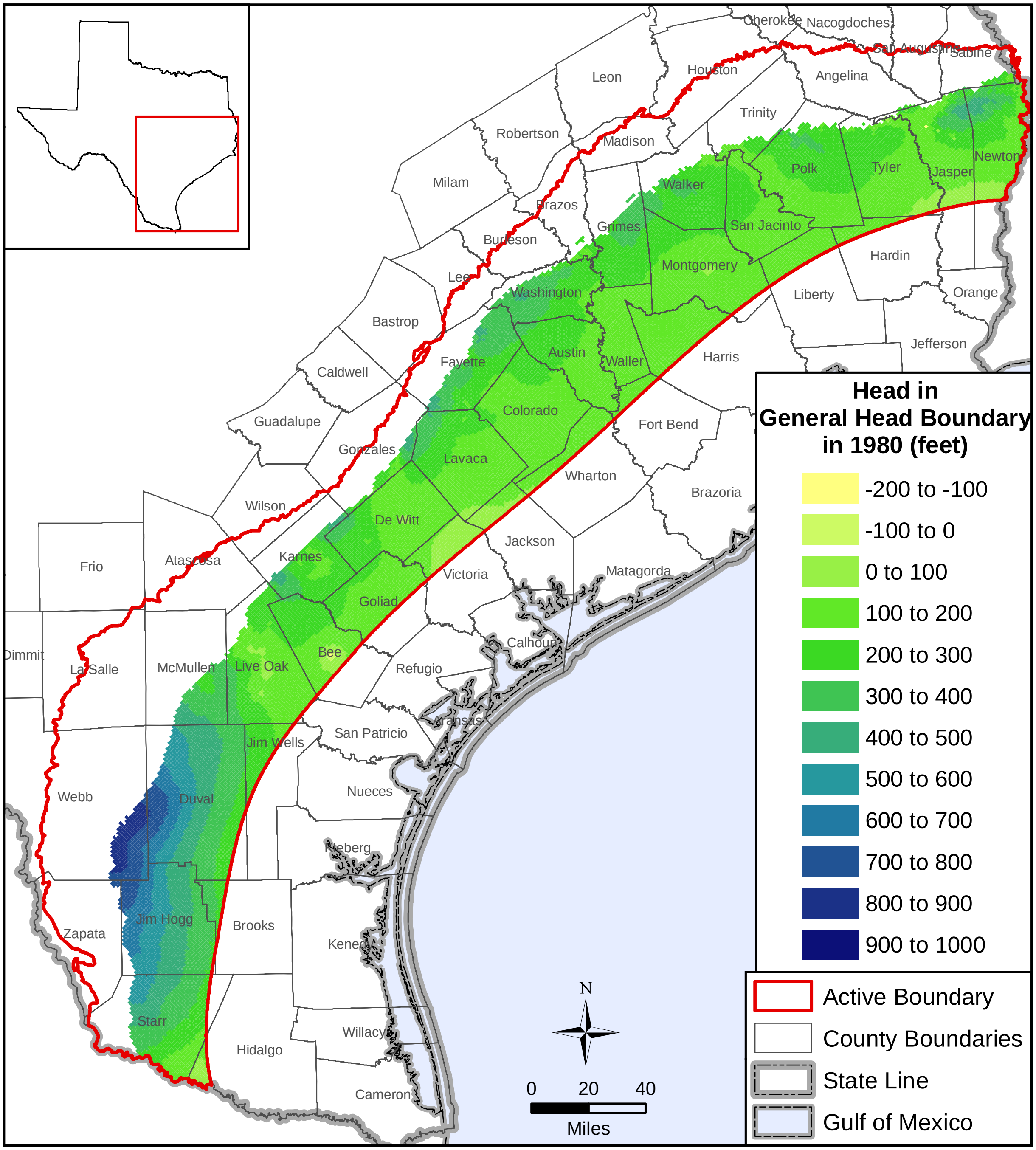


Figure 6.3.8 Layer 1 general head boundary condition for the beginning of the transient model calibration period (1980).

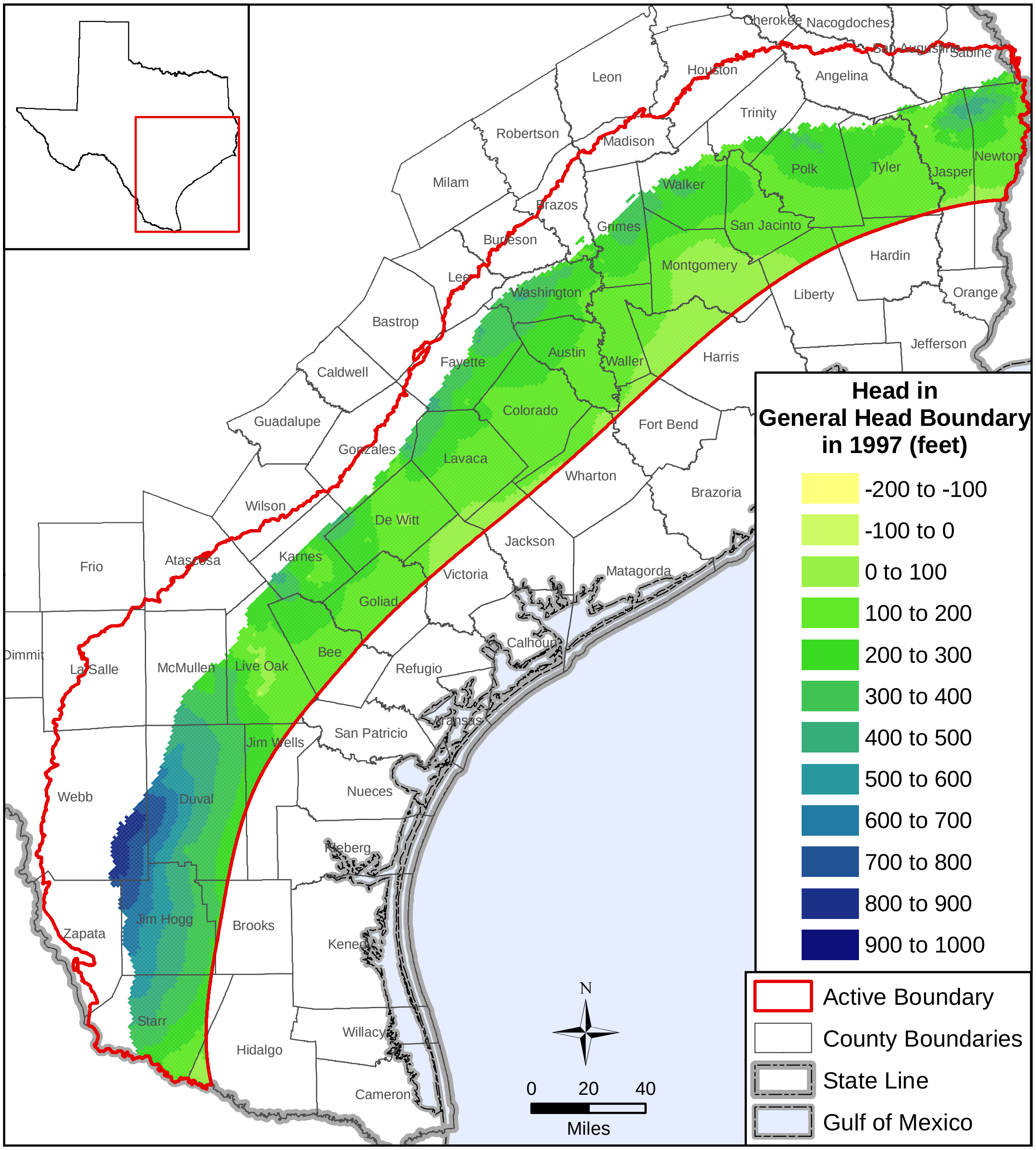


Figure 6.3.9 Layer 1 general head boundary condition for the end of the transient model calibration period (1997).

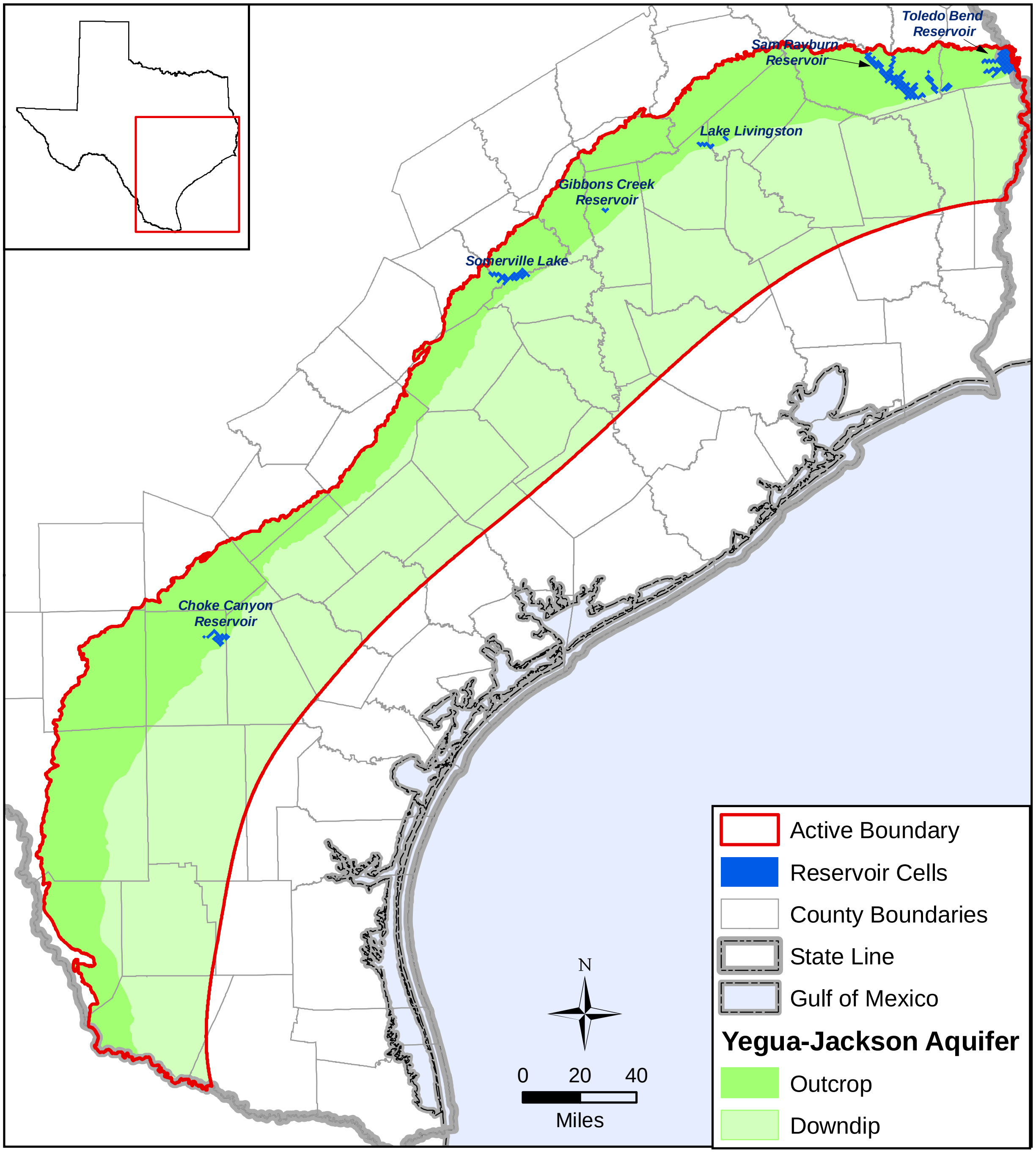


Figure 6.3.10 Reservoir boundary conditions.

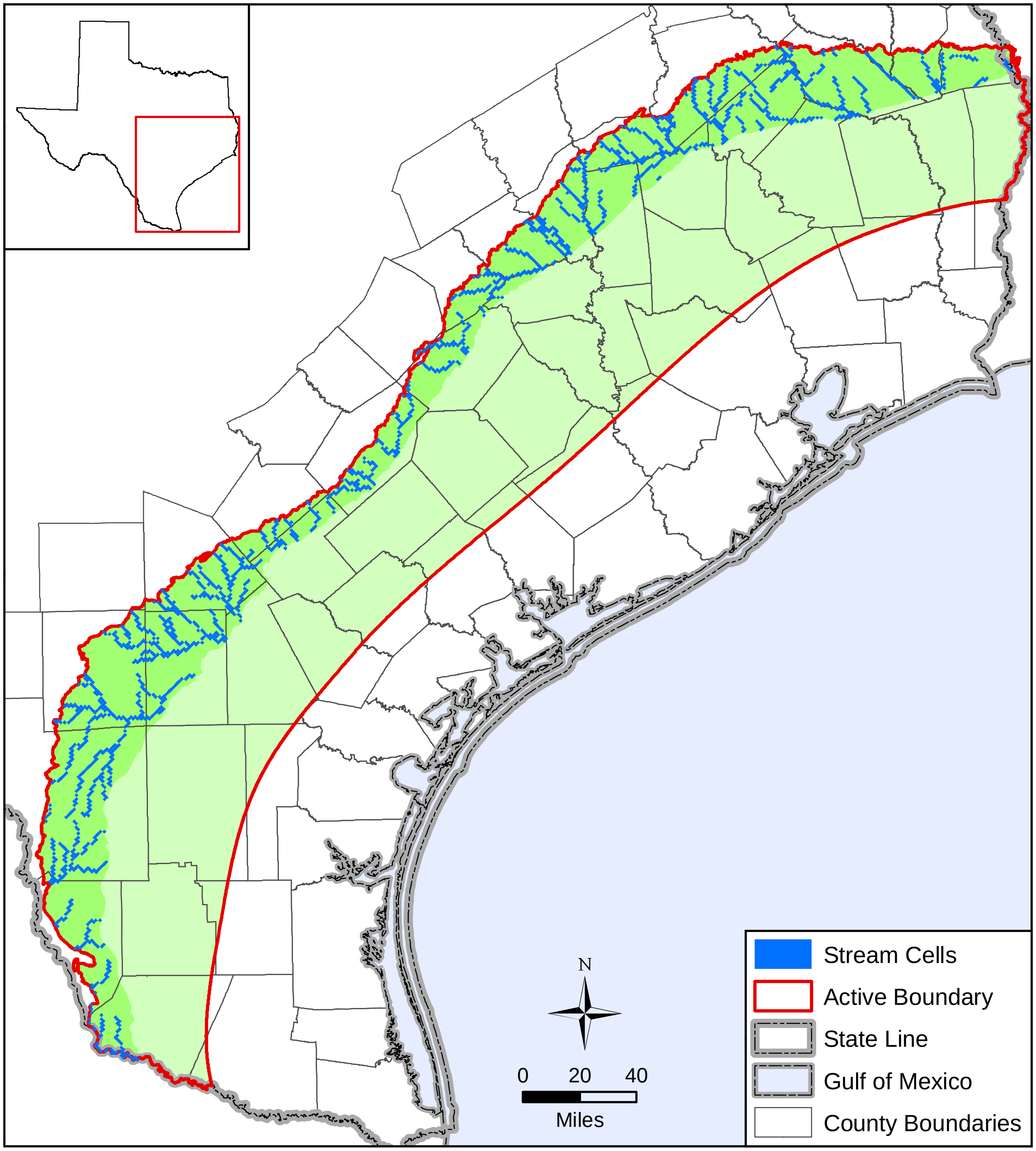


Figure 6.3.11 Stream boundary conditions.

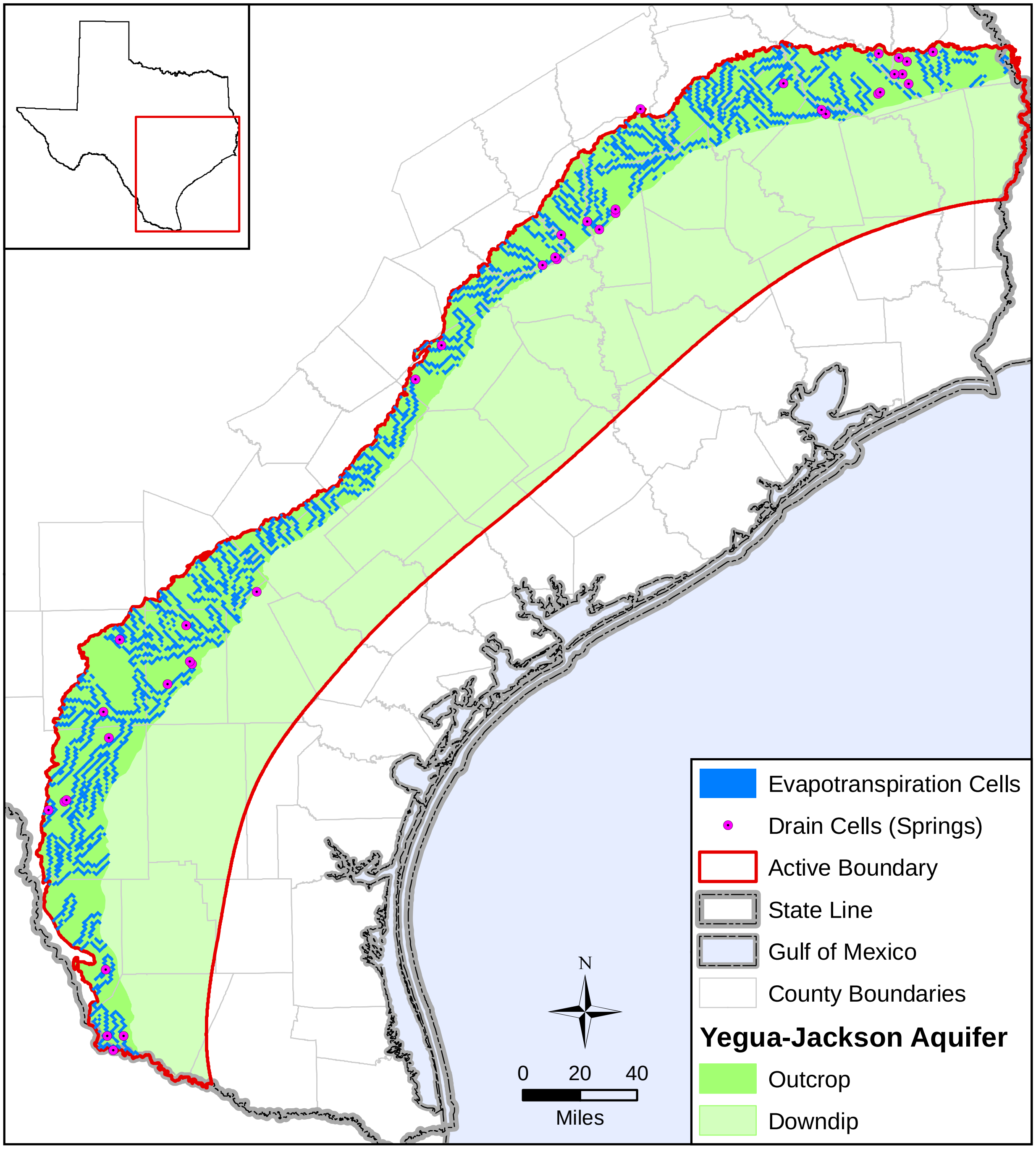


Figure 6.3.12 Drain (spring) and evapotranspiration boundary conditions.

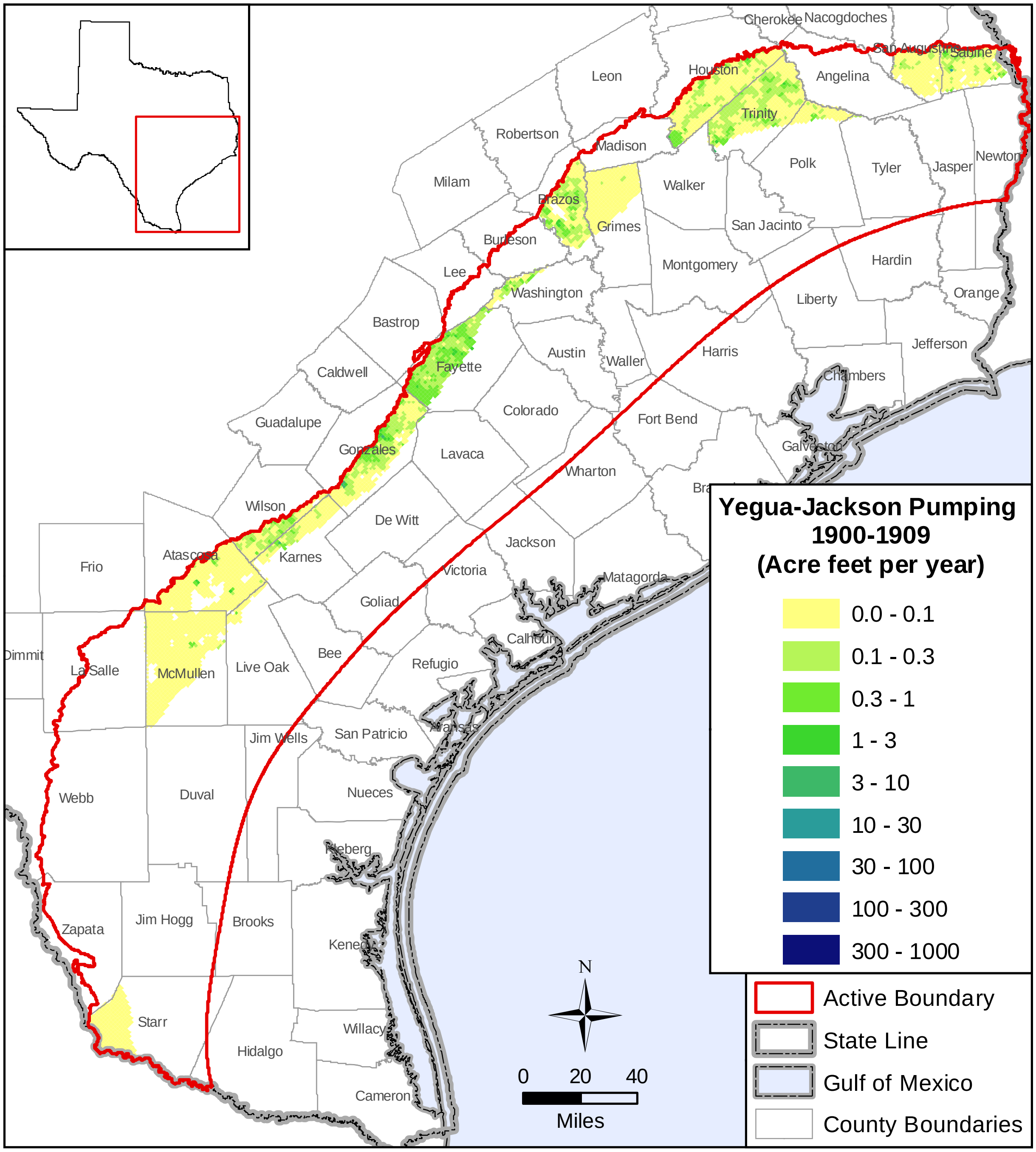


Figure 6.3.13 Pumping distribution in acre-feet per year for the Yegua-Jackson Aquifer at the beginning of the transient model period (1901 through 1910).

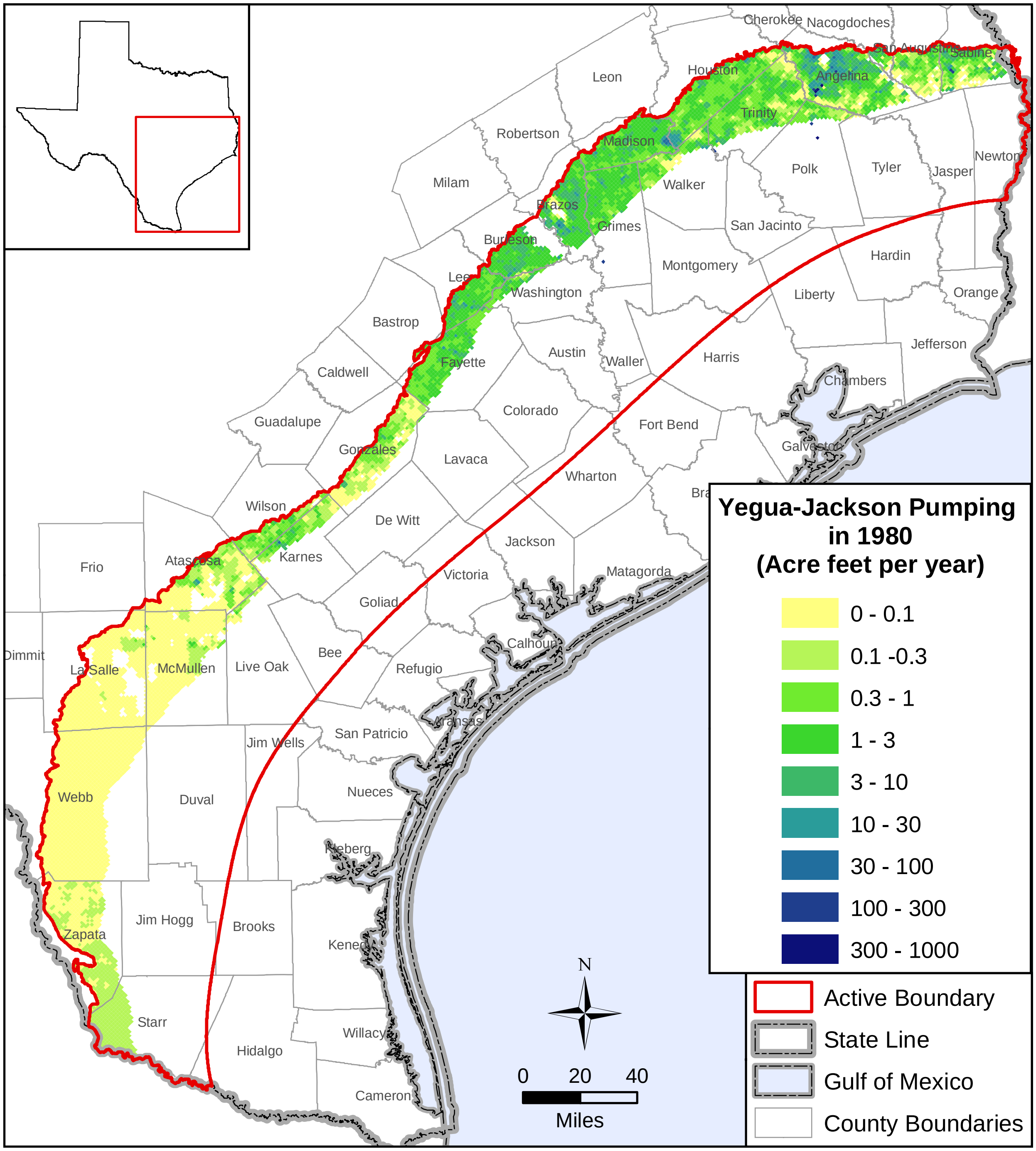


Figure 6.3.14 Pumping distribution in acre-feet per year for the Yegua-Jackson Aquifer at the beginning of the transient model calibration period (1980).

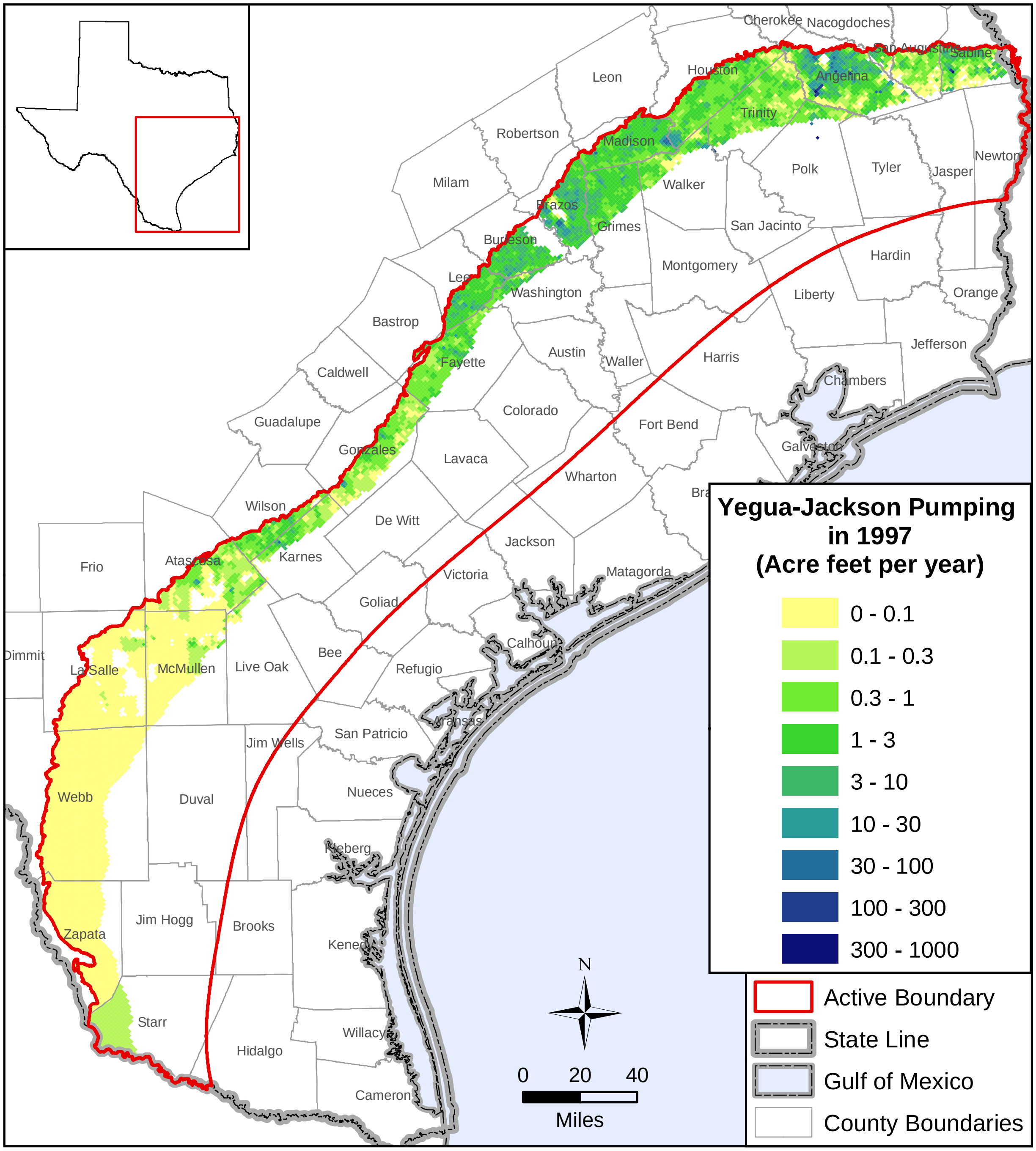


Figure 6.3.15 Pumping distribution in acre-feet per year for the Yegua-Jackson Aquifer at the end of the transient model calibration period (1997).

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6.4 Model Hydraulic Parameters

For the steady-state model, the primary hydraulic parameter to be estimated and distributed across the model grid is hydraulic conductivity. For the transient model, the storage coefficient must also be included.

6.4.1 Hydraulic Conductivity

Development of the conceptualization of horizontal hydraulic conductivity within the Yegua-Jackson Aquifer is described in Section 4.7. In general, horizontal hydraulic conductivity varies as a function of geologic unit (Upper Jackson Unit, Lower Jackson Unit, Upper Yegua Unit, and Lower Yegua Unit), major depositional environment (fluvial, delta, and shelf), and depth of burial. The initial distribution of horizontal hydraulic conductivity in the model was developed using the values for sand given in Table 4.7.6 and the depth trend given in Figure 4.7.11.

Through the model calibration process, the sand horizontal hydraulic conductivity values for each depositional environment type and each geologic unit were adjusted to obtain the final calibrated horizontal hydraulic conductivity field for each model layer as discussed and illustrated in Section 8.

Vertical hydraulic conductivity is not measurable on a regional model scale and is, therefore, generally a parameter that is calibrated within predefined limits. As noted in Section 4.7, the vertical conductivity will primarily be based on the estimated vertical conductivity of the clays, and the clay content in a unit. Overall vertical conductivity was calculated based on equation 4.7.1, with an initial estimated clay conductivity of 0.001 feet per day. The final calibrated vertical conductivities are presented in Section 8.

6.4.2 Storage Coefficient

For unconfined aquifer conditions, the specific yield was assumed to be homogeneous and was assigned a value equal to 0.15 for all geologic units. For the confined portion of the Yegua-Jackson Aquifer, specific storage was calculated based on equation 4.7.2, combining sand and clay:

$$Ss = (A_S f_S + A_C f_C) / [D + 32.8] \qquad (6.4.1)$$

where S_S is the specific storage, A_S is the parameter for sand, A_C is the parameter for clay, f_S and f_C are the fractions of sand and clay, respectively, and D is the depth of burial. The storativity was calculated by multiplying the thickness of the layer by the specific storage. Figures 6.4.1 through 6.4.4 show the variation in storativity for each of the units comprising the Yegua-Jackson Aquifer. Note that in layer 1, storativity was set to 1.0 to simulate ponding on ground surface.

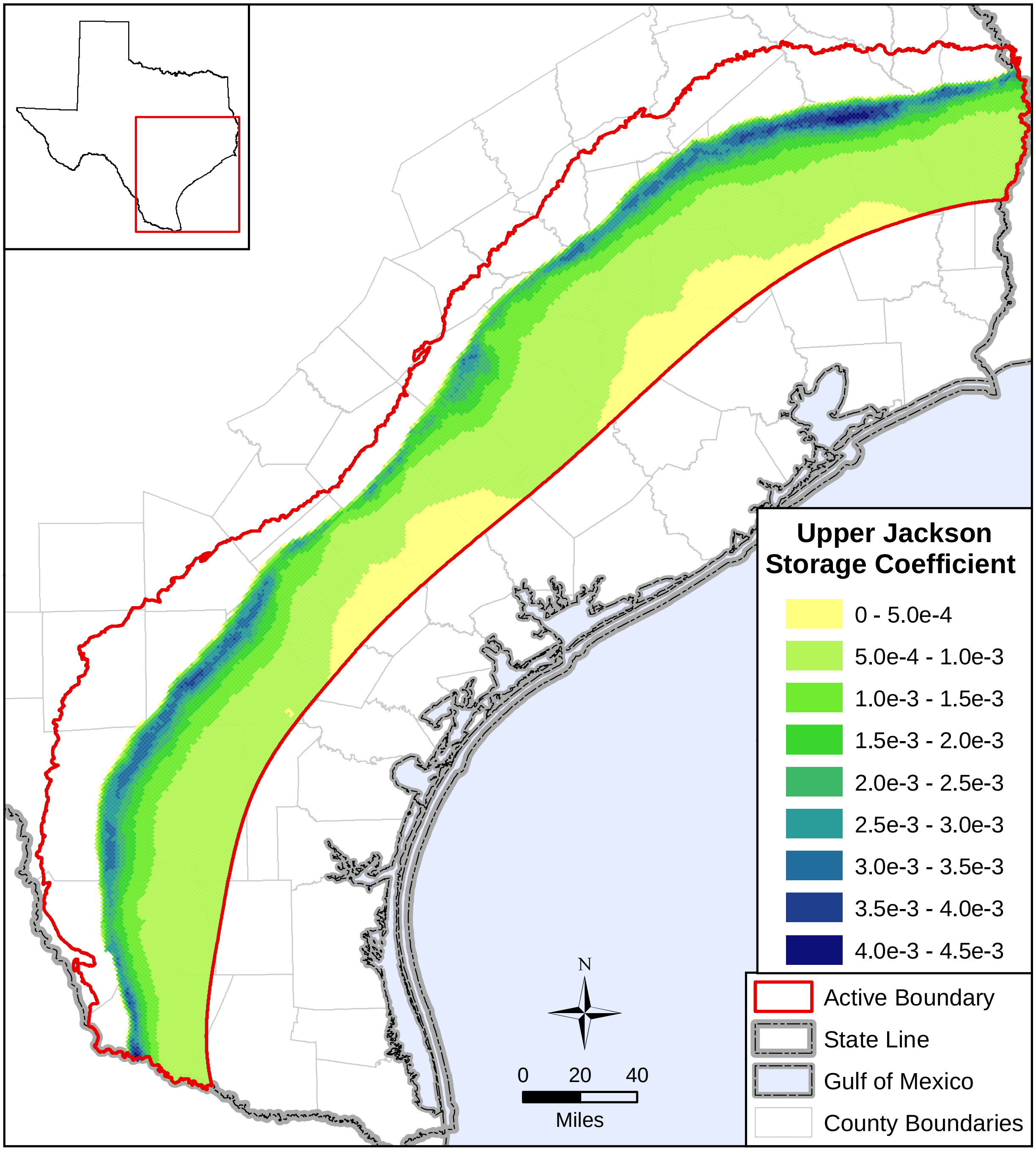


Figure 6.4.1 Storativity in the confined portion of the Upper Jackson Unit

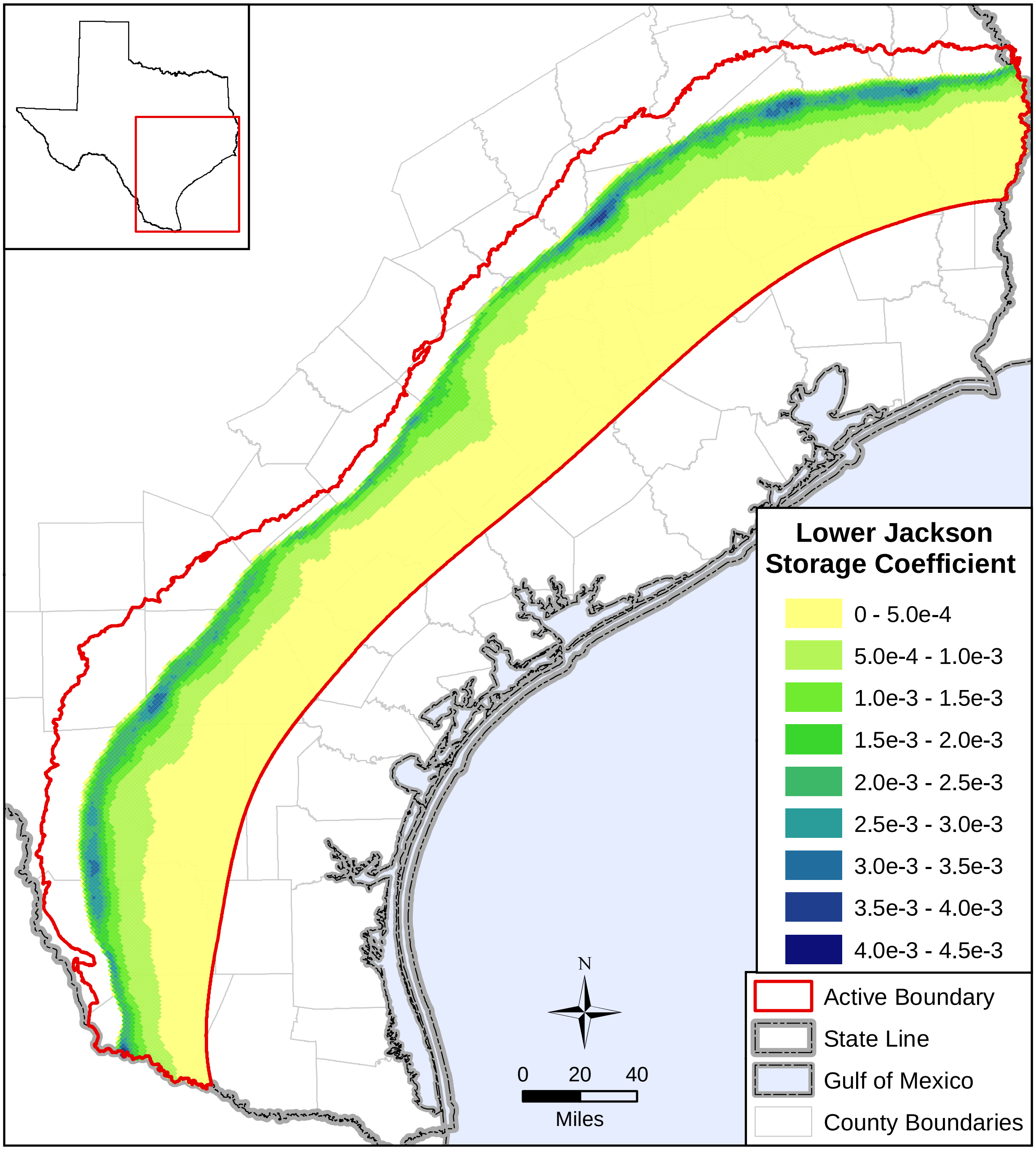


Figure 6.4.2 Storativity in the confined portion of the Lower Jackson Unit

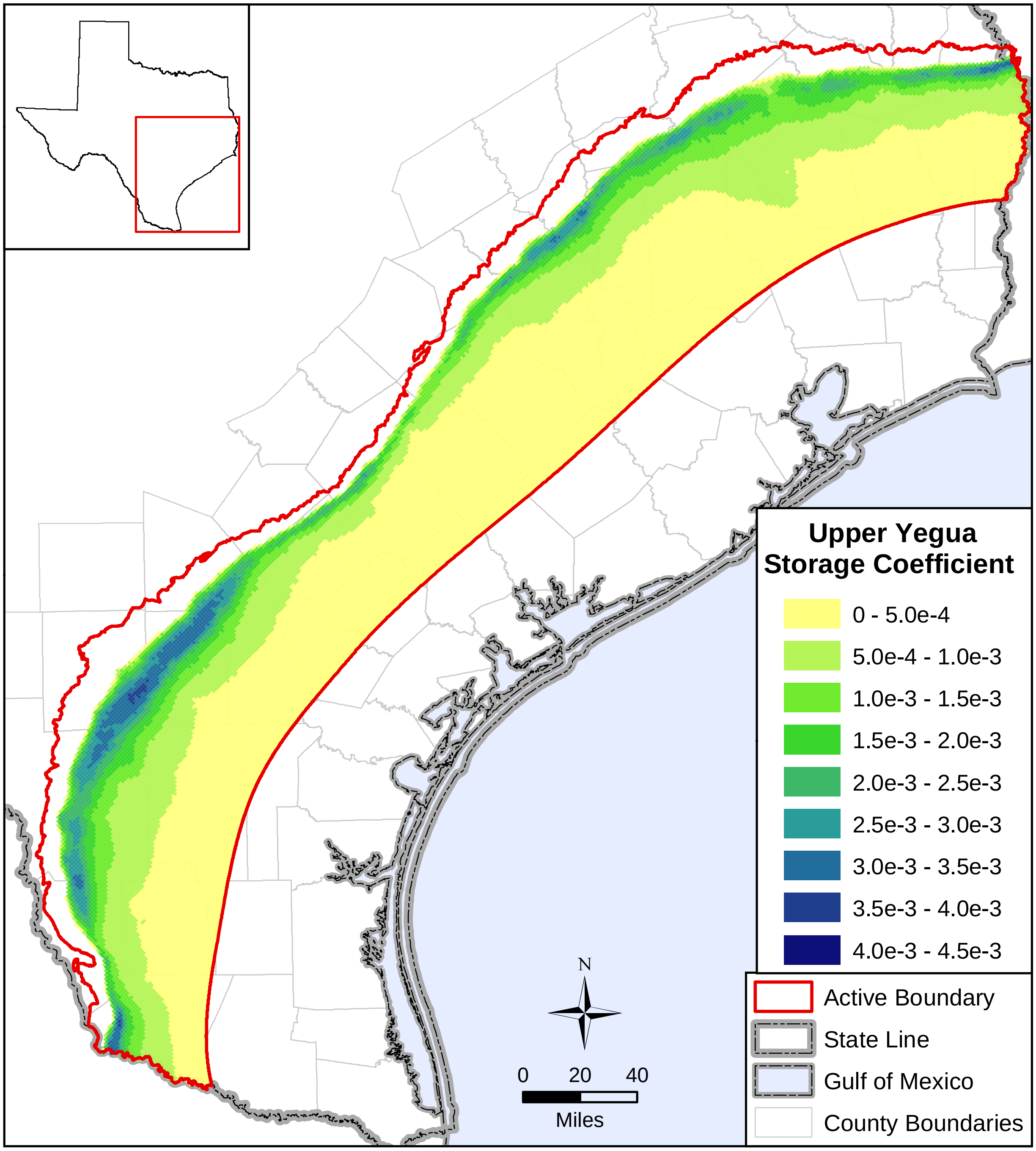


Figure 6.4.3 Storativity in the confined portion of the Upper Yegua Unit

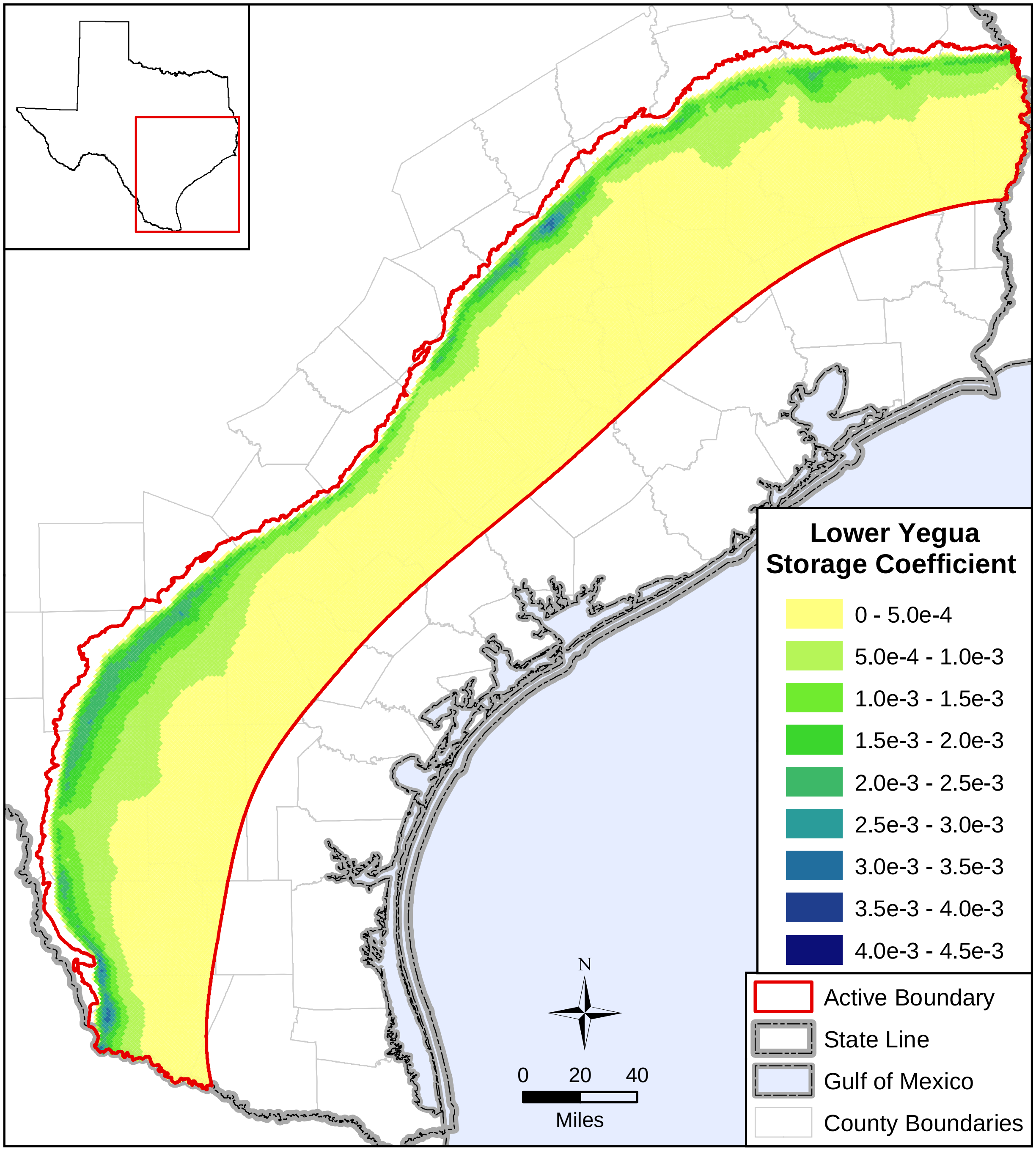


Figure 6.4.4 Storativity in the confined portion of the Lower Yegua Unit

7.0 Modeling Approach

The modeling approach included model calibration and model sensitivity analysis. In the context of groundwater modeling, model calibration can be defined as the process of producing an agreement between model simulated water levels and aquifer discharge, and field measured water levels and aquifer discharge through the adjustment of independent variables. Because the steady-state and transient models are combined within a single model, changes to the model made during calibration were propagated to both the steady-state and transient models.

The generally accepted practice for groundwater calibration includes performance of a sensitivity analysis. A sensitivity analysis entails the systematic variation of the calibrated parameters and stresses with re-simulation of aquifer conditions. Those parameters which strongly change the simulated aquifer water levels and discharges are important parameters to the calibration.

7.1 Calibration

Groundwater models are inherently non-unique, meaning that multiple combinations of hydraulic parameters and aquifer stresses can reproduce measured aquifer water levels. To reduce the impact of non-uniqueness, a calibration method described by Ritchey and Rumbaugh (1996) was employed. This method includes (1) calibrating the model using parameter values (i.e., hydraulic conductivity, storage coefficient, and recharge) that are consistent with measured values, (2) calibrating to multiple hydrologic conditions, and (3) using multiple calibration performance measures such as water levels and discharge rates to assess calibration. Each of these elements is discussed below.

Measured sand hydraulic conductivities for the Yegua-Jackson Aquifer and literature values of clay hydraulic conductivity, specific yield, and sand and clay specific storage were used to initially estimate model parameters. The analysis of hydraulic parameters in Section 4.7 of this report indicates that adequate hydraulic conductivity data for the Yegua-Jackson Aquifer are available for developing initial model values in the active, shallow portion of the aquifer. There were not measurements in the deeper sections, where the water quality is poor. Thus, the conductivity in the deeper section is poorly constrained initially, and because there are no targets in that section, will not be particularly well-constrained during calibration. This has minimal impact on the utility of the model for predicting aquifer conditions in the currently utilized shallower portion of the aquifer.

Vertical hydraulic conductivity is not measurable at the model scale and, thus, cannot be well constrained prior to calibration. We rely on an initial range of clay conductivity values from the literature and previous studies, along with the conceptualization described in Section 4.7. Specific yield for the Yegua-Jackson Aquifer was based on and was reasonably well constrained within literature values. Storativity for the Yegua-Jackson Aquifer was developed based on sand maps and literature values for the specific storage of clay and sand. Storativity is reasonably well constrained by these literature values and approach.

There are no direct measurements of recharge in the study area, although two estimates of “deep” recharge were available from county reports. The estimate of recharge based on baseflow described in Section 4.4.2 provides a minimum constraint on shallow recharge.

Adjustment of all model parameters were held to within plausible ranges based upon the available data and relevant literature. Adjustments to aquifer parameters from initial estimates were minimized, to the extent possible, to meet the calibration criteria. As a general rule, parameters with few measurements were adjusted preferentially as compared to properties with good supporting data.

The model was calibrated for two time periods, one representing pre-development conditions and the other representing transient conditions. The steady-state calibration considers a “pre-development” time period prior to extensive aquifer development. The transient calibration period ran from 1980 through 1997 consistent with groundwater availability model requirements. At a minimum, we report the transient calibration statistics from this period. In addition, we examined hydrographs for the full historical period from 1901 to 1997 and used these as an additional guide during transient calibration.

The actual transient simulation consists of a steady-state period followed by a transient period beginning in 1901 to account for the development and associated impact on storage prior to the 1980 to 1997 transient calibration period. Pumping estimates based upon historical records were applied on an annual time scale in the transient calibration period. Some additional analysis of pumping was required during transient calibration to match the very local drawdowns that occur in the Yegua-Jackson Aquifer. This additional analysis is described in Section 9. Recharge and headwater stream flow remain constant throughout the transient period.

The model was calibrated through a range of hydrological conditions. The steady-state model represents a period of equilibrium where aquifer recharge and aquifer discharge are in balance. The transient calibration period (1980 through 1997) represents a time of transient aquifer behavior. The transient calibration period also helps to constrain the model parameterization because a wider range of hydrologic conditions are encountered and simulated. The sensitivity of the transient model to certain parameters differs from that of the steady-state model.

Calibration requires development of calibration targets and specification of calibration measures. To address the issue of non-uniqueness, it is best to use as many types of calibration targets as possible. The primary type of calibration target is hydraulic head (water level). Simulated water levels were compared to measured water levels at specific observation points through time (hydrographs) to ensure that model water levels are consistent with hydrogeologic interpretations.

Stream baseflow estimates were also used as calibration targets. Because of the higher uncertainty associated with baseflow estimates compared to estimates of water levels, and the issues associated with modeling stream-aquifer interactions on a regional scale, these were considered to be secondary targets. Because the water levels in the Yegua-Jackson Aquifer are relatively stable regionally, baseflow targets were considered to be long-term averages and were, thus, compared to the flux results of the steady-state model.

Springs constitute a small portion of the total discharge from the model domain. Because of the scale of the model grid cells, gross averaging of elevations and local hydraulic properties occur within the model cell. Due to these limitations, springs do not provide much constraint to calibration for the Yegua-Jackson Aquifer. We did adjust model drain elevations and conductivities to ensure a good match for the majority of springs simulated.

Traditional calibration measures (Anderson and Woessner, 1992), such as the mean error and the mean absolute error, quantify the average error in the calibration process. The mean error is the mean of the differences between simulated heads (h_s) and measured heads (h_m):

$$\text{mean error} = \frac{1}{n} \sum_{i=1}^{n} \left(h_s - h_m\right)_i \qquad (7.1.1)$$

where *n* is the number of calibration measurements. The mean absolute error is the mean of the absolute value of the differences between simulated heads (h_s) and measured heads (h_m):

$$\text{mean absolute error} = \frac{1}{n} \sum_{i=1}^{n} \left|\left(h_s - h_m\right)_i\right| \qquad (7.1.2)$$

where *n* is the number of calibration measurements. The difference between the measured hydraulic head and the simulated hydraulic head is termed a residual.

The mean absolute error was used as the basic calibration metric for heads. For the groundwater availability models, the typical calibration criterion for heads is a mean absolute error that is equal to or less than 10 percent of the observed head range in the aquifer being simulated. Because of the relative scarcity of data for the Yegua-Jackson Aquifer in the transient calibration period from 1980 to 1997, we considered the calibration statistics for both the transient period prior to 1980, and for the entire transient calibration period from 1980 to 1997 to judge the change in calibration with time.

The mean absolute error is useful for describing model error on an average basis but, as a single measure, it does not provide insight into spatial trends in the distribution of the residuals. An examination of the distribution of residuals is necessary to determine if they are randomly distributed over the model grid and not spatially biased. Post plots of head residuals for the steady-state, pre-1980 transient, and 1980-1997 transient calibration periods were used to judge the spatial aspects of the calibration. These plots indicate the magnitude and direction of the mismatch between the observed and simulated heads. Finally, plots of simulated versus observed water-level elevations and residual versus observed water levels were used to determine if the head residuals are biased based on the magnitude of the observed head surface.

The conventional approach to model calibration is to make successive incremental changes to the various adjustable model parameters and evaluate the impacts of the changes on the calibration metrics discussed previously. This is called "manual" calibration, where the modeler is directly modifying parameters, typically one at a time. For some models, this process can be enhanced by performing some "automated" calibration, with a software tool such as PEST (Doherty, 2004). With PEST, the modeler specifies the parameters to be adjusted and their range of adjustment, as well as the values of the calibration targets. In addition, the modeler must construct the framework by which PEST can modify input parameters as well as extract model results to compare to the calibration targets. PEST then uses basic optimization techniques to estimate the parameter values within the defined ranges that will improve the calibration statistics. PEST is not a replacement for manual calibration, but can be an important tool in speeding the calibration process.

During calibration, it is important to check the overall water balance periodically to ensure that the difference between simulated inflow and outflow is small. Typically, the overall percent difference should be less than 1%, and ideally less than 0.1%. During calibration, the Yegua-Jackson model consistently produced percent differences of less than 0.1%.

7.2 Calibration Target Uncertainty

Calibration targets are uncertain. In order to not "over-calibrate" a model, which is a stated desire for the groundwater availability models, the calibration criteria should be defined consistently with the uncertainty in calibration targets. Uncertainty in head measurements can be the result of many factors including measurement errors, scale errors, and various types of averaging errors that are both spatial and temporal. The primary calibration criteria for head is a mean absolute error less than or equal to 10 percent of the observed head variation within the aquifer being modeled. Ranges in the observed water levels across the various units in the Yegua-Jackson Aquifer were typically from 250 to 450 feet, which leads to acceptable mean absolute error of about 25 to 45 feet, depending on the unit and time period.

Water-level measurement errors are typically on the order of tenths of feet and, at the groundwater availability model scale, can be considered insignificant. However, measuring-point elevation errors can be significant. The range in ground surface elevations inside a 1-square-mile grid cell extracted from a 30-meter digital elevation model over the Yegua-Jackson Aquifer varied from less than 1 to 257 feet, with a median of 67 feet. This means that the ground surface elevation varies 67 feet within a typical model grid cell. Another error is caused by combining several sediment types into single one-square-mile grid blocks represented by one simulated head. Comparing coincident targets within a single grid block indicates differences averaging 20 feet and exceeding 100 feet in some areas.

Considering the sum of these errors, the average error in model heads could easily equal 30 to 40 feet. Calibrating to mean absolute error values significantly less than 40 feet would constitute over-calibration of the model and parameter adjustments to reach that mean absolute error are not supported by the hydraulic head uncertainty.

7.3 Sensitivity Analysis

A sensitivity analysis was performed on the steady-state and transient calibrated models to determine the impact of changes in a calibrated parameter on the predictions of the calibrated model. A standard “one-off” sensitivity analysis was performed. This means that hydraulic parameters or stresses were adjusted from their calibrated “base case” values one by one while all other hydraulic parameters remained unperturbed. Note that a standard “one-off” sensitivity analysis does not estimate parameter uncertainty, since limited parameter space is investigated and parameter correlation is not considered.

8.0 Steady-State Model

The steady-state model developed for the Yegua-Jackson Aquifer represents a period before significant development began. This section details calibration of the steady-state model and presents the steady-state model results. The sensitivity of the steady-state model to various hydrologic parameters is also described.

8.1 Calibration

This section describes the steady-state calibration targets and potential calibration parameters including horizontal and vertical hydraulic conductivity, recharge, evapotranspiration, general-head boundaries, and stream conductance.

8.1.1 Calibration Targets

Steady-state calibration targets should ideally represent the condition before development of the aquifer has occurred. The water levels that were reported in Section 4.3.2 were used as a starting set of values for calibration. However, while those data were adequate for characterizing basic water levels in each of the units as part of the conceptualization, when starting calibration we decided to use less restrictive selection criteria to help increase the coverage of calibration data.

One change in the selection criteria was the addition of more wells without specific screen information. The analysis in Section 4.3.4 indicated that vertical gradients are not pronounced under natural conditions in the aquifer, so we considered the benefit of additional targets to outweigh the potential error due to vertical mislocation of a monitoring well. The second change was to allow measurements post 1950 to be included. Because the water levels in the Yegua-Jackson aquifer are relatively constant in many regions over the historical period, some measurements taken after 1950 would still be representative of pre-development conditions.

The candidate wells were selected by querying the TWDB Groundwater Database for wells that fell spatially inside the model active area, regardless of aquifer code. The wells were further queried to determine if they had at least one publishable water level measurement. Measurements were considered to be publishable if the [pn_well_visit_mark] field was “P”, and the [remark] field was either null or "01". Those wells without screen information were assumed to have a screen that spanned from the total depth of the well to 50 feet (the approximate average length of screens for wells in the region) above the total depth. The well was then assigned to the model layer that contained the maximum transmissivity across the screen. This maximum transmissivity was recalculated during calibration based on the current estimates of conductivity in each layer. In general, the resulting vertical locations of the wells correlated with the aquifer codes that were assigned to the wells.

To select water levels that were representative of pre-development conditions, we took the maximum water levels measured at a given well. We compared the maximum measurement to the first measurement for each well, and although there was little difference in the general statistics, there were cases where the maximum measurement was more consistent with measurements in neighboring wells. During calibration, we identified some additional measurements that appeared to be impacted by pumping (either this could be seen in the well history, or the target was inconsistent with neighboring targets). Pumping impacts on water levels are inconsistent with the pre-development conceptualization, so these wells were removed from the target dataset. In the final calibration dataset, there were 576 pre-development targets, with over 100 targets in each hydrogeologic unit.

8.1.2 Horizontal and Vertical Conductivities

We used PEST to calibrate the steady-state model prior to calibrating the transient model. The parameters given in Table 4.7.6 were adjusted within reasonable ranges by PEST (along with other model parameters, such as recharge) to determine the optimal values. Although the results from the PEST runs did not improve the calibration dramatically from the initial estimates of conductivity parameters, the head calibration statistics fell within a reasonable range. One consistent result from the PEST runs was that the head calibration was improved by reducing the average recharge from the initial value of 0.5 inches per year to about 0.3 inches per year. However, this did not allow enough flow into the model to match even the smallest of the baseflow targets. The conductivities were too low in the shallow layer to allow sufficient horizontal flow to the streams.

Because the properties of shallow sediments can be quite different from those in the subsurface, due to alluvium soils and the generally less consolidated nature of surface soils, we considered decoupling the properties of the surface sediments from the deeper ones. The surface geology delineations from the Geologic Atlas of Texas were used to guide the parameterization at the surface. What worked best was a simple division of the surface types into either alluvium or non-alluvium. We used a multiplier on the initial conductivity estimate at the surface (which was derived using the techniques described in Section 4.7). The multiplier was higher for the alluvium type than the non-alluvium, and we capped the maximum conductivity for both types. The alluvium was capped at 50 feet per day and the non-alluvium was capped near the maximum measured values for the Yegua-Jackson Aquifer (30 feet per day). The higher conductivities in the shallow layer allowed the majority of the baseflow targets to be met at an average recharge of about 1 inch per year.

Based on the initial PEST runs, our estimates for the conductivities of the deeper sediments were kept near the initial estimates during the first steady-state calibration. However, as discussed in Section 9.1, transient calibration required wholesale reduction of deeper conductivities to match drawdowns in various portions of the aquifer. Therefore, the steady-state model had to be recalibrated with the new, lower conductivities, after the calibration of the transient model. Horizontal conductivities were reduced to the lower range of measured values, and vertical conductivity of clays (which controls the overall vertical conductivity) was reduced from 0.001 to 0.0001 feet per day. Under the constraint of these lower conductivities, the steady-state model was recalibrated primarily by adjusting the conductivities of the shallow soils and recharge.

The calibrated horizontal and vertical hydraulic conductivity distributions are shown in Figures 8.1.1 through 8.1.9. Figure 8.1.1 shows the horizontal hydraulic conductivity in the shallow layer. Note that the horizontal hydraulic conductivity of the Catahoula Formation, which was parameterized as a constant 0.1 feet per day, is not shown in the figure. The conductivity in the shallow layer varies from about 1 foot per day in parts of the Upper Jackson to 50 feet per day in some of the alluvium areas of the Yegua Formation.

Figure 8.1.2 shows the horizontal hydraulic conductivity in the Upper Jackson Unit subcrop. The conductivity ranges from less than 0.03 feet per day in the deepest portion to up to 3 feet per day as it gets shallower near the outcrop. The Upper Jackson Unit is the lowest conductivity unit of the four units comprising the Yegua-Jackson Aquifer. Figure 8.1.3 shows the horizontal hydraulic conductivity in the Lower Jackson Unit subcrop. The conductivity ranges from less than 0.03 feet per day in the deepest portion to up to 3 feet per day as it nears the outcrop. Figure 8.1.4 shows the horizontal hydraulic conductivity of the Upper Yegua Unit subcrop. The conductivity ranges slightly higher than the Upper and Lower Jackson units, at over 3 feet per day in the shallow portions. Figure 8.1.5 shows the horizontal hydraulic conductivity of the Lower Yegua Unit subcrop. This unit has the highest conductivity of the four, with an upper value of up to 10 feet per day.

Figures 8.1.6 through 8.1.9 show the vertical hydraulic conductivity of the four units that comprise the Yegua-Jackson Aquifer. As noted previously, the calibrated clay conductivity was parameterized as $1x10^{-4}$ feet per day. The overall vertical conductivities range over four orders of magnitude from $1x10^{-6}$ to $5x10^{-3}$ feet per day. The distributions shown in the figures reflect the combination of clay content (a harmonic mean is calculated among the sands and clays in a unit) and the decreasing conductivity with depth. As with the horizontal hydraulic conductivities, the vertical hydraulic conductivities are slightly higher in the Yegua Formation than in the Jackson Group, as shown in Figures 8.1.8 and 8.1.9. Some portions of the Upper Yegua Unit contain a very high sand content, which results in higher estimates of vertical conductivity in the shallower regions.

8.1.3 Recharge and Groundwater Evapotranspiration

As noted in the previous section, recharge was initially parameterized as averaging 0.5 inches per year. This was lowered during initial calibration of the steady-state model (using PEST), to about 0.3 inches per year, because it improved the overall calibration of heads. However, this amount of recharge was insufficient to match even the smallest of baseflow target values. Once the conductivity of the shallow layer was increased, recharge was increased to an average of about 1 inch per year, which allowed the majority of the baseflow targets to be met, while keeping sufficient calibration of the head targets.

Also during steady-state calibration, we found that the small amount of recharge that was being put in the southwest portion of the model was (combined with some inflow from losing streams, which is discussed in Section 8.1.5) biasing heads high, compared to the targets. However, the semi-log relationship with precipitation that was initially proposed (see Section 4.4.3) did not allow zero (or even negligible) recharge in regions of low precipitation. Therefore, we devised a polynomial relationship with precipitation that kept the shape of the semi-log curve, but allowed recharge to fall to zero when precipitation fell below some minimum value. The polynomial relationship is shown in Figure 8.1.10, and is compared to the initial recharge relationship. Because the initial relationship was also not physically based, but just a convenient expression of regression results, the new relationship does not alter the conceptualization significantly, and allows the additional conceptualization of a minimum precipitation at which recharge will occur.

The final calibrated recharge is shown in Figure 8.1.11. The distribution reflects the increase in recharge with precipitation from southwest to northeast, and the increase in recharge in the local highlands compared to the lowlands.

Evapotranspiration parameters were not varied during calibration and, thus, the maximum evapotranspiration and rooting depth remained at the initial values described in Section 6.3.4.

8.1.4 General-Head Boundaries

The general head boundaries representing the Jasper Aquifer are attached to the subcrop portion of Layer 1, which represents the Catahoula Formation confining unit. Only minor changes to the general head boundary parameters were made during calibration. The vertical conductivity used in the conductance calculation was reduced from 0.001 to 0.0001 feet per day, to remain consistent with the parameterization in the aquifer units. In addition, the elevations were increased by 60 ft near the outcrop in central Grimes County where the simulated head results from the Gulf Coast Aquifer models, which were used to define the boundary heads, appeared anomalously low. The general head boundary elevations shown in Figures 6.3.7 through 6.3.9 are representative of the calibrated elevations.

8.1.5 Streams

Stream conductances were adjusted during calibration to match baseflow targets. In a few cases, streambed elevations were adjusted during calibration to help match the targets. The adjustment in elevation was limited to the general range of variation in the 30-meter digital elevation model within a grid cell, and streambed elevations were obviously not allowed to drop below the bottom of the shallow layer. As a starting point, streambed elevations were incised 25 feet from the top of the grid cell, which represents an average ground surface elevation. The bed elevations were adjusted downward as much as an additional 25 feet when necessary to improve streamflow calibration. In general, the largest rivers, such as the Brazos and Angelina, were given the highest conductances and the deepest incision from land surface. The calibrated stream conductances are shown in Figure 8.1.12.

Figure 8.1.12 shows that the river conductances in the southwest portion of the model region are typically lower than those in the rest of the model. If these conductances were set higher, the water lost from the streams would cause the water table to rise too high in this area. The low conductance for these streams is consistent with the lower relative permeability that would occur when a zone of unsaturated media lies between a typically losing stream and the water table below.

8.1.6 Drains

Drain conductances were adjusted to match spring targets, where targets were available. In some cases, the spring elevations were lowered compared to the initial estimate in order to ensure flow in the spring. The amount of elevation averaging that occurs over a one-mile-square grid cell (Section 7.2) makes the uncertainty in the effective spring elevation significant, so some variation in the spring elevation during calibration is warranted.

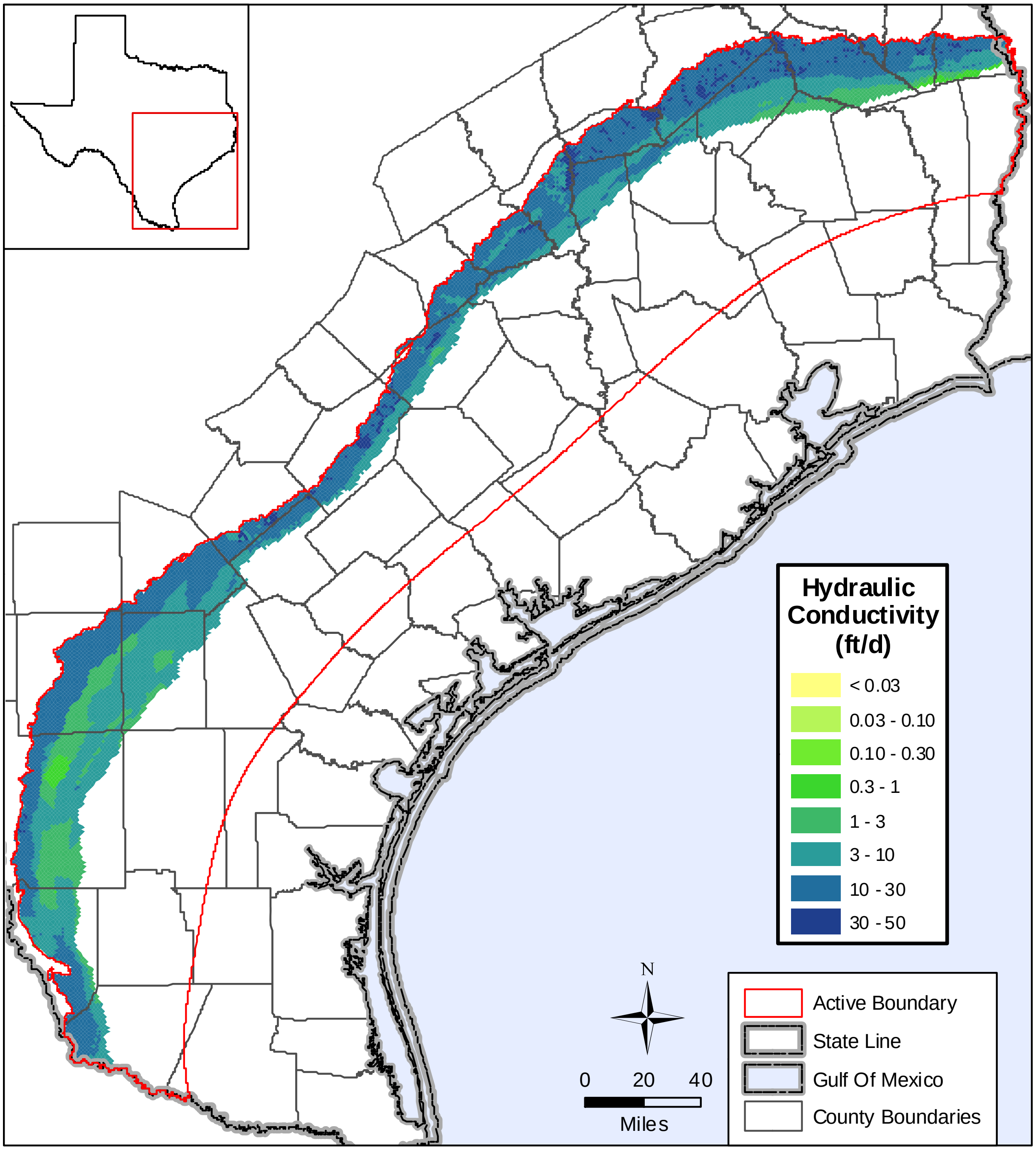


Figure 8.1.1 Horizontal hydraulic conductivity in feet per day of the shallow layer.

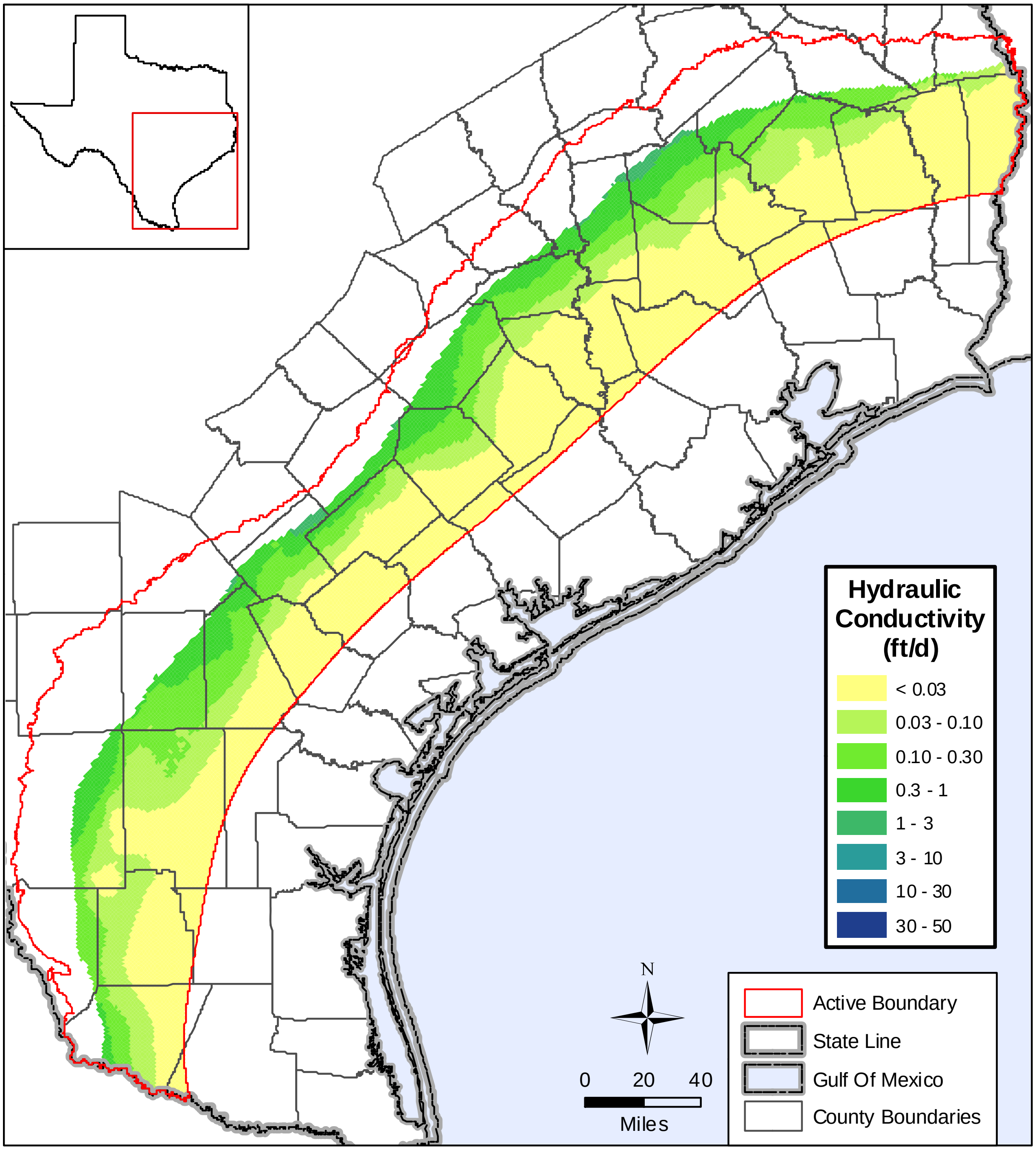


Figure 8.1.2 Horizontal hydraulic conductivity in feet per day of the Upper Jackson Unit subcrop.

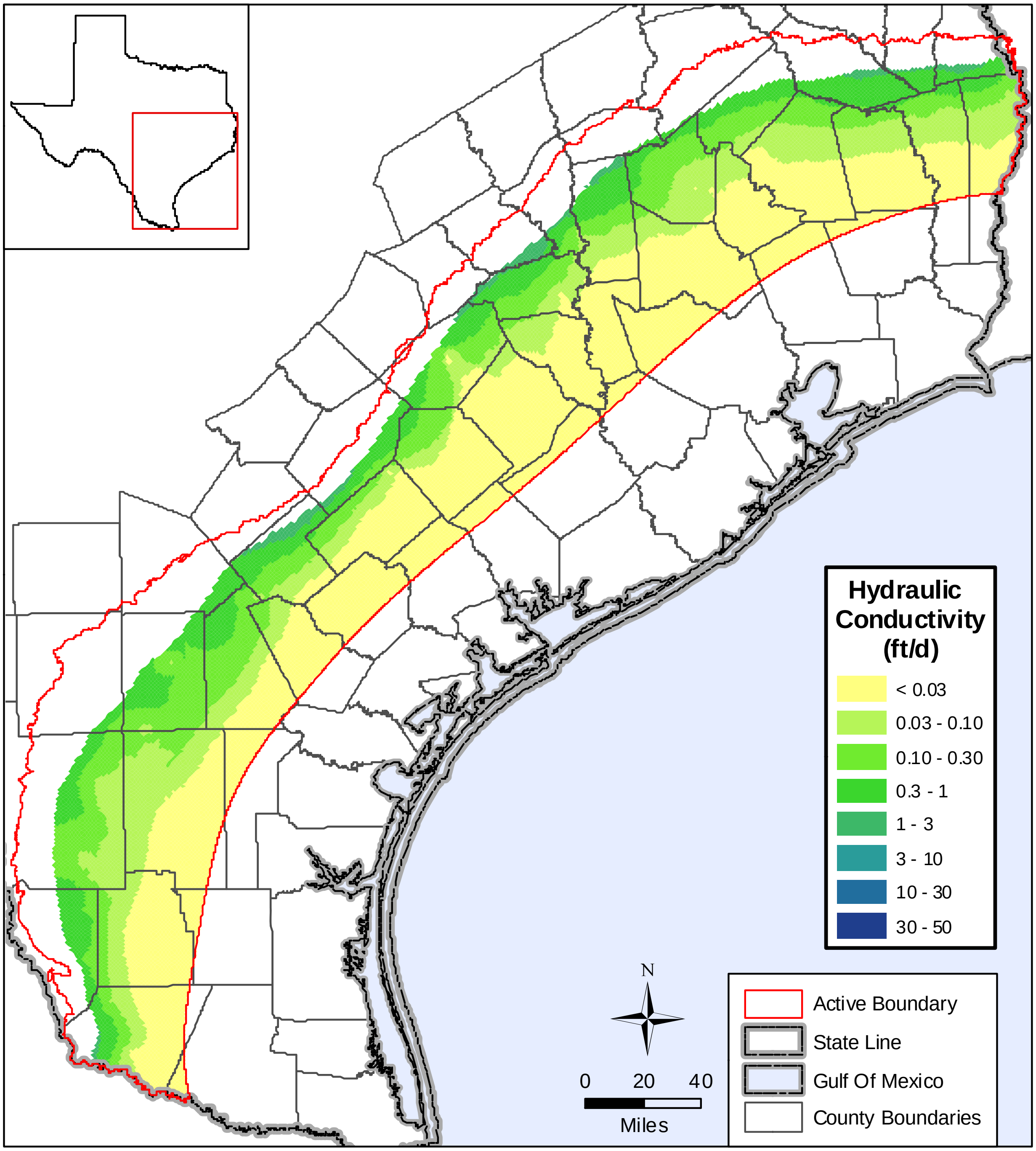


Figure 8.1.3 Horizontal hydraulic conductivity in feet per day of the Lower Jackson Unit subcrop.

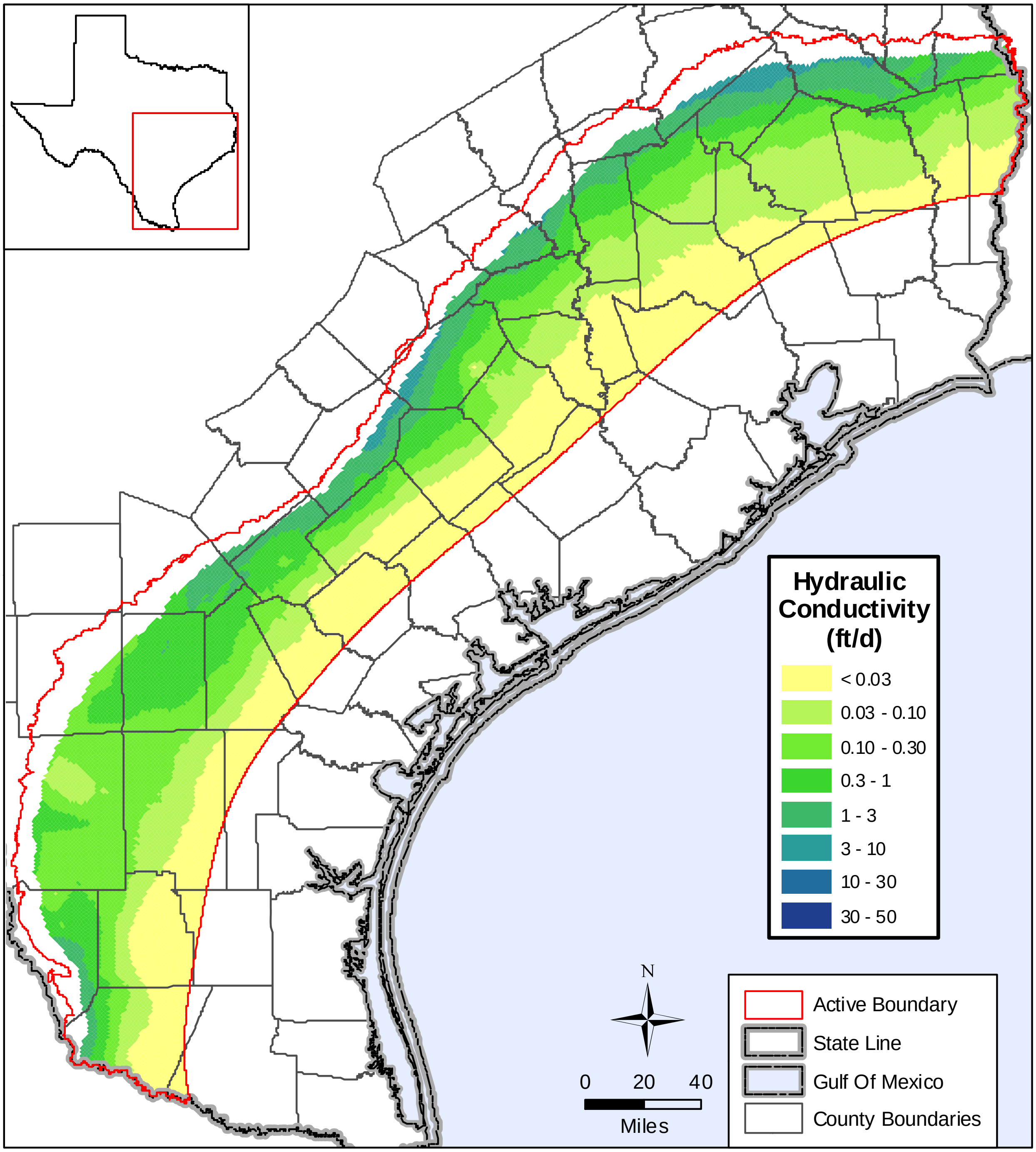


Figure 8.1.4 Horizontal hydraulic conductivity in feet per day of the Upper Yegua Unit subcrop.

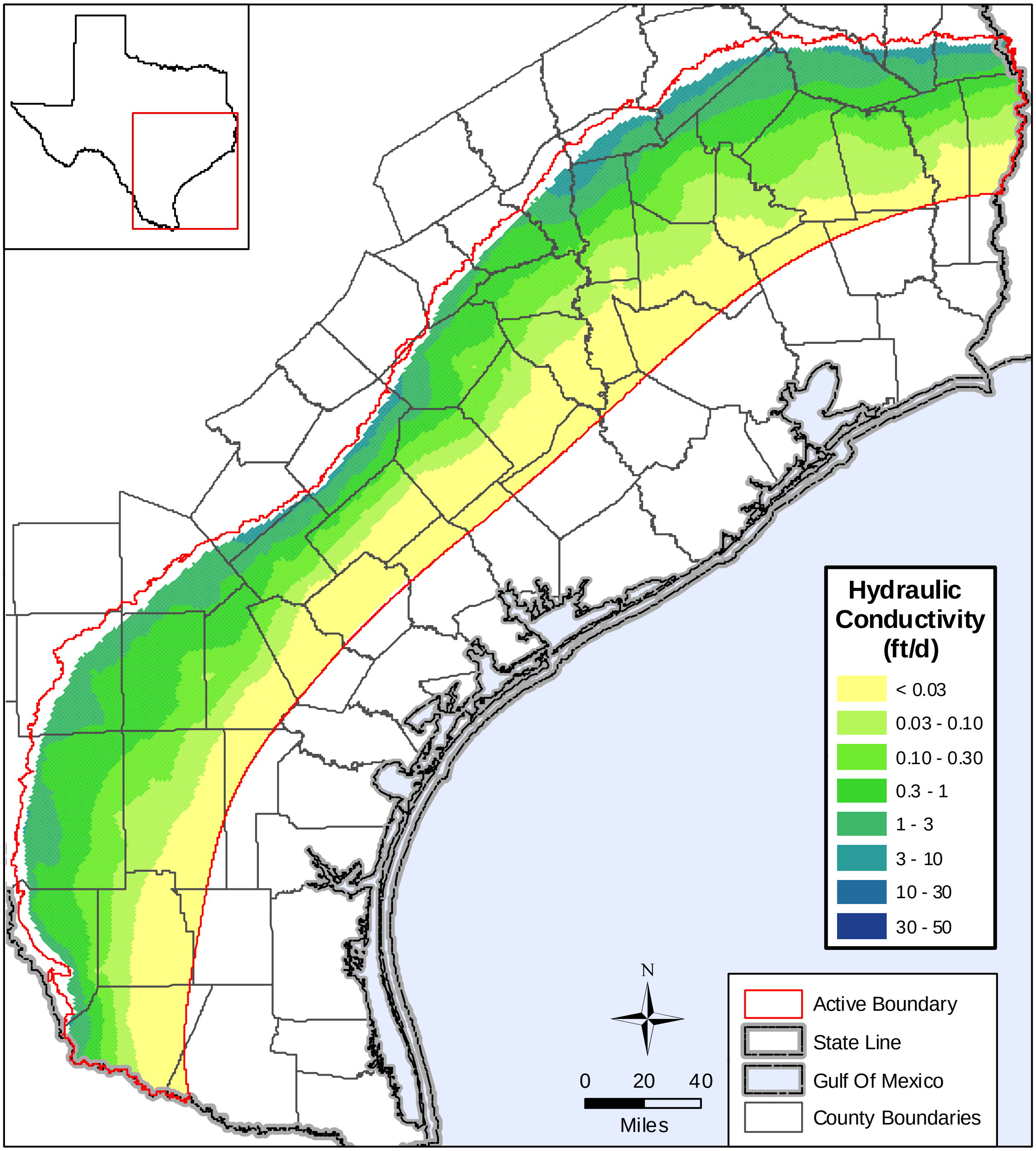


Figure 8.1.5 Horizontal hydraulic conductivity in feet per day of the Lower Yegua Unit subcrop.

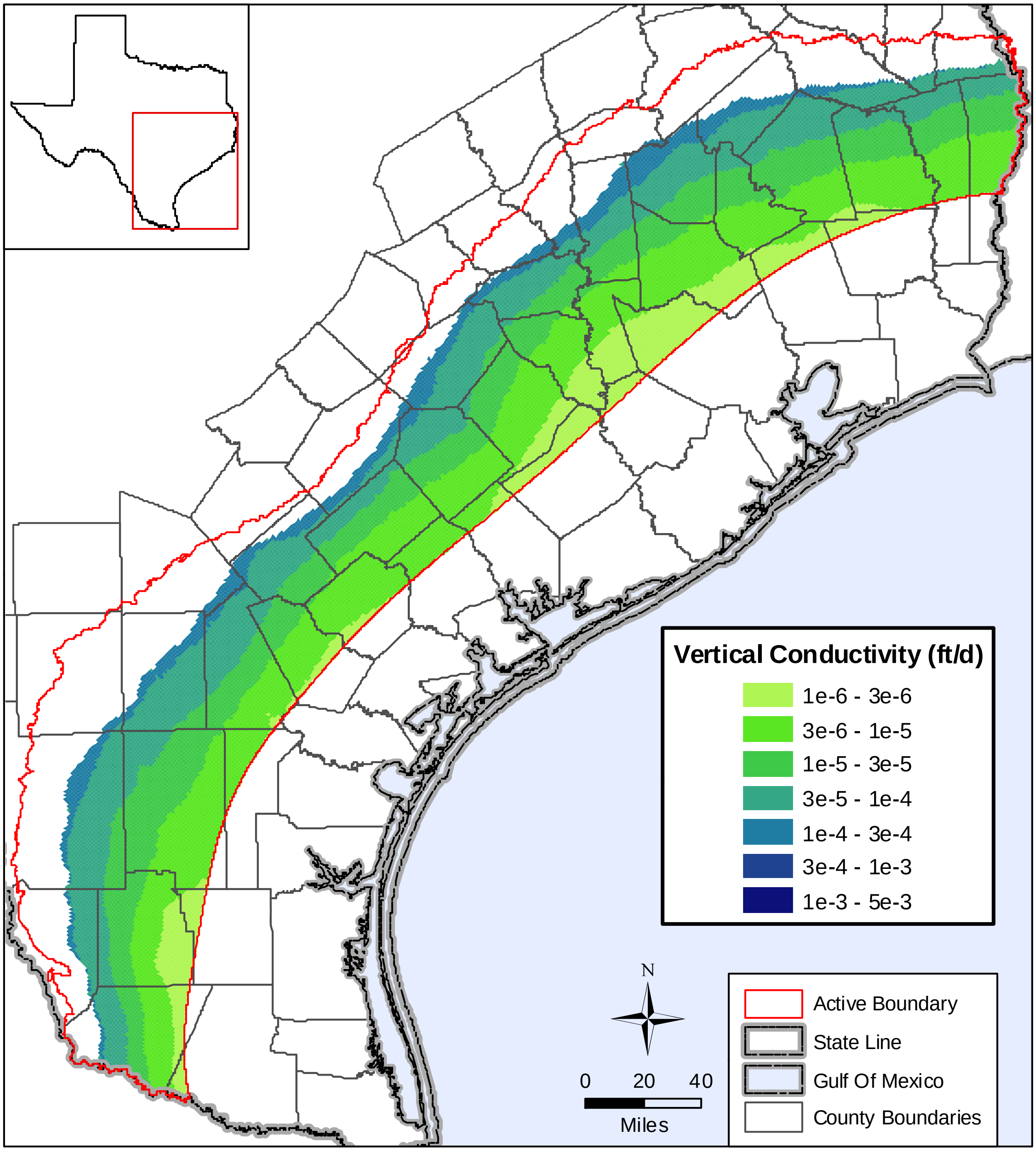


Figure 8.1.6 Vertical hydraulic conductivity in feet per day of the Upper Jackson Unit.

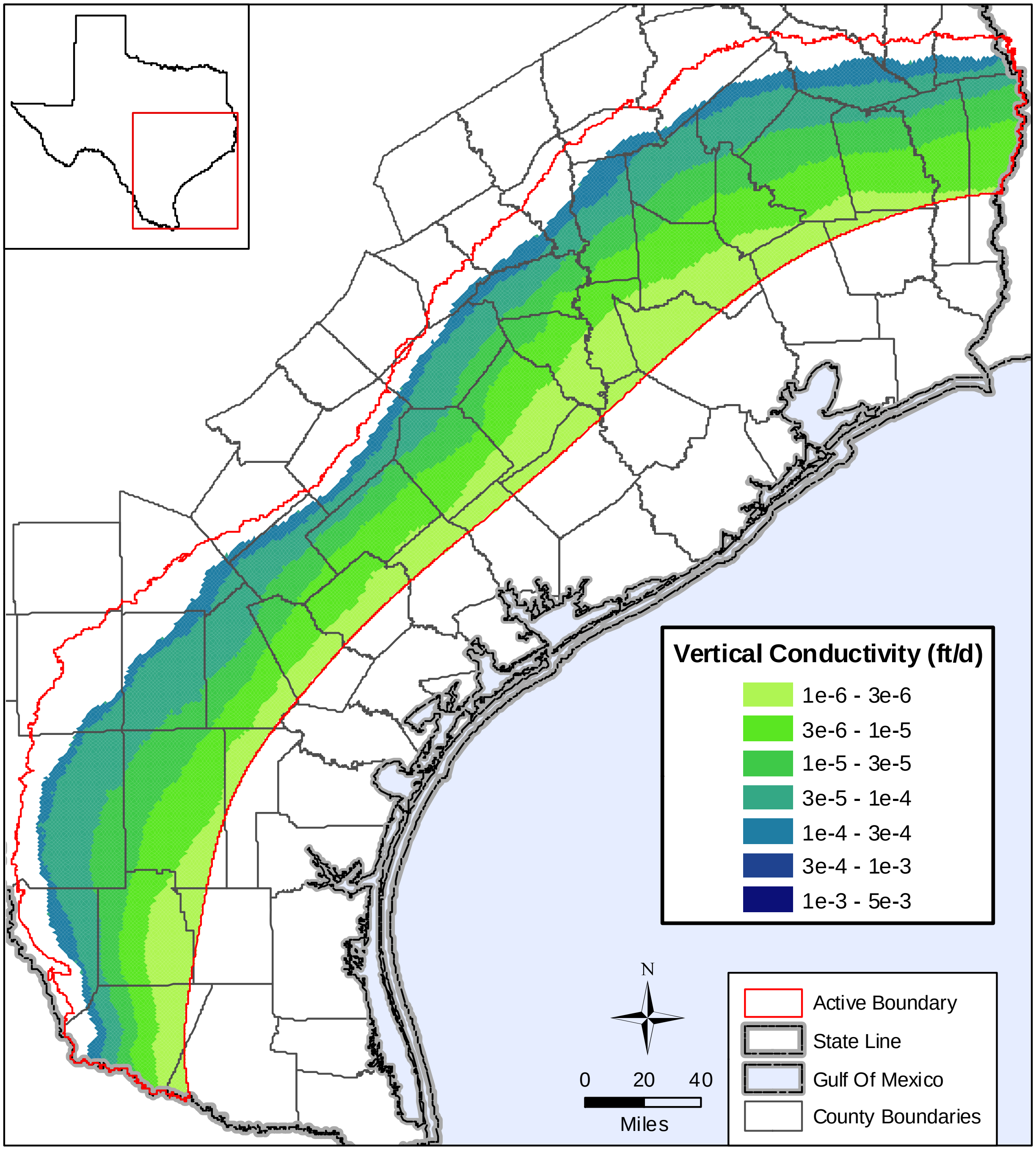


Figure 8.1.7 Vertical hydraulic conductivity in feet per day of the Lower Jackson Unit.

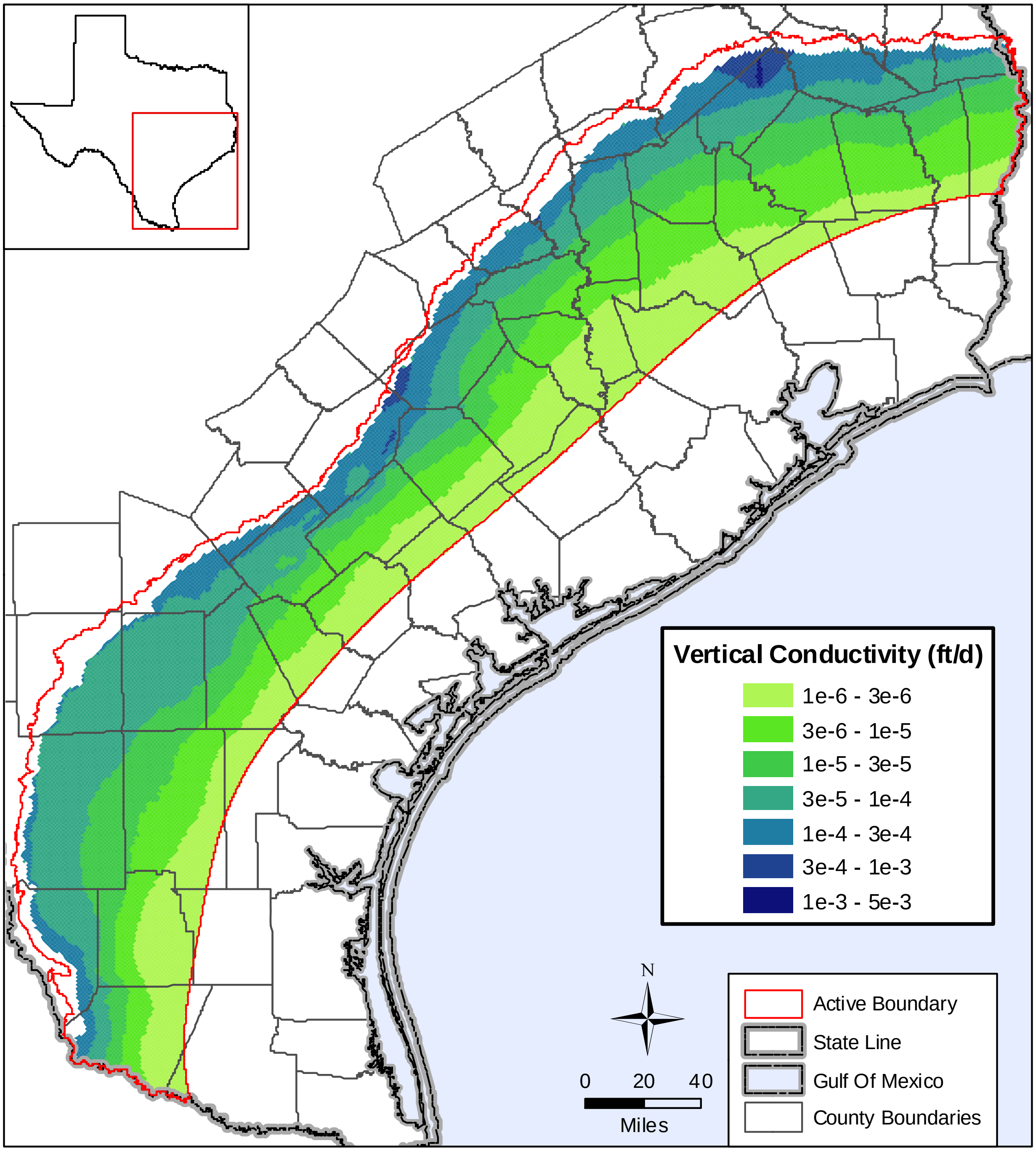


Figure 8.1.8 Vertical hydraulic conductivity in feet per day of the Upper Yegua Unit.

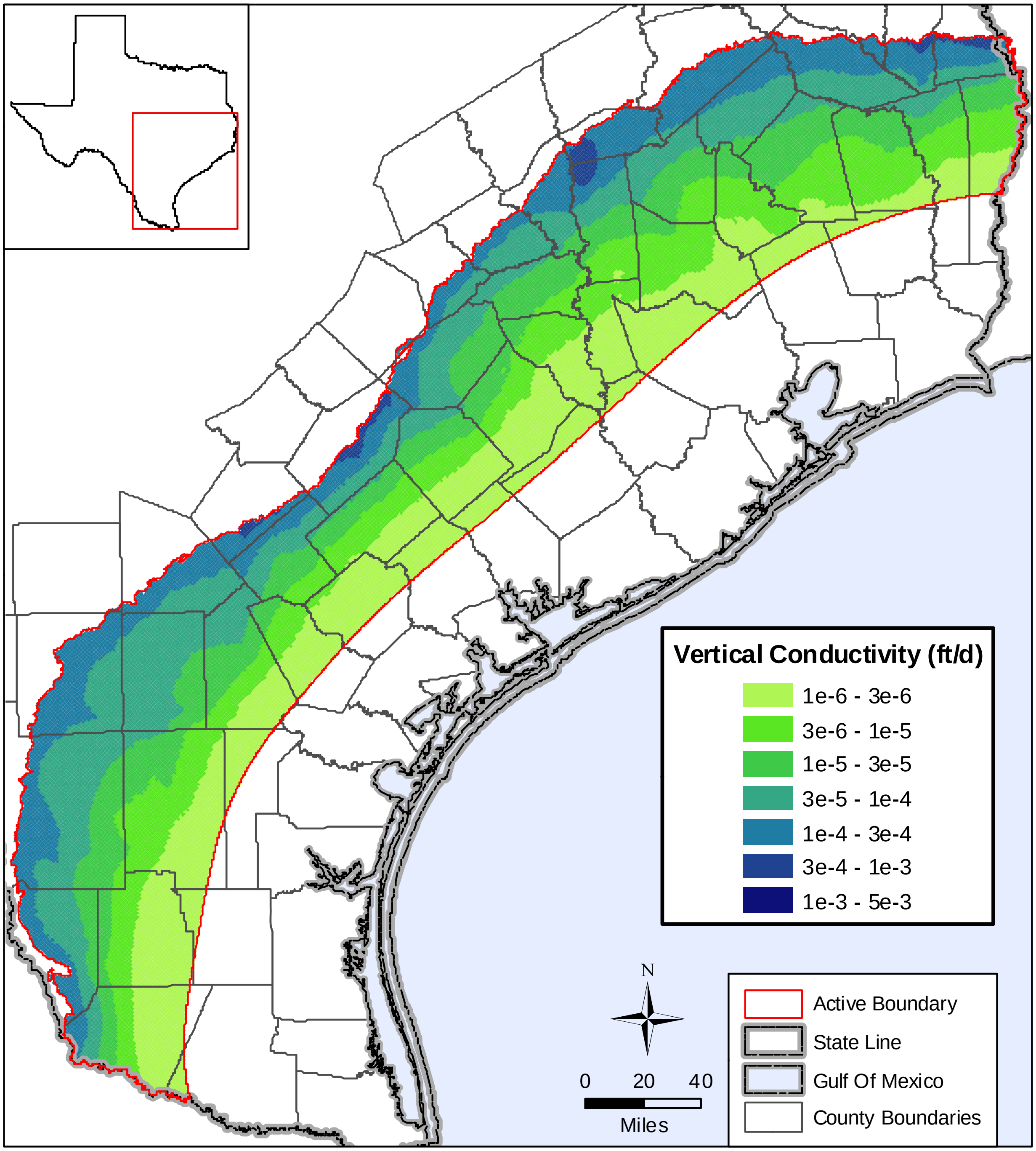
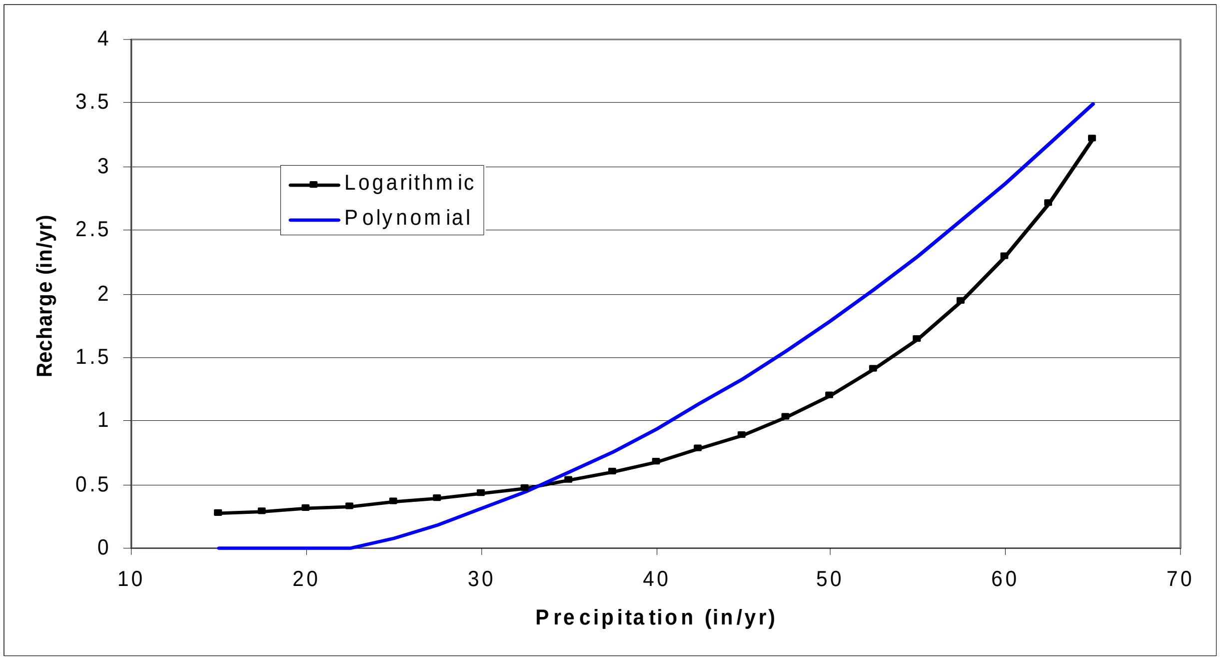


Figure 8.1.9 Vertical hydraulic conductivity in feet per day of the Lower Yegua Unit.



in/yr = inches per year

Figure 8.1.10 Comparison between logarithmic and polynomial recharge functions.

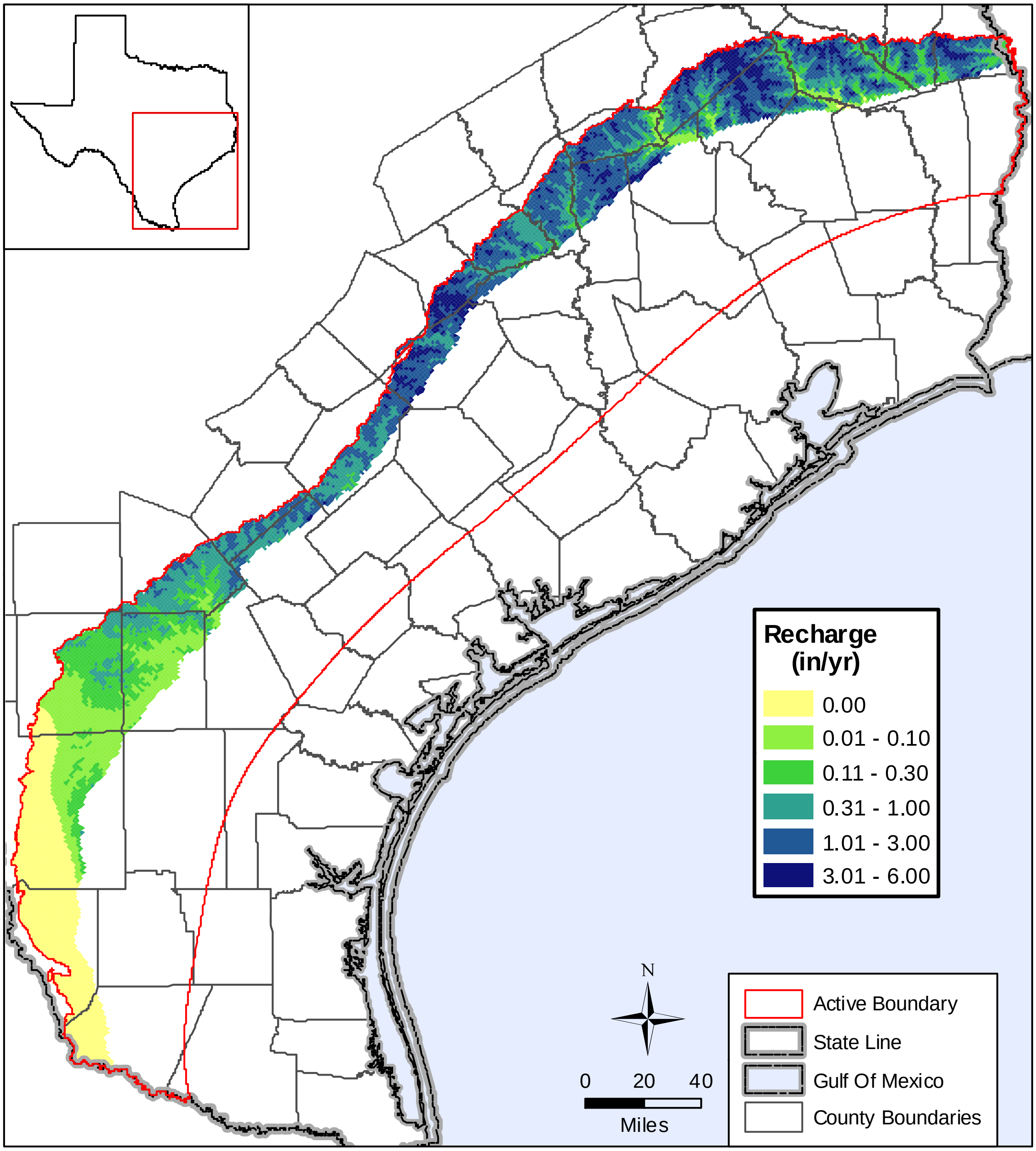


Figure 8.1.11 Calibrated spatial distribution of recharge in inches per year.

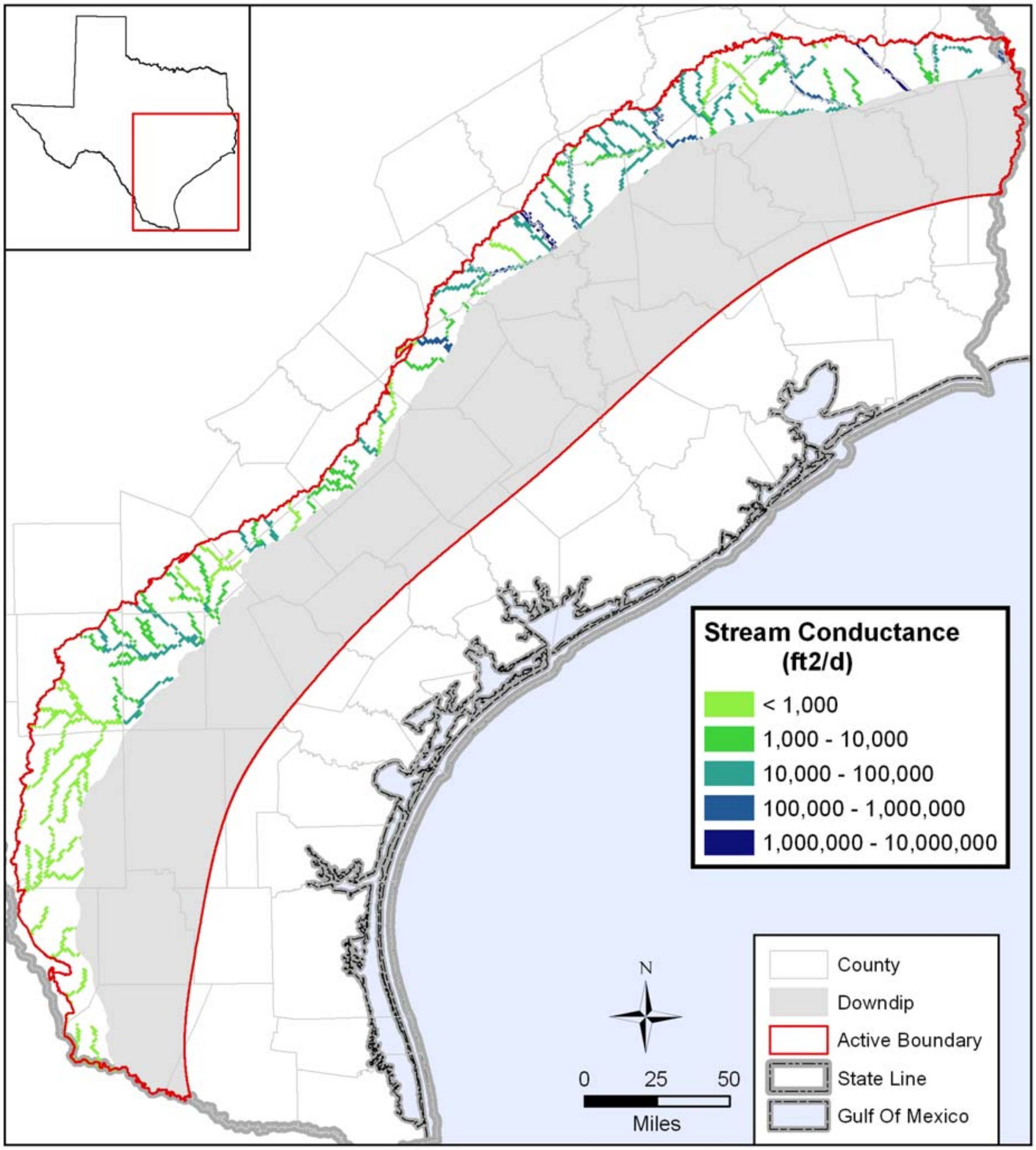


Figure 8.1.12 Calibrated stream cell conductance in square feet per day.

8.2 Simulation Results

8.2.1 Water-Level Elevation

The steady-state model was calibrated to the head targets described in Section 8.1.1. A crossplot of measured versus simulated heads for the steady-state model is shown in Figure 8.2.1. The crossplot shows normal scatter around the 1:1 line, and does not demonstrate significant bias in the lower or higher elevations. Figure 8.2.2 shows a plot of measured heads versus residuals, where residuals are calculated as:

$$residual = head_{measured} - head_{simulated} \qquad (8.2.1)$$

There is a small upward trend in the residuals, from lower elevations to higher elevations, typical of simulating aquifers with a significant unconfined portion with a single model layer. Overall, the residuals show an even distribution of positive and negative around the line of constant zero residual, which is coincident with the x-axis.

Table 8.2.1 shows the calibration statistics for the model. The mean absolute error ranges between 24.5 and 36.4 feet, which is in the same range as the potential errors described in Section 7.2. The mean absolute error divided by the range is about 10 percent in all the units, indicating a good fit, considering the relatively small range in the measured values. The mean error is less than 10 feet for all of the units, confirming that the average bias in the residuals is low.

Figure 8.2.3 shows a post plot of the residuals for all of the targets in the steady-state simulation. The small, black markers indicate an absolute residual of less than 30 feet, which is in the typical range of the mean absolute error. Each county where targets are available shows residuals in this lower range. In addition, each county with more than a few targets has residuals that are both positive (orange markers) and negative (blue markers), indicating little spatial bias on a county basis.

Figures 8.2.4 through 8.2.8 show the simulated steady-state head results. There are no dry cells in steady-state. Figure 8.2.4 shows the heads in the shallow layer, which includes portions of all four of the hydrogeologic units that comprise the Yegua-Jackson Aquifer. The head in the shallow layer reflects the topography, with lower heads in the river basins and higher heads in the interbasin areas. A ridge of higher heads in the southwest region of the active area is due to the higher land surface elevation in this region. Heads in the shallow layer range from about 100 to 500 feet in elevation.

Figure 8.2.5 shows the heads in the Upper Jackson Unit subcrop. Heads in this unit range from about 200 to 600 feet, with the lows in the river valleys still evident. In general, heads decrease gulfward, although some flow directions trend along strike due to topography. Figures 8.2.6 through 8.2.8 for the Lower Jackson Unit, the Upper Yegua Unit, and the Lower Yegua Unit subcrops show similar trends to the Upper Jackson Unit, with the gradients flattening somewhat in the deeper units.

8.2.2 Streams, Springs, and Evapotranspiration

Calibration to stream baseflow targets was one of the primary constraints on recharge in the steady-state model. Without average recharge of at least 1 inch per year, most of the stream baseflow targets could not be matched. Some of the higher magnitude targets could not be matched under any reasonable recharge condition in this regional model.

For the purposes of calibration, the river length in a single one-mile-square grid cell was approximated as one mile, so that 1 acre-feet per year baseflow in a cell corresponded to 1 acre-feet per year per mile. Because the water levels have been nearly constant in the shallower portions of the Yegua-Jackson aquifer throughout the historical period, we considered the gain/loss targets to be appropriate for comparison to steady-state results, regardless of their actual measurement date.

Figure 8.2.9 shows a comparison between simulated and measured stream gains and losses for those stream targets that were approximately 700 acre-feet per mile or less. The simulated results compare favorably to the measured results for these 11 targets. Figure 8.2.10 shows four more stream baseflow targets, where the simulated result was less favorable. For the Neches River, the model significantly underpredicts the amount of baseflow. For Peach Creek, the model significantly overpredicts baseflow. If we reduced the conductance in Peach Creek, or increased the elevation of the streambed to decrease baseflow, heads in the shallow layer near the creek would rise above the head targets. This is either a case of too much recharge in the local area, or the baseflow target is too low.

For the Angelina and Brazos rivers, the targets were much higher than could be simulated in this regional model (Figure 8.2.10). For example, the Brazos River target was 17,000 acre-feet per year per mile. With about 20 miles of river crossing the outcrop, this corresponds to 340,000 acre-feet per year of baseflow to the river, which would represent about 70 percent of the entire water budget of the model. The model scale will not allow the magnitude of recharge required to match these discharge rates while still fitting heads in the shallow layer.

Figure 8.2.11 shows the spatial distribution of stream gains and losses in the model. In general, the streams in the southwest portion of the model are predominantly losing, and the gains increase to the northeast as precipitation and recharge increase. In general, the main channels of the larger rivers, such as the Angelina and Brazos, have the highest discharge rates.

Figure 8.2.12 shows a comparison of maximum measured springflow rates compared to simulated springflow rates. The simulated flow rates compare favorably with the measured values.

8.2.3 Cross-formational Flow

The Yegua-Jackson Aquifer is conceptualized to be active only in the near outcrop portion of the aquifer, with very little flux into the deeper sections exiting upward through cross-formational flow to the Catahoula Formation. Figure 8.2.13 shows the flux through the bottom of Layer 1 of the model. Recall that in the outcrop, Layer 1 represents the shallow portion of the Yegua-Jackson Aquifer, while in the subcrop, Layer 1 represents the Catahoula Formation. In Figure 8.2.13, negative flux rates indicate flow upward into Layer 1, while positive flux rates indicate flow downward out of Layer 1. The figure shows that nearly all of the cross-formational flow happens in the shallow layer, with water moving downward in the interbasin areas, and then discharging back up through the streams. In a few places just gulfward of the outcrop, water is moving either in or out of the Catahoula Formation, but there is no obvious net upward flux of water. This indicates that there is minimal occurrence of recharge that reaches downdip in the Upper Jackson Unit.

8.2.4 Water Budget

The steady-state model had an overall volumetric budget error of 0.07 percent, which is well within the acceptable range. Table 8.2.2 shows the water budget for the steady-state model in terms of net flux into or out of each of the aquifer units in the model. Negative numbers indicate flow out of the unit, while positive numbers indicate flow into the unit. The first two columns detail cross-formational flow in each of the units. The "surficial flow" term represents flow across units in the shallow layer, while the "confined" term represents flow across units in the subcrop between model layers. Overall, the water budget is dominated by recharge and stream discharge, which make up 99 percent of the inflow and 93 percent of the outflow, respectively. The remainder of the outflow occurs through evapotranspiration (6.5 percent) and springs (0.2 percent).

In the Catahoula Formation, a small net flux out (about 1 percent of the overall budget) occurs, which consists of water from the general head boundaries representing the Jasper Aquifer. Similar to the discussion in the previous section, this is indicative of minimal deep recharge from the near outcrop portion of the Yegua-Jackson Aquifer to the subcrop. In the remaining units, most of the inflow occurs through recharge and discharges through the streams. The Lower Yegua Unit has the most recharge, due to its largest outcrop area.

Table 8.2.1 Calibration statistics for the steady-state model.

Unit	Count	Mean Error	Mean Absolute Error	Range	MAE/Range
Upper Jackson	134	-6.0	36.4	335.4	0.109
Lower Jackson	111	-2.6	25.8	247.0	0.104
Upper Yegua	178	3.4	24.5	265.7	0.092
Lower Yegua	153	9.3	26.6	297.6	0.089

MAE = mean absolute error

Table 8.2.2 Water budget for the steady-state model. Values reported in acre-feet per year unless indicated otherwise. Negative numbers indicate flow out of the aquifer unit.

Aquifer Unit	Cross Formational Flow		Recharge	ET	Streams	GHBs	Springs
	Surficial	Confined					
Catahoula Formation	-1,804	-3,508	0	0	0	5,312	0
Upper Jackson	-9,538	1,919	74,310	-6,626	-60,252	0	-96
Lower Jackson	3,320	1,158	92,345	-7,056	-89,840	0	-8
Upper Yegua	30,605	903	127,351	-8,432	-150,516	0	-16
Lower Yegua	-22,496	-471	239,775	-12,877	-203,067	0	-785
Total			533,781	-34,991	-503,675	5,312	-904
Total (%)			99.0%	-6.5%	-93.4%	1.0%	-0.2%

% = percent
ET = evapotranspiration

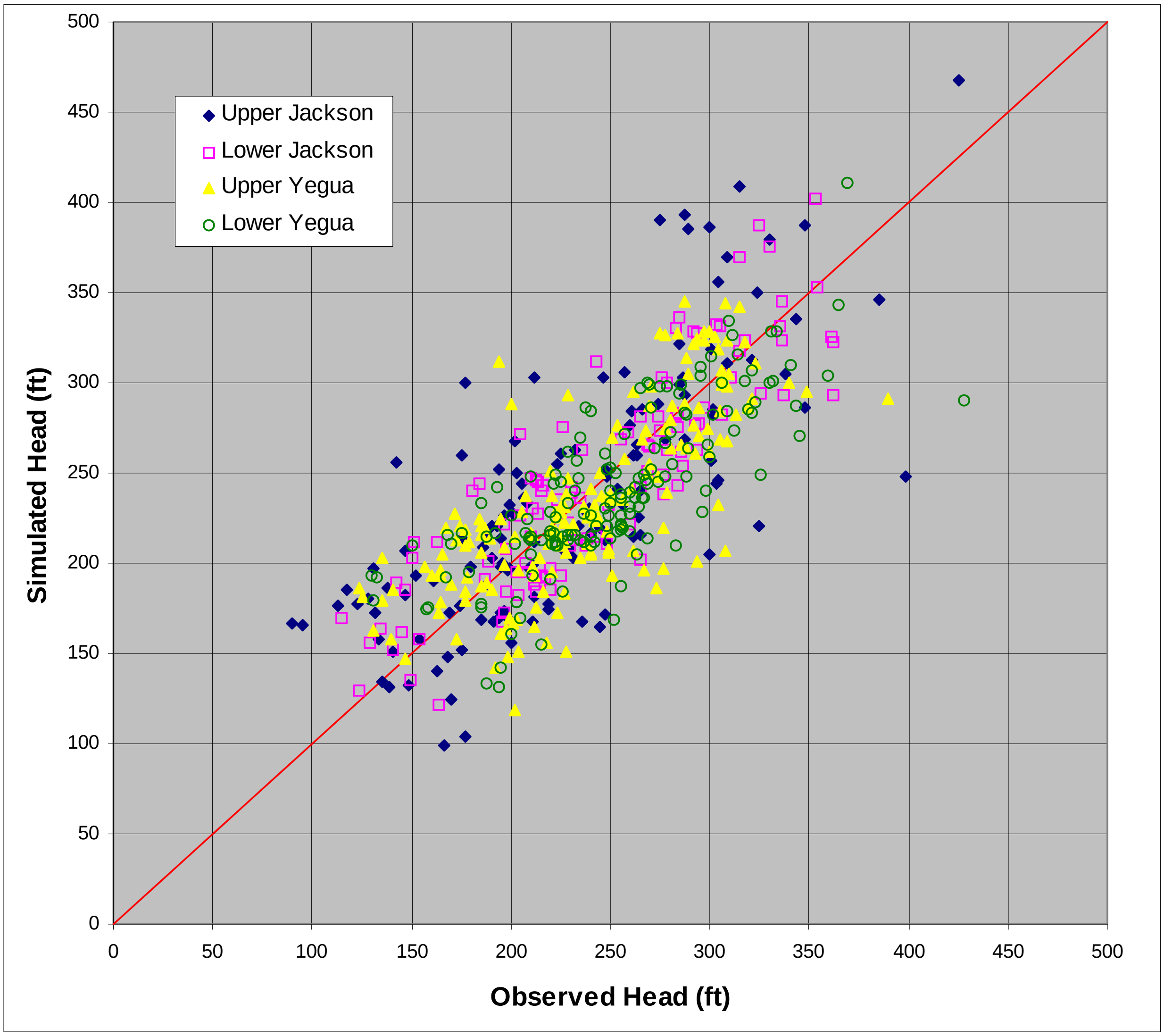


Figure 8.2.1 Crossplot of measured versus simulated heads in feet for the steady-state simulation.

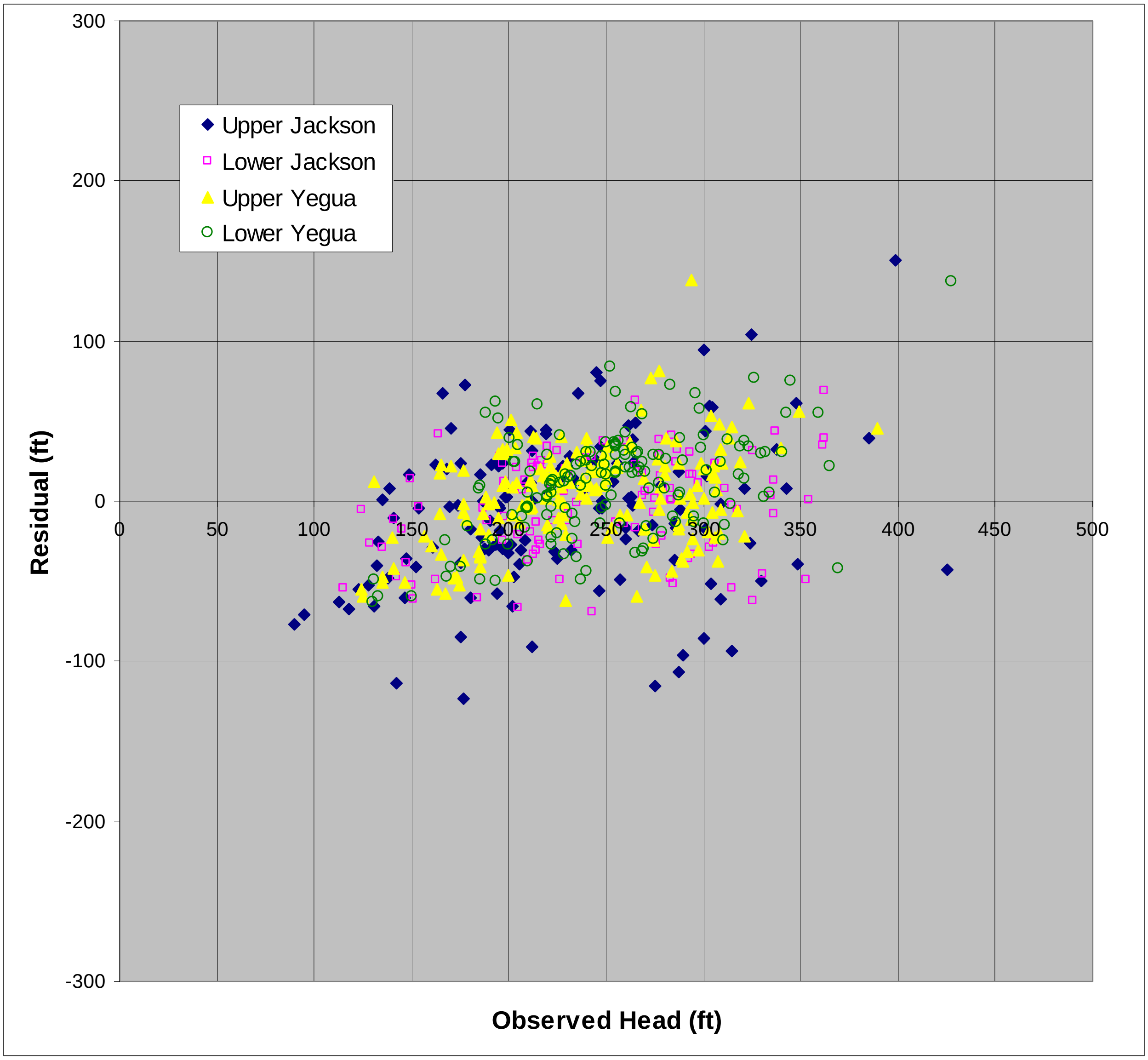


Figure 8.2.2 Plot of measured heads versus residuals in feet for the steady-state simulation.

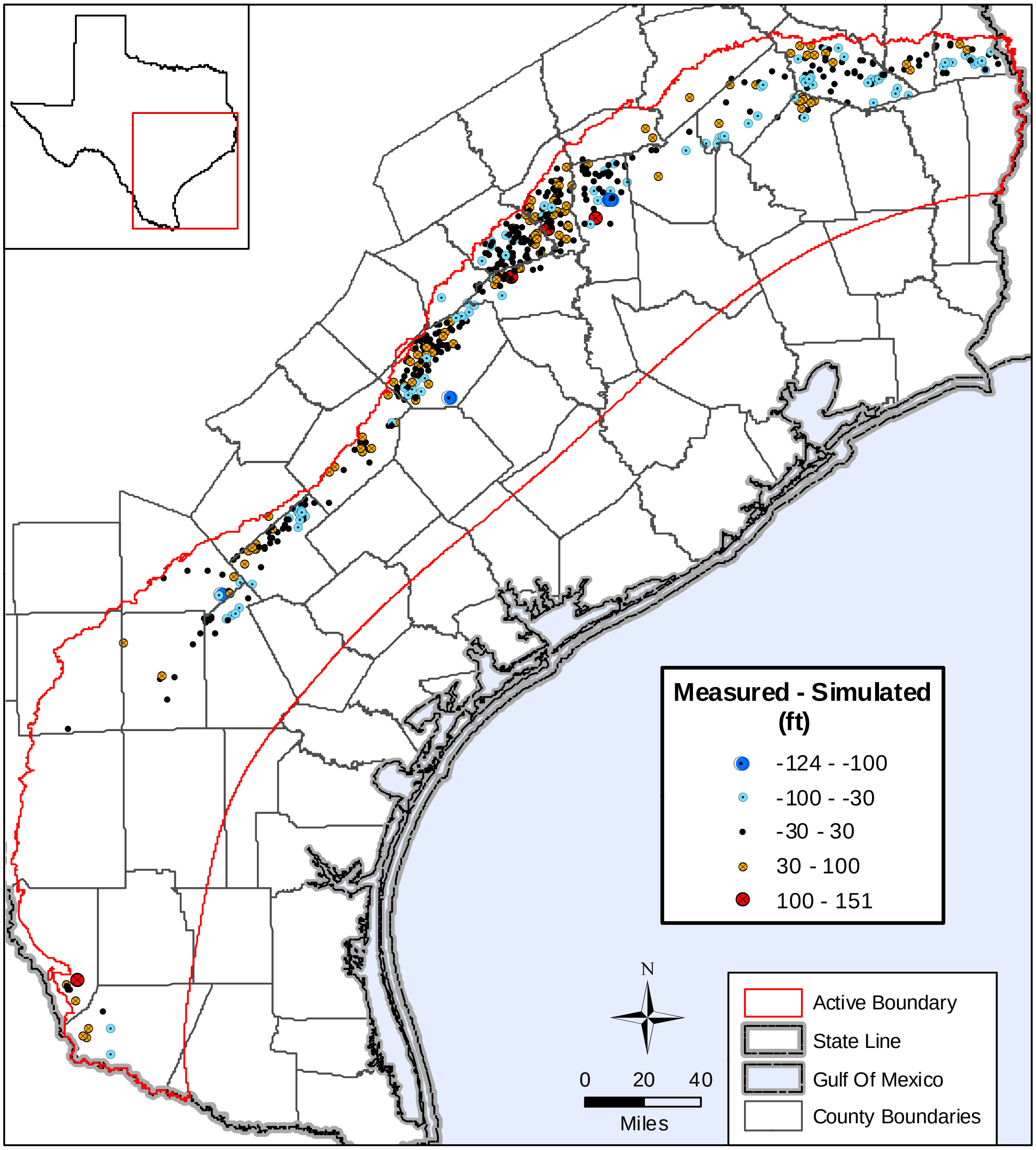


Figure 8.2.3 Spatial distribution of residuals in feet for the steady-state simulation.

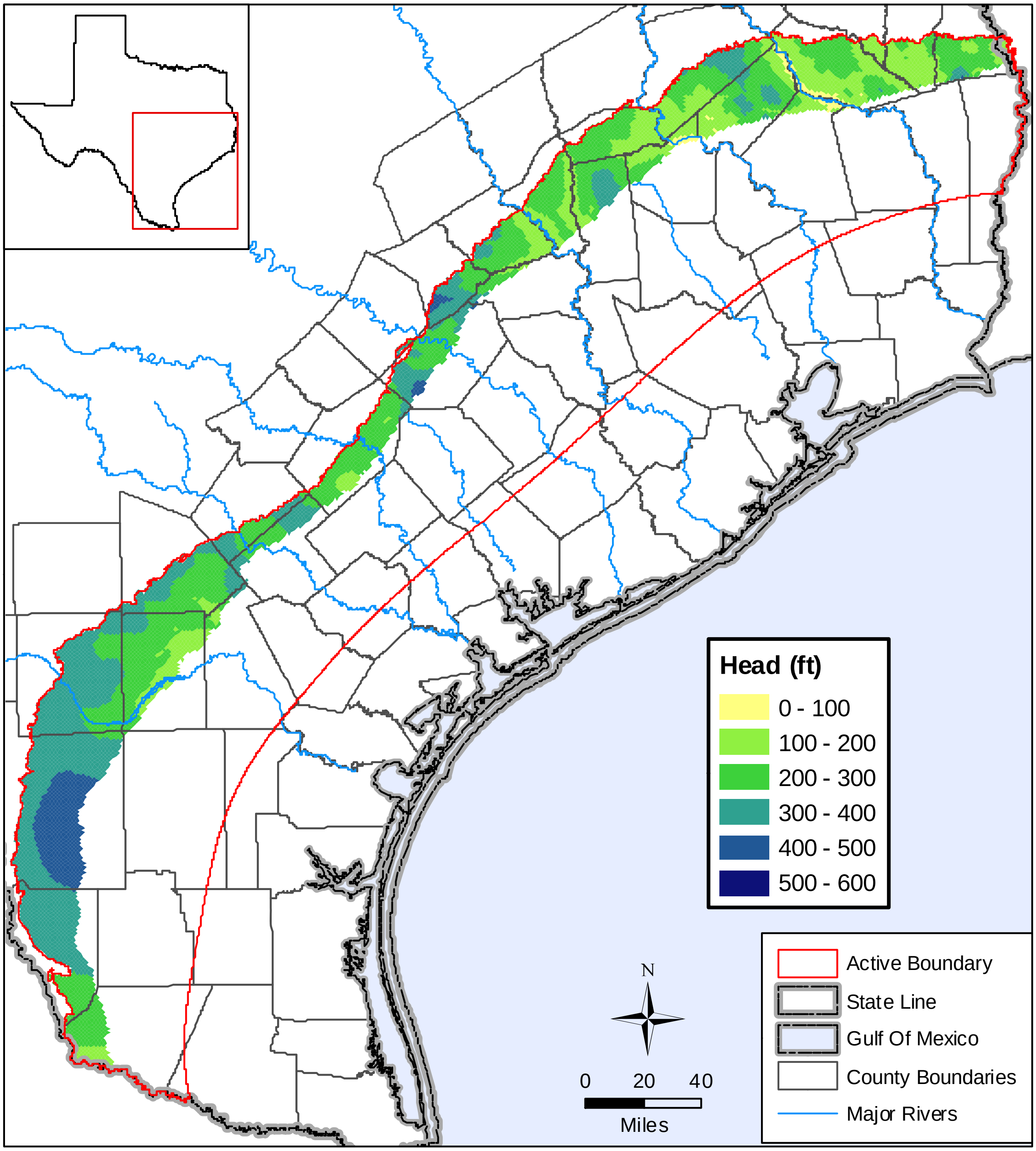


Figure 8.2.4 Simulated hydraulic head in feet in the shallow layer.

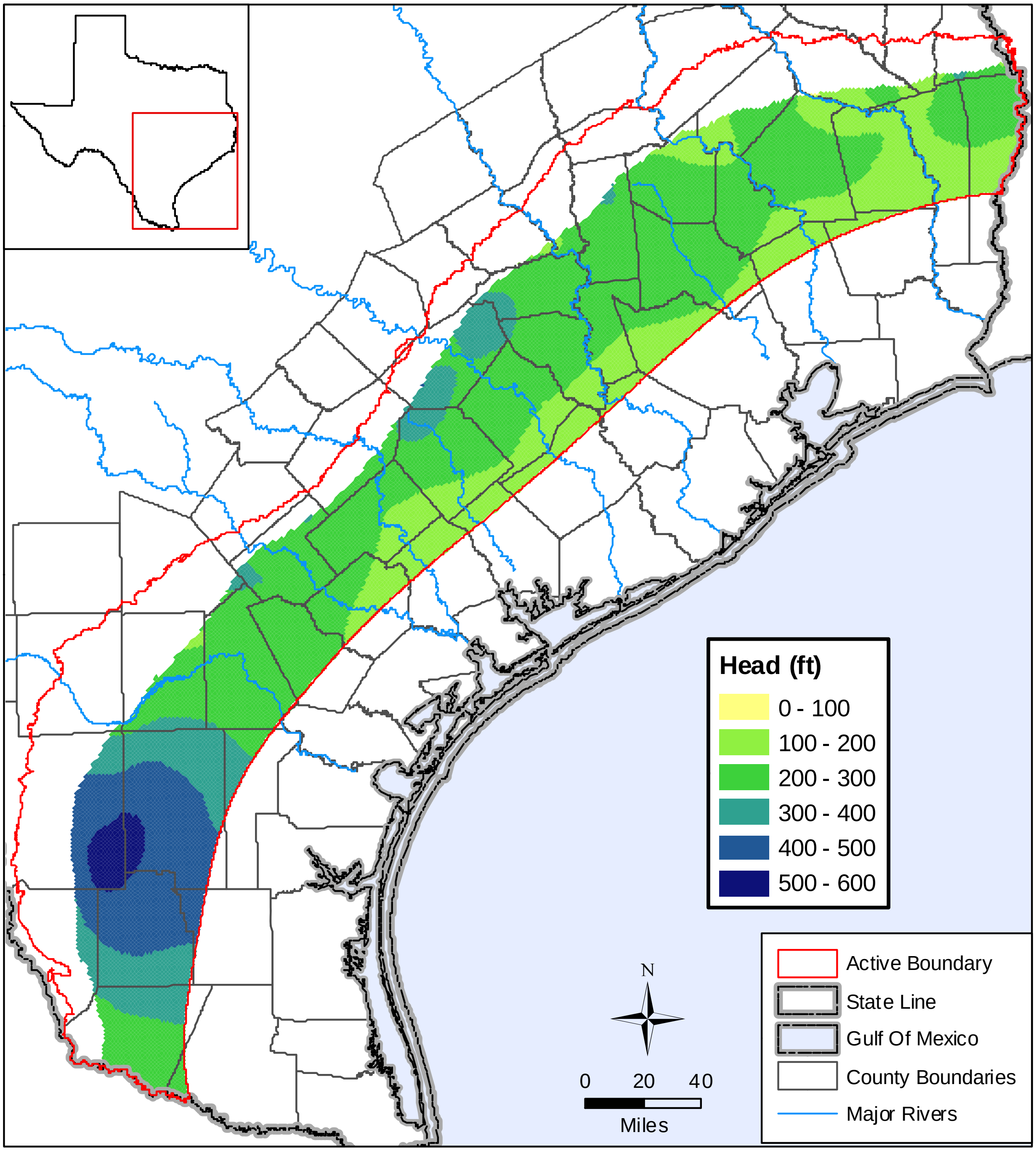


Figure 8.2.5 Simulated hydraulic head in feet in the Upper Jackson Unit subcrop.

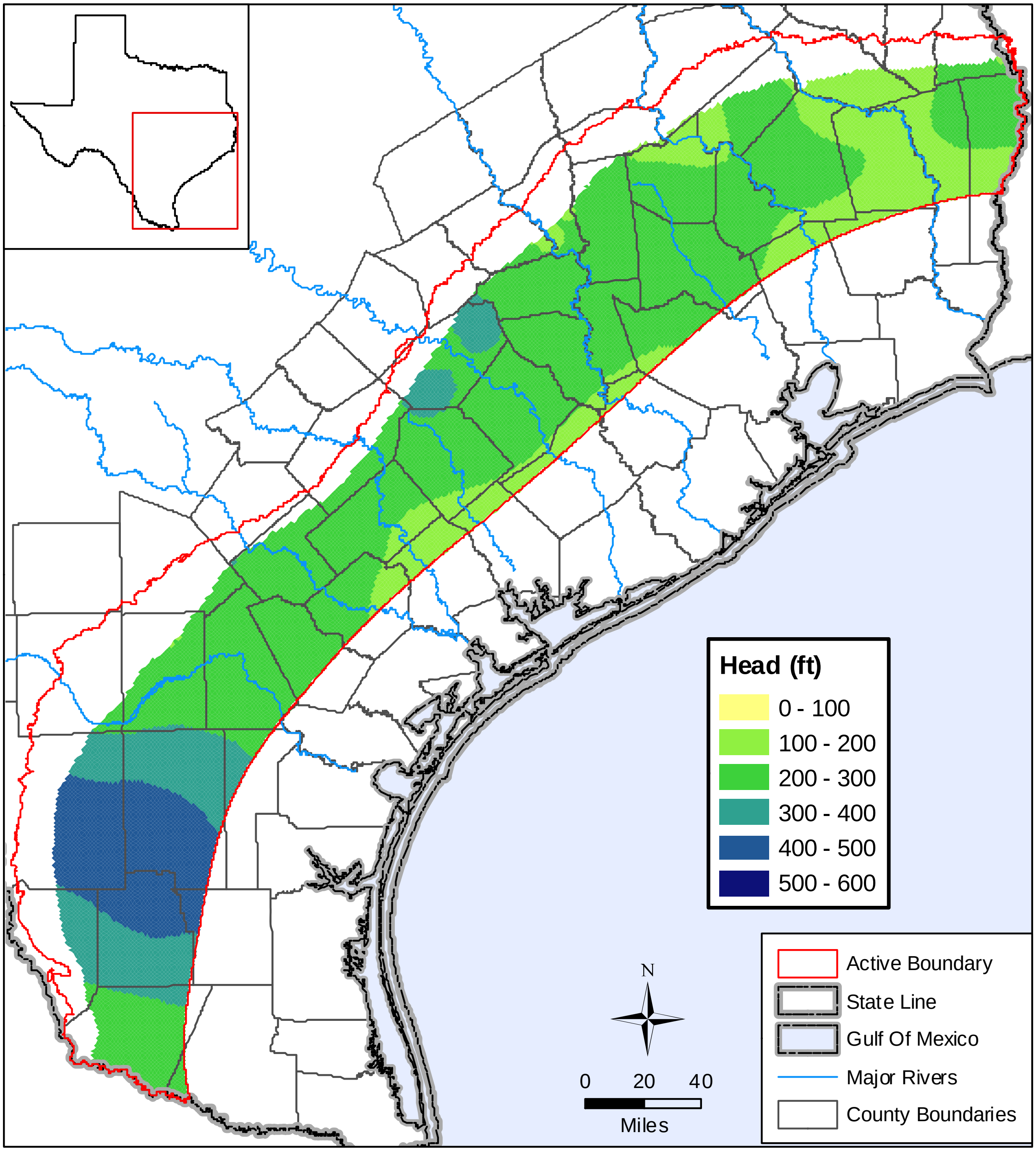


Figure 8.2.6 Simulated hydraulic head in feet in the Lower Jackson Unit subcrop.

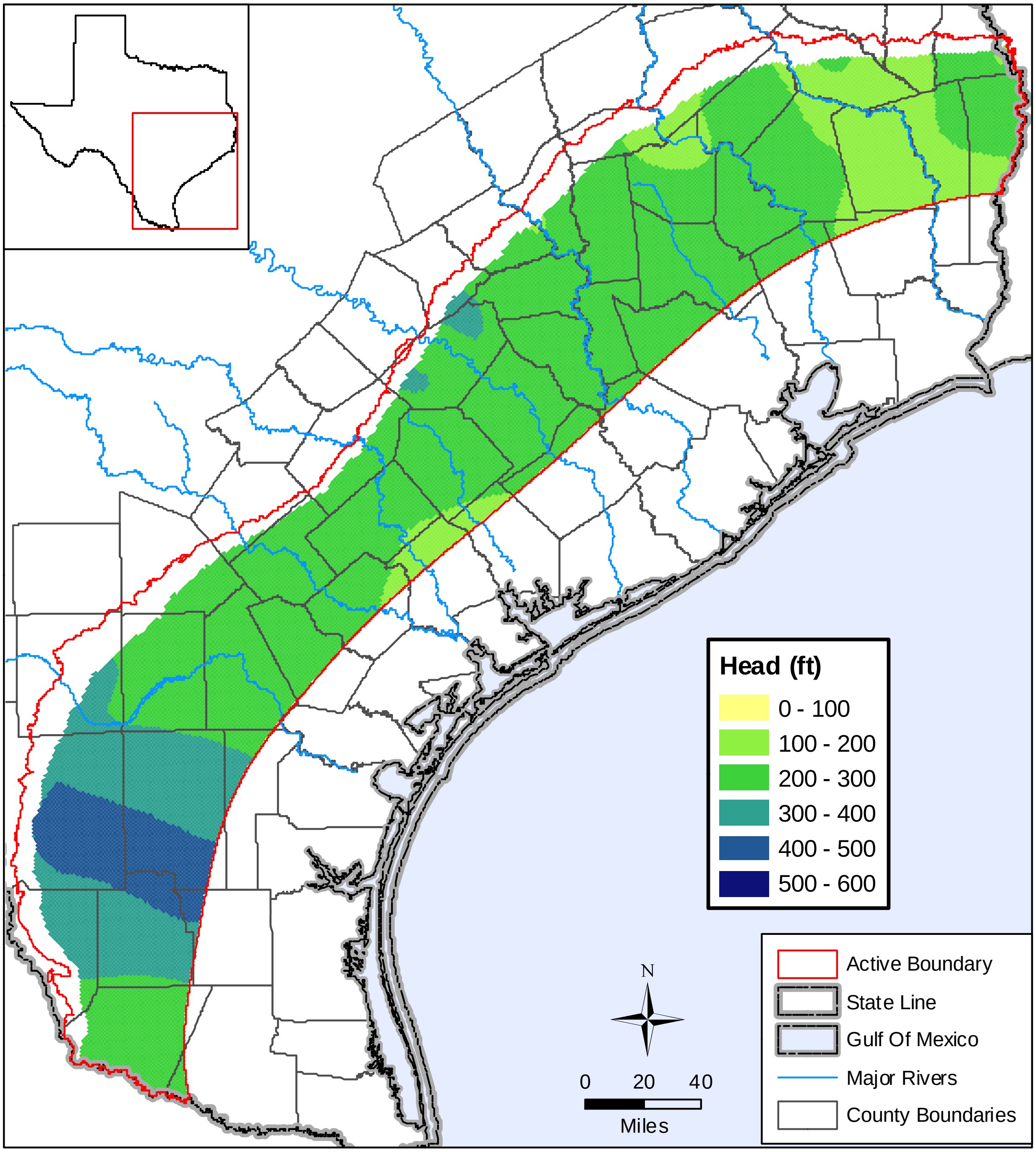


Figure 8.2.7 Simulated hydraulic head in feet in the Upper Yegua Unit subcrop.

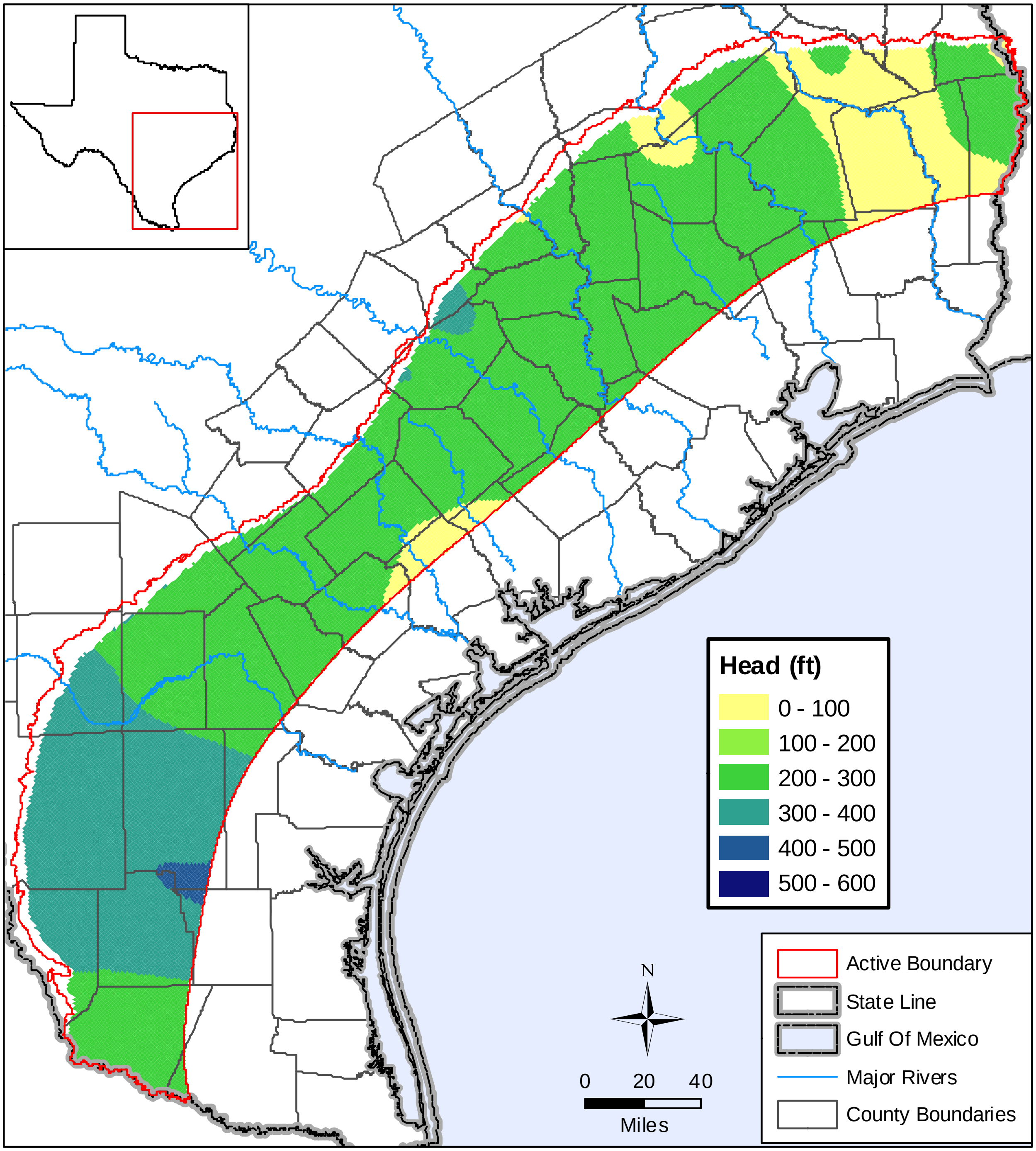
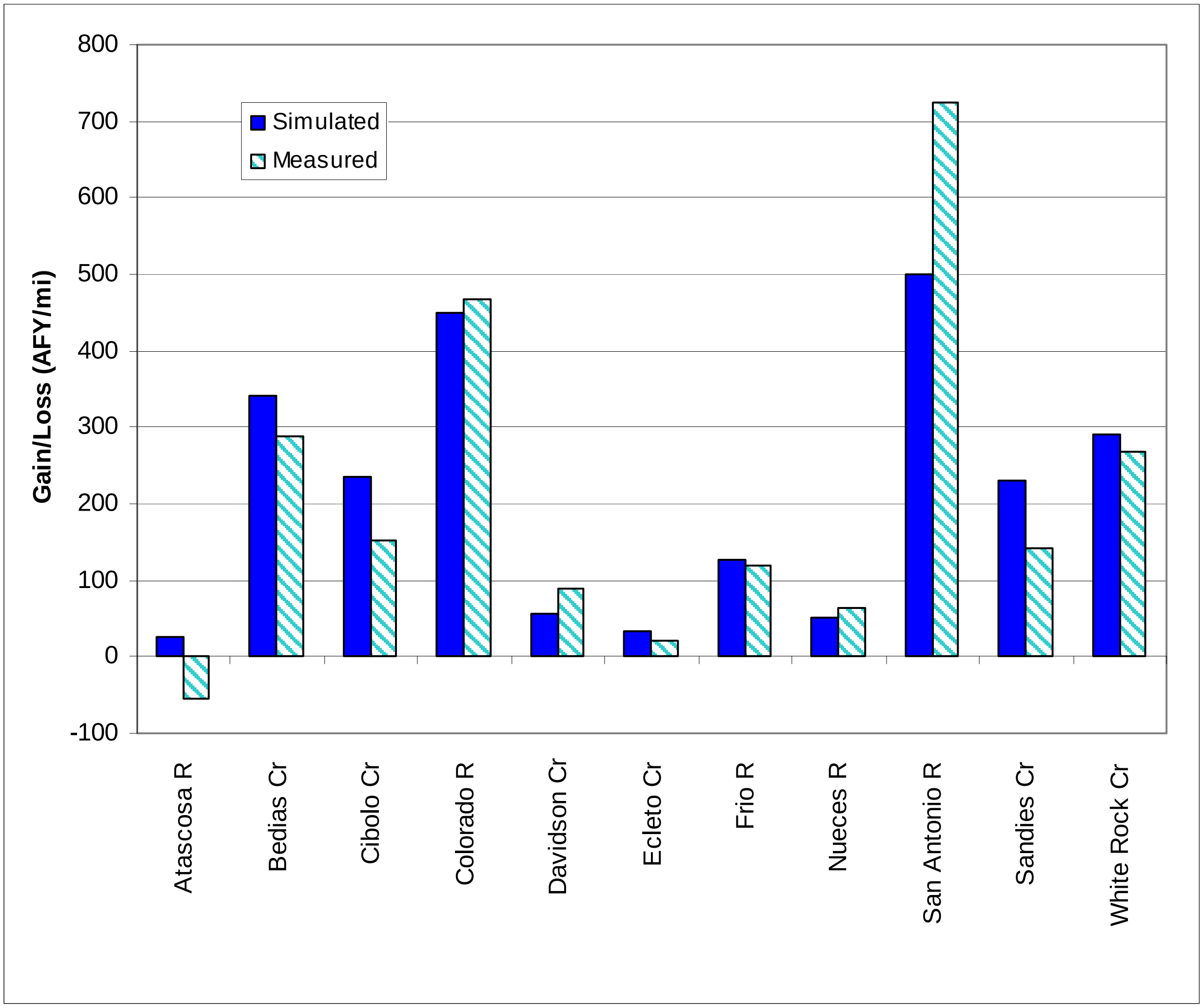
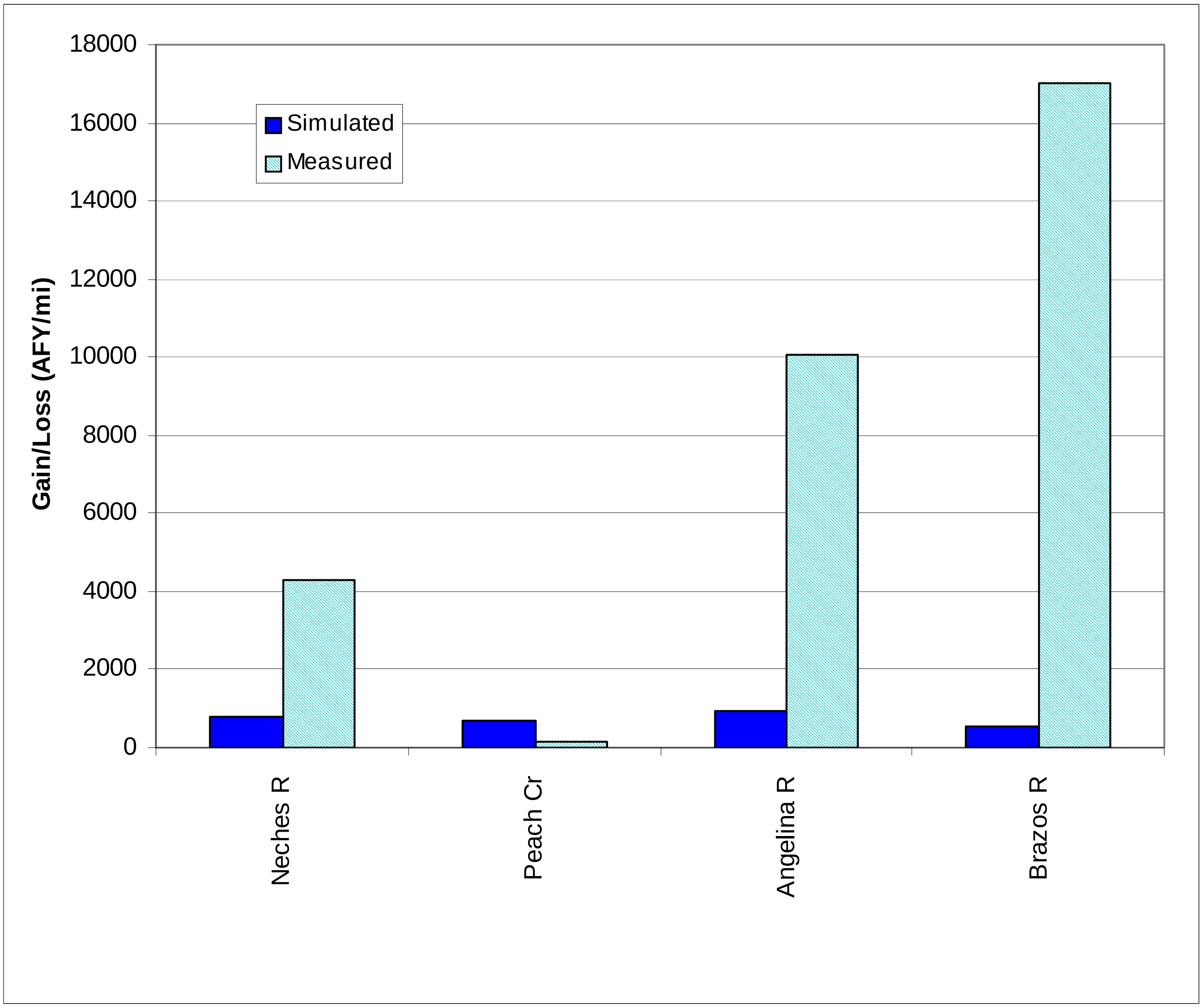


Figure 8.2.8 Simulated hydraulic head in feet in the Lower Yegua Unit subcrop.



R = River Cr = Creek

Figure 8.2.9 Comparison of simulated versus estimated stream gain/loss in acre-feet per year per mile for lower magnitude targets.



R = River Cr = Creek

Figure 8.2.10 Comparison of simulated versus estimated stream gain/loss in acre-feet per year per mile for higher magnitude targets.

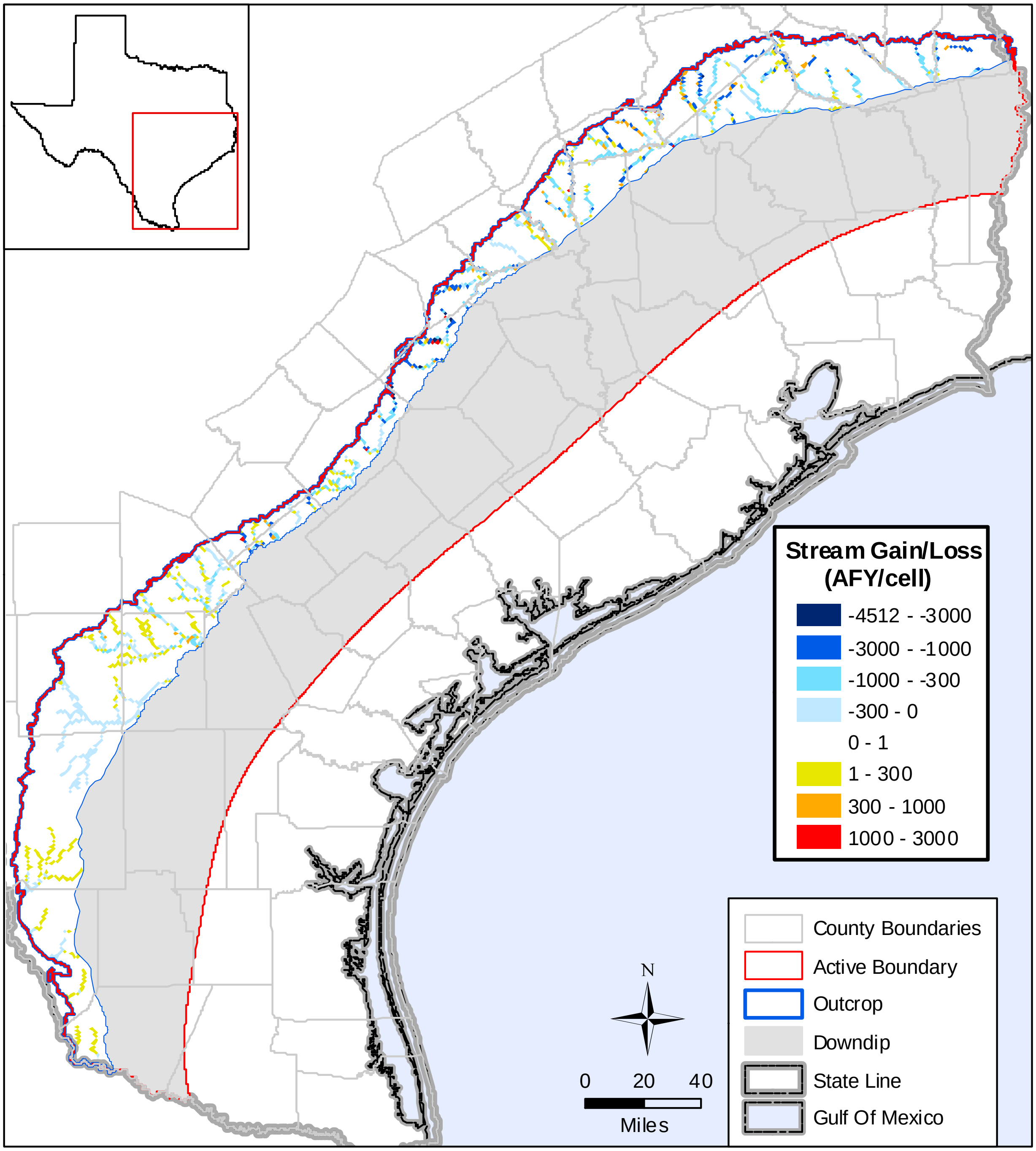


Figure 8.2.11 Spatial distribution of stream gain/loss rate in acre-feet per year per mile.

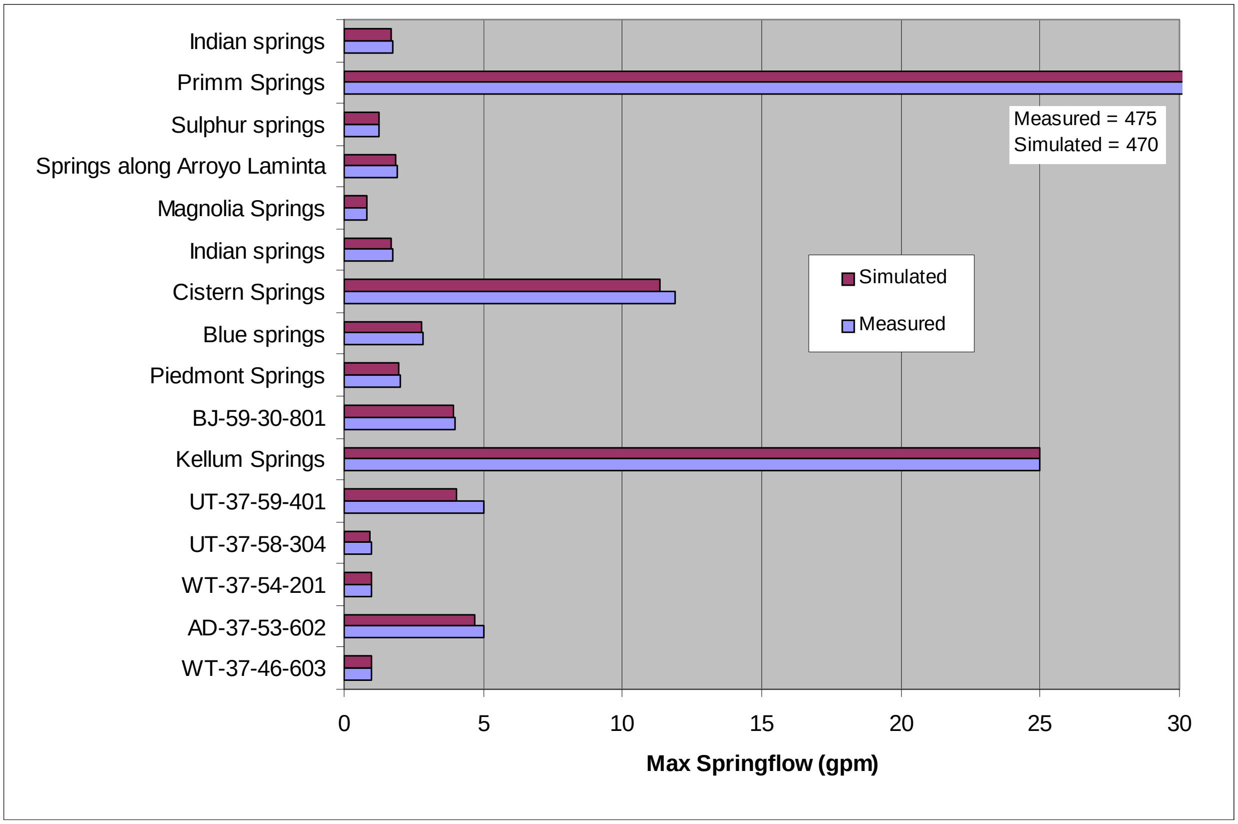


Figure 8.2.12 Comparison of simulated versus measured maximum spring flow rates in gallons per minute.

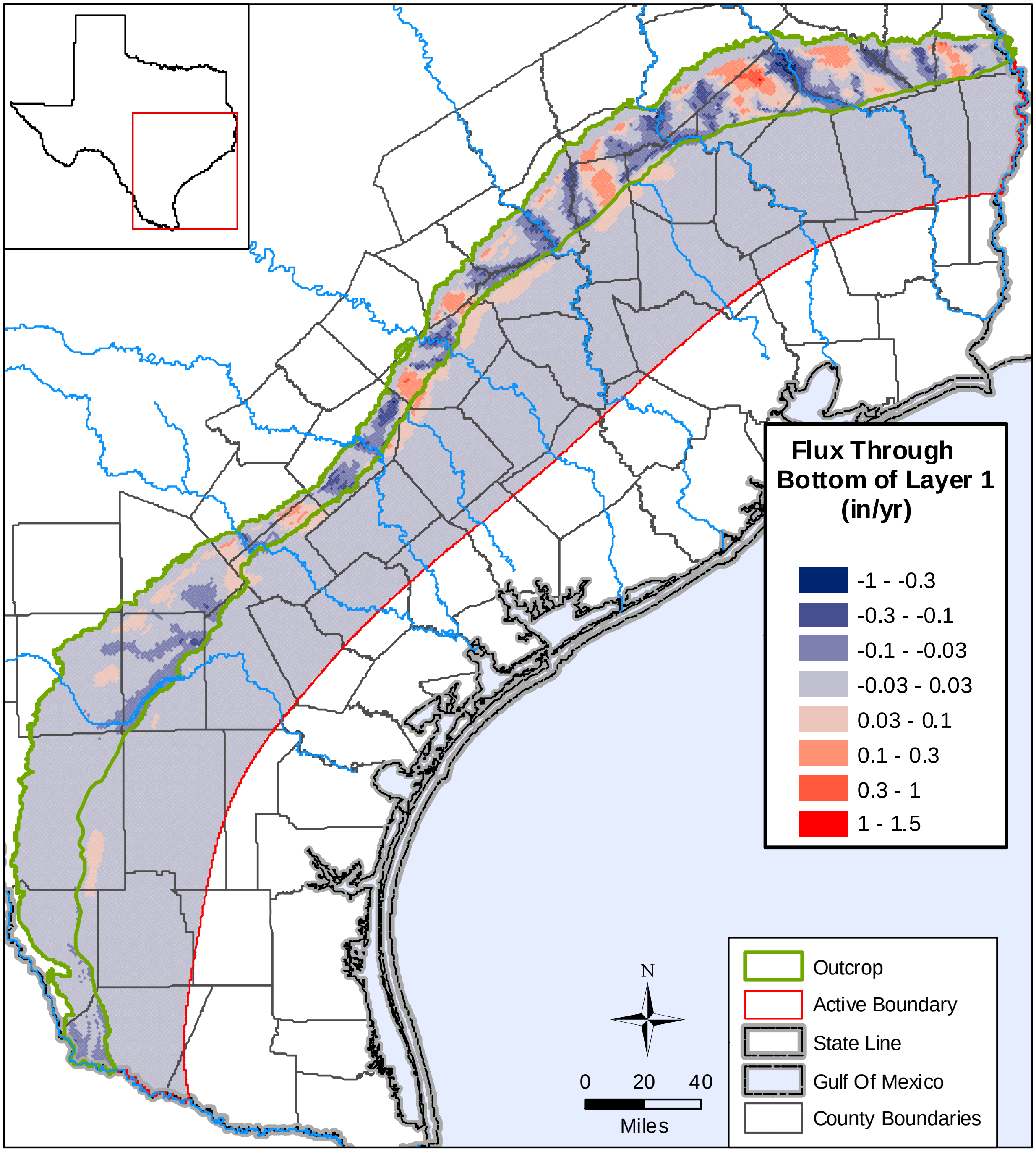


Figure 8.2.13 Flux rates in incher per year through the bottom of the shallow layer (Yegua-Jackson Aquifer outcrop) and Catahoula Formation (subcrop).

8.3 Sensitivity Analysis

A sensitivity analysis was performed on the calibrated steady-state model. A sensitivity analysis provides a means of formally describing the impact of varying specific parameters or groups of parameters on model outputs. In this sensitivity analysis, input parameters were systematically increased and decreased from their calibrated values while the change in water-level elevation or discharge was recorded. Four simulations were completed for each parameter sensitivity, where the input parameters were varied either according to:

$$\text{(new parameter)} = \text{(old parameter)} * \text{factor} \qquad (8.3.1)$$

or

$$\text{(new parameter)} = \text{(old parameter)} * 10^{\text{(factor - 1)}} \qquad (8.3.2)$$

or

$$\text{(new parameter)} = \text{(old parameter)} + ((\text{factor-1}) * 40) \qquad (8.3.3)$$

and the factors were 0.5, 0.9, 1.1, and 1.5. Parameters such as recharge were varied linearly using Equation 8.3.1. For parameters such as hydraulic conductivity, which are typically thought of as log-varying, Equation 8.3.2 was used. For parameters involving elevation changes in boundary conditions, Equation 8.3.3 was used. For head sensitivities, we calculated the mean difference (MDH) between the base simulated head and the sensitivity simulated head:

$$MDH = \frac{1}{n}\sum_{i=1}^{n}\left(h_{sens,i} - h_{cal,i}\right) \qquad (8.3.4)$$

where $h_{sens,i}$ is the sensitivity simulation head at active gridblock i, $h_{cal,i}$ is the calibrated simulation head at active gridblock i, and n is the number of active gridblocks.

For flow sensitivities, we calculated the mean difference (MDQ) between the base simulated flow and the sensitivity simulated flow:

$$MDQ = \frac{1}{n}\sum_{i=1}^{n}\left(Q_{sens,i} - Q_{cal,i}\right) \qquad (8.3.5)$$

where $Q_{sens,i}$ is the sensitivity simulation flow at active gridblock *i*, $Q_{cal,i}$ is the calibrated simulation flow at active gridblock *i*, and *n* is the number of active gridblocks.

Two approaches to applying Equation 8.3.4 to the sensitivity of output heads were considered. First, the heads in all active grid blocks between the sensitivity output and the calibrated output were compared. Second, the heads only at grid blocks where measured targets were available (i.e., *n* = number of targets in that layer) were compared. Because the Yegua-Jackson Aquifer is currently used only in the near-outcrop region, and the targets are located in that region, we chose to evaluate head sensitivities based on values at the head target locations. For the flow sensitivities, flows were compared at all active cells were the flows were potentially present.

For the steady-state sensitivity analysis, twelve parameter sensitivities were investigated:

1. Horizontal hydraulic conductivity of the shallow layer (Kh-Shallow),
2. Horizontal hydraulic conductivity of the Jackson Group (Kh-Jackson),
3. Horizontal hydraulic conductivity of the Yegua Formation (Kh-Yegua),
4. Vertical hydraulic conductivity in the Catahoula Formation (Kv-Catahoula)
5. Vertical hydraulic conductivity in the Jackson Group (Kv-Jackson),
6. Vertical hydraulic conductivity in the Yegua Formation (Kv-Yegua),
7. Recharge, model-wide (Rch),
8. Streambed conductance (Str-Cond),
9. Drain conductance (Drn-Cond),
10. Spring conductance (K-Spring),
11. General-head boundary conductance (GHB-Cond), and
12. General-head boundary elevation (GHB-Elev).

Equation 8.3.1 was used for sensitivity 7, Equation 8.3.2 was used for sensitivities 1-6, and 8-11, and Equation 8.3.3 was used for sensitivity 12.

Figures 8.3.1 through 8.3.3 show the sensitivity of head to changing horizontal and vertical hydraulic conductivities. In the shallow layer (Figure 8.3.1), head is most sensitive to the horizontal hydraulic conductivity in the shallow layer. The horizontal conductivity in the Jackson Group and Yegua Formation have about equal impact on heads in the shallow layer. For the Jackson Group (Figure 8.3.2), the horizontal conductivity in the shallow layer has the most impact on heads, with the horizontal conductivity in the Jackson Group having the second most effect. The horizontal conductivity of the Yegua Formation has a small effect. For heads in the Yegua Formation (Figure 8.3.3), the trend is reversed, in that the horizontal hydraulic conductivity of the Yegua Formation is more important than the conductivity of the Jackson Group. It is intuitive that the conductivity of a given unit would have most effect on heads in that unit. In all of these cases, the conductivity of the shallow layer combines conductivities from all of the units, so it has the largest effect.

Figure 8.3.4 shows the head sensitivity in the shallow layer to various boundary condition parameters. The magnitude of recharge has the largest effect on heads. The stream conductance has an unusual impact on heads, since it does not show an obvious upward or downward trend with increasing or decreasing conductivity. This is because of the change in the magnitude of both gaining and losing streams with changing conductance. Figures 8.3.5 and 8.3.6 show the change in the gain rate and loss rate of the streams, respectively. The figures show that both gaining and losing streams increase their magnitude of gain or loss with increasing conductance. The difference between the gains and losses does not stay constant, thus the result shown in Figure 8.3.4. Figures 8.3.7 and 8.3.8 show the head sensitivity in the Jackson Group and Yegua Formation for the changing boundary condition parameters. Similar to the shallow layer, recharge has the highest overall impact on heads, while stream conductance has a significant, but inconsistent impact.

Figure 8.3.9 shows the sensitivity of springflow to the change in horizontal and vertical conductivities. As with the heads, changing horizontal conductivities have the most effect, with the shallow layer conductivity being most important. Figure 8.3.10 shows the sensitivity of springflow to the changing boundary condition parameters. The same impact of stream conductance is seen here, due to its effect on heads. Because the streams are typically in the low lying areas near the locations of springs, the effect of stream conductance on heads has a large effect on heads near the springs. The drain conductance, which is the conductance of the drains that actually represent the springs, has the second most impact on springflow. Recharge also has some positive correlation with springflow, as would be expected.

Figure 8.3.11 shows the stream gain/loss sensitivity to conductivities. The sensitivity to boundary condition parameters had been shown previously in Figures 8.3.5 and 8.3.6. As with overall heads, changing horizontal hydraulic conductivities have the most effect, with the shallow layer conductivity being most important.

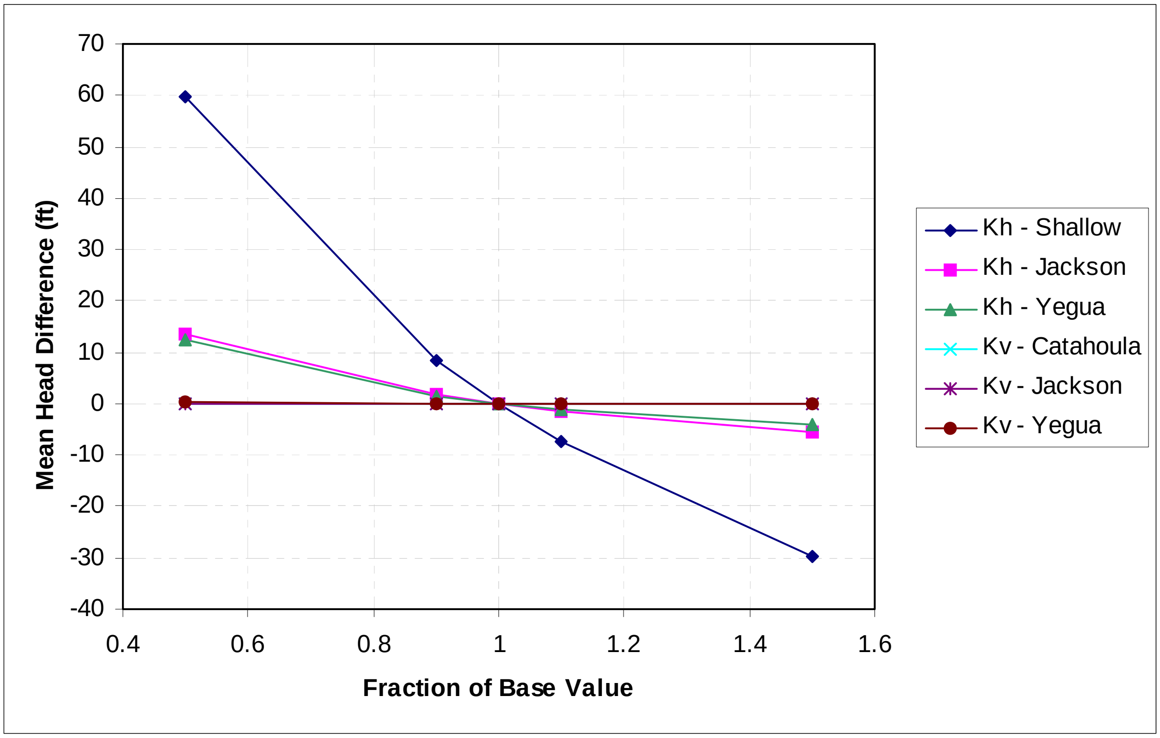


Figure 8.3.1 Steady-state head sensitivity in feet in the shallow layer to changes in hydraulic conductivities.

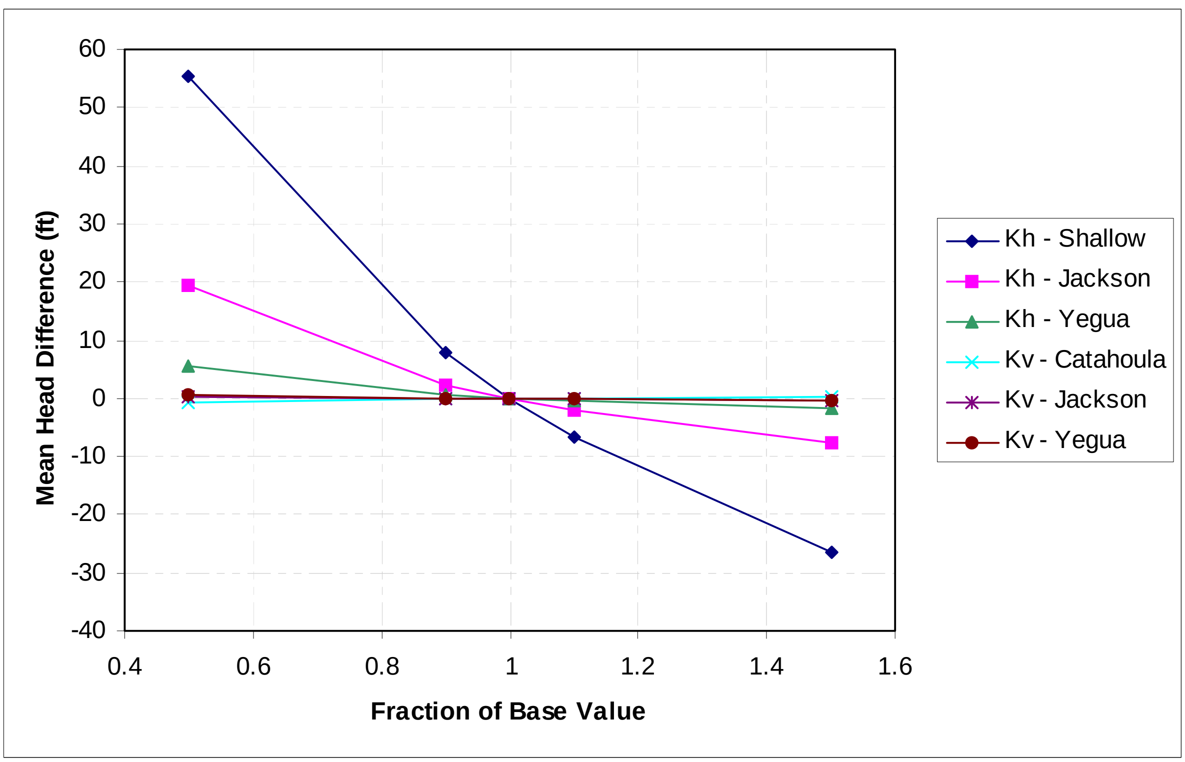


Figure 8.3.2 Steady-state head sensitivity in feet in the Jackson Group to changes in hydraulic conductivities.

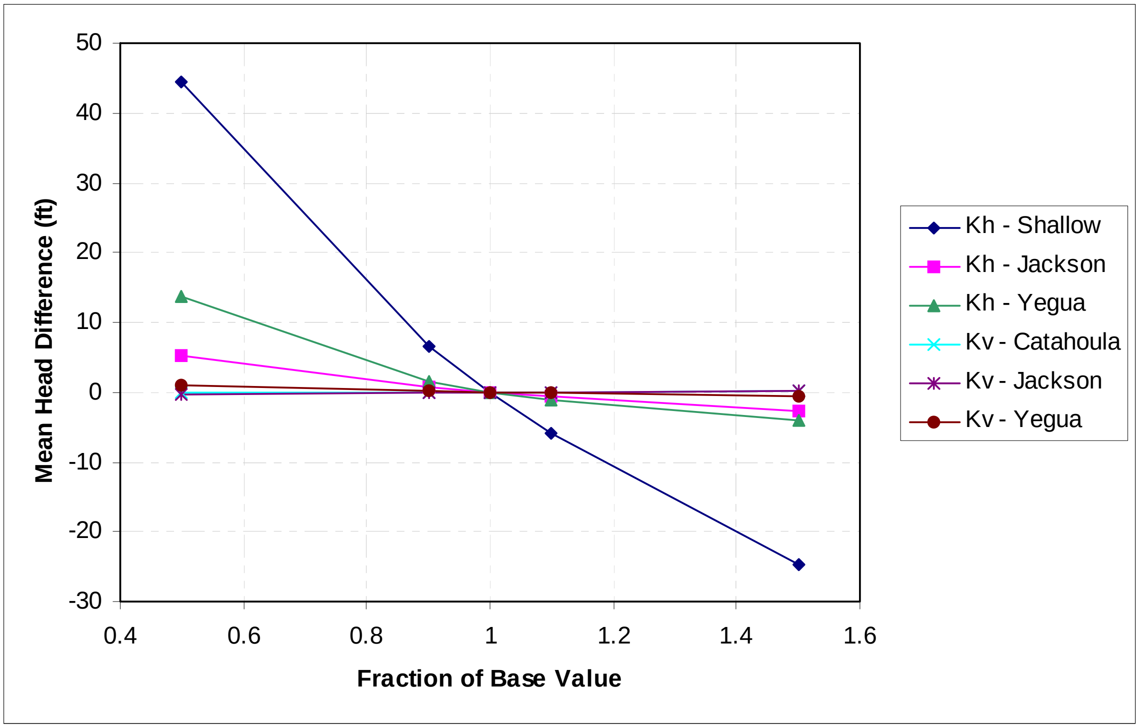


Figure 8.3.3 **Steady-state head sensitivity in feet in the Yegua Formation to changes in hydraulic conductivities.**

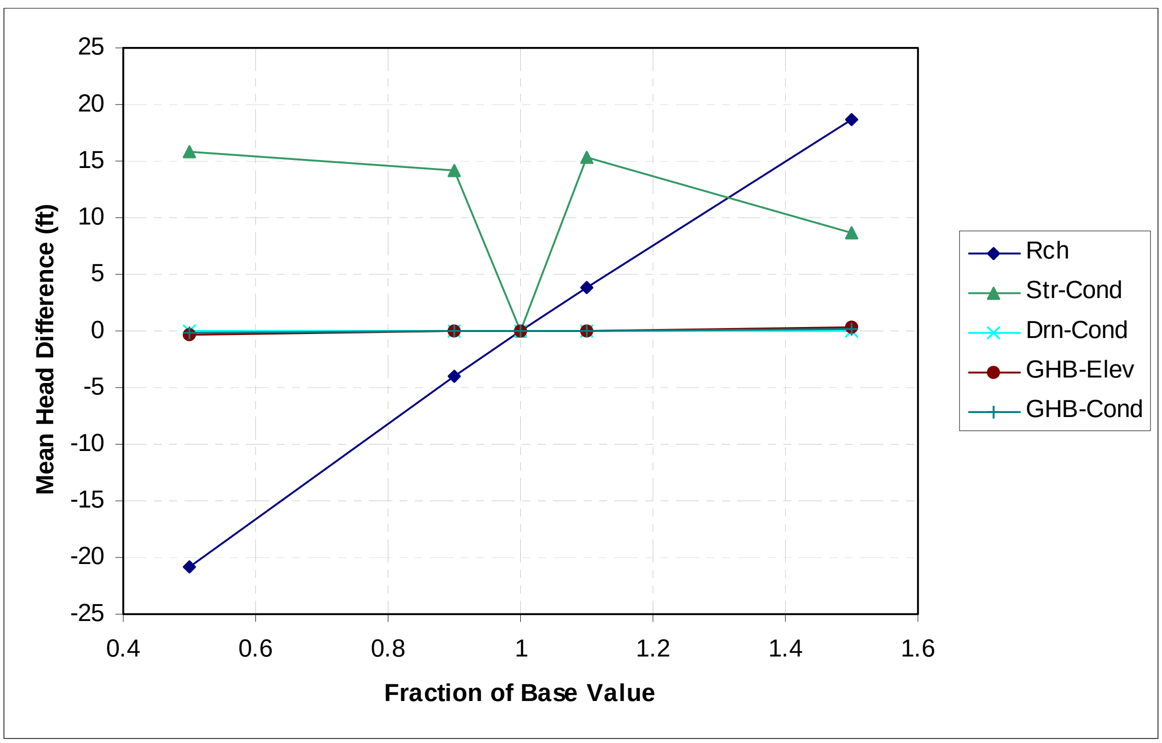


Figure 8.3.4 **Steady-state head sensitivity in feet in the shallow layer to changing boundary conditions.**

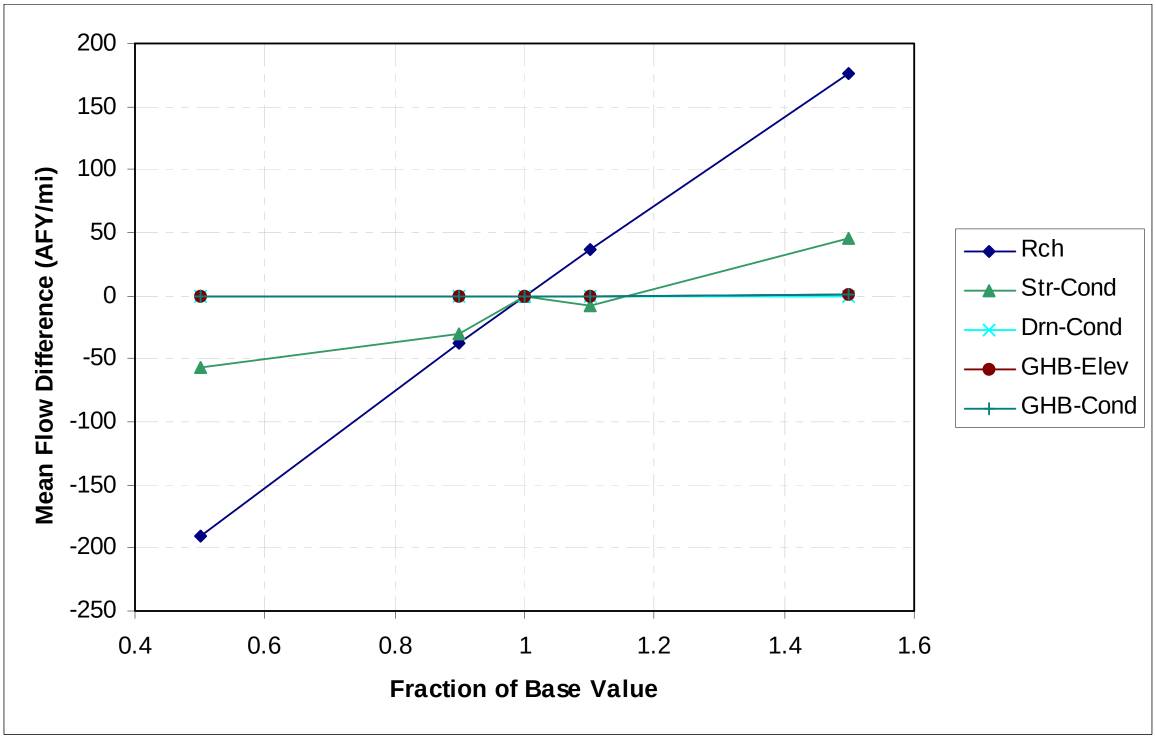


Figure 8.3.5 Stream gain rate sensitivity in acre-feet per year per mile to changing boundary conditions.

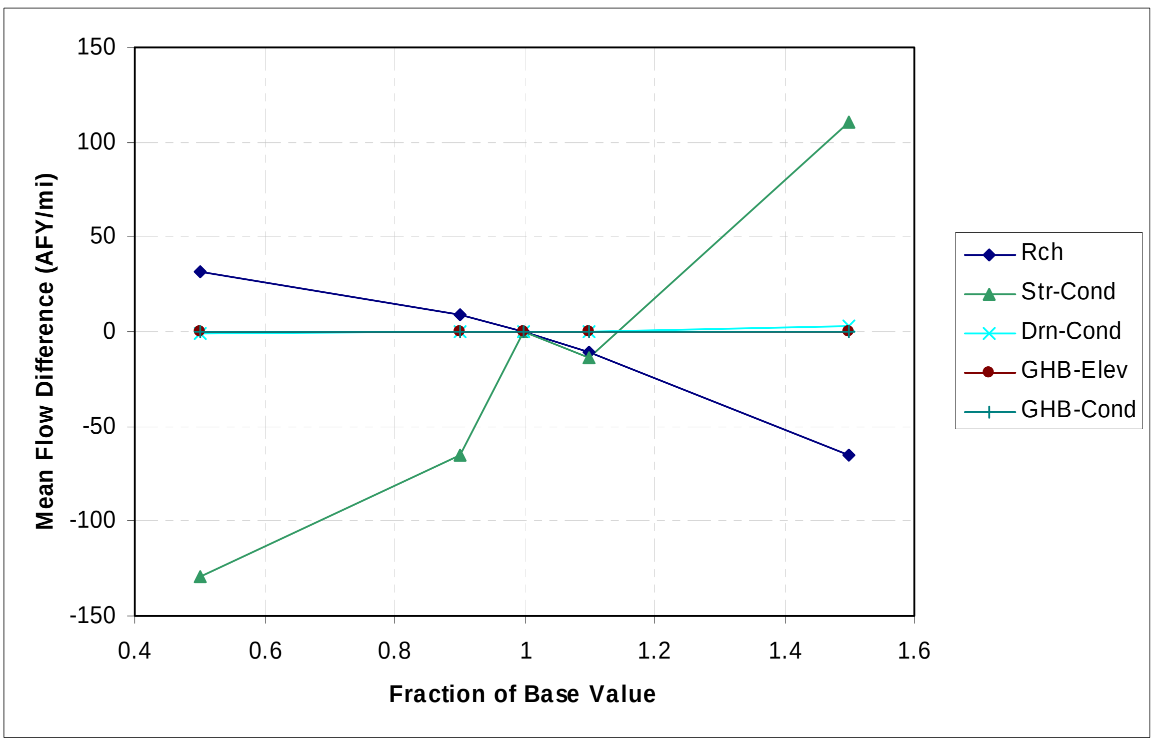


Figure 8.3.6 Stream loss rate sensitivity in acre-feet per year per mile to changing boundary conditions.

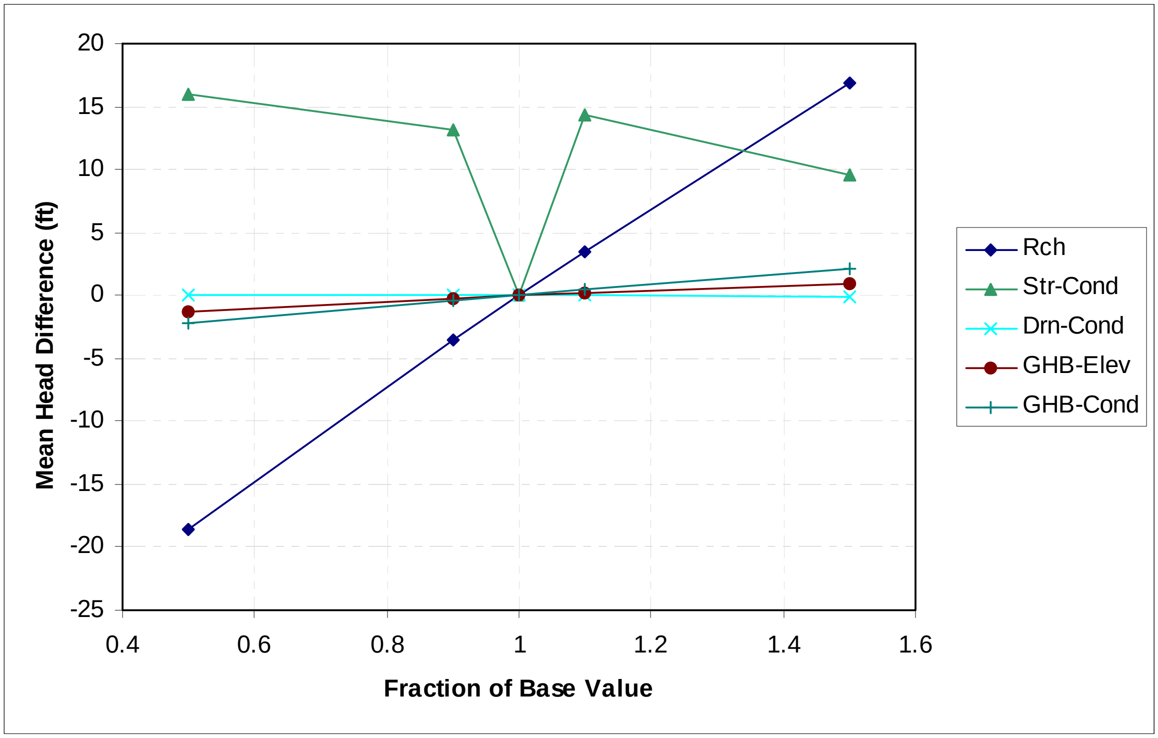


Figure 8.3.7 Head sensitivity in feet in the Jackson Group to changes in boundary conditions.

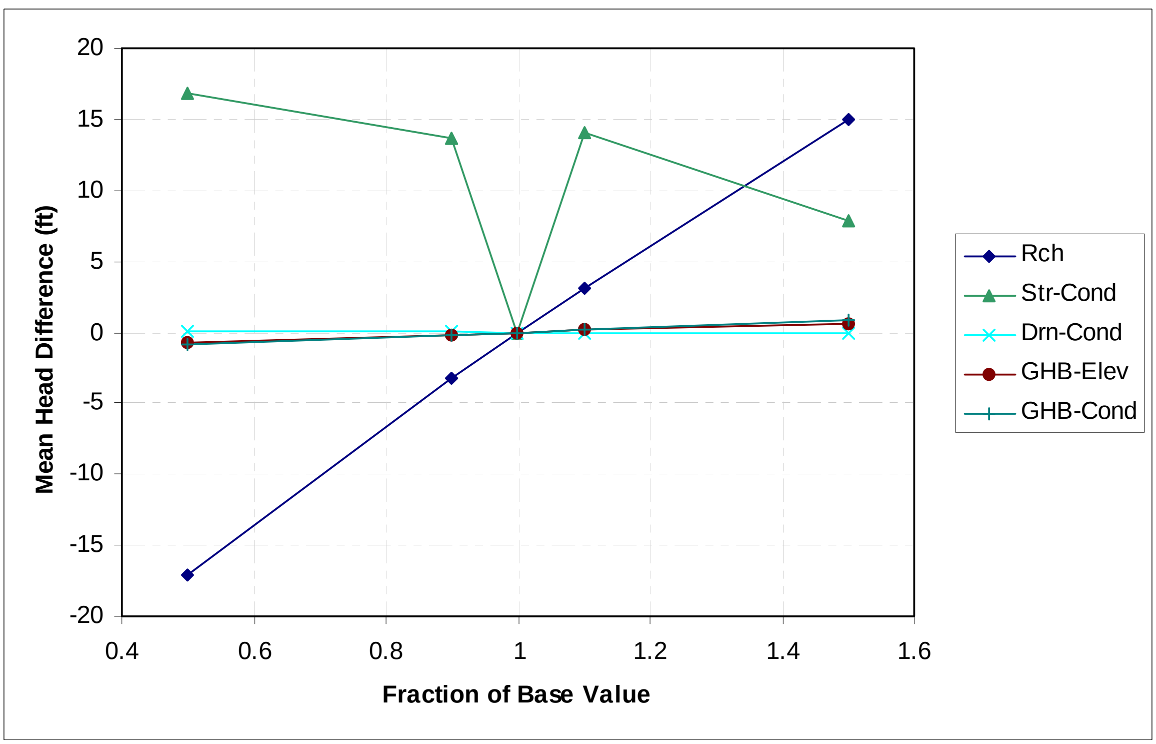


Figure 8.3.8 Head sensitivity in feet in the Yegua Formation to changes in boundary conditions.

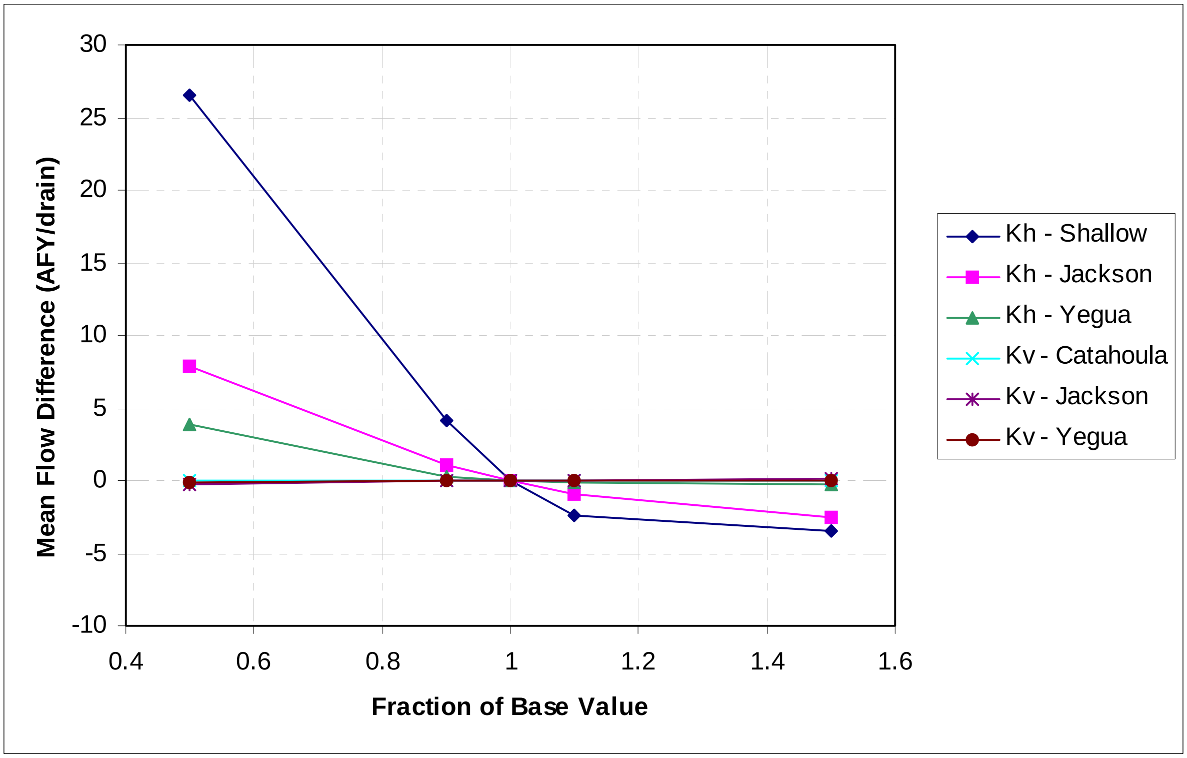


Figure 8.3.9 Springflow sensitivity in acre-feet per year to changes in hydraulic conductivities.

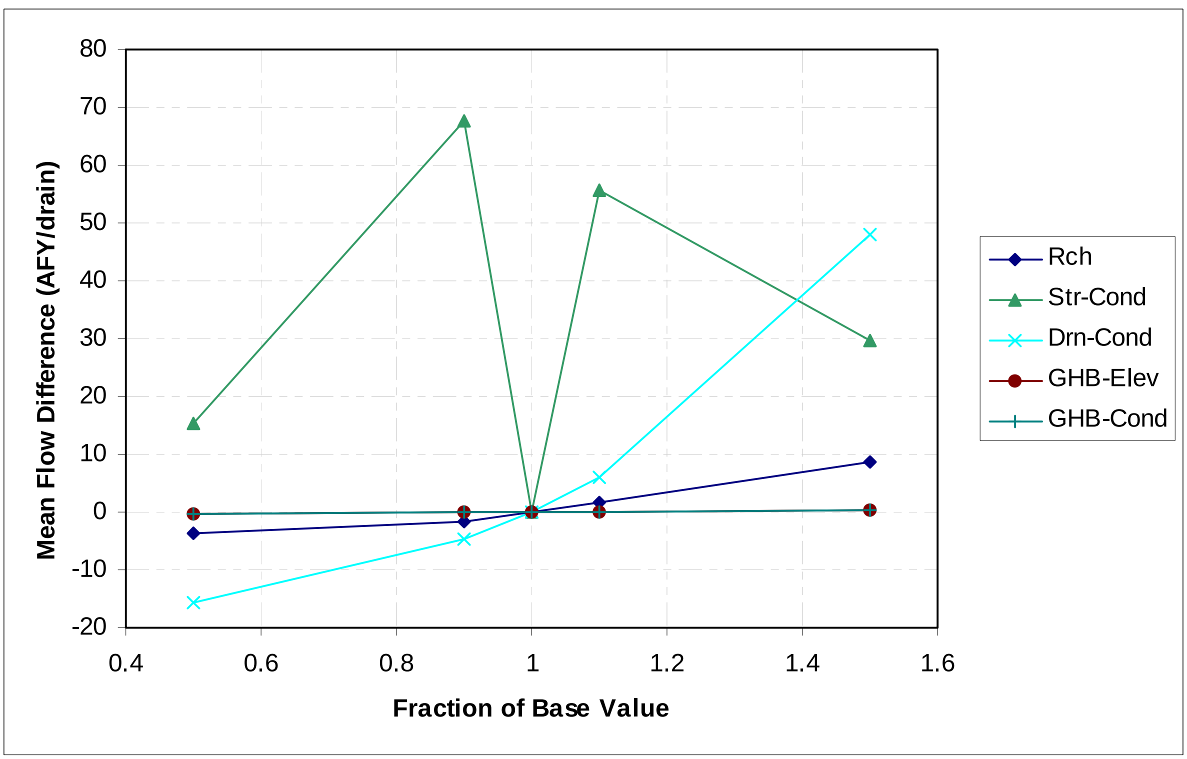


Figure 8.3.10 Springflow sensitivity in acre-feet per year to changes in boundary conditions.

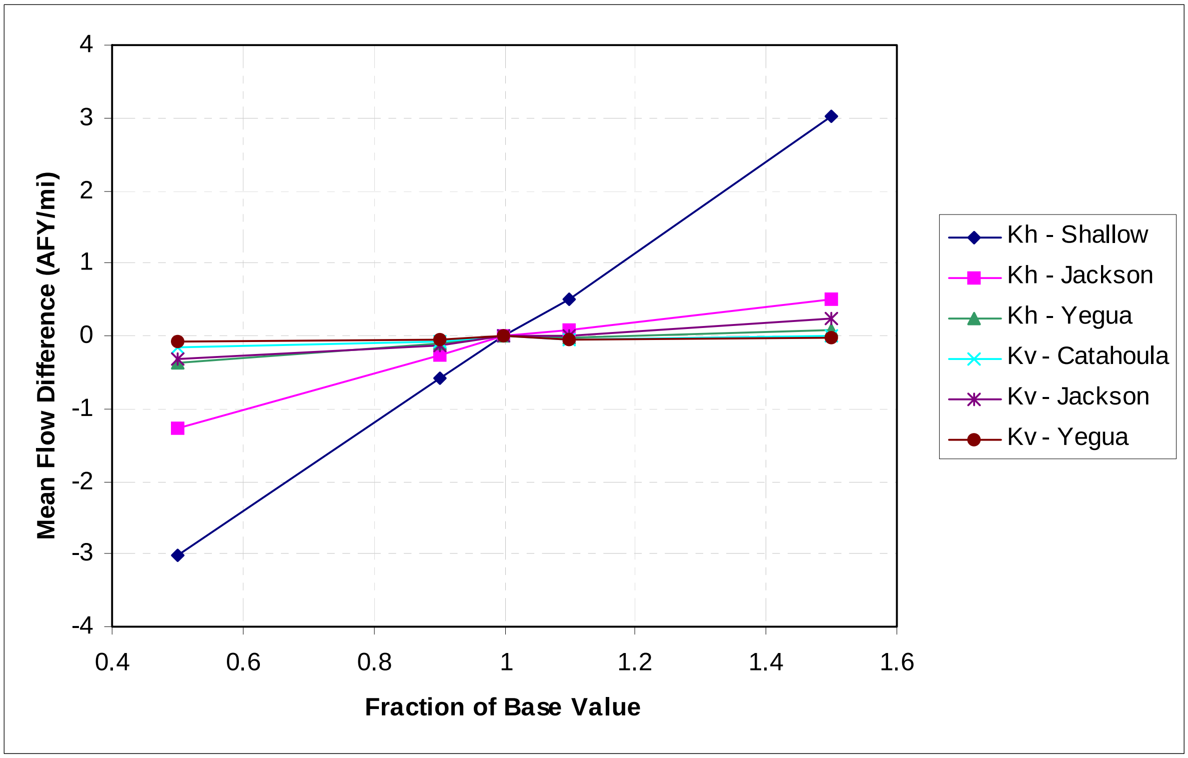


Figure 8.3.11 Stream gain/loss sensitivity in acre-feet per year per mile to changes in hydraulic conductivities.

9.0 Transient Model

The transient model developed for the Yegua-Jackson Aquifer simulates a period from 1901 to 1997. This section details calibration of the transient model and presents the transient model results. The sensitivity of the transient model to various hydrologic parameters is also described.

9.1 Calibration

This section describes the transient calibration targets and calibration parameters that were adjusted during transient model calibration.

9.1.1 Calibration Targets

Wells with transient calibration targets were analyzed in a similar fashion to the steady-state target wells described in Section 8.1.1. The candidate wells were selected from those in the model region with appropriate water level measurements (see Section 8.1.1. for the characteristics of the database query). As with the steady-state targets, the wells were located vertically based on the layer with maximum transmissivity across the well screen interval. For those wells without screen information, a screen interval was assumed that spanned from the total well depth to 50 feet above that total depth.

As described in Section 7.1, the formal calibration period was from 1980 to 1997. Measurements in this period were examined closely to judge their historical record and their consistency with neighboring targets. Of over 100 candidate wells with measurements in the calibration period, five were rejected due to one of these inconsistencies. There were 685 individual measurements used in the calibration period.

Wells for hydrograph comparisons were chosen from the entire historical period from 1901 to 1997. The few hydrographs that showed evidence of drawdown indicated that drawdown began occurring before the calibration period. This is what motivated the inclusion of the pre-1980 measurements in the transient calibration. We chose those wells that had at least five measurements, which resulted in 67 hydrographs.

9.1.2 Storage Properties

Specific yield and storativity were not changed from their initial values during transient calibration. Because of the lack of significant point pumping in the shallow layer, hydrographs were relatively insensitive to specific yield. In the confined layers, modifying storativity was not helpful in fitting simulated drawdowns, since these long-term drawdowns were not very sensitive to changes in the confined storativity (Section 9.3 details the sensitivity analysis). Typically, storativity will be most important under conditions where pumping cycles dramatically over short time periods, which is not the case for the Yegua-Jackson Aquifer. The storativity distributions are shown in Section 6.4.2.

9.1.3 Horizontal and Vertical Hydraulic Conductivities

The majority of adjustment of horizontal and vertical hydraulic conductivities in the confined units of the model occurred during transient calibration. As described in Section 8.1.2, the PEST calibration of the steady-state model resulted in good statistics for the steady-state model. Similarly, for those transient hydrographs that showed little to no change over the course of the historical period, the steady-state parameterization provided a good fit to the transient targets. However, for those few transient targets that showed significant drawdown, the fit was poor.

In a few cases, point pumping was nearly coincident with the wells where drawdown was evident. However, with the initial steady-state parameterization, simulated drawdowns were not sufficient to match the measured drawdowns. To match these drawdowns, horizontal and vertical hydraulic conductivities were reduced from the steady-state calibration estimates (which were generally near the initial estimates). Both horizontal and vertical hydraulic conductivities had to be reduced to simulate drawdowns similar to the measured drawdowns, where simulated pumping was present.

For vertical hydraulic conductivities, the estimated vertical clay conductivity was reduced from $1\text{x}10^{-3}$ to $1\text{x}10^{-4}$ feet per day. For horizontal hydraulic conductivities, the various estimates for sand conductivities of the different facies and units were reduced near their lower ranges, as shown in Table 9.1.1. In general, the sand conductivities were reduced by about a factor of three. The final calibrated horizontal and vertical hydraulic conductivities are presented in Section 8.1.2.

This reduction in hydraulic conductivities improved the characteristics of the simulated drawdowns compared to measured drawdowns in some instances. However, there were still areas with hydrographs that showed significant drawdowns, yet the initial conceptualization of pumping produced minimal or no point pumping in that same area.

9.1.4 Local Reassessment of Pumping

In reassessing some of the pumping estimates from the initial conceptualization of pumping described in Section 4.6.2, we made the assumption that significantly declining water levels were evidence of nearby pumping. Having adjusted intrinsic properties within a reasonable range, we then reassessed those areas that showed significant drawdowns in the absence of significant pumping. In these regions, we augmented pumping in one of three ways:

1. Identified pumping in the TWDB master pumping database that could be fractionally allocated to the Yegua-Jackson Aquifer based on wells associated by *alphanum*.

2. Identified nearby users that could potentially be drawing from the target area, and moved a fraction of the currently allocated pumping to the target area.

3. Identified nearby sources of pumping that could potentially be underestimated.

Approach number 1 results in additional overall pumping for a given county, but is most defensible because there is a direct link between the target area (or wells in that area) and the alphanum in the master database. Approach number 2 does not result in any additional pumping in a county, but rather represents reallocation from one area within the county to another area. Approach 3 represents additional pumping in a county, and is not directly supported by values in the master database. Approach 3 was only used in one instance in Sabine County.

Table 9.1.2 describes the six areas where pumping was augmented. In the table, the well number in the first column is a representative well for that area; that is, we are not proposing that all of the additional pumping occurs in that exact well, but only in the model cell that is concurrent with the well. For wells 3742602 and 3750303, the fractional amount of pumping that was allocated based on the *alphanum* was calculated by assuming that the Yegua-Jackson Aquifer wells were 3 times less productive than Carrizo Formation wells, and simply weighting the pumping allocation by the number of wells. For well 6617614, the only well associated with that *alphanum* was a Yegua-Jackson Aquifer well, so 100 percent of the pumping was allocated. For wells 3751403 and 6006801, pumping from a nearby city was re-allocated to the target area using approach number 2. For Sabine well 3641707, we assumed that the manufacturing pumping near the city of Pineland was underestimated.

For the calibration period from 1980 to 1997, we used the fractional rate from the pumping source (based on the rate in the master pumping database) to determine annual pumping. For the period prior to 1980, we assumed a linear increase in pumping from the point on the hydrographs where it appeared that significant pumping had begun.

Figure 9.1.1 shows the impact of both the decrease in hydraulic conductivities (labeled “New props” in the legend) and the augmented pumping (labeled “Props + Q”) on several of the hydrographs that showed significant drawdown. For the wells in Angelina County, some pumping was already present, so the properties improved the match between simulated and measured. However, with the augmented pumping, the match becomes considerably better. For the wells in Fayette and Trinity counties, minimal pumping was present before the re-analysis, so the augmented pumping, makes the difference between complete misfit and a good fit.

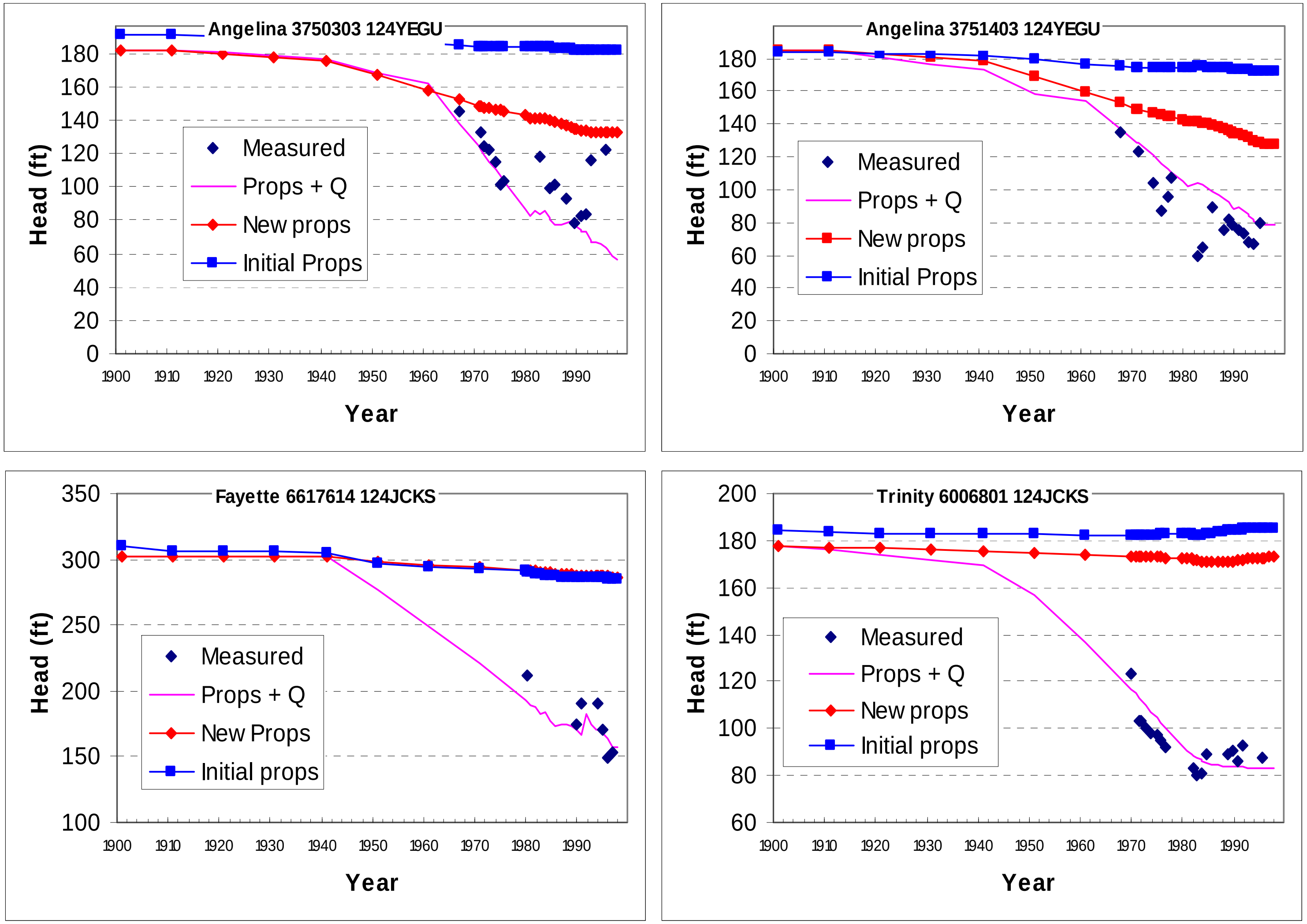
Table 9.1.1 Change in horizontal hydraulic conductivity parameters from initial to calibrated transient model. All values reported in feet per day.

Unit	Facies	Initial	Calibrated
Upper Jackson	fluvial	15	5
	delta	8	3
	shelf	5	1
Lower Jackson	fluvial	15	5
	delta	8	3
	shelf	5	1
Upper Yegua	fluvial	20	7
	delta	15	5
	shelf	5	1
Lower Yegua	fluvial	20	7
	delta	8	3
	shelf	5	1

Table 9.1.2 Description of pumping modifications for transient calibration.

Well	County	Alphanum Source	Pumpamatic Aquifer	Aquifer of Associated Wells	Donor Locations	Fractional Amount	Supplement (AFY)	Comment
3742602	Angelina	399450	Carrizo-Wilcox	5 Yegua-Jackson 1 Carrizo-Wilcox	none	0.625	0	Fractional association
3641707	Sabine	683170	OTHER	Yegua-Jackson	LRC05073455	1	1000	Supplemental pumping estimated as additional manufacturing
3750303	Angelina	519600	Carrizo-Wilcox	7 Yegua Jackson, 2 Sparta, 14 Carrizo-Wilcox	none	0.1	0	Fractional association
3751403	Angelina	696800	Yegua-Jackson	Yegua-Jackson	LRC04044417, LRC04044419, LRC04044418, LRC04045415, LRC04045416	0.5	0	Estimated to be some fraction of City of Dibol pumping
6617614	Fayette	778600	Gulf Coast	Yegua-Jackson	none	1	0	Alphanum potentially misassociated in master table
6006801	Trinity	N/A	N/A	N/A	LRC02033376, LRC0234376	0.666666667	min 350	City of Trinity pumping erratic in master table

AFY = acre-feet per year
N/A = not applicable



Props + Q = decrease in hydraulic conductivity and augmented pumping New Props = decrease in hydraulic conductivity
Initial Props = initial hydraulic conductivity

Figure 9.1.1 Example of calibration improvement from reduction in hydraulic conductivity and increase in pumping.

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9.2 Simulation Results

9.2.1 Water-Level Elevation

The transient model was calibrated to the head targets described in Section 9.1.1. A crossplot of measured versus simulated heads for the transient calibration period is shown in Figure 9.2.1. The crossplot shows normal scatter around the 1:1 line, and does not demonstrate significant bias in the lower or higher elevations. A few single measurements are evident where the observed heads are lower than the measured heads, which might be evidence of underestimated pumping. However, in the absence of long-term trends, we did not consider reevaluating pumping rates in the areas near these few points. Figure 9.2.2 shows a plot of measured heads versus residuals (the calculation of residuals is described in Section 8.2.1). With the exception of the few points described previously, the residuals show a relatively even distribution of positive and negative around the constant zero axis.

Table 9.2.1 shows the calibration statistics for the model in the transient calibration period. For the transient calibration period, there were only a few wells that spanned a small range of measurements in the Upper Jackson Unit, so we considered the combined Upper and Lower Jackson units in total when evaluating statistics. The mean absolute error for the calibration period ranges from 24.5 to 31.1 feet, which is in the same range as the potential errors described in Section 7.2. The mean absolute error divided by the range is about 10 percent or less in all the units, indicating a reasonable fit. The mean error is between -6 and 4 feet for all units, confirming that the average bias in the residuals is low.

Table 9.2.2 shows the calibration statistics for 1900 to 1979, the period prior to the transient calibration period. Examining these statistics from two time periods can provide information about how the calibration changes through time. For this pre-1980 period, the mean absolute error ranges from 25 to 33.4 feet, similar to the results for the 1980 to 1997 period. The mean absolute error divided by the range is about 10 percent or less in all units, similar to the results of the 1980 to 1997 period. The mean error for the pre-1980 period ranges from -8.2 to 11.7 feet, which indicates slightly more bias than in the transient calibration period, but is still within a reasonable range.

Figure 9.2.3 shows a post plot of the average residuals for all of the targets in the transient calibration period. The small, black markers indicate an absolute residual of less than 30 feet, which is in the typical range of the mean absolute error. Each county where targets are available shows residuals in this lower range. In addition, each county that contains several targets has residuals that are both positive (orange markers) and negative (blue markers), indicating little spatial bias on a county basis. Figure 9.2.4 shows the same type of plot for the pre-1980 period. Again, we use these results to determine how spatial bias might be changing through time. The distribution of residuals is similar for this period, with the low residuals (black markers) present in every county, and a mix of both positive and negative residuals in counties with more than a few measurements.

Figures 9.2.5 through 9.2.14 show the simulated head results for 1990 and 1997 in the shallow layer and in the confined section for each of the four units. Figures 9.2.5 and 9.2.6 show the heads in the shallow layer, which includes portions of all four of the hydrogeologic units that comprise the Yegua-Jackson Aquifer. As with the steady-state model, the head in the shallow layer reflects the topography, with lower heads in the river basins and higher heads in the interbasin areas. The change in heads between 1990 and 1997 is unremarkable, reflecting the generally unchanging heads in the unconfined portion of the aquifer.

Figures 9.2.7 and 9.2.8 show the heads in the Upper Jackson Unit subcrop. Heads in this unit range from about 0 to 600 feet, with the two lowest spots in northern Polk County and in Fayette County, where some drawdown has occurred. The overall head surface stays relatively constant from 1990 to 1997. Figures 9.2.9 and 9.2.10 show the heads in the Lower Jackson Unit subcrop. In this unit, heads have changed very little from steady-state, and do not change appreciably between 1990 and 1997. Figures 9.2.11 and 9.2.12 show the heads in the Upper Yegua Unit subcrop. In this unit, we see some evidence of drawdown in western Angelina County. This drawdown increases slightly from 1990 to 1997. Figures 9.2.13 and 9.2.14 show the heads in the Lower Yegua Unit subcrop. In this unit, we see evidence of drawdown in western Angelina County and western Sabine County, which are near the cities of Diboll and Pineland, respectively. Heads do not change significantly from 1990 to 1997.

Figures 9.2.15 through 9.2.23 show representative hydrographs (see Appendix B for a complete reporting of all available hydrographs) from all counties that had hydrograph data (at least five measurements, preferably in the calibration period). The entire historical period is shown on the hydrographs, from 1900 to 1997. In general, the hydrographs plots have a fixed 100-foot range on the y-axis, unless measured or simulated data warrant a larger range. Hydrographs are shown for wells in all units (there were not enough hydrographs for each unit to warrant separate plots for each), and the aquifer codes are plotted on the graphs to help indicate in which unit the well is present.

Figure 9.2.15 shows hydrographs from Zapata and Starr counties. These hydrographs indicate relatively steady measured heads, and the simulated heads are also unchanging. Figure 9.2.16 shows hydrographs form Karnes, Gonzales and Fayette counties. The measured data show a mostly unchanging trend through time, as do the simulated heads. The simulated heads for the well in Fayette County have a slight downward trend from 1950 to 1997, which may be present in the measured data, although it is not conclusive. Figure 9.2.17 shows additional hydrographs in Fayette County. Two of the measured hydrographs show steady heads throughout the historical period, and the simulated heads reflect this trend, although the simulated heads are 20 to 25 feet higher. The third well shows evidence of significant drawdown, which is reflected in the simulated head. Figure 9.2.18 shows hydrographs for Lee, Washington and Burleson counties. The measured heads show flat or slightly upward trends, as do the simulated heads.

Figure 9.2.19 shows hydrographs from Grimes County. Two of the measured hydrographs show relatively flat trends, and the simulated heads are similar, with one underpredicting the magnitude of heads. The other two measured hydrographs show a small drawdown of 10 to 20 feet from the middle of the 1970s to 1997. The simulated hydrographs do not reflect this trend, due to lack of simulated pumping in the area. Because the measured drawdowns were small, we did not feel that they warranted augmenting pumping in this county. Figure 9.2.20 shows hydrographs from Madison and Walker counties. The measured heads show flat trends for three of the four hydrographs, which is reflected in the simulated heads, although the simulated heads are underpredicting in two of the cases. For the well in western Madison County, a slight downward trend (about 10 feet of drawdown) is evident in the measured data that is not reflected in the simulated curve. Again, because the drawdown is so slight, we do not consider the mismatch to be significant.

Figure 9.2.21 shows hydrographs for Trinity and Polk counties. Three of the measured hydrographs show mostly flat trends, with the simulated heads reflecting the same. The well in southern Trinity County shows significant drawdown which is reflected in the simulated hydrograph. Note that measured hydrograph does not capture the full shape of the drawdown curve, as is evidenced by its first measurement of about 125 feet, compared to the other hydrographs updip in Trinity County that show consistent measurements in the 220- to 300-foot range. Figure 9.2.22 shows hydrographs from Angelina County. Three of these hydrographs show evidence of significant drawdown, that is well matched by the simulated heads. One well has a slight measured drawdown, the shape of which is reflected in the simulated curve, although the simulated head underpredicts compared to measured. Figure 9.2.23 shows hydrographs from Sabine County. Two of the measured hydrographs show relatively flat trends (or random oscillations) and the simulated heads overpredict in one case and underpredict in the other. For the well near the city of Pineland (well 3641707), almost 200 feet of drawdown is evident in the measured heads, and is reflected in the simulated heads. For well 3649402, the simulated hydrograph shows some drawdown due to the influence of the pumping near Pineland, while the measured heads do not span a long enough period to indicate whether they are similarly affected.

9.2.3 Water Budget

The transient model had an overall volumetric budget error of 0.08 percent, which is well within the acceptable range. Table 9.2.3 shows the water budget for the transient model in terms of net flux into or out of each of the aquifer units in the model. The conventions are similar to those used in the steady-state water budget. Negative numbers indicate flow out of the unit, while positive numbers indicate flow into the unit. The first two columns detail cross-formational flow in each of the units. The *surficial flow* term represents flow across units within the shallow layer (model layer 1), while the *confined* cross-formational flow is marked by the “Top” and “Bottom” fields and represents flow across units in the subcrop. “Top” indicates flow in or out of the top of a unit in the confined section, while “Bottom” indicates flow in or out of the bottom of a unit in the confined section. Overall, the water budget is dominated by recharge and stream discharge, which make up nearly 100 percent of the inflow and about 86 percent of the outflow, respectively. Pumping makes up between 3 and 4 percent of the discharge, and storage makes up a small fraction of the discharge as well.

Figures 9.2.24 and 9.2.25 show the running total model water budget for the historical period. Figure 9.2.25 shows the same data as Figure 9.2.24, with a narrower y-axis range. Figure 9.2.24 reflects what was previously stated, that recharge and streams dominate the water budget. Because we see evidence of drawdown in a few of the hydrographs, we know storage is contributing to the positive part of the water budget in some areas. We can see this contribution from storage in the water budget in 1950, where storage becomes a net contributor (water is being removed from storage overall). This time period corresponds to the increase in pumping and the begin of declining hydrographs in some areas of the aquifer. By 1970, this contribution from storage is masked by the small amount of recharge that goes into storage over a similar time period, due to decreasing discharge. Discharge to streams decreases slightly in the late 1950s and early 1960s. This is due to the reservoirs being impounded at that time. When the reservoirs are impounded, those streams segments in the eastern portion of the model that were previously regions of discharge are replaced by reservoirs, which are typically losing or only weakly gaining. The recharge that was previously going to those stream segments then is taken in as storage for a short time, as shown in Figure 9.2.25. This figures shows that as the reservoirs go online, evapotranspiration and contribution to storage both increase, with the contribution to storage peaking near 1980 then dropping back off as pumping continues to increase slightly.

Table 9.2.4 shows the water budget by county for year 1997. Table 9.2.7 shows the water budget by Groundwater Conservation District for year 1997. Note that the “Lateral” field indicates water that is moving laterally in to or out of the county. Because of the dominance of recharge and stream discharge in the water budget compared to pumping, lateral flow in to and out of the counties is driven more by the presence of rivers near their borders (e.g., Brazos or Gonzales counties) than by pumping.

Table 9.2.1 Calibration statistics for the transient model calibration period (1980 to 1997).

Unit	Count	Mean Error (ft)	Mean Absolute Error (ft)	Range (ft)	MAE/Range
Jackson Group	263	-5.4	31.1	302.0	0.103
Upper Yegua	257	-0.9	23.9	422.7	0.057
Lower Yegua	165	3.9	24.5	386.0	0.063

ft = feet
MAE = mean absolute error

Table 9.2.2 Calibration statistics for the transient model prior to the transient calibration period (1900 to 1979).

Unit	Count	Mean Error (ft)	Mean Absolute Error (ft)	Range (ft)	MAE/Range
Upper Jackson	198	1.6	33.4	333.3	0.100
Lower Jackson	235	-8.2	27.5	263.0	0.104
Upper Yegua	379	2.4	25.0	302.6	0.083
Lower Yegua	316	11.7	27.1	520.2	0.052

ft = feet
MAE = mean absolute error

Table 9.2.3 Water budget for the transient model. Values reported in acre-feet per year unless indicated otherwise. Negative numbers indicate flow out of the aquifer unit.

1980	Cross Formational Flow			Recharge	ET	Streams	Reservoirs	GHBs	Springs	Pumping	Storage
Aquifer Unit	Surficial	Top	Bottom								
Catahoula Frm.	-1,821	0	-3,565	0	0	0	0	-7,551	0	0	12,938
Upper Jackson	-8,785	1,838	148	74,310	-6,586	-56,408	616	0	-96	-3,042	-1,808
Lower Jackson	1,386	164	328	92,345	-7,547	-76,874	608	0	-7	-1,791	-8,535
Upper Yegua	31,184	2,754	-2,537	127,351	-9,173	-137,514	-560	0	-22	-4,848	-6,578
Lower Yegua	-21,877	9,165	-8,296	239,775	-14,473	-187,477	-559	0	-801	-7,519	-7,841
Total				533,781	-37,780	-458,273	106	-7,551	-927	-17,200	-11,824
Total (%)				100.0%	-7.1%	-85.9%	0.0%	-1.4%	-0.2%	-3.2%	-2.2%

1990	Cross Formational Flow			Recharge	ET	Streams	Reservoirs	GHBs	Springs	Pumping	Storage
Aquifer Unit	Surficial	Top	Bottom								
Catahoula Frm.	-1,754	0	-3,359	0	0	0	0	-10,563	0	0	15,677
Upper Jackson	-8,442	1,738	145	74,310	-6,654	-55,162	1,250	0	-96	-2,919	-3,919
Lower Jackson	784	292	-21	92,345	-9,143	-75,788	26	0	-7	-1,960	-6,440
Upper Yegua	31,235	3,600	-3,262	127,351	-10,915	-137,382	-934	0	-23	-5,354	-4,259
Lower Yegua	-21,737	10,204	-9,336	239,775	-16,897	-187,091	-725	0	-809	-8,149	-5,142
Total				533,781	-43,610	-455,422	-381	-10,563	-935	-18,381	-4,083
Total (%)				100.0%	-8.2%	-85.4%	-0.1%	-2.0%	-0.2%	-3.4%	-0.8%

1997	Cross Formational Flow			Recharge	ET	Streams	Reservoirs	GHBs	Springs	Pumping	Storage
Aquifer Unit	Surficial	Top	Bottom								
Catahoula Frm.	-1,721	0	-3,314	0	0	0	0	-8,755	0	0	13,790
Upper Jackson	-8,547	1,749	126	74,310	-6,721	-55,451	879	0	-96	-2,757	-3,230
Lower Jackson	694	360	-189	92,345	-9,733	-76,408	-266	0	-8	-1,958	-4,730
Upper Yegua	31,549	4,127	-3,674	127,351	-12,230	-137,237	-931	0	-23	-5,694	-3,155
Lower Yegua	-21,889	10,440	-9,625	239,775	-17,731	-186,752	-745	0	-813	-8,440	-4,121
Total				533,781	-46,415	-455,847	-1,063	-8,755	-939	-18,849	-1,445
Total (%)				100.0%	-8.7%	-85.5%	-0.2%	-1.6%	-0.2%	-3.5%	-0.3%

ET = evapotranspiration
GHBs = general head boundaries
Frm. = Formation
% = percent

Table 9.2.4 Water budget by county for year 1997. All values reported in acre-feet per year. Negative numbers indicate flow out of the aquifer unit.

County	Lateral	Recharge	Streams	ET	Drains	GHBs	Reservoirs	Storage	Wells
Angelina	-423	49,174	-31,556	-6,737	-8	72	-134	-4,068	-6,320
Atascosa	2,532	18,393	-16,596	-4,203	0	0	0	90	-216
Austin	-98	0	0	0	0	-589	0	687	0
Bastrop	-1,107	1,656	-529	0	0	0	0	8	-28
Beauregard	-1	0	0	0	0	0	0	1	0
Bee	-2	0	0	0	0	-206	0	208	0
Brazos	4,812	26,539	-29,935	0	-5	-45	0	593	-1,658
Brooks	151	0	0	0	0	-208	0	57	0
Burleson	-3,454	22,459	-11,071	-4,525	0	0	57	-2,572	-778
Colorado	64	0	0	0	0	-666	0	602	0
De Witt	-3	0	0	0	0	-403	0	406	0
Duval	-995	12	0	0	0	430	0	554	0
Fayette	2,200	47,303	-48,802	0	-776	755	0	456	-1,082
Fort Bend	50	0	0	0	0	-362	0	312	0
Frio	-239	240	0	0	0	0	0	0	0
Goliad	48	0	0	0	0	-267	0	219	0
Gonzales	9,230	28,187	-37,488	0	0	207	0	113	-248
Grimes	-7,569	33,978	-22,606	-3,754	-43	357	66	289	-718
Hardin	83	0	0	0	0	-170	0	86	0
Harris	91	0	0	0	0	-2,840	0	2,749	0
Hidalgo	106	0	0	0	0	-193	0	87	0
Houston	-3,399	65,163	-54,938	-6,207	0	0	0	231	-851
Jackson	128	0	0	0	0	-279	0	150	0
Jasper	-124	0	0	0	0	2	0	122	0
Jim Hogg	-712	0	0	0	0	1,895	0	-1,183	0
Jim Wells	166	0	0	0	0	-288	0	122	0
Karnes	26	11,900	-10,910	-1,035	0	98	0	126	-204
La Salle	-38	7,691	-5,591	-2,043	0	0	0	6	-24
Lavaca	-1,119	764	0	0	0	-142	0	503	-5
Lee	-3,040	37,203	-32,535	-44	0	0	-73	-888	-623
Leon	-400	402	0	0	0	0	0	3	-4
Liberty	105	0	0	0	0	-871	0	767	0
Live Oak	734	618	-456	-132	0	-1,595	130	711	-9
Madison	2,807	30,789	-32,663	0	0	0	0	185	-1,118
McMullen	1,744	6,619	-7,311	0	-45	609	475	-2,046	-45
Montgomery	608	0	0	0	0	-6,980	0	6,373	0
Nacogdoches	1,563	3,366	0	-1,798	-33	0	-122	-2,871	-104
Newton	-175	0	0	0	0	26	0	150	0
Polk	-703	4,116	-3,562	-319	-7	203	0	742	-470
Sabine	-806	29,457	-22,334	-3,234	0	-23	-1,695	1,124	-2,490
San Augustine	81	16,194	-10,145	-2,264	-15	0	-168	-3,566	-118
San Jacinto	-129	0	0	0	0	-1,166	0	1,295	0
Starr	1,192	0	-813	-692	-6	449	0	-77	-55
Trinity	7,165	58,396	-55,813	-8,218	0	49	13	-635	-957
Tyler	-220	5	31	0	0	-51	0	236	0
Vernon	-2	0	0	0	0	0	0	2	0

Table 9.2.4, continued

County	Lateral	Recharge	Streams	ET	Drains	GHBs	Reservoirs	Storage	Wells
Victoria	201	0	0	0	0	-350	0	148	0
Walker	-1,121	13,195	-12,065	0	0	446	156	-299	-312
Waller	120	0	0	0	0	-1,557	0	1,437	0
Washington	-3,409	5,528	-1,133	0	0	973	232	-2,056	-134
Webb	-2,311	2,419	-126	-860	0	4,261	0	-3,354	-28
Wharton	207	0	0	0	0	-599	0	393	0
Wilson	-4,811	12,018	-7,112	0	0	0	0	112	-206
Zapata	212	0	213	-350	0	266	0	-300	-41

ET = evapotranspiration
GHBs = general head boundaries

Table 9.2.5 Water budget by Groundwater Conservation District for year 1997. All values reported in acre-feet per year. Negative numbers indicate flow out of the aquifer unit.

GCD	Lateral	Recharge	Streams	ET	Drains	GHBs	Reservoirs	Storage	Wells
Bee GCD	-14	0	0	0	0	-199	0	213	0
Bluebonnet GCD	-8,737	47,257	-34,671	-3,754	-43	-1,353	222	2,111	-1,032
Brazos Valley GCD	4,812	26,539	-29,935	0	-5	-45	0	593	-1,658
Coastal Bend GCD	209	0	0	0	0	-604	0	395	0
Colorado County GCD	62	0	0	0	0	-662	0	600	0
Evergreen UWCD	-2,110	41,827	-34,291	-5,239	0	111	0	328	-626
Fayette County GCD	2,328	47,174	-48,802	0	-776	756	0	456	-1,081
Fort Bend Subsidence District	50	0	0	0	0	-362	0	312	0
Goliad County GCD	48	0	0	0	0	-266	0	219	0
Gonzales County UWCD	7,256	26,108	-33,193	0	0	45	0	17	-233
Harris-Galveston Coastal Subsidence District	83	0	0	0	0	-2,829	0	2,746	0
Live Oak UWCD	734	618	-456	-132	0	-1,595	130	711	-9
Lone Star GCD	613	0	0	0	0	-6,992	0	6,379	0
Lost Pines GCD	-4,147	38,859	-33,064	-44	0	0	-73	-880	-651
Lower Trinity GCD	-1,127	4,114	-3,264	-319	-7	-962	0	2,036	-470
McMullen GCD	1,585	7,101	-7,632	0	-45	609	475	-2,046	-46
Mid-East Texas GCD	2,489	31,108	-32,663	0	0	0	0	187	-1,121
Pecan Valley GCD	10	0	0	0	0	-416	0	406	0
Pineywoods GCD	2,816	52,553	-33,247	-8,535	-41	72	-257	-6,937	-6,425
Post Oak Savannah GCD	-3,454	22,459	-11,071	-4,525	0	0	57	-2,572	-778
Southeast Texas GCD	-436	5	31	0	0	-193	0	594	0
Starr County GCD	982	0	-604	-692	-6	449	0	-75	-55
Texana GCD	128	0	0	0	0	-279	0	150	0
Victoria County GCD	201	0	0	0	0	-350	0	149	0
Wintergarden GCD	47	7,618	-5,604	-2,043	0	0	0	6	-24

GCD = Groundwater Conservation District
ET = evapotranspiration
GHBs = general head boundaries

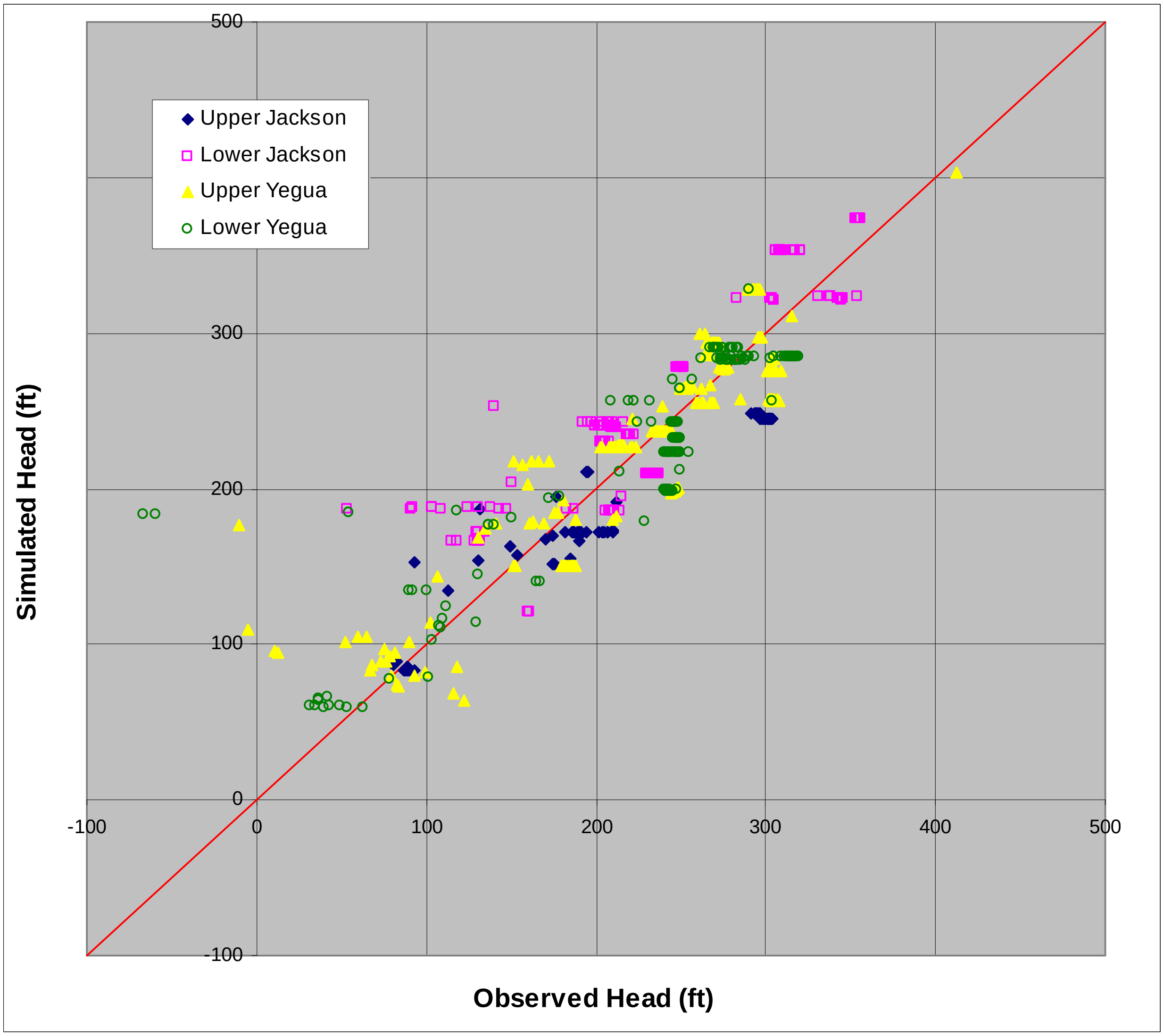

Figure 9.2.1 Crossplot of measured versus simulated heads in feet for the transient calibration period (1980 to 1997).

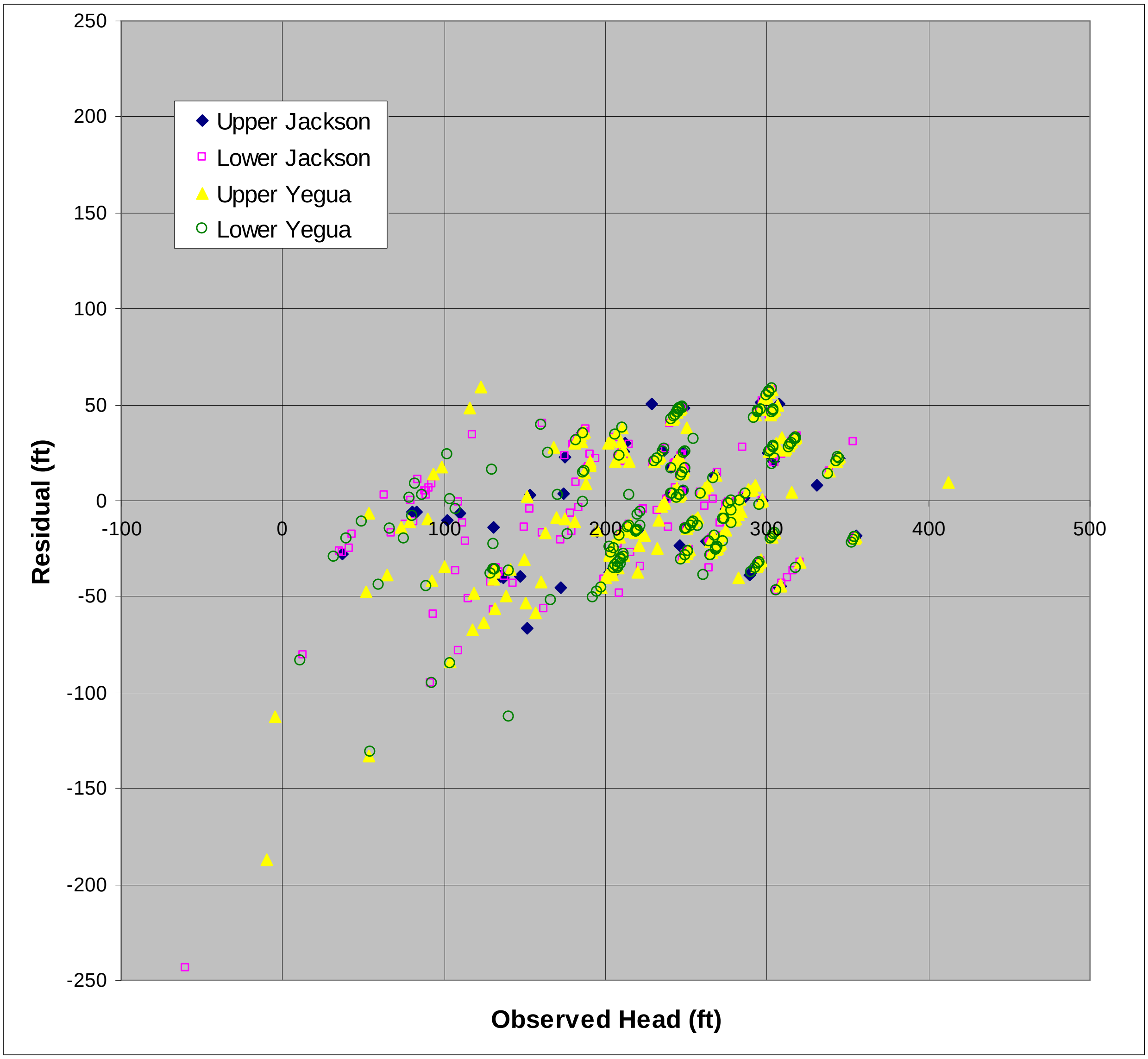

Figure 9.2.2 Plot of measured heads versus residuals in feet for the transient calibration period (1980 to 1997).

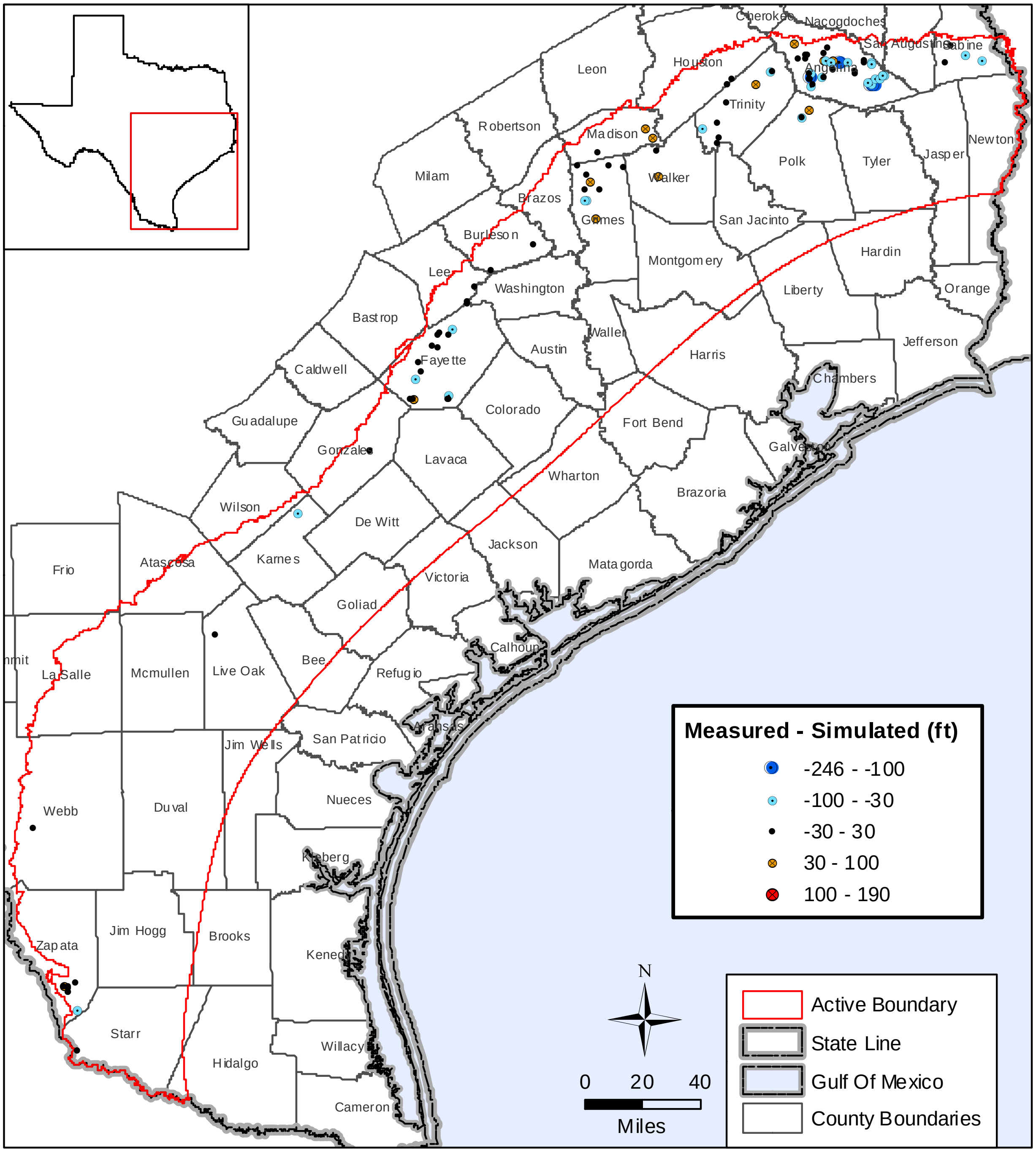

Figure 9.2.3 Spatial distribution of residuals in feet for the transient calibration period (1980 to 1997).

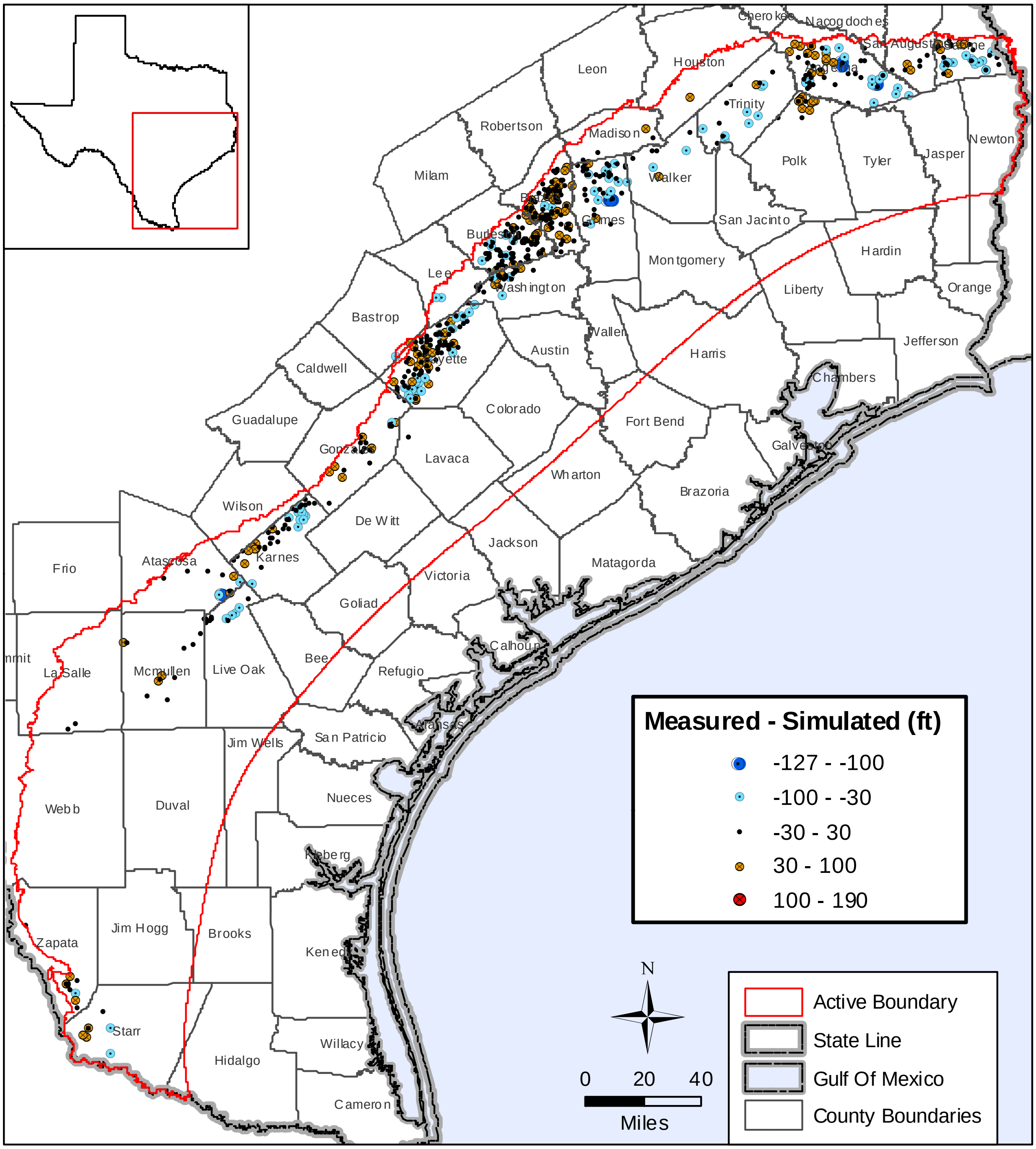

Figure 9.2.4 Spatial distribution of residuals in feet for the period prior to calibration (1900 to 1979).

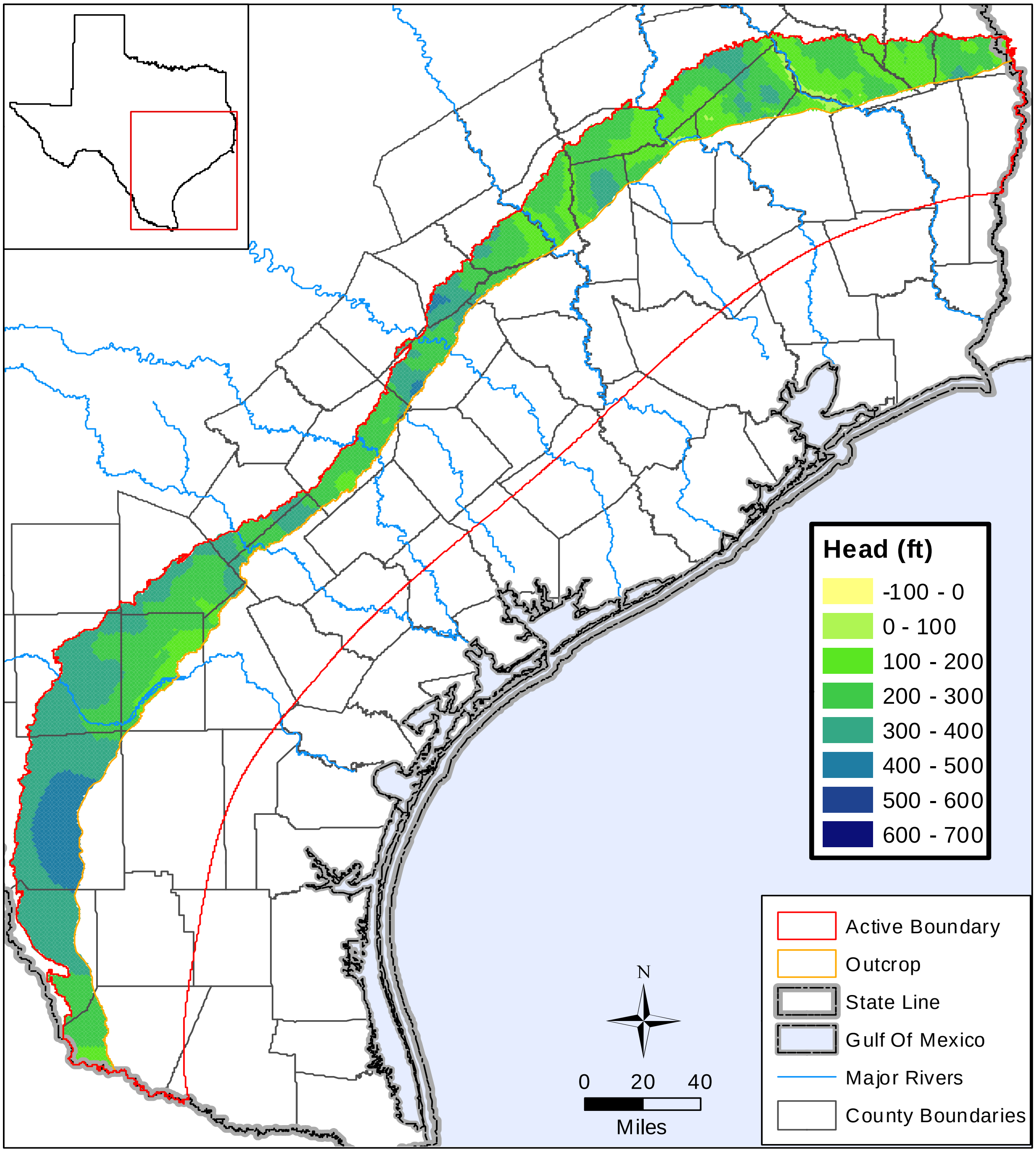

Figure 9.2.5 Simulated hydraulic head in feet in the shallow layer in 1990.

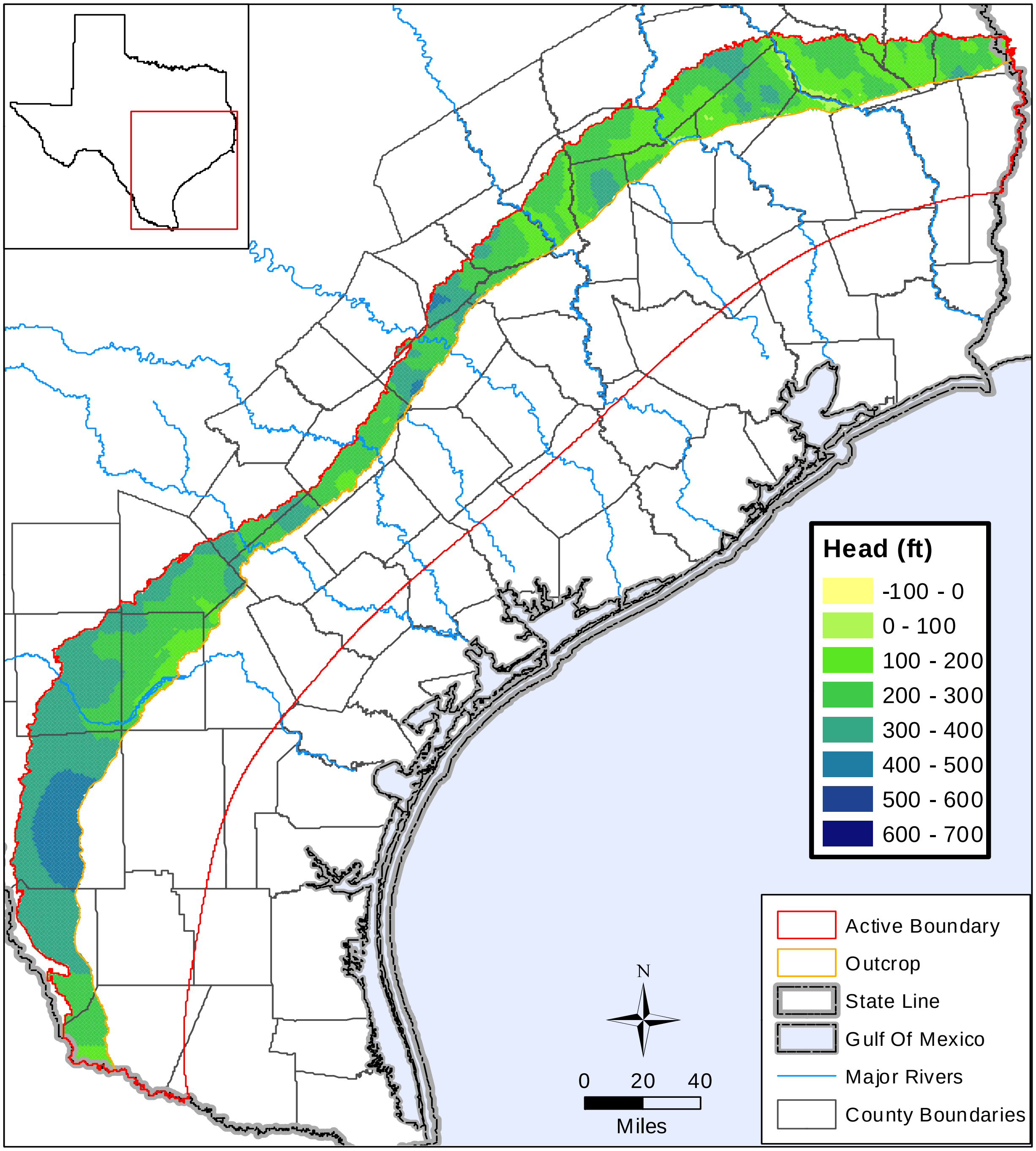

Figure 9.2.6 Simulated hydraulic head in feet in the shallow layer in 1997.

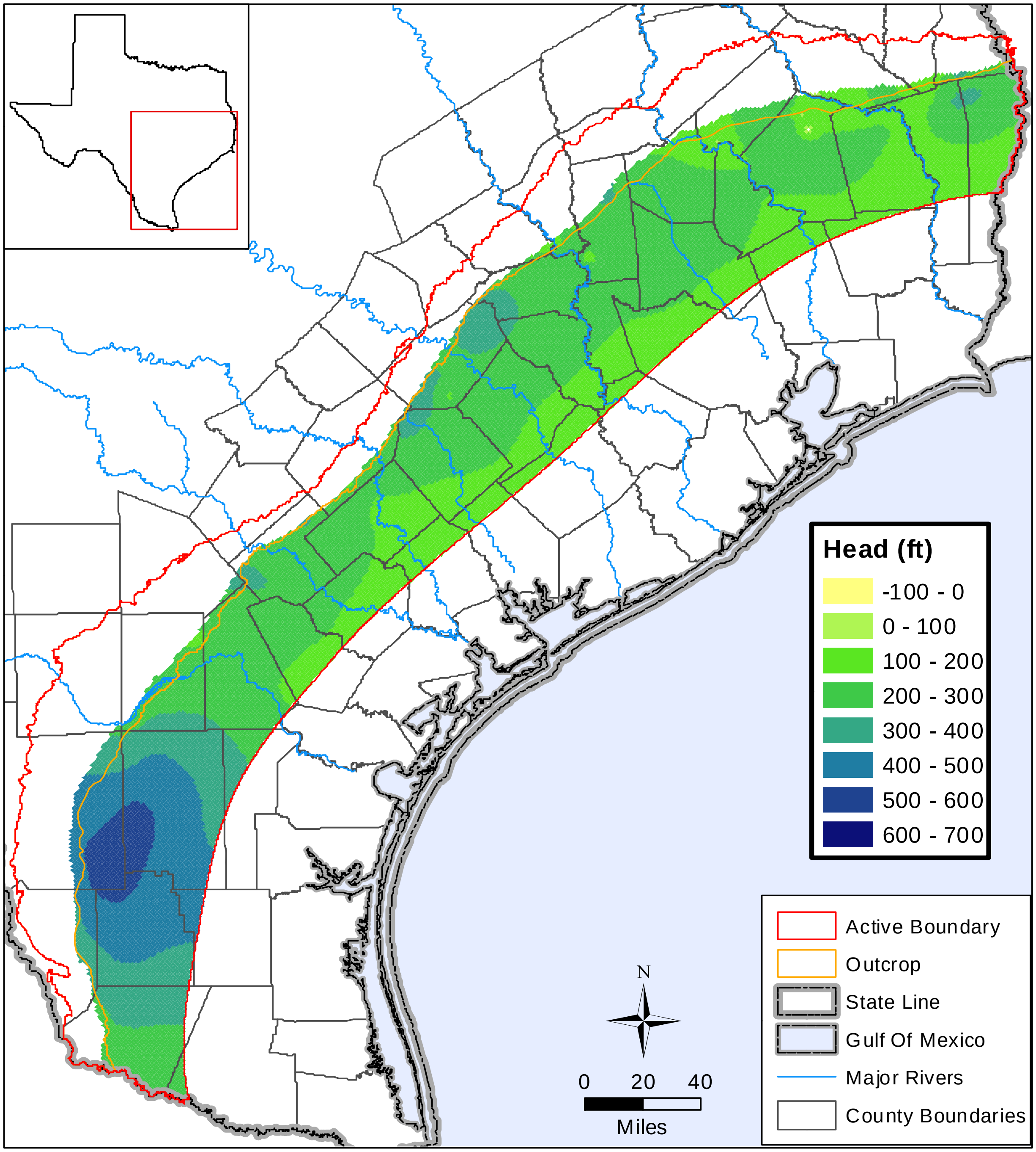

Figure 9.2.7 Simulated hydraulic head in feet in the Upper Jackson Unit subcrop in 1990.

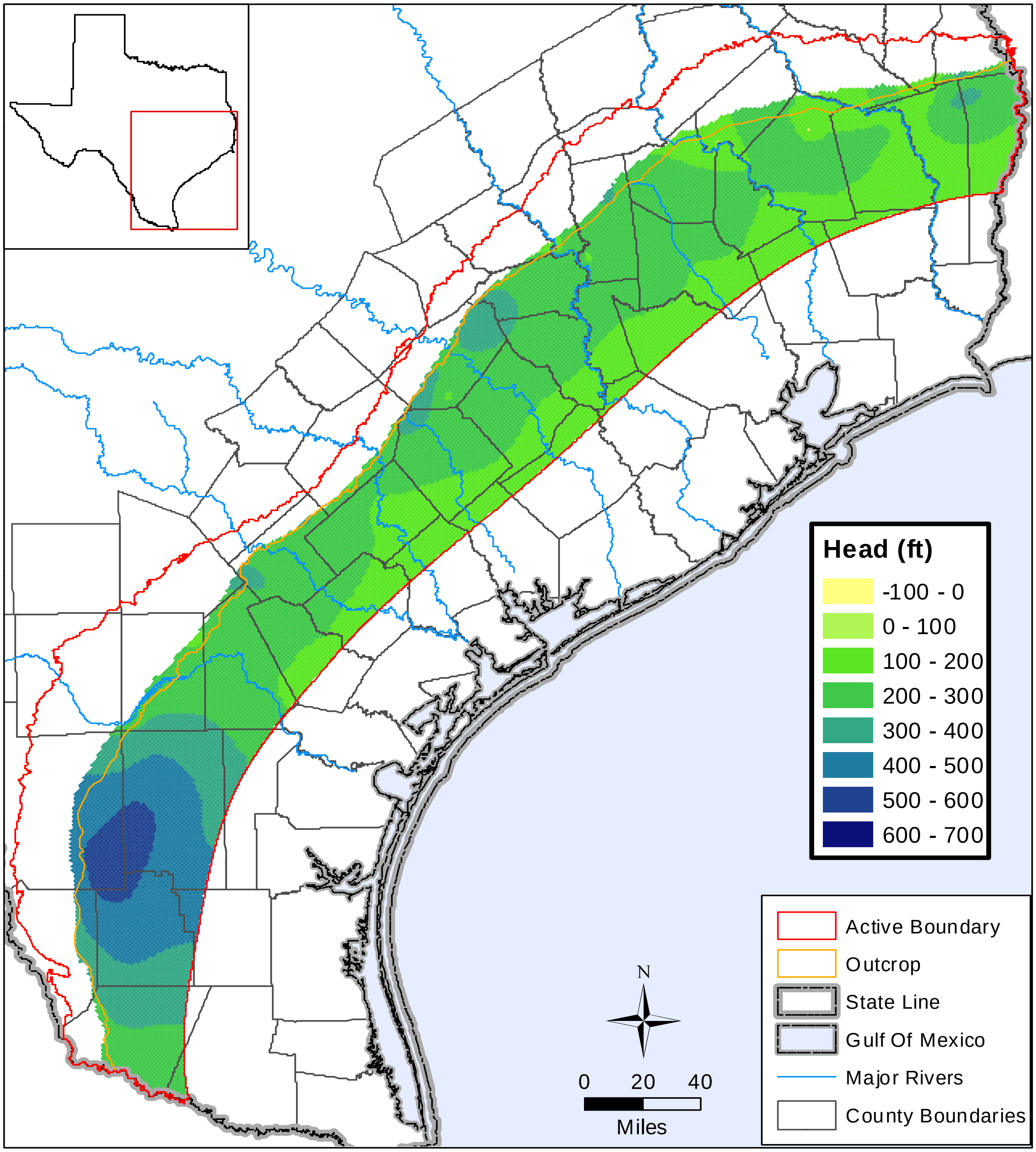

Figure 9.2.8 Simulated hydraulic head in feet in the Upper Jackson Unit subcrop in 1997.

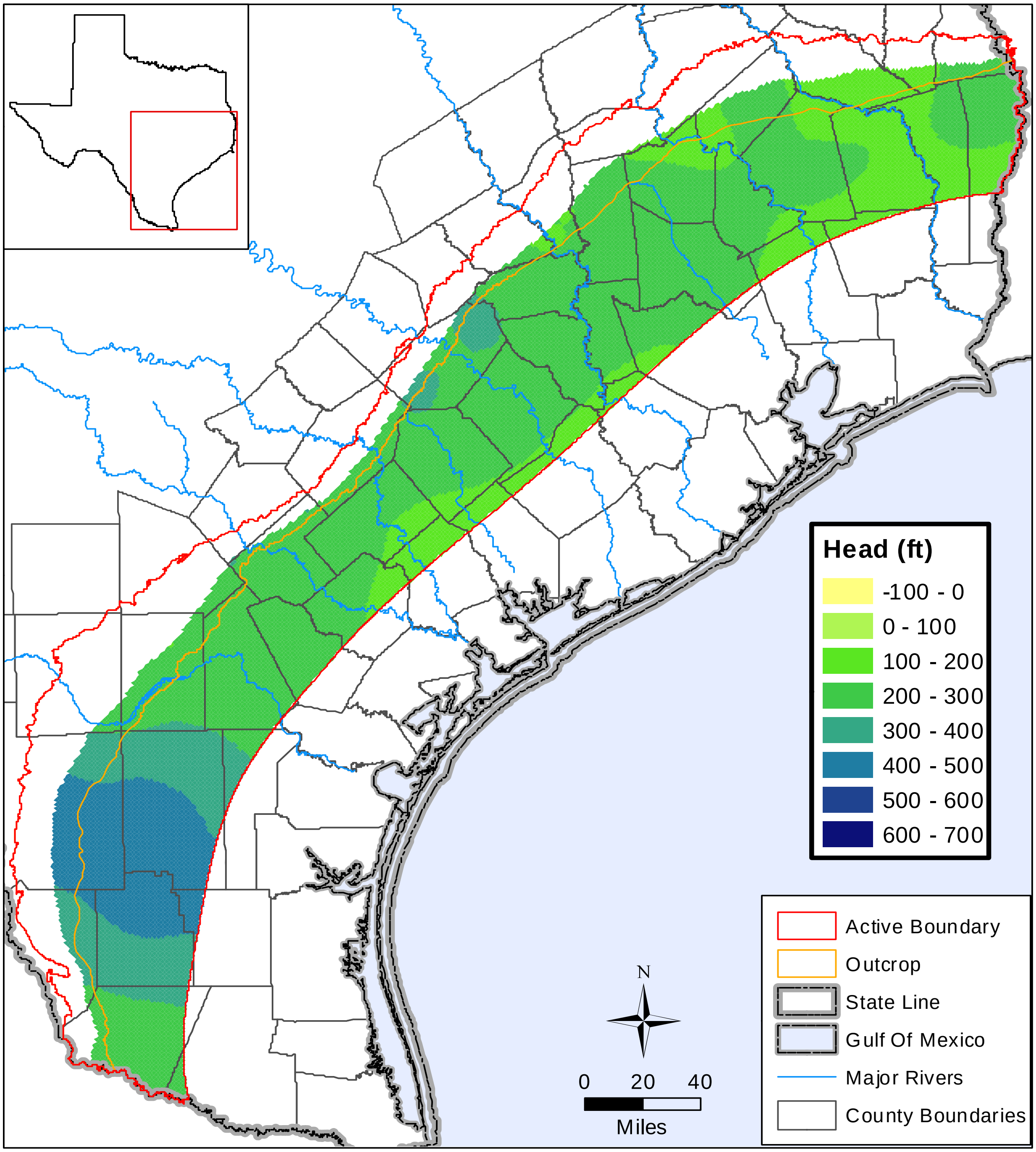

Figure 9.2.9 Simulated hydraulic head in feet in the Lower Jackson Unit subcrop in 1990.

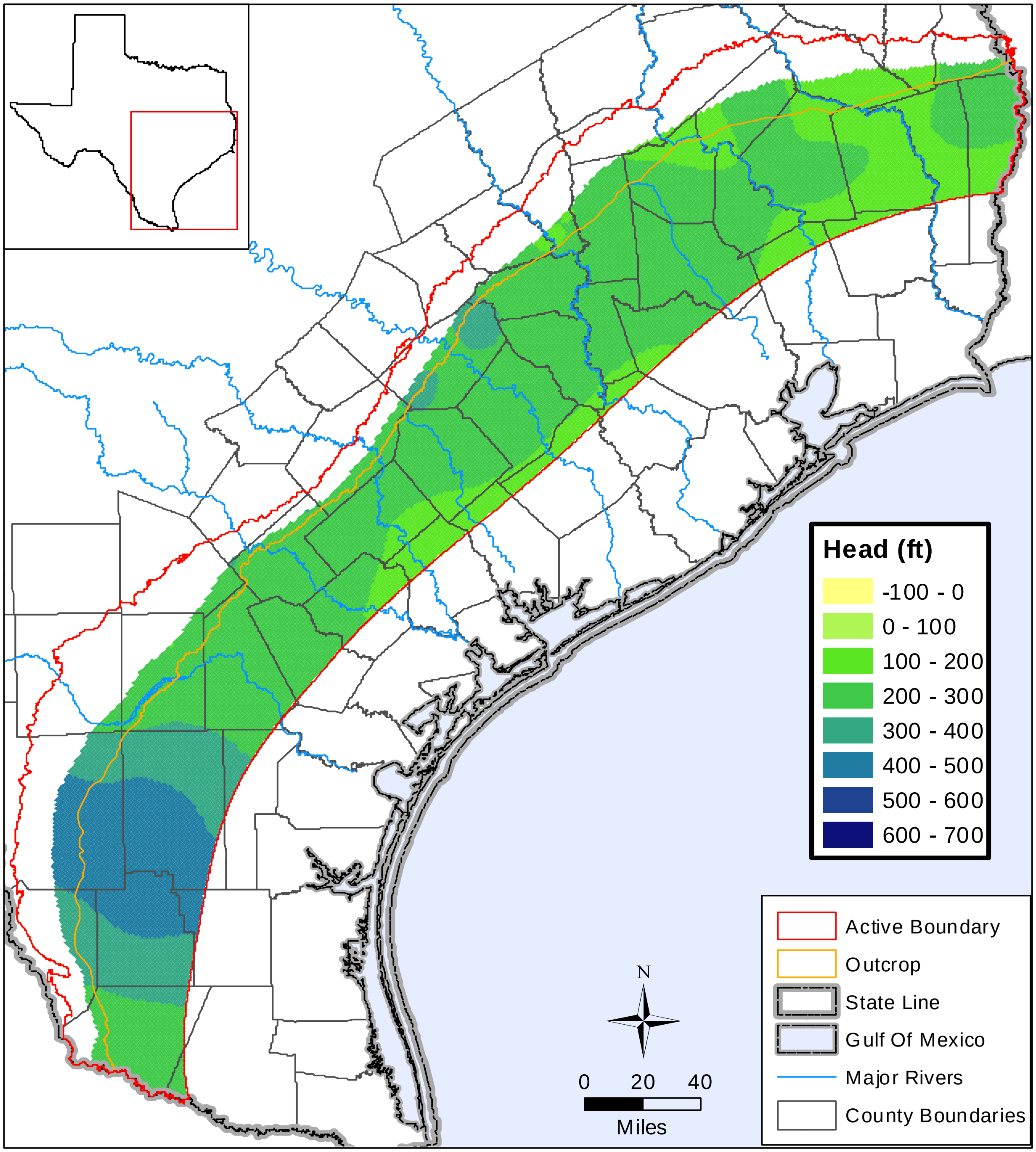

Figure 9.2.10 Simulated hydraulic head in feet in the Lower Jackson Unit subcrop in 1997.

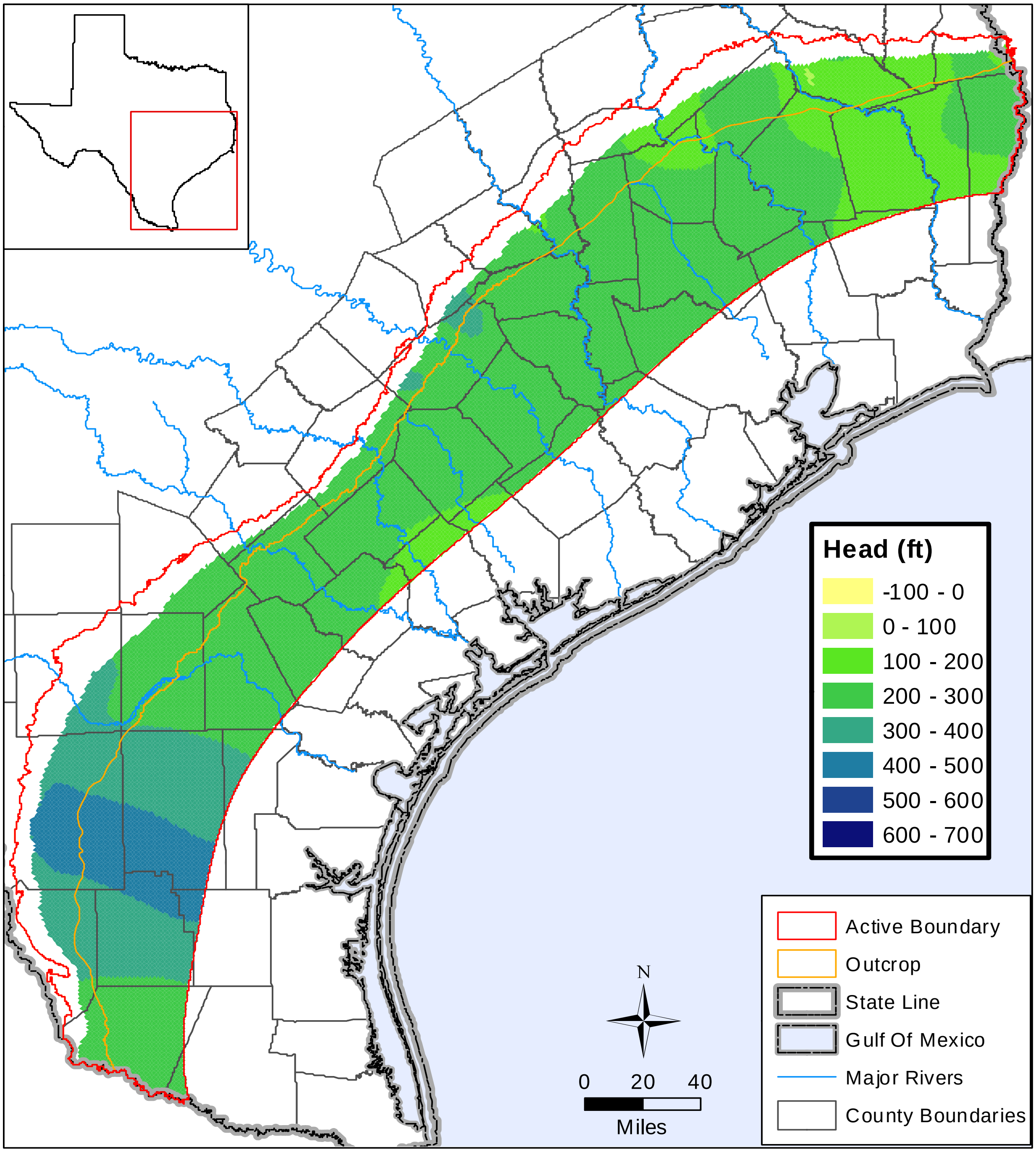

Figure 9.2.11 Simulated hydraulic head in feet in the Upper Yegua Unit subcrop in 1990.

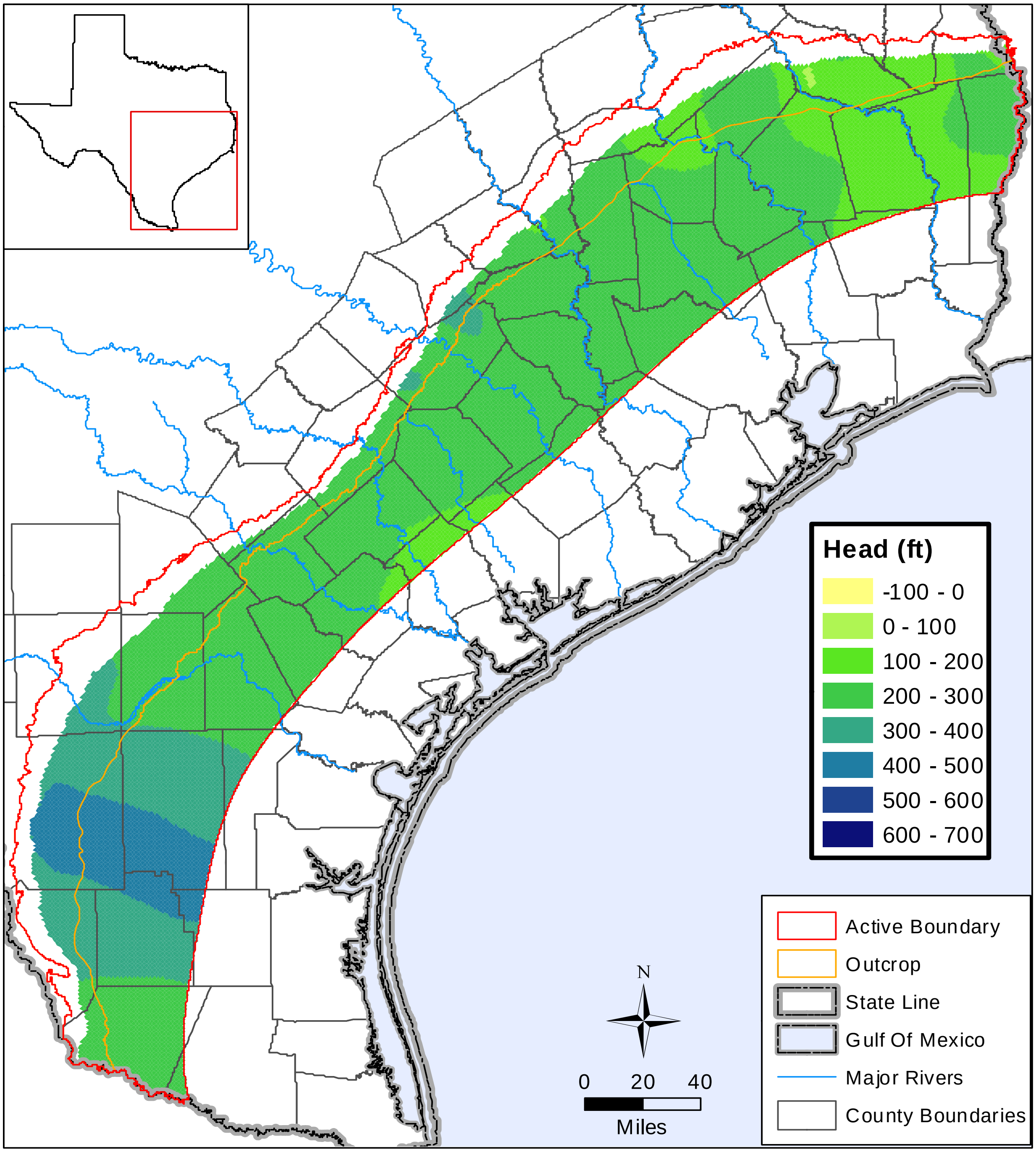

Figure 9.2.12 Simulated hydraulic head in feet in the Upper Yegua Unit subcrop in 1997.

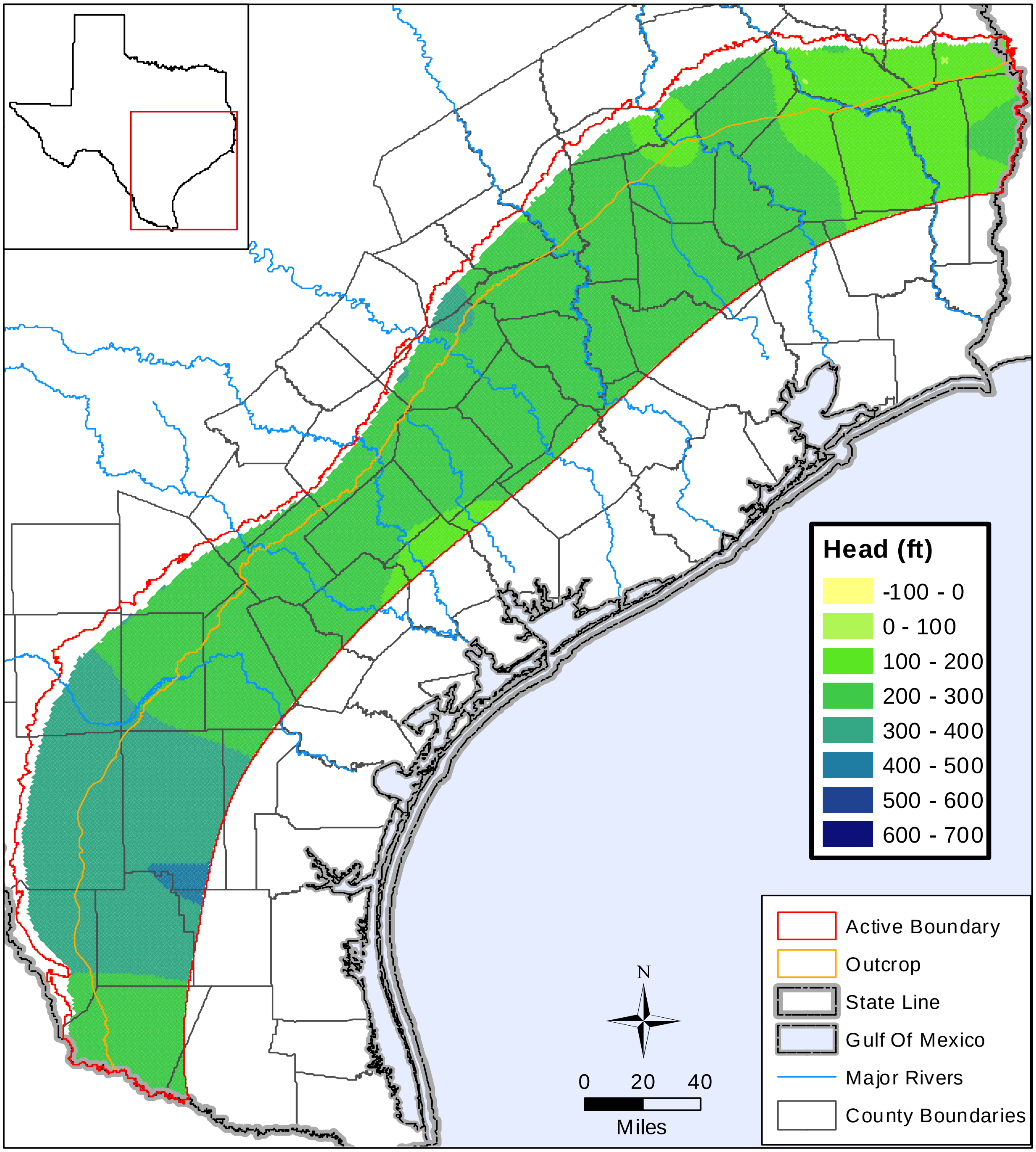

Figure 9.2.13 Simulated hydraulic head in feet in the Lower Yegua Unit subcrop in 1990.

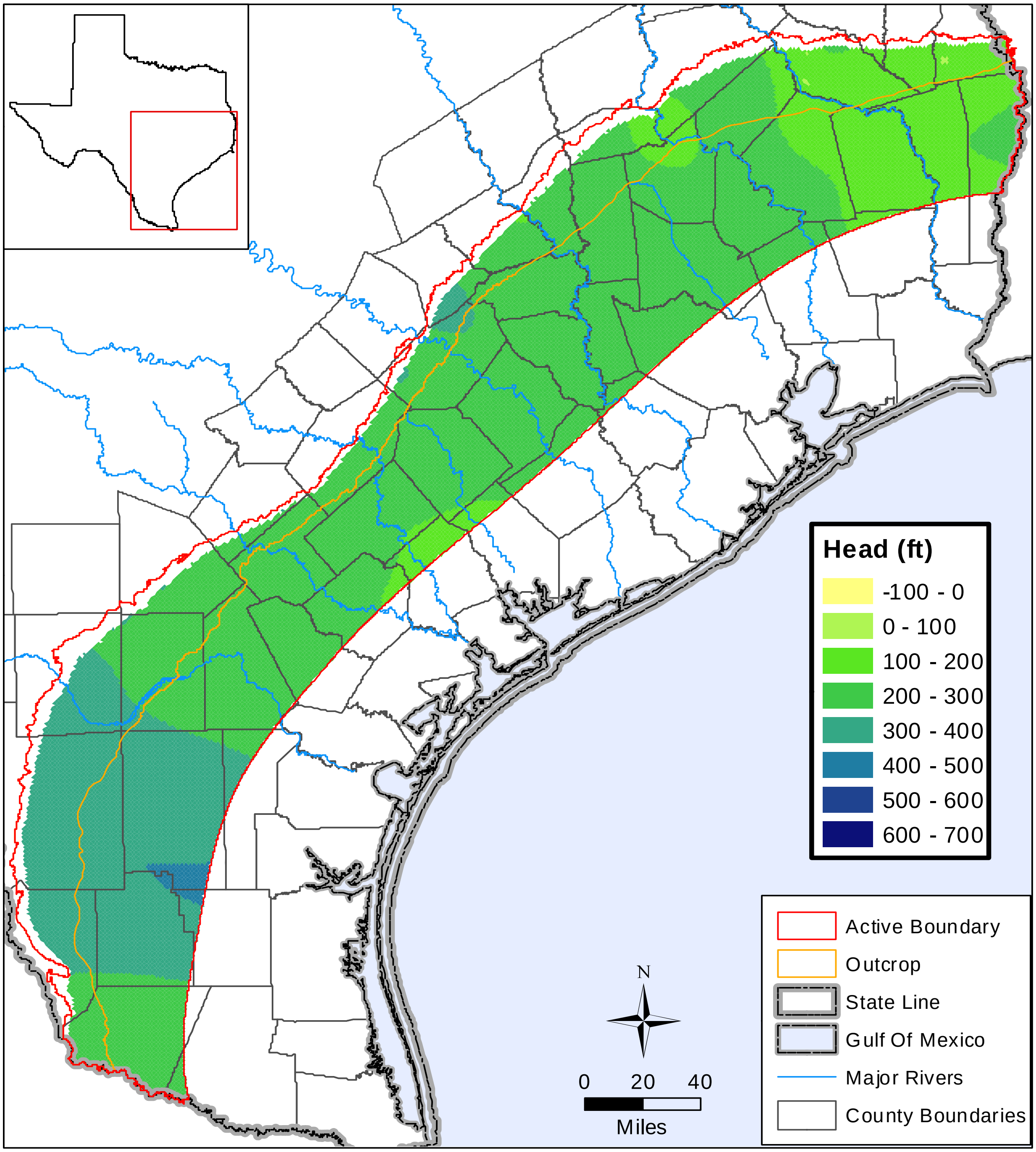

Figure 9.2.14 Simulated hydraulic head in feet in the Lower Yegua Unit subcrop in 1997.

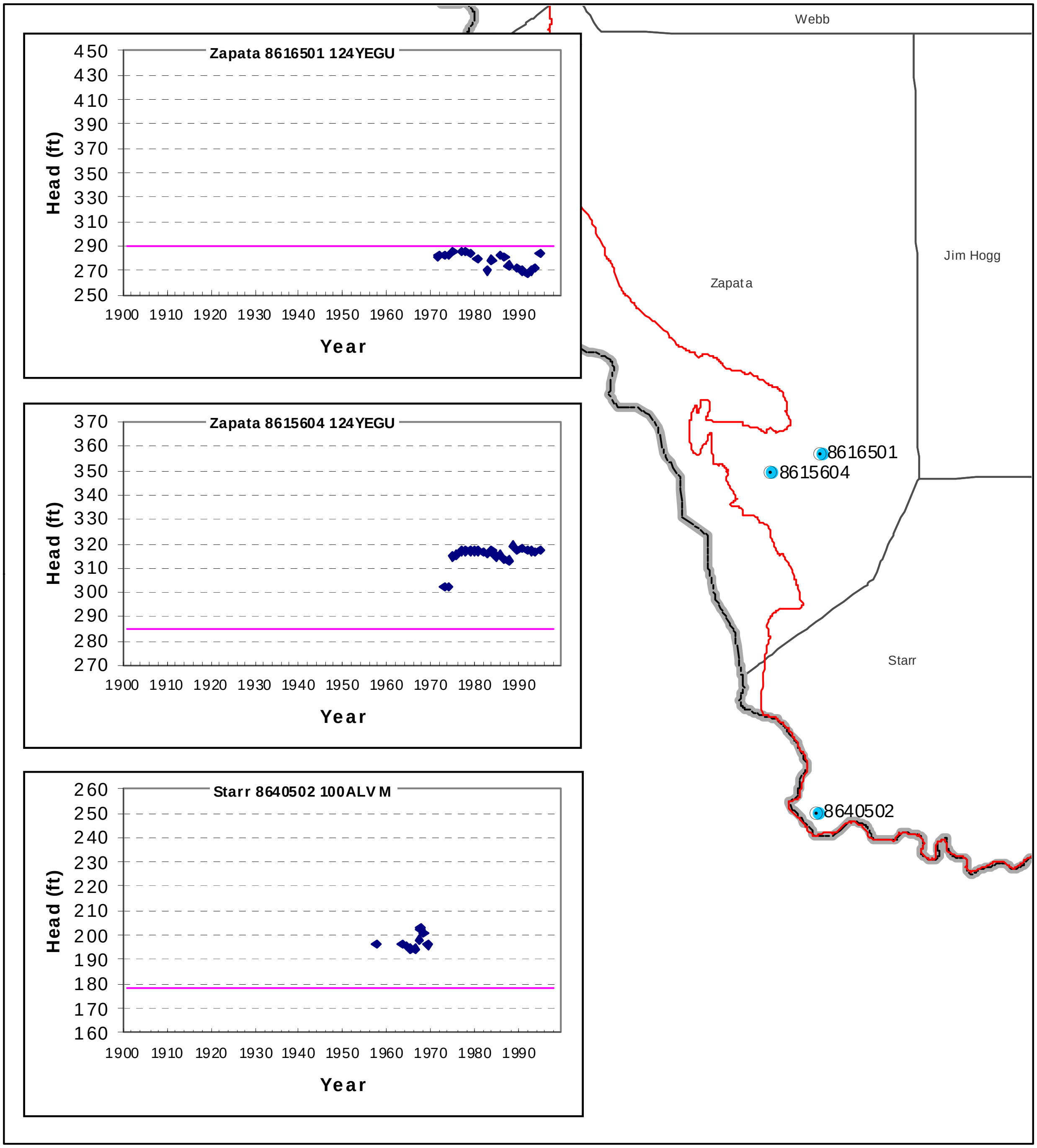

Figure 9.2.15 Selected hydrographs from Zapata and Starr counties showing head in feet. (Symbols indicate measured heads and solid lines indicate simulated heads.)

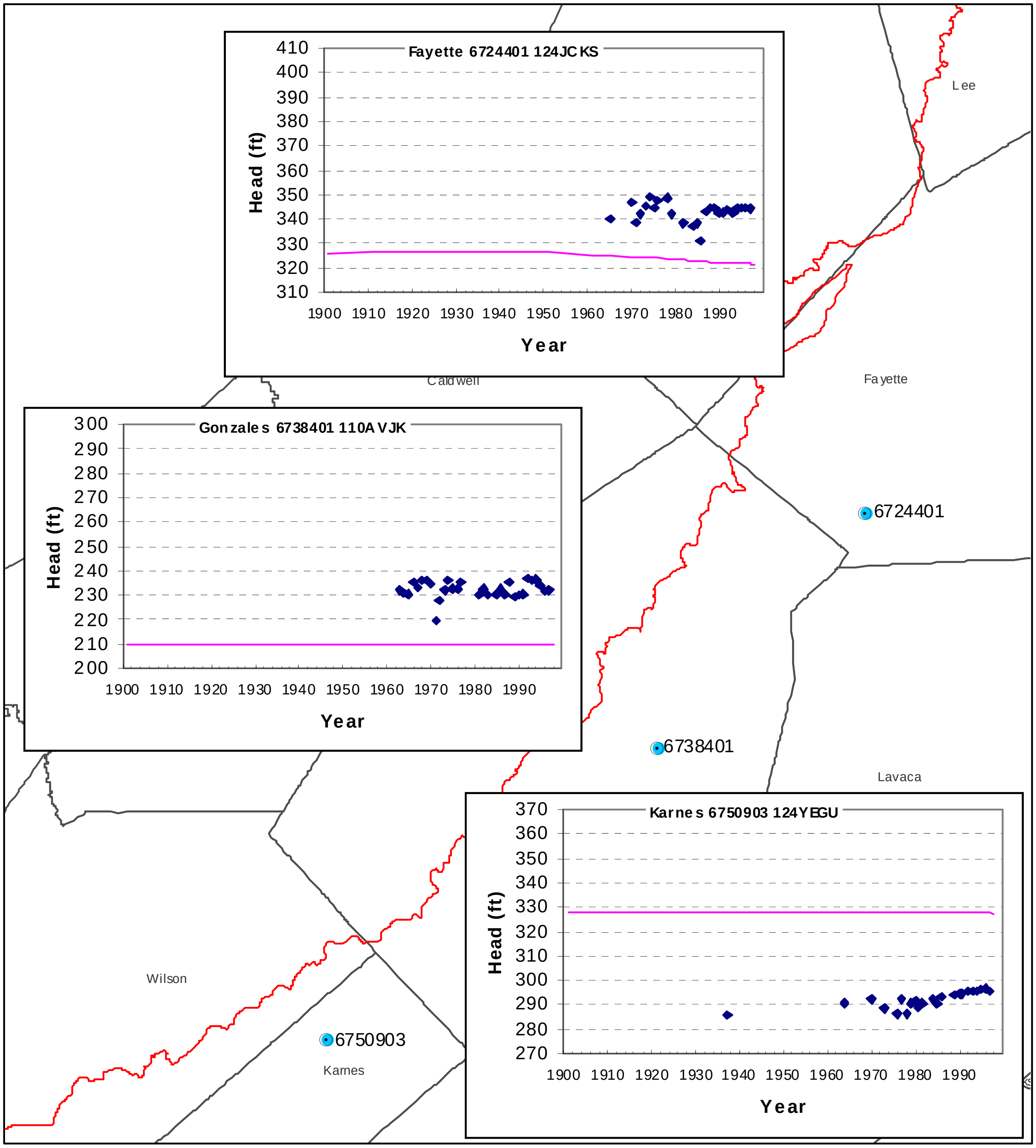

Figure 9.2.16 Selected hydrographs from Karnes, Gonzales, and Fayette counties showing head in feet. (Symbols indicate measured heads and solid lines indicate simulated heads.)

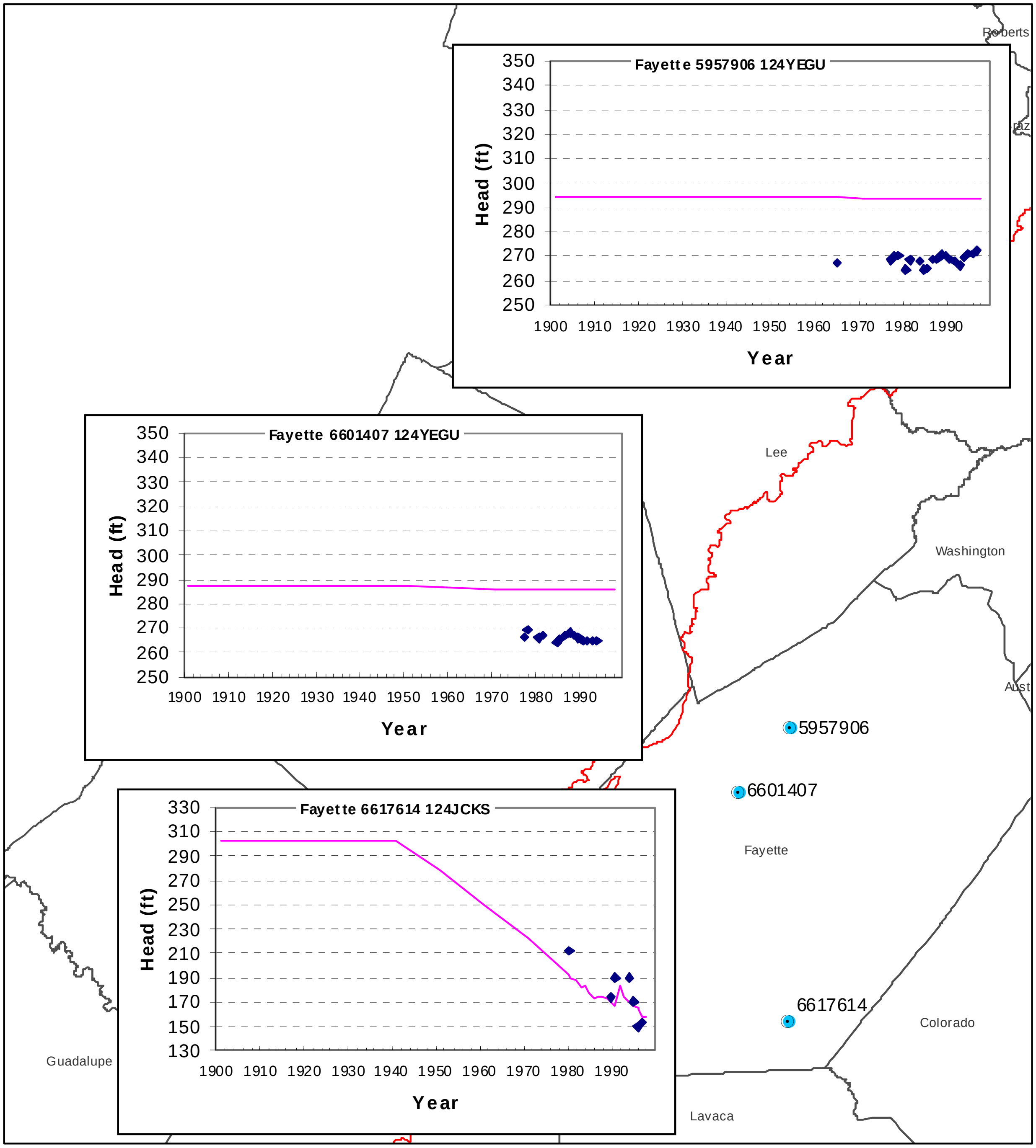

Figure 9.2.17 Selected hydrographs from Fayette County showing head in feet. (Symbols indicate measured heads and solid lines indicate simulated heads.)

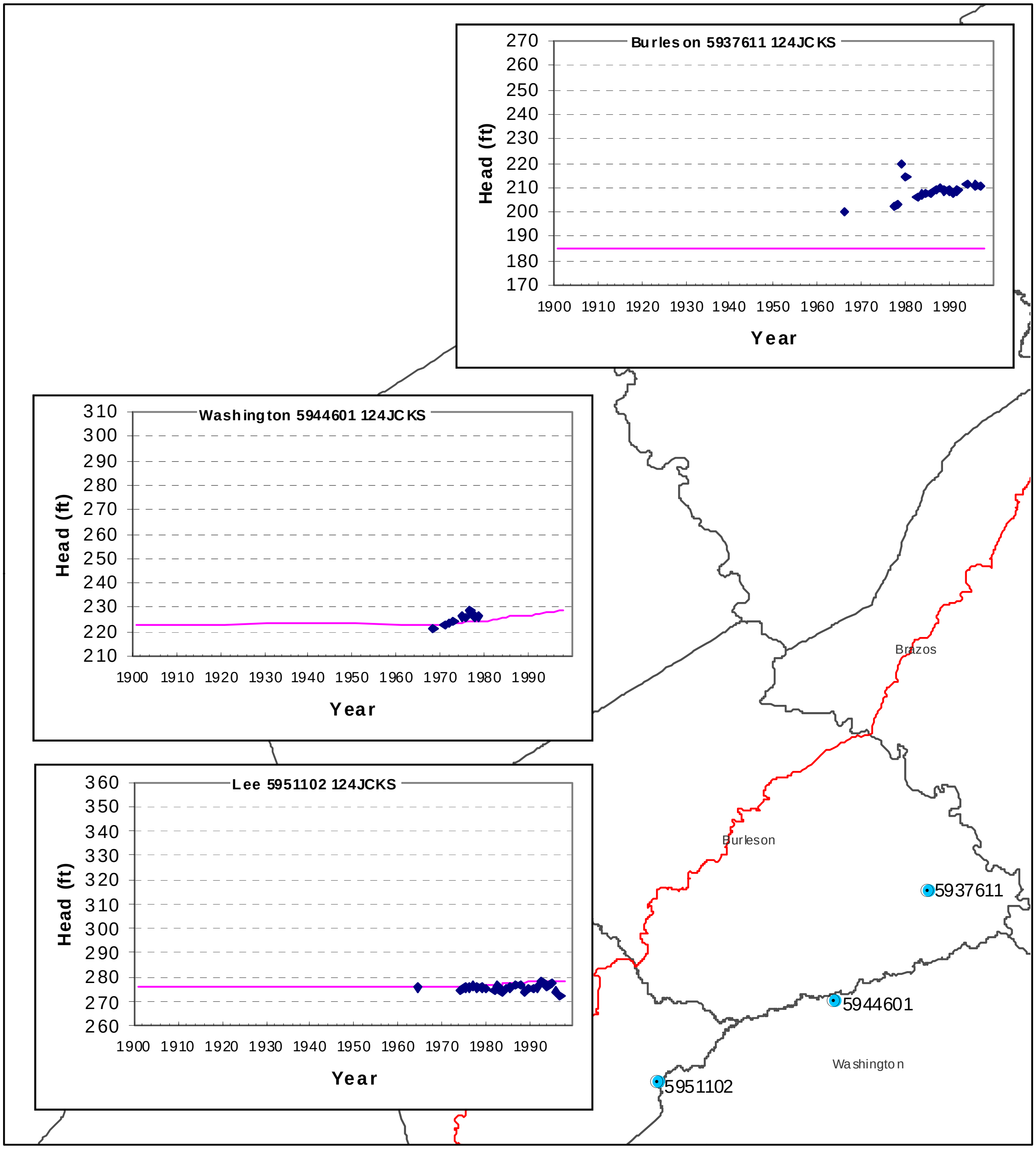

Figure 9.2.18 Selected hydrographs from Lee, Washington, and Burleson counties showing head in feet. (Symbols indicate measured heads and solid lines indicate simulated heads.)

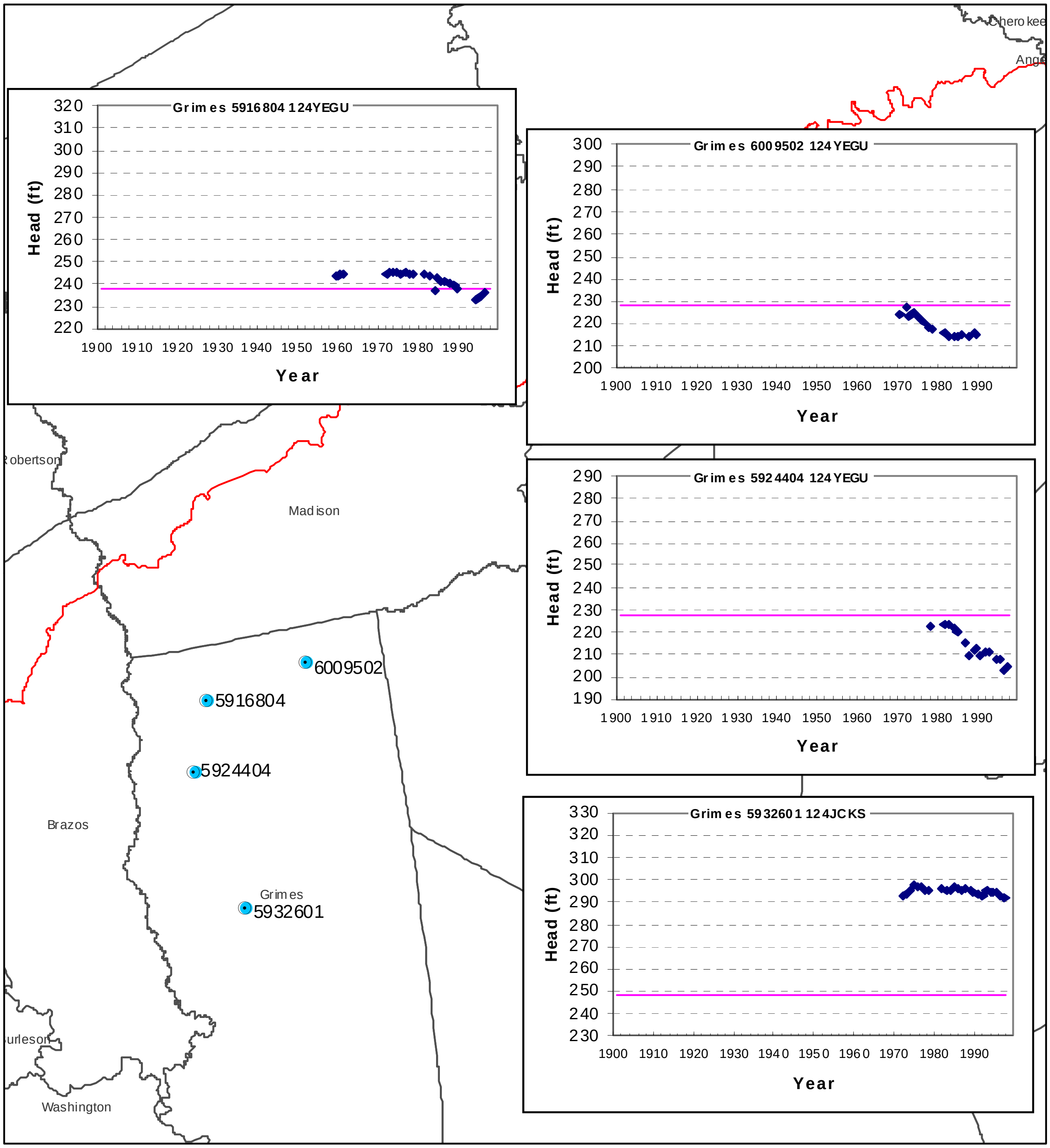

Figure 9.2.19 **Selected hydrographs from Grimes County showing head in feet. (Symbols indicate measured heads and solid lines indicate simulated heads.)**

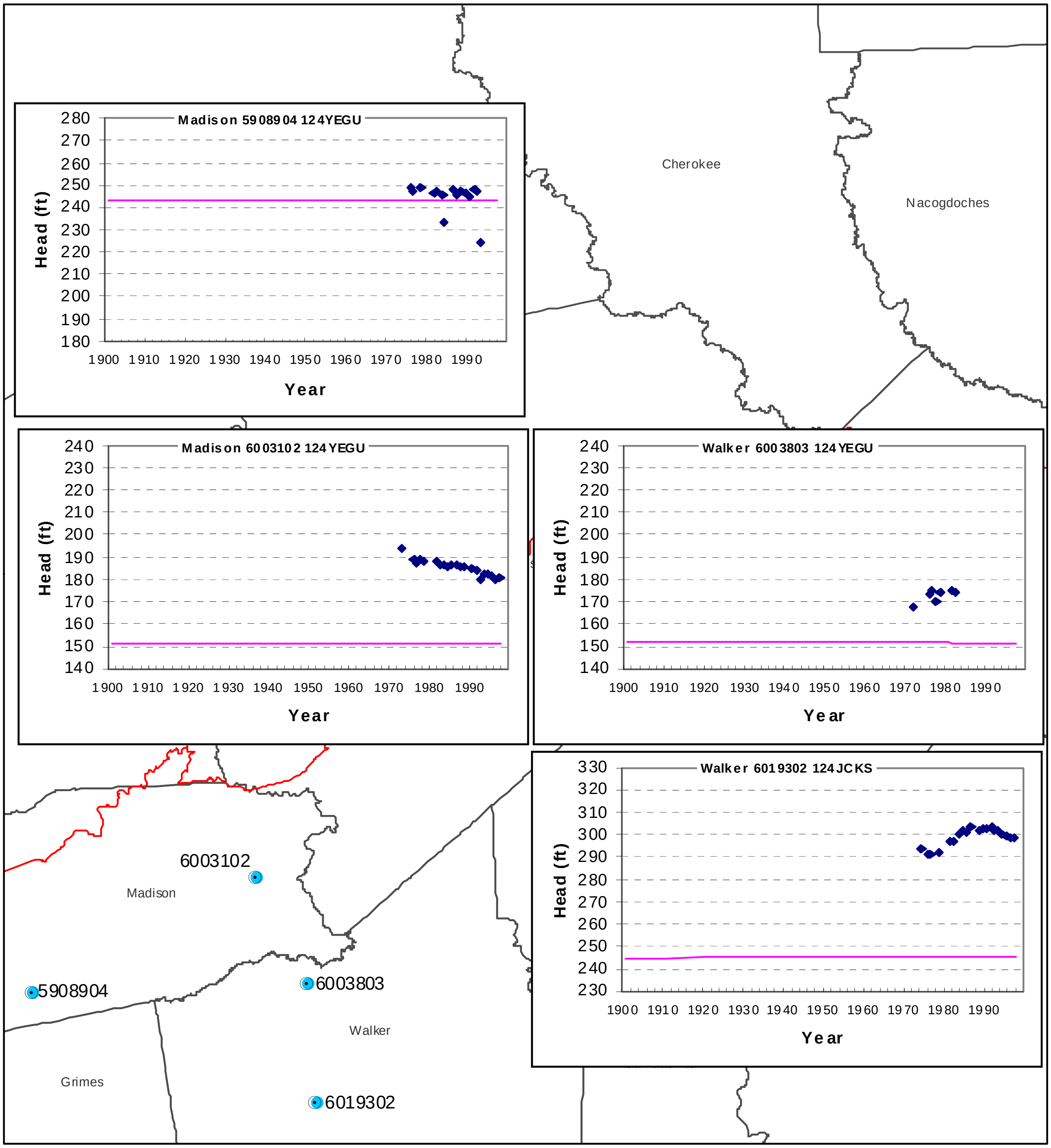

Figure 9.2.20 Selected hydrographs from Madison and Walker counties showing head in feet. (Symbols indicate measured heads and solid lines indicate simulated heads.)

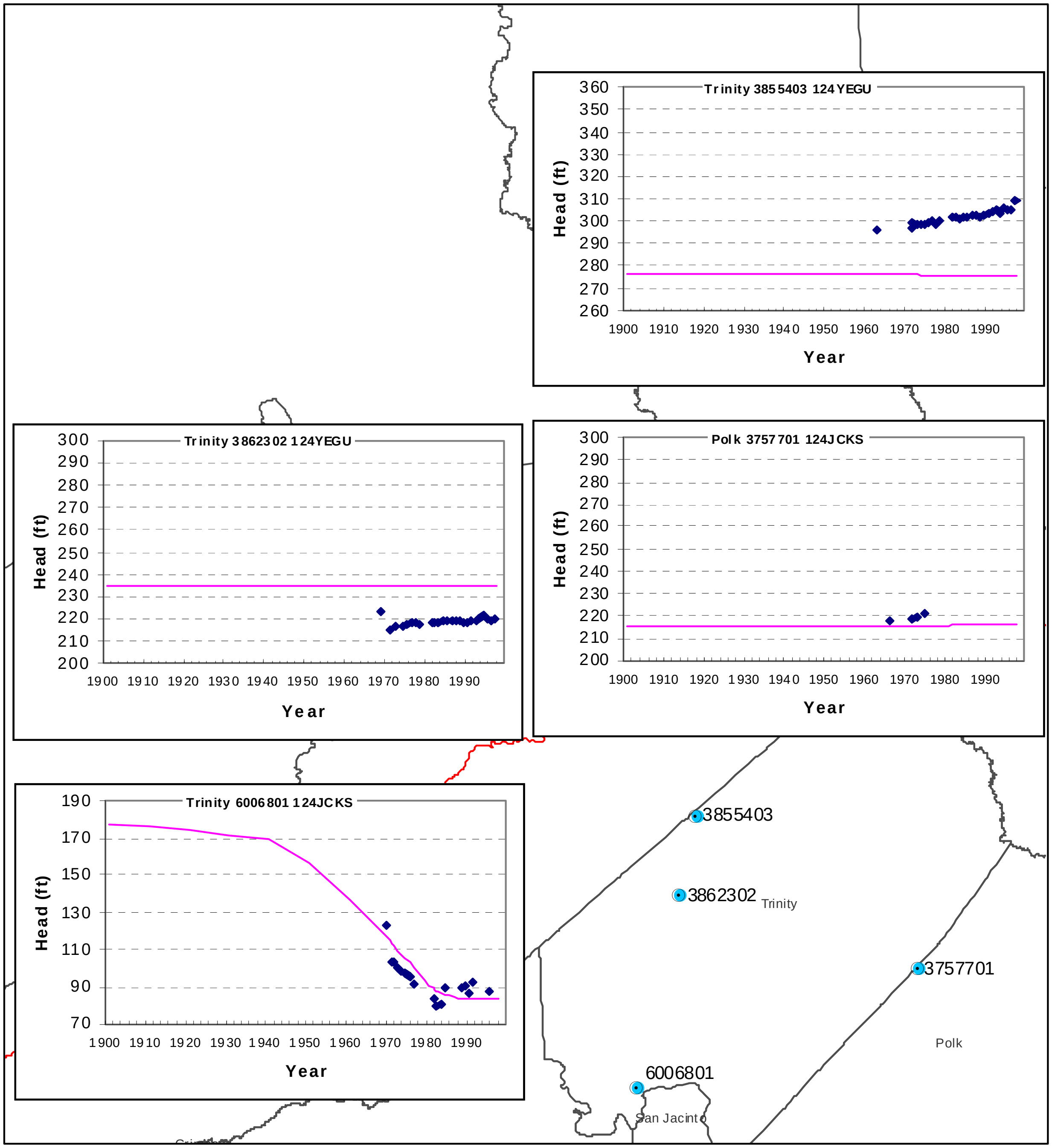

Figure 9.2.21 Selected hydrographs from Trinity and Polk counties showing head in feet. (Symbols indicate measured heads and solid lines indicate simulated heads.)

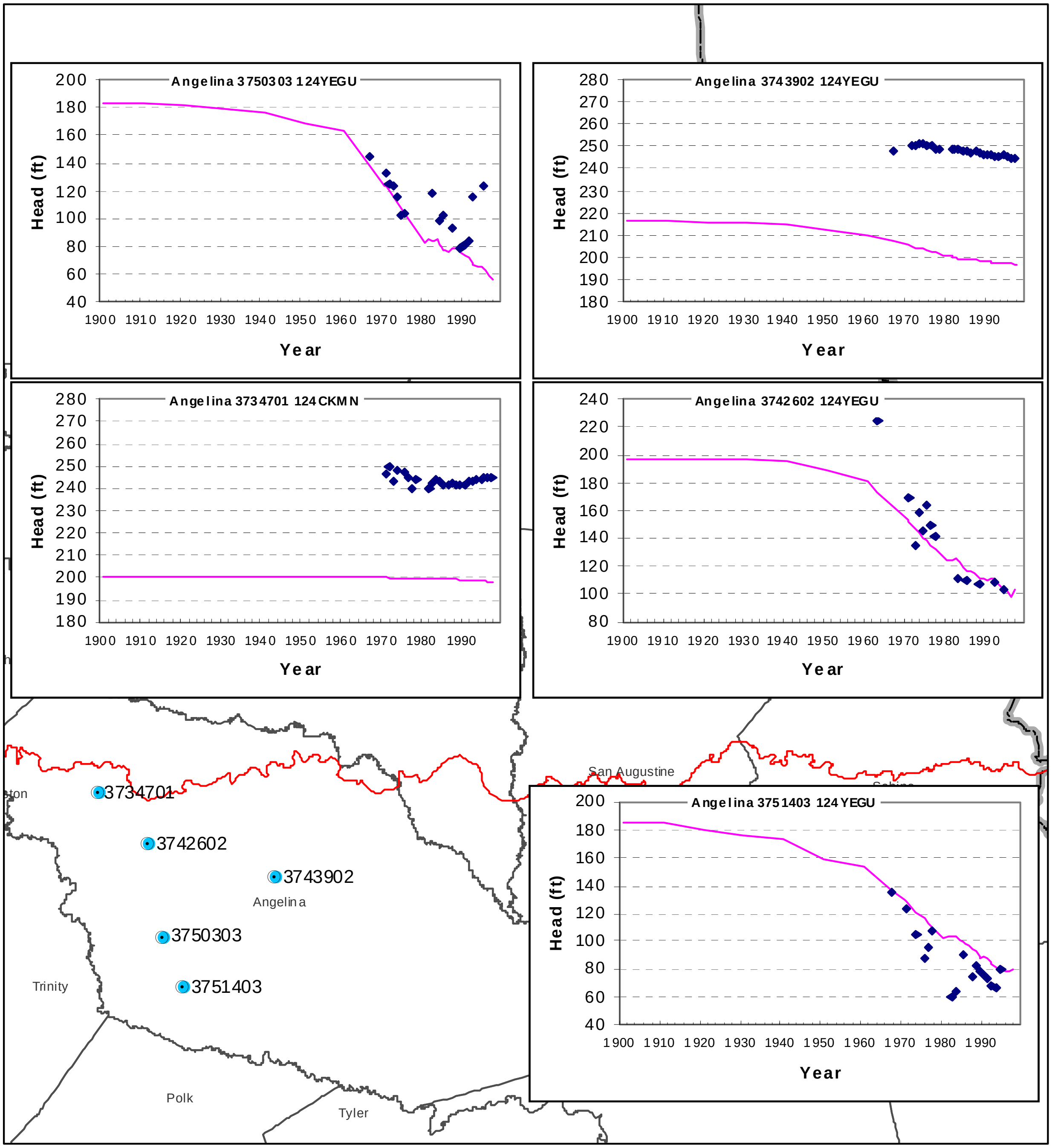

Figure 9.2.22 Selected hydrographs from Angelina County showing head in feet. (Symbols indicate measured heads and solid lines indicate simulated heads.)

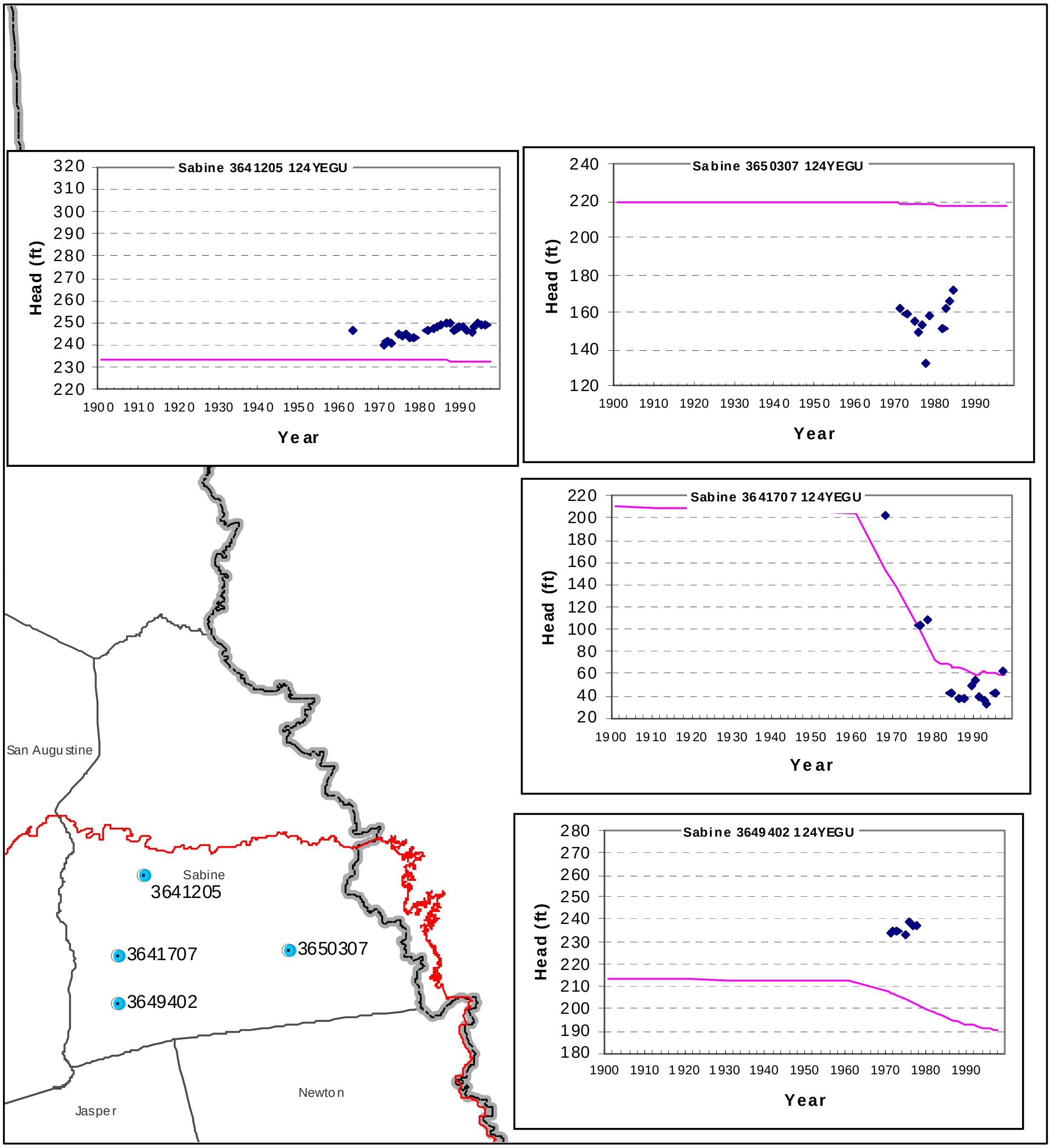

Figure 9.2.23 Selected hydrographs from Sabine County showing head in feet. (Symbols indicate measured heads and solid lines indicate simulated heads.)

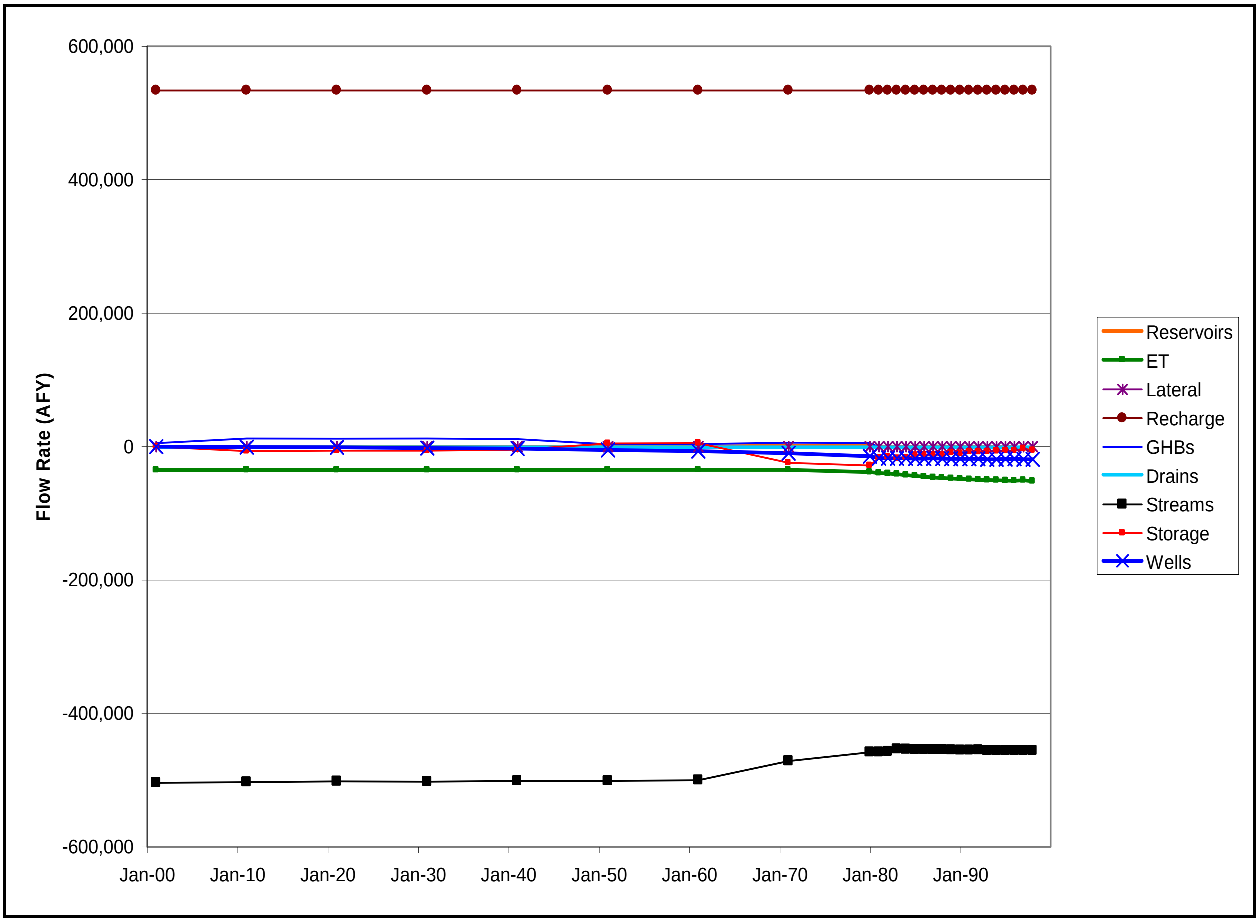

Figure 9.2.24 Total model water budget in acre-feet per year from 1900 to 1997.

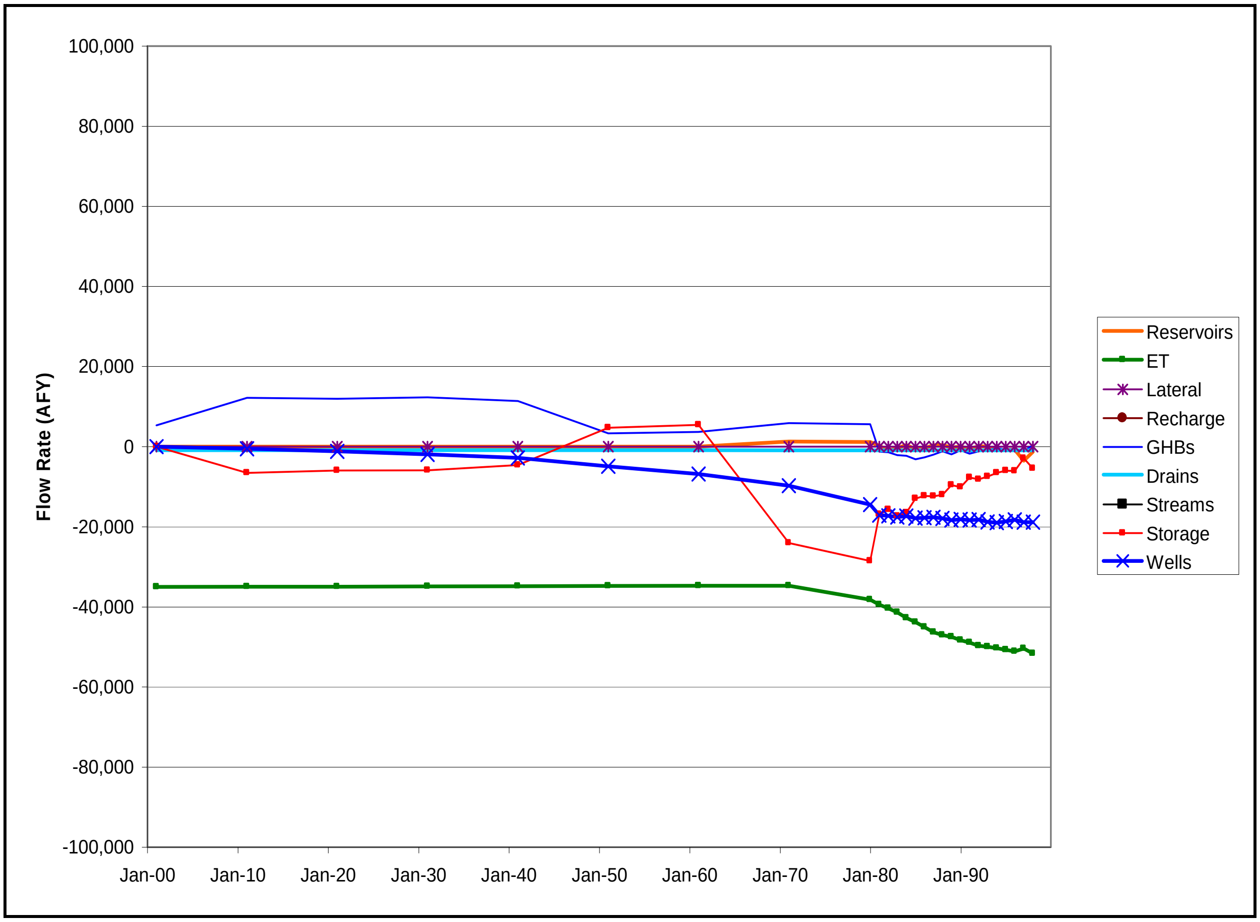

Figure 9.2.25 Total model water budget in acre-feet per year from 1900 to 1997 with expanded scale (major components recharge and stream discharge not shown).

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9.3 Sensitivity Analysis

A sensitivity analysis was performed on the calibrated transient model. For the transient sensitivity analysis, 14 parameter sensitivities were investigated:

1. Horizontal hydraulic conductivity of the shallow layer (Kh-Shallow),
2. Horizontal hydraulic conductivity of the Jackson Group (Kh-Jackson),
3. Horizontal hydraulic conductivity of the Yegua Formation (Kh-Yegua),
4. Vertical hydraulic conductivity in the Catahoula Formation (Kv-Catahoula)
5. Vertical hydraulic conductivity in the Jackson Group (Kv-Jackson),
6. Vertical hydraulic conductivity in the Yegua Formation (Kv-Yegua),
7. Specific yield of the shallow layer (Sy),
8. Storativity, model-wide (S),
9. Recharge, model-wide (Rch),
10. Streambed conductance (Str-Cond),
11. Drain conductance (Drn-Cond),
12. Spring conductance (K-Spring),
13. General-head boundary conductance (GHB-Cond), and
14. General-head boundary elevation (GHB-Elev).

Equation 8.3.1 was used for sensitivities 7 and 9, Equation 8.3.2 was used for sensitivities 1-7 and 10-13, and Equation 8.3.3 was used for sensitivity 14.

Because the steady-state model is used to initialize the transient model, the sensitivities for the transient model are very similar to those of the steady-state model for many of the parameters. Rather than repeating the bulk of the discussion from Section 8.3, in the current section we will focus on the parameters that are unique to the transient model.

Figures 9.3.1 through 9.3.3 show the change in head due to changing hydraulic conductivities and storage parameters. Of the layers, we would expect the shallow layer to be affected by changing specific yield, since it is the only unconfined layer. Figure 9.3.1 shows that specific yield has a minimal impact on heads compared to horizontal conductivities. For the Jackson Group and Yegua Formation, slight changes in head occur due to changing storativity, with a slight increase in head with increasing storativity. Figures 9.3.4 to 9.3.6 show the sensitivity of heads to changes in boundary condition parameters. Pumping has little effect on heads specifically in the shallow layer, as shown in Figure 9.3.4. However, in the confined sections of the Jackson Group and Yegua Formation, pumping has the expected negative correlation with heads. Reservoir conductivity has minimal effect on heads in any case.

Figures 9.3.7 shows the effect of changing hydraulic conductivities and storage parameters on springflow. The results are nearly identical to those in the steady-state, with minimal transient impact from the storage parameters. Figure 9.3.8 shows the effect of changing boundary condition parameters on springflow. Again, the parameters that are considered in transient simulation, such as pumping and reservoir conductance, have minimal impact compared to stream conductance, spring conductance, and recharge. Figure 9.3.9 shows the effect on streamflow of changing hydraulic conductivities and storage parameters. The storage parameters have minimal impact compared to the horizontal conductivities. Figure 9.3.10 shows the effect on streamflow of changing boundary condition parameters. Because pumping has little effect on heads in the shallow layer, it also has minimal effect on stream discharge, compared to recharge and stream conductance.

Figures 9.3.11 through 9.3.14 show head hydrograph sensitivities to selected model parameters. Figure 9.3.11 shows two hydrographs with downward trends and two hydrographs with flat trends in the Jackson Group, where horizontal and vertical hydraulic conductivity was varied in the Jackson Group. The horizontal hydraulic conductivity has the most effect on drawdowns, while the effect of vertical hydraulic conductivity is more visible in the flatter trending hydrographs. Figure 9.3.12 shows hydrographs in the Yegua Formation where horizontal and vertical hydraulic conductivities were varied in the Yegua Formation. The impact of lowering horizontal hydraulic conductivity is evident not only in the drawdowns (which increase) but also in the steady-state heads (which also may increase). Vertical hydraulic conductivity has a significant effect in two cases (wells 3750303 and 3742602) but has a less pronounced effect in the other two hydrographs. Figure 9.3.13 shows the impact on hydrographs when storage parameters are varied model-wide. As expected, storativity has a small effect on the magnitude of drawdowns, with increasing drawdown corresponding to decreasing storativity. The specific yield has minimal impact on heads in any of the hydrographs. Figure 9.3.14 shows the effect of varying pumping or recharge model-wide on several hydrographs. As expected, where drawdowns are occurring, pumping has a strong positive correlation with drawdown. Recharge affects the initial head that results from the steady-state model, but does not impact the shape of the hydrographs.

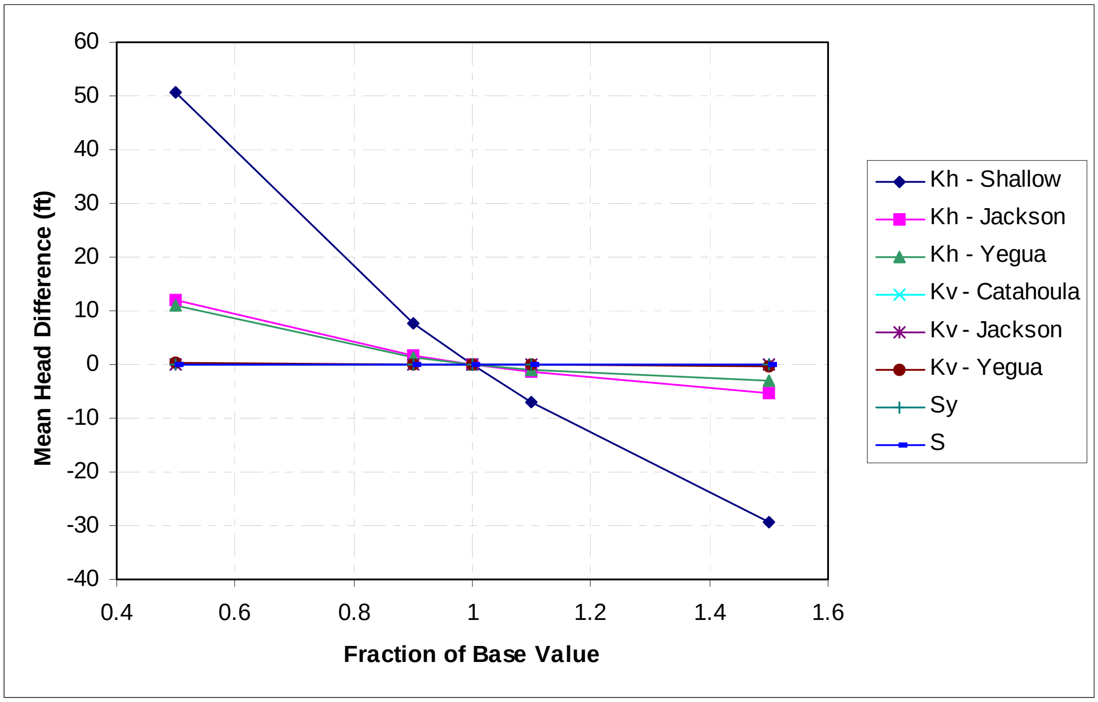

Figure 9.3.1 Transient head sensitivity in feet in the shallow layer to changes in hydraulic conductivities and storage parameters.

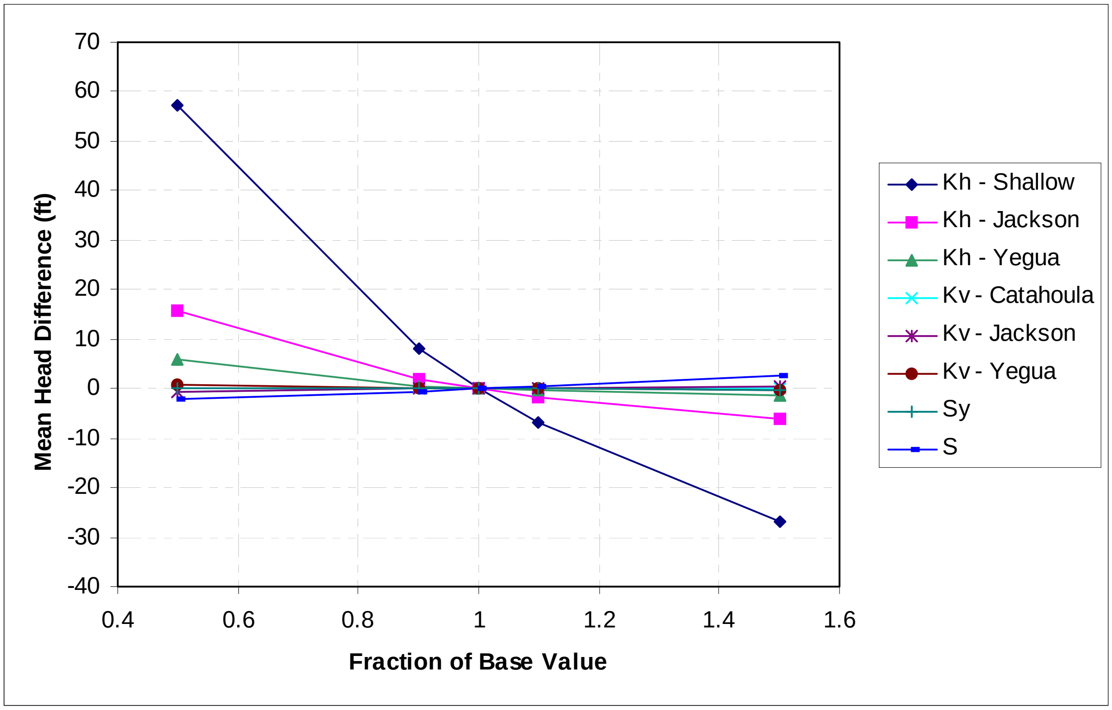

Figure 9.3.2 Transient head sensitivity in feet in the Jackson Group to changes in hydraulic conductivities and storage parameters.

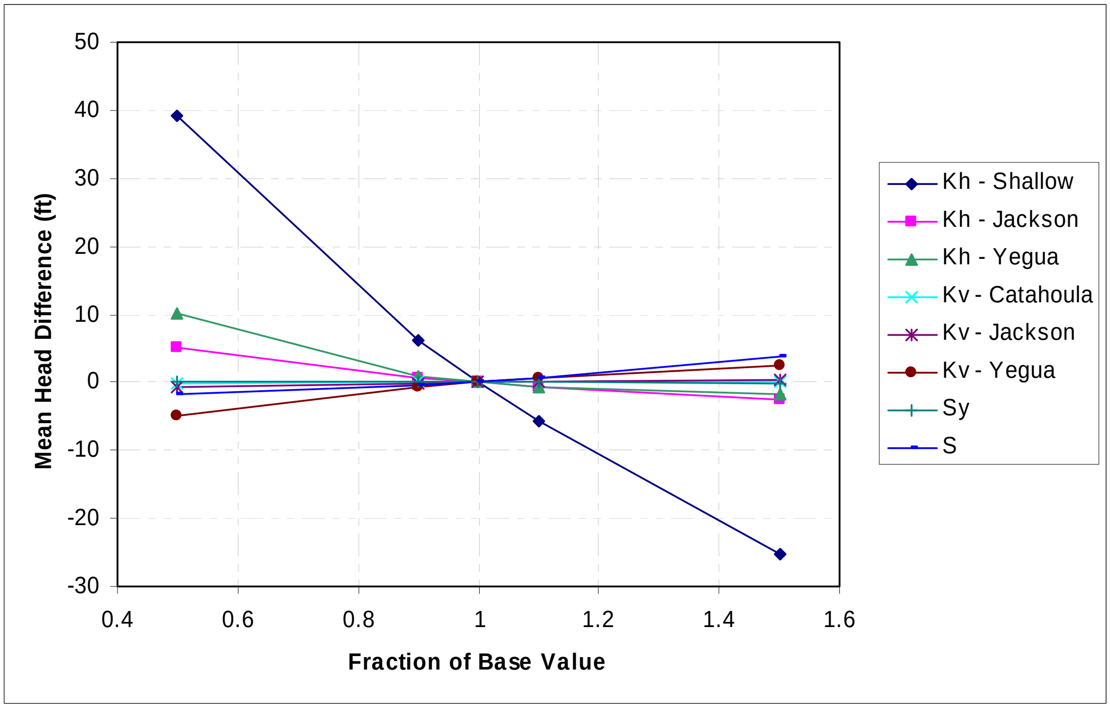

Figure 9.3.3 **Transient head sensitivity in feet in the Yegua Formation to changes in hydraulic conductivities and storage parameters.**

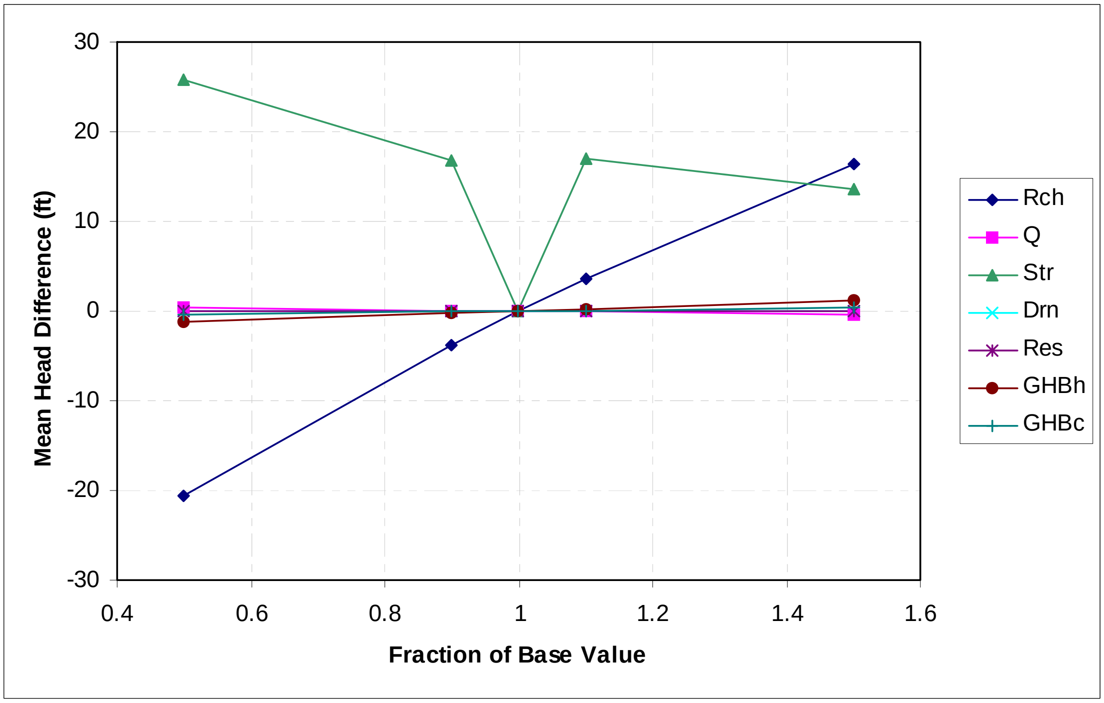

Figure 9.3.4 **Transient head sensitivity in feet in the shallow layer to changing boundary conditions.**

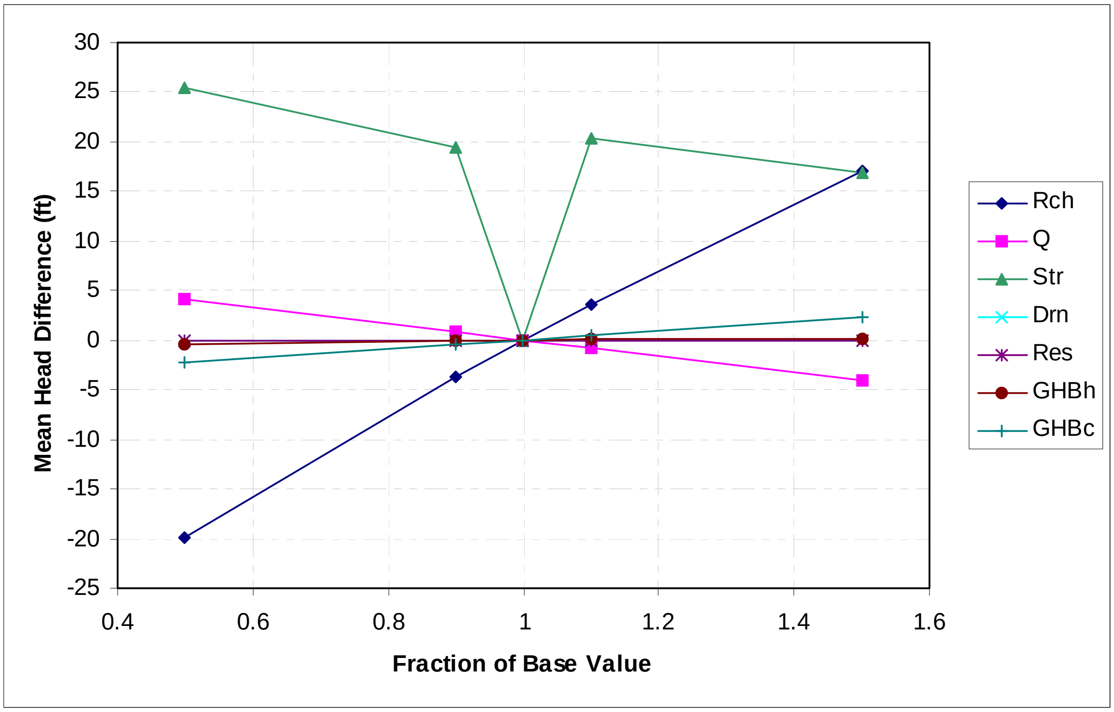

Figure 9.3.5 Transient head sensitivity in feet in the Jackson Group to changes in boundary conditions.

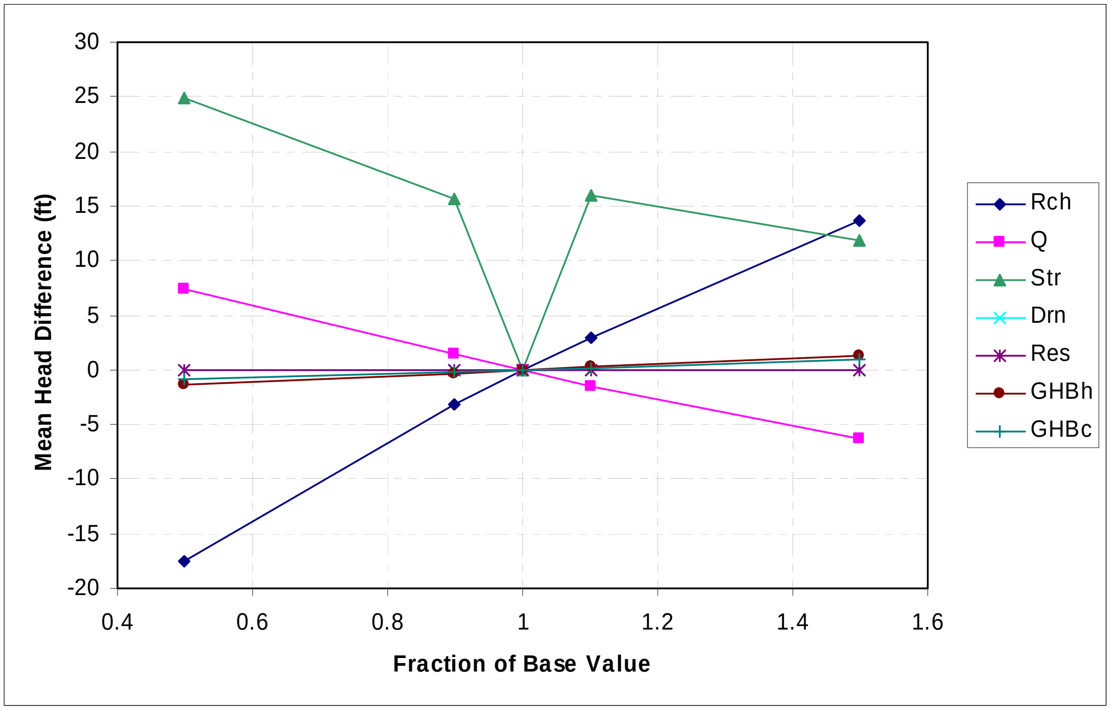

Figure 9.3.6 Transient head sensitivity in feet in the Yegua Formation to changes in boundary conditions.

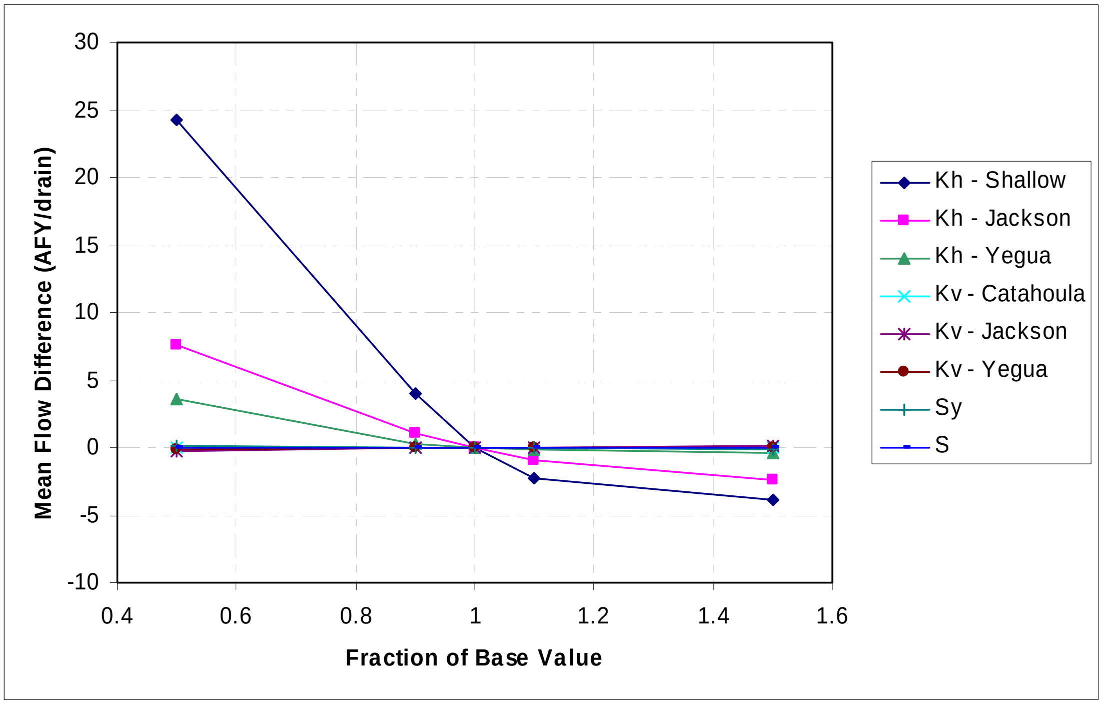

Figure 9.3.7 Springflow sensitivity in acre-feet per year to changes in hydraulic conductivities and storage parameters.

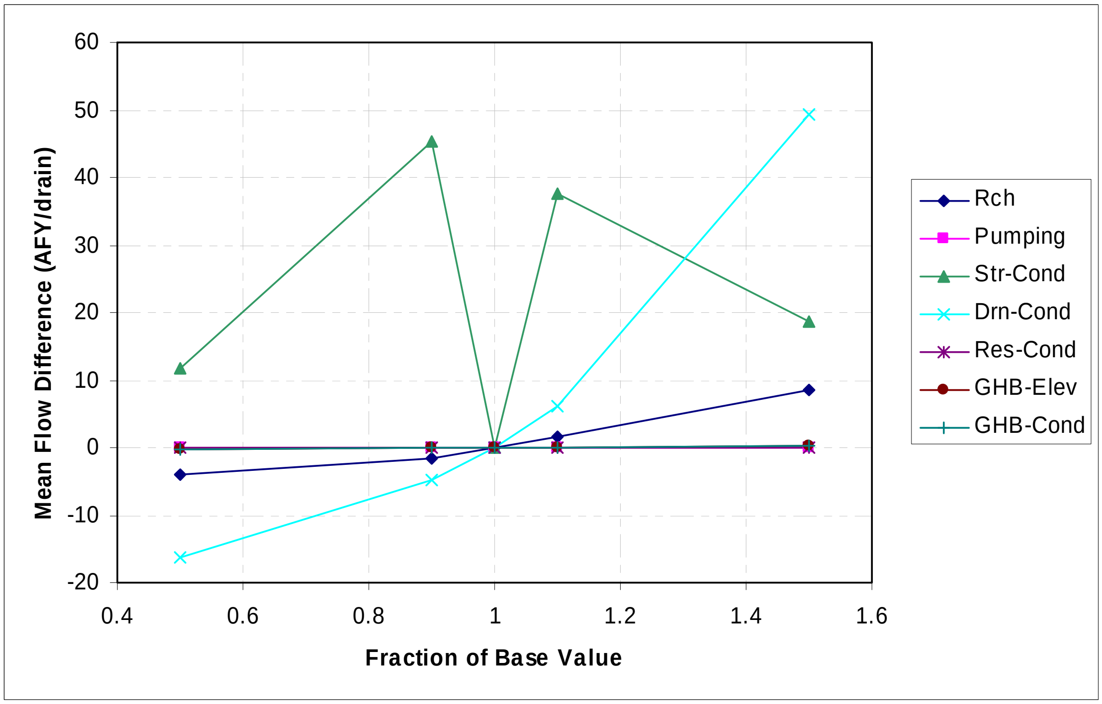

Figure 9.3.8 Springflow sensitivity in acre-feet per year to changes in boundary conditions.

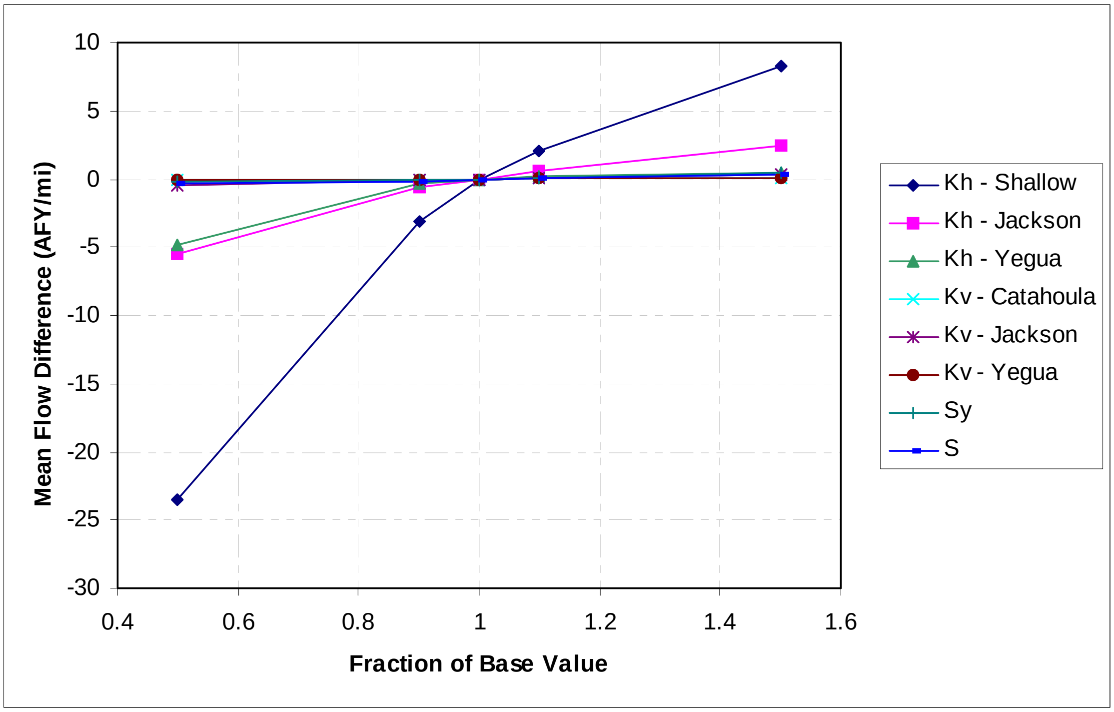

Figure 9.3.9 Stream gain/loss sensitivity in acre-feet per year per mile to changes in hydraulic conductivities and storage parameters.

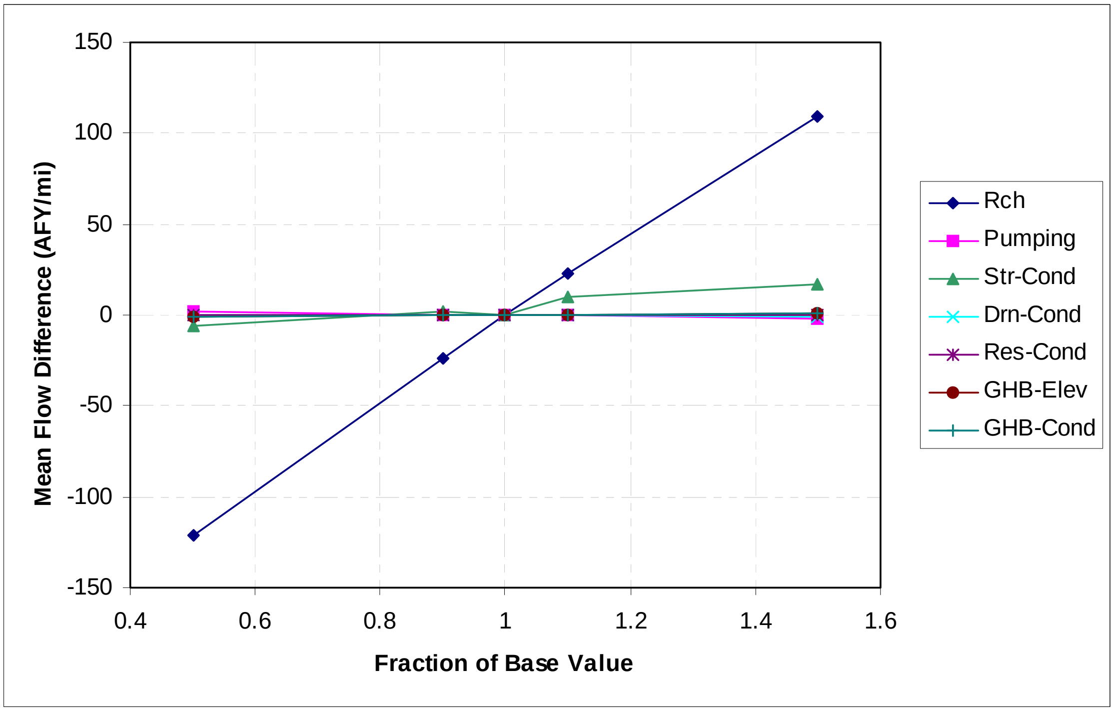

Figure 9.3.10 Stream gain/loss sensitivity in acre-feet per year per mile to changes in boundary conditions.

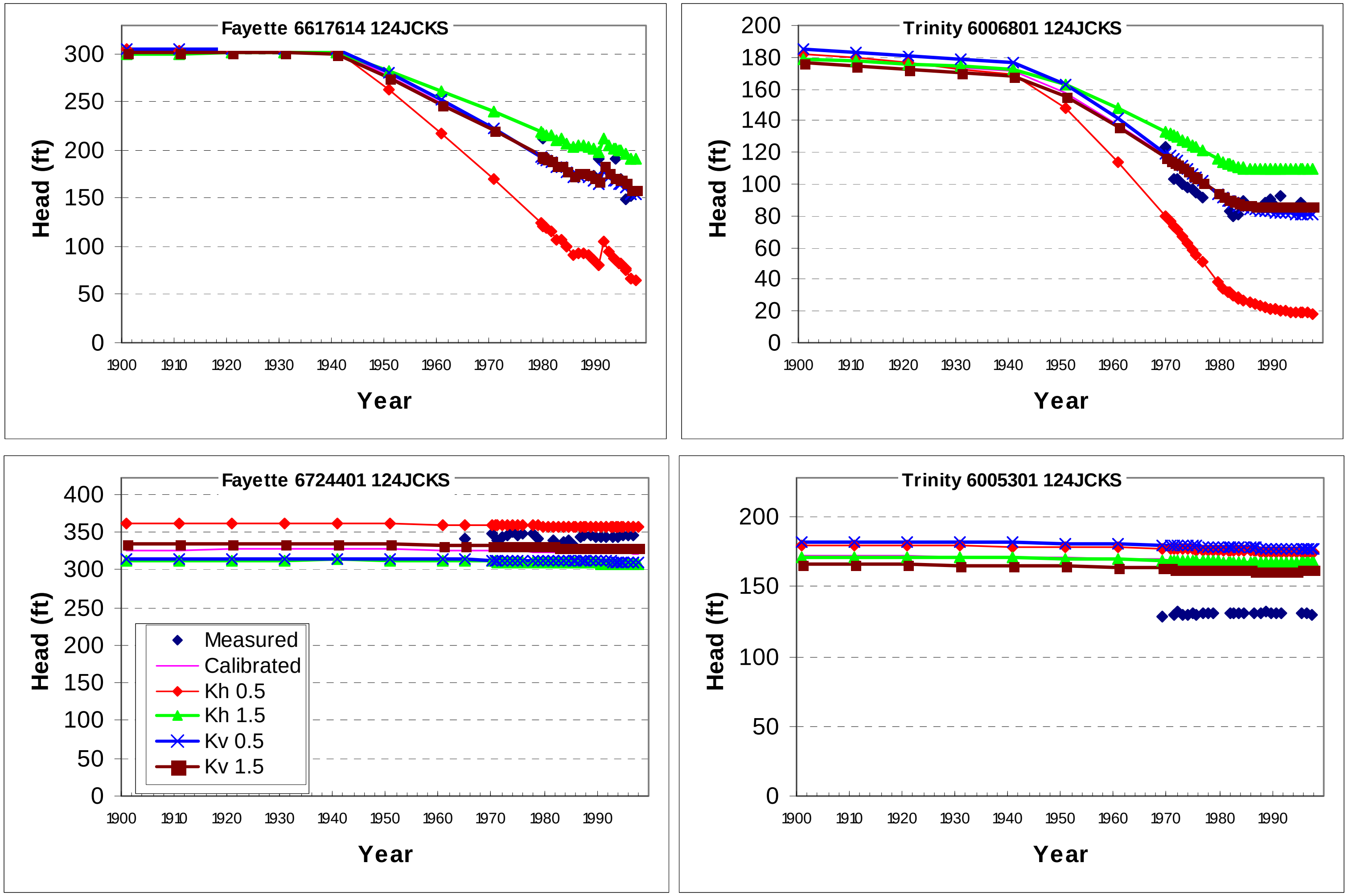

Figure 9.3.11 Hydrograph sensitivities in feet to hydraulic conductivities in the Jackson Group. Legend in lower left plot applies to all plots on page.

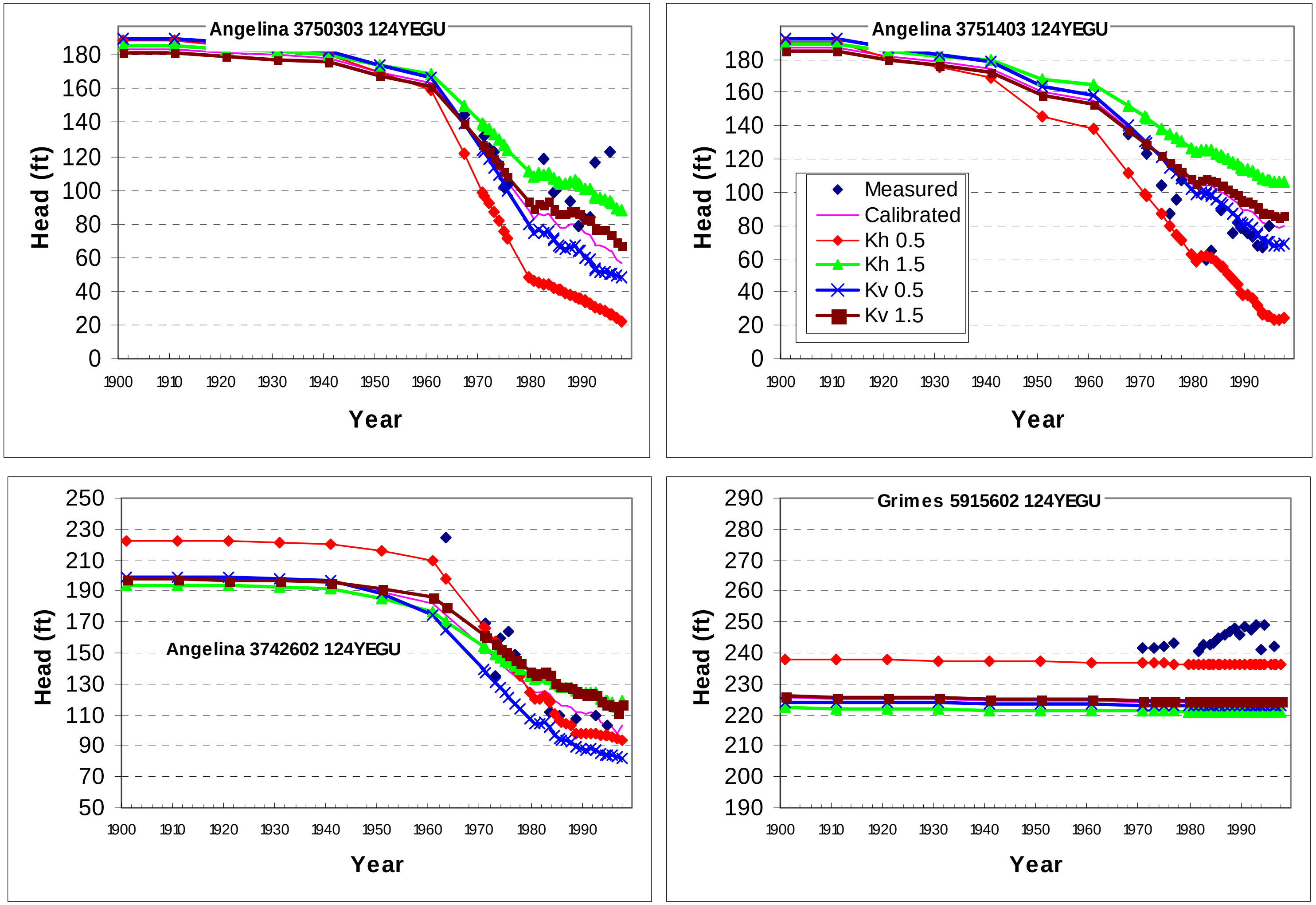

Figure 9.3.12 Hydrograph sensitivities in feet to hydraulic conductivities in the Yegua Formation. Legend in the upper right plot applies to all plots.

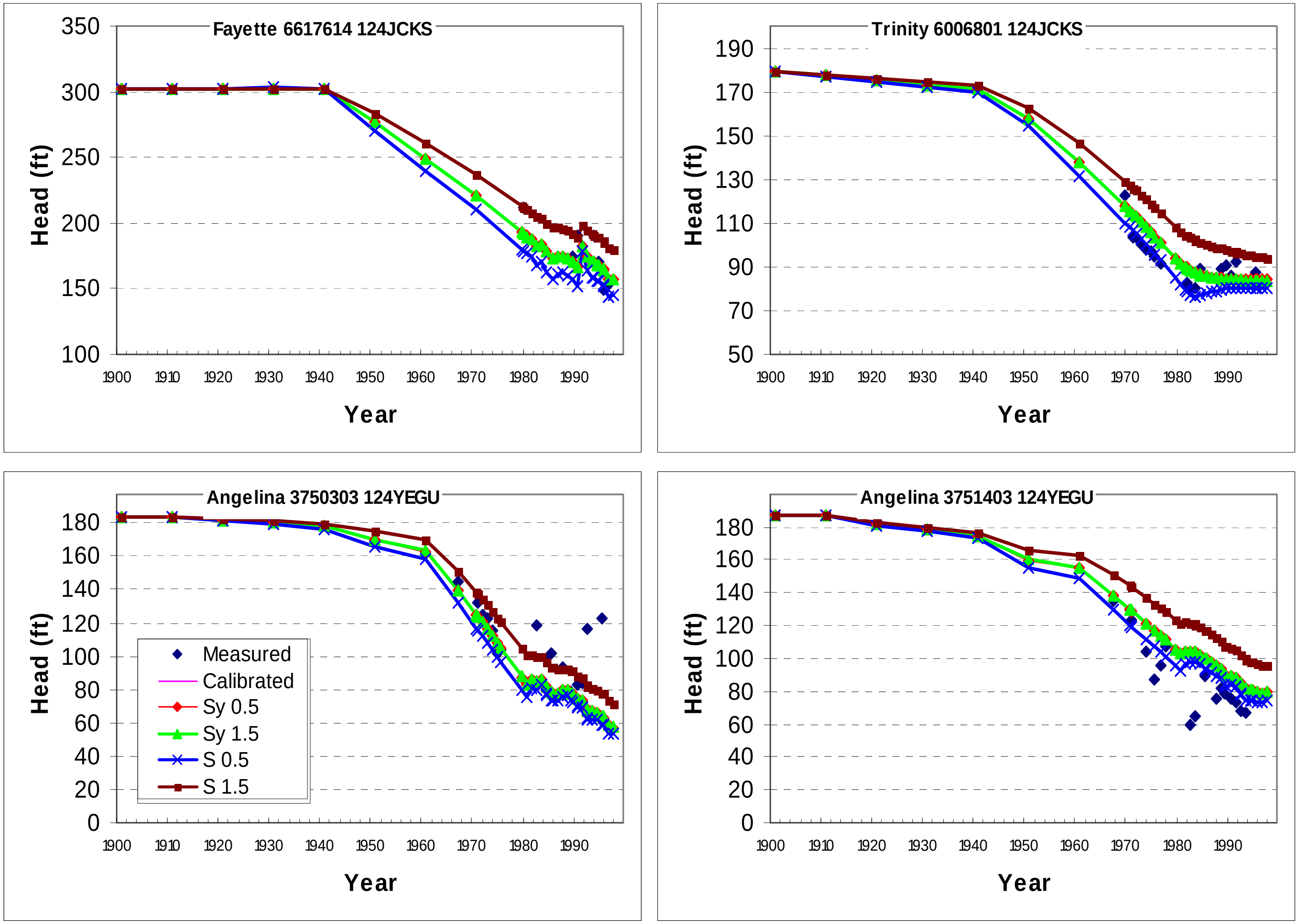

Figure 9.3.13 Hydrograph sensitivities in feet to storage parameters. Legend in the lower left plot applies to all plots.

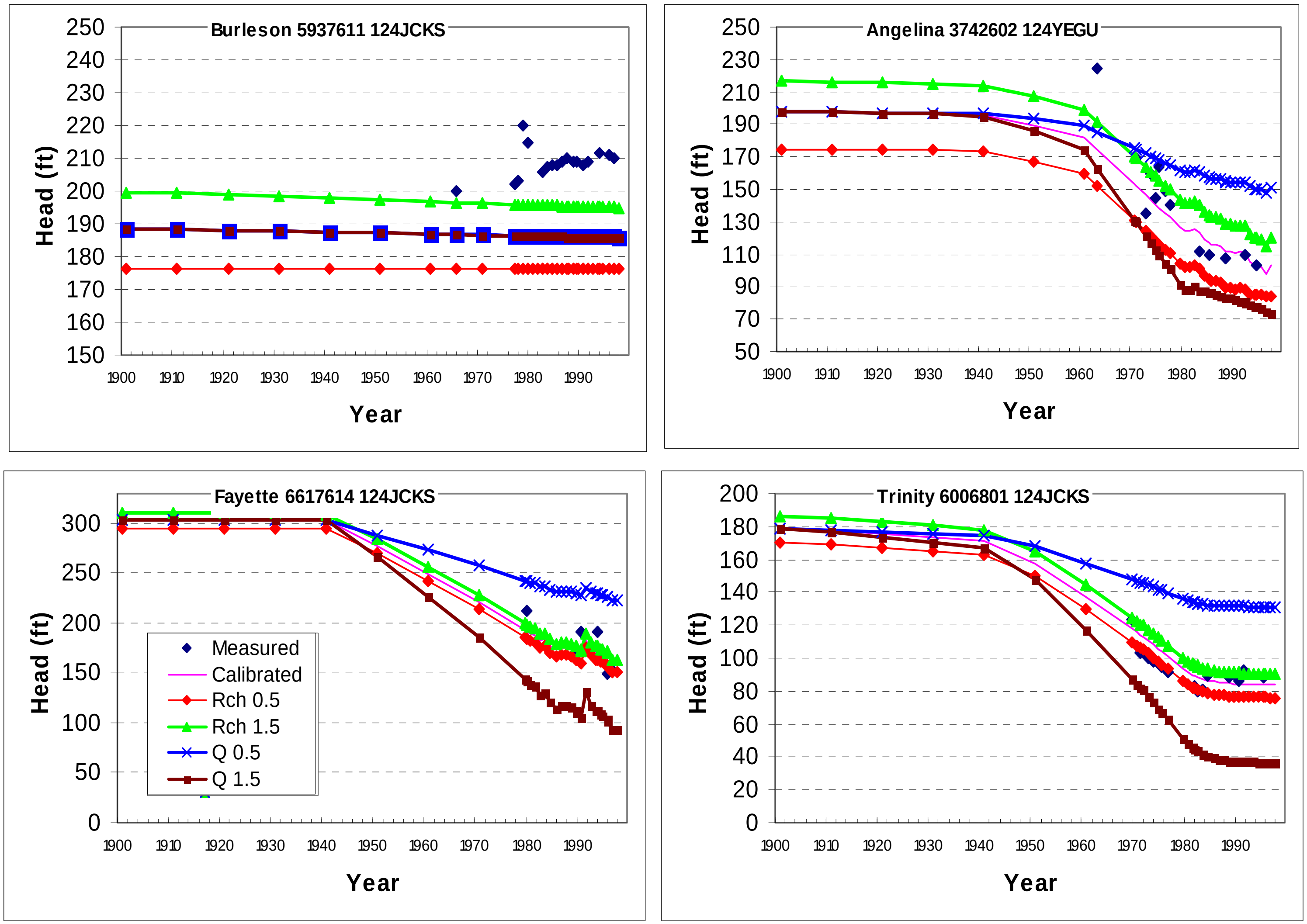

Figure 9.3.14 Hydrograph sensitivities in feet to recharge and pumping discharge. Legend in the lower left plot applies to all plots.

10.0 Limitations of the Model

A model can be defined as a representation of reality that attempts to explain the behavior of some aspect of it, but is always less complex than the real system it represents (Domenico, 1972). As a result, limitations are intrinsic to models. Model limitations can be grouped into several categories including: (1) limitations in the data supporting a model; (2) limitations in the implementation of a model, which may include assumptions inherent to the model application; and (3) limitations regarding model applicability. The limitations of this modeling study are discussed in the following paragraphs consistent with the groupings above.

10.1 Limitations of Supporting Data

Developing the supporting database for a regional model with a large number of grid cells is a challenge. The primary limitations of the supporting database for the Yegua-Jackson Aquifer groundwater availability model are:

- Limited hydraulic properties data for the Yegua-Jackson Aquifer,
- Limited water-level targets spatially and temporally in each of the four units making up the aquifer,
- Limited data quantifying cross-formational flow between the units within the Yegua-Jackson Aquifer,
- Limited frequency of water-level measurements to describe seasonal trends in the aquifer,
- Limitations in stream baseflow targets, and
- Limitations to data defining pumping from the Yegua-Jackson Aquifer.

Each of these database limitations is discussed below.

We typically rely on pump test data for estimating horizontal hydraulic conductivities. There were no previous interpretations of pump test data for the Yegua-Jackson Aquifer. From the Texas Commission of Environmental Quality Public Water Supply records, we were able to process data for and then successfully interpret about 50 pump tests conducted in the aquifer. Although this provided a reasonable range of hydraulic conductivities for the aquifer as a whole, the data were somewhat sparse in terms of spatial coverage per unit. We found no data for the downdip region gulfward of the outcrop. Vertical hydraulic conductivities cannot be measured on a regional scale and were, thus, calibrated within a reasonable range from literature values. There were no available estimates of storativity or specific yield, so these were set at values within ranges from the literature.

The primary type of calibration target used in most models, including this groundwater availability model, is hydraulic head. In some counties of the Yegua-Jackson Aquifer in the active area in or near the outcrop, there is a lack of available head data for both pre-development and transient conditions. There is little to no head data gulfward of the outcrop in the downdip section.

For those wells that have head measurements, the lack of completion interval data for many of the wells increases uncertainty in estimating the unit into which the water level is applicable. This limitation, combined with the paucity of nearby wells completed in different units, limits the ability to evaluate cross-formational flow between the units and to evaluate the models ability to match cross-formational flow conditions within the aquifer.

The temporal frequency of available water-level measurements was insufficient to identify any seasonal trends in Yegua-Jackson Aquifer water levels. This lack of seasonal water-level data precludes calibrating the model to seasonal variations in hydrologic conditions.

Although we compiled a good number of stream baseflow targets from hydrograph separation analyses and literature reported gain/loss studies, we suspect there is significant uncertainty in these targets. When authors of gain/loss studies perform simple uncertainty propagation on their results, a significant percentage of the results turn out to have a higher potential measurement error than the actual estimated value (e.g., Turco and others, 2007). We did not perform a rigorous uncertainty analysis on the baseflow separation approach, so the uncertainty in those estimates is unknown.

There are areas in the Yegua-Jackson Aquifer where measured drawdown data indicate the occurrence of pumping but there is no reported pumping. Limitations in reported pumping can have a large impact in the ability of the model to represent hydrologic conditions in these regions. Although we augmented pumping in a few areas based on re-analysis of the pumping datasets, there are still some regions where head levels suggest that more pumping exists than is reported.

10.2 Assessment of Assumptions

There are several assumptions that are key to the model regarding construction, calibration, and, although not included in this modeling effort, prediction. These assumptions are related to the following aspects of the Yegua-Jackson Aquifer groundwater availability model:

- No-flow boundaries on the bottom of the model,
- Impact of evapotranspiration on the estimate of recharge,
- Recharge spatial and temporal variation,
- Density dependent flow,
- Lack of drawdown in the shallow portion of the aquifer
- Calibration to local drawdowns at regional grid scale, and

We assume that the contact between the Lower Yegua Unit and the Cook Mountain Formation is a no-flow boundary. We think this is a reasonable assumption for this regional model. There may be local areas where the assumption is not as valid, but we do not have direct evidence to support invalidating the assumption.

Average recharge is basically a calibrated parameter. Our initial estimates were based on the assumption of a balance between shallow recharge and baseflow. During calibration, we adjusted average recharge to approximately match most of the baseflow targets. Some fraction of the recharge discharges as evapotranspiration. There are no measurements to allow estimates of what that fraction should be, so we assumed that the discharge to evapotranspiration is much less than the discharge to baseflow. If the discharge to evapotranspiration is in fact much higher, then recharge is underestimated in the model.

Recharge is distributed spatially based on a well-founded conceptualization, but we assume that the conceptualization is applicable to the Yegua-Jackson Aquifer, and have no actual recharge measurements to confirm it. This is typical of regional models. We do not vary recharge temporally with changing precipitation, assuming that the year-to-year variation in recharge does not impact heads significantly. We found no evidence in the hydrographs that heads varied significantly with precipitation in the Yegua-Jackson Aquifer.

Groundwater quality degrades quickly in regions in the subcrop gulfward of the Upper Jackson Unit/Catahoula Formation contact. The increasing total dissolved solids concentration increases the density of the fluid. MODFLOW does not consider density dependent flow and, thus, we assume that density effects have an insignificant impact on results. Because the aquifer is not active in these areas (i.e., there is limited production and very little flow under natural conditions), we feel the assumption is valid.

Horizontal hydraulic conductivities in the shallow layer were adjusted during calibration so that most of the baseflow targets could be met. We assumed that this provides a reasonable lower constraint on the horizontal hydraulic conductivities. However, because there is not enough pumping in the shallow portion of the aquifer to have created any drawdowns, the horizontal hydraulic conductivities were not constrained by the need to fit water levels under heavy pumping conditions. If future pumping conditions create drawdowns in the shallow portion of the aquifer, the reported head and pumping data can be used to better constrain the conductivities in the shallow layer.

The water levels in the Yegua-Jackson Aquifer are stable in the majority of counties in the active portion in and near the outcrop. There are a handful of areas where one or more hydrographs show significant drawdown due to pumping. For the cases where there were only one or two hydrographs that showed the drawdown, we calibrated the simulated heads to these hydrographs. This assumes that drawdowns are occurring on a scale that is commensurate with the model grid scale. Unfortunately, we did not have sufficient spatial hydrograph coverage to really evaluate the scale of the drawdowns, so this assumption is currently untested. If the drawdowns are more localized, then we should correct for the grid-scale effects. In order to understand the scale issues related to the regional grid-block sizes, we will introduce the concept of an equivalent grid block radius. Beljin 1987) provided a good summary of these concepts. For a square grid with x-length ($\triangle x$) equal to the y-length ($\triangle y$), as in our case, the effective grid block radius (Re) is equal to:

$$Re = 0.198 \ \triangle x \qquad (10.2.1)$$

In the case of the groundwater availability models, the effective grid block radius is equal to approximately 1,045 feet. A typical high production well in the Yegua-Jackson Aquifer might have a screen or casing with a 6-inch effective radius. Table 10.2.1 summarizes the steady-state drawdown predicted for a 12-inch well versus a groundwater availability model grid block with an effective radius of 1,045 feet for production rates of 300 and 500 gallons per minute. This example assumes a hydraulic conductivity of 7 feet per day, a specific storage of $3x10^{-6}$ inverse feet, and a fully penetrated aquifer 500-feet thick. For the case of a 500 gallons per minute production rate, the well would observe a drawdown of 47 feet versus the groundwater availability model grid observed drawdown of 16 feet. For the case of a 300 gallon per minute production rate, the well would observe a drawdown of 28 feet versus 10 feet of observed drawdown for the groundwater availability model grid.

If our assumption that the hydrographs represent drawdowns at the scale of the model is invalid, we have the potential to overcompensate for these scale effects during calibration by excessively lowering conductivities or increasing pumping too much.

Table 10.2.1 Comparison of steady-state drawdown for a 12-inch production well and a groundwater availability model grid block.

Effective Radius of Observation	500 gpm	300 gpm
Well (6 inch or 0.5 feet)	46.7	28.0
Effective GAM Grid Block Radius (1,045 feet)	16.3	9.8

gpm = gallons per minute
GAM = groundwater availability model

10.3 Limits for Model Applicability

In general, groundwater availability models are created for determining how regional water levels will respond to water resource development in an area smaller than a county and larger than a square mile. In the current case, this is accomplished by developing a regional model using a grid-block size of one square mile. These two design criteria limit the applicability of the Yegua-Jackson Aquifer groundwater availability model. The accuracy of the model is likely representative at a scale of tens of miles. Because of the model grid scale of one square mile, the model is not capable of being used in its current state to predict aquifer responses at specific points such as a selected well at a particular municipality.

When the model grid was created, the elevation of the bottom of the Lower Yegua unit was decreased in some cases to ensure that the no dry cells were simulated. This was a compromise between consistency with the conceptualization of the structure for the Lower Yegua in some areas, and creating a stable numerical model. These areas may, in reality, be dry, so localized volumetric calculations may overestimate water in place. If this type of calculation is desired, the original surfaces that are available in the geodatabase may be used to avoid the overestimation.

The lack of data for short time periods for use in describing model boundary conditions means that stress periods of less than one year were not warranted. Use of annual stress periods precludes the ability of the model to predict seasonal head or flow variability.

The groundwater availability model provides a first-order approach to coupling surface water to groundwater, which is adequate for the stated purposes of the model. However, the model does not provide a rigorous solution to surface-water modeling. The same applies to simulation of springflows.

The groundwater availability model does not simulate transport of solutes and cannot explicitly address water quality issues. A preliminary assessment of water quality is given in this report in Section 4.8. Currently, there is minimal pumping in the portion of the Yegua-Jackson Aquifer that shows consistently poor water quality. Should there be future interest in development of the more saline, downdip sections of the aquifer, the model may need to be re-evaluated as to the error caused by ignoring density dependence.

11.0 Future Improvements

To use models to predict future conditions requires a commitment to improve the model as new data become available or when modeling assumptions or implementation issues change. This groundwater availability model is no different. Through the modeling process, one generally learns what can be done to improve the model's performance or what data would help better constrain the model calibration. Future improvements to the model, beyond the scope of the current groundwater availability model, are discussed below.

11.1 Additional Supporting Data

Several types of data could be collected to better support future enhancement of the Yegua-Jackson Aquifer groundwater availability model. These include additional water-level monitoring in areas of the Yegua-Jackson Aquifer with sparse measurements, additional surface water/groundwater studies (including estimates of groundwater evapotranspiration in the riparian areas), and additional evaluation of pumping from the Yegua-Jackson Aquifer.

For water-level monitoring, increased spatial coverage would be helpful in constraining properties in some areas with sparse measurements. Most importantly, a better understanding of the spatial extent of drawdown in those areas with downward trending hydrographs would help resolve the grid-scale uncertainty posed in Section 10.2.

More refined vertical coverage of head measurements would be helpful in improving understanding of cross-formational flow, both among the units, and between the Upper Jackson Unit and the Catahoula Formation. A better understanding of the cross-formational flow would improve our estimates of downdip flow and "deep" recharge.

Additional studies of baseflow in some of the larger rivers in the wetter areas would help to verify whether the model's inability to duplicate the largest magnitude baseflow targets (such as in the Brazos River) is due to the model scale, or an overestimate of the target value. Similarly, we do not have good constraint on estimates of groundwater evapotranspiration, which adds to the uncertainty in the recharge/discharge analysis. Understanding baseflow and other components of surficial discharge is one of the keys to constraining shallow recharge and quantifying potential sources of capture.

Recharge is conceptualized as being negligible in the western portion of the model where precipitation is less than 22 inches per year. A study of sources of recharge in this region of Texas would help evaluation this conceptualization.

In several counties, pumping for the Yegua-Jackson Aquifer is inconsistent with well observations. Better reporting of magnitude and pumping location would improve future models of the Yegua-Jackson Aquifer.

11.2 Future Model Implementation Improvements

As mentioned in Section 10.3, the Yegua-Jackson Aquifer groundwater availability model is applicable for simulating water levels at a scale of tens of miles. If more refined simulations are desired in developed areas or areas with very local drawdowns, a refined model of a one- or two-county portion of the Yegua-Jackson Aquifer could be considered. The existing Yegua-Jackson Aquifer groundwater availability model could be used to constrain conditions at the boundaries of any refined models.

If the model is going to be used to predict responses in downdip areas where salinity is high, a variable-density version of the model, using a code like SEAWAT, might be considered.

12.0 Conclusions

This report documents a three-dimensional groundwater model developed for the Yegua-Jackson Aquifer to the groundwater availability model standards defined by the TWDB. This regional-scale model was developed using MODFLOW with various packages for simulating interaction with surface features, including the stream-routing package to simulate stream/aquifer interaction, the drain package to simulate springs, the reservoir package to simulate reservoirs, and the evapotranspiration package to simulate groundwater evapotranspiration.

The Yegua-Jackson Aquifer is modeled as five layers. The first layer represents the shallow outcrop section for all units as well as the Catahoula Formation gulfward of the outcrop. The next four layers represent the deeper sections of the Upper Jackson Unit, Lower Jackson Unit, Upper Yegua Unit, and Lower Yegua Unit.

The purpose of this groundwater availability model is to provide a calibrated numerical model of the Yegua-Jackson Aquifer that can be used to assess groundwater availability in regional water plans and to assess the effects of various proposed water management strategies on the aquifer system. This groundwater availability model provides an integrated tool for the assessment of water management strategies to directly benefit state planners, Regional Water Planning Groups, Groundwater Conservation Districts, and Groundwater Management Areas.

This groundwater availability model was developed using a modeling protocol which is standard to the groundwater model industry. This protocol includes: (1) the development of a conceptual model for groundwater flow in the aquifer; (2) model design; (3) model calibration; (4) sensitivity analysis; and (5) reporting.

This model, like all models, has limitations and can be improved. The groundwater availability model reproduced the pre-development and transient conditions of the aquifer within the required calibration measures. More importantly, this calibrated groundwater availability model provides a documented, publicly-available tool for the assessment of future groundwater availability in the Yegua-Jackson Aquifer.

The model was first calibrated to pre-development conditions. The steady-state model reproduces pre-development water levels well and within the uncertainty of the head estimates. The steady-state model also matches most of the baseflow targets, with the exception of two targets that are of the highest magnitude. In the steady-state model, recharge and stream discharge account for 99.0 percent and 93.4 percent of the recharge and discharge, respectively. Evapotranspiration accounted for 6.5 percent and the minimal remainder went to springs.

A sensitivity analysis was performed to determine which parameters had the most influence on aquifer performance and calibration. The property parameters for the steady-state model that have the greatest effect on heads are the horizontal hydraulic conductivities, especially in the shallow layer. The boundary condition parameters that have the greatest effect on heads are recharge and stream conductance. The surficial discharge mechanisms such as stream discharge and spring flow are sensitive to both their inherent conductances as well as the parameters that most effect heads in the shallow layer.

The model was also successfully calibrated to transient aquifer conditions from 1980 through 1997. The model satisfactorily reproduced aquifer heads during this time period. The model also performs well in the period before 1980. In many parts of the Yegua-Jackson Aquifer, water levels are relatively constant through time. For the few areas where drawdowns are evident in the hydrographs, the model also performs well. In some areas, we had to re-analyze the local pumping location and rates to improve the match to these drawdowns.

At the end of the transient calibration period, recharge accounts for 100.0 percent of the inflow, while stream discharge accounts for 85.5 percent of the outflow. Pumping accounts for 3.5 percent of the outflow, and evapotranspiration accounts for 8.7 percent of the outflow. The minimal remainder goes to springs, reservoirs, cross-formational flow to general head boundaries, and to storage.

A sensitivity analysis was performed on the transient model. Similar to the steady-state model, the property parameters that have the greatest effect on heads are the horizontal hydraulic conductivities, especially in the shallow layer. The boundary condition parameters that have the greatest effect on heads are recharge and stream conductance, although pumping can also have a significant impact. As with the steady-state model, the surficial discharge mechanisms such as stream discharge and spring flow are sensitive to both their inherent conductances as well as the parameters that most effect heads in the shallow layer.

The Yegua-Jackson Aquifer model was built to determine how regional water levels will respond to water resource development in an area smaller than a county and larger than a square mile. In addition, the model is useful in estimating consistent boundary conditions and hydraulic properties on a regional scale that could be applied to any refined models of individual outcrops or subcrop regions of the aquifer.

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APPENDIX A

Results of Evaluation of Model Layer for each Well

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Appendix A Results of Evaluation of Model Layer for each Well

State Well Number	County	Aquifer Code in TWDB Database	Screen Interval Available(1)	Well Depth Available(1)	Model Layer (2)	Description
3735712	Angelina	124YEGU	N	Y	4	Lower Yegua Unit
3735713	Angelina	124YEGU	N	Y	4	Lower Yegua Unit
3734803	Angelina	124YEGU	N	Y	4	Lower Yegua Unit
3736702	Angelina	124YEGU	N	Y	4	Lower Yegua Unit
3741301	Angelina	124YEGU	Y	Y	4	Lower Yegua Unit
3741302	Angelina	124YEGU	N	Y	na	layer could not be conclusively determined
3742201	Angelina	124YEGU	Y	Y	4	Lower Yegua Unit
3742203	Angelina	124YEGU	N	Y	4	Lower Yegua Unit
3742301	Angelina	124YEGU	Y	Y	na	elevation of screened interval below base of Lower Yegua Unit
3742302	Angelina	124YEGU	Y	Y	4	Lower Yegua Unit
3742303	Angelina	124YEGU	N	Y	4	Lower Yegua Unit
3742402	Angelina	124YEGU	Y	Y	4	Lower Yegua Unit
3742501	Angelina	124YEGU	Y	Y	4	Lower Yegua Unit
3742502	Angelina	124YEGU	Y	Y	4	Lower Yegua Unit
3742503	Angelina	124YEGU	N	Y	3	Upper Yegua Unit
3742505	Angelina	124YEGU	N	Y	3	Upper Yegua Unit
3742506	Angelina	124YEGU	N	Y	na	layer could not be conclusively determined
3742601	Angelina	124YEGU	Y	Y	4	Lower Yegua Unit
3742602	Angelina	124YEGU	Y	Y	4 & below	Lower Yegua Unit & underlying unit
3742604	Angelina	124YEGU	Y	Y	4	Lower Yegua Unit
3742606	Angelina	124YEGU	Y	Y	4	Lower Yegua Unit
3742701	Angelina	124YEGU	N	Y	3	Upper Yegua Unit
3742702	Angelina	124YEGU	N	Y	3	Upper Yegua Unit
3742703	Angelina	124YEGU	N	Y	3	Upper Yegua Unit
3742901	Angelina	124YEGU	Y	Y	4	Lower Yegua Unit
3743101	Angelina	124YEGU	N	Y	4	Lower Yegua Unit
3743102	Angelina	124YEGU	Y	Y	na	elevation of screened interval below base of Lower Yegua Unit
3743202	Angelina	124YEGU	N	Y	4	Lower Yegua Unit
3743301	Angelina	124YEGU	Y	Y	4	Lower Yegua Unit
3743302	Angelina	124YEGU	N	Y	4	Lower Yegua Unit
3743306	Angelina	124YEGU	Y	Y	4	Lower Yegua Unit
3743401	Angelina	124YEGU	Y	Y	4	Lower Yegua Unit
3743402	Angelina	124YEGU	N	Y	3	Upper Yegua Unit
3743501	Angelina	124YEGU	Y	Y	4 & below	Lower Yegua Unit & underlying unit
3743502	Angelina	124YEGU	N	Y	3	Upper Yegua Unit
3743503	Angelina	124YEGU	Y	Y	4	Lower Yegua Unit
3743504	Angelina	124YEGU	Y	Y	4	Lower Yegua Unit
3743505	Angelina	124YEGU	N	Y	3	Upper Yegua Unit
3743506	Angelina	124YEGU	N	Y	3	Upper Yegua Unit
3743602	Angelina	124YEGU	N	Y	3	Upper Yegua Unit

State Well Number	County	Aquifer Code in TWDB Database	Screen Interval Available(1)	Well Depth Available(1)	Model Layer (2)	Description
3743701	Angelina	124YEGU	Y	Y	3	Upper Yegua Unit
3743803	Angelina	124YEGU	N	Y	3	Upper Yegua Unit
3743901	Angelina	124YEGU	N	Y	na	layer could not be conclusively determined
3743902	Angelina	124YEGU	Y	Y	3	Upper Yegua Unit
3743903	Angelina	124YEGU	Y	Y	4	Lower Yegua Unit
3743905	Angelina	124YEGU	Y	Y	4	Lower Yegua Unit
3743907	Angelina	124YEGU	Y	Y	4	Lower Yegua Unit
3743909	Angelina	124YEGU	Y	Y	4	Lower Yegua Unit
3744101	Angelina	124YEGU	Y	Y	4	Lower Yegua Unit
3744401	Angelina	124YEGU	N	Y	3	Upper Yegua Unit
3744501	Angelina	124YEGU	Y	Y	4	Lower Yegua Unit
3744703	Angelina	124YEGU	Y	Y	4	Lower Yegua Unit
3744801	Angelina	124YEGU	Y	Y	4	Lower Yegua Unit
3744802	Angelina	124YEGU	Y	Y	4	Lower Yegua Unit
3744803	Angelina	124YEGU	Y	Y	3	Upper Yegua Unit
3744804	Angelina	124YEGU	Y	Y	4	Lower Yegua Unit
3744805	Angelina	124YEGU	Y	Y	4	Lower Yegua Unit
3744902	Angelina	124YEGU	N	Y	na	layer could not be conclusively determined
3744903	Angelina	124YEGU	N	Y	na	layer could not be conclusively determined
3744904	Angelina	124YEGU	Y	Y	4	Lower Yegua Unit
3745401	Angelina	124YEGU	Y	Y	4	Lower Yegua Unit
3745701	Angelina	124YEGU	Y	Y	3	Upper Yegua Unit
3745802	Angelina	124YEGU	N	Y	na	layer could not be conclusively determined
3745803	Angelina	124YEGU	N	Y	na	layer could not be conclusively determined
3745804	Angelina	124YEGU	Y	Y	3	Upper Yegua Unit
3745805	Angelina	124YEGU	Y	Y	3	Upper Yegua Unit
3745903	Angelina	124YEGU	Y	Y	3	Upper Yegua Unit
3745904	Angelina	124YEGU	Y	Y	3	Upper Yegua Unit
3750202	Angelina	124YEGU	Y	Y	3	Upper Yegua Unit
3750302	Angelina	124YEGU	Y	Y	4	Lower Yegua Unit
3750303	Angelina	124YEGU	Y	Y	3	Upper Yegua Unit
3750304	Angelina	124YEGU	Y	Y	3	Upper Yegua Unit
3750305	Angelina	124YEGU	N	Y	na	layer could not be conclusively determined
3750501	Angelina	124YEGU	Y	Y	3	Upper Yegua Unit
3750602	Angelina	124YEGU	N	Y	na	layer could not be conclusively determined
3750603	Angelina	124YEGU	Y	Y	4	Lower Yegua Unit
3750604	Angelina	124YEGU	Y	Y	4	Lower Yegua Unit
3750605	Angelina	124YEGU	Y	Y	3	Upper Yegua Unit
3750606	Angelina	124YEGU	Y	Y	3	Upper Yegua Unit
3750607	Angelina	124YEGU	Y	Y	2	Lower Jackson Unit
3750608	Angelina	124YEGU	Y	Y	3	Upper Yegua Unit
3750609	Angelina	124YEGU	Y	Y	3	Upper Yegua Unit

State Well Number	County	Aquifer Code in TWDB Database	Screen Interval Available(1)	Well Depth Available(1)	Model Layer (2)	Description
3750610	Angelina	124YEGU	Y	Y	4	Lower Yegua Unit
3750611	Angelina	124YEGU	Y	Y	3	Upper Yegua Unit
3750612	Angelina	124YEGU	Y	Y	4	Lower Yegua Unit
3750901	Angelina	124YEGU	Y	Y	3	Upper Yegua Unit
3751102	Angelina	124YEGU	N	Y	3	Upper Yegua Unit
3751201	Angelina	124YEGU	Y	Y	3	Upper Yegua Unit
3751202	Angelina	124YEGU	Y	Y	3	Upper Yegua Unit
3751204	Angelina	124YEGU	Y	Y	3	Upper Yegua Unit
3751205	Angelina	124YEGU	Y	Y	3	Upper Yegua Unit
3751301	Angelina	124YEGU	N	Y	3	Upper Yegua Unit
3751302	Angelina	124YEGU	Y	Y	3	Upper Yegua Unit
3751403	Angelina	124YEGU	Y	Y	3	Upper Yegua Unit
3751404	Angelina	124YEGU	N	Y	na	layer could not be conclusively determined
3751503	Angelina	124YEGU	N	Y	3	Upper Yegua Unit
3751505	Angelina	124YEGU	N	Y	na	layer could not be conclusively determined
3751901	Angelina	124JCKS	N	Y	1	Upper Jackson Unit
3751902	Angelina	124JCKS	N	Y	1	Upper Jackson Unit
3751903	Angelina	124YEGU	N	Y	na	layer could not be conclusively determined
3752201	Angelina	124YEGU	N	Y	na	layer could not be conclusively determined
3752202	Angelina	124YEGU	Y	Y	2	Lower Jackson Unit
3752203	Angelina	124YEGU	N	Y	3	Upper Yegua Unit
3752402	Angelina	124YEGU	Y	Y	3	Upper Yegua Unit
3752501	Angelina	124YEGU	N	Y	na	layer could not be conclusively determined
3752602	Angelina	124YEGU	N	Y	3	Upper Yegua Unit
3752801	Angelina	124YEGU	N	Y	na	layer could not be conclusively determined
3753101	Angelina	124YEGU	Y	Y	2	Lower Jackson Unit
3753102	Angelina	124YEGU	N	Y	3	Upper Yegua Unit
3753103	Angelina	124YEGU	Y	Y	3	Upper Yegua Unit
3753202	Angelina	124JCKS	N	Y	2	Lower Jackson Unit
3753401	Angelina	124YEGU	Y	Y	3	Upper Yegua Unit
3753501	Angelina	124YEGU	Y	Y	3	Upper Yegua Unit
3753603	Angelina	124JCKS	N	Y	2	Lower Jackson Unit
3753604	Angelina	124YEGU	Y	Y	2	Lower Jackson Unit
3753605	Angelina	124YEGU	Y	Y	1	Upper Jackson Unit
3753606	Angelina	124JCKS	Y	Y	2	Lower Jackson Unit
3753901	Angelina	124JCKS	Y	Y	1	Upper Jackson Unit
3753902	Angelina	124JCKS	N	Y	1	Upper Jackson Unit
3753904	Angelina	124YEGU	Y	Y	2	Lower Jackson Unit
3753906	Angelina	124JCKS	N	Y	1	Upper Jackson Unit
3753907	Angelina	124YEGU	Y	Y	3	Upper Yegua Unit
3754102	Angelina	124YEGU	N	Y	na	layer could not be conclusively determined
3754401	Angelina	124YEGU	Y	Y	2	Lower Jackson Unit

State Well Number	County	Aquifer Code in TWDB Database	Screen Interval Available[(1)]	Well Depth Available[(1)]	Model Layer [(2)]	Description
3754403	Angelina	124YEGU	Y	Y	2	Lower Jackson Unit
3754404	Angelina	124YEGU	Y	Y	2	Lower Jackson Unit
3754405	Angelina	124YEGU	Y	Y	2	Lower Jackson Unit
3754407	Angelina	124YEGU	Y	Y	2	Lower Jackson Unit
3754412	Angelina	124YEGU	Y	Y	2	Lower Jackson Unit
3754901	Angelina	124JCKS	Y	Y	1	Upper Jackson Unit
3760101	Angelina	124JCKS	N	Y	1	Upper Jackson Unit
3760201	Angelina	124JCKS	Y	Y	1	Upper Jackson Unit
3760501	Angelina	124JCKS	Y	Y	1	Upper Jackson Unit
3761202	Angelina	124JCKS	N	Y	1	Upper Jackson Unit
3761203	Angelina	124JCKS	N	Y	1	Upper Jackson Unit
3761601	Angelina	124JCKS	Y	Y	1	Upper Jackson Unit
3762202	Angelina	124JCKS	N	Y	na	elevation of well base above top of Upper Jackson Unit
3762301	Angelina	124JCKS	Y	Y	1	Upper Jackson Unit
3763201	Angelina	124JCKS	Y	Y	1	Upper Jackson Unit
6861808	Atascosa	124JCKS	N	Y	na	well plots outside of boundary of Yegua-Jackson Aquifer
7805402	Atascosa	124JCKS	N	Y	na	well plots outside of boundary of Yegua-Jackson Aquifer
7805602	Atascosa	124JCKS	N	Y	na	well plots outside of boundary of Yegua-Jackson Aquifer
7813202	Atascosa	124YEGU	N	Y	na	layer could not be conclusively determined
7814202	Atascosa	124YEGU	N	Y	3	Upper Yegua Unit
7815401	Atascosa	124YEGU	N	Y	3	Upper Yegua Unit
7815601	Atascosa	124JCKS	N	Y	1	Upper Jackson Unit
7815603	Atascosa	124JCKS	N	Y	na	layer could not be conclusively determined
7823102	Atascosa	124JCKS	N	Y	na	layer could not be conclusively determined
7823103	Atascosa	124JCKS	N	Y	na	layer could not be conclusively determined
7823201	Atascosa	124JCKS	N	Y	1	Upper Jackson Unit
7823203	Atascosa	124JCKS	N	Y	1	Upper Jackson Unit
5930101	Brazos	124YGC M	N	Y	na	layer could not be conclusively determined
5939614	Brazos	124JCKS	N	Y	na	elevation of well base above top of Upper Jackson Unit
5914102	Brazos	124YEGU	N	Y	na	well plots outside of boundary of Yegua-Jackson Aquifer
5914601	Brazos	124YEGU	N	Y	4	Lower Yegua Unit
5914603	Brazos	124YEGU	N	Y	4	Lower Yegua Unit
5914901	Brazos	124YEGU	N	Y	4	Lower Yegua Unit
5914904	Brazos	124YEGU	N	Y	4	Lower Yegua Unit
5915402	Brazos	124YEGU	N	Y	4	Lower Yegua Unit
5915403	Brazos	124YEGU	N	Y	4	Lower Yegua Unit
5915404	Brazos	124YEGU	N	Y	4	Lower Yegua Unit
5915501	Brazos	124YEGU	N	Y	4	Lower Yegua Unit

State Well Number	County	Aquifer Code in TWDB Database	Screen Interval Available[(1)]	Well Depth Available[(1)]	Model Layer [(2)]	Description
5915701	Brazos	124YEGU	N	Y	4	Lower Yegua Unit
5915702	Brazos	124YEGU	N	Y	4	Lower Yegua Unit
5915704	Brazos	124YEGU	N	Y	4	Lower Yegua Unit
5915706	Brazos	124YEGU	N	Y	4	Lower Yegua Unit
5915801	Brazos	124YEGU	N	Y	4	Lower Yegua Unit
5915803	Brazos	124YEGU	N	Y	4	Lower Yegua Unit
5921407	Brazos	124YEGU	N	Y	na	well plots outside of boundary of Yegua-Jackson Aquifer
5921503	Brazos	124YEGU	N	Y	na	well plots outside of boundary of Yegua-Jackson Aquifer
5921506	Brazos	124YEGU	N	Y	4	Lower Yegua Unit
5921508	Brazos	124YEGU	N	Y	4	Lower Yegua Unit
5921603	Brazos	124YEGU	N	Y	4	Lower Yegua Unit
5921604	Brazos	124YEGU	N	Y	4	Lower Yegua Unit
5921901	Brazos	124YEGU	N	Y	4	Lower Yegua Unit
5921903	Brazos	124YEGU	N	Y	4	Lower Yegua Unit
5921904	Brazos	124YEGU	N	Y	4	Lower Yegua Unit
5921905	Brazos	124YEGU	N	Y	4	Lower Yegua Unit
5921906	Brazos	124YEGU	N	Y	4	Lower Yegua Unit
5921907	Brazos	124YEGU	N	Y	4	Lower Yegua Unit
5922102	Brazos	124YEGU	N	Y	4	Lower Yegua Unit
5922103	Brazos	124YEGU	N	Y	4	Lower Yegua Unit
5922107	Brazos	124YEGU	N	Y	4	Lower Yegua Unit
5922201	Brazos	124YEGU	N	Y	4	Lower Yegua Unit
5922301	Brazos	124YEGU	N	Y	4	Lower Yegua Unit
5922304	Brazos	124YEGU	N	Y	4	Lower Yegua Unit
5922305	Brazos	124YEGU	N	Y	4	Lower Yegua Unit
5922404	Brazos	124YEGU	N	Y	4	Lower Yegua Unit
5922501	Brazos	124YEGU	N	Y	4	Lower Yegua Unit
5922502	Brazos	124YEGU	N	Y	4	Lower Yegua Unit
5922503	Brazos	124YEGU	N	Y	4	Lower Yegua Unit
5922504	Brazos	124YEGU	N	Y	4	Lower Yegua Unit
5922505	Brazos	124YEGU	N	Y	4	Lower Yegua Unit
5922506	Brazos	124YEGU	N	Y	4	Lower Yegua Unit
5922601	Brazos	124YEGU	N	Y	4	Lower Yegua Unit
5922602	Brazos	124YEGU	N	Y	4	Lower Yegua Unit
5922603	Brazos	124YEGU	N	Y	4	Lower Yegua Unit
5922604	Brazos	124YEGU	N	Y	4	Lower Yegua Unit
5922605	Brazos	124YEGU	N	Y	4	Lower Yegua Unit
5922606	Brazos	124YEGU	N	Y	4	Lower Yegua Unit
5922607	Brazos	124YEGU	N	Y	na	layer could not be conclusively determined
5922609	Brazos	124YEGU	N	Y	4	Lower Yegua Unit
5922901	Brazos	124YEGU	N	Y	na	layer could not be conclusively determined
5922902	Brazos	124YEGU	N	Y	na	layer could not be conclusively determined
5922903	Brazos	124YEGU	N	Y	3	Upper Yegua Unit

State Well Number	County	Aquifer Code in TWDB Database	Screen Interval Available(1)	Well Depth Available(1)	Model Layer (2)	Description
5922904	Brazos	124YEGU	N	Y	na	layer could not be conclusively determined
5922906	Brazos	124YEGU	N	Y	na	layer could not be conclusively determined
5922907	Brazos	124YEGU	N	Y	na	layer could not be conclusively determined
5923101	Brazos	124YEGU	N	Y	4	Lower Yegua Unit
5923102	Brazos	124YEGU	N	Y	4	Lower Yegua Unit
5923103	Brazos	124YEGU	N	Y	4	Lower Yegua Unit
5923104	Brazos	124YEGU	N	Y	4	Lower Yegua Unit
5923201	Brazos	124YEGU	N	Y	3	Upper Yegua Unit
5923401	Brazos	124YEGU	N	Y	na	layer could not be conclusively determined
5923402	Brazos	124YEGU	N	Y	na	layer could not be conclusively determined
5923404	Brazos	124YEGU	N	N	3	Upper Yegua Unit
5923502	Brazos	124YEGU	N	Y	na	layer could not be conclusively determined
5923701	Brazos	124YEGU	N	Y	3	Upper Yegua Unit
5929203	Brazos	124YEGU	N	Y	4	Lower Yegua Unit
5929205	Brazos	124YEGU	N	Y	4	Lower Yegua Unit
5929208	Brazos	124YEGU	N	Y	4	Lower Yegua Unit
5929209	Brazos	124YEGU	N	Y	4	Lower Yegua Unit
5929302	Brazos	124YEGU	N	Y	4	Lower Yegua Unit
5929303	Brazos	124YEGU	N	Y	4	Lower Yegua Unit
5929305	Brazos	124YEGU	N	Y	4	Lower Yegua Unit
5929306	Brazos	124YEGU	N	Y	4	Lower Yegua Unit
5929604	Brazos	124YEGU	N	Y	4	Lower Yegua Unit
5929605	Brazos	124YEGU	N	Y	4	Lower Yegua Unit
5929606	Brazos	124YEGU	N	Y	4	Lower Yegua Unit
5930102	Brazos	124YEGU	N	Y	4	Lower Yegua Unit
5930202	Brazos	124YEGU	N	Y	4	Lower Yegua Unit
5930205	Brazos	124YEGU	N	Y	na	layer could not be conclusively determined
5930206	Brazos	124YEGU	N	Y	na	layer could not be conclusively determined
5930301	Brazos	124YEGU	N	Y	na	layer could not be conclusively determined
5930303	Brazos	124YEGU	N	Y	3	Upper Yegua Unit
5930304	Brazos	124YEGU	N	Y	3	Upper Yegua Unit
5930306	Brazos	124YEGU	N	Y	3	Upper Yegua Unit
5930307	Brazos	124YEGU	N	Y	3	Upper Yegua Unit
5930401	Brazos	124YEGU	N	Y	na	layer could not be conclusively determined
5930402	Brazos	124YEGU	N	Y	na	layer could not be conclusively determined
5930404	Brazos	124YEGU	N	Y	na	layer could not be conclusively determined
5930405	Brazos	124YEGU	N	Y	na	layer could not be

State Well Number	County	Aquifer Code in TWDB Database	Screen Interval Available(1)	Well Depth Available(1)	Model Layer (2)	Description
						conclusively determined
5930406	Brazos	124YEGU	N	Y	na	layer could not be conclusively determined
5930407	Brazos	124YEGU	N	Y	na	layer could not be conclusively determined
5930501	Brazos	124YEGU	N	Y	na	layer could not be conclusively determined
5930502	Brazos	124YEGU	N	Y	na	layer could not be conclusively determined
5930503	Brazos	124YEGU	N	Y	4	Lower Yegua Unit
5930504	Brazos	124YEGU	N	Y	3	Upper Yegua Unit
5930506	Brazos	124YEGU	N	Y	3	Upper Yegua Unit
5930601	Brazos	124YEGU	N	Y	na	layer could not be conclusively determined
5930802	Brazos	124YEGU	N	Y	3	Upper Yegua Unit
5930803	Brazos	124JCKS	N	Y	2	Lower Jackson Unit
5930804	Brazos	124JCKS	N	Y	na	layer could not be conclusively determined
5930805	Brazos	124YEGU	N	Y	na	layer could not be conclusively determined
5930806	Brazos	124YEGU	N	Y	na	layer could not be conclusively determined
5930807	Brazos	124YEGU	N	Y	na	layer could not be conclusively determined
5931101	Brazos	124JCKS	N	Y	2	Lower Jackson Unit
5931201	Brazos	124YEGU	N	Y	3	Upper Yegua Unit
5931202	Brazos	124YEGU	N	Y	3	Upper Yegua Unit
5931401	Brazos	124YEGU	N	Y	3	Upper Yegua Unit
5931701	Brazos	124JCKS	N	Y	2	Lower Jackson Unit
5931801	Brazos	124JCKS	N	Y	2	Lower Jackson Unit
5931802	Brazos	124JCKS	N	Y	2	Lower Jackson Unit
5931803	Brazos	124JCKS	N	Y	na	layer could not be conclusively determined
5931804	Brazos	124JCKS	N	Y	na	layer could not be conclusively determined
5931805	Brazos	124JCKS	N	Y	1	Upper Jackson Unit
5938202	Brazos	124JCKS	N	Y	2	Lower Jackson Unit
5938925	Brazos	124YEGU	N	Y	na	layer could not be conclusively determined
5939110	Brazos	124YEGU	N	Y	na	layer could not be conclusively determined
5939401	Brazos	124JCKS	N	Y	1	Upper Jackson Unit
5939402	Brazos	124JCKS	N	Y	1	Upper Jackson Unit
5939403	Brazos	124JCKS	N	Y	1	Upper Jackson Unit
5939404	Brazos	124JCKS	N	Y	1	Upper Jackson Unit
5939505	Brazos	124JCKS	N	Y	1	Upper Jackson Unit
5939507	Brazos	124JCKS	N	Y	na	elevation of well base above top of Upper Jackson Unit

State Well Number	County	Aquifer Code in TWDB Database	Screen Interval Available(1)	Well Depth Available(1)	Model Layer (2)	Description
5939712	Brazos	124YEGU	N	Y	na	layer could not be conclusively determined
5928508	Burleson	124YEGU	N	Y	4	Lower Yegua Unit
5928801	Burleson	124YEGU	N	Y	4	Lower Yegua Unit
5928902	Burleson	124YEGU	N	Y	4	Lower Yegua Unit
5928904	Burleson	124YEGU	N	Y	4	Lower Yegua Unit
5928907	Burleson	124YEGU	N	Y	4	Lower Yegua Unit
5928909	Burleson	124YEGU	N	Y	na	layer could not be conclusively determined
5929450	Burleson	124YEGU	N	Y	4	Lower Yegua Unit
5929731	Burleson	124YEGU	N	Y	na	layer could not be conclusively determined
5934902	Burleson	124YEGU	N	Y	na	well plots outside of boundary of Yegua-Jackson Aquifer
5935304	Burleson	124YEGU	N	Y	4	Lower Yegua Unit
5935501	Burleson	124YEGU	N	Y	4	Lower Yegua Unit
5935502	Burleson	124YEGU	N	Y	4	Lower Yegua Unit
5935603	Burleson	124YEGU	N	Y	4	Lower Yegua Unit
5935604	Burleson	124YEGU	N	Y	4	Lower Yegua Unit
5935605	Burleson	124YEGU	N	Y	4	Lower Yegua Unit
5935802	Burleson	124YEGU	N	Y	na	layer could not be conclusively determined
5935803	Burleson	124YEGU	N	Y	4	Lower Yegua Unit
5935901	Burleson	124YEGU	N	Y	na	layer could not be conclusively determined
5935902	Burleson	124YEGU	N	Y	na	layer could not be conclusively determined
5935903	Burleson	124YEGU	N	Y	na	layer could not be conclusively determined
5935906	Burleson	124YEGU	N	Y	3	Upper Yegua Unit
5936201	Burleson	124YEGU	N	Y	na	layer could not be conclusively determined
5936202	Burleson	124YEGU	N	Y	na	layer could not be conclusively determined
5936203	Burleson	124YEGU	N	Y	4	Lower Yegua Unit
5936204	Burleson	124YEGU	N	Y	na	layer could not be conclusively determined
5936206	Burleson	124YEGU	N	Y	4	Lower Yegua Unit
5936301	Burleson	124YEGU	N	Y	3	Upper Yegua Unit
5936302	Burleson	124YEGU	N	Y	na	layer could not be conclusively determined
5936303	Burleson	124YEGU	N	Y	na	layer could not be conclusively determined
5936601	Burleson	124YEGU	N	Y	3	Upper Yegua Unit
5936602	Burleson	124YEGU	N	Y	3	Upper Yegua Unit
5936603	Burleson	124YEGU	N	Y	3	Upper Yegua Unit
5936701	Burleson	124YEGU	N	Y	na	layer could not be conclusively determined
5936702	Burleson	124YEGU	N	Y	na	layer could not be

State Well Number	County	Aquifer Code in TWDB Database	Screen Interval Available[(1)]	Well Depth Available[(1)]	Model Layer [(2)]	Description
						conclusively determined
5936703	Burleson	124YEGU	N	Y	na	layer could not be conclusively determined
5936704	Burleson	124YEGU	N	Y	na	layer could not be conclusively determined
5936706	Burleson	124YEGU	N	Y	3	Upper Yegua Unit
5936801	Burleson	124YEGU	N	Y	3	Upper Yegua Unit
5936803	Burleson	124YEGU	N	Y	3	Upper Yegua Unit
5936804	Burleson	124YEGU	N	Y	na	layer could not be conclusively determined
5936901	Burleson	124YEGU	N	Y	3	Upper Yegua Unit
5936902	Burleson	124YEGU	N	Y	3	Upper Yegua Unit
5936903	Burleson	124YEGU	N	Y	3	Upper Yegua Unit
5936904	Burleson	124YEGU	N	Y	3	Upper Yegua Unit
5937109	Burleson	124YEGU	N	Y	3	Upper Yegua Unit
5937110	Burleson	124YEGU	N	Y	3	Upper Yegua Unit
5937111	Burleson	124YEGU	N	Y	3	Upper Yegua Unit
5937112	Burleson	124YEGU	Y	Y	na	elevation of screened interval below base of Lower Yegua Unit
5937209	Burleson	124YEGU	N	Y	3	Upper Yegua Unit
5937402	Burleson	124YEGU	N	Y	3	Upper Yegua Unit
5937501	Burleson	124YEGU	N	Y	3	Upper Yegua Unit
5937502	Burleson	124JCKS	N	Y	2	Lower Jackson Unit
5937503	Burleson	124YEGU	N	Y	3	Upper Yegua Unit
5937609	Burleson	124YEGU	N	Y	3	Upper Yegua Unit
5937611	Burleson	124JCKS	Y	Y	2	Lower Jackson Unit
5937802	Burleson	124YEGU	N	Y	3	Upper Yegua Unit
5937803	Burleson	124JCKS	N	Y	na	layer could not be conclusively determined
5937804	Burleson	124JCKS	N	Y	1	Upper Jackson Unit
5937901	Burleson	124JCKS	N	Y	1	Upper Jackson Unit
5938706	Burleson	124JCKS	N	Y	1	Upper Jackson Unit
5943101	Burleson	124YEGU	N	Y	4	Lower Yegua Unit
5943103	Burleson	124YEGU	Y	Y	4 & below	Lower Yegua Unit & underlying unit
5943202	Burleson	124YEGU	N	Y	na	layer could not be conclusively determined
5943204	Burleson	124YEGU	N	Y	3	Upper Yegua Unit
5943404	Burleson	124YEGU	N	Y	4	Lower Yegua Unit
5943602	Burleson	124JCKS	N	Y	na	layer could not be conclusively determined
5943604	Burleson	124YEGU	Y	Y	3 & 4	Upper & Lower Yegua Units
5943608	Burleson	124YEGU	Y	Y	4	Lower Yegua Unit
5944101	Burleson	124JCKS	N	Y	na	layer could not be conclusively determined
5944103	Burleson	124YEGU	N	Y	3	Upper Yegua Unit
5944104	Burleson	124JCKS	N	Y	2	Lower Jackson Unit

State Well Number	County	Aquifer Code in TWDB Database	Screen Interval Available(1)	Well Depth Available(1)	Model Layer (2)	Description
5944105	Burleson	124JCKS	N	Y	na	layer could not be conclusively determined
5944107	Burleson	124JCKS	N	Y	na	layer could not be conclusively determined
5944108	Burleson	124YEGU	N	Y	3	Upper Yegua Unit
5944110	Burleson	124YEGU	N	Y	3	Upper Yegua Unit
5944201	Burleson	124JCKS	N	Y	2	Lower Jackson Unit
5944303	Burleson	124JCKS	N	Y	2	Lower Jackson Unit
5944307	Burleson	124YEGU	N	Y	3	Upper Yegua Unit
5944308	Burleson	124JCKS	N	Y	2	Lower Jackson Unit
5944309	Burleson	124JCKS	N	Y	1	Upper Jackson Unit
5944401	Burleson	124JCKS	N	Y	2	Lower Jackson Unit
5944402	Burleson	124JCKS	N	Y	na	layer could not be conclusively determined
5945101	Burleson	124JCKS	N	Y	na	layer could not be conclusively determined
5945201	Burleson	124JCKS	N	Y	1	Upper Jackson Unit
5945202	Burleson	124JCKS	N	N	1	Upper Jackson Unit
5945203	Burleson	124JCKS	N	Y	1	Upper Jackson Unit
6759502	De Witt	124JCKS	Y	Y	na	elevation of screened interval above top of Upper Jackson Unit
5864809	Fayette	124YEGU	N	Y	na	well plots outside of boundary of Yegua-Jackson Aquifer
5864901	Fayette	124YEGU	N	Y	4	Lower Yegua Unit
5864904	Fayette	124YEGU	N	Y	4	Lower Yegua Unit
5950902	Fayette	124JCKS	N	Y	na	layer could not be conclusively determined
5950906	Fayette	124YEGU	Y	Y	2	Lower Jackson Unit
5950907	Fayette	124YEGU	Y	Y	2 & 3	Lower Jackson Unit & Upper Yegua Unit
5950908	Fayette	124JCKS	N	Y	1	Upper Jackson Unit
5957401	Fayette	124YEGU	N	Y	3	Upper Yegua Unit
5957503	Fayette	124YEGU	N	Y	3	Upper Yegua Unit
5957601	Fayette	124YEGU	Y	Y	3	Upper Yegua Unit
5957604	Fayette	124JCKS	N	Y	2	Lower Jackson Unit
5957607	Fayette	124JCKS	N	Y	na	layer could not be conclusively determined
5957701	Fayette	124YEGU	Y	Y	3	Upper Yegua Unit
5957803	Fayette	124JCKS	N	Y	na	layer could not be conclusively determined
5957804	Fayette	124JCKS	Y	Y	3 & 4	Upper & Lower Yegua Units
5957805	Fayette	124JCKS	N	Y	na	layer could not be conclusively determined
5957901	Fayette	124JCKS	Y	Y	3	Upper Yegua Unit
5957903	Fayette	124JCKS	N	Y	na	layer could not be conclusively determined
5957904	Fayette	124YEGU	N	Y	3	Upper Yegua Unit
5957905	Fayette	124YEGU	Y	Y	3	Upper Yegua Unit

State Well Number	County	Aquifer Code in TWDB Database	Screen Interval Available(1)	Well Depth Available(1)	Model Layer (2)	Description
5957906	Fayette	124YEGU	Y	Y	3	Upper Yegua Unit
5958101	Fayette	124YEGU	N	Y	3	Upper Yegua Unit
5958102	Fayette	124JCKS	N	Y	2	Lower Jackson Unit
5958204	Fayette	124JCKS	N	Y	1	Upper Jackson Unit
5958205	Fayette	124JCKS	N	Y	1	Upper Jackson Unit
5958301	Fayette	124JCKS	N	Y	1	Upper Jackson Unit
5958302	Fayette	124JCKS	N	Y	na	elevation of well base above top of Upper Jackson Unit
5958303	Fayette	124JCKS	N	Y	1	Upper Jackson Unit
5958502	Fayette	124JCKS	N	Y	na	layer could not be conclusively determined
5958503	Fayette	124JCKS	N	Y	1	Upper Jackson Unit
5958505	Fayette	124JCKS	N	Y	1	Upper Jackson Unit
5958506	Fayette	124JCKS	Y	Y	2	Lower Jackson Unit
5958704	Fayette	124JCKS	N	Y	1	Upper Jackson Unit
6601105	Fayette	124JCKS	N	Y	2	Lower Jackson Unit
6601203	Fayette	124JCKS	N	Y	na	layer could not be conclusively determined
6601302	Fayette	124JCKS	N	Y	1	Upper Jackson Unit
6601403	Fayette	124YEGU	N	Y	na	layer could not be conclusively determined
6601407	Fayette	124YEGU	Y	Y	3	Upper Yegua Unit
6601412	Fayette	124YEGU	N	Y	na	layer could not be conclusively determined
6601413	Fayette	124YEGU	N	Y	na	layer could not be conclusively determined
6601414	Fayette	124YEGU	N	Y	na	layer could not be conclusively determined
6601606	Fayette	124JCKS	N	Y	1	Upper Jackson Unit
6601609	Fayette	124JCKS	N	Y	1	Upper Jackson Unit
6601610	Fayette	124JCKS	N	Y	1	Upper Jackson Unit
6601701	Fayette	124JCKS	N	Y	na	layer could not be conclusively determined
6601805	Fayette	124JCKS	N	Y	1	Upper Jackson Unit
6601806	Fayette	124JCKS	N	Y	1	Upper Jackson Unit
6601902	Fayette	124JCKS	Y	Y	1	Upper Jackson Unit
6601905	Fayette	124JCKS	Y	Y	1	Upper Jackson Unit
6602103	Fayette	124JCKS	N	Y	1	Upper Jackson Unit
6602401	Fayette	124JCKS	N	Y	1	Upper Jackson Unit
6609102	Fayette	124JCKS	Y	Y	1	Upper Jackson Unit
6609105	Fayette	124JCKS	N	Y	1	Upper Jackson Unit
6609106	Fayette	124JCKS	N	Y	1	Upper Jackson Unit
6617614	Fayette	124JCKS	Y	Y	1	Upper Jackson Unit
6617616	Fayette	124JCKS	Y	Y	1	Upper Jackson Unit
6617617	Fayette	124JCKS	Y	Y	1	Upper Jackson Unit
6707802	Fayette	124YEGU	N	Y	na	well plots outside of boundary of Yegua-Jackson Aquifer
6707902	Fayette	124YEGU	N	Y	4	Lower Yegua Unit

State Well Number	County	Aquifer Code in TWDB Database	Screen Interval Available(1)	Well Depth Available(1)	Model Layer (2)	Description
6707903	Fayette	124YEGU	N	Y	na	well plots outside of boundary of Yegua-Jackson Aquifer
6708202	Fayette	124YEGU	N	Y	4	Lower Yegua Unit
6708303	Fayette	124YEGU	N	Y	4	Lower Yegua Unit
6708404	Fayette	124YEGU	N	Y	4	Lower Yegua Unit
6708501	Fayette	124YEGU	N	Y	3	Upper Yegua Unit
6708504	Fayette	124YEGU	N	Y	3	Upper Yegua Unit
6708601	Fayette	124YEGU	N	Y	3	Upper Yegua Unit
6708603	Fayette	124YEGU	N	Y	na	layer could not be conclusively determined
6708605	Fayette	124YEGU	N	Y	3	Upper Yegua Unit
6708607	Fayette	124YEGU	N	Y	3	Upper Yegua Unit
6708703	Fayette	124YEGU	N	Y	4	Lower Yegua Unit
6708706	Fayette	124YEGU	N	N	na	no screen or well depth data available to determine model layer
6708707	Fayette	124YEGU	N	Y	na	layer could not be conclusively determined
6708801	Fayette	124YEGU	N	Y	na	layer could not be conclusively determined
6708802	Fayette	124YEGU	N	Y	3	Upper Yegua Unit
6708902	Fayette	124YEGU	N	Y	na	layer could not be conclusively determined
6708903	Fayette	124YEGU	N	Y	na	layer could not be conclusively determined
6708904	Fayette	124YEGU	N	Y	3	Upper Yegua Unit
6708905	Fayette	124JCKS	N	Y	2	Lower Jackson Unit
6715305	Fayette	124YEGU	N	Y	4	Lower Yegua Unit
6715306	Fayette	124YEGU	N	Y	3	Upper Yegua Unit
6715307	Fayette	124YEGU	N	Y	na	layer could not be conclusively determined
6715505	Fayette	124YEGU	N	Y	na	layer could not be conclusively determined
6715601	Fayette	124YEGU	N	Y	3	Upper Yegua Unit
6715604	Fayette	124YEGU	N	Y	3	Upper Yegua Unit
6715605	Fayette	124YEGU	N	N	3	Upper Yegua Unit
6716101	Fayette	124YEGU	N	Y	3	Upper Yegua Unit
6716201	Fayette	124YEGU	N	Y	na	layer could not be conclusively determined
6716202	Fayette	124YEGU	Y	Y	2	Lower Jackson Unit
6716302	Fayette	124YEGU	Y	Y	3	Upper Yegua Unit
6716304	Fayette	124YEGU	N	Y	na	layer could not be conclusively determined
6716305	Fayette	124JCKS	N	Y	na	layer could not be conclusively determined
6716401	Fayette	124YEGU	N	Y	3	Upper Yegua Unit
6716402	Fayette	124YEGU	N	Y	3	Upper Yegua Unit
6716403	Fayette	124YEGU	N	Y	3	Upper Yegua Unit
6716405	Fayette	124YEGU	N	Y	na	layer could not be

State Well Number	County	Aquifer Code in TWDB Database	Screen Interval Available(1)	Well Depth Available(1)	Model Layer (2)	Description
						conclusively determined
6716501	Fayette	124YEGU	N	Y	3	Upper Yegua Unit
6716503	Fayette	124YEGU	Y	Y	3	Upper Yegua Unit
6716504	Fayette	124YEGU	Y	Y	3	Upper Yegua Unit
6716507	Fayette	124YEGU	N	Y	na	layer could not be conclusively determined
6716604	Fayette	124JCKS	N	Y	1	Upper Jackson Unit
6716704	Fayette	124JCKS	N	Y	na	layer could not be conclusively determined
6716705	Fayette	124JCKS	N	Y	na	layer could not be conclusively determined
6716803	Fayette	124JCKS	N	Y	1	Upper Jackson Unit
6716904	Fayette	124JCKS	N	Y	1	Upper Jackson Unit
6723101	Fayette	124JCKS	N	Y	na	layer could not be conclusively determined
6723205	Fayette	124JCKS	N	Y	na	layer could not be conclusively determined
6723305	Fayette	124YEGU	N	Y	na	layer could not be conclusively determined
6723306	Fayette	124YEGU	N	Y	3	Upper Yegua Unit
6723507	Fayette	124JCKS	N	Y	2	Lower Jackson Unit
6723508	Fayette	124JCKS	N	Y	2	Lower Jackson Unit
6723603	Fayette	124JCKS	N	Y	na	layer could not be conclusively determined
6723604	Fayette	124YGJK	Y	Y	2	Lower Jackson Unit
6723608	Fayette	124JCKS	N	Y	1	Upper Jackson Unit
6723609	Fayette	124JCKS	N	Y	na	layer could not be conclusively determined
6724101	Fayette	124YGJK	Y	Y	2	Lower Jackson Unit
6724104	Fayette	124JCKS	N	Y	na	layer could not be conclusively determined
6724105	Fayette	124JCKS	N	Y	1	Upper Jackson Unit
6724106	Fayette	124JCKS	N	Y	1	Upper Jackson Unit
6724205	Fayette	124JCKS	N	Y	1	Upper Jackson Unit
6724401	Fayette	124JCKS	Y	Y	1 & 2	Upper & Lower Jackson Units
6724404	Fayette	124JCKS	N	Y	na	layer could not be conclusively determined
6724412	Fayette	124JCKS	Y	Y	2	Lower Jackson Unit
6724413	Fayette	124JCKS	Y	Y	2	Lower Jackson Unit
6724416	Fayette	124JCKS	N	Y	na	layer could not be conclusively determined
6722906	Gonzales	124YEGU	N	Y	na	layer could not be conclusively determined
6729802	Gonzales	124YEGU	N	Y	4	Lower Yegua Unit
6729804	Gonzales	124YEGU	N	Y	4	Lower Yegua Unit
6730404	Gonzales	124YEGU	N	Y	4	Lower Yegua Unit
6730601	Gonzales	124JCKS	Y	Y	2	Lower Jackson Unit
6730602	Gonzales	124YEGU	Y	Y	2	Lower Jackson Unit
6731403	Gonzales	124JCKS	Y	Y	2	Lower Jackson Unit

State Well Number	County	Aquifer Code in TWDB Database	Screen Interval Available[(1)]	Well Depth Available[(1)]	Model Layer [(2)]	Description
6731404	Gonzales	124JCKS	Y	Y	2	Lower Jackson Unit
6731405	Gonzales	124YEGU	N	Y	na	layer could not be conclusively determined
6731407	Gonzales	124JCKS	Y	Y	1	Upper Jackson Unit
6731701	Gonzales	124JCKS	N	Y	1	Upper Jackson Unit
6731703	Gonzales	124JCKS	N	Y	1	Upper Jackson Unit
6737303	Gonzales	124YEGU	Y	Y	3	Upper Yegua Unit
6737304	Gonzales	124YEGU	N	Y	na	layer could not be conclusively determined
6737402	Gonzales	124YEGU	N	Y	4	Lower Yegua Unit
6737501	Gonzales	124YEGU	N	Y	3	Upper Yegua Unit
6737602	Gonzales	124YEGU	N	Y	3	Upper Yegua Unit
6738102	Gonzales	124YEGU	N	N	na	no screen or well depth data available to determine model layer
6738601	Gonzales	124JCKS	N	Y	na	elevation of well base above top of Upper Jackson Unit
6744301	Gonzales	124YEGU	N	Y	3	Upper Yegua Unit
6744601	Gonzales	124YEGU	N	Y	3	Upper Yegua Unit
6745301	Gonzales	124JCKS	N	Y	1	Upper Jackson Unit
6752401	Gonzales	124JCKS	N	Y	1	Upper Jackson Unit
6752502	Gonzales	124JCKS	N	Y	1	Upper Jackson Unit
5915602	Grimes	124YEGU	N	Y	4	Lower Yegua Unit
5916402	Grimes	124YEGU	N	Y	3	Upper Yegua Unit
5916403	Grimes	124YEGU	N	Y	na	layer could not be conclusively determined
5916404	Grimes	124YEGU	N	Y	na	layer could not be conclusively determined
5916501	Grimes	124YEGU	N	Y	3	Upper Yegua Unit
5916502	Grimes	124YEGU	N	Y	na	layer could not be conclusively determined
5916801	Grimes	124YEGU	N	Y	3	Upper Yegua Unit
5916802	Grimes	124YEGU	N	Y	3	Upper Yegua Unit
5916803	Grimes	124YEGU	N	Y	na	layer could not be conclusively determined
5916804	Grimes	124YEGU	N	Y	3	Upper Yegua Unit
5916806	Grimes	124YEGU	N	Y	na	layer could not be conclusively determined
5916901	Grimes	124YEGU	N	Y	3	Upper Yegua Unit
5916902	Grimes	124YEGU	N	Y	3	Upper Yegua Unit
5924203	Grimes	124YEGU	Y	Y	4	Lower Yegua Unit
5924301	Grimes	124YEGU	N	Y	3	Upper Yegua Unit
5924402	Grimes	124YEGU	Y	Y	2 & 3	Lower Jackson Unit & Upper Yegua Unit
5924403	Grimes	124YEGU	N	Y	3	Upper Yegua Unit
5924404	Grimes	124YEGU	Y	Y	3	Upper Yegua Unit
5924501	Grimes	124YEGU	N	Y	na	layer could not be conclusively determined
5924601	Grimes	124YEGU	N	Y	na	layer could not be

State Well Number	County	Aquifer Code in TWDB Database	Screen Interval Available(1)	Well Depth Available(1)	Model Layer (2)	Description
						conclusively determined
5924702	Grimes	124YEGU	Y	Y	2	Lower Jackson Unit
5924703	Grimes	124YEGU	Y	Y	2	Lower Jackson Unit
5924801	Grimes	124JCKS	N	Y	2	Lower Jackson Unit
5924902	Grimes	124JCKS	N	Y	2	Lower Jackson Unit
5932201	Grimes	124JCKS	N	Y	1	Upper Jackson Unit
5932501	Grimes	124JCKS	N	Y	1	Upper Jackson Unit
5932601	Grimes	124JCKS	N	Y	na	elevation of well base above top of Upper Jackson Unit
5932701	Grimes	124JCKS	Y	Y	1	Upper Jackson Unit
5932705	Grimes	124JCKS	N	Y	1	Upper Jackson Unit
5932706	Grimes	124JCKS	N	Y	na	layer could not be conclusively determined
5932801	Grimes	124JCKS	N	Y	na	elevation of well base above top of Upper Jackson Unit
5932802	Grimes	124JCKS	N	Y	1	Upper Jackson Unit
5940102	Grimes	124JCKS	N	Y	na	elevation of well base above top of Upper Jackson Unit
5940201	Grimes	124JCKS	N	Y	na	elevation of well base above top of Upper Jackson Unit
5940202	Grimes	124JCKS	N	Y	na	elevation of well base above top of Upper Jackson Unit
5940203	Grimes	124JCKS	N	Y	na	elevation of well base above top of Upper Jackson Unit
6009201	Grimes	124YEGU	N	Y	3	Upper Yegua Unit
6009401	Grimes	124YEGU	N	Y	na	layer could not be conclusively determined
6009501	Grimes	124YEGU	N	Y	na	layer could not be conclusively determined
6009502	Grimes	124YEGU	Y	Y	3	Upper Yegua Unit
6009601	Grimes	124YEGU	N	Y	3	Upper Yegua Unit
6009702	Grimes	124YEGU	N	Y	na	layer could not be conclusively determined
6009703	Grimes	124YEGU	N	Y	3	Upper Yegua Unit
6009704	Grimes	124YEGU	N	Y	na	layer could not be conclusively determined
6009801	Grimes	124YEGU	N	Y	3	Upper Yegua Unit
6009803	Grimes	124YEGU	Y	Y	2	Lower Jackson Unit
6009804	Grimes	124YEGU	N	Y	na	layer could not be conclusively determined
6009805	Grimes	124YEGU	N	Y	na	layer could not be conclusively determined
6010401	Grimes	124YEGU	N	Y	3	Upper Yegua Unit
6010402	Grimes	124YEGU	Y	Y	2	Lower Jackson Unit
6017101	Grimes	124YEGU	N	Y	na	layer could not be conclusively determined
6017201	Grimes	124JCKS	Y	Y	1	Upper Jackson Unit
6017301	Grimes	124JCKS	N	Y	1	Upper Jackson Unit

State Well Number	County	Aquifer Code in TWDB Database	Screen Interval Available[1]	Well Depth Available[1]	Model Layer [2]	Description
6017302	Grimes	124JCKS	N	Y	na	layer could not be conclusively determined
6017401	Grimes	124JCKS	N	Y	na	layer could not be conclusively determined
6017403	Grimes	124JCKS	N	Y	1	Upper Jackson Unit
6017501	Grimes	124JCKS	N	Y	1	Upper Jackson Unit
6017601	Grimes	124JCKS	N	Y	1	Upper Jackson Unit
6017801	Grimes	124JCKS	N	Y	1	Upper Jackson Unit
6017802	Grimes	124JCKS	N	Y	1	Upper Jackson Unit
6017803	Grimes	124JCKS	N	Y	1	Upper Jackson Unit
6017901	Grimes	124JCKS	N	Y	1	Upper Jackson Unit
6018101	Grimes	124JCKS	N	Y	1	Upper Jackson Unit
6018402	Grimes	124JCKS	Y	Y	na	elevation of screened interval above top of Upper Jackson Unit
6025201	Grimes	124JCKS	Y	Y	na	elevation of screened interval above top of Upper Jackson Unit
6025506	Grimes	124JCKS	Y	Y	1	Upper Jackson Unit
6025702	Grimes	124JCKS	N	Y	na	elevation of well base above top of Upper Jackson Unit
6025703	Grimes	124JCKS	N	Y	na	elevation of well base above top of Upper Jackson Unit
6025805	Grimes	124JCKS	N	Y	1	Upper Jackson Unit
3852705	Houston	124YEGU	N	Y	4	Lower Yegua Unit
3853701	Houston	124YEGU	N	Y	3	Upper Yegua Unit
3855101	Houston	124YEGU	Y	Y	3	Upper Yegua Unit
6750602	Karnes	124YEGU	N	Y	3	Upper Yegua Unit
6750801	Karnes	124YEGU	N	Y	na	layer could not be conclusively determined
6750802	Karnes	124YEGU	N	Y	3	Upper Yegua Unit
6750903	Karnes	124YEGU	N	Y	3	Upper Yegua Unit
6750904	Karnes	124YEGU	N	Y	3	Upper Yegua Unit
6750905	Karnes	124YEGU	N	Y	na	layer could not be conclusively determined
6750906	Karnes	124YEGU	N	Y	3	Upper Yegua Unit
6750907	Karnes	124YEGU	N	Y	3	Upper Yegua Unit
6750908	Karnes	124YEGU	N	Y	3	Upper Yegua Unit
6750909	Karnes	124YEGU	N	Y	3	Upper Yegua Unit
6750910	Karnes	124YEGU	N	Y	3	Upper Yegua Unit
6750911	Karnes	124YEGU	N	Y	3	Upper Yegua Unit
6751402	Karnes	124YEGU	N	Y	na	layer could not be conclusively determined
6751403	Karnes	124YEGU	N	Y	3	Upper Yegua Unit
6751503	Karnes	124JCKS	N	Y	na	layer could not be conclusively determined
6757502	Karnes	124YEGU	N	Y	na	layer could not be conclusively determined
6757503	Karnes	124YEGU	N	Y	3	Upper Yegua Unit

State Well Number	County	Aquifer Code in TWDB Database	Screen Interval Available[(1)]	Well Depth Available[(1)]	Model Layer [(2)]	Description
6757801	Karnes	124JCKS	N	Y	na	layer could not be conclusively determined
6757802	Karnes	124JCKS	N	Y	na	layer could not be conclusively determined
6757804	Karnes	124JCKS	N	Y	na	layer could not be conclusively determined
6757901	Karnes	124JCKS	N	Y	1	Upper Jackson Unit
6757902	Karnes	124JCKS	N	Y	2	Lower Jackson Unit
6758101	Karnes	124YEGU	N	Y	3	Upper Yegua Unit
6758102	Karnes	124YEGU	N	Y	3	Upper Yegua Unit
6758103	Karnes	124YEGU	N	Y	na	layer could not be conclusively determined
6758301	Karnes	124JCKS	N	Y	2	Lower Jackson Unit
6758302	Karnes	124JCKS	N	Y	2	Lower Jackson Unit
6758303	Karnes	124JCKS	N	N	na	no screen or well depth data available to determine model layer
6758304	Karnes	124JCKS	N	Y	na	layer could not be conclusively determined
6758305	Karnes	124JCKS	N	Y	2	Lower Jackson Unit
6758306	Karnes	124JCKS	N	N	na	no screen or well depth data available to determine model layer
6758401	Karnes	124YEGU	Y	Y	3	Upper Yegua Unit
6758402	Karnes	124JCKS	N	Y	2	Lower Jackson Unit
6758403	Karnes	124JCKS	N	Y	1	Upper Jackson Unit
6758502	Karnes	124JCKS	N	Y	1	Upper Jackson Unit
6758503	Karnes	124JCKS	N	Y	1	Upper Jackson Unit
6758601	Karnes	124JCKS	N	N	1	Upper Jackson Unit
6758703	Karnes	124JCKS	N	N	na	no screen or well depth data available to determine model layer
6759101	Karnes	124JCKS	N	N	1	Upper Jackson Unit
7807604	Karnes	124JCKS	N	Y	na	layer could not be conclusively determined
7807904	Karnes	124JCKS	N	Y	2	Lower Jackson Unit
7808205	Karnes	124JCKS	N	Y	na	layer could not be conclusively determined
7808305	Karnes	124JCKS	N	Y	2	Lower Jackson Unit
7808402	Karnes	124JCKS	N	Y	na	layer could not be conclusively determined
7808403	Karnes	124JCKS	N	N	na	no screen or well depth data available to determine model layer
7808501	Karnes	124JCKS	N	Y	na	layer could not be conclusively determined
7808502	Karnes	124JCKS	N	Y	1	Upper Jackson Unit
7808504	Karnes	124JCKS	N	Y	1	Upper Jackson Unit
7808604	Karnes	124JCKS	N	Y	1	Upper Jackson Unit
7808605	Karnes	124JCKS	N	Y	1	Upper Jackson Unit

State Well Number	County	Aquifer Code in TWDB Database	Screen Interval Available(1)	Well Depth Available(1)	Model Layer (2)	Description
7808606	Karnes	124JCKS	N	Y	1	Upper Jackson Unit
7808705	Karnes	124JCKS	N	Y	na	layer could not be conclusively determined
7808801	Karnes	124JCKS	N	Y	1	Upper Jackson Unit
7808803	Karnes	124JCKS	N	Y	1	Upper Jackson Unit
7815302	Karnes	124YEGU	Y	Y	1	Upper Jackson Unit
7815303	Karnes	124JCKS	N	Y	na	elevation of well base above top of Upper Jackson Unit
7816103	Karnes	124JCKS	N	N	na	no screen or well depth data available to determine model layer
7816201	Karnes	124JCKS	Y	Y	1	Upper Jackson Unit
7816402	Karnes	124JCKS	Y	Y	1	Upper Jackson Unit
7816803	Karnes	124JCKS	Y	Y	1	Upper Jackson Unit
7901101	Karnes	124JCKS	N	Y	na	layer could not be conclusively determined
7901103	Karnes	124JCKS	N	Y	1	Upper Jackson Unit
7901104	Karnes	124JCKS	N	Y	1	Upper Jackson Unit
7901204	Karnes	124JCKS	N	Y	1	Upper Jackson Unit
7901302	Karnes	124JCKS	N	Y	1	Upper Jackson Unit
7901401	Karnes	124JCKS	N	Y	1	Upper Jackson Unit
7901403	Karnes	124JCKS	N	Y	1	Upper Jackson Unit
7909401	Karnes	124JCKS	Y	Y	na	elevation of screened interval above top of Upper Jackson Unit
7763301	La Salle	124YEGU	Y	Y	4 & below	Lower Yegua Unit & underlying unit
7764201	La Salle	124YEGU	Y	Y	3 & 4	Upper & Lower Yegua Units
7764402	La Salle	124YEGU	Y	Y	4	Lower Yegua Unit
7764502	La Salle	124YEGU	N	Y	na	layer could not be conclusively determined
6739301	Lavaca	124JCKS	N	Y	na	layer could not be conclusively determined
5950401	Lee	124YEGU	Y	Y	3 & 4	Upper & Lower Yegua Units
5951102	Lee	124JCKS	Y	Y	3	Upper Yegua Unit
5957201	Lee	124YEGU	Y	Y	3	Upper Yegua Unit
7823601	Live Oak	124JCKS	N	Y	1	Upper Jackson Unit
7823801	Live Oak	124JCKS	N	Y	1	Upper Jackson Unit
7823902	Live Oak	124JCKS	N	Y	1	Upper Jackson Unit
7823904	Live Oak	124JCKS	N	Y	1	Upper Jackson Unit
7824101	Live Oak	124JCKS	N	Y	1	Upper Jackson Unit
7830201	Live Oak	124JCKS	N	Y	1	Upper Jackson Unit
7830202	Live Oak	124JCKS	N	Y	1	Upper Jackson Unit
7830203	Live Oak	124JCKS	N	Y	1	Upper Jackson Unit
7830204	Live Oak	124JCKS	N	Y	1	Upper Jackson Unit
7830205	Live Oak	124JCKS	N	Y	1	Upper Jackson Unit
7830206	Live Oak	124JCKS	N	Y	1	Upper Jackson Unit
7830207	Live Oak	124JCKS	N	Y	1	Upper Jackson Unit
7830208	Live Oak	124JCKS	N	Y	1	Upper Jackson Unit

State Well Number	County	Aquifer Code in TWDB Database	Screen Interval Available[(1)]	Well Depth Available[(1)]	Model Layer [(2)]	Description
7830501	Live Oak	124JCKS	N	Y	1	Upper Jackson Unit
7830901	Live Oak	124JCKS	Y	Y	1	Upper Jackson Unit
7831102	Live Oak	124JCKS	N	N	na	no screen or well depth data available to determine model layer
7831201	Live Oak	124JCKS	N	Y	1	Upper Jackson Unit
7831202	Live Oak	124JCKS	N	Y	1	Upper Jackson Unit
7831301	Live Oak	124JCKS	N	Y	na	elevation of well base above top of Upper Jackson Unit
5908903	Madison	124YEGU	Y	Y	4	Lower Yegua Unit
5908904	Madison	124YEGU	Y	Y	4	Lower Yegua Unit
5916101	Madison	124YEGU	N	Y	4	Lower Yegua Unit
6002401	Madison	124YEGU	N	Y	3	Upper Yegua Unit
6003102	Madison	124YEGU	Y	Y	3	Upper Yegua Unit
6003501	Madison	124YEGU	Y	Y	3	Upper Yegua Unit
7830702	McMullen	124JCKS	N	Y	1	Upper Jackson Unit
7834301	McMullen	124YEGU	N	Y	na	layer could not be conclusively determined
7834302	McMullen	124YEGU	N	Y	na	layer could not be conclusively determined
7834303	McMullen	124YEGU	N	Y	na	layer could not be conclusively determined
7835401	McMullen	124YEGU	N	N	3	Upper Yegua Unit
7836801	McMullen	124JCKS	N	Y	1	Upper Jackson Unit
7836802	McMullen	124JCKS	N	N	na	no screen or well depth data available to determine model layer
7837202	McMullen	124JCKS	N	Y	1	Upper Jackson Unit
7837303	McMullen	124JCKS	N	Y	1	Upper Jackson Unit
7844401	McMullen	124JCKS	N	Y	1	Upper Jackson Unit
7844402	McMullen	124JCKS	N	Y	1	Upper Jackson Unit
7844501	McMullen	124JCKS	N	Y	1	Upper Jackson Unit
7852201	McMullen	124JCKS	N	Y	1	Upper Jackson Unit
3745202	Nacogdoches	124YEGU	Y	Y	4	Lower Yegua Unit
3746402	Nacogdoches	124YEGU	N	Y	4	Lower Yegua Unit
3757701	Polk	124JCKS	N	Y	1	Upper Jackson Unit
3757702	Polk	124JCKS	N	Y	1	Upper Jackson Unit
3757802	Polk	124JCKS	N	Y	na	elevation of well base above top of Upper Jackson Unit
3758101	Polk	124JCKS	N	Y	1	Upper Jackson Unit
3758104	Polk	124YEGU	N	Y	na	layer could not be conclusively determined
3758105	Polk	124JCKS	N	Y	1	Upper Jackson Unit
3758106	Polk	124YEGU	N	Y	3	Upper Yegua Unit
3758201	Polk	124JCKS	N	Y	1	Upper Jackson Unit
3758202	Polk	124JCKS	N	Y	1	Upper Jackson Unit
3758203	Polk	124JCKS	N	Y	1	Upper Jackson Unit

State Well Number	County	Aquifer Code in TWDB Database	Screen Interval Available[(1)]	Well Depth Available[(1)]	Model Layer [(2)]	Description
3758204	Polk	124JCKS	N	Y	na	elevation of well base above top of Upper Jackson Unit
3758205	Polk	124JCKS	N	Y	1	Upper Jackson Unit
3758303	Polk	124JCKS	N	Y	1	Upper Jackson Unit
3758305	Polk	124JCKS	N	Y	1	Upper Jackson Unit
3758306	Polk	124JCKS	N	Y	1	Upper Jackson Unit
3758307	Polk	124JCKS	N	Y	1	Upper Jackson Unit
3758309	Polk	124JCKS	N	Y	1	Upper Jackson Unit
3758310	Polk	124JCKS	N	Y	1	Upper Jackson Unit
3758501	Polk	124JCKS	N	Y	1	Upper Jackson Unit
3758601	Polk	124JCKS	N	Y	1	Upper Jackson Unit
3758602	Polk	124JCKS	Y	Y	1	Upper Jackson Unit
3758702	Polk	124JCKS	N	Y	na	elevation of well base above top of Upper Jackson Unit
3758802	Polk	124JCKS	N	Y	1	Upper Jackson Unit
3758803	Polk	124JCKS	N	Y	1	Upper Jackson Unit
3758804	Polk	124JCKS	N	Y	1	Upper Jackson Unit
3758805	Polk	124JCKS	N	Y	1	Upper Jackson Unit
3758807	Polk	124JCKS	N	Y	na	elevation of well base above top of Upper Jackson Unit
3758808	Polk	124JCKS	N	Y	1	Upper Jackson Unit
3758809	Polk	124JCKS	N	Y	1	Upper Jackson Unit
3758810	Polk	124JCKS	N	Y	1	Upper Jackson Unit
3758811	Polk	124JCKS	N	Y	1	Upper Jackson Unit
3758812	Polk	124JCKS	N	Y	na	elevation of well base above top of Upper Jackson Unit
3758813	Polk	124JCKS	N	Y	1	Upper Jackson Unit
3758815	Polk	124JCKS	N	Y	na	elevation of well base above top of Upper Jackson Unit
3758817	Polk	124JCKS	N	Y	na	elevation of well base above top of Upper Jackson Unit
3758818	Polk	124JCKS	N	Y	na	elevation of well base above top of Upper Jackson Unit
3758821	Polk	124JCKS	Y	Y	1	Upper Jackson Unit
3758822	Polk	124JCKS	Y	Y	1	Upper Jackson Unit
3758823	Polk	124JCKS	Y	Y	na	elevation of screened interval above top of Upper Jackson Unit
3758904	Polk	124JCKS	Y	Y	1	Upper Jackson Unit
3759702	Polk	124JCKS	N	Y	1	Upper Jackson Unit
6101101	Polk	124JCKS	Y	Y	1	Upper Jackson Unit
6101103	Polk	124JCKS	N	Y	na	elevation of well base above top of Upper Jackson Unit
6101301	Polk	124JCKS	N	Y	na	elevation of well base above top of Upper Jackson Unit
6102108	Polk	124JCKS	Y	Y	na	elevation of screened interval above top of Upper Jackson Unit
6102202	Polk	124JCKS	Y	Y	na	elevation of screened interval

State Well Number	County	Aquifer Code in TWDB Database	Screen Interval Available(1)	Well Depth Available(1)	Model Layer (2)	Description
						above top of Upper Jackson Unit
6102203	Polk	124JCKS	Y	Y	na	elevation of screened interval above top of Upper Jackson Unit
3635702	Sabine	124YEGU	N	Y	na	well plots outside of boundary of Yegua-Jackson Aquifer
3641101	Sabine	124YEGU	N	Y	4	Lower Yegua Unit
3641202	Sabine	124YEGU	N	Y	4	Lower Yegua Unit
3641204	Sabine	124YEGU	N	Y	4	Lower Yegua Unit
3641205	Sabine	124YEGU	Y	Y	4	Lower Yegua Unit
3641206	Sabine	124YEGU	N	Y	4	Lower Yegua Unit
3641302	Sabine	124YEGU	N	Y	4	Lower Yegua Unit
3641305	Sabine	124YEGU	N	Y	4	Lower Yegua Unit
3641601	Sabine	124YEGU	Y	Y	4	Lower Yegua Unit
3641702	Sabine	124YEGU	Y	Y	4	Lower Yegua Unit
3641703	Sabine	124YEGU	N	Y	na	layer could not be conclusively determined
3641704	Sabine	124YEGU	N	Y	na	layer could not be conclusively determined
3641705	Sabine	124YEGU	N	Y	na	layer could not be conclusively determined
3641706	Sabine	124YEGU	N	Y	na	layer could not be conclusively determined
3641707	Sabine	124YEGU	Y	Y	3 & 4	Upper & Lower Yegua Units
3641802	Sabine	124YEGU	N	Y	3	Upper Yegua Unit
3642104	Sabine	124YEGU	N	Y	4	Lower Yegua Unit
3642401	Sabine	124YEGU	N	Y	4	Lower Yegua Unit
3642502	Sabine	124YEGU	N	Y	4	Lower Yegua Unit
3642702	Sabine	124YEGU	N	Y	3	Upper Yegua Unit
3642801	Sabine	124YEGU	N	Y	3	Upper Yegua Unit
3642806	Sabine	124YEGU	N	Y	3	Upper Yegua Unit
3642807	Sabine	124YEGU	N	Y	3	Upper Yegua Unit
3642809	Sabine	124JCKS	N	Y	2	Lower Jackson Unit
3642810	Sabine	124JCKS	N	Y	na	layer could not be conclusively determined
3642811	Sabine	124JCKS	N	Y	na	layer could not be conclusively determined
3643701	Sabine	124YEGU	N	Y	3	Upper Yegua Unit
3643702	Sabine	124YEGU	N	Y	3	Upper Yegua Unit
3643801	Sabine	124YEGU	N	Y	na	layer could not be conclusively determined
3643803	Sabine	124YEGU	N	Y	na	layer could not be conclusively determined
3649102	Sabine	124YEGU	N	Y	na	layer could not be conclusively determined
3649103	Sabine	124YEGU	Y	Y	3	Upper Yegua Unit
3649104	Sabine	124YEGU	N	Y	3	Upper Yegua Unit
3649106	Sabine	124YEGU	Y	Y	4	Lower Yegua Unit

State Well Number	County	Aquifer Code in TWDB Database	Screen Interval Available(1)	Well Depth Available(1)	Model Layer (2)	Description
3649109	Sabine	124YEGU	N	Y	3	Upper Yegua Unit
3649111	Sabine	124JCKS	N	Y	2	Lower Jackson Unit
3649401	Sabine	124YEGU	N	Y	3	Upper Yegua Unit
3649402	Sabine	124YEGU	N	Y	3	Upper Yegua Unit
3649705	Sabine	124JCKS	N	Y	1	Upper Jackson Unit
3649706	Sabine	124JCKS	N	Y	1	Upper Jackson Unit
3650202	Sabine	124JCKS	N	Y	2	Lower Jackson Unit
3650302	Sabine	124JCKS	N	Y	2	Lower Jackson Unit
3650305	Sabine	124JCKS	N	Y	na	layer could not be conclusively determined
3650306	Sabine	124JCKS	N	Y	2	Lower Jackson Unit
3650307	Sabine	124YEGU	Y	Y	3	Upper Yegua Unit
3651302	Sabine	124JCKS	N	Y	1	Upper Jackson Unit
3651401	Sabine	124JCKS	N	Y	1	Upper Jackson Unit
3651403	Sabine	124JCKS	N	Y	1	Upper Jackson Unit
3651404	Sabine	124JCKS	N	Y	1	Upper Jackson Unit
3651405	Sabine	124JCKS	N	Y	1	Upper Jackson Unit
3651406	Sabine	124JCKS	N	Y	1	Upper Jackson Unit
3651407	Sabine	124JCKS	N	Y	na	elevation of well base above top of Upper Jackson Unit
3651408	Sabine	124JCKS	N	Y	1	Upper Jackson Unit
3748303	Sabine	124YEGU	N	Y	4	Lower Yegua Unit
3748304	Sabine	124YEGU	N	Y	4	Lower Yegua Unit
3748602	Sabine	124YEGU	N	Y	na	layer could not be conclusively determined
3748603	Sabine	124YEGU	N	Y	na	layer could not be conclusively determined
3748604	Sabine	124YEGU	N	Y	na	layer could not be conclusively determined
3748606	Sabine	124YEGU	N	Y	3	Upper Yegua Unit
3746301	San Augustine	124YEGU	N	Y	4	Lower Yegua Unit
3746604	San Augustine	124YEGU	N	Y	na	layer could not be conclusively determined
3747403	San Augustine	124YEGU	Y	Y	4	Lower Yegua Unit
3747602	San Augustine	124YEGU	N	Y	4	Lower Yegua Unit
3747804	San Augustine	124YEGU	N	Y	3	Upper Yegua Unit
3747903	San Augustine	124YEGU	N	Y	3	Upper Yegua Unit
3748201	San Augustine	124YEGU	N	Y	4	Lower Yegua Unit
3748202	San Augustine	124YEGU	N	Y	4	Lower Yegua Unit
3748401	San Augustine	124YEGU	N	Y	3	Upper Yegua Unit
3748701	San	124YEGU	Y	Y	3	Upper Yegua Unit

State Well Number	County	Aquifer Code in TWDB Database	Screen Interval Available[(1)]	Well Depth Available[(1)]	Model Layer [(2)]	Description
	Augustine					
3754301	San Augustine	124YEGU	N	Y	na	layer could not be conclusively determined
3755101	San Augustine	124YEGU	N	Y	3	Upper Yegua Unit
3755202	San Augustine	124YEGU	N	Y	na	layer could not be conclusively determined
3755203	San Augustine	124YEGU	N	Y	na	layer could not be conclusively determined
3755205	San Augustine	124YEGU	N	Y	na	layer could not be conclusively determined
3755301	San Augustine	124YEGU	N	Y	na	layer could not be conclusively determined
8624801	Starr	124YEGU	N	Y	4	Lower Yegua Unit
8624901	Starr	124YEGU	N	Y	na	layer could not be conclusively determined
8632101	Starr	124YEGU	N	Y	4	Lower Yegua Unit
8632201	Starr	124YEGU	N	Y	4	Lower Yegua Unit
8632202	Starr	124YEGU	N	Y	4	Lower Yegua Unit
8632203	Starr	124YEGU	N	Y	4	Lower Yegua Unit
8632301	Starr	124YEGU	N	Y	na	layer could not be conclusively determined
8632302	Starr	124YEGU	N	Y	na	layer could not be conclusively determined
8632401	Starr	124YEGU	N	Y	4	Lower Yegua Unit
8632403	Starr	124YEGU	Y	Y	na	elevation of screened interval below base of Lower Yegua Unit
8632601	Starr	124YEGU	Y	Y	4	Lower Yegua Unit
8632602	Starr	124YEGU	N	Y	na	layer could not be conclusively determined
8632603	Starr	124JCKS	N	Y	na	well plots outside of boundary of Yegua-Jackson Aquifer
8632604	Starr	124JCKS	Y	Y	3	Upper Yegua Unit
8632605	Starr	124JCKS	N	Y	na	layer could not be conclusively determined
8632801	Starr	124YEGU	N	Y	4	Lower Yegua Unit
8632901	Starr	124JCKS	Y	Y	3	Upper Yegua Unit
8632903	Starr	124JCKS	Y	Y	3	Upper Yegua Unit
8632904	Starr	124JCKS	N	Y	na	layer could not be conclusively determined
8632905	Starr	124YEGU	Y	Y	3	Upper Yegua Unit
8632906	Starr	124JCKS	N	Y	na	layer could not be conclusively determined
8640201	Starr	124JCKS	N	Y	na	layer could not be conclusively determined
8640202	Starr	124JCKS	N	Y	na	layer could not be conclusively determined
8640203	Starr	124JCKS	N	Y	na	layer could not be conclusively determined

State Well Number	County	Aquifer Code in TWDB Database	Screen Interval Available(1)	Well Depth Available(1)	Model Layer (2)	Description
8640301	Starr	124YEGU	N	Y	3	Upper Yegua Unit
8640501	Starr	124YEGU	N	Y	na	layer could not be conclusively determined
8640601	Starr	124YEGU	N	Y	3	Upper Yegua Unit
8640901	Starr	124JCKS	N	Y	na	layer could not be conclusively determined
8709801	Starr	124JCKS	N	Y	na	elevation of well base above top of Upper Jackson Unit
8717101	Starr	124JCKS	N	Y	1	Upper Jackson Unit
8717202	Starr	124JCKS	N	Y	na	elevation of well base above top of Upper Jackson Unit
8717401	Starr	124JCKS	Y	Y	1	Upper Jackson Unit
8717701	Starr	124JCKS	N	Y	na	layer could not be conclusively determined
8717801	Starr	124JCKS	Y	Y	1	Upper Jackson Unit
8725101	Starr	124JCKS	N	Y	na	layer could not be conclusively determined
8725201	Starr	124JCKS	Y	Y	1	Upper Jackson Unit
8725401	Starr	124JCKS	N	Y	na	layer could not be conclusively determined
8725501	Starr	124JCKS	Y	Y	1	Upper Jackson Unit
8725603	Starr	124JCKS	N	Y	1	Upper Jackson Unit
8725802	Starr	124JCKS	Y	Y	1	Upper Jackson Unit
8726704	Starr	124YEGU	Y	Y	na	elevation of screened interval above top of Upper Jackson Unit
8733203	Starr	124JCKS	Y	Y	1	Upper Jackson Unit
8733501	Starr	124JCKS	N	Y	na	layer could not be conclusively determined
8733502	Starr	124JCKS	N	Y	1	Upper Jackson Unit
8733601	Starr	124JCKS	Y	Y	1	Upper Jackson Unit
8733801	Starr	124JCKS	Y	Y	1	Upper Jackson Unit
3741401	Trinity	124YEGU	N	Y	na	layer could not be conclusively determined
3741702	Trinity	124YEGU	Y	Y	3	Upper Yegua Unit
3741703	Trinity	124YEGU	Y	Y	3	Upper Yegua Unit
3741704	Trinity	124YEGU	Y	Y	3	Upper Yegua Unit
3749102	Trinity	124YEGU	Y	Y	3	Upper Yegua Unit
3749301	Trinity	124YEGU	Y	Y	3	Upper Yegua Unit
3855403	Trinity	124YEGU	N	Y	3	Upper Yegua Unit
3855404	Trinity	124YEGU	Y	Y	3	Upper Yegua Unit
3855405	Trinity	124YEGU	Y	Y	3	Upper Yegua Unit
3855601	Trinity	124YEGU	N	Y	3	Upper Yegua Unit
3856501	Trinity	124YEGU	N	Y	3	Upper Yegua Unit
3856502	Trinity	124YEGU	N	Y	3	Upper Yegua Unit
3856503	Trinity	124YEGU	Y	Y	3	Upper Yegua Unit
3856601	Trinity	124YEGU	Y	Y	4	Lower Yegua Unit
3862302	Trinity	124YEGU	Y	Y	2	Lower Jackson Unit
3862801	Trinity	124JCKS	Y	Y	1	Upper Jackson Unit

State Well Number	County	Aquifer Code in TWDB Database	Screen Interval Available(1)	Well Depth Available(1)	Model Layer (2)	Description
3862802	Trinity	124YEGU	Y	Y	na	elevation of screened interval below base of Lower Yegua Unit
3863602	Trinity	124JCKS	N	Y	na	layer could not be conclusively determined
3863604	Trinity	124YEGU	Y	Y	1 & 2	Upper & Lower Jackson Units
3863901	Trinity	124YEGU	Y	Y	1	Upper Jackson Unit
3864401	Trinity	124JCKS	N	Y	1	Upper Jackson Unit
3864801	Trinity	124YEGU	Y	Y	1	Upper Jackson Unit
6005301	Trinity	124JCKS	Y	Y	2	Lower Jackson Unit
6005901	Trinity	124JCKS	N	Y	1	Upper Jackson Unit
6005907	Trinity	124JCKS	Y	Y	1	Upper Jackson Unit
6006501	Trinity	124JCKS	Y	Y	1	Upper Jackson Unit
6006602	Trinity	124YEGU	N	Y	na	layer could not be conclusively determined
6006603	Trinity	124JCKS	Y	Y	1	Upper Jackson Unit
6006604	Trinity	124JCKS	Y	Y	1	Upper Jackson Unit
6006605	Trinity	124JCKS	Y	Y	na	elevation of screened interval above top of Upper Jackson Unit
6006801	Trinity	124JCKS	Y	Y	1	Upper Jackson Unit
3761903	Tyler	124JCKS	N	Y	1	Upper Jackson Unit
3861704	Walker	124JCKS	N	Y	2	Lower Jackson Unit
6003802	Walker	124JCKS	N	Y	1	Upper Jackson Unit
6003803	Walker	124YEGU	Y	Y	1	Upper Jackson Unit
6004901	Walker	124JCKS	Y	Y	1	Upper Jackson Unit
6005101	Walker	124JCKS	N	Y	1	Upper Jackson Unit
6005102	Walker	124JKYG	N	Y	1	Upper Jackson Unit
6010202	Walker	124YEGU	N	Y	na	layer could not be conclusively determined
6011502	Walker	124JCKS	N	Y	1	Upper Jackson Unit
6019302	Walker	124JCKS	Y	Y	1	Upper Jackson Unit
6019303	Walker	124JCKS	Y	Y	na	elevation of screened interval above top of Upper Jackson Unit
5943902	Washington	124JCKS	N	Y	2	Lower Jackson Unit
5943905	Washington	124JCKS	N	Y	2	Lower Jackson Unit
5943906	Washington	124JCKS	N	Y	na	layer could not be conclusively determined
5944601	Washington	124JCKS	Y	Y	2	Lower Jackson Unit
5944602	Washington	124JCKS	Y	Y	2	Lower Jackson Unit
5944603	Washington	124JCKS	N	Y	1	Upper Jackson Unit
5944604	Washington	124JCKS	N	Y	1	Upper Jackson Unit
5944701	Washington	124JCKS	N	Y	na	layer could not be conclusively determined
5944702	Washington	124JCKS	N	Y	na	layer could not be conclusively determined
5944704	Washington	124JCKS	N	Y	1	Upper Jackson Unit
5944705	Washington	124JCKS	N	Y	na	layer could not be

State Well Number	County	Aquifer Code in TWDB Database	Screen Interval Available(1)	Well Depth Available(1)	Model Layer (2)	Description
						conclusively determined
5944706	Washington	124JCKS	N	Y	1	Upper Jackson Unit
5944801	Washington	124JCKS	N	Y	na	layer could not be conclusively determined
5944802	Washington	124JCKS	N	Y	na	layer could not be conclusively determined
5944803	Washington	124JCKS	N	Y	1	Upper Jackson Unit
5944804	Washington	124JCKS	N	Y	1	Upper Jackson Unit
5944805	Washington	124JCKS	N	Y	1	Upper Jackson Unit
5944806	Washington	124JCKS	N	Y	1	Upper Jackson Unit
5944807	Washington	124JCKS	N	Y	na	layer could not be conclusively determined
5944902	Washington	124JCKS	N	Y	1	Upper Jackson Unit
5944903	Washington	124JCKS	N	Y	1	Upper Jackson Unit
5945402	Washington	124JCKS	N	Y	1	Upper Jackson Unit
5945403	Washington	124JCKS	N	Y	1	Upper Jackson Unit
5945606	Washington	124JCKS	N	Y	1	Upper Jackson Unit
5945608	Washington	124JCKS	Y	Y	na	elevation of screened interval above top of Upper Jackson Unit
5945801	Washington	124JCKS	N	Y	na	elevation of well base above top of Upper Jackson Unit
5945802	Washington	124JCKS	N	Y	na	elevation of well base above top of Upper Jackson Unit
5945803	Washington	124JCKS	N	Y	na	elevation of well base above top of Upper Jackson Unit
5946306	Washington	124JCKS	N	Y	na	elevation of well base above top of Upper Jackson Unit
5946411	Washington	124JCKS	Y	Y	1	Upper Jackson Unit
5947102	Washington	124JCKS	N	Y	na	elevation of well base above top of Upper Jackson Unit
5950905	Washington	124JCKS	N	Y	1	Upper Jackson Unit
5951104	Washington	124JCKS	N	Y	na	layer could not be conclusively determined
5951105	Washington	124JCKS	N	Y	2	Lower Jackson Unit
5951106	Washington	124JCKS	N	Y	na	layer could not be conclusively determined
5951202	Washington	124JCKS	N	Y	1	Upper Jackson Unit
5951302	Washington	124JCKS	N	Y	1	Upper Jackson Unit
5951703	Washington	124JCKS	N	Y	1	Upper Jackson Unit
5952103	Washington	124JCKS	N	Y	1	Upper Jackson Unit
5952401	Washington	124JCKS	N	Y	1	Upper Jackson Unit
5952407	Washington	124JCKS	Y	Y	1	Upper Jackson Unit
8433101	Webb	124JCKS	Y	Y	na	elevation of screened interval above top of Upper Jackson Unit
8433102	Webb	124JCKS	Y	Y	na	elevation of screened interval above top of Upper Jackson Unit

State Well Number	County	Aquifer Code in TWDB Database	Screen Interval Available(1)	Well Depth Available(1)	Model Layer (2)	Description
8433103	Webb	124JCKS	Y	Y	na	elevation of screened interval above top of Upper Jackson Unit
8514901	Webb	124YEGU	N	N	na	no screen or well depth data available to determine model layer
8515102	Webb	124YEGU	N	N	3	Upper Yegua Unit
8515201	Webb	124YEGU	N	N	3	Upper Yegua Unit
8515401	Webb	124YEGU	N	N	3	Upper Yegua Unit
8515702	Webb	124YEGU	N	N	na	no screen or well depth data available to determine model layer
8522101	Webb	124YEGU	N	N	4	Lower Yegua Unit
8522202	Webb	124YEGU	N	N	na	no screen or well depth data available to determine model layer
8522601	Webb	124YEGU	N	N	na	no screen or well depth data available to determine model layer
8530102	Webb	124YEGU	N	Y	4	Lower Yegua Unit
8530201	Webb	124YEGU	N	Y	3	Upper Yegua Unit
8530501	Webb	124YEGU	N	Y	3	Upper Yegua Unit
8531102	Webb	124YEGU	N	N	na	no screen or well depth data available to determine model layer
8531103	Webb	124YEGU	N	N	na	no screen or well depth data available to determine model layer
8531104	Webb	124YEGU	N	N	na	no screen or well depth data available to determine model layer
8531501	Webb	124YEGU	N	N	na	no screen or well depth data available to determine model layer
6757102	Wilson	124YEGU	Y	Y	na	elevation of screened interval below base of Lower Yegua Unit
6757204	Wilson	124YEGU	Y	Y	na	elevation of screened interval below base of Lower Yegua Unit
7807601	Wilson	124JCKS	N	Y	na	layer could not be conclusively determined
7807602	Wilson	124YEGU	N	Y	na	layer could not be conclusively determined
7808401	Wilson	124JCKS	Y	Y	2	Lower Jackson Unit
8562101	Zapata	124YEGU	N	Y	4	Lower Yegua Unit
8606901	Zapata	124YEGU	N	Y	na	well plots outside of boundary of Yegua-Jackson Aquifer
8607402	Zapata	124YEGU	N	Y	4	Lower Yegua Unit
8615604	Zapata	124YEGU	Y	Y	4	Lower Yegua Unit

State Well Number	County	Aquifer Code in TWDB Database	Screen Interval Available[1]	Well Depth Available[1]	Model Layer [2]	Description
8615902	Zapata	124YEGU	Y	Y	4	Lower Yegua Unit
8616401	Zapata	124YEGU	Y	Y	4	Lower Yegua Unit
8616402	Zapata	124YEGU	Y	Y	4	Lower Yegua Unit
8616403	Zapata	124YEGU	N	Y	4	Lower Yegua Unit
8616501	Zapata	124YEGU	Y	Y	4	Lower Yegua Unit
8616701	Zapata	124YEGU	Y	Y	4	Lower Yegua Unit
8616705	Zapata	124YEGU	Y	Y	4	Lower Yegua Unit
8616706	Zapata	124YEGU	N	Y	4	Lower Yegua Unit
8616707	Zapata	124YEGU	Y	Y	4	Lower Yegua Unit
8624201	Zapata	124YEGU	Y	Y	4	Lower Yegua Unit
8624202	Zapata	124YEGU	Y	Y	4	Lower Yegua Unit
8624501	Zapata	124YEGU	N	Y	na	layer could not be conclusively determined
8624502	Zapata	124YEGU	N	Y	4	Lower Yegua Unit
8624503	Zapata	124YEGU	Y	Y	4	Lower Yegua Unit
8632103	Zapata	124JCKS	N	Y	na	well plots outside of boundary of Yegua-Jackson Aquifer
8709101	Zapata	124JCKS	Y	Y	1	Upper Jackson Unit

[1] Y - yes; N - no

[2] 1 - Upper Jackson Unit; 2 - Lower Jackson Unit; 3 - Upper Yegua Unit; 4 - Lower Yegua Unit; na - could not be determined

APPENDIX B

All Transient Hydrographs for the Yegua-Jackson Aquifer for the Transient Period (1901 through 1997)

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This appendix contains all hydrographs of simulated and observed water-level elevations for targets in the Yegua-Jackson Aquifer for the historical period (1901 through 1997). Hydrographs are only for wells having five or more water-level measurements during the historical period. On the hydrographs, the model simulated response is shown by a line and the measured water-level elevations are shown as symbols.

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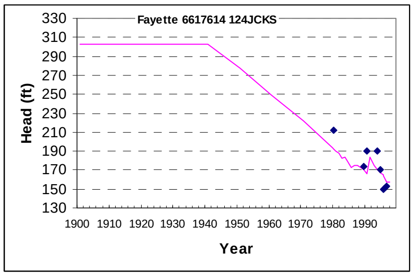
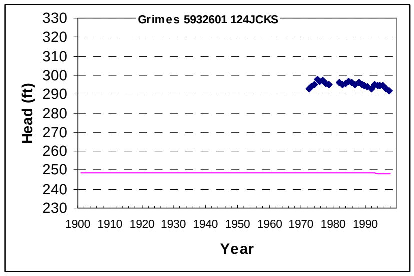
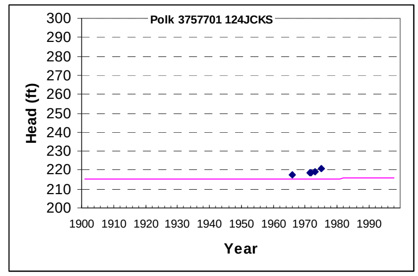
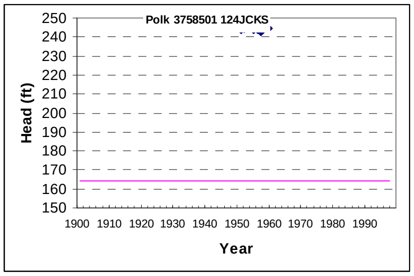
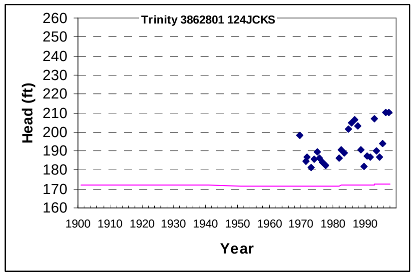
HYDROGRAPHS FOR THE UPPER JACKSON UNIT

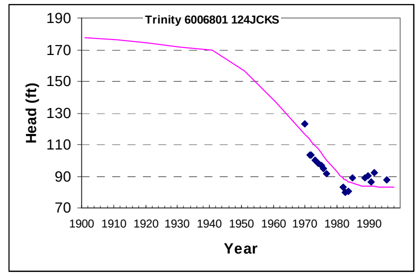

Fayette 6617614 124JCKS
Head (ft)
330 310 290 270 250 230 210 190 170 150 130
1900 1910 1920 1930 1940 1950 1960 1970 1980 1990
Year

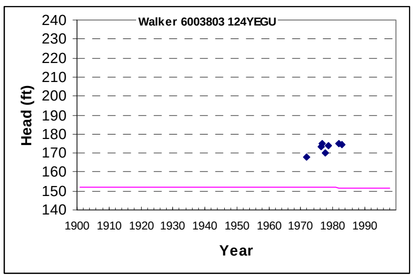

Grimes 5932601 124JCKS
Head (ft)
330 320 310 300 290 280 270 260 250 240 230
1900 1910 1920 1930 1940 1950 1960 1970 1980 1990
Year

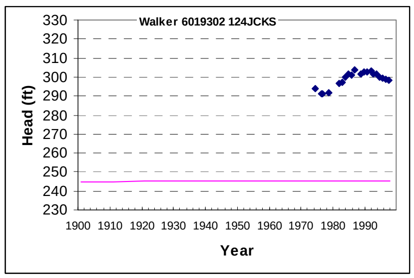

Polk 3757701 124JCKS
Head (ft)
300 290 280 270 260 250 240 230 220 210 200
1900 1910 1920 1930 1940 1950 1960 1970 1980 1990
Year


Polk 3758501 124JCKS
Head (ft)
250 240 230 220 210 200 190 180 170 160 150
1900 1910 1920 1930 1940 1950 1960 1970 1980 1990
Year

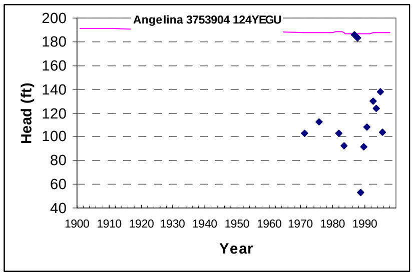

Trinity 3862801 124JCKS
Head (ft)
260 250 240 230 220 210 200 190 180 170 160
1900 1910 1920 1930 1940 1950 1960 1970 1980 1990
Year

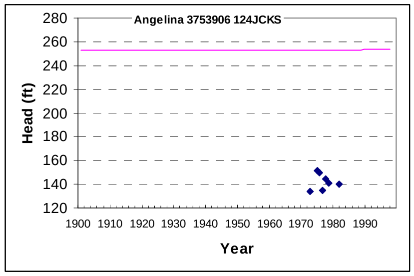

Trinity 6006801 124JCKS
Head (ft)
190 170 150 130 110 90 70
1900 1910 1920 1930 1940 1950 1960 1970 1980 1990
Year

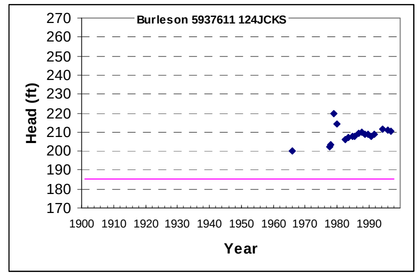

Walker 6003803 124YEGU
Head (ft)
240 230 220 210 200 190 180 170 160 150 140
1900 1910 1920 1930 1940 1950 1960 1970 1980 1990
Year

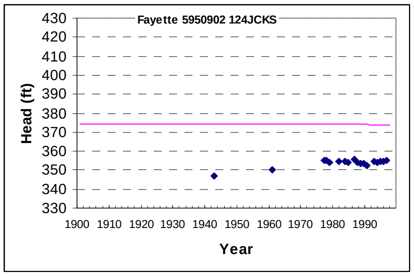

Walker 6019302 124JCKS
Head (ft)
330 320 310 300 290 280 270 260 250 240 230
1900 1910 1920 1930 1940 1950 1960 1970 1980 1990
Year

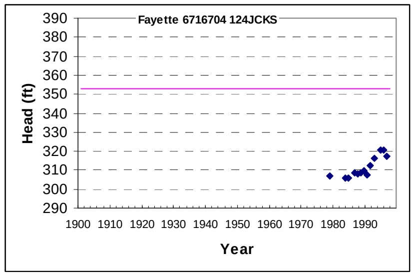
HYDROGRAPHS FOR THE LOWER JACKSON UNIT

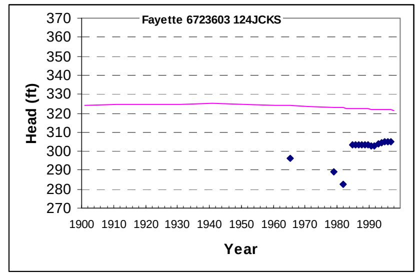

Angelina 3753904 124YEGU
Head (ft)
Year

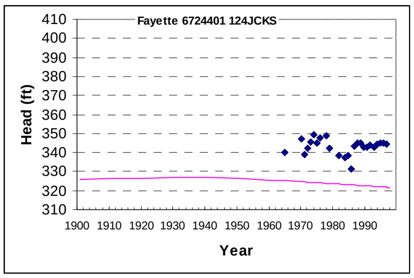

Angelina 3753906 124JCKS
Head (ft)
Year

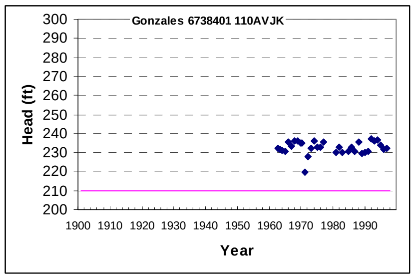

Burleson 5937611 124JCKS
Head (ft)
Year

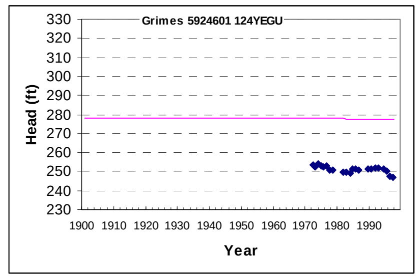

Fayette 5950902 124JCKS
Head (ft)
Year

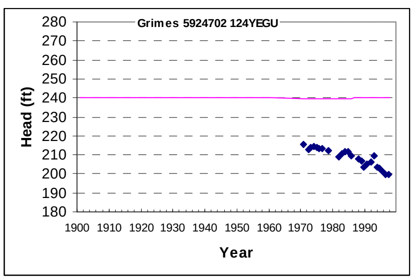

Fayette 6716704 124JCKS
Head (ft)
Year

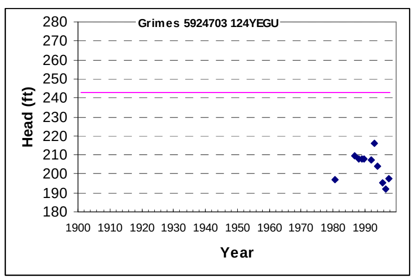

Fayette 6723603 124JCKS
Head (ft)
Year

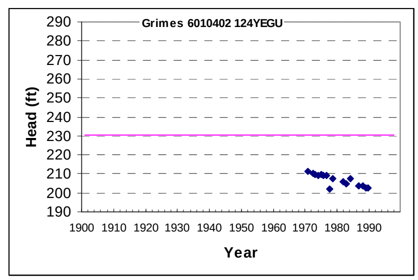

Fayette 6724401 124JCKS
Head (ft)
Year

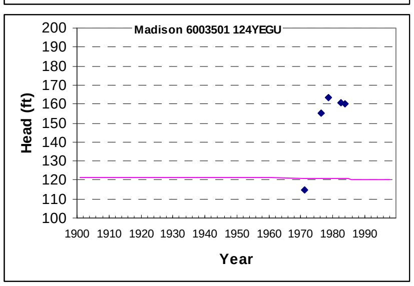

Gonzales 6738401 110AVJK
Head (ft)
Year

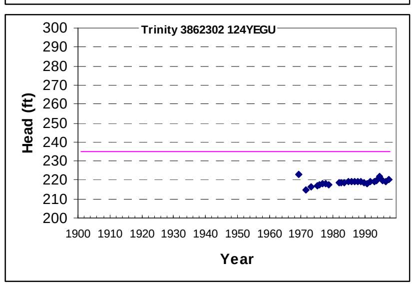

Grimes 5924601 124YEGU
Head (ft)
Year

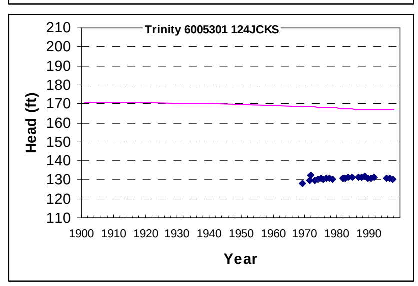

Grimes 5924702 124YEGU
Head (ft)
Year

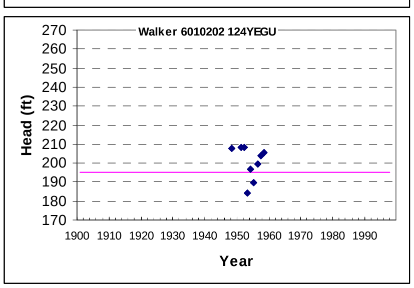

Grimes 5924703 124YEGU
Head (ft)
Year

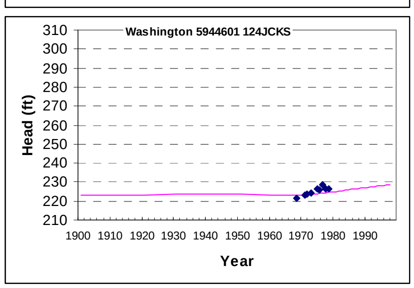

Grimes 6010402 124YEGU
Head (ft)
Year


Madison 6003501 124YEGU
Head (ft)
Year

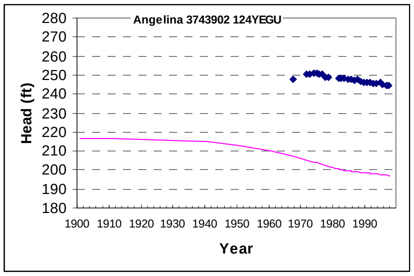

Trinity 3862302 124YEGU
Head (ft)
Year

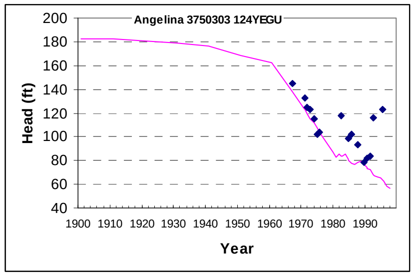

Trinity 6005301 124JCKS
Head (ft)
Year

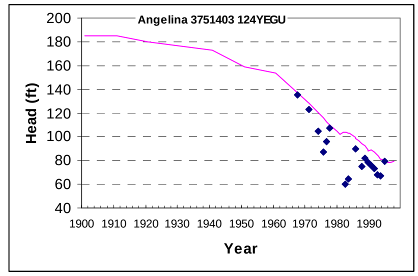

Walker 6010202 124YEGU
Head (ft)
Year

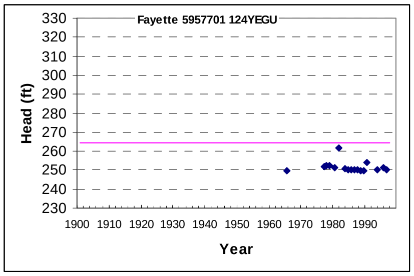

Washington 5944601 124JCKS
Head (ft)
Year

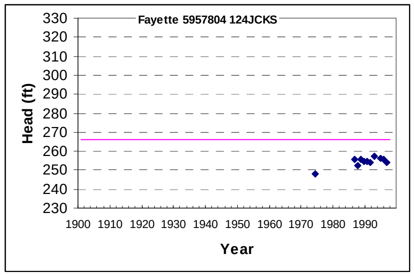
HYDROGRAPHS FOR THE UPPER YEGUA UNIT

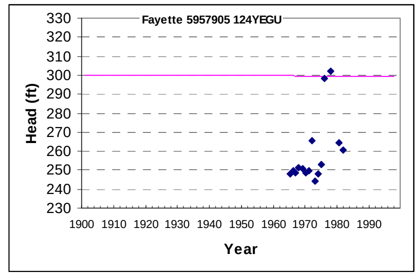

Angelina 3743902 124YEGU
Head (ft)
Year

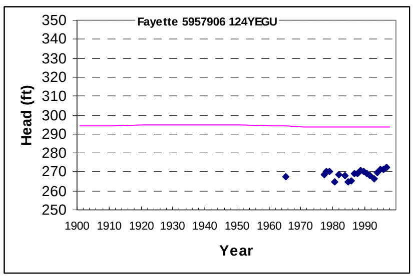

Angelina 3750303 124YEGU
Head (ft)
Year

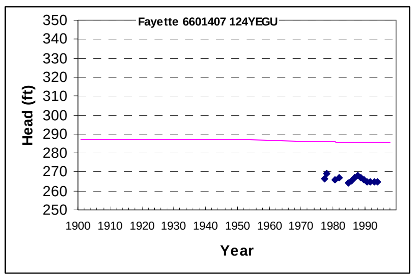

Angelina 3751403 124YEGU
Head (ft)
Year

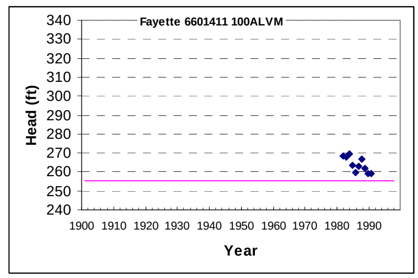

Fayette 5957701 124YEGU
Head (ft)
Year

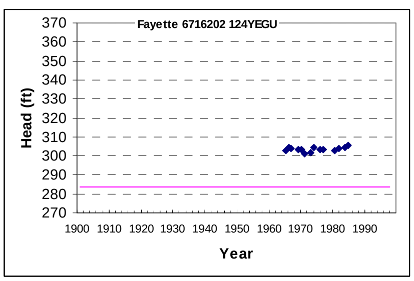

Fayette 5957804 124JCKS
Head (ft)
Year

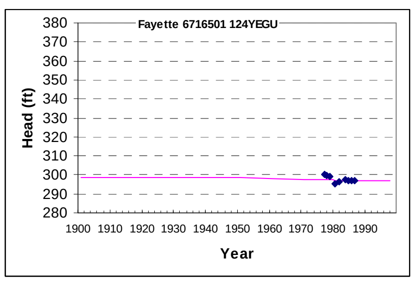

Fayette 5957905 124YEGU
Head (ft)
Year


Fayette 5957906 124YEGU
Head (ft)
Year


Fayette 6601407 124YEGU
Head (ft)
Year


Fayette 6601411 100ALVM
Head (ft)
Year


Fayette 6716202 124YEGU
Head (ft)
Year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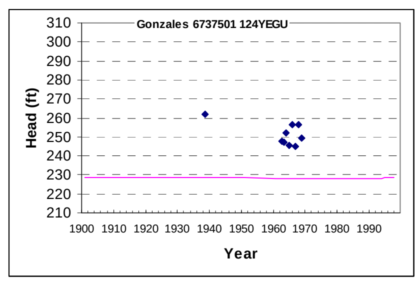
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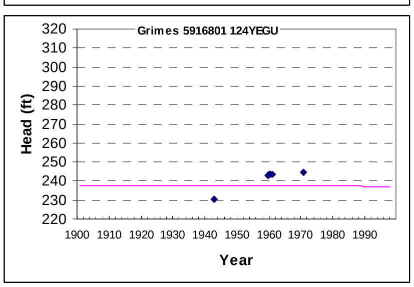
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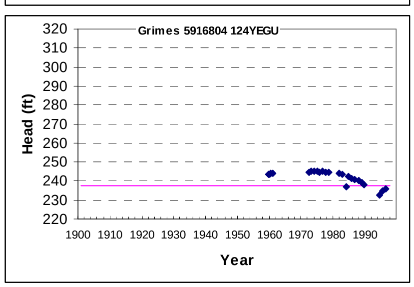
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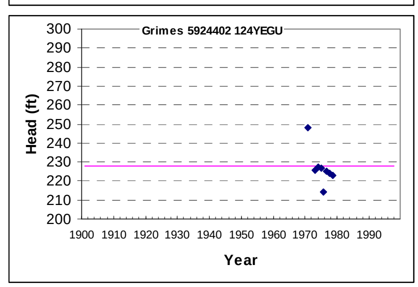
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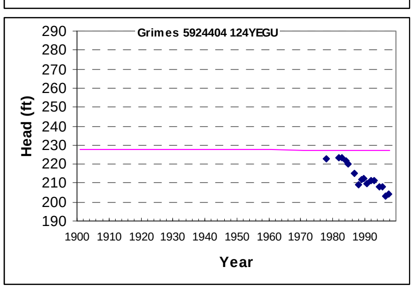
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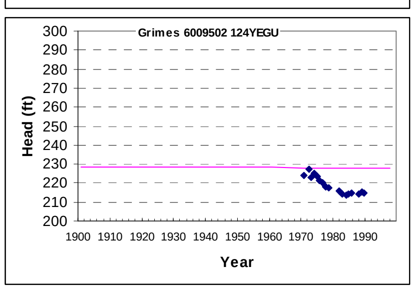
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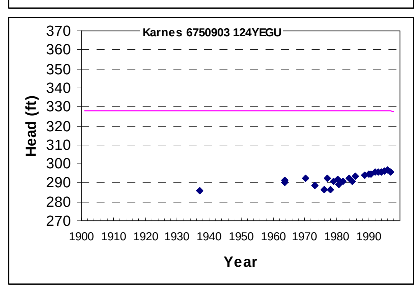
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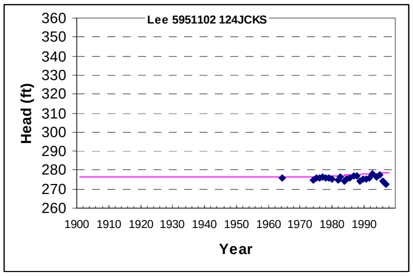
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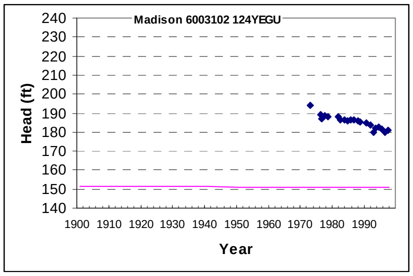
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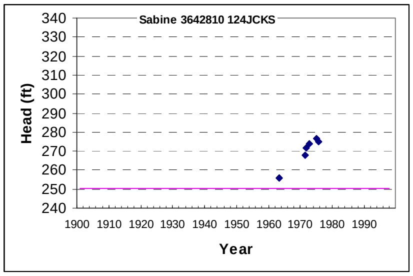
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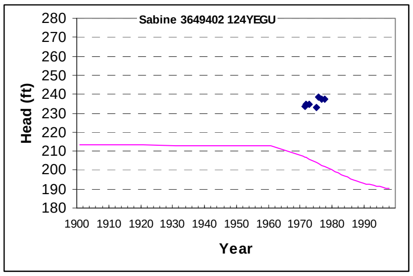
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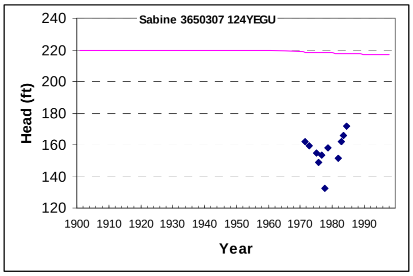
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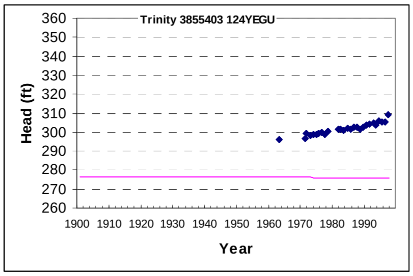
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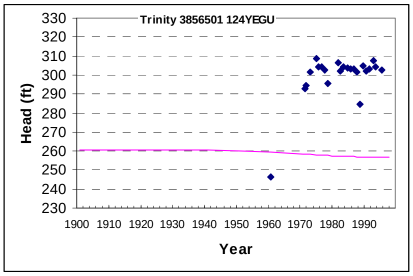
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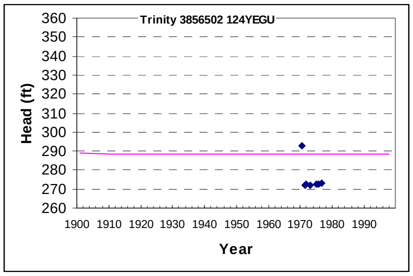
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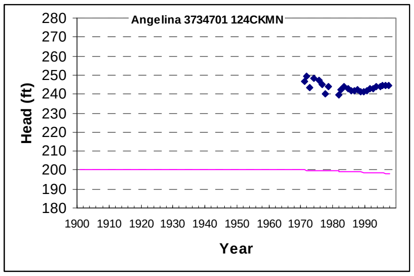
HYDROGRAPHS FOR THE LOWER YEGUA UNIT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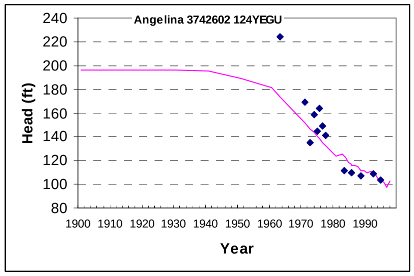
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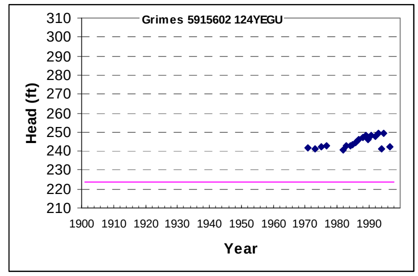
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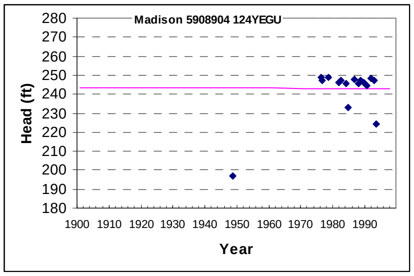
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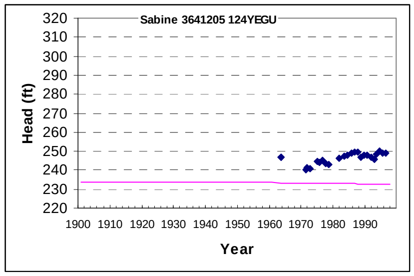
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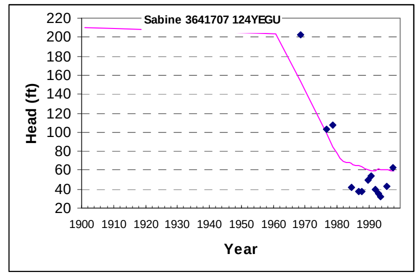
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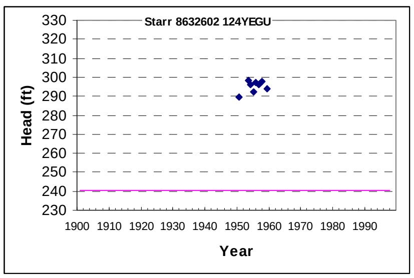
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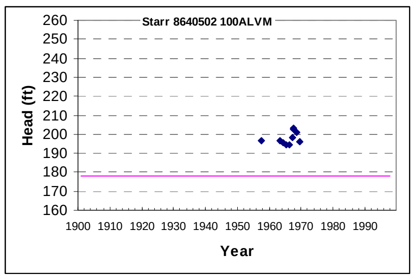
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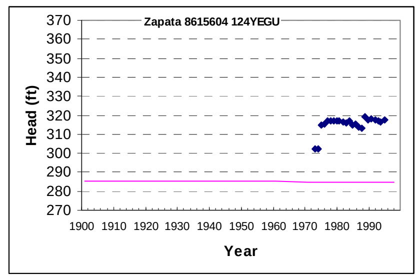
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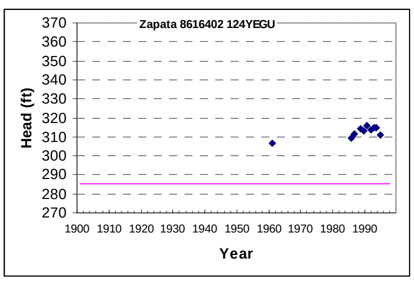
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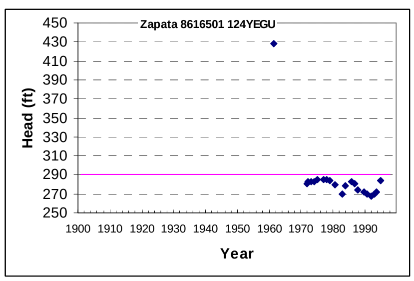
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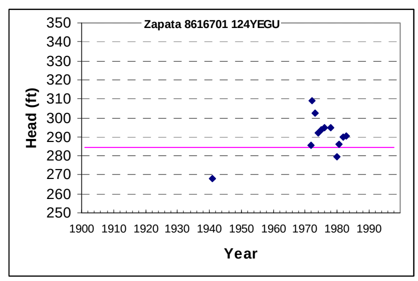
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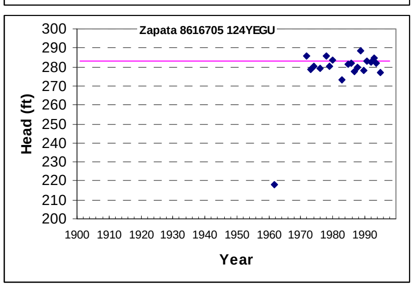
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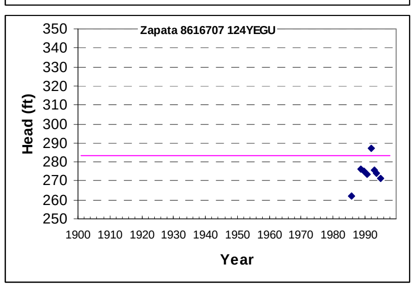
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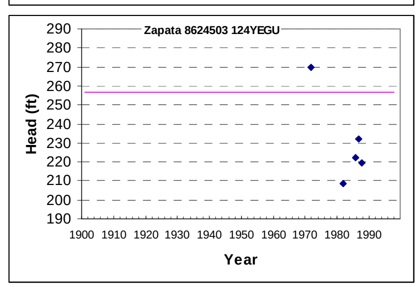
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APPENDIX C
Draft Conceptual Model Report Comments and Responses

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Review Comments on the
Draft Conceptual Model for the Yegua-Jackson Aquifer Groundwater Availability Model

Prepared by Deeds and others (2009)

General Comments

This is a well written, comprehensive report, with adequate supporting documentation. It provides detailed explanations of each topic discussed and goes an extra length in exploring different approaches for addressing various conceptual modeling issues. It was difficult to find problems with the approaches or the content of the report.

Specific Comments

1. Section 1.0, Page 1-2, line 1: An intersection of counties and aquifer boundary yields 34 counties. Please revise.
   Completed. See Section 1.0, paragraph 4.

2. Section 1.0, page 1-3, paragraph 3: Please change “stakeholder forums” to “stakeholder advisory forums”.
   Completed. See Section 1.0, last paragraph.

3. Section 1.0, page 1-3, paragraph 3: Please change “…for the evaluation of …” to “… for evaluating …”.
   Completed. See Section 1.0, last paragraph.

4. Section 2.0, Page 2-1, paragraph 2: Please change the citation “TWDB, 2007” to “Knox and others, 2007”.
   Completed. See Section 2.0, paragraph 2.

5. Section 2.0, Page 2-1, paragraph 2: Please change the citation “TWDB, 2007” to “Knox and others, 2007”.
   Repeat of comment 4.

6. Section 2.0, Page 2-2, paragraph 1: Please delete “…and Underground Water Conservation Districts (UWCDs)…” and “… and UWCDs”.
   Completed. See 2.0, paragraph 5.

7. Section 2.0, Page 2-2, paragraph 1: In this paragraph, please revise the text to reflect the number of regional water planning areas, groundwater conservation districts, groundwater management areas, and river authorities that intersect the aquifer and not the study area.
   Completed. See 2.0, paragraph 5.

8. Section 2.0, Page 2-2, paragraph 2: In this paragraph, please revise the text to reflect the number of river basins that intersect the aquifer and not the study area.
Completed. See 2.0, last paragraph.

9. Figure 2.1.1: Please delete the Blackland Prairies from this map.
Completed. See Figure 2.1.1.

10. Section 2.1, Page 2-15, paragraph 1: Please point out that the only the Interior Coastal Plains coincides with the aquifer outcrop.
Completed. See Section 2.1, first paragraph.

11. Section 2.1, Page 2-18, Figure 2.1.2: There appears to be an error in the topographic map in the southern half of Cameron County. Please review and correct as needed.
Completed. See Figure 2.1.2.

12. Section 2.1, Page 2-19, Figure 2.1.3: Please add the climate classification transition zones to the legend.
Completed. See Figure 2.1.3.

13. Section 2.1, Page 2-26, Figure 2.1.10: Please document the source of the average monthly lake evaporation rates in the figure.
Completed. See Figure 2.1.10.

14. Section 2.2, Page 2-28, paragraphs 2 through 4: Please move these paragraphs to Section 3.
Completed. See Section 3, paragraphs 2 through 5.

15. Section 3.0, Page 3-3: Suggest adding paragraph of how new modeling effort compares to and differs from previous modeling efforts.
No change. Since the Yegua Formation and Jackson Group were a minor part of the previous models and often combined with other units, a specific comparison between models is not possible.

16. Page 4-1: Section 4.0 refers to Hydrologic Setting. Should this rather be "Hydrogeologic Setting". This suggestion is provided as we discuss hydrostratigraphy, structure in this section
Completed. See Section 4.0, page 4-1.

17. Section 4.1, Page 4-2, paragraph 3: Please add a figure showing the lateral equivalents of the Jackson Group outlined in this paragraph.
Completed. See Figure 4.1.1.

18. Section 4.2.2, Page 4-10, paragraph 3: The methodology for estimating the location of the aquifer outcrop does not seem to take into account the relative locations of the two wells or differences in ground-surface elevations. Please address these issues.

Completed. See Section 4.2.2, heading Additional Well Control, paragraphs 2 and 3.

19. Figure 4.2.2: Please change "Knox (2007)" to "Knox and others (2007)".
Completed. See Figure 4.2.2.

20. Figure 4.2.3: Please change "Knox (2007)" to "Knox and others (2007)".
Completed. See Figure 4.2.3.

21. Figure 4.2.3: Please revise legend to look like the other figures.
Completed. See Figure 4.2.3.

22. Figure 4.2.6: Please change "Knox (2007)" to "Knox and others (2007)".
Completed. See Figure 4.2.6.

23. Figure 4.2.6: Please revise legend to look like the other figures.
Completed. See Figure 4.2.6.

24. Page 4-43: In this section, the authors describe results on structure and water level intersections and discuss how to properly assign the measure water levels to appropriate aquifers. They note that many of the wells in the TWDB groundwater database are incorrectly labeled and therefore, were re-assigned to a different aquifer after this analysis. We request that these results be included in the report as an appendix or the analysis results are provided to the TWDB so that the groundwater database can be updated accordingly.
Completed. See Appendix A.

25. Section 4.4: Please move this section (rivers, streams, springs, and lakes) to section 4.5 and move recharge – currently in section 4.5 – to section 4.4.
Completed. See Section 4.4 and 4.5.

26. Figure 4.4.5: In the legend, please change "Ockerman (2008)" to "Ockerman (2007)" and "Saunders (2005)" to "Saunders (2006)".
Completed. See Figure 4.5.5.

27. Page 4-130, paragraph 3: Please change "4.5.4 and 4.5.5" to "4.5.5 and 4.5.6".
Completed. Changed to 4.4.5 and 4.4.6, see Section 4.4.3, paragraph 6.

28. Page 4-130, paragraph 3: Please specify how "deep recharge" is quantified.
No change. In parentheses, we note that the deep recharge was estimated in the literature for two counties as described in Section 4.5.2.

29. Figures 4.5.5 and 4.5.6: Please add the coefficient of determination value for each correlation.
No change. These coefficients are already available in Table 4.4.2.

30. Page 4-131, paragraph 1: According to this methodology, there will be recharge even if there is not precipitation. This is counter intuitive. Please incorporate the concept of a threshold below which there will be no recharge.
The correlation is not physically based, but is rather a mathematical expression of a relationship that occurs over a specific precipitation range. We added some explanation to this effect in the noted in Section 4.4.3, paragraph 7.

31. Section 4.5, Page 4-135, Table 4.5.2: Please add the source of the baseflow lag times. The specific methods used for determining this in the text (page 4-130) were missing or need clarification.
No. change. The lag was based on optimizing the coefficient of determination. This is noted in the paragraph describing the regression process in Section 4.4.3, paragraph 5.

32. Page 4-136: This section presents a block diagram showing groundwater recharge assignments into various components of the hydrologic system. A paragraph discussing how this was done will prove useful to the reader and will stand in support of the diagram.
Completed. Additional explanation was added to the last paragraph of Section 4.4.1 which introduces the figure.

33. Page 4-142: Figure 4.5.8. This figure caption states “example distribution of long term average recharge”. It is not understood why it is called example recharge. It may be more appropriate to call it “estimated recharge distribution based on long term average precipitation record (year-year)”.
Completed. Text was edited to reflect this comment in Section 4.4.3, last paragraph.

34. Page 4-143: Figure 4.5.9. This figure reports topographic effects on recharge. The legend shows color bands indicating recharge and/or discharge areas. However, the units of this color bands are not presented. Please clarify and update as needed.
Modified change. The purpose of the figure is to show relative variation in recharge due to topography, not to present a topographic multiplier. The text has been reworded and the label in the figure has been changed.

35. Section 4.5, Page 4-144, Figure 4.5.10a: Please clarify why there are sharp changes in the value of Ksat between McMullen County and adjacent counties. From the description of the methods for calculating Ksat on page 4-133, one would not expect large variations at political boundaries.
There is a sharp change in the calculated average Ksat for McMullen County because there is a sharp difference in the SSURGO Ksat values that were average. The difference is not a result of the method used for calculating the average but rather the underlying values that were averaged. A sentence has been added to the text to reflect the fact that the SSURGO Ksat values in McMullen County are lower than those in surrounding counties. See Section 4.4.6, paragraph3.

36. Section 4.5.3, Page 4-130, paragraph 3: Please change "4.5.4 and 4.5.5" to "4.5.5 and 4.5.6".
Repeat of comment 27.

37. Section 4.5.3, Page 4-130, paragraph 3: Please specify how "deep recharge" is quantified.
Repeat of comment 28.

38. Figures 4.5.5 and 4.5.6: Please add the coefficient of determination value for each correlation.
Repeat of comment 29.

39. Section 4.5.3, Page 4-131, paragraph 1: According to this methodology, there will be recharge even if there is not precipitation. This is counter intuitive. Please incorporate the concept of a threshold below which there will be no recharge
Repeat of comment 30.

40. Section 4.6.2, Page 4-151: The Sparta Aquifer is referred to as a major aquifer though it is classified by the TWDB as a minor aquifer, please update text appropriately and verify that pumping in the Sparta (or other minor aquifers) was not assigned to the Yegua-Jackson aquifer.
Completed. The text was edited to correct the reference to Sparta as a major aquifer. The intention of the text was to note that the major aquifers (and some of the minor aquifers, such as the Sparta) were explicitly assigned pumping in the database. Pumping in those aquifers was not assigned to Yegua-Jackson. See Section 4.6.2, paragraph 5.

41. Page 4-190, paragraph 2: Please change "Tyler and Finley, 1981" to "Tyler and Finley, 1991".
Completed. See Section 4.7.2, last paragraph.

42. Page 4-192, paragraph 1: Please change "Lame" to "Lambe and Whitman".
Completed. See Section 4.7.3, heading Lithology, first paragraph.

43. Page 4-192, paragraph 3: Please change "… the Upper and Lower Yegua." to "… the Upper and Lower Yegua units." and change "… the Upper and Lower Jackson." to "… the Upper and Lower Jackson units.".
Completed. See Section 4.7.3, heading Lithology, paragraph 3.

44. Page 4-194, paragraph 1: Please change "Young and Kelley" to "Young and others".
No change. Young and Kelley are the editors and, thus, should be the only ones cited. The contributing authors included in the reference section were removed.

45. Page 4-195, paragraph 3: Please change "1200 millidarcies" to "1,200 millidarcies".
Completed. See Section 4.7.5, paragraph 4.

46. Page 4-195, paragraph 3: Please change “2.74E-3” to “2.74×10-3”.
Completed. See Section 4.7.5, paragraph 4.

47. Page 4-196, paragraph 2: Please change “1000 permeability” to “1,000 permeability” and change “Yegua sandstones” to “Yegua Formation sandstones”.
Completed. See Section 4.7.5, last paragraph.

48. Page 4-196, paragraph 4: Please change “Evan” to “Evans”, and “control flows” to “control groundwater flow”.
Completed. See Section 4.7.6, paragraph 2.

49. Page 4-196, paragraph 4: Please add “Evans and others (2007)” to the list of references or change (2007) to (1997).
Completed. “Evans and others (2007)” has been corrected to “Evans and others (1997)”. See Section 4.7.6, paragraph 2.

50. Page 4-196, paragraph 4: Please change “… porosity reduction remains relatively …” to “… porosity reduction rate remains relatively …”.
Completed. See Section 4.7.6, paragraph 2.

51. Page 4-197, paragraph 4: Please add Young (2007, 2009) to the list of references.
Completed. Citations changed to Young and Kelley (2006) and Young and others (2008). See Section 4.7.7, paragraph 3.

52. Page 4-199, paragraph 5: Please change “2E-4 to 1E-3 1/ft” to “2×10-4 to 10-3 per foot”.
Completed. See Section 4.7.6, last paragraph.

53. Page 4-209 through 4-212. Please consider replacing “facies environments” with “sedimentary facies environments” or “depositional facies” or “depositional environments” in the figure caption. Facies environments alone are an incomplete characterization of a depositional environment. Please expand discussion to explain if correlating pump test derived hydraulic conductivity information with depositional facies was a useful exercise..
Completed. See Figures 4.7.5 through 4.7.8 and Section 4.7.4, paragraph 3.

54. Page 4-224, paragraph 3: please change “… Yegua and Jackson Group …” to “…Yegua Formation and Jackson Group …”.
Completed. See Section 4.8.3, first paragraph.

55. Section 5.0: Many of the citations in this section are not included in the references section (e.g. Togers, 1967; Domineco and Robbins, 1985; and Bredehoft, 2002). Please add missing references to the references section.
Completed. See Section 14.

56. Section 5.0 Figure 5.1: If the younger sediments will be represented as a layer in the model, they should be represented as a rectangular box in this figure similar to the other model layers. Please revise the figure to reflect this.
Completed. See Figure 5.0.1.

57. Page 5-5: The conceptual block diagram is missing evapotranspiration and springs components of the flow system.
Completed. See Figure 5.0.1.

58. Section 6.0, Page 6-1, paragraph 1: Please change “Adida” to “Adidas”.
Completed. See Section 14.

59. Section 6.0, Page 6-8, paragraph 1: Please change “Meyers, B.N. …” to “Myers, B.N. …”.
Completed. See Section 14.

60. Section 6.0, Page 6-8, paragraph 9: Please add the secondary authors to the reference.
This publication has only one author. The name has been changed from “Pettijohn et al.” to “Pettijohn R.A.” See Section 14.

61. Section 6.0, Page 6-8, paragraph 11: Please add the title of the paper by Preston (2006).
Completed. See Section 14.

62. Section 6.0, Page 6-10, paragraph 3: Please add the publication year to this reference.
Completed. See Section 14.

63. Section 6.0, Page 6-12, paragraph 10: The Williamson and others (1990) reference appears twice, please delete one occurrence.
Completed. See Section 14.

64. Section 6.0, Please add Alley and others (1999), Bredehoeft (2002), Domenico and Robbins (1985), Lonsdale (1966), Reece (2003), Togers (1967), TWDB (2008b), Williamson and Grubb (2001) to the list of references.
Completed. Added Alley and others (1999), Bredehoeft (2002), Domenico and Robbins (1985), and Williamson and Grubb (2001) have been added, See Section 14. Lonsdale (1966) should have been Alexander and White, which is in the list of references and was corrected in the text (See Section 3.0, Table 3.0.1). Reece (2003) was found in the text, the citation was Heitmuller and Reece (2003), which is in the list of references. Togers (1967) should have been Rogers (1967), which is in the list of references and was corrected in the text.

65. Section 6.0, Please delete Bloch (1991), Gluyas and Cade (1997), Kelley and others (2006), Magara (1980), USGS (2009)
Completed. See Section 14.

66. Section 6.0, The following references are not in alphabetical order, please correct: Alpay (1972), Bureau of Economic Geology (1996), Scanlon and others (2003, 2005), and Shestakov (2002).
Completed. See Section 14.

Geodatabase and Figures

67. Figure 1.0.1: Please revise figure to include Pecos Alluvium as referenced in the legend.
Completed. Pecos Alluvium has been, See Figure 1.0.1.

68. Figure 2.0.4: Features from "maj_rivers_outcrop" do not line up with features from "EPA_RF1_RiverReach" and appear confusing. Suggest using a single source for the figure.
These two feature classes serve for two different figures. Feature class "EPA_RF1_RiverReach" in feature dataset "SurfaceHydro" was used to show all the rivers in Figure 2.0.4. This feature class came with the Geodatabase template from TWDB. Feature class "maj_rivers_outcrop" was used to show major rivers in the outcrop area in Figure 4.4.1. It was downloaded from TWDB GIS data webpage (http://www.twdb.state.tx.us/mapping/gisdata.asp).

69. Figure 2.0.8: San Patricio County Groundwater Conservation District intersects the active area, but it was not included in the map. Please revise.
Completed. San Patricio County Groundwater Conservation District was added to the GCD coverage. See feature class "TWDB_GCDS_1008_dd83_YJ_0527" in the feature dataset "Boundary" in the Geodatabase.

70. Figure 2.1.1: Blackland Prairies is shown on the map, but it's not labeled. Please update figure with label.
Blackland Prairies was deleted. See Figure 2.1.1.

71. Figure 2.1.2: Please revise this figure. At the southern most tip of Texas there is a graphic error. The raster dataset seems to be fine.
Completed. See Figure 2.1.2.

72. Figures 2.1.4 and 2.1.5: Please specify what period of time has been averaged and update, if necessary, so the same period is time is used. The GAM website includes a Climatic Digital Atlas of Texas that covers both temperature and precipitation over the same periods of time.
Completed. Period of time for Figure 2.1.4 has been added. Figure 2.1.5 has been updated using the Digital Climate Atlas of Texas from TWDB website.

73. Figures 2.1.7 and 2.1.8: Please include time series data presented in these figures.
Completed. The data for Figure 2.1.7 and 2.1.8 have been uploaded to the Geodatabase: table "precip_coop_tx_annual_for_geodatabase" and table "precip_coop_tx_monthly_for_geodatabase" respectively.

74. Figure 2.1.9: Source and caption do not agree. Please update for consistency.
Completed. The reference under the figure (which was wrong) has been deleted.

75. Figure 2.2.1: Please include a feature class that includes faults and other delineations present in the figure.
No change. The faults and other delineations were placed on this figure by hand and not with shapefiles.

76. Figures 2.2.2a and 2.2.2b: Suggest removing the gray outline in the symbology because it overruns the unit colors.
Completed. See Figures 2.2.2a,b

77. Figures 2.2.4 and 2.2.5: Please include a feature class that shows the locations of the two cross sections present in these figures.
No change. The locations for these two cross sections were draw by hand.

78. Figure 3.0.1: Please include a feature class for previous model study areas.
Completed. See feature classes "ryder_outline" and "williamson_outline" in the feature dataset "Boundary" in the Geodatabase.

79. Figure 4.2.1: Please include a feature class of cross sections and well locations. If wells already exist as part of a larger wells feature class, please add an attribute field that shows they have been used in cross sections.
Completed. See feature classes "PKDip", "PKStrike_A_B", PKStrike_C", and "well_logs" in the feature dataset "Geology" in the Geodatabase.

80. Figures 4.2.2, 4.2.3, and 4.2.6: Please include feature classes for previous studies boundaries.
Completed. See feature classes "Barnes_1992_Boundary", and "Knox_others_2007_Boundary_new" in the feature dataset "Geology" in the Geodatabase.

81. Figure 4.2.6: Please include a feature class for environmental facies.
Completed. See feature class "Environmental_Facies" in feature dataset "Geology: in the Geodatabase.

82. Figure 4.2.7: We could not locate the base of the Yegua-Jackson in the "GeologyGrids" raster catalog. According to metadata, none of the rasters is the base of Yegua-Jackson. Please add it to the catalog. As a suggestion, please use slightly more descriptive names for rasters in this catalog.
Completed. The names for rasters in "GeologyGrids" catalog have been revised to be self-explaining. "Base_of_Aquifer_ele" is the elevation of base of Yegua-Jackson Aquifer.

83. Figure 4.2.8: The raster dataset shows a minimum value of -8477 feet, while the figure legend shows -8091. Please revise.
No change. Figure 4.2.8 shows the elevation of top of Lower Yegua Unit which is represented by raster "top_of_Lower_Yegua_elev" (previously "tly_str_ocdd") in the "GeologyGrids" raster catalog. This raster ranges from -8091.2 feet to 694.3 feet. No revision is needed.

84. Figure 4.2.11: The thickness raster for the Upper Yegua (uy_isp_c25) is missing metadata. Please revise.
The metadata of raster "Upper_Yegua_thickness" (previously "uy_isp_c25") in the "GeologyGrids" raster catalog is not missing.

85. Figures 4.2.20 through 4.2.23: Please include feature classes for depositional facies.
Completed. See feature classes "lower_jackson_facies", "Lower_Yegua_Facies", "upper_jackson_jacies", and "upper_yegua_facies" in feature dataset "Geology" in the Geodatabase.

86. Table 4.3.1: Our analysis of the "Yegua_Jackson_WL_Data" table shows the following discrepancies in totals (note: we excluded all records with comments = "did not use*"):
    a. Burleson: 60 (report: 61)
    b. Fayette: 85 (report: 88)
    c. LaSalle: 3 (report 4)
    d. Lee: 3 (report 4)
    e. Sabine: 44 (report: 45)
    f. Trinity: 26 (report: 27)
    g. Tyler: 0 (report: 1)

    Completed. See Table 4.3.1.

87. Table 4.3.2: It appears you counted water level measurements twice for dual completion wells. Please specify that either on the table or in the text. According to the "Yegua_Jackson_WL_Data" table, the well in Tyler County was not used. Please remove it from tables 4.3.1 and 4.3.2.
Completed. See Tables 4.3.1 and 4.3.2.

88. Figures 4.3.3 through 4.3.18: Please include measurement units in the legend or caption.
Completed. See figure caption for Figures 4.3.3 through 4.3.18.

89. Figures 4.3.20 through 4.3.22: As a suggestion, please replace "Decrease > 10 & < 50 feet" with "10 < Decrease < 50 feet".
Completed. See Figure 4.3.20 through 4.3.22.

90. Table 4.4.5: Please adjust surface area numbers to match actual numbers from the 'reservoirs_ygjk_gam_outcrop" feature class.
Completed. See feature class "reservoirs_ygjk_gam_outcrop" in feature dataset "SurfaceHydro" in the Geodatabase.

91. Figures 4.4.2a and 4.4.2b: Please include a feature class for stream gages and time series data for graphs.
Completed. See feature class "tx_gages_Clip" and table "Stream_Flow_Hydrograph_Data_" in feature dataset "Surface Hydro" in the Geodatabase.

92. Figure 4.4.3: Please include tabular data to support this graph.
Completed. See table "Flow_Duration_Curve_Data_" in the Geodatabase.

93. Figure 4.4.4: Please include a feature class for locations in the Slade studies.
Completed. See feature class "slade_gamcs_yj" in feature dataset "SurfaceHydro" in the Geodatabase.

94. Figure 4.4.5: Please include a feature class for locations in the Ockerman (2008) and Saunders (2005) studies. You can choose to combine features from comment above into one feature class with proper attributes.
Completed. See feature class "tx_gages_Clip" in feature dataset "SurfaceHydro" in the Geodatabase.

95. Figure 4.4.6: Please include tabular data to support this graph.
No change. This figure shows only example data.

96. Figures 4.4.7a through 4.4.8b: When you add the stream gages feature class, please add appropriate attributes to support these figures.
Completed. See feature class "tx_gages_Clip" in feature dataset "SurfaceHydro" in the Geodatabase.

97. Figure 4.4.11: Please include time series data to support water level graphs in this figure.
Completed. See the three tables in the Geodatabase: "SURFACEHYDRO_reservoir_sam_rayburn_gdbs", "SURFACEHYDRO_reservoir_somerville_gdbs" and "SURFACEHYDRO_reservoir_choke_canyon_gdbs".

98. Tables 4.5.1 and 4.5.2 (and associated figures 4.5.2 and 4.5.3): Please add supporting data to the future stream gages feature class or as tabular data.
Completed. See tables "Hydro_Sep_Outcrop_Flux_" and "Baseflow_Regression_Anal_Result_" in the Geodatabase.

99. Figure 4.5.4: Please include a sub-watersheds feature class.
Completed. Completed. See feature class "gage_subbasins_wgs72d" in feature dataset "SurfaceHydro" in the Geodatabase.

100. Figures 4.5.5 through 4.5.7: Please include supporting tabular data.

Completed. Tabular data for Figures 4.4.5 and 4.4.6 can be found in table "Baseflow_vs_Precip_Data_" in the Geodatabase. Since the curve in Figure 4.4.7 graphically shows Equation 4.4.1, the tabular data are theoretical and were not added to the Geodatabase.

101. Figure 4.5.9: As a suggestion, using a two color scheme (positive or negative values) yields a clearer picture of recharge and discharge areas.
Completed. See Figure 4.4.9.

102. Figures 4.5.10a and 4.5.10b: Please include a feature class or raster dataset for saturated soil conductivity.
Completed. See rasters is in "SoilGrids" in the Geodatabase.

103. Table 4.6.3: Please verify the totals listed in the "SUBHYD_pumping_municipal_by_county" table. Numbers by county do not add up to the totals listed.
Completed. See Table 4.6.3 in the report and table "MUN_Pumping_by_ County_Rev_" in the Geodatabase.

104. Table 4.6.4: This table and the "SUBHYD_pumping_manufacturing_by_county" table show inconsistent use of double-type (floating) numbers. Please revise the tables and the totals.
Completed. See table 4.6.4 in the report and table "MFG_Pumping_by _County_Rev_" in the Geodatabase.

105. Tables 4.6.5 through 4.6.8: Same issue as comment 38 above. Please revise (some totals are significantly different).
Completed. See tables 4.6.5 through 4.6.7 in the report and tables "IRR_Pumping_by_County_Rev_", "STK_Pumping_ by_County_Rev_", and"RD_Pumping_by_County_Rev_" in the Geodatabase. Note that Table 4.6.8 was removed from the report and corresponding table "SUBHYD_pumping_ mining_by_county"was removed from the database..

106. Figure 4.6.1: Please include a feature class/raster dataset for potential ET.
Completed. See raster "pet" in "ClimatePRISM".

107. Figure 4.6.2: Please include a feature class/raster dataset for GAP vegetation coverage.
Completed. "See raster "land_cov" in "ConservationLandUse"

108. Figures 4.6.5a and 4.6.5b: Please include a feature class for population density.
Completed. See feature class "census_blocks_outcrop" in Boundary feature dataset in the Geodatabase.

109. Figures 4.7.1 through 4.7.3: Please include tabular data to support these figures.

Completed. See table "Sand_Clay_Percent_by_Unit_DepFa_" in the Geodatabase.

110. Figures 4.7.5 through 4.7.8: Please include supporting facies data.
Completed. See feature classes "ower_jackson_facies", "lower_Yegua_facies", "upper_jackson_facies", and "upper_yegua_facies" in feature dataset "Geology".

111. Figure 4.8.1: Please include the georeferenced map used in this figure.
Completed. See raster "pj_uc_gam" in SubSurfaceHydroHydraulics catalog

112. Please revise the following top elevation surfaces: top of lower Yegua (TLY), top of upper Yegua (TUY), top of lower Jackson (TLJ), and top of upper Jackson (TUJ). We subtracted the vertically adjacent surfaces and concluded that the surfaces intersect. For example TLY is above TUY.
Completed. The elevation rasters have been corrected.

Geodatabase Metadata

113. 'Cities' feature class: incomplete
This feature class and metadata came with the Geodatabase template from TWDB.

114. 'County' feature class: incomplete
This feature class and metadata came with the Geodatabase template from TWDB.

115. 'uy_isp_c25' raster: missing
The metadata of raster "uy_isp_c25" is not missing.

116. 'lyfrac_c0' raster: missing
The metadata of raster "lyfrac_c0" is not missing.

117. 'EPA_RF1_RiverReach' feature class: incomplete
This feature class and metadata came with the Geodatabase template from TWDB.

118. 'TX_Reservoirs' feature class: incomplete
This feature class and metadata came with the Geodatabase template from TWDB.

119. 'TX_RiverBasins' feature class: incomplete
This feature class and metadata came with the Geodatabase template from TWDB.

120. There are some feature classes that you brought from external sources which have endless fields in the attribute tables. Unless you're willing to document what each field represents, I suggest you remove them if you didn't use them.
Completed.

121. Please document attribute fields in the metadata where necessary.
Completed.

Suggestions:

122. Page 2-29, paragraph 4: Please add hyphen to "sand rich".
Completed. See Section 2.2, paragraph 5.

123. Page 2-29, paragraph 5: Please add "the" before "shale-rich".
Completed. See Section 2.2, paragraph 6/

124. Table 3.0.1: Please change "Alexander (1966)" to "Alexander and others (1966)".
Completed. Changed to "Alexander and White (1966)" since the report has only two authors. See Table 3.0.1.

125. Table 3.0.1: Please change "Baker, … (1974)" to "Baker and others (1974)".
Completed. See Table 3.0.1.

126. Table 3.0.1: Please change "Loskot, … (1982)" to "Loskot and others (1982)".
Completed. See Table 3.0.1.

127. Page 4-1, paragraph 4: Please add a comma after "East Texas" and "Formation" after "Mountain".
Completed. See Section 4.1, paragraph 3.

128. Page 4-2, paragraph 2: Please change "The Yegua varies …" to "The Yegua Formation varies …".
Completed. See Section 4.1, paragraph 4.

129. Page 4-2, paragraph 3: Please change "…Whitsett transitions …" to "…Whitsett Formation transitions …".
Completed. See Section 4.1, paragraph 5.

130. Page 4-4, paragraph 1: Please change "Barnes (1974a," to "Barnes, 1974a".
Completed. See Section 4.1, paragraph 10.

131. Page 4-5, paragraph 3: Please change "aquifer" to "Aquifer".
Completed. See Section 4.2.2, first paragraph.

132. Page 4-11, paragraph 1: Please capitalize "River" and "Creek" when part of the name of a river/creek.

Completed. See Section 4.2.2, heading Environmental Facies, first paragraph.

133. Page 4-12: For Consistency and clarify, please place the Lower Yegua Unit in a section/paragraph of its own as you did with the other units.
Completed. See Section 4.2.2, heading Aquifer Structure Contour Net Sand Maps.

134. Page 4-14, paragraph 2: Please change "Catahoula, …" to "Catahoula Formation, …".
Completed. See Section 4.2.2, heading Upper Jackson Unit, first paragraph.

135. Page 4-43, paragraph 2 (end): Wells completed above the top of the Lower Jackson Unit would fall into the Upper Jackson Unit interval. They should be used for in evaluating water-level data.
Completed. Sentence revised to say wells completed above the top of the Upper Jackson Unit. See Section 4.3, paragraph 2.

136. Table 4.3.4: Your definitions for trends are somewhat inconsistent. For example:
    - 6724401: 343.1 – 343.7 – 345.6 = stable-increase
    - 3757702: 221.6 – 221.7 – 222.7 = increase (would have expected stable-increase)

    Please revise the table.
Completed. See Table 4.3.4 and corresponding changes to text in Section 4.3.3 and Figures 4.3.19 through 4.3.22.

137. Figure 4.6.1: Please reverse the color gradient as it's currently against the visual perception of high and low.
Completed. See Figure 4.6.1.

138. Table 4.4.4: Please ensure that all names are capitalized.
Completed. See Table 4.5.4.

139. Table 4.4.4: Please correct the spelling of "sulhper springs".
Completed. See Table 4.5.4.

140. Page 4-130, paragraph 2: Please delete "(R2)" and change "… an R2 greater than …" to "… a coefficient of determination greater than …".
Completed. See Section 4.4.3, paragraph 5.

141. Page 4-197, paragraph 1: Please make the text in parentheses a separate sentence.
Completed. See Section 4.7.6, last paragraph.

142. Page 4-198, paragraph 1: Please change "1000" to "1,000".
Completed. See Section 4.7.7, heading Transmissivity, paragraph 4.

143. Page 4-221, paragraph 4: Please change "… not used the water quality …" to "… not used in the water quality …".
Completed. See Section 4.8.1, first paragraph.

144. Page 4-222, paragraph 4: Please change “saltiness” to “salinity”.
Completed. See Section 4.8.2, paragraph 3.

145. Page 4-222, paragraph 4: Please change “The degradation of quality …” to “The degradation of water quality …”.
Completed. See Section 4.8.2, paragraph 3.

146. Page 4-223, paragraph 1: Please change “… increasing TDS concentration, …” to “… increasing total dissolved solids, …”.
Completed. See Section 4.8.2, paragraph 4.

147. Page 4-223, paragraph 1: Please change “… 1300 milligrams per liter in 1960 to over 1700 …” to “… 1,300 milligrams per liter in 1960 to over 1,700 …”.
Completed. See Section 4.8.2, paragraph 4.

148. Page 4-223, paragraph 2: Please change “… exceed 1000 …” to “… exceed 1,000 …”.
Completed. See Section 4.8.2, paragraph 5.

149. Page 4-223, paragraph 3: Please capitalize “group” and change “Figure 4.8.6 and 4.8.7” to “Figures 4.8.6 and 4.8.7”.
Completed. See Section 4.8.2, paragraph 6.

150. Page 4-224, paragraph 2: Please change “saltiness” to “salinity”.
Completed. See Section 4.8.2, last paragraph.

151. Page 5-2, paragraph 2: Please add “at the surface” after “… surface water or evaporates …”.
Completed. See Section 5.0, paragraph 4.

152. Page 5-3, paragraph 2: Please change “base flow” to “baseflow”.
Completed. See Section 5.0, paragraph 7.

153. Page 5-3, paragraph 3: Please replace the parentheses with commas.
Completed. See Section 5.0, paragraph 8.

154. Page 5-4, paragraph 1: Please change “base flow” to “baseflow”.
Completed. See Section 5.0, last paragraph.

155. empty

156. Please spell out all abbreviations except TWDB.
Completed.

157. Please change “Formations” to “formations” where it occurs in the text.
Completed.

158. Please reverse the order of elevation intervals in the legends in figures.
Completed.

159. Please change “steady-state conditions” to “pre-development conditions”.
Completed.

160. Please change “Yegua-Jackson” to “Yegua-Jackson Aquifer” where referring to the aquifer.
Completed.

161. Please remove TWDB logos and address, and TWDB report number.
Completed.

162. Please change “et al.” to “and others”.
Completed.

163. Please change the reference for TWDB (2008) to TWDB (2008a) where it appears in the text.
Completed. Changed to 2008a or 2008b as appropriate.

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APPENDIX D

Draft Groundwater Availability Model Report Comments and Responses

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Appendix D
Draft Groundwater Availability Model Report
Comments and Responses

General Comments

This is a well written, comprehensive report, with adequate supporting documentation. It provides detailed explanations of each topic discussed. It was difficult to find problems with the approaches or the content of the report. Staff however did identify some minor corrections that are outlined below.

Specific Comments

1. Page 2-2, paragraph 2: Please name the rivers that lose water to the underlying formations in the southwestern parts of the study area and/or refer to appropriate section in the report that this is discussed. Also, please refer to a figure that contains the rivers and label the rivers.
   Completed. See Section 2.0, last paragraph.
2. Page 2-15, paragraph 2: Section discusses land surface elevation in the study area as wells as in specific counties; however, the county map is not labeled (Figure 2.1.2). Please update Figure 2.1.2 so text and figure agrees.
   Completed. See Figure 2.1.2.
3. Page 2-27: Please update this section with appropriate references to support the following statements on opening of the Gulf of Mexico, salt formation and extent, and transfer faults.
   Completed. See Section 2.2, paragraph 2.
4. Page 2-28, paragraph 2: Section talks about Toledo Bend Reservoir and refers to Figure 2.2.2.a,b but the figure does not show the reservoir. Please update figure so figure and text agree.
   Completed. See figure 2.2.2a
5. Page 2-30. Figure 2.2.1: Please correct spelling from “Mayor Sediment Sources” to “Major Sediment Sources”. Please put references in the caption for different structural elements presented on the map such as transfer faults and limits of salt deposition. Also please define in the text what transfer faults mean.
   Completed. See Figure 2.2.1 and Section 2.2, paragraph 2.
6. Page 3-1, paragraph 3: Please change “aquifer geochemistry” to “groundwater geochemistry”.
   Completed. See Section 3.0, third paragraph.
7. Page 3-3, paragraph 2: Please change the sentence “Williamson and Grubb (2001) extended the earlier efforts to included modeling of density dependent flow” to “Williamson and Grubb (2001) extended the earlier efforts and included modeling of density dependent flow to better characterize effects of salinity on groundwater movement in the aquifers.”
   Completed. See Section 3.0, paragraph 9.
8. Page 4-8, paragraph 1: Please define transfer fault before describing their distribution in the study area (see comment 5).
   Completed. See Section 4.2.1, last paragraph.

9. Page 4-10, paragraph 2: Please correct spelling from “chronostratigaphic” to “chronostratigraphic”
Completed. See Section 4.2.2, paragraph 6.

10. Page 4-11, paragraph 3: Please refer to figure that contains the three boundaries (e.g., Knox and others (2007), Barnes (1992) and the current boundary).
Completed. See new Figure 4.2.2.

11. Page 4-14, 1st paragraph: This paragraph discusses figure 4.2.6 and states an area between the Brazos and Navasota rivers shows a mix of lithologies. Please update and label the Brazos and Navasota rivers in figure 4.2.6 to clarify the area in the figure that the text is referencing.
Completed. See Figure 4.2.7 (previously Figure 4.2.6).

12. Page 4-22 and 4-23: Please label each of the boundaries for what they represent.
Completed. See Figures 4.2.3 and 4.2.4 (previously Figures 4.2.2 and 4.2.3).

13. Section New Hydrograph Separation Analyses, pages 4-128 to 4-129, Figure 4.5.6 on page 4-143 and Section 5.0, page 5-3. first paragraph: Please clarify you are referencing Gonzales County, Texas and update all references from Gonzalez County to Gonzales County.
Completed. See Section 4.5.1, New Hydrograph Separation Analyses Heading; paragraph 1, Figure 4.5.6 title; and Section 5.0, paragraph 7.

14. Section 4.8.2 Drinking Water Quality, paragraph 6, last sentence: Please clarify you are referencing Angelina County, Texas and update all references from Angeline County to Angelina County.
Completed. See Section 4.8.2, paragraph 6.

15. Figure 4.6.25, page 4-186: The “Total” line is missing from the graph. Please update figure to include total pumpage.
Completed. See Figure 4.6.25.

16. Figure 5.0.1, page 5-4: Please correct the spelling of Catahoula.
Completed. See Figure 5.0.1.

17. Section 6.1, page 6-1, paragraph 3: Please update with version of Groundwater Vistas used for files submitted. Text references version 4; however, this version is not compatible with the reservoir package therefore version 5.2 or later is more appropriate.
Completed. See Section 14. Groundwater Vistas version has been updated to 5.41.

18. Section 6.3.4, page 6-14: Section references Scanlon and others (2005); however, the report developed for the TWDB entitled Evapotranspiration Estimates with Emphasis on Groundwater Evapotranspiration in Texas by Scanlon and others (2005) may be a more valid reference. Please clarify and update the reference section and appropriate text citations throughout the report as needed.
Completed. See Section 14.

19. Section 7.1, pages 7-1 to 7-4: Per Exhibit B, Attachment 1, Section 3.3, paragraph 2: Please expand discussion to discuss difference between the total simulated inflow and the total simulated outflow (that is, the water balance) shall be less than one percent and ideally less that 0.1 percent.

Completed.

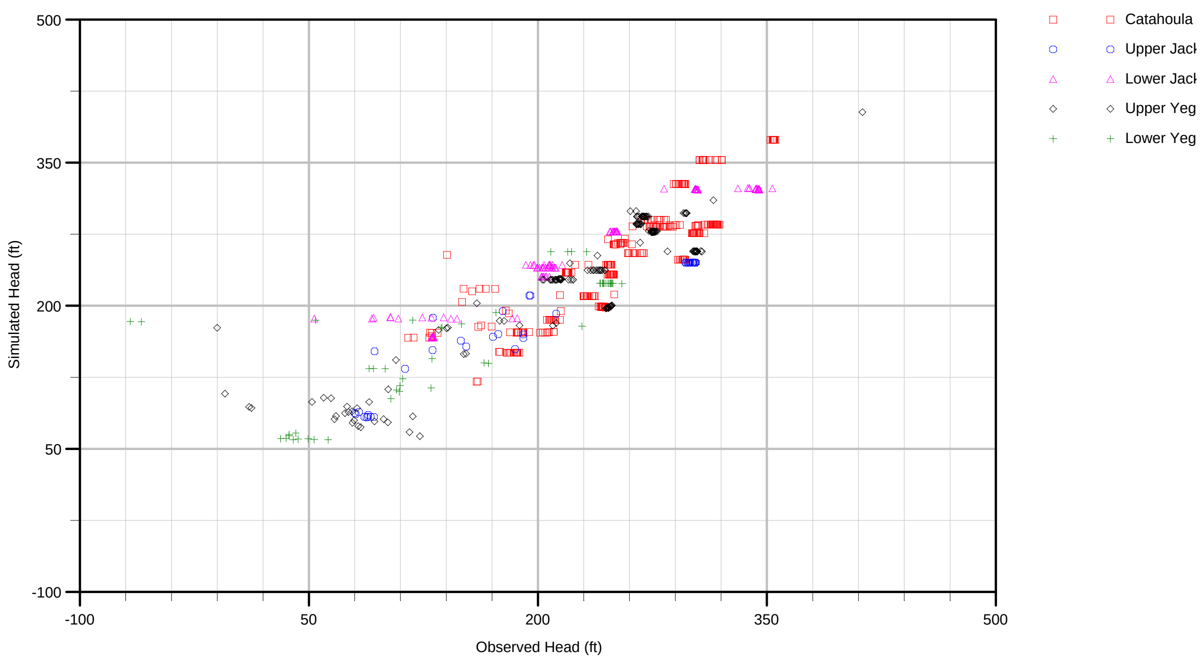
20. Section 7.1, pages 7-1 to 7-4: Please introduce Parameter Estimation (PEST) software as an approach for calibration including a brief description of the software, purpose, and approach used.
Completed.

21. Section 8.1.4, first paragraph: Please provide more details on where and by how much the boundary heads were adjusted from the original values.
Completed. Text added, and a full description of GHB construction and modification, along with code are enclosed with the data model, as per Comment 33.

22. Figure 8.1.12, page 8-18: Updip extent of model in figure matches the legend indicating stream conductance (ft2/d) of 1,000,000 to 10,000,000 and active boundary (indicated as red in the legend) is missing in the figure. Please revise figure so active boundary is noted in red.
Completed.

23. Section 8.0, all figures: Please update all appropriate figures and/or captions to explain abbreviations in the legends such as ft/d, in/yr, ft2/d, ft, AFY/cell and gpm.
Completed. See Figure 8.1.10, all other figures in this section have the abbreviations spelled out in the figure title.

24. Page 9-19. Model output results for simulated versus observed heads for the transient model for 1997 look somewhat different than what has been presented in Figure 9.2.1. Differences are mostly in the assignment of a few targets with respect to the aquifers. Also, cross-plots in the report do not show the Catahoula heads, which may still be useful to see the level of fit between observed and simulated heads.

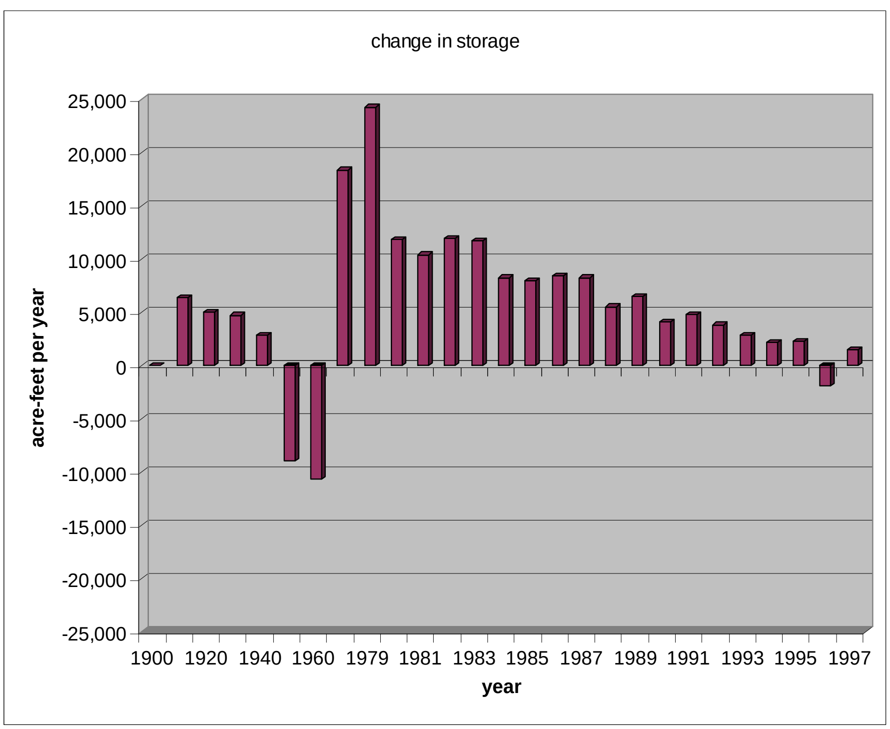


Completed. Figure 9.2.1 has been updated. It is consistent with the above figure after the update. Since Catahoula Formation represents a boundary condition only, the

model calibration does not include any head targets from the Catahoula Formation. Therefore, the cross-plots in the report do not show the Catahoula heads. The head targets in model layer 1 represent Yegua-Jackson Aquifer heads in the shallow layer of the model.

25. Section 9.2.3, first paragraph: Please clarify discussion of the cross-formation flow for surficial and confined. Is "confined flow" the top and bottom values? For the "surficial flow" is this flow out of the base of layer 1?
Completed. Surficial is flow between units within Layer 1. Top and bottom are the confined flow (not Layer 1) between units. An explanation was added to this section.

26. Section 9.2.3, 2nd paragraph: The discussion of the water budget does not make note of the decline in storage in the 1950's and 1960's shown in the following plot (please note signs have been switched on the model budget output for this figure so that negative change in storage indicates declining heads). Please discuss this switch from net rising heads to declining heads then back to net rising. It seems to correspond in time to the sharp decline observed in several hydrographs.
Completed. The slight increase in storage before 1940 is due to the small contribution of water to the Catahoula (Layer 1, gulfward of the outcrop) from the Jasper, represented by the GHBs. The rising heads are not significant in any of the active portions of the model (i.e., the Yegua-Jackson units), as evidenced by the flat hydrographs before 1950 or so. When pumping begins in some portions of the model around 1950, storage becomes a net contributor (water is removed from storage) as heads decline. This trend would continue, were it not for the contribution to storage from recharge due to the influence of the reservoirs coming online in the 1960s. This increased contribution from recharge is due to the replacement of gaining streams with reservoirs in some areas. This explanation was added to the text.



27. Section 11.0, pages 11-1 to 11-2: Please expand section to relate future improvements to sensitivity analyses, in other words, since the model is sensitive to adjustments to selected parameters for example recharge, stream conductance, horizontal conductivity of the shallow layer then additional studies of these parameters would better constrain the model and provide additional insight. For example the assumption of no recharge in the southern portion of the model if precipitation was less than around 22 inches per year would be a project that could be conducted to validate this assumption.
Completed. The section already contains recommendations for additional studies of recharge and discharge relationships, including baseflow studies. Additional recommendations regarding recharge studies were added.

Comments from Draft Conceptual Model

28. Response to comment 1: Section 1.0, Page 1-2, line 1: An intersection of counties and aquifer boundary yields 34 counties. Please revise. *Please adjust response to reference paragraph 4 instead of paragraph 3.*
Completed. See Appendix C, comment 1.

29. Response to comment 6: Section 2.0, Page 2-2, paragraph 1: Please delete "…and Underground Water Conservation Districts (UWCDs)…" and "… and UWCDs". *Please adjust response to reference paragraph 5 instead of paragraph 4.*
Completed. See Appendix C, comment 6.

30. Response to comment 7: Section 2.0, Page 2-2, paragraph 1: In this paragraph, please revise the text to reflect the number of regional water planning areas, groundwater conservation districts, groundwater management areas, and river authorities that intersect the aquifer and not the study area. *Please adjust response to reference paragraph 5 instead of paragraph 4.*
Completed. See Appendix C, comment 7

31. Response to comment 29: Figures 4.5.5 and 4.5.6: Please add the coefficient of determination value for each correlation. Section 5.0 Figure 5.1: If the younger sediments will be represented as a layer in the model, they should be represented as a rectangular box in this figure similar to the other model layers. *Please revise the figure to reflect this. Please adjust response to reference table 4.4.2 instead of table 4.5.2.*
Completed. See Appendix C, comment 29.

32. Response to comment 90: Geodatabase and Figures, Table 4.4.5: Please adjust surface area numbers to match actual numbers from the 'reservoirs_ygjk_gam_outcrop" feature class. *Please clarify if the name of the feature dataset is "SurfafceHydro" or "SurfaceHydro" and adjust the response as needed.*
Completed. See Appendix C, comment 90.

Model Review

33. As discussed in Section 6.3.2 Vertical Boundaries, pages 6-10 to 6-12: Please provide under separate cover scripts or additional information concerning the extraction and interpolation of heads from the Gulf Coast Aquifer groundwater availability models so this may be replicated for the development of predictive simulations. Also include specific locations where this was adjusted during calibration including the amount of adjustment, as applicable.

Completed. See "scripts" directory in data model submittal.

Geodatabase

34. The top elevation surfaces, as they were delivered, still intersect the DEM. If you used a different DEM or applied smoothing, please provide the surface so we can better interpret the data.
Completed. A 0.2-mile-average DEM was used for the outcrop elevation surfaces instead of the original 30-meter DEM. The 0.20-mile-average DEM has been uploaded to GeologyGrids raster dataset as dem5th.

35. Figure 4.8.6: The spatial distribution of wells in this figure does not match that of the feature class "JCKS_N_most_recentshp". Please revise.
Completed. Figure 4.8.6 has been corrected.

36. Figure 4.8.7: The spatial distribution of wells in this figure does not match that of the feature class "YEGUA_N_most_recentshp". Please revise.
Completed. Figure 4.8.7 has been corrected.

37. Figure 6.3.13 does not accurately represent the data (pumping present in the table is missing from large areas in the figure). Please revise.
Completed. Figure 6.3.13 has been updated to show the exact pumping.

38. Figures 8.1.6 – 8.1.9: Please include a feature class for the vertical hydraulic property.
Completed. A feature class "vertical conductivity" has been uploaded to ModelHydraulicProperties feature dataset.

39. Several feature classes that are based on the model grid have negative areas in the Shape_Area field. Please run the Repair Geometry tool on these feature classes to correct the ring ordering.
Completed.

40. Figures 9.2.15 – 9.2.23: Please add a note distinguishing between measured and simulated water levels.
Completed. The figure captions were modified to indicate the symbols for measured and simulated water levels.

41. Please correct metadata (figure references) for "frame_up" and "frame_low" feature class to match report.
Completed.

42. Please correct metadata for "GulfOfMexico" feature class. It currently refers to PRISM data.
Completed.

43. Please correct metadata for "ppt_yr7100in" raster. It currently mentions maximum temperature and both monthly and annual precipitation.
Completed.

44. Please add metadata for "pet" raster.
The "pet" raster has been replaced by "evtmax_yj" raster and the metadata is added.

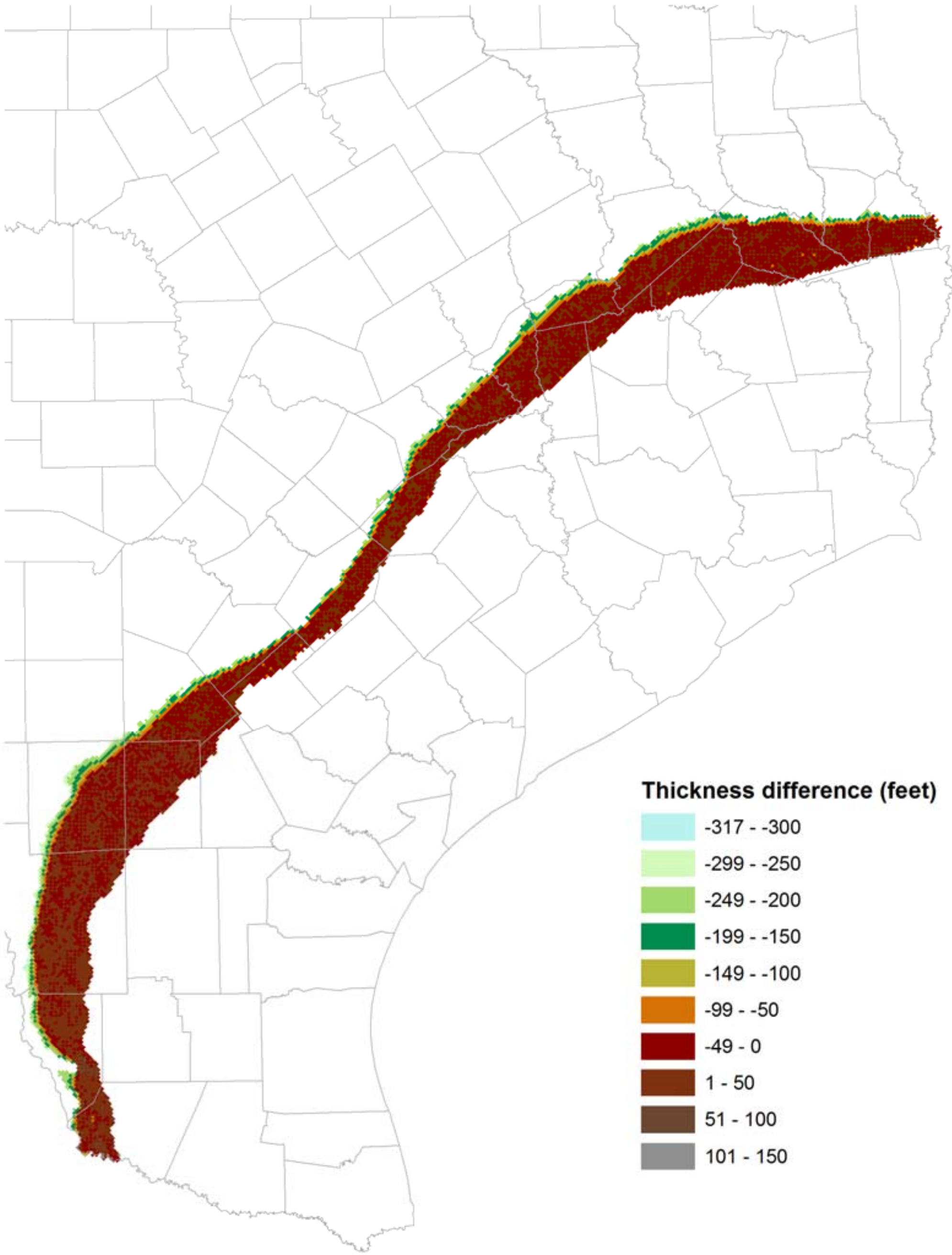
45. Please revise the names of the following feature classes: “Layer1_1980” through “Layer4_1997” because the model has five layers and the numbering is inconsistent with the aquifer unit they represent.
Completed. The names of feature classes “Layer1_1980” through “Layer4_1997” have been changed to “UpperJackson_1980” through “LowerYegua_1997”.

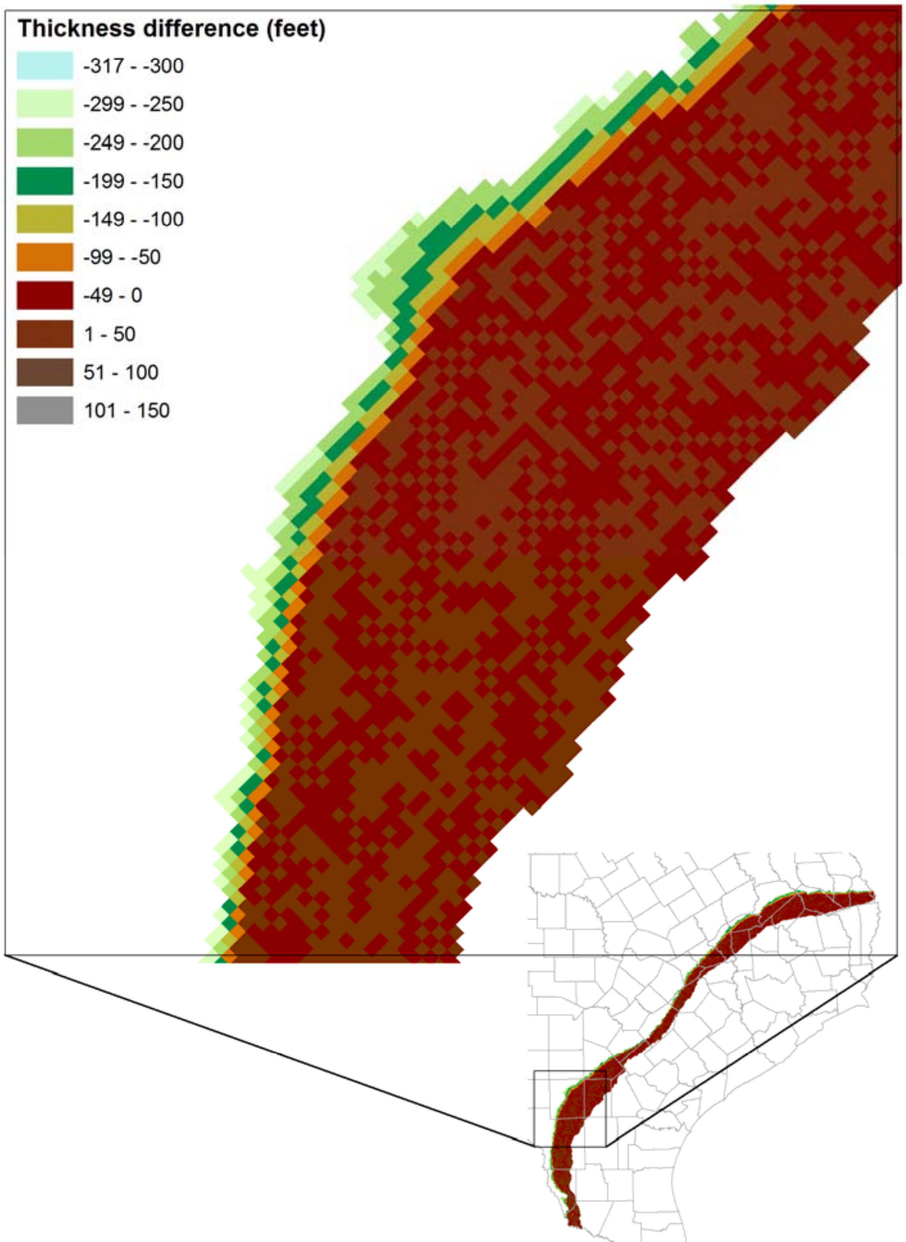
46. Please revise the names of the following feature classes: “SS_Layer1” through “SS_Layer4” because the model has five layers and the numbering is inconsistent with the aquifer unit they represent.
Completed. The names of feature classes “SS_Layer1” through “SS_Layer4” have been changed to “SS_UpperJackson” through “ss_LowerYegua”.

47. Please correct numerous misspellings throughout the geodatabase metadata.
Completed. We took another look at all of the data descriptions and corrected misspellings that were found.

48. We compared the total thickness of the aquifer in the outcrop using both the raster surfaces and the model derived thickness and discovered a consistent increase of the model thickness in the updip portion of the aquifer. Below are the steps used to calculate and compare:
    - We subtracted the bottom of the aquifer from the DEM and performed a zonal statistics (MEAN) using the model grid.
    - We extracted from the model the top of layer 1 and the bottom of layer 5 and subtracted the bottom from the top on a cell-by-cell basis.
    - We then compared the two thicknesses on a cell-by-cell basis.

    The comparison shows good match with the exception of the updip area across the entire aquifer where there’s a clear pattern of thickening. Please provide an explanation (see following two figures).
    This inconsistency in the furthest updip portion of the aquifer was caused by setting the minimum depth of layer 1 (the shallow layer) to the approximate water table, in order to eliminate dry cells and increase model stability. We have added text to Section 6 noting this effect, and have added text to Section 10.3 (Limitations to Model Applicability) to describe how this might impact “water-in-place” calculations of water availability.


Thickness difference (feet)
-317 - -300
-299 - -250
-249 - -200
-199 - -150
-149 - -100
-99 - -50
-49 - 0
1 - 50
51 - 100
101 - 150



Additional Suggestions

49. Introduction, Section 1.0, page 1-1, paragraph 2; Study Area, Section 2.0, page 2-1, paragraph 2; Irrigation Return Flow, Section 4.4.4, page 4-110, paragraph 3, and Table 4.5.1, page 4-132: Please delete the word “River” when referencing the Rio Grande as this is redundant.

Completed. See Section 1.0, paragraph 2; Section 2.0, paragraph 2; Section 2.2, paragraph 3; Section 4.4.4, paragraph 3; and Table 4.5.1.

50. Section 1.0, 5th paragraph and Section 2.0, paragraph 2, last sentence: Please change the spelling of desalinization to desalination.
Completed. See Section 1.0, paragraph 5 and Section 2.0, paragraph 2..

51. Section 2.1, 2nd to last sentence of Paragraph 1: Please change "…outcrop lies completed in the …" to " … outcrop lies completely in the…"
Completed. See Section 2.1, paragraph 1.

52. Section 4.2.2, paragraph 4, 1st sentence: Please insert "of" between use and geophysical logs—"use of geophysical logs".
Completed. See Section 4.2.2, paragraph 4.

53. Section 4.4.1, first sentence in first full paragraph: Please change "…where recharge primary occurs…" to "…where recharge primarily occurs…"
Completed. See Section 4.4.1, paragraph 4.

54. Table 4.5.1, page 4-132: Please add leading zero to gage 8024400 to be consistent with other U.S. Geological Survey gages.
Completed. See Table 4.5.1.

55. Table 4.5.4, pages 4-134 to 4-135: Please verify spelling in Spring name/number column, such as "Ceistern" and "Aqua Verde (geen water) Springs" and update as needed.
Completed. See Table 4.5.4.

56. Figure 4.6.2: Please include classification number with written description of vegetation cover in the legend for easier comparison with Figure 4.6.3.
Completed. See Figure 4.6.2.

57. Section 4.7.3, Lithology, paragraph 4, 1st sentence: Please change "… exist were sand percentages…" to " …exist where sand percentages…".
Completed. See Section 4.7.3, Lithology Heading, last paragraph.

58. Section 4.7.6, 1st paragraph, 1st sentence: Please change "Although the primarily …" to "Although the primary…"
Completed. See Section 4.7.6, first paragraph.

59. Section 4.7.7, Storativity, last sentence of last paragraph: Please change "… to calibrate a regioned model …" to "… to calibrate a regional model …"
Completed. See Section 4.7.7, last paragraph.

60. Section 4.8.2 Drinking Water Quality, paragraph 4, last sentence: Please insert well number (8616705) after Zapata County so reader can more easily locate graph on Figure 4.8.3.
Completed. See Section 4.8.2, paragraph 4.

61. Section 6.3.5, paragraph 3, second to last sentence: Please change "…interval fell with a single …" to "… interval fell within a single…"
Completed. See Section 6.3.5, paragraph 4.

62. Section 7.1, paragraph 11, last sentence: Please change "We did adjusted model drain …" to "We did adjust model drain …"
Completed. See Section 7.1, paragraph 11.

63. Section 8.1.2, page 8-3, third paragraph: Please revise reference of "..from about 1 feet per day…" to "…from about 1 foot per day…"
Completed. See Section 8.1.2, paragraph 4.

64. Section 8.3, page 8-38, last sentence: Please revise from "…head is most sensitivity to the…" to "…head is most sensitive to the…"
Completed. See Section 8.3, paragraph 6.

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