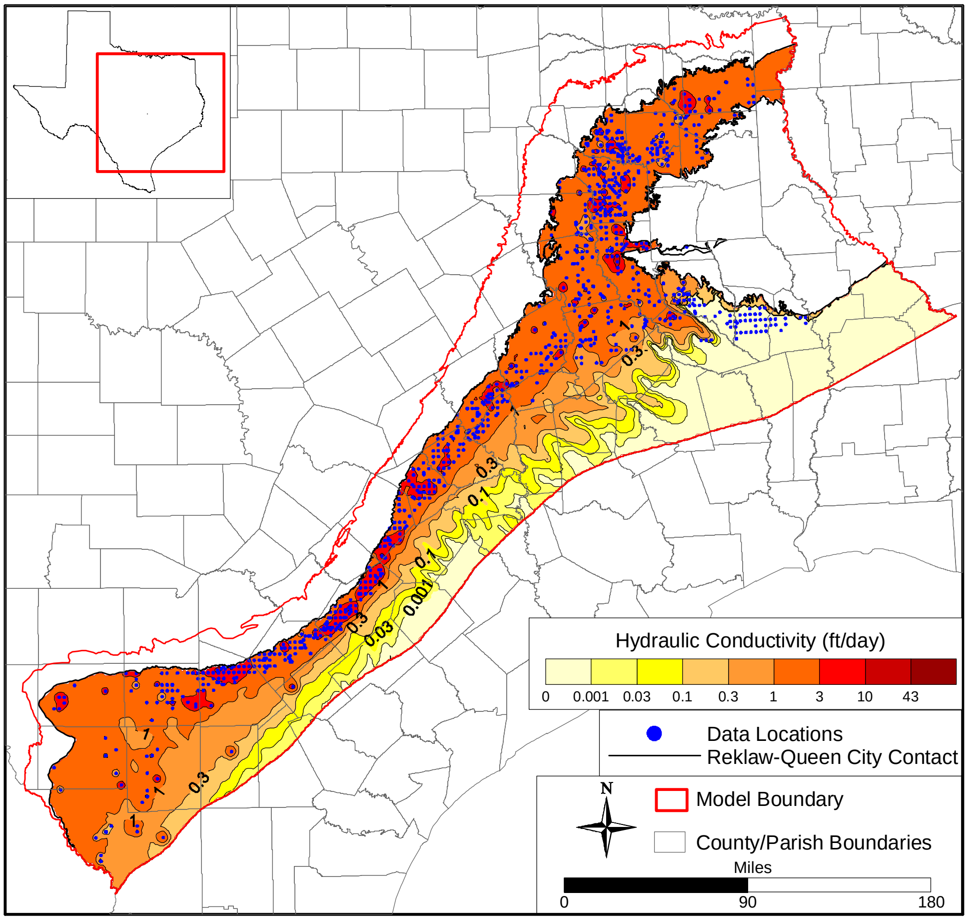
FINAL REPORT

Groundwater Availability Models for the Queen City and Sparta Aquifers



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Texas Water Development Board

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October, 2004

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ABSTRACT

This report documents three-dimensional groundwater flow models developed for the Queen City and Sparta aquifers in Texas. The Queen City and Sparta aquifers are classified as minor aquifers and overlie the Carrizo-Wilcox aquifer. The Queen City and Sparta aquifers were added to the three Carrizo-Wilcox GAMs completed in January of 2003. The Queen City and Sparta GAMs were developed using the same model grids and boundaries as were used for the Southern, Central, and Northern Carrizo-Wilcox GAMs. The boundaries of the three models overlap significantly. In the three Queen City and Sparta GAMs documented herein, all model parameters have been developed consistently. In addition, the Carrizo and Reklaw Formation properties and stresses have been made consistent among the three models. Therefore, these models supercede the existing Carrizo-Wilcox GAMs. This report does not reproduce documentation currently available on the construction and performance of the Carrizo-Wilcox GAMs except to the degree necessary to explain the development of the Queen City and Sparta GAMs or as a result of required changes to the Carrizo and Reklaw Formation model layers.

The three Queen City and Sparta GAMs were developed using MODFLOW. Each model consists of eight model layers representing the Sparta, Queen City, and Carrizo-Wilcox aquifers, as well as the intervening aquitards. The models incorporate the available information on structure, hydrostratigraphy, hydraulic properties, stream flow, and recharge estimates. Original data and interpretation regarding Queen City and Sparta aquifer structure and hydraulic properties is presented in this report.

The purpose of these models is to provide a tool for making predictions of groundwater availability through 2050 based on current projections of groundwater demands during drought-of-record conditions. They have been calibrated to predevelopment conditions (prior to significant groundwater withdrawal), which are considered to be at steady state. The steady-state models reproduce the predevelopment aquifer heads within the estimated head uncertainty. The GAMs were also calibrated to transient aquifer conditions from January 1980 through December 1989, incorporating yearly variations in recharge, ET, streamflow, and pumping. The transient models reproduce aquifer heads within the calibration measures and available estimates of aquifer-stream interaction. The transient-calibrated models were verified by simulating aquifer conditions for the verification period between January 1990 and December 1999, reproducing

observed aquifer heads within the calibration measures and available estimates of aquifer-stream interaction. Minor adjustments of hydraulic properties were required to calibrate the transient models with the exception of the Northern GAM, where vertical hydraulic conductivity of the Reklaw required significant reduction to match historical groundwater levels in the East Texas Basin.

The calibrated GAMs were used to make predictions of aquifer conditions for the next 50 years based upon projected pumping demands as developed by the Regional Water Planning Groups. The predictive modeling indicated drawdown within the Sparta and Queen City aquifers in the Southern GAM in southern Atascosa County and along the northeastern model boundary. In the Central GAM the most persistent drawdown in the Sparta and Queen City aquifers occurred within Fayette and adjoining counties. In the Northern GAM, Sparta and Queen City aquifer drawdowns are predicted to be more isolated and of lesser magnitude than in the Central GAM.

The GAMs documented in this report provide an integrated tool for the assessment of water management strategies to directly benefit state planners, Regional Water Planning Groups (RWPGs), and Groundwater Conservation Districts (GCDs). The models are developed at a grid scale of one square mile. At this scale, the models are not capable of predicting aquifer responses at specific points such as a particular well. The GAMs are accurate at the scale of tens of miles, which is adequate for understanding groundwater availability at the regional scale. The GAM models are well suited for refinement for study of more local-scale issues related to specific water resource questions. Questions regarding local drawdown to a well should be based upon analytical solutions to the diffusion equation or a refined numerical model.

The three Queen City and Sparta GAMs have significant overlap areas. To address this conundrum, Section 11.3 of this report provides recommendations regarding which GAM should apply in the various planning regions in Texas. This should not preclude an individual GCD from developing a sub-regional model which may use pieces from two GAMs.

1.0 INTRODUCTION

The Queen City and Sparta aquifers are classified as minor aquifers in Texas (Ashworth and Hopkins, 1995). Groundwater use for the Queen City and Sparta aquifers is relatively minor with reported water uses of 14,000 and 6,800 acre-feet per year (AFY) in 1997, respectively (TWDB, 2002). However, these two minor aquifers are important water resources in the state with groundwater availability estimates of 680,000 AFY for the Queen City aquifer and 160,000 AFY for the Sparta aquifer under drought conditions in the year 2000 (TWDB, 2002). These aquifers extend from the Frio River in south Texas to east Texas with the Sparta aquifer continuing into Louisiana and Arkansas. The Queen City aquifer provides water to all or parts of 31 Texas counties. The Queen City is used primarily for livestock and domestic purposes with significant municipal and industrial use in northeast Texas (Ashworth and Hopkins, 1995). The Sparta aquifer provides water to all or parts of 20 Texas counties. The Sparta aquifer is used for livestock and domestic needs along its extent with some municipal, industrial, and irrigation use locally (Ashworth and Hopkins, 1995).

The Texas Water Code codified the requirement for the development 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, 2002). Senate Bill 1 and subsequent legislation directed the Texas Water Development Board (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 and predicting future aquifer conditions. Inherent to the groundwater model are a set of equations which are developed and applied to describe the physical processes considered to be controlling groundwater flow in the aquifer system. It can be argued that groundwater models are essential to performing complex analyses and in making informed predictions and related decisions (Anderson and Woessner, 1992). As a result, development of Groundwater

Availability Models (GAMs) for the major and minor Texas aquifers is integral to the state water planning process. The purpose of the GAM 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 Queen City and Sparta GAMs were developed using a modeling protocol that 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) model verification, (5) sensitivity analysis, (6) model prediction, and (7) reporting. The conceptual model is a conceptual description of the physical processes that govern 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, in this case 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., groundwater levels in wells) can be reproduced. The Queen City and Sparta GAMs were calibrated to predevelopment conditions (i.e., conditions prior to significant resource use and assumed to be at steady-state) and to transient aquifer conditions from 1980 through 1989. Model verification is the process of using the calibrated model to reproduce observed field measurements not used in the calibration to test the model's predictive ability. The Queen City and Sparta GAMs were verified against measured aquifer conditions from 1990 through 1999. Sensitivity analyses have been performed on both the steady-state and transient models to offer insight on the uniqueness of the model and on the uncertainty in model parameter estimates. Model predictions were performed from 2000 to 2050 to estimate aquifer conditions for the next 50 years based upon projected pumping demands developed by the Regional Water Planning Groups (RWPGs). This report documents the Queen City and Sparta GAMs and their development, calibration, and application consistent with standard requirements specified by the TWDB in their Request for Qualifications.

Consistent with the state water planning policy, the Queen City and Sparta GAMs have been developed with the support of stakeholders through quarterly stakeholder forums. The purpose of these GAMs is to provide a tool for RWPGs, Groundwater Conservation Districts

(GCDs), River Authorities, and state planners for the evaluation of groundwater availability and to support the development of water management strategies and drought planning. The Queen City and Sparta GAMs intersect ten of the sixteen Texas RWPGs. The Queen City aquifer is projected to experience an increase in demand of nearly 65 percent from existing sources in Texas by the year 2010 (TWDB, 2002). The Sparta aquifer demand from existing sources is expected to remain at or below the year 2000 estimate (40,034 AFY) which is significantly higher than the reported use in 1997 of 6,800 AFY (TWDB, 2002). The Queen City and Sparta GAMs provide tools for use in assessing these strategies.

The Queen City and Sparta aquifers overlie the Carrizo-Wilcox aquifer. The Queen City and Sparta GAMs are unique because they were added to the three Carrizo-Wilcox GAMs which were completed in January of 2003. The existing Carrizo-Wilcox GAMs are fully documented in three reports (Deeds et al., 2003; Dutton et al., 2003; and Fryar et al., 2003) and are available to the public at http://www.twdb.state.tx.us/RWPG/rpfgm_rpts.asp. The existing Carrizo-Wilcox GAMs have significant overlap between their model boundaries. In addition, the three GAMs were developed somewhat independently by different modeling teams. As a result, some differences in hydraulic parameters and pumping distribution exist between the three GAMs in the overlap regions.

The scope of the Queen City and Sparta GAMs was modified so that the Carrizo aquifer GAM properties could be made consistent in the overlap regions. This report does not reproduce documentation currently available on the construction and performance of the Carrizo-Wilcox GAMs except to the degree necessary to explain the development of the Queen City and Sparta GAMs or as a result of required changes to the Carrizo-Wilcox model layers necessitated by incorporation of the Queen City and Sparta aquifers.

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2.0 STUDY AREA

The Queen City and Sparta aquifers, composed of sediments of the Tertiary Claiborne Group, extend from south Texas northeastward through east Texas. The Queen City aquifer consists of sand, loosely-cemented sandstone, and interbedded clays filling the East Texas Embayment and gently dipping towards the Gulf Coast (Ashworth and Hopkins, 1995). The Sparta aquifer consists of sand and interbedded clays with massive basal sands which gently dip to the Gulf Coast reaching a maximum thickness of 300 feet (Ashworth and Hopkins, 1995). These two aquifers are separated by the Weches Formation which is a glauconitic and marly mud confining unit (Guevara and Garcia, 1972). The Queen City and Sparta aquifers are classified as minor aquifers in Texas (Ashworth and Hopkins, 1995).

As previously discussed, the Queen City and Sparta aquifers were added to the existing Carrizo-Wilcox GAMs. Because these aquifers span Texas from the Rio Grande River to the Sabine River, the Carrizo-Wilcox, Queen City, and Sparta aquifers have been divided into three areas for the purpose of modeling, with each area being modeled separately. The three Queen City and Sparta GAMs are the Northern Queen City and Sparta GAM, the Central Queen City and Sparta GAM, and the Southern Queen City and Sparta GAM (Figure 2.1). These models have significant overlap as shown in Figure 2.1. This report documents all three Queen City and Sparta GAMs. Figure 2.2 shows the active model region (highlighted by the irregular red boundary) with the counties labeled. The model area shown in Figure 2.2 includes all or part of 66 Texas counties, seven Louisiana parishes, and one Arkansas county. Figure 2.3 shows the major cultural features (cities, towns, and highways) and streams and lakes in the study area.

Figure 2.4 shows the surface outcrop and downdip subcrop of the major aquifers in the study area. The major aquifers in the study area include the Carrizo-Wilcox and the Gulf Coast aquifers. Figure 2.5 shows the surface outcrop and downdip subcrop of the minor aquifers modeled in the study area. The minor aquifers in the study area include the Queen City and Sparta aquifers. In addition to these two minor aquifers, the Yegua-Jackson aquifer and the Brazos River Alluvium have also been designated as minor aquifers by the TWDB but are not included in Figure 2.5. The Queen City and Sparta aquifers outcrop between the Carrizo-Wilcox aquifer and the Gulf Coast aquifer in a band paralleling the Gulf Coast from south Texas to east

Texas. The Queen City aquifer and, in isolated locations, the Sparta aquifer also outcrop in the East Texas Basin.

Groundwater model boundaries are typically defined on the basis of surface or groundwater hydrologic boundaries. The study area encompassing all three Queen City and Sparta GAMs is laterally bounded by the Rio Grande River to the southwest and the Red River in southwestern Arkansas and western Louisiana. The upper model boundary is defined by the ground surface between the Midway-Wilcox contact and the Sparta-Cook Mountain contact. South of the Sparta outcrop, the upper model boundary is defined by the top of the Sparta Formation. The lower model boundary is the base of the Wilcox Group representing the top of the Midway Formation. The down-dip boundary of the Queen City and Sparta aquifers has been extended past the limits of fresh water to the updip limit of the Wilcox growth fault zone to be consistent with the Carrizo-Wilcox layers from the Carrizo-Wilcox GAMs. This study area boundary, projected to plan view, is shown in report figures as a red line and provides the limits of the active model area.

The study area encompasses all or part of ten RWPGs from west to east (Figure 2.6): (1) the Rio Grande RWPG (Region M), (2) the South Central Texas RWPG (Region L), (3) the Coastal Bend RWPG (Region N), (4) the Lavaca RWPG (Region P), (5) the Lower Colorado RWPG (Region K), (6) the Brazos RWPG (Region G), (7) the Region H RWPG, (8) the Region C RWPG, (9) the East Texas RWPG (Region I), and (10) the North East Texas RWPG (Region D). The study area includes all or parts of 25 GCDs and Underground Water Conservation Districts (UWCD) (Figure 2.7). These are also listed in Table 2.1. The model study area also contains the southernmost extension of the Bexar Metropolitan Water District.

The study area intersects 12 river authorities: (1) the Nueces River Authority, (2) the San Antonio River Authority, (3) the Guadalupe-Blanco River Authority, (4) the Lavaca-Navidad River Authority, (5) the Lower Colorado River Authority, (6) the Brazos River Authority, (7) the San Jacinto River Authority, (8) the Trinity River Authority, (9) the Angelina-Neches River Authority, (10) the Sabine River Authority, (11) the Sulphur River Basin Authority, and (12) the Red River Authority.

Figure 2.8 shows the Texas river basins in the study area. The model area intersects 16 of the 23 river basins in Texas and 12 of the 13 major Texas river basins. Climate is the major control on flow in rivers and streams. The primary climatic factors are precipitation and evapotranspiration (ET). In general, flow in rivers in the western portion of the model area is episodic with extended periods of low flow, or no flow conditions. These rivers tend to lose water to the underlying formations on average. In contrast, rivers and streams in the central and eastern GAM study area are perennial and tend to gain flow from the underlying geology.

Table 2.1 Groundwater Conservation Districts and Underground Water Conservation Districts within the study area.

Southern Area	Central Area	Northern Area
Bee GCD	Bluebonnet GCD	Anderson County UWCD
Edwards Aquifer Authority	Brazos Valley GCD	Neches and Trinity Valleys GCD
Evergreen UWCD	Fayette County GCD	Pineywoods GCD
Gonzales County UWCD	Lone Star GCD	Rusk County GCD*
Guadalupe County GCD	Lost Pines GCD	Southeast Texas GCD*
Live Oak UWCD	Mid-East Texas GCD	
Medina County GCD	Plum Creek CD	
McMullen GCD	Post Oak Savannah GCD	
Pecan Valley GCD	Lavaca County GCD*	
Uvalde County UWCD		
Wintergarden GCD		

Notes: UWCD is Underground Water Conservation District, GCD is Groundwater Conservation District, and CD is Conservation District.

* Pending confirmation

Table 2.2 provides a listing of the major river basins in the study area along with the river length in Texas, the river basin drainage area in Texas, and the number of major reservoirs within the river basin in Texas (Wermund, 1996a).

Table 2.2 Major river basins in the Queen City and Sparta GAM study area (after Wermund, 1996a).

River Basin	Texas River Length (miles)	Texas River Basin Drainage Area (square miles)	Number of Major Reservoirs
Rio Grande	1,250	48,259	3
Nueces	315	16,950	2
San Antonio	225	4,180	2
Guadalupe	250	6,070	2
Lavaca	74	2,309	1
Colorado	600	39,893	11
Brazos	840	42,800	19
San Jacinto	70	5,600	2
Trinity	550	17,696	14
Neches	416	10,011	4
Sabine	360	7,426	2
Red	680	30,823	7

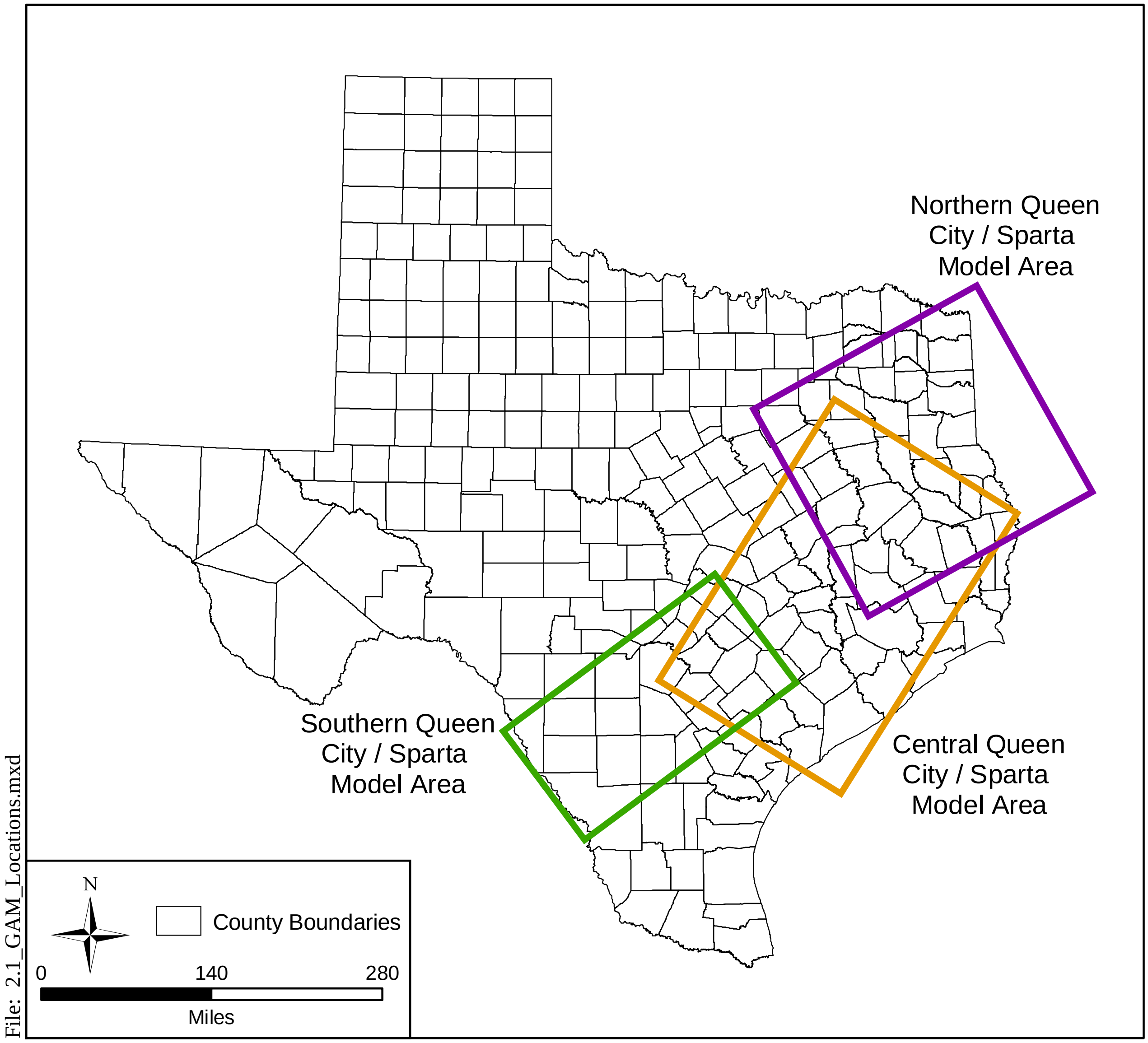

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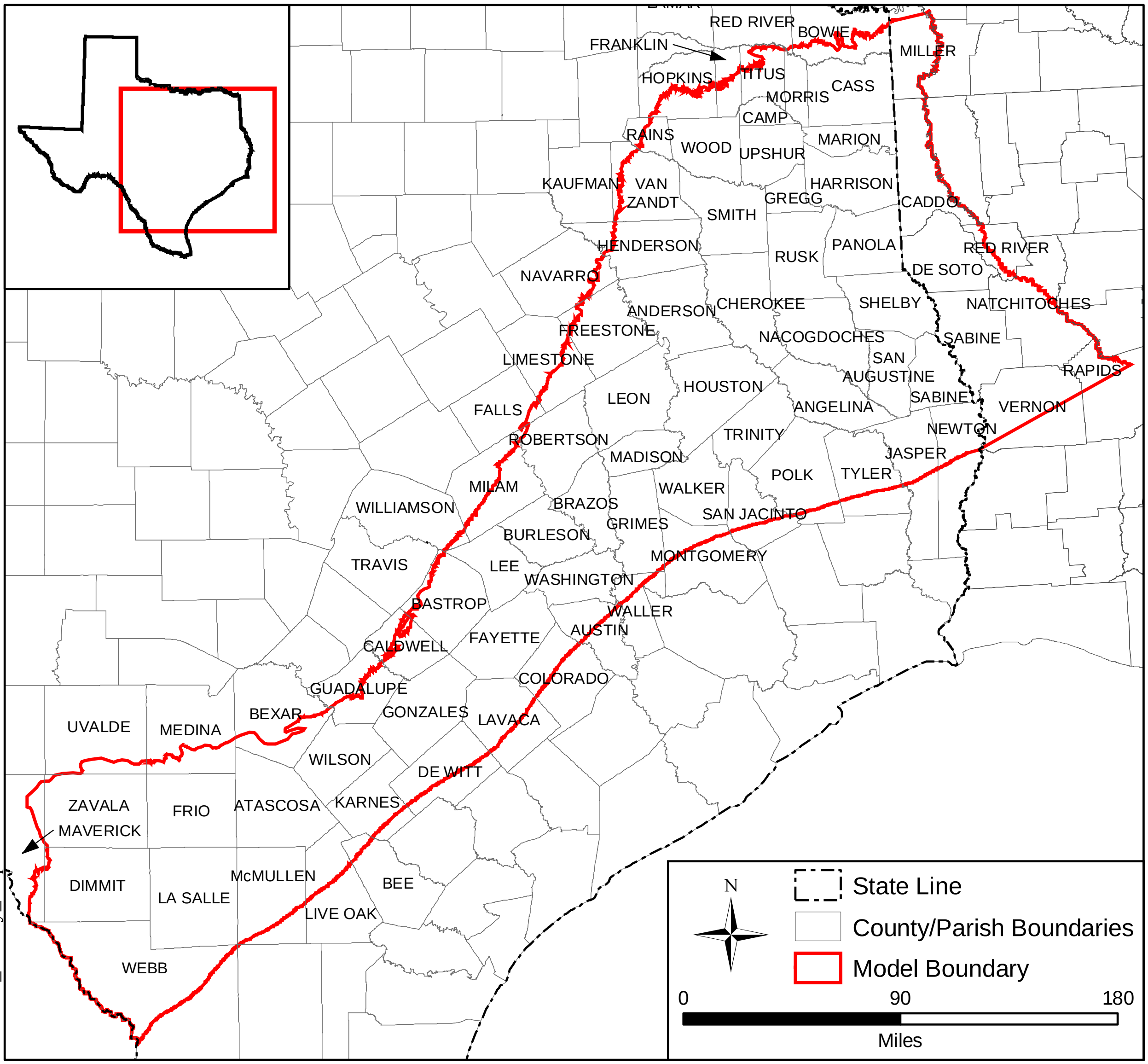
Figure 2.1 Location of the three Queen City and Sparta GAMs.



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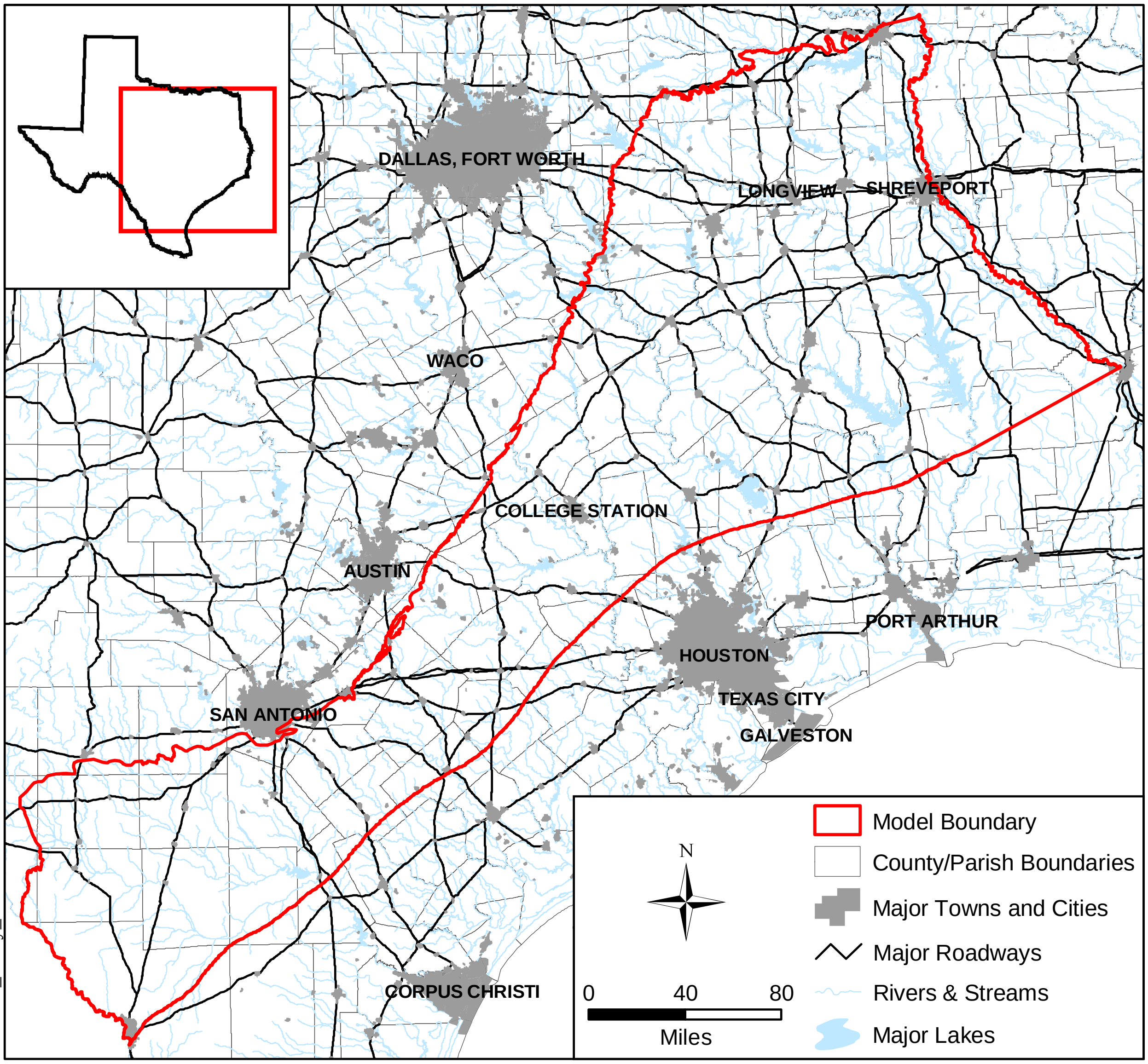
Source: Online: Texas General Land Office, September 2002

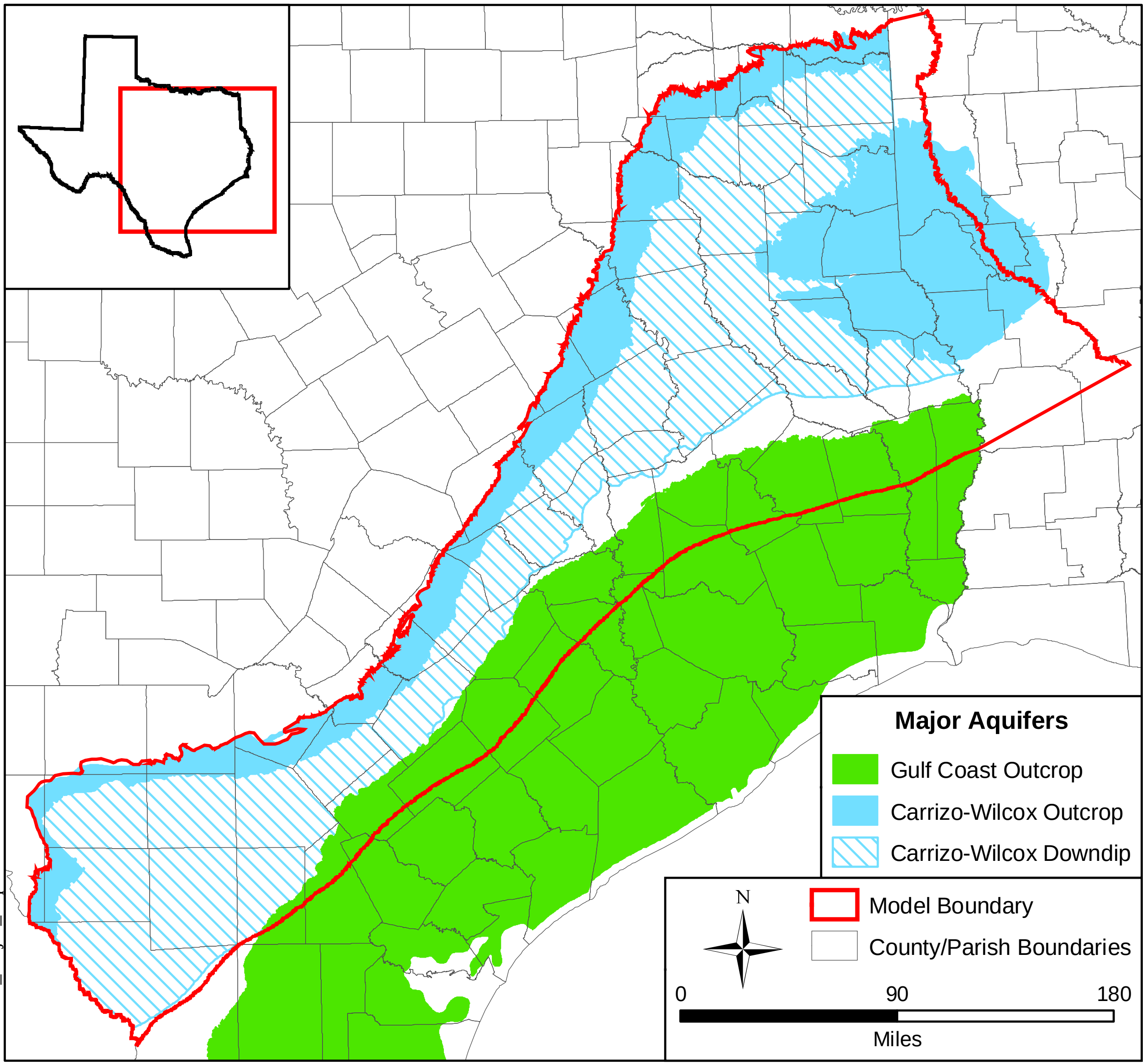
Figure 2.2 Location of the study area showing county boundaries.



File: 2.3_Study_Area

Source: Online: Texas General Land Office, September 2002

Figure 2.3 Locations of cities, lakes, and significant streams in the study area.



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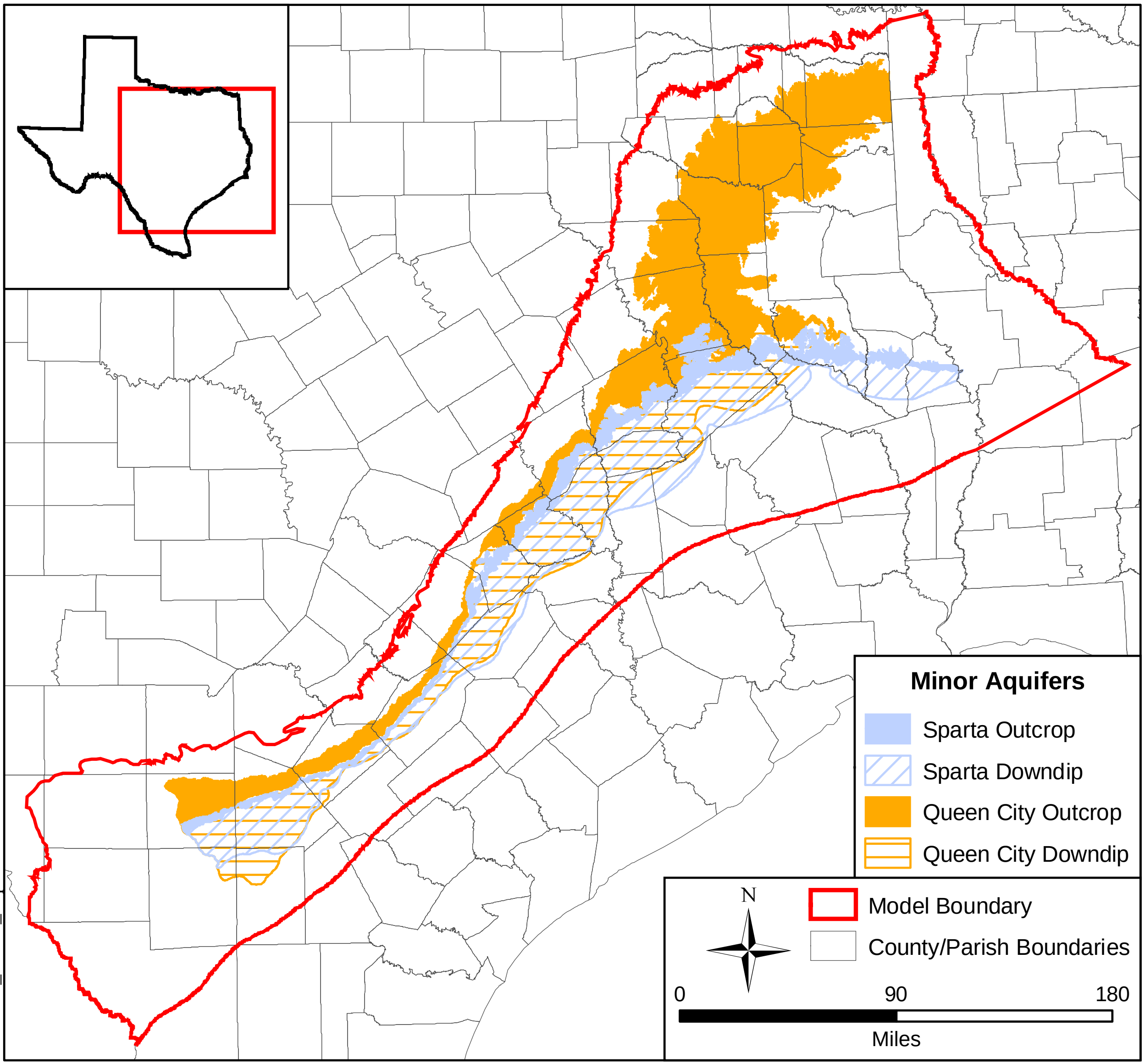
Source: Online: Texas Water Development Board, September 2002, Bureau of Economic Geology

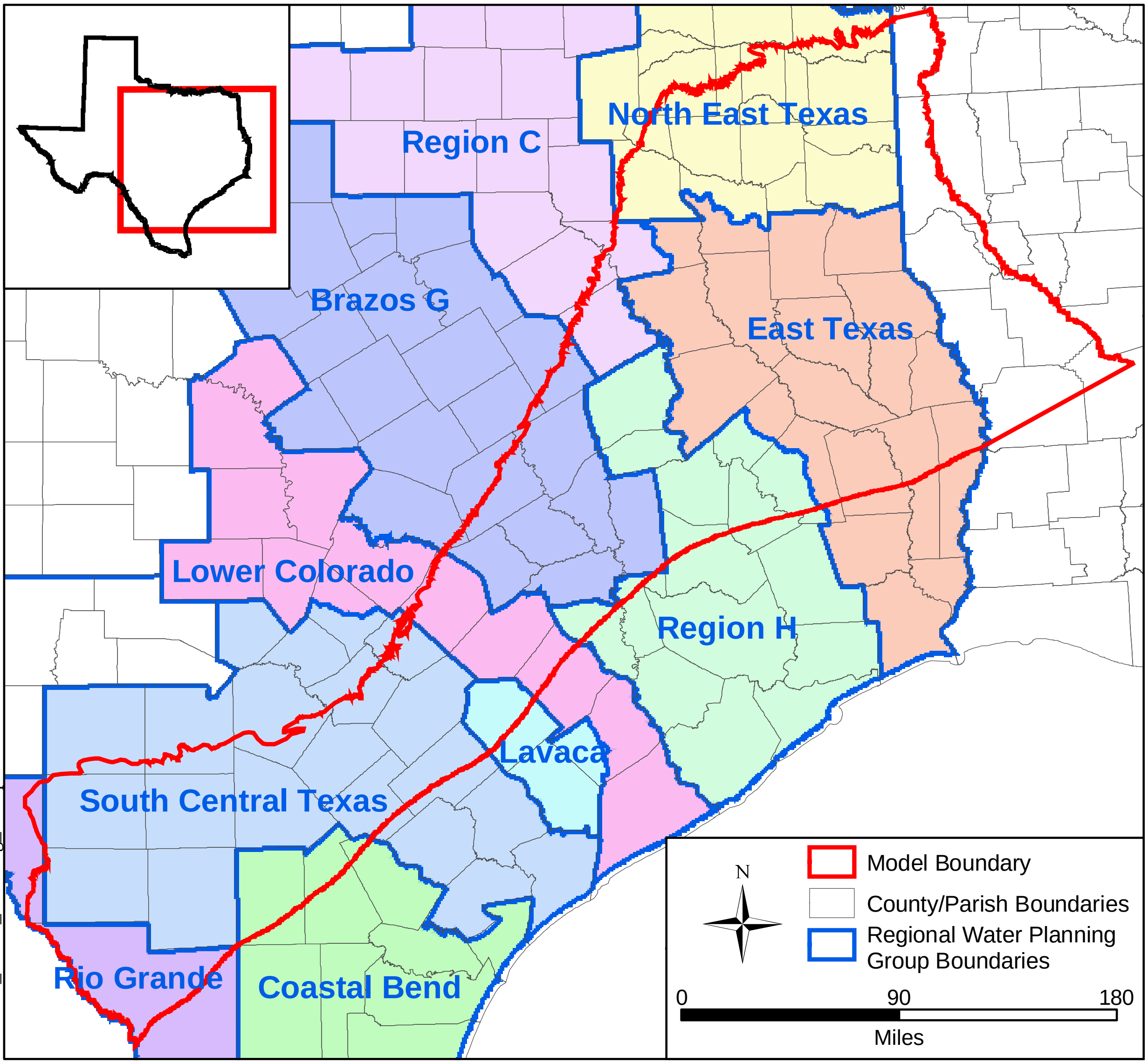
Figure 2.4 Areal extent of the major aquifers in the study area.



File: 2.5_Minor_Aquifers.mxd

Source: Online: Texas Water Development Board, September 2002, Bureau of Economic Geology

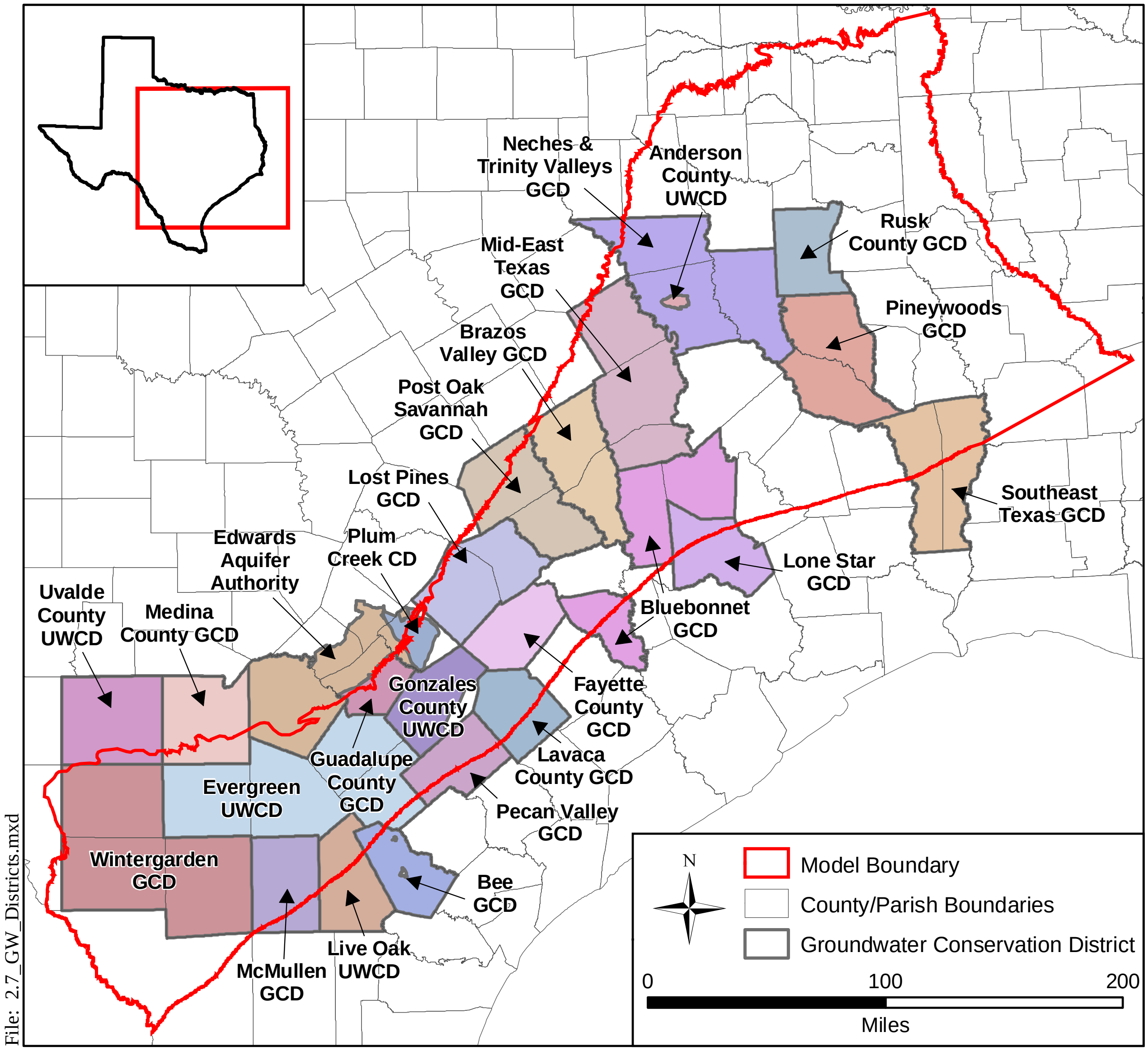
Figure 2.5 Areal extent of the minor aquifers modeled in the study area.



File: 2.6_Water_Planning_Groups.mxd

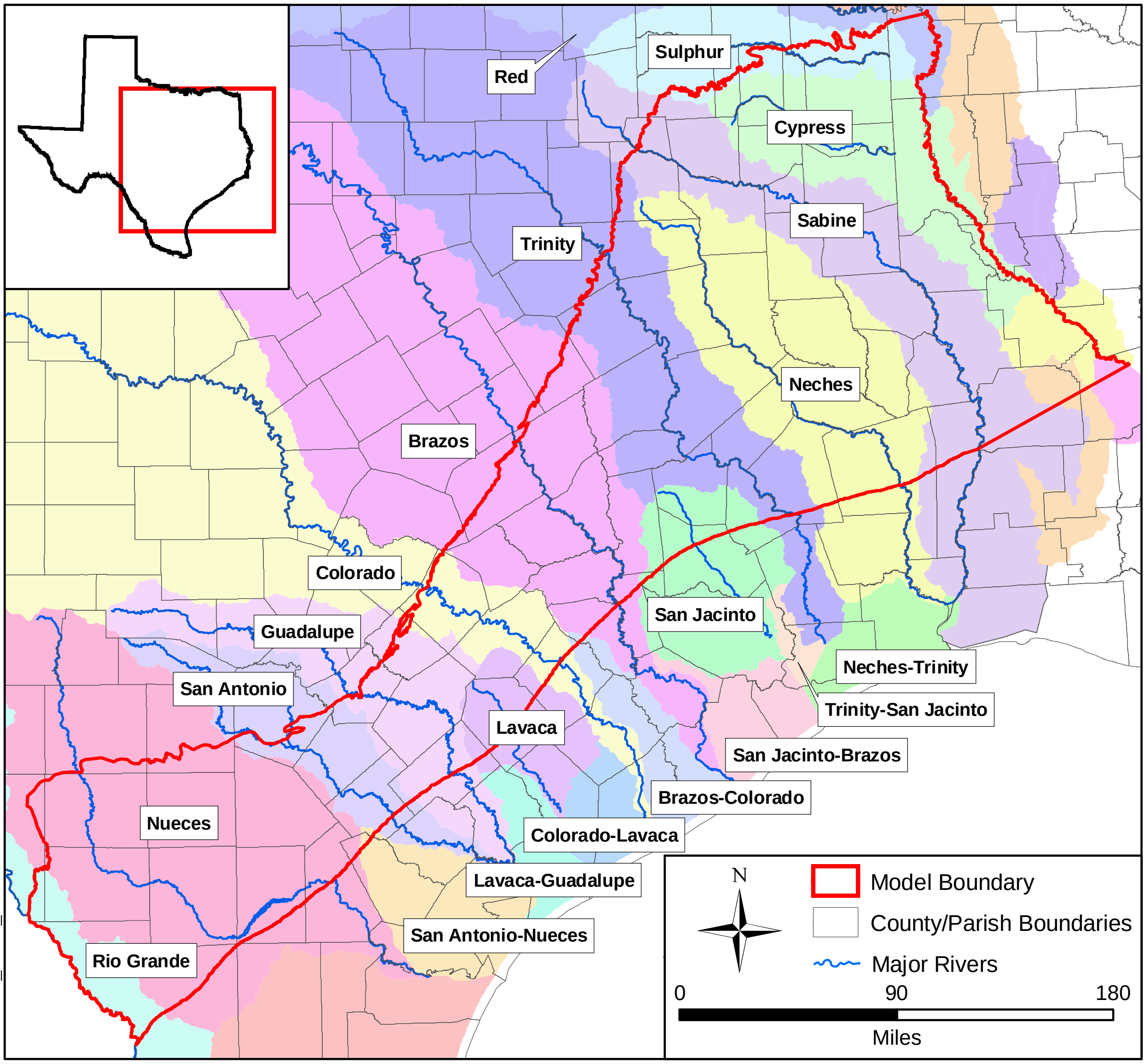
Source: Online: Texas Water Development Board, September 2002

Figure 2.6 Location of Regional Water Planning Groups in the study area.



Source: Online: Texas Water Development Board, June 8, 2004

Figure 2.7 Location of confirmed and pending Groundwater Conservation Districts and Underground Water Conservation Districts in the study area.



File: 2.8_River_Basins

Source: Texas Water Development Board, September 2002

Figure 2.8 River basins in the study area.

2.1 Physiography and Climate

The study area is located in the Interior Coastal Plains subprovince of the Gulf Coastal Plains physiographic province (Wermund, 1996b). Figure 2.9 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. The Coastal Prairies subprovince is generally south of the study area between the study area and the Gulf of Mexico. The study area is bordered on the north by the Blackland Prairies subprovince in the northern and central study areas and by the Balcones Escarpment in the southwest. The Interior Coastal Plains are comprised of alternating sequences of unconsolidated sands and clays. 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 2.10 provides a topographic map of the study area. Generally, the study area is characterized as having low relief with ground surface elevations gently decreasing from the southwest to the northeast and southeast. Ground surface elevation varies from over 800 feet above sea level in the far western portion of the study area to less than 100 feet above sea level in river valleys and in the southeasternmost regions of the study area. The gentle gulfward decrease in ground surface elevation is interrupted by resistant Tertiary sandstone outcrops. River valleys are broadly incised with terraced valleys that are hundreds of feet lower than the surface basin divide elevations.

The study area is characterized by pine and hardwood forests in the northeast with a dense network of perennial streams. The density of trees in the study area decreases from the north to the south and south of San Antonio trees are generally replaced by chaparral brush and grasses (Wermund, 1996b). The Interior Coastal Plains physiographic province is further subdivided into ecological regions. Figure 2.11 shows the ecological regions that fall within the study area.

The study area resides in the cool portion of the Temperate Zone of the Northern hemisphere. Figure 2.12 shows the climatic zones in the study area after Larkin and Bomar (1983). The study area intersects three climatic zones in Texas: the Subtropical Humid division; the Subtropical Subhumid division; and the Subtropical Steppe division (Larkin and

Bomar, 1983). Most of the study area has a Modified Marine climate termed Subtropical which is dominated by the onshore flow of humid tropical air from the Gulf of Mexico. The amount of moisture decreases as it flows from the east to the west and as continental air masses intrude from the north, resulting in the climate subdivisions of humid, semihumid, and semi-arid. The Subtropical Humid climate zone extends from the Texas/Louisiana border in the northeastern part of the study area to approximately Guadalupe and Wilson counties to the southwest. This climate is characterized as having warm summers. The Subtropical Subhumid climate zone exists between Guadalupe and Wilson counties and Zavala and Dimmit counties in the southern study area. This climate zone is characterized as having hot summers and dry winters. The Subtropical Steppe zone extends westward from Zavala and Dimmit counties to the Rio Grande River. The Subtropical Steppe climate is characterized as having semi-arid to arid conditions (Larkin and Bomar, 1983). In the southern portion of the study region, the average annual temperature ranges from 73°F to 70°F from southwest to northeast (Hamlin, 1988). In the central and northern portion of the study area, the average annual temperature ranges from 70°F to 65°F from southwest to northeast (Larkin and Bomar, 1983).

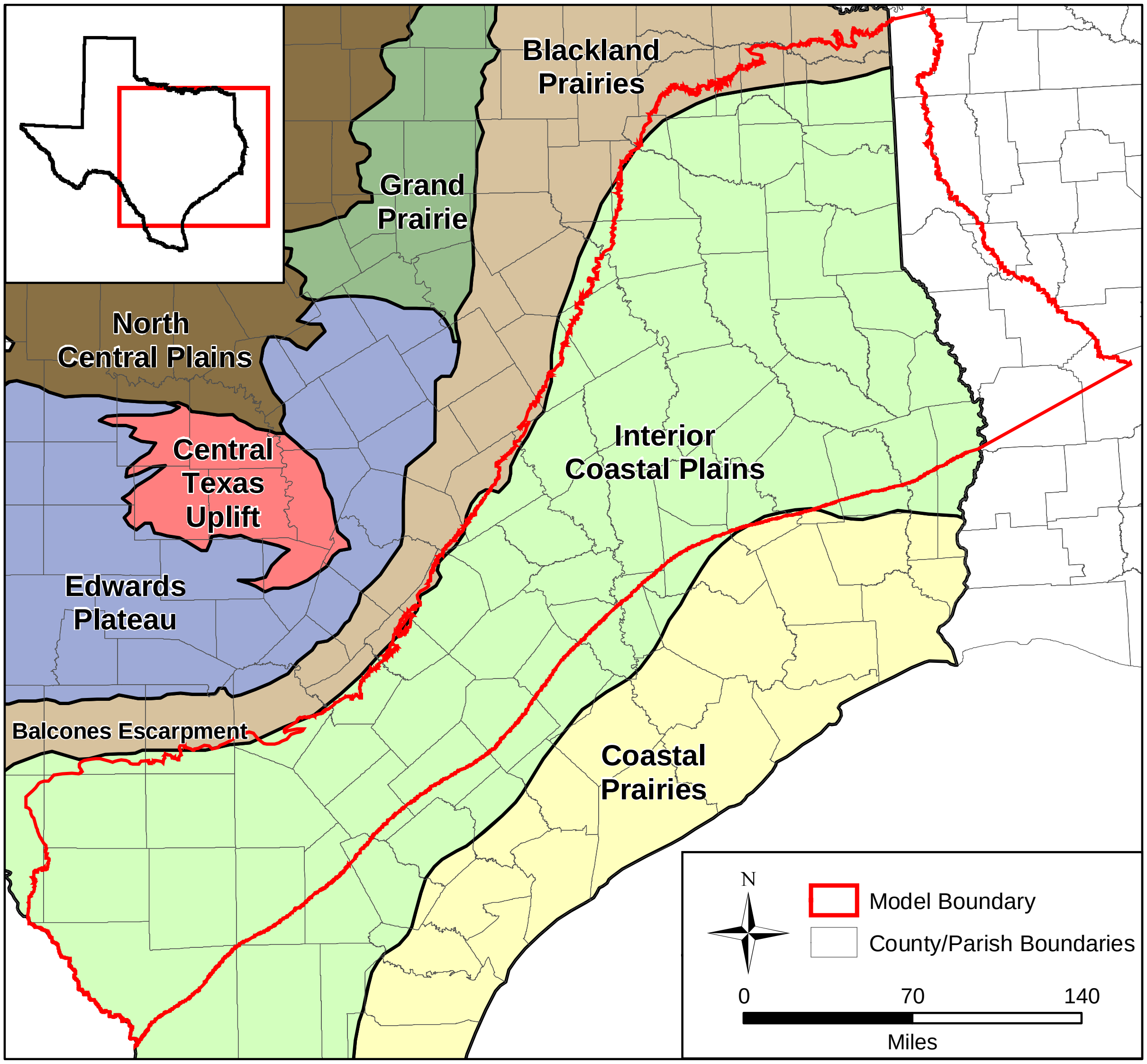
Historical daily precipitation data are available at approximately 344 stations (Figures 2.13a through 2.13c) from 1900 through 1999 for the study area. The spatial distribution is relatively dense in the model domain across the period of record. However, the number of available gages in any given year is quite variable with a general chronological increase in the number of gages available. Most gages began measuring precipitation in the 1930s or 1940s.

Historical average annual precipitation varies from a low of 20.9 inches at Eagle Pass to a high of 59.9 inches in Jasper County. The PRISM (Parameter-elevation Regressions on Independent Slopes Model) precipitation data set developed and presented online by the Oregon Climate Service at Oregon State University provides a good distribution of average annual precipitation across the model area based upon the period of record from 1961 to 1990. Figure 2.14 provides a raster data post plot of average annual precipitation across the model study area. Generally, the average annual precipitation decreases from the east to the west. In the northern half of the study area, precipitation also increases with proximity to the coast.

Figure 2.15 shows annual precipitation recorded at five precipitation gages with long periods of record located in Cass, Cherokee, Milam, Caldwell, and Frio counties. The long-term (period of record) average-annual precipitation depth is included for each gage.

ET, including evaporation from bare soil and transpiration from plants, generally constitutes the second largest component of the water budget, after precipitation. The average annual net pan evaporation depth in the study area ranges from a low of 38.3 inches per year in the far northeast portion of the study area to a high of 65.9 inches per year in the southwest corner of the study area (Figure 2.16). In general, the pan evaporation rate exceeds the annual average rainfall. Annual rainfall exceeds pan evaporation rate in limited portions of the study area including far northeastern Texas and southwestern Louisiana. The greatest rainfall deficit with regards to the net evaporation rate occurs in the far southwestern portion of the study area and equals approximately 48 inches per year. ET would only reach levels approaching the pan evaporation rate on open water bodies and potentially in areas where the water table is basically at the surface.

ET directly from groundwater is caused primarily by deep rooted phreatophytes and can be a significant component of groundwater discharge for many aquifers. Estimates of groundwater ET at the scale of the GAM models and for the aquifers being simulated are not available. However, it is expected that groundwater ET will be an important aquifer discharge process in areas where water tables intersect phreatophyte root zones. Groundwater ET rates would be expected to be small in comparison to pan evaporation rates. Groundwater ET is also a function of rooting depths which varies by climate and by plant species. The majority of plants have rooting depths less than 2 to 3 meters (6.5 to 9.8 feet) with trees having the greatest rooting depths capable of exceeding 7 meters (23 feet) (Canadell et al., 1996).



File: 2.9_Physiographic_Provinces

Source: Texas Bureau of Economic Geology

Figure 2.9 Physiographic provinces in the study area.

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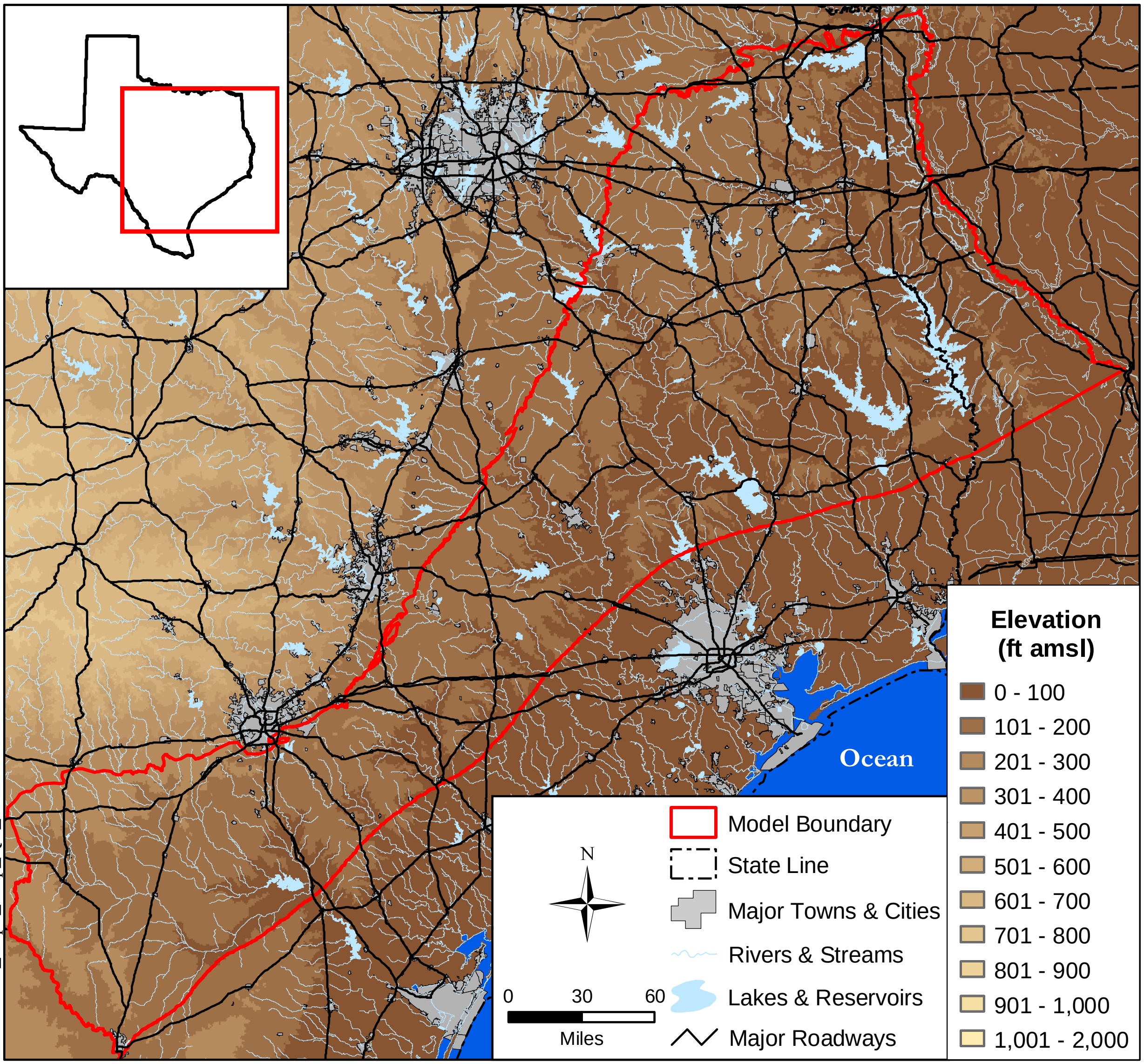
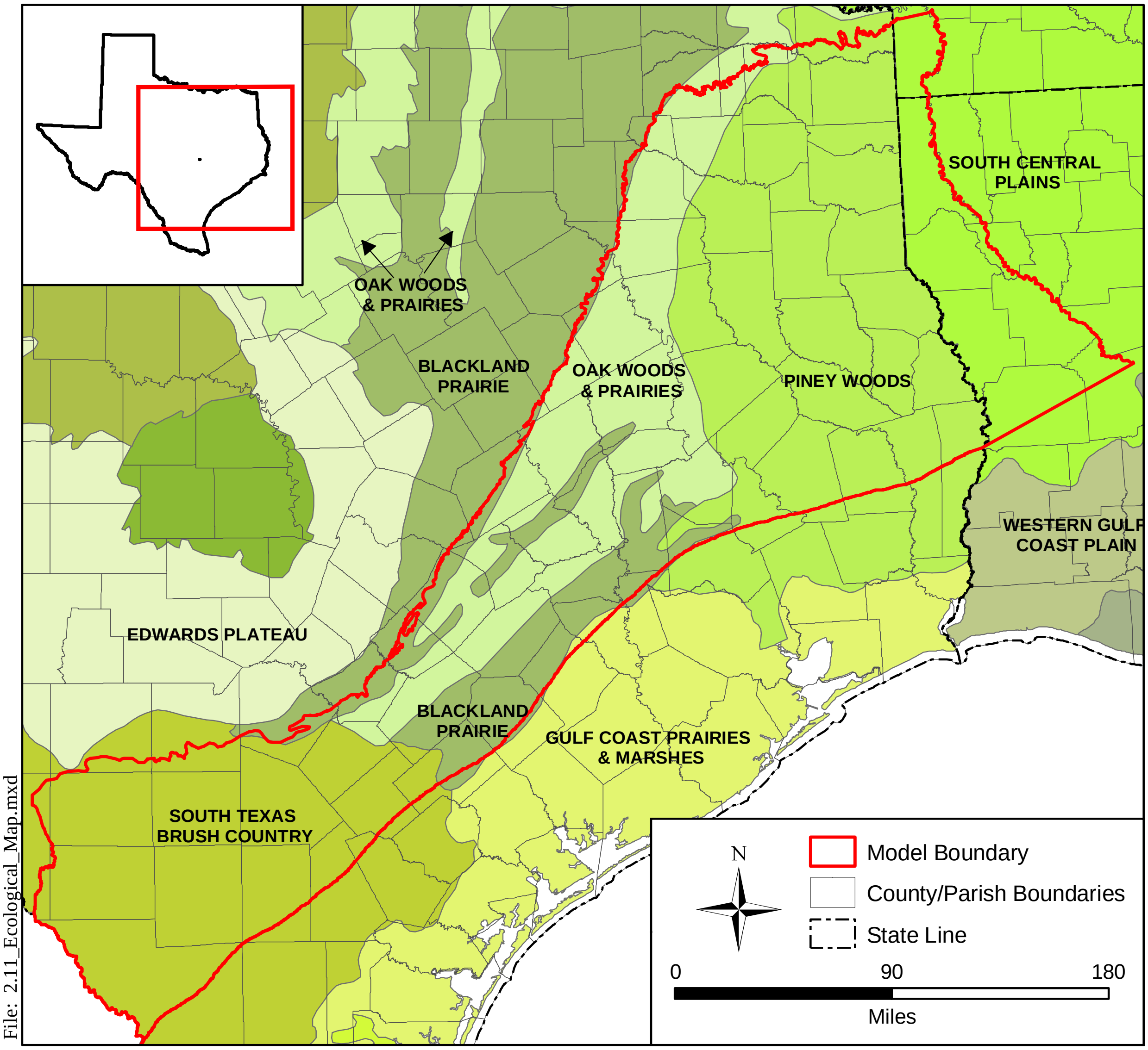


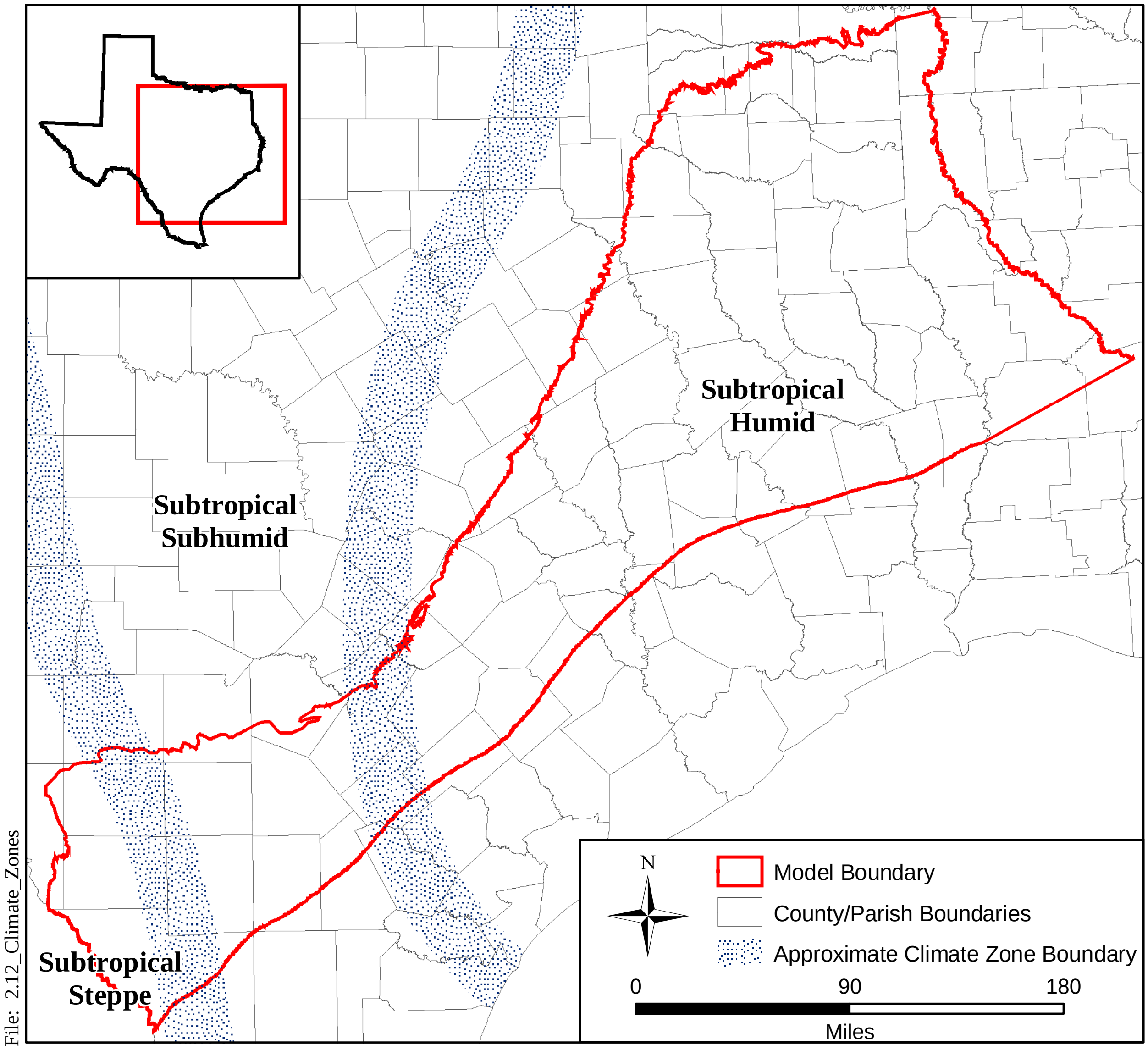
Source: United States Geological Survey

Figure 2.10 Topographic map of the study area.



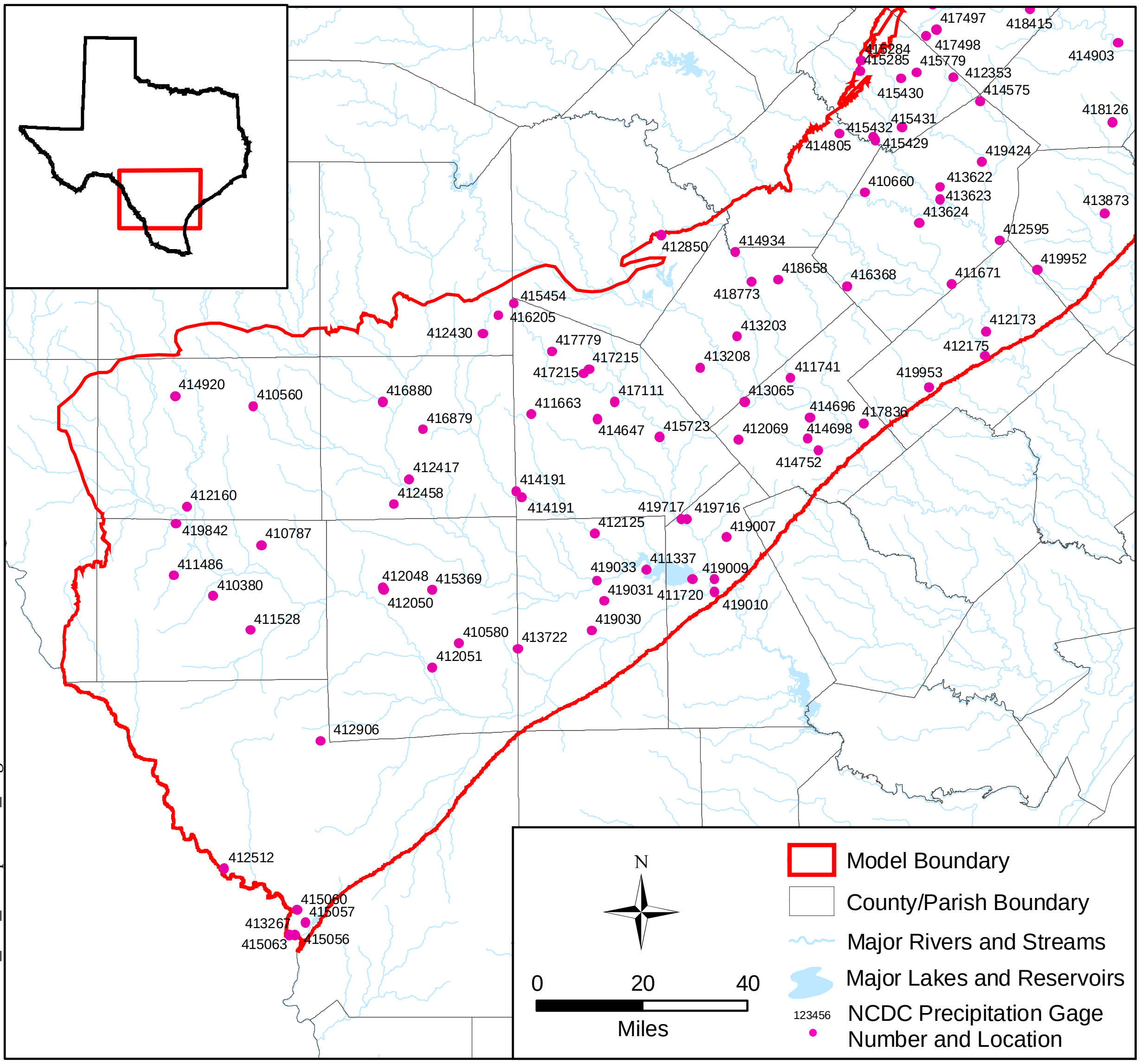
Source: Online: Texas Parks and Wildlife, September 2002

Figure 2.11 **Ecological regions within the study area.**



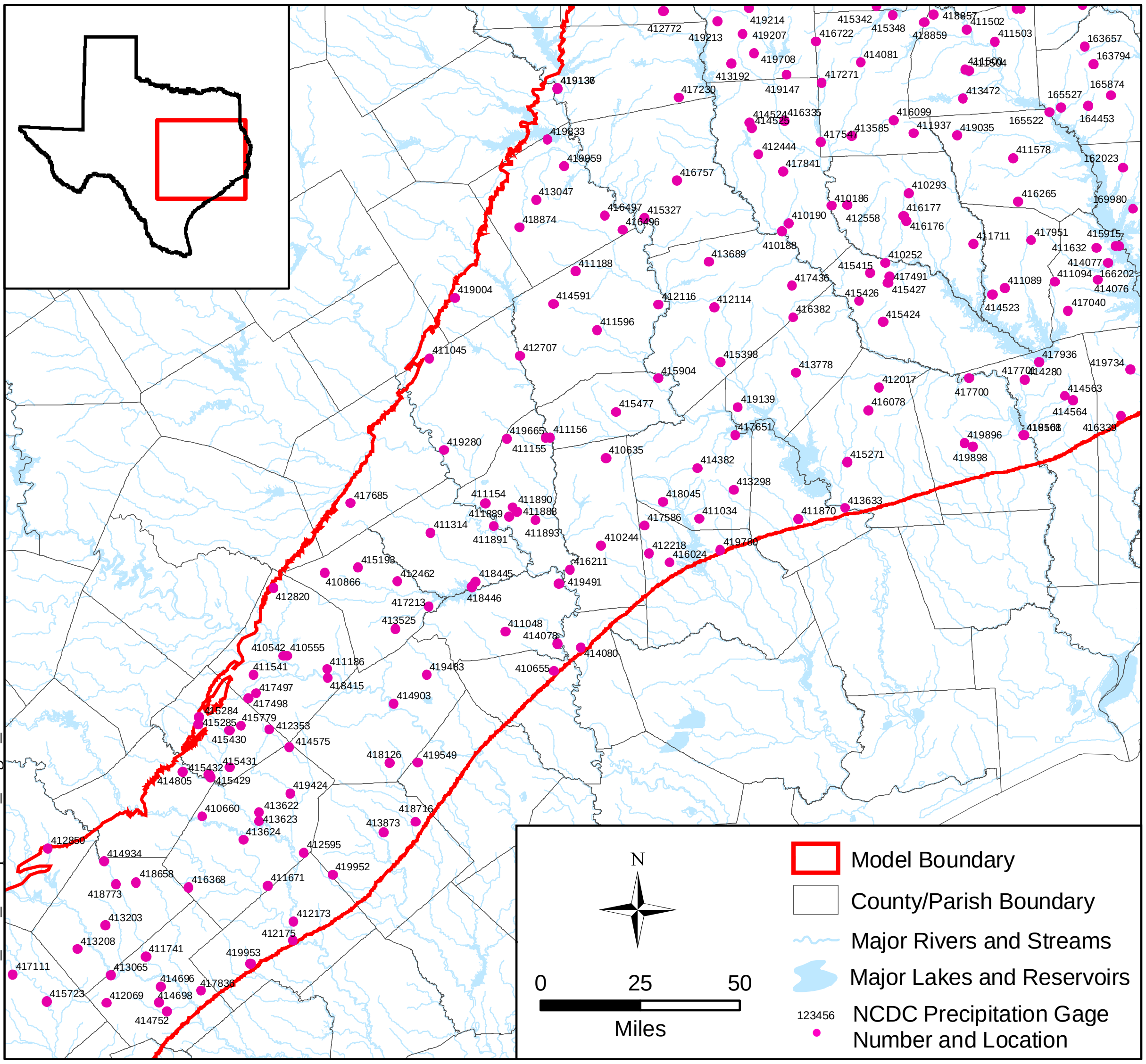
Source: Larkin and Bomar (1983)

Figure 2.12 Warm temporate climate zones in the study area.



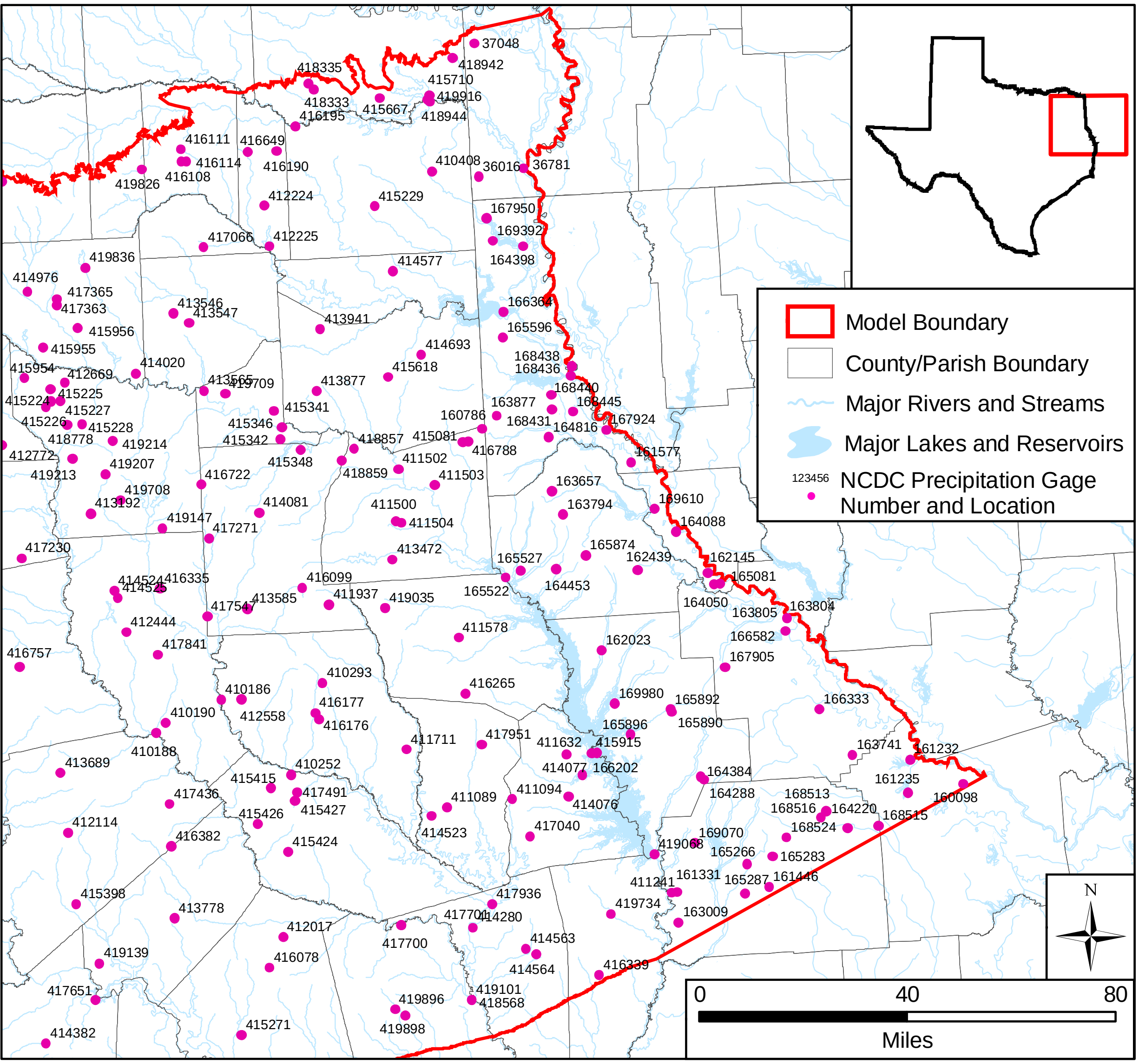
File: 2.13a_SW_Precipitation_Gages.mxd

Figure 2.13a Location of precipitation gages in the southern study area.



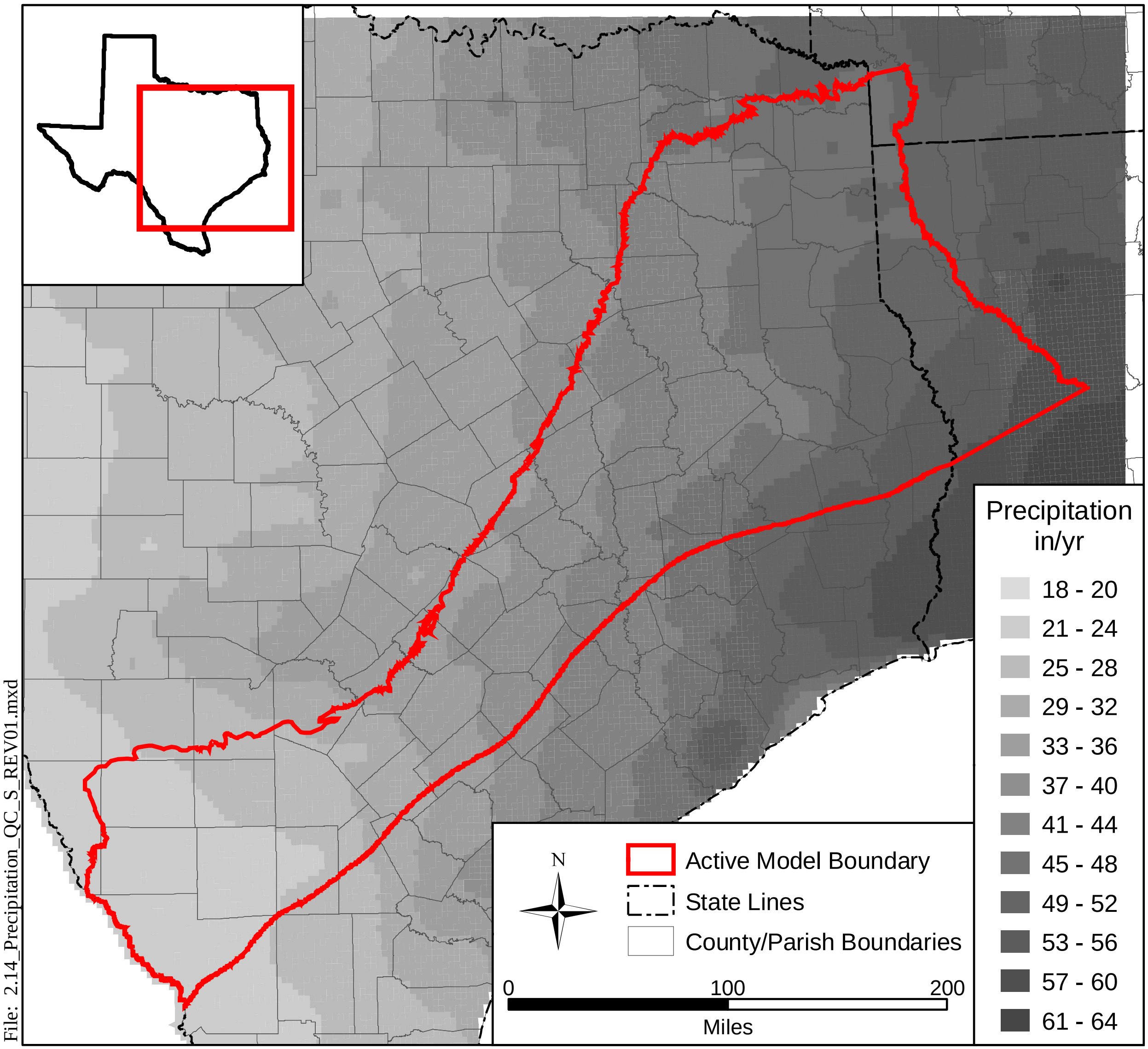
File: 2.13b_Cen_Precipitation_Gages_REV01

Figure 2.13b Location of precipitation gages in the central study area.



File: 2.13c_NE_Precipitation_Gages_REV01

Figure 2.13c Location of precipitation gages in the northern study area.



Source: Online: Oregon State University's Spatial Climate Analysis Service

Figure 2.14 **Average annual precipitation (1961-1990) over the study area in inches per year (Source: Oregon Climate Service, Oregon State University, PRISM data set).**

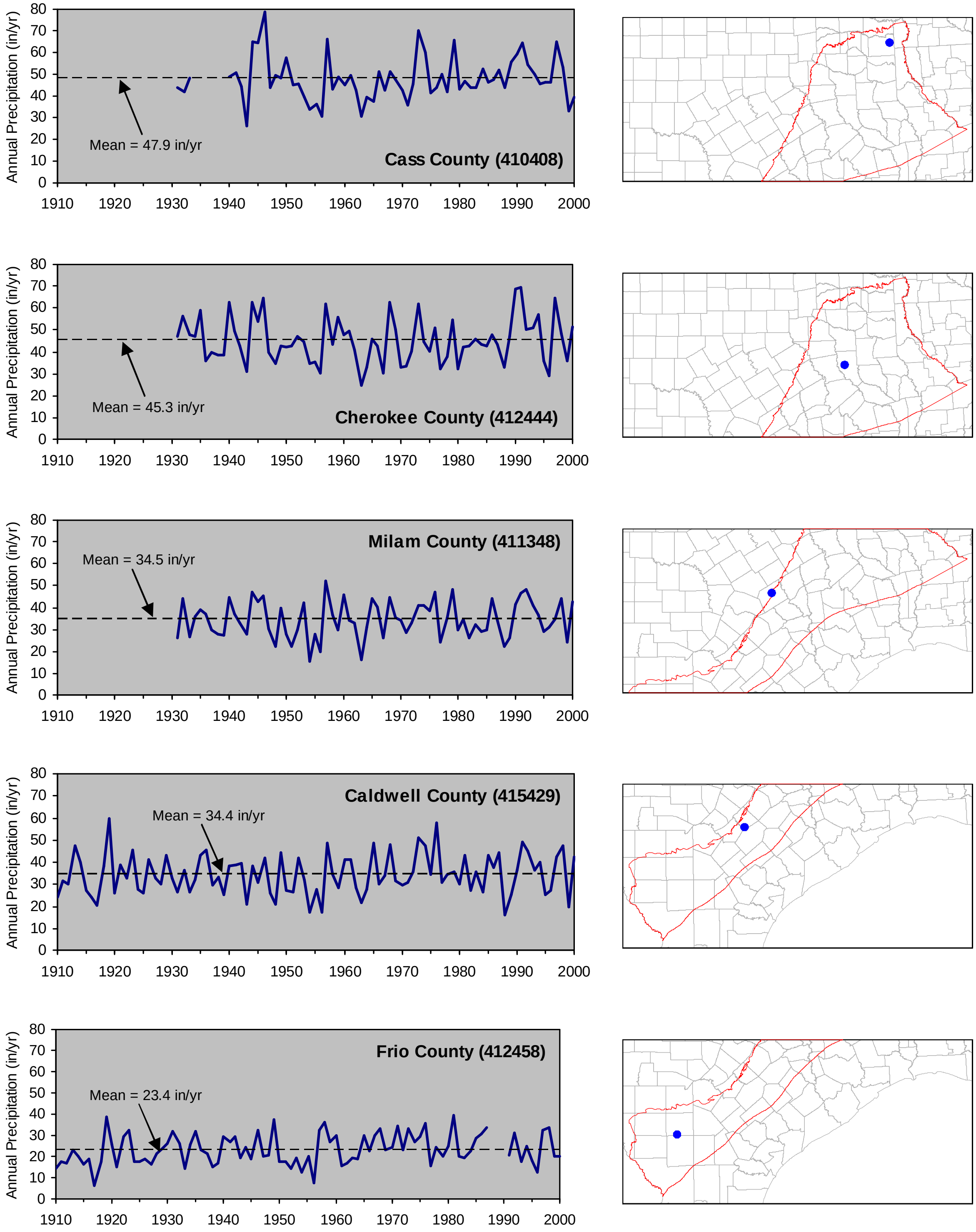
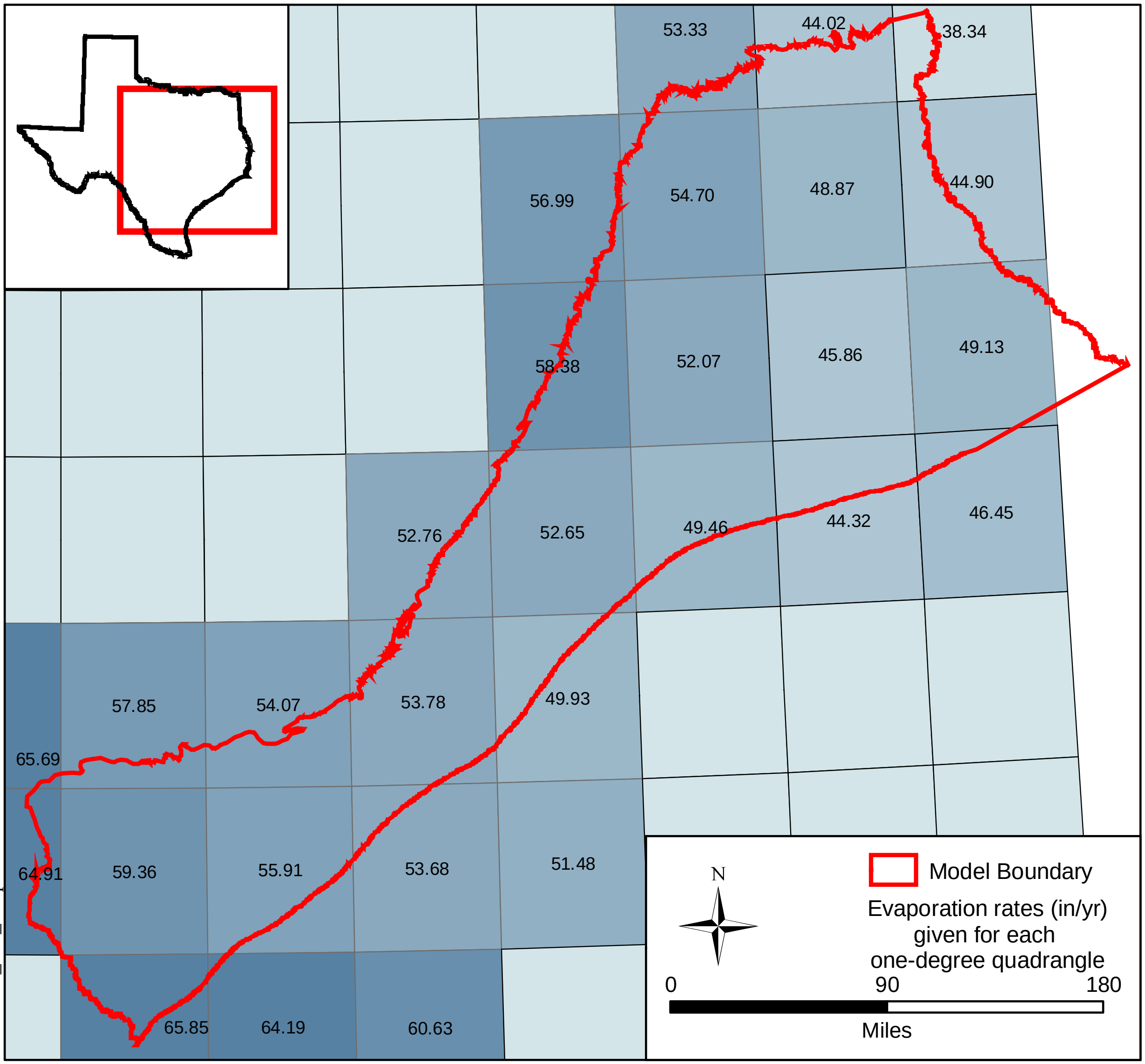


Figure 2.15 Representative annual precipitation time series for the study area (gages in Cass, Cherokee, Milam, Caldwell, and Frio counties).



File: 2.16_Pan_Evaporation.mxd

Source: Online: Texas Water Development Board, September 2002

Figure 2.16 Average annual net pan evaporation rate in inches per year.

2.2 Geology

The structural setting for the active model area is shown in Figure 2.17. The fault traces are modified from Ewing (1990) and the other structural features were modified from Guevara and Garcia (1972), Galloway (1982), and Galloway et al. (2000). Sediment deposition in the model area was focused in the East Texas Embayment, the Houston Embayment, and the Rio Grande Embayment. Deposition has been influenced by basement structural highs including the Sabine Uplift and the San Marcos Arch.

There are several regional fault zones within the modeled region including the Wilcox Fault Zone, the Karnes Mexia Fault Zone, and the Balcones Fault Zone (Ewing, 1990). The Wilcox Fault Zone delineates the downdip limit of the modeled aquifers. This fault zone is a series of growth faults caused by sediment progradation onto marine clays and resulting basinward slippage and subsidence. The Karnes Mexia Fault Zone is a series of normal faults marking the updip limit of the Louann Salt. These faults were active throughout the Eocene. The Balcones Fault Zone is a series of normal faults formed at the perimeter of the Gulf Coast Basin.

The sediments that form the aquifers in the study area are part of a gulf-ward thickening wedge of Cenozoic sediments deposited in the Rio Grande Embayment and Houston Embayment of the northwest Gulf Coast Basin. Deposition has been influenced by regional crust subsidence, episodes of sediment inflow from areas outside of the Gulf Coastal Plain, and eustatic sea-level change (Grubb, 1997). Galloway et al. (1994) characterized Cenozoic sequences in the Gulf Coast in the following three ways. Deposition of Cenozoic sequences is characterized as an offlapping progression of successive, basinward thickening wedges. These depositional wedges aggraded the continental platform and prograded the shelf margin and continental slope from the Cretaceous shelf edge to the current Texas coastline. Deposition occurred along sand-rich, continental margin deltaic depocenters within embayments (Rio Grande, Houston, and Mississippi Embayments) and was modified by growth faults and salt dome development.

The primary Paleogene depositional sequences in ascending stratigraphic order are the lower Wilcox, the upper Wilcox, the Carrizo, the Queen City, the Sparta, the Yegua-Cockfield, the Jackson, and the Vicksburg-Frio (Galloway et al., 1994). Each of these depositional sequences is bounded by marine shales and finer grained sediments representing transgressions (e.g., Reklaw and Weches formations). The sequences that are being explicitly modeled in the Queen City and Sparta GAMs include the upper and lower Wilcox, the Carrizo, the Queen City, and the Sparta. Stratigraphic units above the Sparta were not explicitly modeled in the Queen City and Sparta GAMs. The Carrizo-Wilcox GAMs have already been completed (Deeds et al., 2003; Dutton et al., 2003; and Fryar et al., 2003) as stand alone models and are also included in the Queen City and Sparta GAMs.

Figures 2.18a and 2.18b are geologic maps of the area (north and south) showing the Tertiary sediments comprising the aquifers of interest as well as the Quaternary undivided sediments. Inspection of the surface geology shows that the general outcrop pattern for the southern and central study areas is from southwest to northeast coincident with depositional strike and the Balcones Fault Zone, and normal to basin subsidence. In northeast Texas, the Carrizo and Wilcox outcrop along the northern edge of the study area paralleling the Mexia Talco Fault Zone. The Wilcox and Carrizo also outcrop on the Sabine Uplift in east Texas and Louisiana. The Queen City Formation is at ground surface across the majority of the East Texas Basin. In limited areas of the East Texas Basin, the Queen City Formation is overlain by isolated islands of Sparta and Weches. However, south of the Sabine Uplift, the Sparta and Weches outcrops are oriented southwest-northeast coincident with depositional strike and the paleo-shelf, and normal to basin subsidence.

Figure 2.19 shows a generalized stratigraphic section for the study area. The Midway Formation, composed of marine clays deposited in a major marine transgression, represents the bottom of the stratigraphic column of interest. The Queen City, Weches, and Sparta formations overlie the Reklaw and Carrizo formations and the Wilcox Group. The Queen City Formation is composed of several fluvio-deltaic depositional systems. In the northern study area, the Queen City Formation was deposited as part of a high-constructive, lobate delta system (Guevara and Garcia, 1972). The deltaic sands of the Queen City Formation thin toward the southeastern portion of the study area near the Texas/Louisiana line. In south-central Texas (western Fayette to Wilson county), the dominant depositional facies for the Queen City Formation is the strandplain facies which is characterized as having strike oriented sand trends (Guevara and Garcia, 1972). In south Texas, the Queen City Formation was deposited as part of a high-destructive, wave dominated, delta system (Guevara and Gacia, 1972). The Queen City sands thicken in the western part of the study area and extend southward into Mexico along the Rio Grande Embayment. West of the Frio River, the Reklaw thins significantly and is equivalent to the base of the Bigford Formation, and the Queen City Formation thickens and correlates to the Bigford Formation and the lower part of the El Pico Clay. The Bigford can be composed of up to 75 percent sands. West of the Frio River, the upper Queen City and the Weches Formation become indistinguishable and interfinger with the clays of the El Pico Clay. This study developed a net sand map for the Queen City aquifer in Texas (Figure 4.2.12) based upon the studies of Guevara (1972) and Garcia (1972) which is discussed later in this report (see Section 4.2.4).

The Queen City Formation is overlain by the Weches Formation, a marine unit composed of glauconitic muds. This formation represents a marine transgression between Queen City and Sparta deposition. The Weches is a thin formation, generally less than 100 feet thick. West of the Frio River, the Weches Formation becomes indistinguishable from the underlying Queen City and is considered part of the El Pico Clay.

Overlying the Weches Formation is the Sparta Formation. Ricoy and Brown (1977) identified three principal depositional facies within the Sparta: a high-constructive delta facies in east Texas, a strandplain/barrier bar facies in central Texas, and a high-destructive wave dominated deltaic facies in south Texas. The Sparta is very identifiable in Texas as a sand rich unit overlain and underlain by marly marine transgressive units, the Cook Mountain and Weches formations, respectively. The sources of sand to the Sparta delta systems were primarily from east and south Texas with the strand plain facies being fed by longshore currents in central Texas. The Sparta is significantly thicker east of the study area in Louisiana, Arkansas, and Mississippi and also thickens southwest of the study area in northeastern Mexico (Ricoy and Brown, 1977). The Sparta and overlying Cook Mountain grade into the Laredo Formation west of the Frio River. This study developed a net sand map for the Sparta aquifer (Figure 4.2.13) in Texas based upon the studies of Payne (1968) and Ricoy (1976) which is discussed later in this report (see Section 4.2.4).

Figure 2.20 shows two structural cross-sections in the study area. Cross-section A-A' shows the Tertiary formations from the Midway Formation through the Sparta Formation in east Texas. The primary structural features in the eastern part of the study area are the East Texas

Basin, the Sabine Uplift, and the Houston Embayment. From Figure 2.20 it can be seen that the Queen City Formation outcrops in the East Texas Basin. In portions of the East Texas Basin, the Weches and overlying Sparta formations are still present and confine the Queen City Formation. The Queen City, Weches, and Sparta formations are eroded and not present over the Sabine Uplift. South of the Sabine Uplift, these formations outcrop in a narrow band parallel to the present day coastline. The entire Tertiary section steeply dips into the Gulf Coast Basin south of the Sabine Uplift and the East Texas Basin.

Westward through central and south Texas, the Queen City, Weches, and Sparta formations outcrop in a narrow band paralleling the present day coast and dipping strongly towards the Gulf Coast Basin. Cross-section B-B' (see Figure 2.20) is representative of central and south Texas. The dip of the formations in the subsurface can reach 250 feet per mile in portions of south and central Texas.

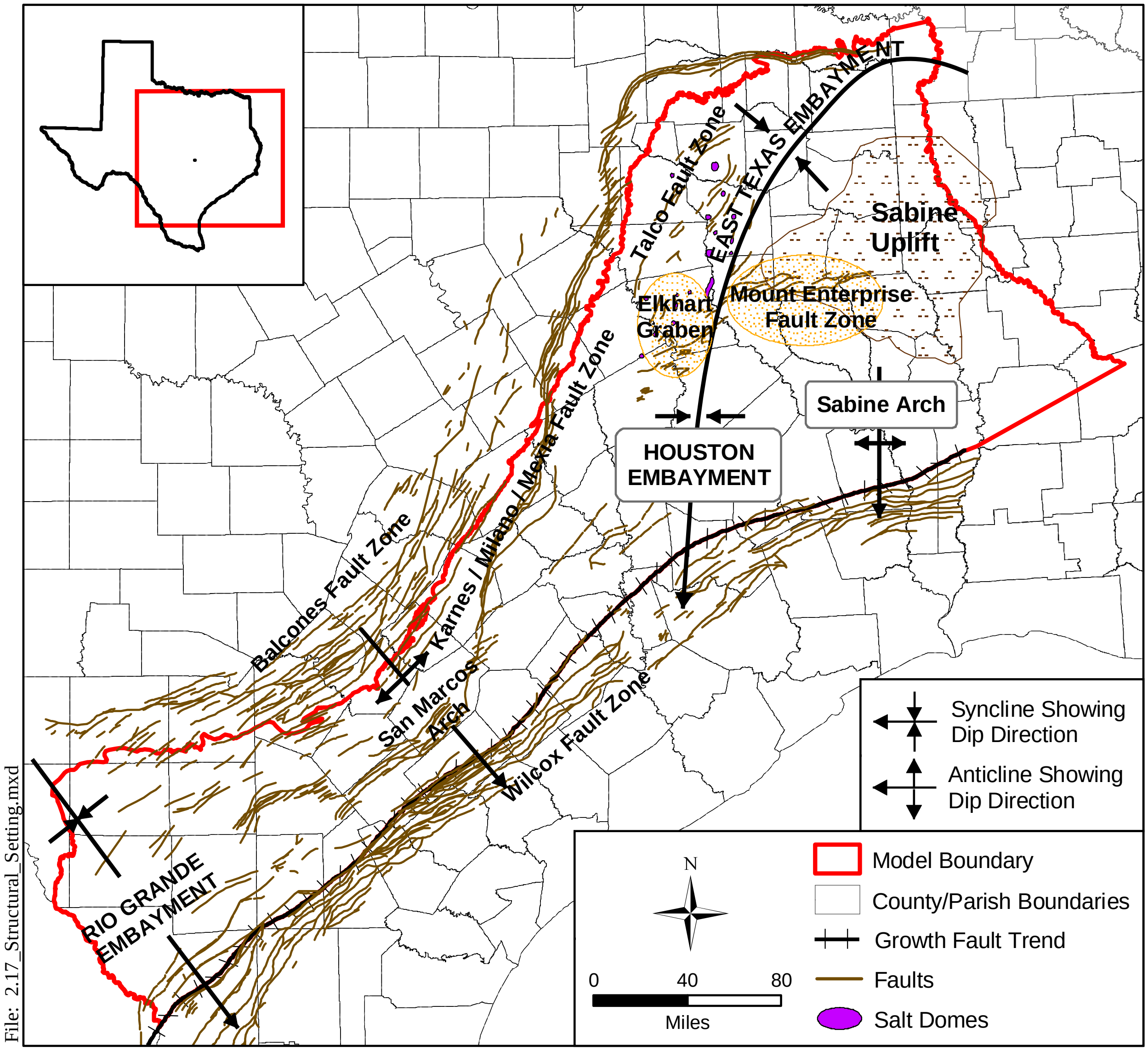
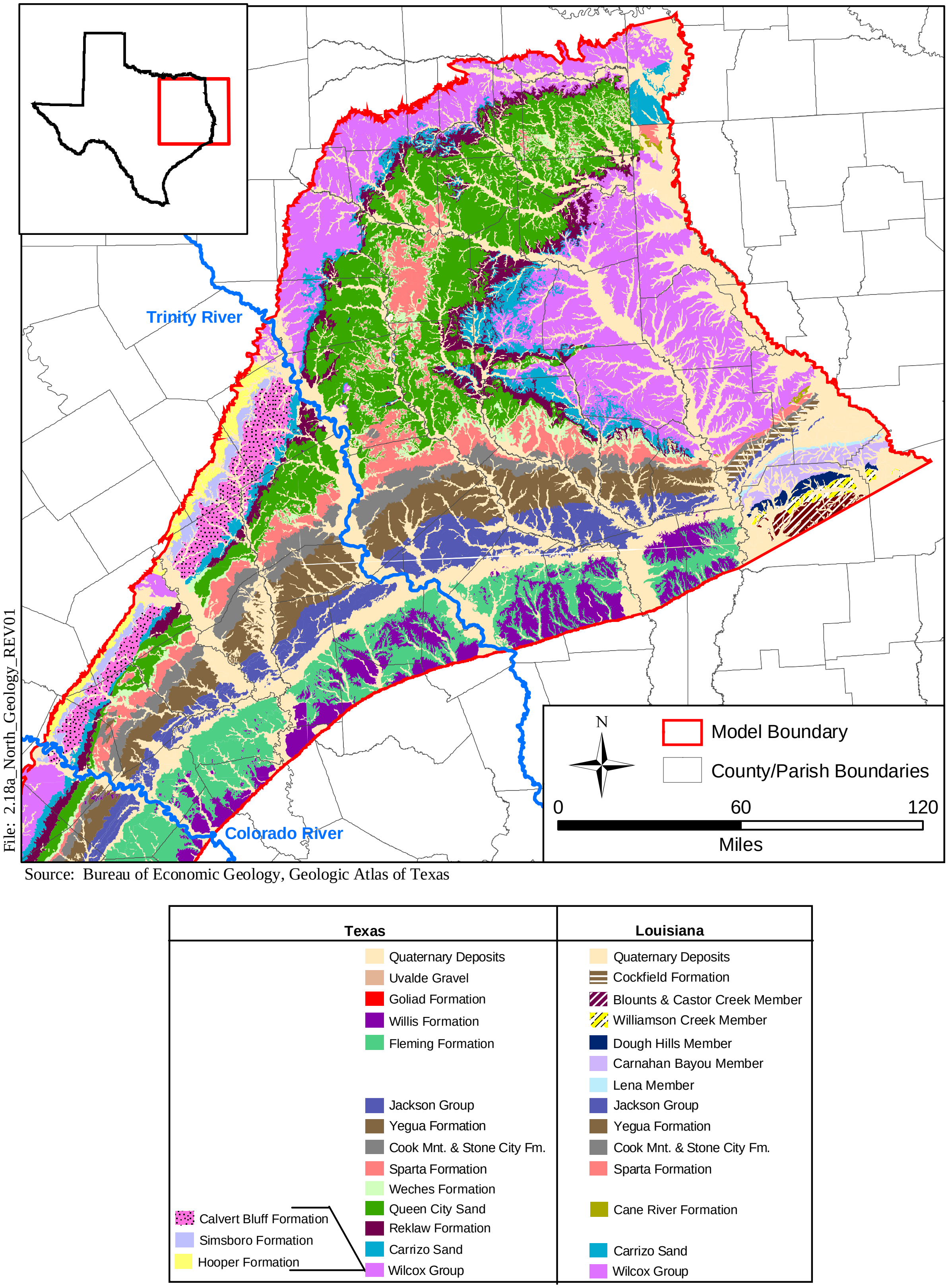
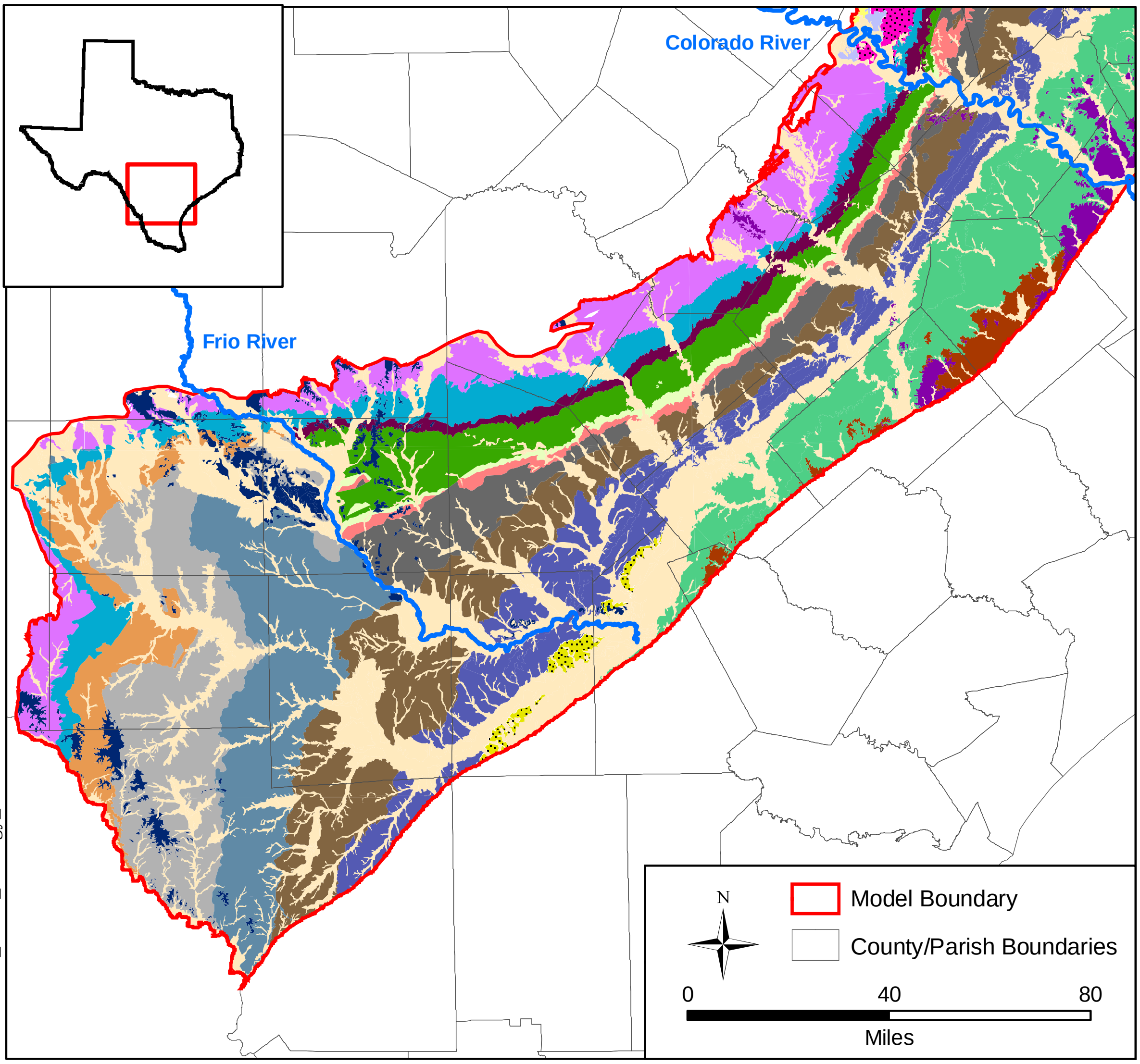


Figure 2.17 Map of major faults and structural features for the Texas Coastal Plain and East Texas Embayment. Faults modifed from Ewing (1990). Structure axes modified from Guevara and Garcia (1972), Galloway (1982), and Galloway et al. (2000).



Source: Bureau of Economic Geology, Geologic Atlas of Texas

Figure 2.18a Surface geology of the study area (north).



File: 2.18b_South_Geology_REV01.mxd

Source: Bureau of Economic Geology, Geologic Atlas of Texas

West of Frio	East of Frio
■ Quaternary Deposits	■ Quaternary Deposits
■ Uvalde Gravel	■ Uvalde Gravel
	■ Goliad Formation
	■ Willis Formation
▨ Frio Formation	▨ Frio Formation
	■ Fleming Formation
■ Jackson Group	■ Jackson Group
■ Yegua Formation	■ Yegua Formation
■ Laredo Formation	■ Cook Mnt. & Stone City Fm.
	■ Sparta Formation
■ El Pico Clay	■ Weches Formation
	■ Queen City Sand
■ Bigford Formation	■ Reklaw Formation
■ Carrizo Sand	■ Carrizo Sand
■ Wilcox Group	■ Wilcox Group

Figure 2.18b Surface geology of the study area (south).

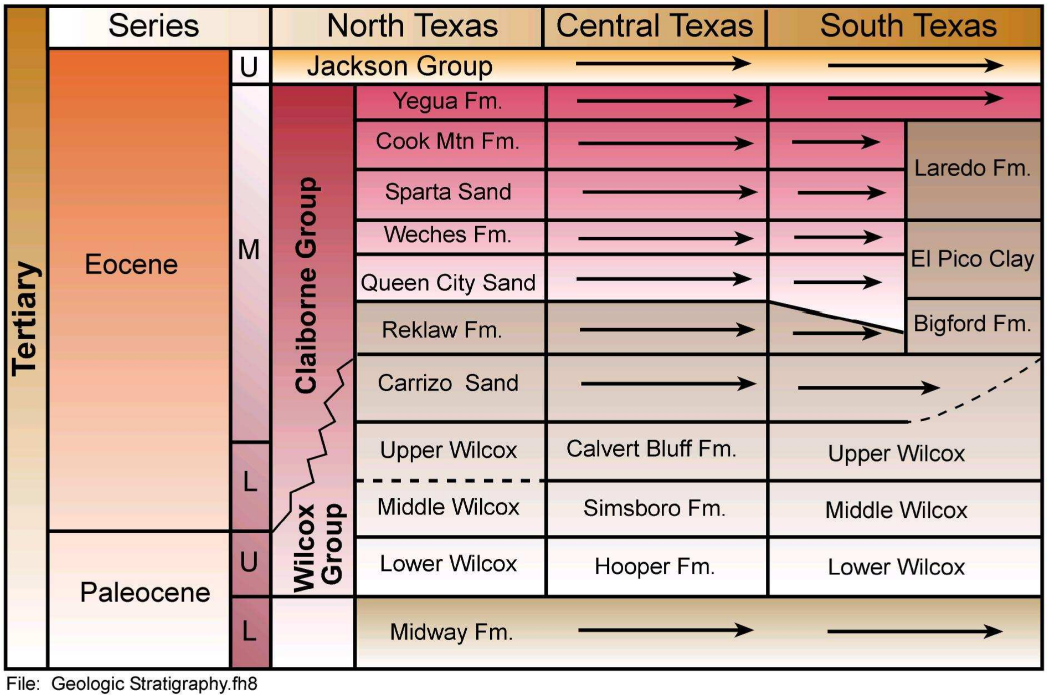


Figure 2.19 Generalized stratigraphic section for the Wilcox and Claiborne groups in Texas (after Ayers and Lewis, 1985; Hamlin, 1988; Kaiser, 1978; Ricoy and Brown, 1977; Guevara and Garcia, 1972; and Payne, 1968).

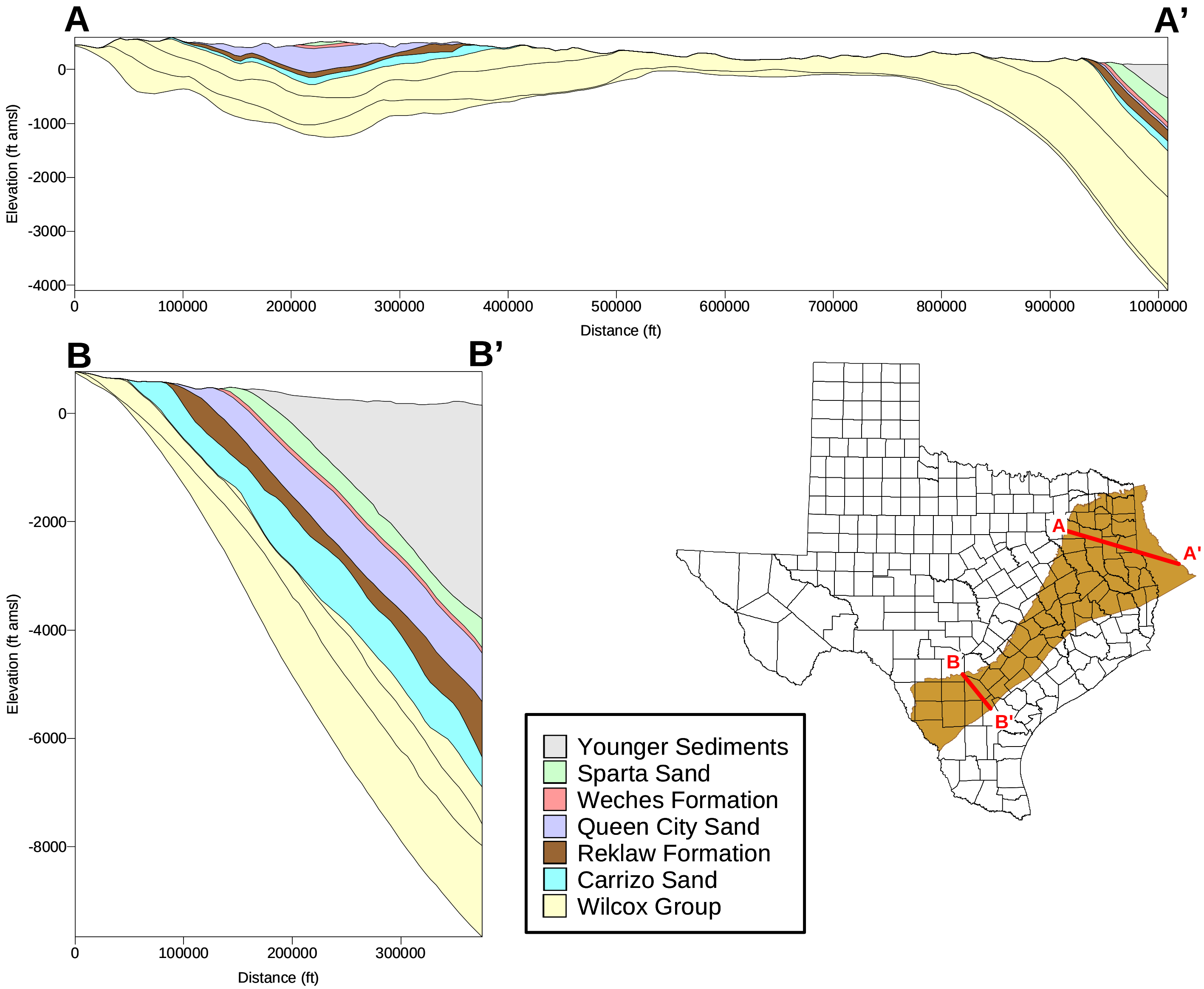


Figure 2.20 **Structural cross-sections in the study area.**

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3.0 PREVIOUS INVESTIGATIONS

The Queen City and Sparta aquifers have been studied by many investigators and numerous groundwater bulletins have been developed by the TWDB for the counties in the study area. A review of groundwater development in these aquifers based upon the available county groundwater reports can be found in Appendix A of this report. Several investigators have studied the stratigraphy and depositional history of the coastal plain sediments of Texas including the Queen City, Weches, and Sparta formations. The most relevant of these include Payne (1968), Guevara (1972), Garcia (1972), Guevara and Garcia (1972), Ricoy (1976), Ricoy and Brown (1977), Baker (1995), and an unpublished east Texas stratigraphic and modeling study performed by the TWDB.

Payne (1968) documented a study of the hydrologic significance of the Sparta Sand in Arkansas, Louisiana, Mississippi, and Texas in a United States Geological Survey (USGS) Professional Paper as part of a larger Claiborne Group geohydrologic study being performed by the USGS. His study included contributions regarding Sparta structure, lithology, net sand maps, hydraulic properties, and groundwater quality. In the early 1970s, the Sparta and Queen City formations were studied by university graduate students working in cooperation with the Bureau of Economic Geology. Studies of the Sparta Formation by Ricoy (1976) and studies of the Queen City Formation in northeast Texas by Guevara (1972) and in south Texas by Garcia (1972) provided stratigraphic cross sections of the different formations and well-log-based net-sand calculations for approximately 900 wells from the Texas coastal plain study area.

Baker (1995) developed four detailed dip sections and four strike sections of the gulf coastal plain sediments in Texas, including the Queen City, Weches, and Sparta formations in support of the USGS RASA (Regional Aquifer-System Analysis) Project. The focus of his work was to develop a consistent stratigraphic nomenclature for these sediments. The cross-sections extended down to 18,000 feet of burial and hydrostratigraphic intervals with total dissolved solids less than 3,000 milligrams per liter (mg/L) were identified. In the 1990s, the TWDB performed a detailed stratigraphic study in the eastern model area to support an east Texas groundwater model including the Wilcox Group and the Carrizo, Reklaw, Queen City, Weches, and Sparta formations.

The development of the Queen City and Sparta GAMs has borrowed extensively from the works described above. This is especially true for the works of Guevara (1972), Garcia (1972), Ricoy (1976), and the unpublished TWDB east Texas model.

In addition to these stratigraphic studies, there have been several groundwater models developed with model domains that overlap the Queen City and Sparta GAM study areas. Figure 3.1 shows the model boundaries for the previous modeling studies. Table 3.1 lists these previous investigations along with some basic model characteristics to provide a basis for the following discussion. Included in Figure 3.1 and Table 3.1 is any modeling study that was performed for the Carrizo-Wilcox and/or the Queen City and Sparta aquifers because the Queen City and Sparta GAMs include the Carrizo-Wilcox aquifer. However, the following discussion only focuses on those models that explicitly included the Queen City or Sparta aquifers. For a description of the models listed for the Carrizo-Wilcox aquifer, refer to Dutton et al. (2003), Fryar et al. (2003), and Deeds et al. (2003).

The earliest models which included the Queen City and Sparta aquifers in Texas were super-regional models developed by the USGS as part of their national RASA Project. These studies included aquifers from the Midway Formation through the Gulf Coast Aquifer System. The Queen City aquifer, Weches, and the Sparta aquifer were modeled as one model layer in all of the RASA models and were collectively termed the Middle-Claiborne aquifer. These models are documented in Ryder (1988), Williamson et al. (1990), and Ryder and Ardis (1991).

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. A steady-state calibration to predevelopment conditions was performed using a research code developed by Kuiper (1985).

The entire U.S. Gulf Coast aquifer system above the Midway Formation was modeled by Williamson et al. (1990) using the research code developed by Kuiper (1985). The 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”.

Ryder and Ardis (1991) extended the work performed by Ryder (1988) and developed another model of the coastal plain aquifers in Texas. The model, developed using the research code developed by Kuiper (1985), 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. The objectives for the modeling study consisted of: (1) defining the hydrogeologic framework and hydraulic characteristics of the aquifer systems, (2) delineating the extent of fresh to slightly saline water in various hydrogeologic units, (3) describing and quantifying the groundwater flow system, (4) analyzing the hydrologic effects of man’s development on the flow system, and (5) assessing the potential of the aquifer systems for further development.

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 et al. (1976) Carrizo model and modeled from the base of the Wilcox through the Yegua Formation. The Queen City was modeled as a single layer. The Weches Formation and all units younger were modeled as the uppermost model layer. The model was developed with MODFLOW and results from the groundwater model were used to predict changes in surface water flows using proprietary surface water models of the area’s river basins developed by HDR Engineering, Inc. Two model calibrations were performed: a steady-state calibration to predevelopment conditions (1910) and a transient calibration from 1910 through 1994. The calibrated model was then used to predict future conditions from 1994 through 2050 for three future pumping scenarios: (1) 1994 pumping (249,890 AFY), (2) 2050 pumping from 1994 through 2050 (264,715 AFY), and (3) 2050 plus (449,952 AFY including 185,237 additional AFY in Atascosa, Dimmit, Gonzales, and Wilson counties). The documentation of model calibration is poor and no assessment of Queen City calibration is possible from the report.

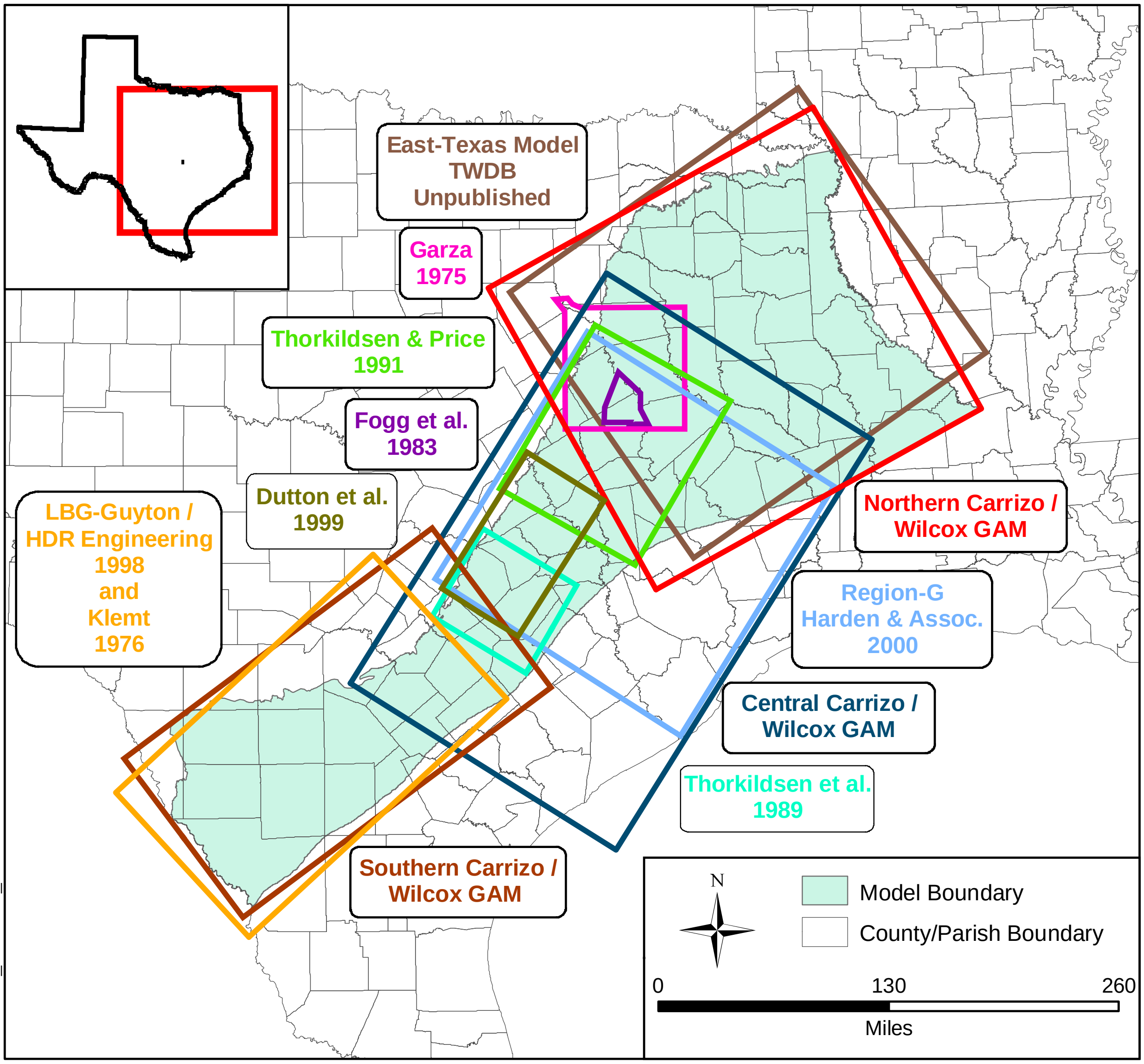
The Northern and Southern Carrizo-Wilcox GAMs (Fryar et al., 2003 and Deeds et al., 2003, respectively) modeled the Queen City aquifer as a single model layer. These GAM models were calibrated to predevelopment conditions (steady-state) and transient (1980 to

1989) conditions. These models did not include the Sparta aquifer explicitly. The Central Carrizo-Wilcox GAM (Dutton et al., 2003) did not include the Queen City aquifer explicitly.

Each of these models provides information which is both relevant and useful to the study of groundwater availability in the Queen City and Sparta aquifers study area. However, many traits of the previous investigations have made development of the current GAM necessary to meet the GAM specifications defined by the TWDB. Specifically, GAM models are expected to (1) be well documented and publicly available, (2) utilize standard modeling tools which are non proprietary (MODFLOW), and (3) be calibrated both steady-state and transiently and capable of adequately simulating a verification period to a pre-defined calibration criteria. The RASA models did not model the Queen City and Sparta aquifers separately and do not meet GAM specifications. The Northern and Southern Carrizo-Wilcox GAMs did model the Queen City aquifer but calibration of the Queen City layer was not the focus of those models.

Table 3.1 Previous groundwater models of the Carrizo-Wilcox and Queen City and Sparta aquifers in the study area.

Model	Code	No. of Carrizo-Wilcox Layers	Modeled Queen City and or Sparta	Calibration	Predictive Simulations
USGS RASA Models					
Ryder (1988)	Research	2	Yes (1 layer)	Steady-state	No
Williamson et al. (1990)	Research	2	Yes (1 layer)	Steady-state (1980)	No
Ryder & Ardis (1991)	Research	2	Yes (1 layer)	Steady-state (1910) Transient (1910-1982)	Yes
Southern GAM Model Area					
Klemt et al. (1976)	Research	1	No	unknown	1970-2020
Thorkildsen et al. (1989)	MODFLOW	4	Unknown	Steady-state (1985)	1985-2029
LBG-Guyton & HDR (1998)	MODFLOW	2	Yes (2 layers; 1 for Queen City and 1 for Younger)	Steady-state (1910); Transient (1910-1994)	1994-2050
Deeds et al. (2003) – GAM	MODFLOW	4	Yes (1 for Queen City)	Steady-state (1900); Transient (1980-1999)	2000-2050
Central GAM Model Area					
Garza (1975)	Unknown	Unknown	Unknown	Unknown	Unknown
Thorkildsen & Price (1991)	Unknown	4	Unknown	Unknown	Unknown
Dutton et al. (1999)	MODFLOW	4	No		
Harden and Assoc. (2001)	MODFLOW	5	No	Steady-state (1950) Transient (1950 - 1998)	50 year
Dutton et al. (2003) – GAM	MODFLOW	4	No	Steady-state (1900); Transient (1980-1999)	2000-2050
Northern GAM Model Area					
Fogg et al. (1983)	TERZAGI	3	No	Steady-state	No
Thorkildsen and Price (1991)	Unknown	Unknown	Unknown	Unknown	Unknown
TWDB East-Texas Model (unpublished)	MODFLOW	4	Yes (Queen City and Sparta as individual model layers)	Steady-state (1985) Transient	2050
Fryar et al. (2003) – GAM	MODFLOW	4	Yes (Queen City 1 layer)	Steady-state (1900); Transient (1980-1999)	2000-2050



File: 3.1_Previous_Studies.mxd

Figure 3.1 Previous model studies that intersect the Queen City and Sparta GAMs. The Queen City and Sparta GAMs are coincident with the Northern, Central, and Southern Carrizo-Wilcox GAMs.

4.0 HYDROGEOLOGIC SETTING

4.1 Hydrostratigraphy

The Queen City and Sparta aquifer system is composed of five hydrostratigraphic units with distinct hydraulic properties. From oldest to youngest they are the Reklaw Formation, the Queen City Formation, the Weches Formation, the Sparta Formation, and the Cook Mountain Formation. All of these formations are within the Claiborne Group which is of Eocene age. The Carrizo-Wilcox aquifer described in Deeds et al. (2003), Dutton et al. (2003), and Fryar et al. (2003) is directly overlain by the Reklaw Formation.

Consistent with their classification as minor aquifers in Texas, the Queen City and Sparta formations generally contain thick, laterally continuous and permeable fluvio-deltaic sands. In comparison, the Reklaw, Weches, and Cook Mountain formations exhibit marine hydrostratigraphic character and are typically made up of clay, silt, and sand mixtures. These three formations are generally considered confining units within the Queen City and Sparta aquifers and the Carrizo aquifer. Sand bodies within the Reklaw, Weches, and Cook Mountain formations are common in the updip but they are in general finer, thinner, and less continuous than the sands of the Queen City and Sparta formations. These confining units occasionally contain limestone layers in the extreme south of the study area and lignite deposits across the entire study area.

The relationships between the different formations described in the previous paragraph are less appropriate south of the Sabine Uplift and west of the Frio River. South of Sabine Uplift and in Louisiana, the Queen City Formation decreases to a negligible thickness and its stratigraphic equivalent, the Cane River Formation, is typically described as an aquitard separating the Carrizo-Wilcox aquifer from the Sparta aquifer. In Louisiana, the Sparta Formation becomes considerably thicker and develops into a major aquifer. West of the Frio River in south Texas, the Queen City Formation becomes more clayey while the Reklaw Formation becomes sandier. West of the Frio River, the interval between the Carrizo-Wilcox aquifer and the Weches aquitard contains a series of local aquitards and aquifers with water of poor quality.

4.2 Structure

4.2.1 Structural Setting

Depositional patterns of Claiborne Group sedimentation were influenced by the tectonic evolution of the Gulf of Mexico Basin. Early Mesozoic history of the basin included rifting and creation of numerous subbasins. During the Jurassic, marine flooding and restricted circulation resulted in accumulation of halite beds in these subbasins (Jackson, 1982). Subsidence continued as the rifted continental crust cooled. The sediment column records the effects of changes in relative rates of sediment progradation, basin subsidence, and sea level change. More than 50,000 feet of sediment has accumulated in the Gulf of Mexico Basin (Salvador, 1991).

The Rio Grande and Houston Embayments, East Texas Embayment (sometimes referred to as the East Texas Basin), Sabine Uplift, and San Marcos Arch (see Figure 2.17) are the main structural features underlying the onshore part of the Gulf of Mexico Basin (Jackson, 1982; Galloway et al., 2000). Sediment input for the Queen City Formation was focused in the Rio Grande Embayment whereas, for the Sparta Formation, the main sediment input was to the east in the central Mississippi axis (Galloway et al., 2000). The East Texas Embayment is one of the major subbasins formed early in the Mesozoic, and it had significant thicknesses of halite deposition. Subsidence, tilting, and differential loading by Cenozoic sediments caused the displacement of halite beds and the formation of various salt-tectonic features such as salt ridges and salt diapirs or domes (Jackson, 1982). The Sabine Uplift, which lies at the eastern edge of the study area and extends into Louisiana, is a broad structural dome. Its topographic expression influenced sediment deposition in the East Texas Embayment during the Tertiary (Fogg et al., 1991). The San Marcos Arch is a structurally high basement feature beneath the central part of the Texas Coastal Plain separating the East Texas and Rio Grande Basins, areas that had greater rates of subsidence. The Queen City and Sparta formations drape over the San Marcos Arch.

Various fault zones are associated with the basin history of crustal warping, subsidence, and sediment loading. From coastward to inland, these include (1) the Wilcox Growth Fault Zone, (2) the Karnes Mexia Fault Zone, (3) the Elkhart-Mt. Enterprise Fault Zone, and (4) the Balcones Fault Zone (see Figure 2.17). The Wilcox Growth Fault Zone lies at the eastern or downdip limit of the study area (see Figure 2.17). Saline water predominates in this area. The growth or listric faults formed as thick packages of Wilcox sediment prograded onto the uncompacted marine clay and mud deposited in the subsiding basin beyond the Cretaceous shelf edge. Continued downward slippage on the gulfward side of the faults and sustained sediment deposition resulted in the Wilcox Group thickening across the growth fault zone (Hatcher, 1995). Petroleum exploration drilling and geophysical studies within the study area have indicated that many of these large, listric growth faults can offset sediments by 3,000 feet or more. The listric fault planes are curved, the dip of the faults decreases with depth, and the faults die out in the deeply buried shale beds. Complex fault patterns evolved, with antithetic faults forming various closed structures. The major faults of the Wilcox Growth Fault Zone extend upward into the Claiborne Group. The growth fault zone forms structural traps that hold major oil and gas reservoirs in the Wilcox Group (Fisher and McGowen, 1967; Galloway et al., 1983; Kosters et al., 1989) as well as smaller reservoirs in the Queen City and Sparta formations (Guevara and Garcia, 1972; Ricoy and Brown, 1977).

Displacement of halite beds resulting from subsidence, tilting, and sediment loading is the likely mechanism resulting in a zone of normal faults that offset strata in the freshwater-bearing parts of the Queen City and Sparta formations in the study area. The Karnes Trough Fault Zone, Milano Fault Zone, and Mexia Fault Zone (Jackson, 1982; Ewing, 1990) are collectively referred to as the Karnes Mexia Fault Zone in this report (see Figure 2.17). The fault zone marks the updip limit of the Jurassic Louann Salt (Jackson, 1982). Displacement along the Karnes Mexia Fault Zone occurred throughout Mesozoic deposition along the Gulf Coast and continued at least through the Eocene, resulting in noticeable syndepositional features. Numerous faults with as much as 800 feet of displacement that exhibit no syndepositional features are also present throughout the Karnes Mexia Fault Zone (Jackson, 1982). In the central part of the study area, the Karnes Mexia Fault Zone displaces sediments by more than 1,000 feet in some areas, restricting the hydraulic communication between outcrop and downdip sections of aquifers and dropping out areas of outcrop of the Queen City and Sparta formations. The Karnes Mexia Fault Zone goes updip of the Queen City Formation in Lee and Milam counties (see Figure 2.17).

The Elkhart-Mt. Enterprise Fault Zone lies along the structural high between the East Texas Embayment and the Gulf of Mexico Basin. Flexure with subsidence in these two basins formed extensional faults and associated graben structures in the Queen City and Sparta formations (see Figure 2.17). The Balcones Fault Zone consists of numerous fault strands that swing from northeasterly in the southern part of the study area to northerly in the central and northern parts of the area (see Figure 2.17). The Balcones Fault Zone lies updip of the Queen City and Sparta aquifers. Although the Balcones trend follows the thrust-fault trends of the late Paleozoic Ouachita Orogeny (Ewing, 1990), activity was mostly limited to the Late Cretaceous and Tertiary (Collins and Laubach, 1990). Some evidence points toward movement of this system as recently as Plio-Pleistocene times (Collins and Laubach, 1990). The zone results from tilting along the perimeter of the Gulf Coast Basin, flexure, and gulfward extension (Murray, 1961; Collins et al., 1992). Faults in this trend are of normal displacement, dominantly dipping to the southeast (basinward), although some northwest-dipping antithetic faults occur (Collins and Laubach, 1990).

4.2.2 Well-log Studies

Studies of the Sparta Formation by Ricoy (1976) and studies of the Queen City Formation in northeast Texas by Guevara (1972) and in south Texas by Garcia (1972) provided stratigraphic cross sections of the different formations and well-log-based net-sand calculations for approximately 900 wells from the Texas coastal plain study area. Out of those 900 wells, a total of approximately 250 well logs were selected for stratigraphic correlation and calculation of elevations of the selected stratigraphic horizons (Figure 4.2.1). The selected wells largely correspond to those used by Ricoy (1976), Garcia (1972), and Guevara (1972) to prepare cross sections. Some additional wells were correlated to the cross sections and added from areas between those that were represented by the published cross sections. Well locations were digitized from location maps provided by the Surface Casing Unit at the Texas Commission on Environmental Quality (TCEQ) in Austin, Texas. Surface datums to which well depths were referenced were taken from well logs where available; otherwise, ground-level elevations at well sites were used as surface datums and were estimated by intersecting well locations with digital elevation models (DEMs) (30-m resolution) in ArcView©. Dependability of DEM-derived elevations was checked by comparing well-log data with DEM data in wells that reported datum elevations. Correspondence was usually very good with divergences in the two types of data generally being less than 20 feet, although a few instances of divergence approaching 100 feet were encountered.

Stratigraphic boundaries were based on interpreted regional stratigraphic horizons, that is study-area-wide boundaries above which all strata are younger than strata below, rather than on lithologic criteria (e.g., the uppermost or lowermost occurrences of sandstone in individual wells). Formation names used in this study refer to operational units within which outcropping strata with the same names are contained. The upper and lower boundaries of formations in outcrop do not necessarily correspond precisely to the stratigraphic boundaries that were selected for the subsurface operational units.

Well-log depths to the top of the Sparta Formation were correlated to stratigraphic cross sections that were provided by Ricoy (1976). In general, the well-log responses used for this horizon show a minimum in an overall upward reduction of spontaneous potential (SP) and resistivity values recorded in the shaley rocks that occur between the uppermost Sparta sandstone and the lowermost Yegua sandstone in a given well. These responses suggest a transition from an overall upward decrease in clastic sediment texture to an upward increase in texture that marked the initiation of Yegua progradation. In sequence-stratigraphic terms, this horizon represents a regional maximum flooding surface at the top of the Sparta operational unit. In outcrop, the shaley rocks above the Sparta sandstone and below the Yegua sandstone are referred to as the Cook Mountain Formation; therefore, it is likely that the stratigraphic horizon selected for the top of the Sparta operational unit is equivalent to some horizon within the outcropping Cook Mountain. The base of the Sparta Formation (top of Weches Formation) was positioned at a horizon where overall upward increasing well-log SP and resistivity responses suggested upward textural coarsening deposition of clastic sediment that was interpreted to mark the onset of Sparta progradation. Payne (1968) applied lithologic criteria for his Sparta correlations and defined the top and base of the Sparta Formation on the basis of the uppermost and lowermost occurrences of sandstone. Payne’s 1968 structure map of the base of the Sparta Formation is similar to that based on the stratigraphic definitions used in this report, although his Sparta-Formation thicknesses are less than those produced by the correlations used in this project. These differences result from the use of a stratigraphic marker that is generally above the uppermost Sparta sand in a given well.

The upper boundary of the Queen City Formation was placed on top of an area-wide horizon defined by a positive SP and elevated resistivity response that is conspicuous because the well-log responses for tens to hundreds of feet above and below it show generally much lower

SP and resistivity values that are indicative of shale units. The conspicuous marker is interpreted to be a horizon that is approximately correlative to the uppermost Queen City sandstone in the most updip parts of the study area. However, this widespread stratigraphic marker has been informally interpreted by some to be a laterally continuous marl interval within the Weches Formation. In most places, the marker is very near the uppermost sandstone in the Queen City interval. Payne (1968) defined the upper boundary of the Queen City in the same way. The base of the Queen City Formation (top of Reklaw Formation) is defined in this work at a low-SP/low-resistivity well-log horizon that is interpreted to mark the maximum flooding surface of the Reklaw Formation and, thus, the onset of Queen City progradation.

In areas west of the Frio River, the Sparta Formation and overlying Cook Mountain-equivalent strata have been interpreted to occur in the outcropping Laredo Formation. The Queen City Formation and overlying Weches-equivalent strata are interpreted to occur in the outcropping El Pico Clay and Reklaw-equivalent strata have been interpreted to occur in the outcropping sandstone-dominated Bigford Formation (Eargle, 1968). Garcia (1972) included the Bigford sandstone in his Queen City interval. Ricoy (1976) and Garcia (1972) correlated Sparta and Queen City boundaries, respectively, into the area west of the Frio River. Those correlations were maintained for the data-compilation phase of the present study. In east Texas, south of the Sabine Uplift near the Louisiana state line, and in Louisiana, the Reklaw, Queen City, and Weches formations are indistinguishable. They are equivalent to the Cane River Formation in Louisiana (Eargle, 1968).

Preliminary mapping of the structure data revealed a number of structure and formation thickness anomalies (i.e., spatially abrupt changes in elevations of formation boundaries or formation thickness). Some of these probably reflect fault occurrences or salt-related structures. Salt domes and associated structures have been mapped in parts of the study area, especially in the Houston Embayment (Jackson and Seni, 1984). In south Texas, salt-withdrawal structures (Fiduk and Hamilton, 1995) and raft-detachment structures (Anderson and Fiduk, 2003) have been interpreted and mapped. These structural features produce abrupt changes in structure elevations and locally thickened Tertiary sedimentary sections.

4.2.3 Construction of the Structural Surfaces

Structure of an aquifer system in a modeling context consists of the physical dimensions of the aquifer and its confining layers. These dimensions are the surfaces describing the elevations of the tops and bottoms and the position of the sides of the model layers. The aquifer-system structure is probably one of the best characterized model input parameters. The structure of the top and bottom of the aquifers is defined by numerous wells, topography of the land surface, water levels which define the top of the aquifer in the outcrop zone, and geologic maps providing the lateral extent of formation outcrops. Although formation structure is not measured at every model grid cell center, the uncertainty in structure is considered acceptable for a regional groundwater model.

Construction of structural surfaces of layer elevations for input to the computer model required compilation and digitizing of structure information from a number of sources. Sources on subsurface structure included Payne (1968), Garcia (1972), Guevara and Garcia (1972), Guevara (1972), Ricoy (1976), Ricoy and Brown (1977), unpublished data from an east Texas ground water model developed by the TWDB, and USGS RASA data (Wilson and Hosman, 1988). In addition, tabulated geologic determinations from geophysical logs gathered at the TCEQ Surface Casing Unit were used as described in Section 4.2.2. A three-arc second DEM of the outcrop of the Queen City, Weches, Sparta, and related formations was downloaded from a USGS web site. DEM data were used to define the top elevations of the formations in their outcrop. Since the scale of interest is a one-mile square cell, cell elevations at the cell center were obtained by calculating the arithmetic average of all the elevation values falling within the cell. Outcrop elevations were computed using the same data for the three models. However, since the cell centers do not fall at the exact same location in the overlap areas, overlapping cells between two models have different ground-surface elevations.

Likewise, two overlapping cells will not necessarily have the same numerical value for a given structural surface. A dip of 200 feet per mile will yield a difference in elevation of 50 feet if the centers of approximately equivalent cells are one-quarter mile apart in the dip direction.

Construction of the structural surfaces was constrained by the self-imposed rule modifying the top of the Carrizo-Wilcox aquifer as little as possible in order to maintain maximum consistency with the three underlying Carrizo-Wilcox GAMs. Construction of the surfaces relied on two assumptions: the top of the Carrizo Formation will only be minimally changed and the base of the Sparta Formation is the best known amongst the four other structural surfaces.

Tops of the Carrizo Formation across the three Carrizo-Wilcox GAMs were in general consistent but showed some discrepancies, in particular in the downdip area of the overlap between the central and northern models and the central and southern models. To remove these initial discrepancies, tops of the Carrizo Formation as determined for the Carrizo-Wilcox GAMs were adjusted in the following way using the Trinity and Guadalupe rivers as boundaries. South of the Guadalupe River, both southern and central models used data from the southern Carrizo-Wilcox model, north of the Trinity River, both northern and central models used data from the northern Carrizo-Wilcox model. Between the Guadalupe and Trinity rivers, all three models use data from the central Carrizo-Wilcox model. To allow a smooth transition across the rivers, data were merged in a band of approximately 20 cells in width centered on the river cells. Consequently, the top of the Carrizo for those cells along the Trinity and Guadalupe rivers is some intermediate value between the two overlapping Carrizo-Wilcox models. To prevent undesirable consequences to outcrop parameters, in particular recharge and stream flow, those changes were not made in the outcrop areas. Outcrop cell elevations were computed differently in the Central Carrizo-Wilcox GAM as compared to the Northern Carrizo-Wilcox and Southern Carrizo-Wilcox GAMs. Those differences still exist in the Queen City and Sparta GAMs for the Wilcox layers. Another difference in treatment carried over from the Carrizo-Wilcox GAMs to the Queen City and Sparta GAMs is the addition of alluvial deposits associated with the Colorado, Brazos, and Trinity rivers to the Central Carrizo-Wilcox GAM. The Northern and Southern Carrizo-Wilcox GAMs did not model alluvium. Alluvium was not explicitly modeled as a model layer in the Queen City and Sparta GAMs.

The base of the Sparta Formation included information from 171 TCEQ Surface Casing Unit geophysical well logs as described in Section 4.2.2 and 161 well logs from the unpublished east Texas model. This data set was complemented in Louisiana by three well logs extracted from the USGS RASA database and by contour lines digitized from Payne (1968). In other areas lacking information, points from the Payne (1968) study were used. Outcrop DEM data completed the data set. The structure data set was processed and kriged using the Surfer© mapping software and individual cell elevations extracted. The top of the Sparta Formation and the base of the Weches Formation were obtained by adding and subtracting the thickness of the Sparta and Weches formations, respectively, to the base of the Sparta. Thicknesses were obtained by kriging the thicknesses derived from the geophysical well logs and, locally, from the unpublished east Texas model well logs.

The vertical interval containing the Reklaw and Queen City formations (see Figure 2.19) is constrained by the choice of anchoring the models on the top of the Carrizo Formation and the base of the Sparta Formation (or the base of Weches Formation since its thickness is already computed). In most cases, the total thickness of the Reklaw and Queen City formations as derived from the well logs fall within this interval with an acceptable deviation. However, in a few instances, in particular where the top of Carrizo Formation was data poor at the time the Carrizo-Wilcox GAMs were developed, this interval is not large enough to include both the Reklaw and Queen City formations. In this case, the thickness of the Queen City Formation as calculated from the geophysical well logs was honored and the thickness of the Reklaw aquitard was artificially reduced.

The largely unconfined section of the Queen City Formation in the East Texas Embayment is partly covered by Weches and Sparta formation remnants, the so-called Sparta Islands (see Figure 2.18a). A few TCEQ Surface Casing Unit geophysical logs, in addition to the surface geology, helped in determining the elevations of the top of the Weches and Queen City surfaces. To facilitate convergence of the numerical model, outcrop cells in the Sparta Islands and elsewhere were assigned a thickness of at least 50 feet when possible. Downdip sections of the model assumed a minimum thickness of 20 feet.

The elevation of the top of the Carrizo Formation (base of the Reklaw Formation) ranges from ground surface at the updip limit of the formation to as much as 7,200 feet below sea level at the downdip limit of the study area (Figure 4.2.2). The formation dip generally increases with depth. It also shows well developed anticlines such as the feature present where Washington, Waller, and Austin counties meet or synclines in east Texas across Wood, Upshur, Smith, and Anderson counties and in the Wintergarden coincident with the Rio Grande Embayment. Other maps of structural surface elevation (Figures 4.2.3 to 4.2.6) show the same general features of a surface gently dipping to the southeast towards the Gulf of Mexico.

The thickness of the Carrizo is shown in Figure 4.2.7. As described earlier, the Carrizo structure was made consistent between the three Carrizo-Wilcox GAMs. Thicknesses of the Sparta and Weches formations were tallied from the geophysical log sources and contoured in Surfer© while thicknesses of the Queen City and Reklaw formations were computed from differences in elevations of the structural surfaces. All formations thicken towards the Gulf of Mexico, which is the regional depocenter. Thicknesses of both the Reklaw and Queen City formations increase towards the southwest while the thickness of the Sparta Formation increases towards the northeast and Louisiana.

The thickness of the Reklaw Formation and its stratigraphic equivalents is generally below 500 feet (Figure 4.2.8) but can locally reach 1,000 feet west of the Frio River in the southern model area, especially in the vicinity of the Nueces River where the structural basin of the Rio Grande Embayment is centered. The Reklaw Formation is approximately 100 feet thick from Cass to Smith to Leon counties. In these counties, the Reklaw, Queen City, and Weches formations are not differentiated and make the transition to the Cane River Formation in Louisiana. Further south, in Wilson and Atascosa counties, the thickness of the formation is 200 to 300 feet. West of the Frio River, the clayey Reklaw Formation intermingles with its stratigraphic equivalent, the sandy Bigford Formation, and is between 300 to 600 feet thick and locally more than 1,000 feet thick. Sandy intervals of the top of the Bigford Formation have been included in the Queen City Formation as defined in this work.

The thickness of the Queen City Formation and its stratigraphic equivalents increases considerably from almost nothing at the Louisiana state line to more than 2,000 feet at the Mexican border (Figure 4.2.9). The thickness of the Queen City Formation in east Texas north and west of the Sabine Uplift along the East Texas Embayment is generally between 200 and 400 feet but locally reaches more than 500 feet in Smith County. The Queen City Formation as a deltaic sandy aquifer pinches out south of the Sabine Uplift and, there, its stratigraphic equivalent is part of the marine Cane River Formation. An arbitrary thickness of 20 feet has been assigned to the formation south of the Sabine Uplift and in Louisiana. Towards the southwest, the thickness gradually increases from about 400 feet in Leon County to about 800 feet in Wilson County. Further south, approaching the center of the Rio Grande Embayment, the thickness of the Queen City Formation increases dramatically to more than 1,200 feet and becomes more clayey, transitioning to its stratigraphic equivalent west of the Frio

River, the El Pico Clay. The stratigraphic equivalent of the Reklaw, Queen City, and Weches formations west of the Frio River are the Bigford Formation and the El Pico Clay. West of the Frio River, the sandy Queen City Formation transitions into the more clayey El Pico Clay while the Reklaw Formation grades into a more sand rich Bigford Formation. A large section of the Bigford Formation, defined by its abundance in sands, has been added to the El Pico Clay to be included in what has been defined as the Queen City Formation in this work. This results in a Queen City Formation thickness that can locally reach more than 2,000 feet.

The thickness of the Weches Formation is generally under 100 feet and reaches values above 200 feet only downdip at the study area boundary (Figure 4.2.10). A typical thickness in east Texas is in the range of 30 to 80 feet. In Louisiana and south of the Sabine Uplift, the stratigraphic equivalent of the Weches Formation is the Cane River Formation, which also includes the stratigraphic equivalent of the Queen City and Reklaw formations. Similar thicknesses are maintained across central Texas. West of the Frio River, the Weches Formation loses its marine character and merges laterally into the El Pico Clay. The thickness retained in this work from the geophysical logs is again in the same range of 30 to 100 feet except downdip where the thickness can increase to more than 200 feet.

The thickness of the Sparta Formation varies gradually from more than 700 feet at the Red River in Louisiana to about 200 feet in the updip subsurface in south Texas (Figure 4.2.11). The thickness of the formation generally increases with depth. The thickness also varies locally along strike, correlating with the axes of the fluvio-deltaic deposition centers. In particular, the expression of the San Marcos Arch is visible in Gonzales County with a local decrease of the formation thickness. The same feature is even more visible on the sand thickness map (Figure 4.2.13). West of the Frio River, the Sparta Formation merges into the Laredo Formation that also comprises the stratigraphic equivalent to the Cook Mountain Formation. This work recognizes that the stratigraphic equivalent to the Sparta Formation can be correlated in the geophysical logs across the Frio River.

4.2.4 Net Sand Thickness Maps

Net sand thicknesses for the Queen City and Sparta formations were taken from maps published in Guevara and Garcia (1972) and Ricoy and Brown (1977), respectively. These maps are based in the work of Payne (1968), Ricoy (1976), Garcia (1972), and Guevara (1972) and are reproduced in Figures 4.2.12 and 4.2.13. Ricoy (1976), Garcia (1972), and Guevara (1972) did not explicitly define the subsurface boundaries of the Sparta and Queen City formations. Rather, they calculated net-sand values within stratigraphic intervals in a given well that were generally bounded top and bottom by sandstone strata that they interpreted as occurring in underlying and overlying formations. Ricoy (1976) measured Sparta net sand in intervals that occurred between the uppermost Queen City-equivalent sandstone and the lowermost Cook Mountain or Yegua sandstone. Guevara (1972) and Garcia (1972) measured Queen City Formation net sand in intervals that occurred between the uppermost Carrizo-equivalent sandstone and the lowermost Sparta sandstone. The original stratigraphic definitions of the authors were maintained in this study so that their net-sand data could be used in the GAM models.

Net-sand values were provided in appendices that accompanied the reports of Ricoy (1976), Guevara (1972), and Garcia (1972). The maps were digitized and imported into Arcview©. These data are estimates because semi-quantitative criteria were applied to SP and resistivity well logs to interpret sandstone intervals (Guevara, 2003, personal communication). In general, sandstone intervals are marked by a positive SP response coupled with elevated resistivity values. Shales are marked by low-SP and low-resistivity values. In most cases, sandstones were interpreted where SP values exceeded a cutoff value of two-thirds the distance between minimum values ("shale base line") and maximum values ("non-shaley sandstone") on a given well log. In some cases, sandstone was interpreted where suppressed SP responses accompanied elevated resistivity responses, which is typical for sandstones that contain groundwater that is much fresher than the water used to make the drilling mud.

The Payne (1968) Sparta net-sand values in some areas were significantly lower than those of Ricoy (1976), although Payne's boundaries for the Sparta sandstone-dominated interval generally agreed with Ricoy's. Neither Ricoy (1976) nor Payne (1968) specified well-log criteria with which they interpreted sandstone occurrences. Based on examination of Payne's cross-sections, however, it appears that he may have measured as sandstone only those intervals that obviously contained fresh water (suppressed SP and elevated resistivity responses). If so, his maps would be better identified as net-freshwater-sandstone maps.

The sand thickness maps (Figures 4.2.12 and 4.2.13) follow the picture established for the total thickness of the formation in the strike direction. In the dip direction, that is, in the direction of the basin away from the sediment sources, the sand thickness typically decreases as sand bodies are progressively replaced by mud. The impact of the basement high of the San Marcos Arch is also apparent in decreasing sand thickness of both the Queen City and Sparta formations. The Queen City Formation sand thickness in the updip subsurface varies from more than 250 feet in east Texas southwest of the Sabine Uplift to more than 1,000 feet in the Rio Grande Embayment. The lobate complex shape of the contour lines, particularly in east and central Texas, reflects the individual fluvial sand input centers. Slightly less lobate contour lines in south Texas suggest that the sediments were partially reworked and redistributed. The Sparta Formation sand thickness in the updip subsurface is more constant throughout the study area at approximately 200 to 300 feet with again the influence of the San Marcos Arch in Wilson, Gonzales, and Fayette counties with a reduced sand thickness of about 100 feet. The contour lines show well developed lobes on either side of the arch but are parallel to the formation strike at the arch location. This is explained by a lack of terrestrial sediment input during the time of the Sparta sedimentation on the San Marcos Arch and by lateral sediment transport along the coast of the ancestral Gulf of Mexico (Ricoy, 1976).

As part of the scope of the development of the Queen City and Sparta GAMs, the Carrizo net-sand thickness map was re-interpreted from thicknesses reported in Deeds et al. (2003), Dutton et al. (2003), and Fryar et al. (2003) to make a consistent map across all three GAMs. The only new data included in the new net-sand map is a detailed net-sand thickness map developed for the Gonzales County UWCD by David Thiede. This map was provided to INTERA by the Gonzales County UWCD and is included in the data model which accompanies this report.

File: 4.2.1_Well_Location_Map.mxd

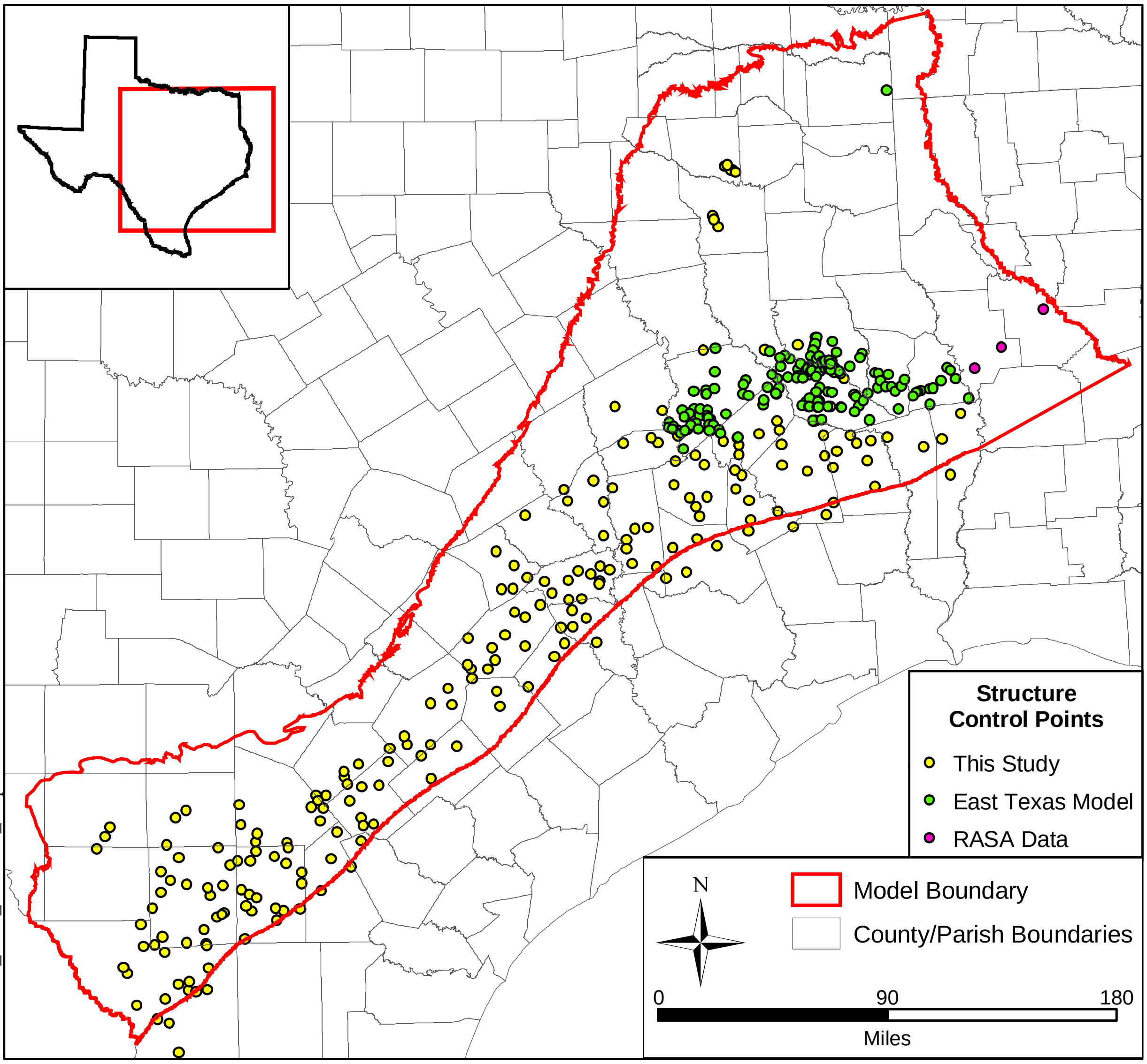


Figure 4.2.1 Well log locations.

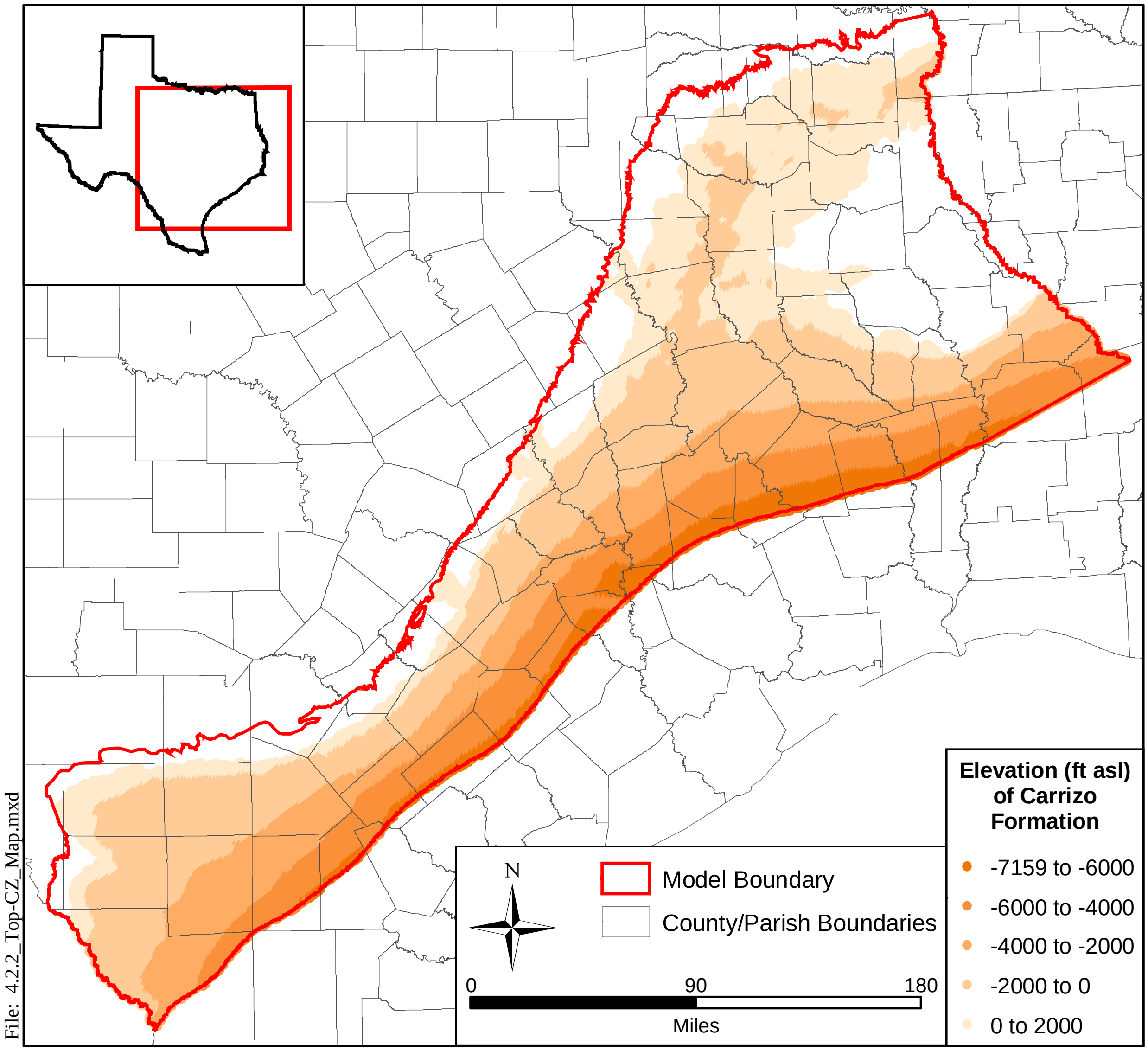


Figure 4.2.2 Top of Carrizo Formation.

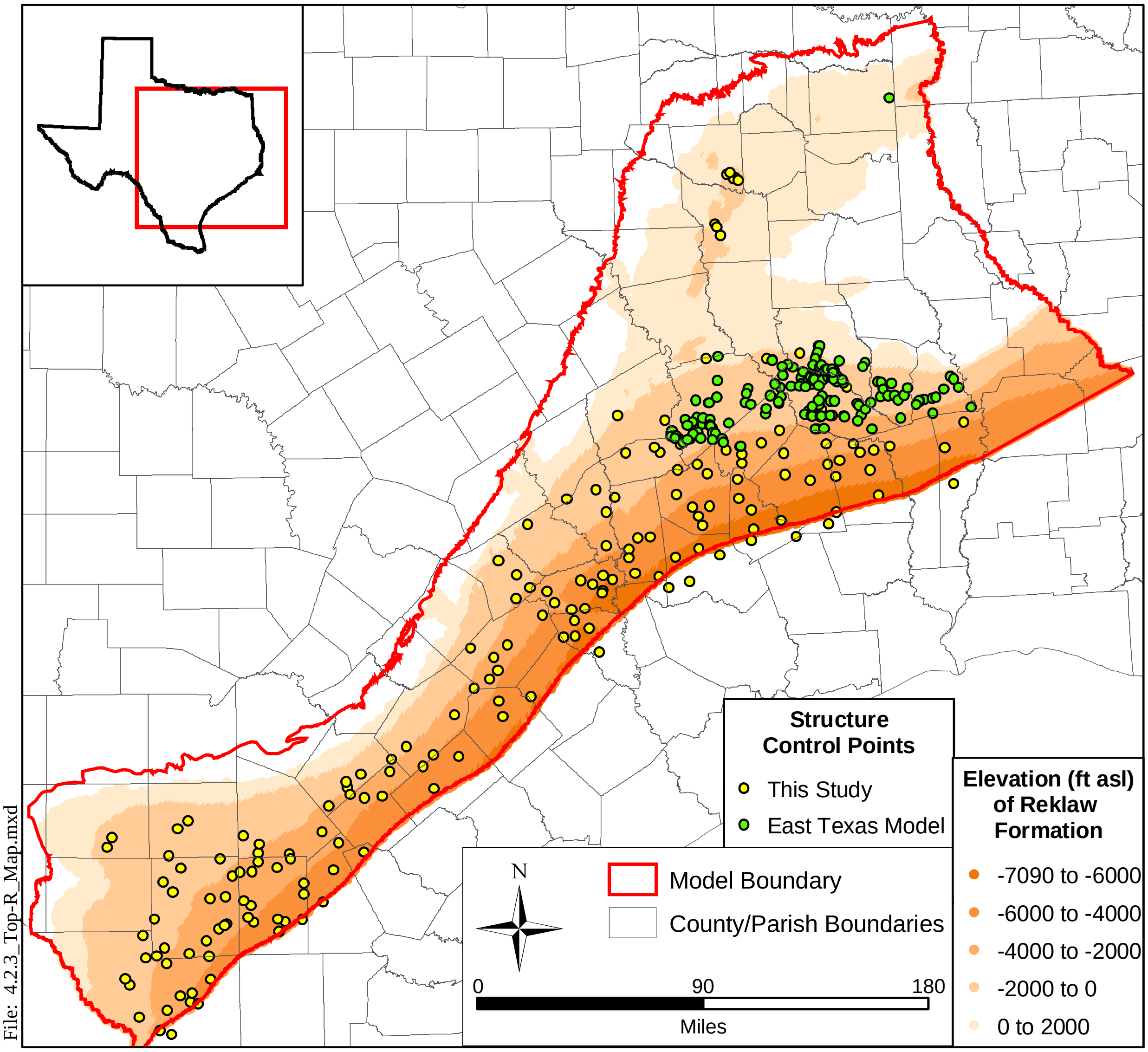


Figure 4.2.3 Top of Reklaw Formation.

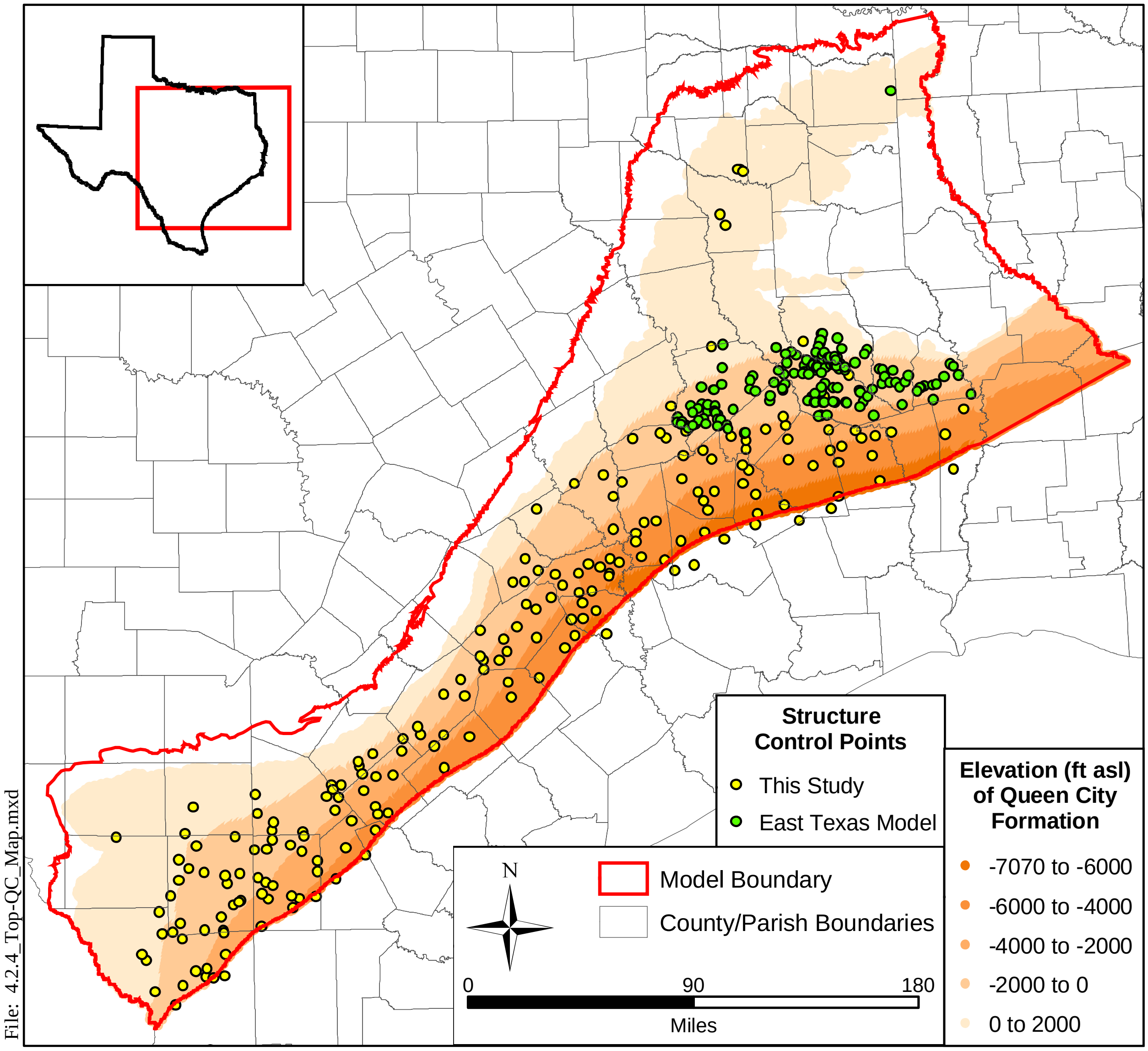


Figure 4.2.4 Top of Queen City Formation.

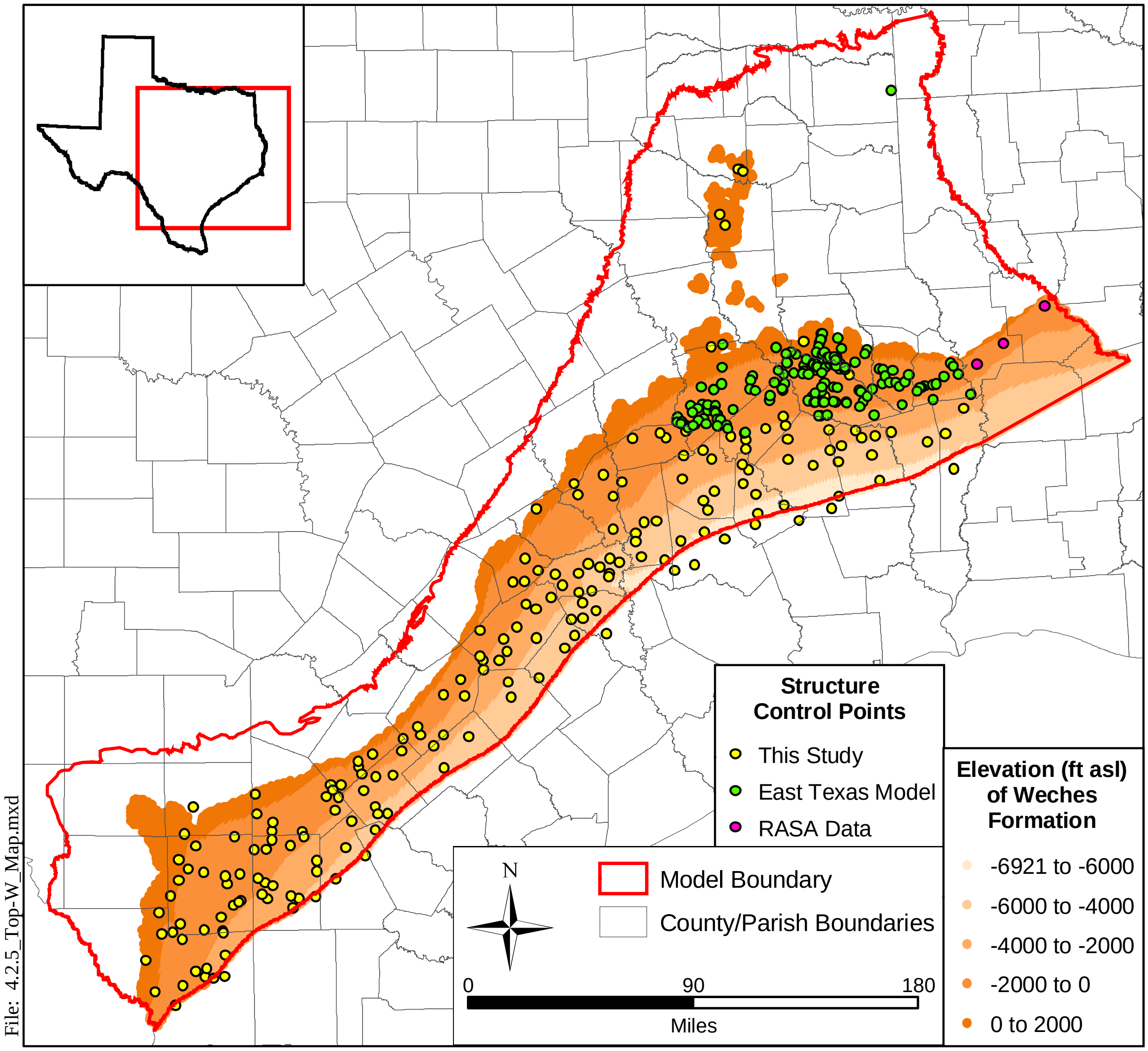


Figure 4.2.5 Top of Weches Formation.

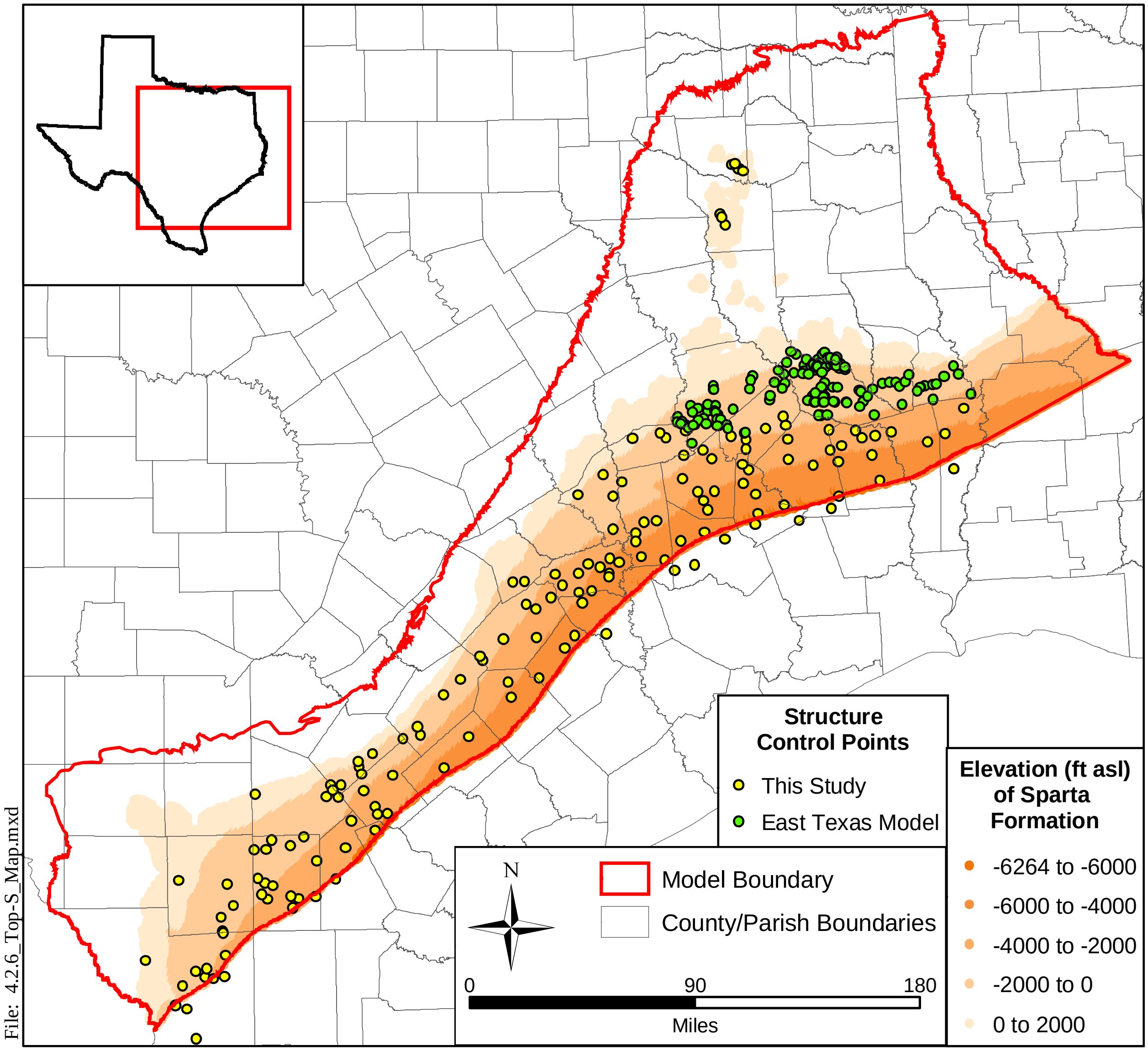


Figure 4.2.6 Top of Sparta Formation.

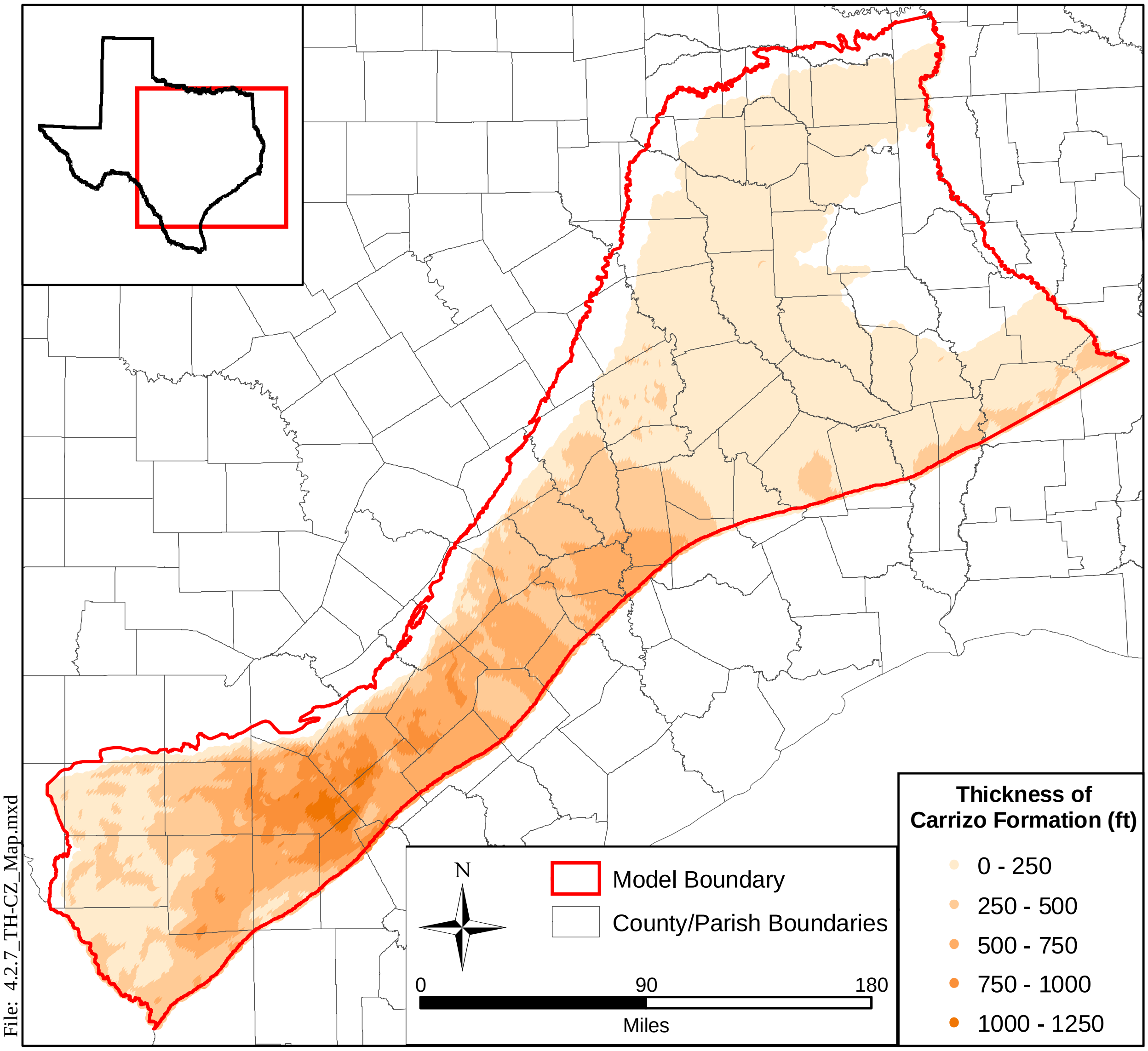


Figure 4.2.7 Thickness of the Carrizo Formation.

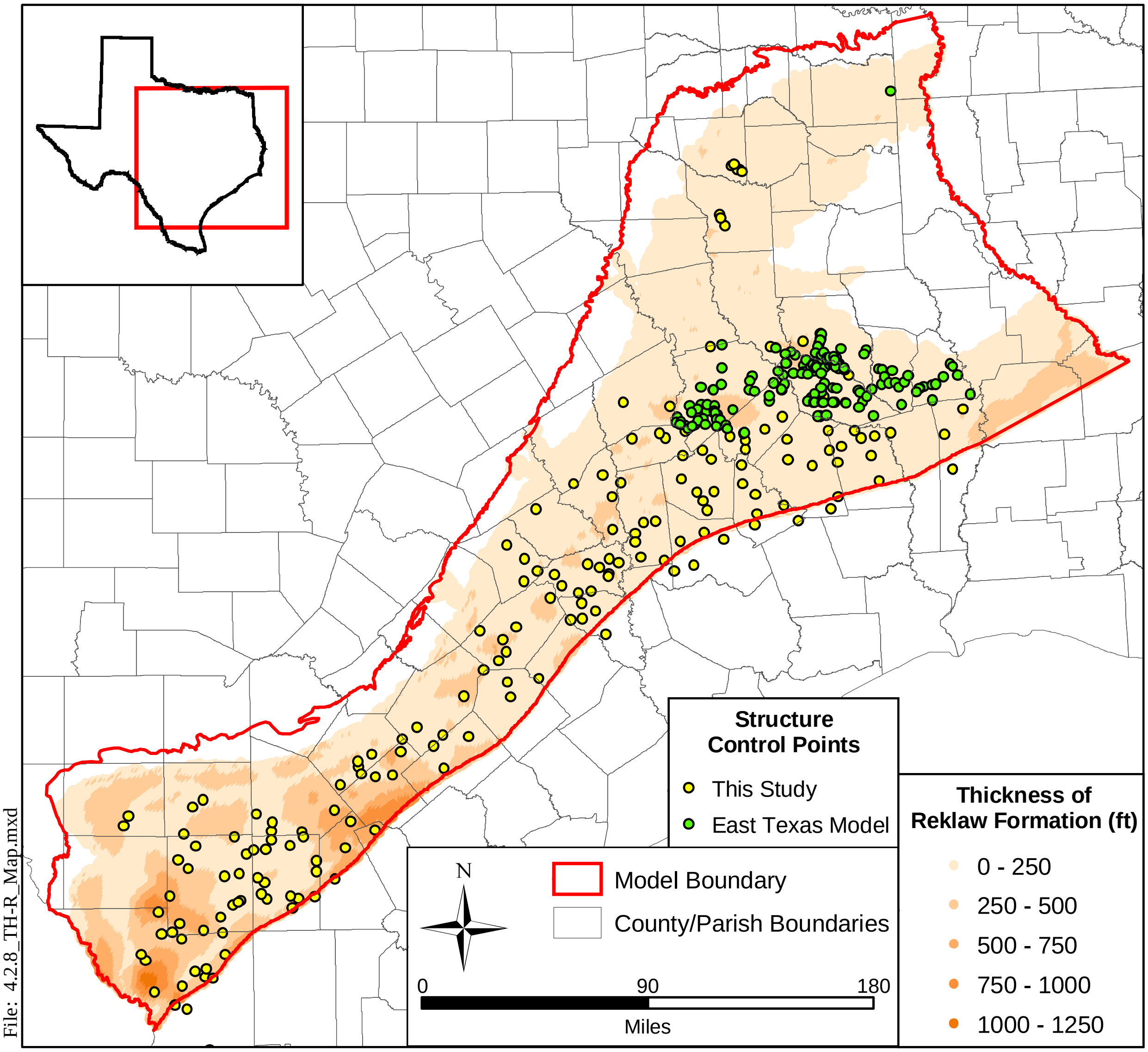
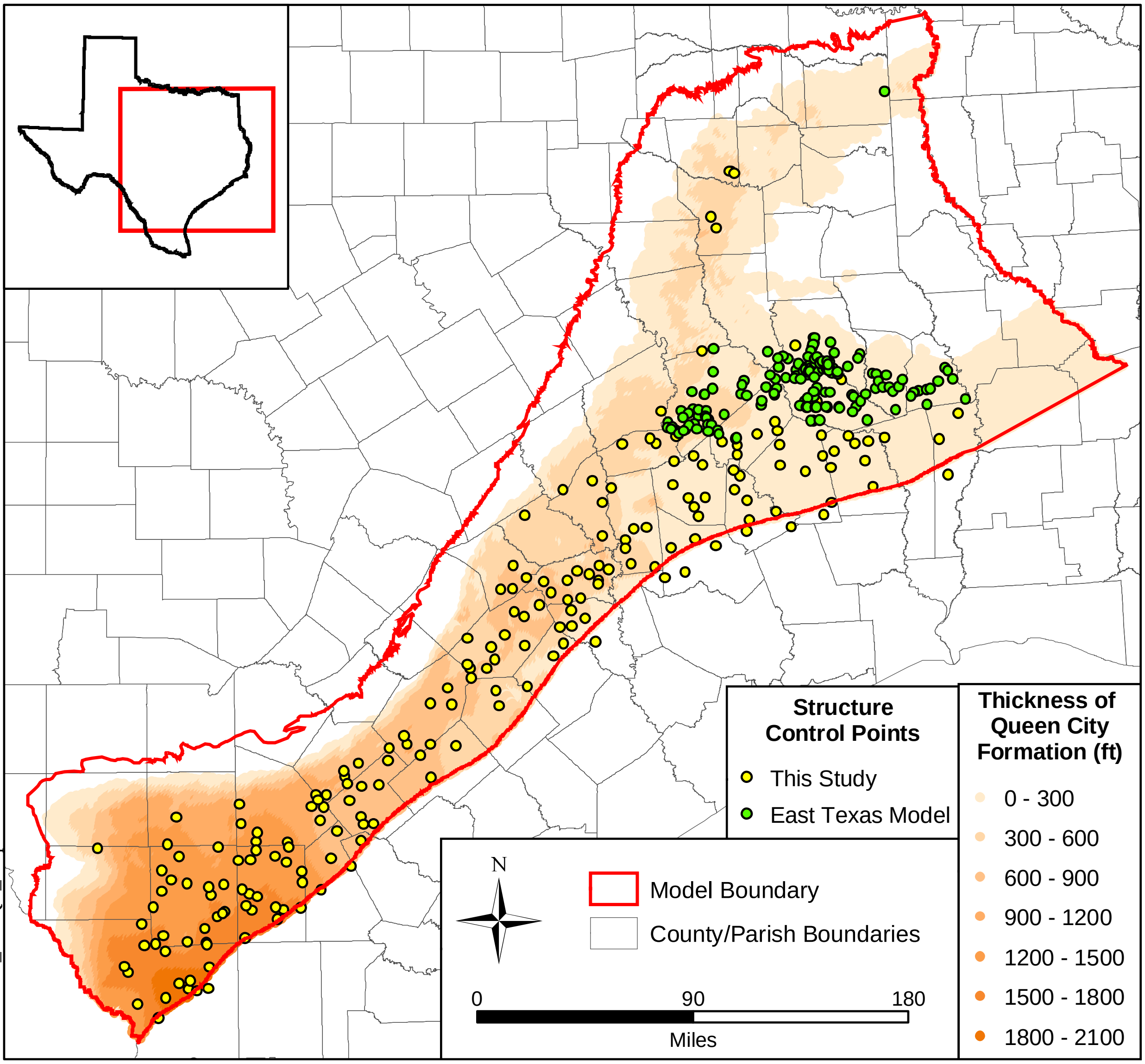


Figure 4.2.8 Thickness of Reklaw Formation.



File: 4.2.9_TH-QC_Map.mxd

Figure 4.2.9 Thickness of Queen City Formation.

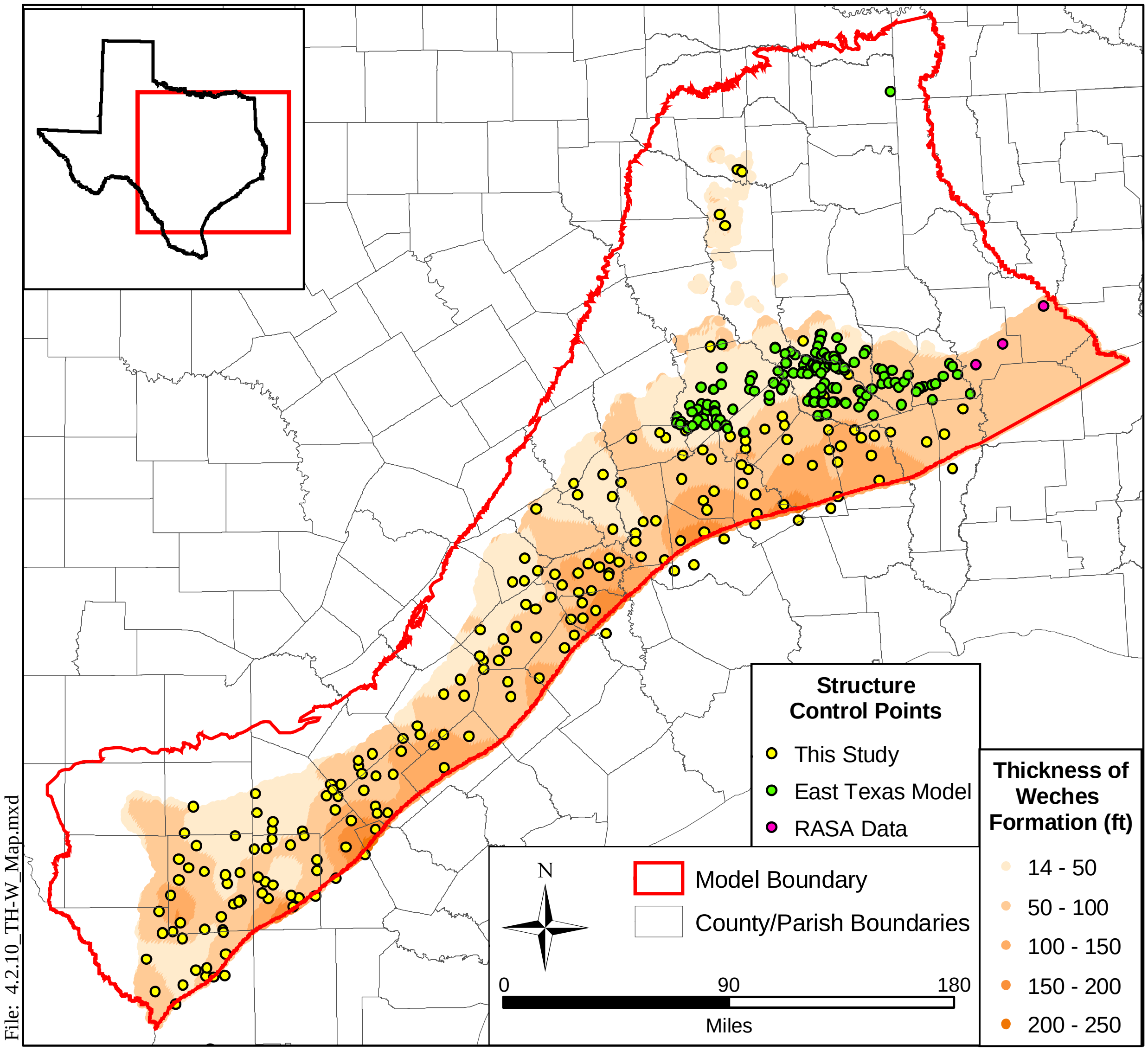


Figure 4.2.10 Thickness of Weches Formation.

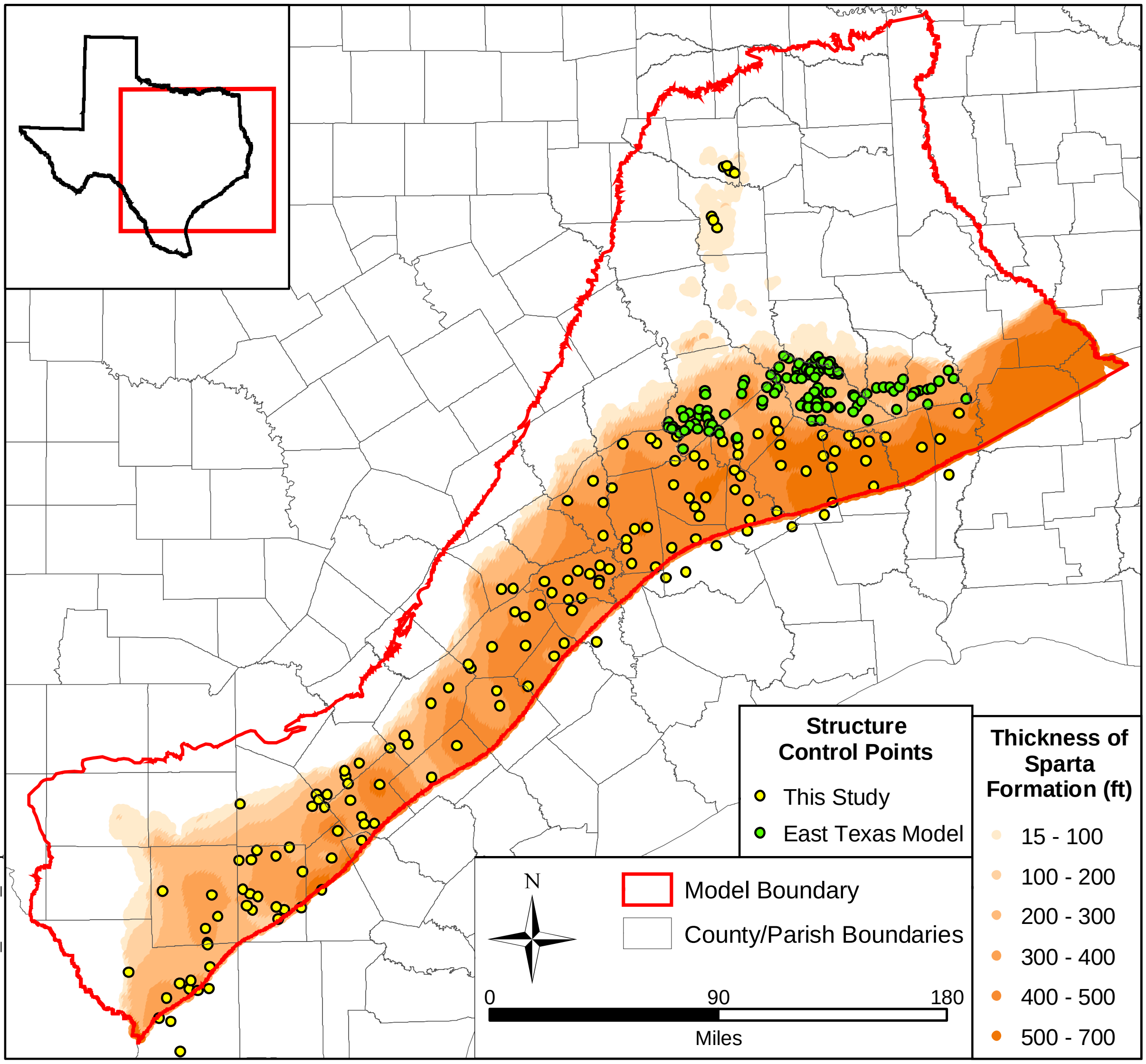


Figure 4.2.11 Thickness of Sparta Formation.

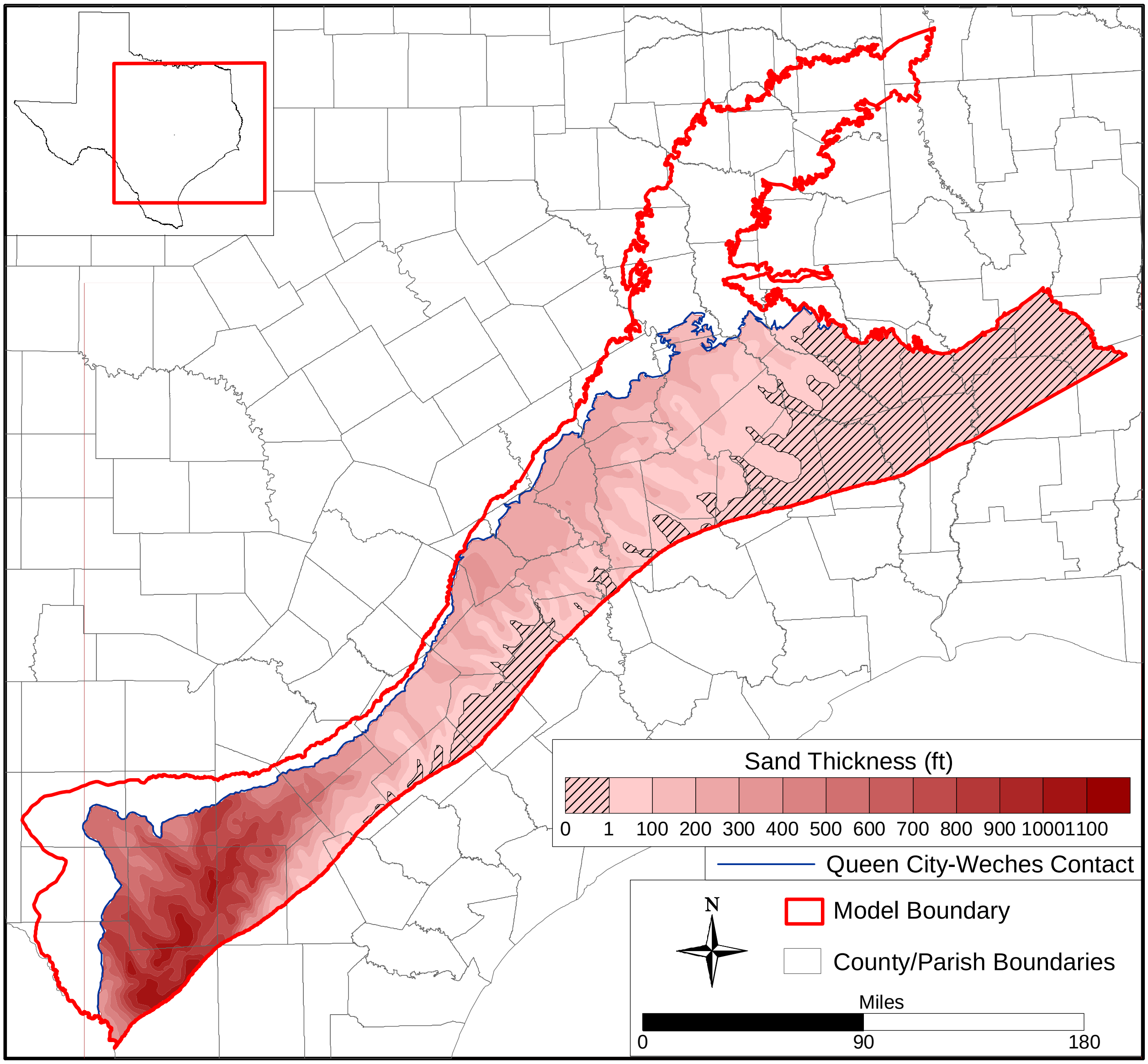


Figure 4.2.12 **Queen City sand thickness (after Guevara and Garcia, 1972).**

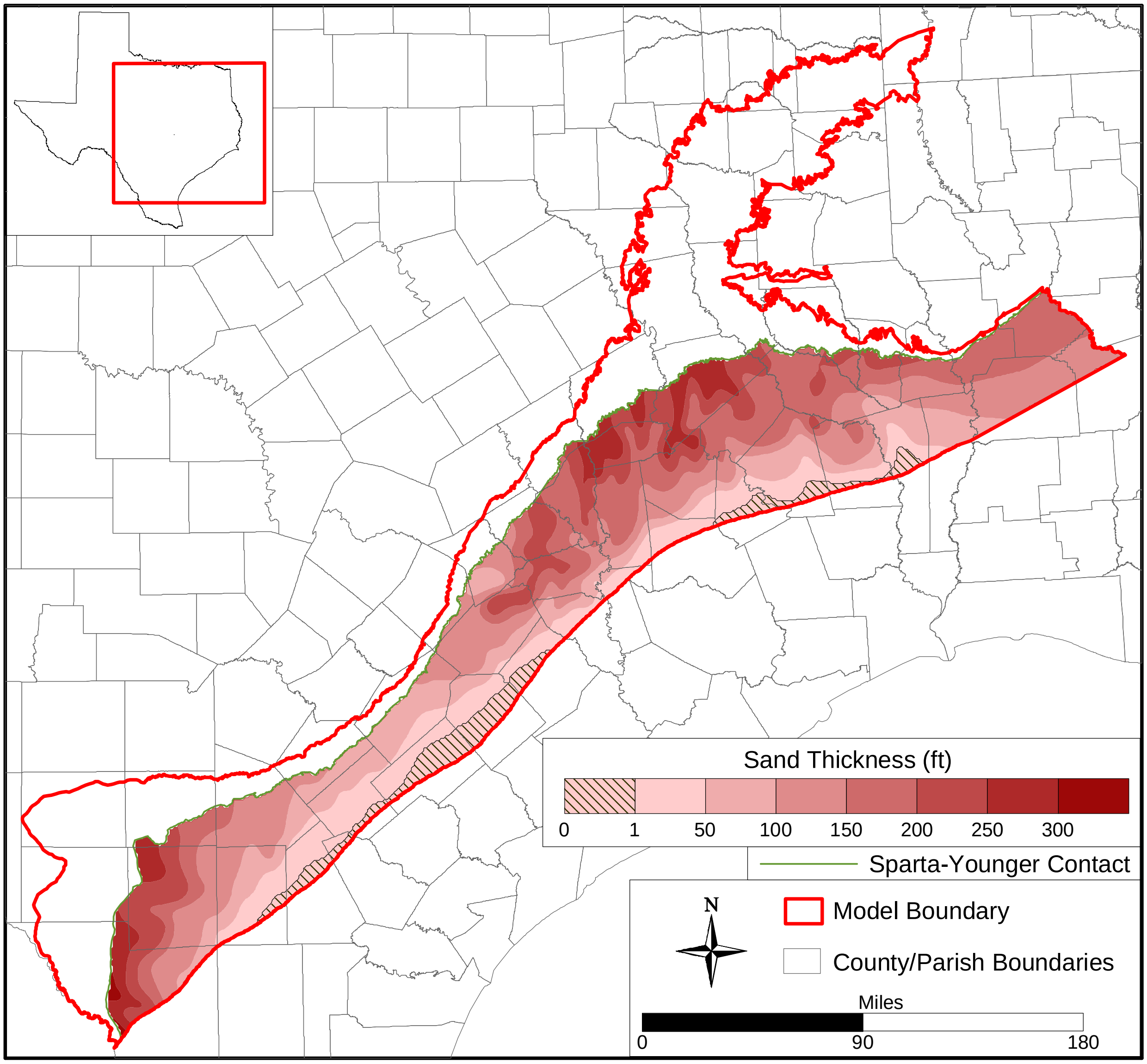


Figure 4.2.13 Sparta sand thickness (after Ricoy and Brown, 1977).

4.3 Hydraulic Properties

4.3.1 Acquiring Specific Capacity Data for the Study Area

Specific capacity data were compiled from the well records at the TCEQ in Austin, Texas. These data were used to calculate hydraulic conductivity as described in Section 4.3.2. Extensive information was extracted from the paper files. This information included location known at least to the closest 2.5-minute quadrangle centroid, well owner, date drilled, well diameter and depth, gravel pack, if any, number of screened intervals and their elevations, type of screen, depth to water, and well test information (duration, pump rate, drawdown, and type of test). Well locations were assigned to the centroid of the 2.5-minute quadrangle or more accurately when possible. The types of tests included pumped, jetted, or bailed. A total of 1,076 measurements fell within the vertical and horizontal footprint of the Queen City and Sparta aquifers as determined by the structure presented in Section 4.2. Since jetted and pumped tests provide much more accurate specific capacity data than do bailed tests, bailed tests were removed from the database, leaving 963 measurements. A total of 911 measurements were attributed to the Queen City aquifer while only 52 measurements were attributed to the Sparta aquifer. In addition, several wells whose locations are not accurately known were assigned to the same quadrangle centroid. This resulted in a total of 617 and 38 unique locations for the Queen City and Sparta aquifers, respectively.

Direct hydraulic conductivity data for the Queen City aquifer were extracted from the Mace et al. (2002) database. First, wells with a location inside the Queen City or Sparta aquifer footprint were queried. Of the resulting 3,151 wells, a majority were Carrizo-Wilcox wells. Wells with an identical location and total depth compared to wells in the TCEQ data described above were removed, resulting in 240 removals. Finally, wells that were screened more than half in the Queen City or Sparta aquifer based on the structure reported in this study were attributed to that formation. This screening process resulted in 412 wells in the Queen City aquifer and no wells in the Sparta aquifer.

In the remainder of Section 4.3, the data that were gathered from the TCEQ for this study will be called “TCEQ data” and the data from the Mace et al. (2002) database will be called “Mace et al. data”.

4.3.2 Calculation of Hydraulic Conductivity from Specific Capacity

Because specific capacity is relatively easy to measure, requiring knowledge of only the pumping rate and drawdown, it is commonly reported in well records. However, hydraulic conductivity is a more useful parameter than specific capacity for regional groundwater modeling. The methodology presented in Mace (2001) was used to estimate hydraulic conductivity from specific capacity. Hydraulic conductivity is reported as part of the Mace et al. data. Therefore, the calculation of hydraulic conductivity from specific capacity was performed in the current study only for the TCEQ data.

Transmissivity can also be determined from an empirical relationship, provided benchmarking measurements of both transmissivity and specific capacity exist at the same location. This empirical relationship could not be derived for the Queen City and Sparta aquifers due to the paucity of such locations. Instead, a scaled version of the empirical relationship developed for the Carrizo-Wilcox aquifer (Mace et al., 2002) was used for those points where the Theis et al. (1963) equilibrium analytical method failed to converge (a total of 6 measurements) and as a general check of the results.

Computation of transmissivity from specific capacity requires knowledge of the storativity of the aquifer. A value of 2×10^{-4} was assumed in this study, based on available literature (see Section 4.3.8). Although the Theis et al. (1963) formulation is strictly valid only for confined aquifers, it can also be applied to unconfined aquifers provided that the drawdown is small relative to the aquifer thickness. Specific yield is then used in lieu of storativity. An average value of 0.15 was assumed for specific yield in this study (see Section 4.3.8). Either storativity or specific yield was used as dictated by the structure presented in Section 4.2. Since storativity or specific yield enters the equation in a logarithm term, the transmissivity is relatively insensitive to these parameters. A decrease by one order of magnitude of the storativity to 2×10^{-5} or of the specific yield to 0.05 generates a transmissivity increase of 15 and 20 percent, respectively. Conversely, an increase in storativity to 2×10^{-3} and in specific yield to 0.30 generates a transmissivity decrease of about 20 and 12 percent, respectively. Obtaining more accurate results also entails correcting for well loss, which typically amplifies drawdown. Drawdown measurements were corrected according to Equation 64 of Mace (2001). Corrections are typically less than 5 percent. Conductivity was then obtained from transmissivity by dividing by the screen length. When multiple results existed at a single location, the geometric average of the conductivity was assigned to that location.

4.3.3 Analysis of the Hydraulic Property Data

Figure 4.3.1 shows histograms of the hydraulic conductivity data for the Queen City and Sparta aquifers. Note that the horizontal scale on these figures is logarithmic. Table 4.3.1 shows summary statistics for these data. The histograms indicate that the hydraulic conductivity data are nearly lognormally distributed. Additional evidence can be found in Table 4.3.1 where the geometric mean of each dataset is similar to the median. The Sparta aquifer data distribution is not as symmetrical as the Queen City aquifer histograms, likely due to the smaller population. This lack of data for the Sparta aquifer is the most significant difference between the Queen City and Sparta datasets.

The Mace et al. data has a slightly higher median value [5.0 feet per day (ft/day)] compared to the TCEQ dataset (3.9 ft/day). This higher median is reflected in Figure 4.3.1, where the Mace et al. distribution is shifted slightly towards the higher conductivity values, especially in the 10 to 30 ft/day bin.

Table 4.3.1 Summary statistics for hydraulic conductivity data (ft/day).

Statistic	Queen City			Sparta
	TCEQ	Mace	Combined	
Number of Samples	617	412	1,029	38
Arithmetic Mean	9.8	17.0	12.7	18.3
Median	3.9	5.0	4.2	5.7
Geometric Mean	3.8	5.7	4.5	5.8
Standard Deviation K	18.0	52.7	36.3	30.0
Standard Deviation Log10(K)	0.62	0.64	0.63	0.80

4.3.4 Correlation of Hydraulic Conductivity to Sand Distribution or Depth

Figures 4.3.2 through 4.3.4 show post plots of the location of the hydraulic conductivity data for the Queen City and Sparta aquifers. Figures 4.3.2 and 4.3.3, which show the Queen City TCEQ and Mace et al. data, respectively, indicate a similar coverage for both datasets. That is, the majority of the data is in or near the outcrops of the Queen City aquifer. Very few measurements in the Queen City aquifer are located even halfway between the outcrop-subcrop interface and the downdip limit. In the Sparta aquifer (Figure 4.3.4), data is very sparse in general and similarly concentrated in or near the outcrop.

Because properties must be estimated in all regions of the model, several methods of "filling in" those areas that lack measurements must be considered. The simplest method would be to take an overall mean or median value from the measured conductivity data and use it in the portion of the aquifer where measurements are unavailable. However, this method ignores other potential secondary sources of data for hydraulic conductivity. Prudic (1991) evaluates two parameters, depth of burial and sand thickness, for his correlation to measured hydraulic conductivity. His overall evaluation was of the Gulf Coast regional aquifer systems. One of the units evaluated by Prudic (1991) was termed the "middle Claiborne aquifer" and consists of the combined Queen City and Sparta aquifers. In 30 of the 41 aquifer/region combinations, including the middle Claiborne, he found that hydraulic conductivity decreased with depth. Based on 31 measurements in the middle Claiborne, Prudic (1991) derived an equation relating hydraulic conductivity to depth as follows:

$$K = 20/10^{0.00030\,D} \tag{4.1}$$

where K is hydraulic conductivity in ft/day and D is the depth below land surface in feet. Figure 4.3.5 shows a crossplot of hydraulic conductivity versus well depth for the TCEQ data, where the hydraulic conductivity is log transformed. No correlation is evident in the crossplot. This lack of visual correlation is supported by a correlation coefficient of 0.12. The poor correlation may be due to the location of the measured data. With data located predominantly in the shallow updip section of the aquifer, the range of depth is relatively small, exacerbating the uncertainty in the regression.

Based on values reported by Payne (1968), Prudic (1991) made a plot of hydraulic conductivity versus sand thickness for the Sparta aquifer. This plot shows a linear increase in hydraulic conductivity with sand thickness. However, in general, Prudic (1991) could find no significant correlation between sand thickness and hydraulic conductivity. Note also that the Payne (1968) data is likely from the Sparta aquifer (or corresponding formation) east of Texas in Louisiana or Arkansas.

Guevera and Garcia (1972) created a detailed sand map for the Queen City aquifer, shown in Figure 4.2.12, constrained to the model area. Ricoy and Brown (1977) created a detailed sand map for the Sparta aquifer, shown in Figure 4.2.13, also constrained to the model area. The contours from the original maps were digitized and interpolated onto grids. The sand thickness was sampled at each location where a hydraulic conductivity was estimated. Figure 4.3.6 shows a crossplot of sand thickness versus hydraulic conductivity, where the hydraulic conductivity is logarithmically transformed. This figure indicates that no correlation can be seen between sand thickness and hydraulic conductivity for this data. The lack of visual evidence for correlation is supported by a correlation coefficient of 0.14. The analysis could indicate that either no correlation exists in reality, or the data lack the spatial accuracy necessary to show the correlation. Because most of the hydraulic conductivity measurements are in or near the outcrop, and the sand maps stop at the interface between the outcrop and the subcrop, the comparisons occur predominantly along the edges of the sand map.

4.3.5 Variogram Analysis of Hydraulic Conductivity

The spatial distribution of hydraulic properties can be characterized by a variogram analysis. A variogram analysis quantifies spatial correlation and variability [for detailed background information on geostatistics, refer to Isaaks and Srivastava (1989)]. Typical hydrogeologic properties show some spatial correlation indicated by lower variance for nearby measurements. As the distance between measurements increases, variance increases until it becomes constant, which corresponds to the ensemble variance of the entire data set. At the separation distance where the variance becomes constant, no correlation between measurements exists. The variogram describes the degree of spatial variability between observation points as a function of distance. Spatial variability is described in terms of the nugget (variance at zero separation), the range (correlation length), and the sill (ensemble variance). The variogram can also be used as a tool to characterize horizontal anisotropy in hydraulic conductivity. In an aquifer with horizontal anisotropy, hydraulic conductivity is a function of horizontal direction. For a detailed explanation of directional variogram terminology and calculation, see Deutsch and Journel (1992).

The TCEQ and Mace et al. datasets were first analyzed separately, then combined for the final analysis. The analyses were completed on logarithmically transformed hydraulic conductivity data. For all datasets, directional variograms were calculated along strike and towards dip, and compared to an omnidirectional variogram of the data to help delineate any directional trends. For the directional variograms, the search tolerance was 30 degrees, the direction along strike was approximately 50 degrees, and the direction towards dip was approximately -40 degrees. For all variograms, the number of lags was 25, the lag width was from 10,000 to 20,000 feet (about 2 to 4 miles), and the total lag distance was 264,000 feet (50 miles).

Figure 4.3.7 shows the variograms calculated separately for both the Mace et al. and TCEQ datasets. The sills for all three Mace et al. variograms are similar at about 0.35. The smallest nugget, about 0.21, occurs in the direction of strike. This nugget is still more than half of the sill, indicating that poor correlation in hydraulic conductivity measurements exists even at small distances. The range of the variogram is about 6 miles, or 32,000 feet, indicating that beyond 6 miles no significant correlation between hydraulic conductivity measurements can be expected. Some increase in variance with distance can be seen in the omnidirectional variogram. The dip direction variogram shows an oscillating trend that would be consistent with bands of changing hydraulic conductivity with distance. However, over most of the model region, the data is available over only short distances in the dip direction. This oscillation may be due to the data in the northeast near the Sabine Uplift, where some formation outcrops are encountered twice in a given direction.

The TCEQ variograms also have similar sills of between 0.25 and 0.30. The omnidirectional and strike direction variograms show a slight upward trend in variance up to the maximum range. However, the strike direction variogram is relatively flat between 10 and 20 miles, so the upward trend beyond that distance may be an artifact of the unusual data geometry, where a long thin band of data in the southern and central parts of the model are attached to a wider arc of data in the northeast. The strike direction variogram has a slightly smaller nugget than the omnidirectional variogram at 0.17. As with the Mace et al. data, the nugget is greater than half of the sill. The range of this variogram is about 10 miles, or 53,000 feet. This range is larger than the range calculated along strike for the Mace et al. data, so correlation occurs over a larger distance in the TCEQ dataset.

Figure 4.3.8 shows the variograms for the combined dataset. The combined variograms are similar to the TCEQ variograms. The smallest nugget occurs along the strike direction. The dip direction variogram shows the oscillations seen in the dip direction variogram of the TCEQ data. Also, the slight upward trend at large distances is evident in the strike direction variogram. An exponential variogram model is shown on the strike and dip directional variogram plots. The same model fits the two variograms relatively well, so no anisotropy was included in the model. The equation for the exponential variogram model is:

$$\gamma(h) = C_0 + C_1 \exp(\frac{-h}{A}) \tag{4.2}$$

where C_0 is the nugget, C_1 is the contribution of the exponential term to the sill (basically, sill minus nugget), A is the range, and h is the lag distance. The model fit to the variograms had the following parameter values: $C_0 = 0.15$, $C_1 = 0.17$, and $A = 12{,}000$ feet.

4.3.6 Spatial Distribution of Hydraulic Conductivity

The exponential variogram model described in the previous section was used in kriging the hydraulic conductivity field for the Queen City aquifer. The Sparta dataset was too small to create a meaningful kriged hydraulic conductivity field. The kriging software was set to full data search, which limits the impact of measurements to approximately the range of the model variogram. Figure 4.3.9 shows the results of the kriging after the antilog transformation. The figure shows that where no data support exists, kriging assigns the overall average value. Because the kriging was performed on logarithmically transformed data, this average value will be the geometric mean of the dataset. Where data support exists, much of the area still shows values similar to the geometric mean. The figure does show a higher than average region of hydraulic conductivity predominantly in Gonzales County. This region coincides with the strandplain sands observed by Guevera and Garcia (1972).

In Section 4.3.4, the lack of correlation between hydraulic conductivity and depth determined in the current study was discussed, and it was concluded that there is a lack of data in the necessary locations to show the correlation. Hydraulic conductivity should decrease with depth in unconsolidated sediments (Prudic, 1991). Increasing depth brings increasing overburden pressures and sediment compaction, resulting in more resistance to flow.

To implement this concept, the Prudic (1991) correlation (Equation 4.1) was used. The intercept in Equation 4.1 was adjusted to the median of the current data. For the Queen City, this makes the correlation equation read:

$$K = 4.2/10^{0.00030\,D} \tag{4.3}$$

while the Sparta equation is:

$$K = 5.7/10^{0.00030\,D} \tag{4.4}$$

In the current implementation, *D* was taken as the depth below ground surface of the midpoint of the formation. Figures 4.3.10 and 4.3.11 show the calculated hydraulic conductivity fields for the Queen City and Sparta aquifers, respectively. For the Sparta aquifer, the depth estimated conductivity was used as the basis for the model hydraulic conductivity.

For the Queen City aquifer, the kriged field is based on measurements predominantly in or near the outcrop. The depth correlation provides a means of estimating hydraulic conductivity in the downdip regions. The two fields were merged by creating a weighting matrix based on the kriging standard deviations. Kriging standard deviations reflect the density and variation of the measured data, so they provide an effective method of weighting the appropriate influence of the kriged data versus the depth trend. Within the range of the model variogram (12,000 feet) the kriged field was assigned exclusively. About 10,000 feet of transition area exists beyond the variogram range where a combination of the kriged and depth estimated fields was used, with the influence of the depth estimated field increasing with distance away from the measured data. The transition area is shown in Figure 4.3.12 based on the kriging standard deviations. Beyond that transition area, the depth estimated field dominates. The merged result for the Queen City aquifer (Figure 4.3.13) was used as the basis for the model aquifer hydraulic conductivity. The horizontal hydraulic conductivity values used in this study are similar to values used in previous modeling studies that included the Sparta and Queen City aquifers (see Table 4.3.2).

4.3.7 Vertical Hydraulic Conductivity

Specific data on vertical hydraulic conductivity within the Queen City and Sparta aquifers, and more importantly for the Weches and Cook Mountain confining units, are not available at the scale of this study. It is generally accepted that groundwater models provide the best means for estimation of vertical hydraulic conductivity at a regional scale (Anderson and

Woessner, 1992). Models that have included either the Queen City or Sparta aquifers explicitly within, or proximal to, the study area are listed in Table 4.3.2. The vertical hydraulic conductivities estimated for the Queen City aquifer through calibration of the Southern and Northern Carrizo-Wilcox GAMs are included in Table 4.3.2. Table 4.3.2 also includes horizontal hydraulic conductivity for completeness and for comparison to the analysis of horizontal hydraulic conductivity of these aquifers found in the preceding section.

McWreath et al. (1991) developed a MODFLOW model of the Sparta aquifer in Louisiana east of the Red River bordering the GAM study area. In the western portion of this model, the Sparta aquifer was assigned a vertical hydraulic conductivity of $9x10^{-5}$ ft/day. The USGS RASA model for the Texas Gulf Coast aquifer systems reported a vertical hydraulic conductivity of the Upper Claiborne aquifer (equivalent to the Queen City, Weches, and Sparta formations) of $1x10^{-5}$ to 0.01 ft/day for their calibrated transient model (Ryder and Ardis, 1991). Williamson et al. (1990) transiently calibrated a value of $3x10^{-4}$ ft/day for the Upper Claiborne aquifer. Ryder (1988) used a vertical hydraulic conductivity of 0.01 ft/day for his steady-state predevelopment model. The Southern and Northern Carrizo-Wilcox GAMs calibrated vertical hydraulic conductivities from 0.01 to $2x10^{-3}$ ft/day for the Queen City aquifer (Deeds et al., 2003 and Fryar et al., 2003). In general, one would expect the RASA models to have a lower vertical hydraulic conductivity because they incorporate the Weches in the Upper Claiborne aquifer. Likewise, in Louisiana, the Sparta is a much thicker unit incorporating facies equivalents to the Queen City and Weches and this lumped unit would be expected to offer more vertical resistance than an individual aquifer.

Table 4.3.2 Queen City and Sparta aquifer hydraulic conductivities from previous modeling studies (ft/day).

Modeling Study	Horizontal Hydraulic Conductivity (ft/day)	Vertical Hydraulic Conductivity (ft/day)
McWreath et al. (1991) East of Red River^1	15 to 20	9×10^{-5}
Ryder and Ardis (1991)^3	15	1×10^{-5} to 1×10^{-2}
Williamson et al. (1990)^3	22 (0.003 clay)	3×10^{-4}
Ryder (1988) ^{3}	55	1×10^{-2}
LBG-HDR (1998)^2	2 (0.5 west of Frio River)	Not Reported
Deeds et al. (2003)^2	1 to 30 (0.5 west of Frio River)	3×10^{-2} to 1 (2×10^{-3} west of Frio River)
Fryar et al. (2003)^2	5 to 25	5×10^{-3} to 2.5×10^{-2}

Notes: 1 Sparta aquifer (does not include aquitard)
2 Queen City aquifer (does not include aquitard)
3 Queen City, Weches, and Sparta (includes aquitard)

While models do offer a means of estimating vertical hydraulic conductivity, the calibrated vertical conductivity is dependent upon the type of calibration (steady state versus transient), the availability of vertical head targets, and the model layering relative to the hydrostratigraphic units. Therefore, it is useful to review some of the more relevant theoretical studies regarding vertical hydraulic conductivity in the study area.

The most complete theoretical and modeling investigation into the characterization of vertical hydraulic conductivity within Texas coastal plain sediments is the work of Graham Fogg in the Wilcox Group of the East Texas Embayment. Because of the similarity of the stratigraphy and depositional environments between the Wilcox Group and Claiborne Groups (Galloway et al., 1994), his conclusions are relevant to the Queen City and Sparta aquifers.

Fogg et al. (1983) developed a three-dimensional model of the Carrizo-Wilcox aquifer in Leon and Freestone counties in the Trinity River Basin. The major contribution of this study was the investigation of methods for developing effective grid block hydraulic conductivities for the heterogeneous stacked channel sequences which typify the fluvio-deltaic sediments of the Claiborne and Wilcox groups. Fogg et al. (1983) also performed a detailed sensitivity analysis to constrain the plausible ranges of horizontal to vertical hydraulic conductivity, K_h/K_v (hereafter referred to as anisotropy ratio). Fogg et al. (1983) concluded that a maximum reasonable anisotropy ratio for the Carrizo-Wilcox sequence was on the order of 10,000 to 1,000 based on reproducing the vertical head gradients within the Carrizo-Wilcox aquifer. An anisotropy ratio of 1,000,000 was considered too high to reproduce the general pressure-depth gradients across the model domain.

Fogg (1989) performed a detailed stochastic modeling study of a generic aquifer system consisting of two contrasting hydraulic conductivity facies (channel sands and finer grained interchannel sediments) having various degrees of vertical interconnection. His study concluded that the effective vertical conductivity applicable at a regional model scale ranges between the weighted geometric and harmonic mean conductivities.

To provide insight into expected vertical hydraulic conductivity ranges, Table 4.3.3 provides a scoping analysis for both horizontal and vertical hydraulic conductivity. Two hydrostratigraphic units are considered, one with 80 percent sand and 20 percent clay (more typical of an aquifer) and one with 20 percent sand and 80 percent clay (more typical of a confining unit). Table 4.3.3 assumes that the sand hydraulic conductivity is equal to 5 ft/day and that the clay hydraulic conductivity is equal to 3x10^{-5} ft/day [average marine clay from Freeze and Cherry (1979)]. The horizontal hydraulic conductivity is calculated as a weighted arithmetic average. The vertical hydraulic conductivity is calculated as both the weighted geometric mean and the weighted harmonic mean assuming that the correct value falls between these two averages.

Based on this scoping analysis, the vertical anisotropy in the aquifer units would be expected to range from about 10 to 1,000. In confining units, a reasonable lower limit for the vertical hydraulic conductivity would be the clay conductivity (average literature 10^{-5} ft/day). Theoretical studies have demonstrated that the vertical hydraulic conductivity would not exceed the weighted geometric average which in the scoping study is approximately 10^{-4} ft/day. These estimates result in anisotropy ratios for confining units of 3,000 to 25,000, which are consistent with previous models and the sensitivity results of Fogg et al. (1983).

Table 4.3.3 Hydraulic conductivity scoping analysis.

Lithology	Horizontal K^1 (ft/day)	Vertical K^2 (ft/day)	Vertical K^3 (ft/day)
80% sand 20 % clay	4	4.5×10^{-1}	1.5×10^{-4}
20% sand 80% clay	1	3.3×10^{-4}	3.8×10^{-5}

Notes:
Hydraulic conductivity clay = 3×10^{-5} ft/day (median marine clay; Freeze and Cherry, 1979)
Hydraulic conductivity sand assumed to be 5 ft/day
K^1 is a weighted arithmetic average
K^2 is a weighted geometric average
K^3 is a weighted harmonic average

4.3.8 Storativity

The specific storage of a confined saturated aquifer is defined as the volume of water that a unit volume of aquifer releases from storage under a unit decline in hydraulic head (Freeze and Cherry, 1979). The storativity is equal to the product of specific storage and aquifer thickness and is dimensionless. For unconfined conditions, the storativity is referred to as the specific yield and is defined as the volume of water an unconfined aquifer releases from storage per unit surface area of aquifer per unit decline in water table (Freeze and Cherry, 1979).

A literature review was conducted for storativity of the Queen City and Sparta aquifers (Table 4.3.4). Storativity ranged in magnitude from $1.0\text{x}10^{-4}$ to $5.2\text{x}10^{-3}$ with a geometric mean equal to $2.35\text{x}10^{-4}$. Figure 4.3.14 shows the locations of well specific storativity estimates and a histogram of those estimates. Estimates for the Carrizo-Wilcox are discussed in Deeds et al. (2003), Dutton et al. (2003), and Fryar et al. (2003).

There are few specific yield estimates for the Queen City and Sparta aquifers (Table 4.3.5). Domenico and Schwartz (1998) list values of specific yield that range from 0.03 to 0.28 for materials similar to the sediments in the study area. Lohman (1972) gives 0.1 and 0.3 as general limits for the specific yield of unconfined aquifers. Estimates for the Carrizo-Wilcox aquifer are discussed in Deeds et al. (2003), Dutton et al. (2003), and Fryar et al. (2003).

Table 4.3.4 Summary of literature estimates of Queen City and Sparta confined storativity.

Aquifer	County	Well Number	Storativity	Reference
Cypress	Marion	3512802	0.00014	Broom (1971)
Cypress	Titus	1649709	0.00015 (Drawdn) 0.00015 (Recov.)	Broom et al. (1965)
Queen City	Atascosa	7805103 Pleasanton	0.0001	Alexander and White (1966)
Queen City	Atascosa	7805105 Pleasanton	0.0001	Alexander and White (1966)
Queen City	Houston	--------	0.0002	Tarver (1966)
Queen City	Lee	5949505 Giddings	0.0002	Thompson (1966)
Queen City	Upshur	3432402	0.0003	Broom (1969)
Queen City/Sparta			0.00052 to 0.0025	Ryder and Ardis (1991)
Queen City/Sparta			0.00141 (based on mean thickness)	Williamson et al. (1990)
Sparta	--------	--------	0.00026 to 0.00052	Peckham et al. (1963)
Sparta	Brazos	5921206 Bryan #1	0.00028	Follett (1974)
Sparta	Brazos	5921206 Bryan #1	0.00022	Follett (1974)
Sparta	Brazos	5921302 Bryan #2	0.00023	Follett (1974)
Sparta	Brazos	5921302 Bryan #2	0.00025	Follett (1974)
Sparta	Brazos	5921304 Bryan #3	0.00015	Follett (1974)
Sparta	Brazos	5921715 USAFB #2	0.00022	Follett (1974)
Sparta	Brazos	5921715 USAFB #2	0.00023	Follett (1974)

Table 4.3.4, continued

Aquifer	County	Well Number	Storage	Reference
Sparta	Brazos	5921715 USAFB #2	0.00023	Follett (1974)
Sparta	Brazos	5921717 USAFB #4	0.00015	Follett (1974)
Sparta	Brazos	5921717 USAFB #4	0.00016	Follett (1974)
Sparta	Brazos	5921718 USAFB #5	0.00017	Follett (1974)
Sparta	Houston	--------	0.0002	Tarver (1966)
Sparta	Lee	5942203 Dime Box	0.0004	Thompson (1966)
Sparta	Nacogdoches	3735104	0.00038	Guyton and Associates (1970)
Sparta	Nacogdoches	3735104	0.00047	Guyton and Associates (1970)
Sparta	Nacogdoches	3735204	0.00026	Guyton and Associates (1970)
Sparta	Nacogdoches	3736107	0.00017	Guyton and Associates (1970)
Sparta	northern Angelina/ southern Nacogdoches	--------	0.00026 to 0.00052	Baker et al. (1963)
Sparta	Smith	3446204	0.00017	Dillard (1963)
Sparta	Smith	3446205	0.00017	Dillard (1963)
Sparta	Natchitoches	Na - 142 Tenn. Gas Trans. Co.	0.0002	Newcome et al. (1963)
Sparta			0.0001	McWreath et al. (1991)

Table 4.3.5 Summary of literature estimates of Queen City and Sparta outcrop specific yield.

Aquifer	Specific Yield	Reference	Description
Queen City	0.25	Deeds et al. (2003)	Model calibrated.
Queen City	0.20	Fryar et al. (2003)	Model calibrated.
Queen City, Weches, Sparta	Variable, 0.15 max	Ryder and Ardis (1991)	Model calibrated.
Sparta	0.01	Fitzpatrick et al. (1990)	Model calibrated.
Sparta	0.01	McWreath et al. (1991)	Model calibrated.

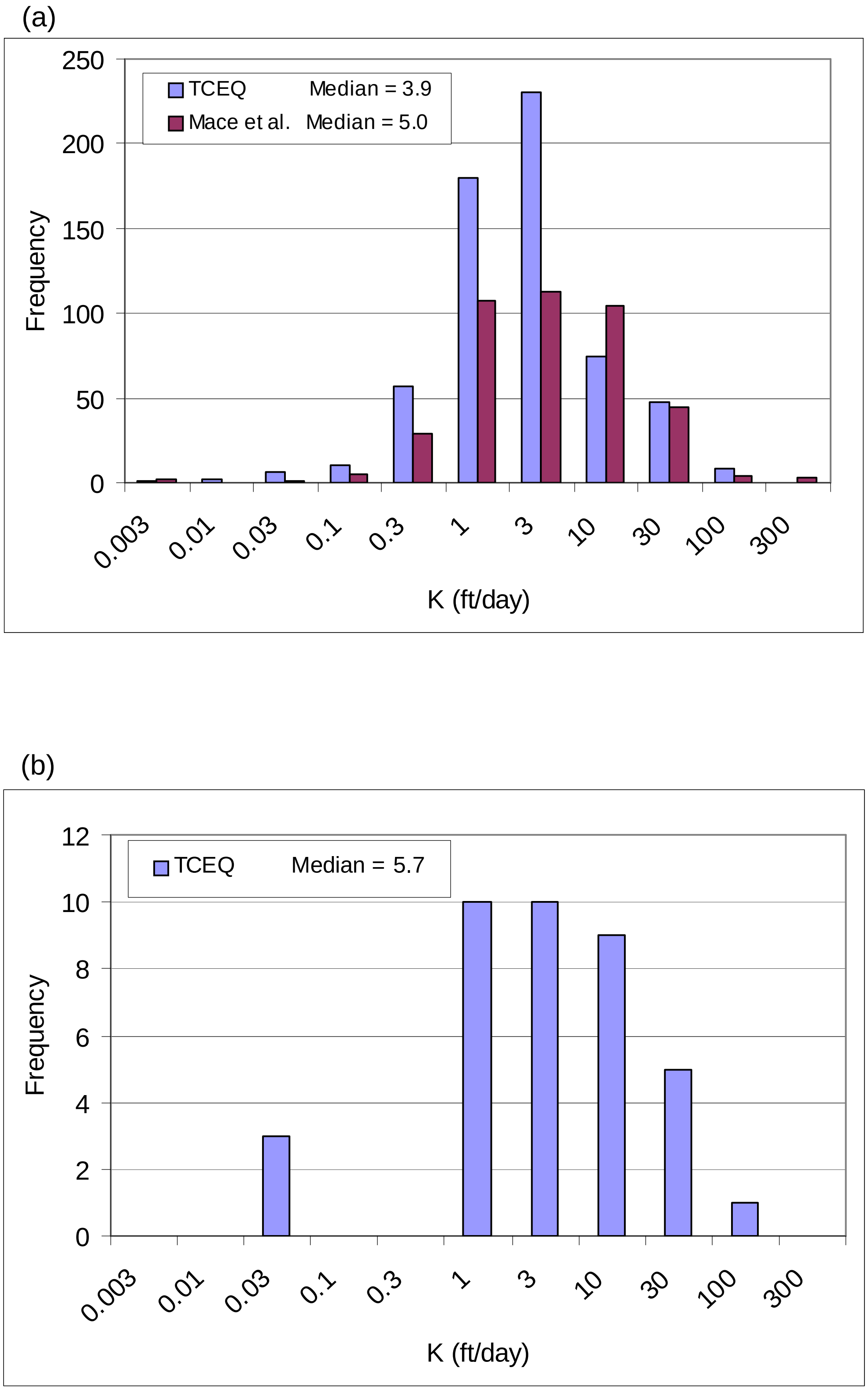


Figure 4.3.1 **Histograms of hydraulic conductivity data for (a) the Queen City aquifer and (b) the Sparta aquifer.**

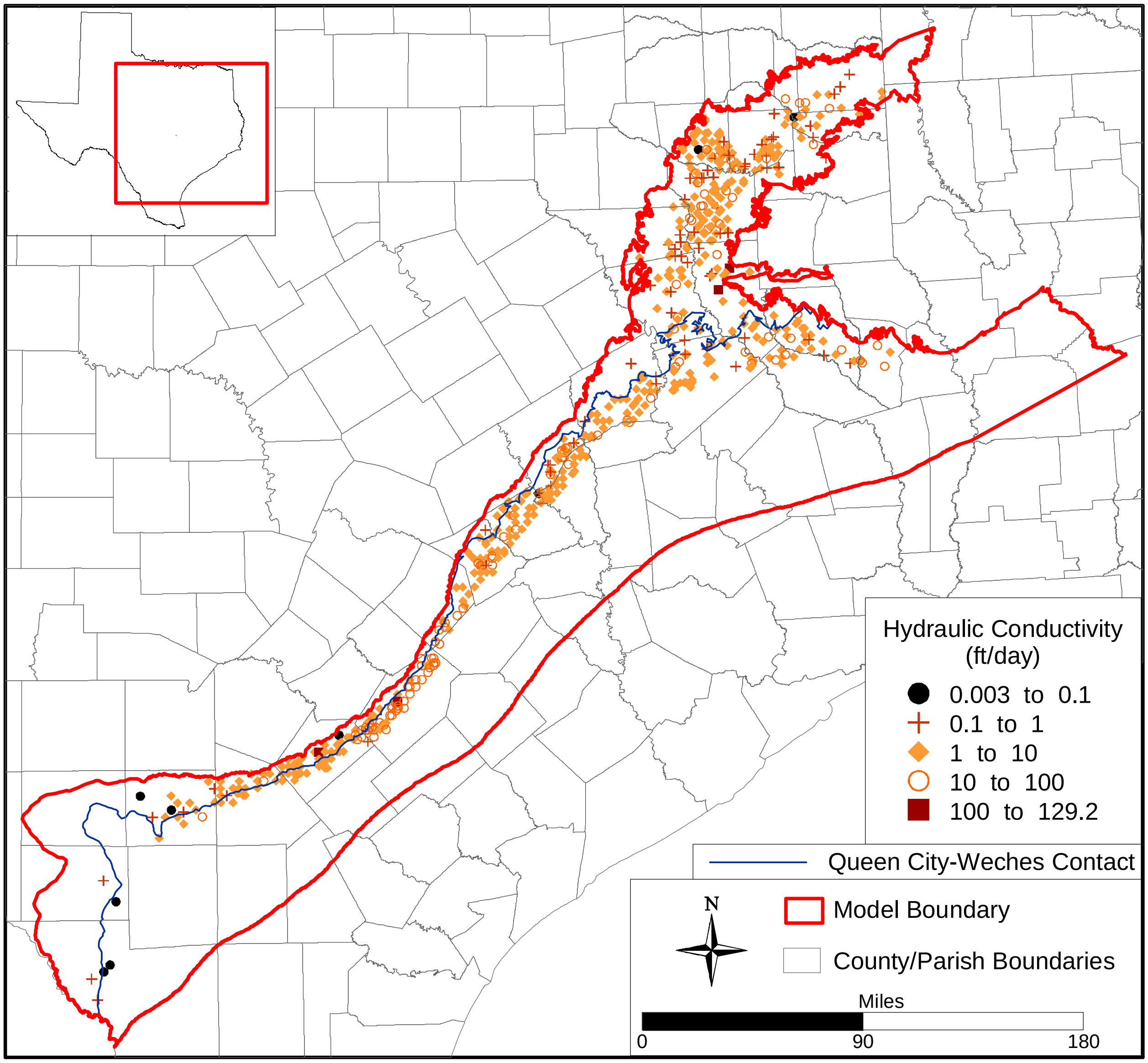


Figure 4.3.2 Post plot of TCEQ hydraulic conductivity data for the Queen City aquifer.

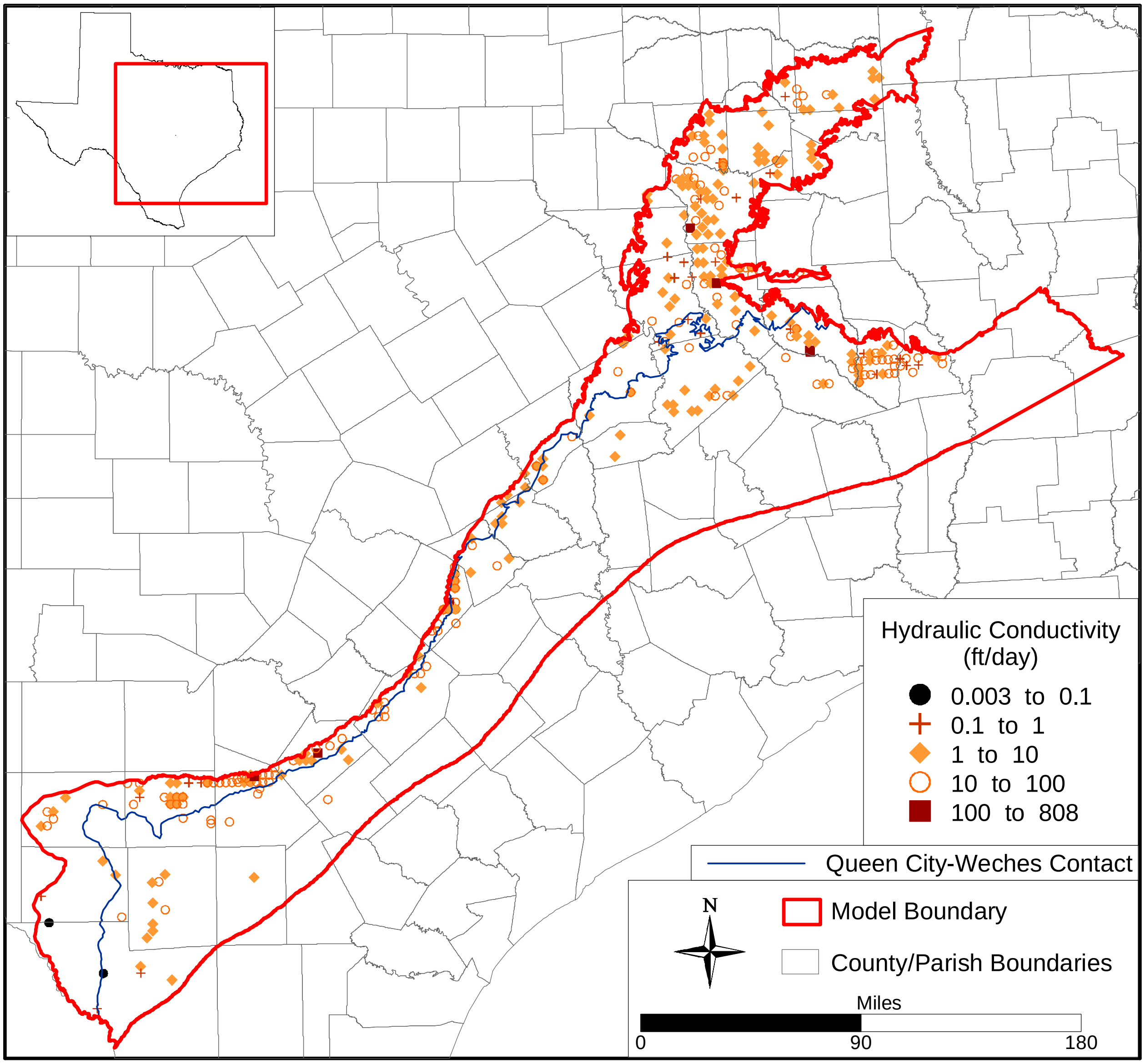


Figure 4.3.3 Post plot of the Mace et al. hydraulic conductivity data for the Queen City aquifer.

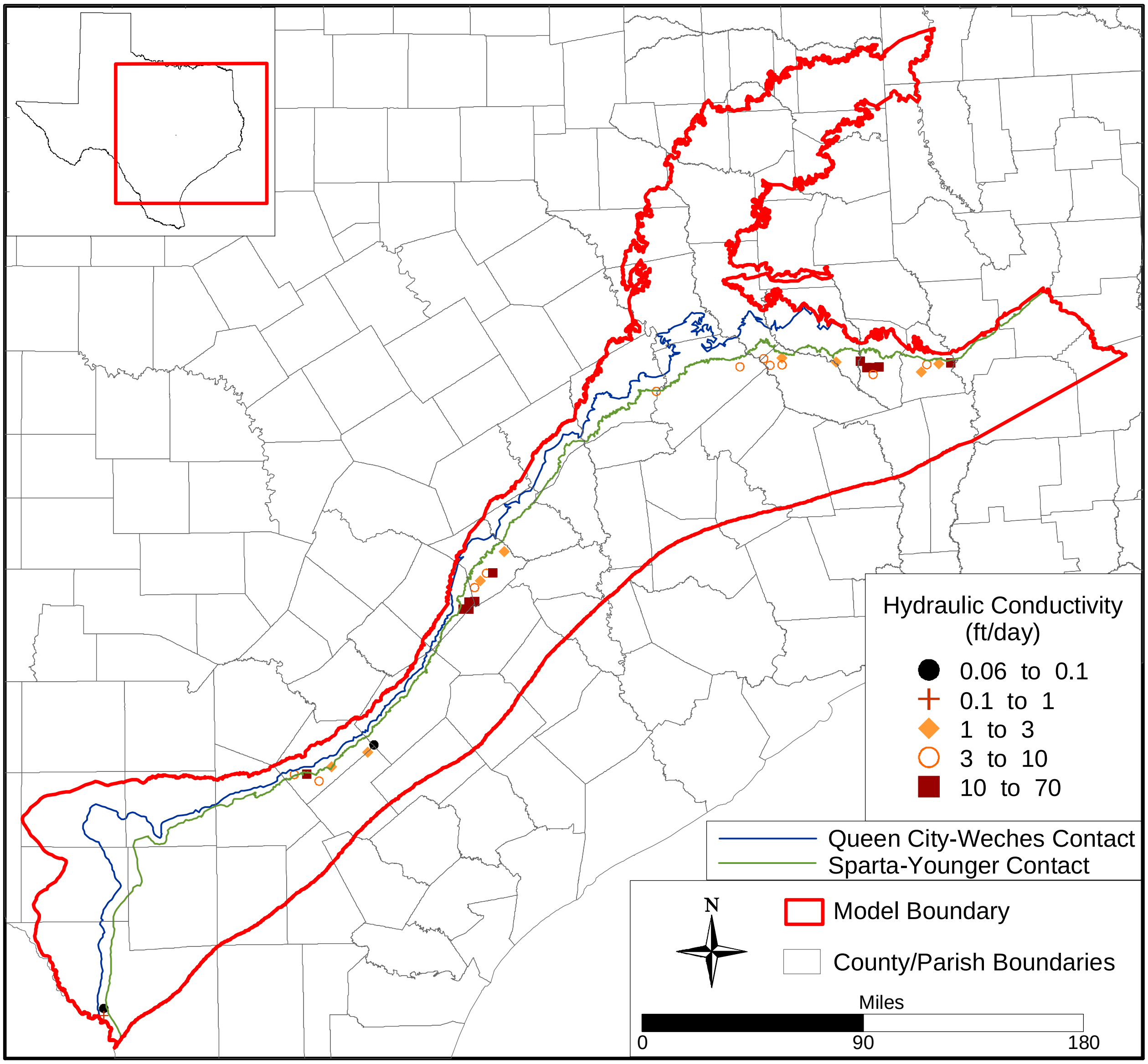


Figure 4.3.4 Post plot of the TCEQ hydraulic conductivity data for the Sparta aquifer.

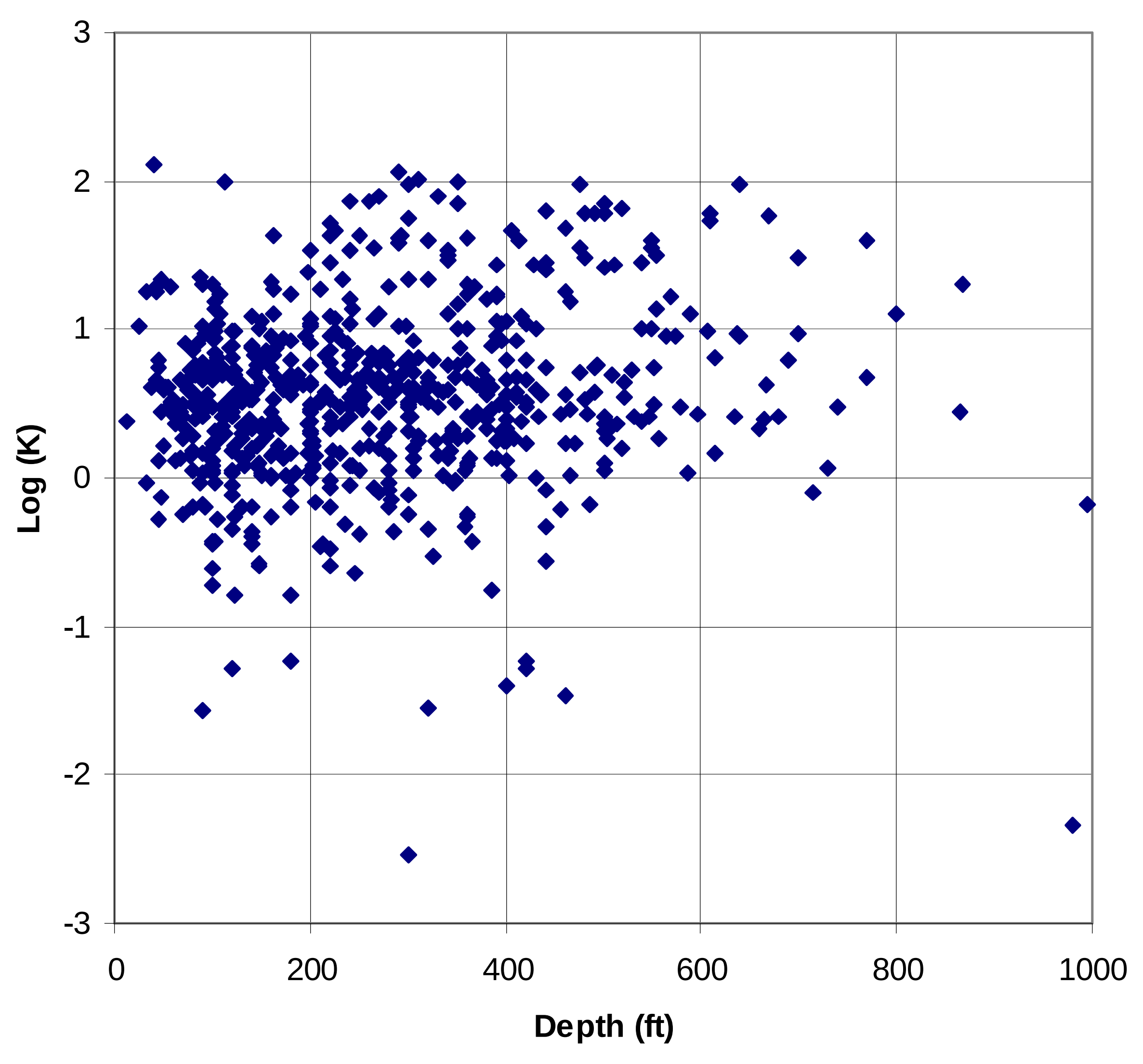


Figure 4.3.5 **Crossplot of hydraulic conductivity versus well depth.**

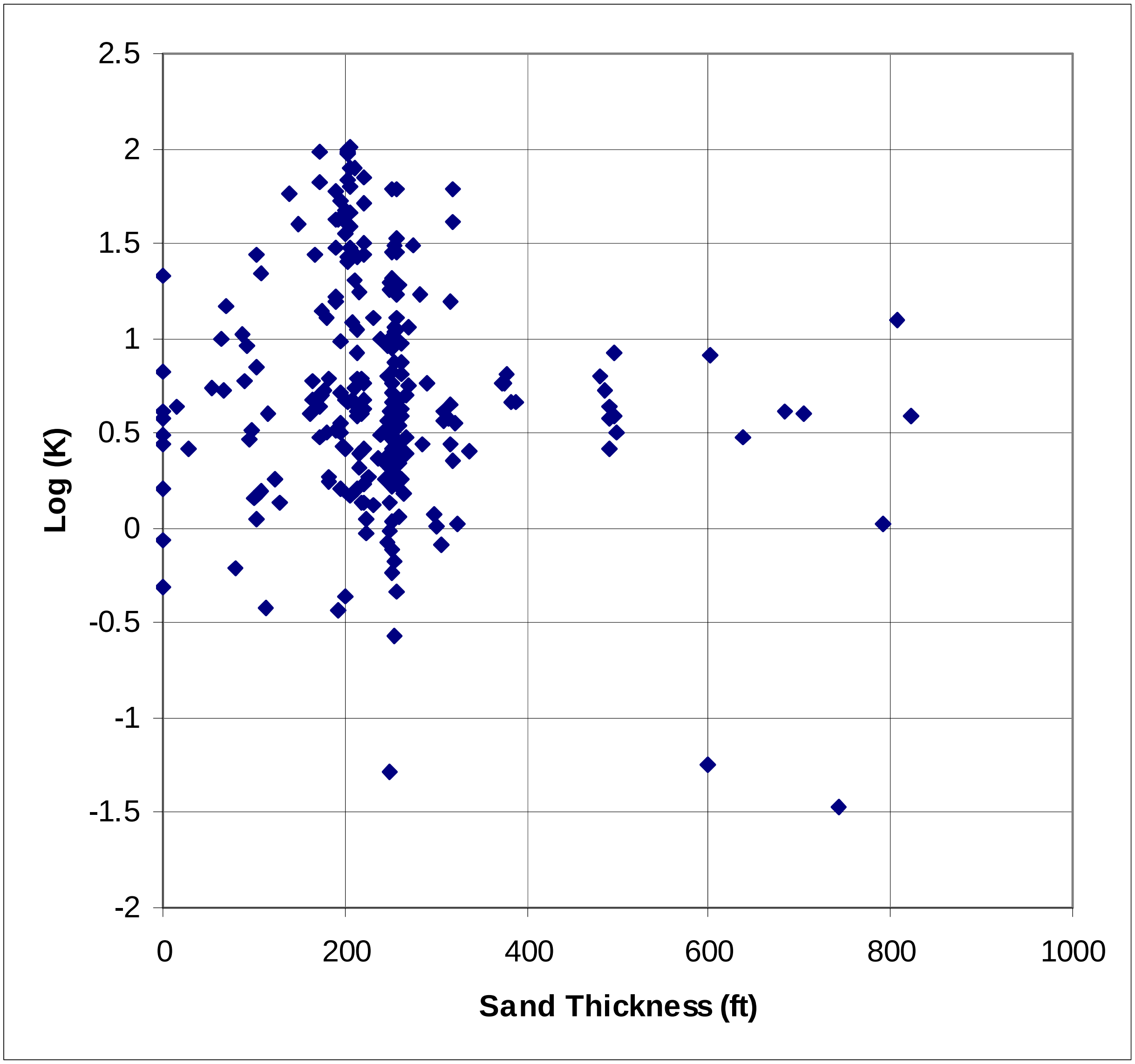


Figure 4.3.6 Crossplot of hydraulic conductivity versus sand thickness.

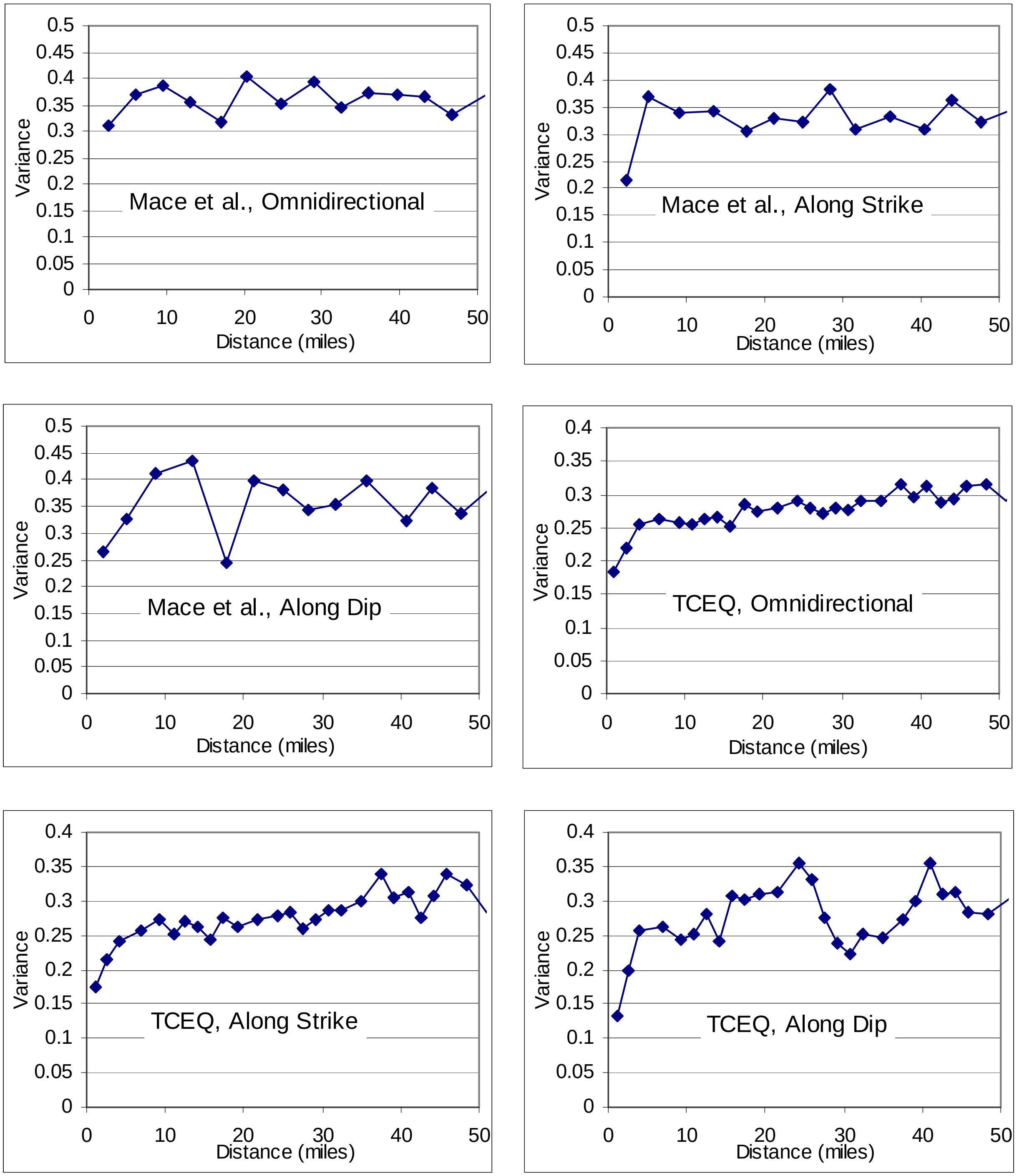


Figure 4.3.7 Variograms for the Mace et al. and TCEQ datasets.

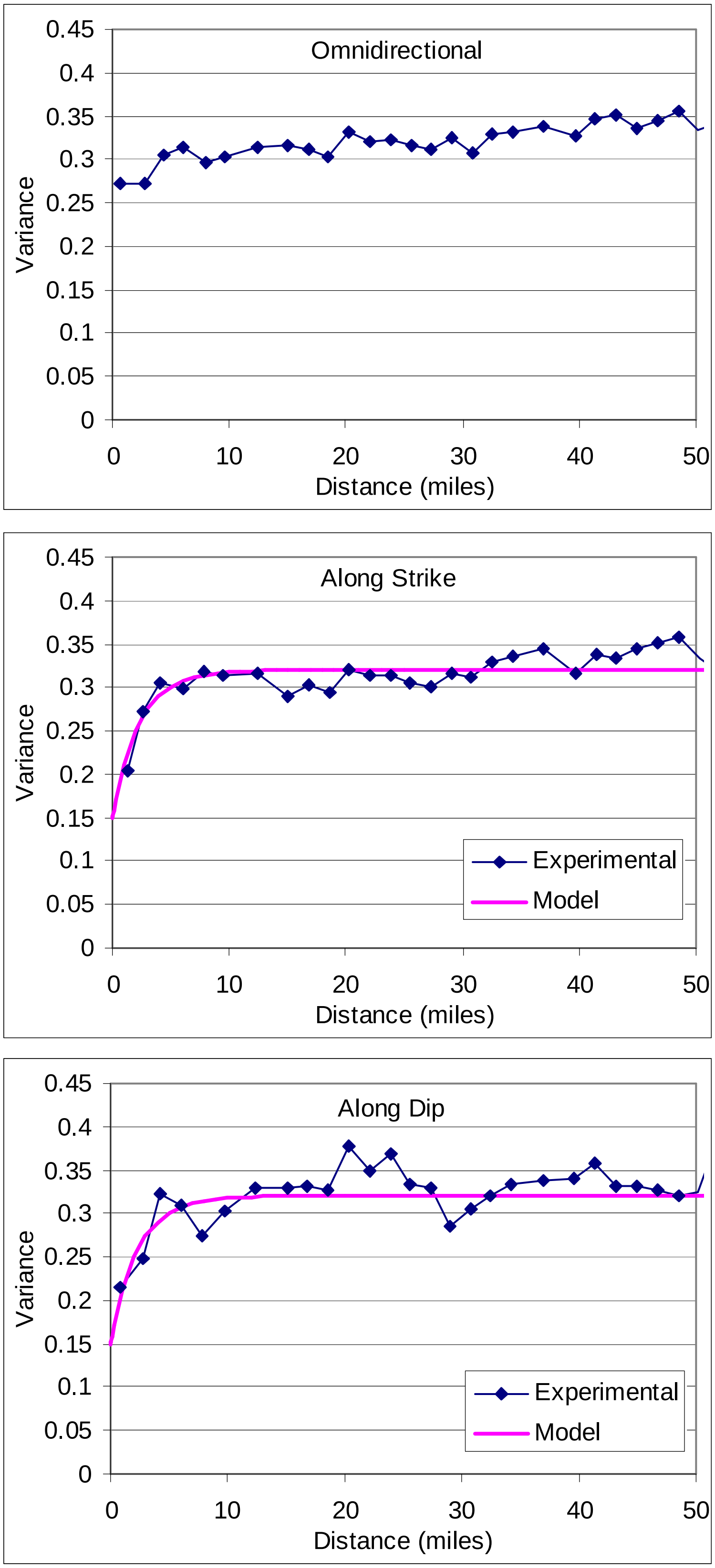


Figure 4.3.8 Variograms for the combined dataset.

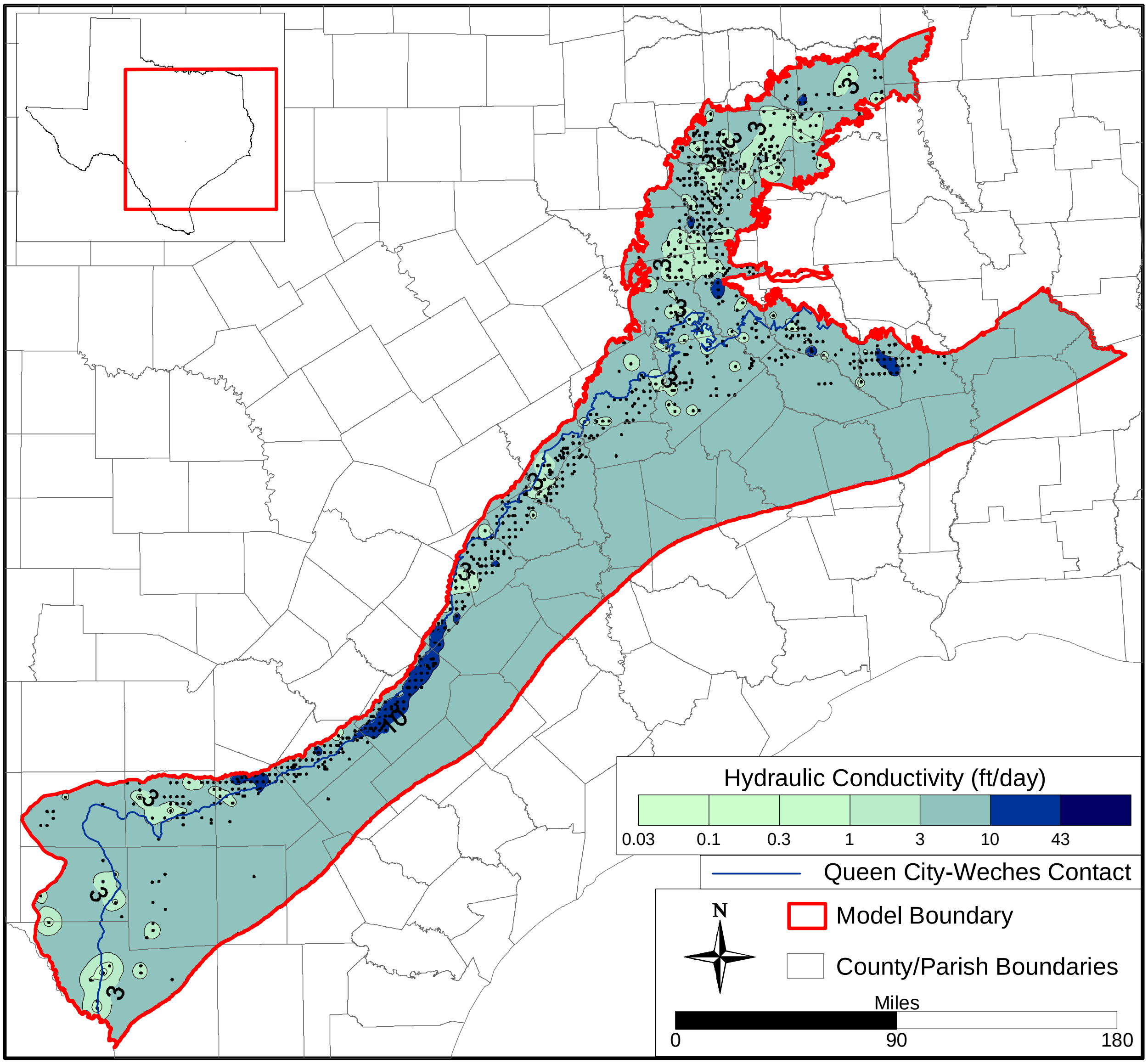


Figure 4.3.9 Kriged Queen City hydraulic conductivity field.

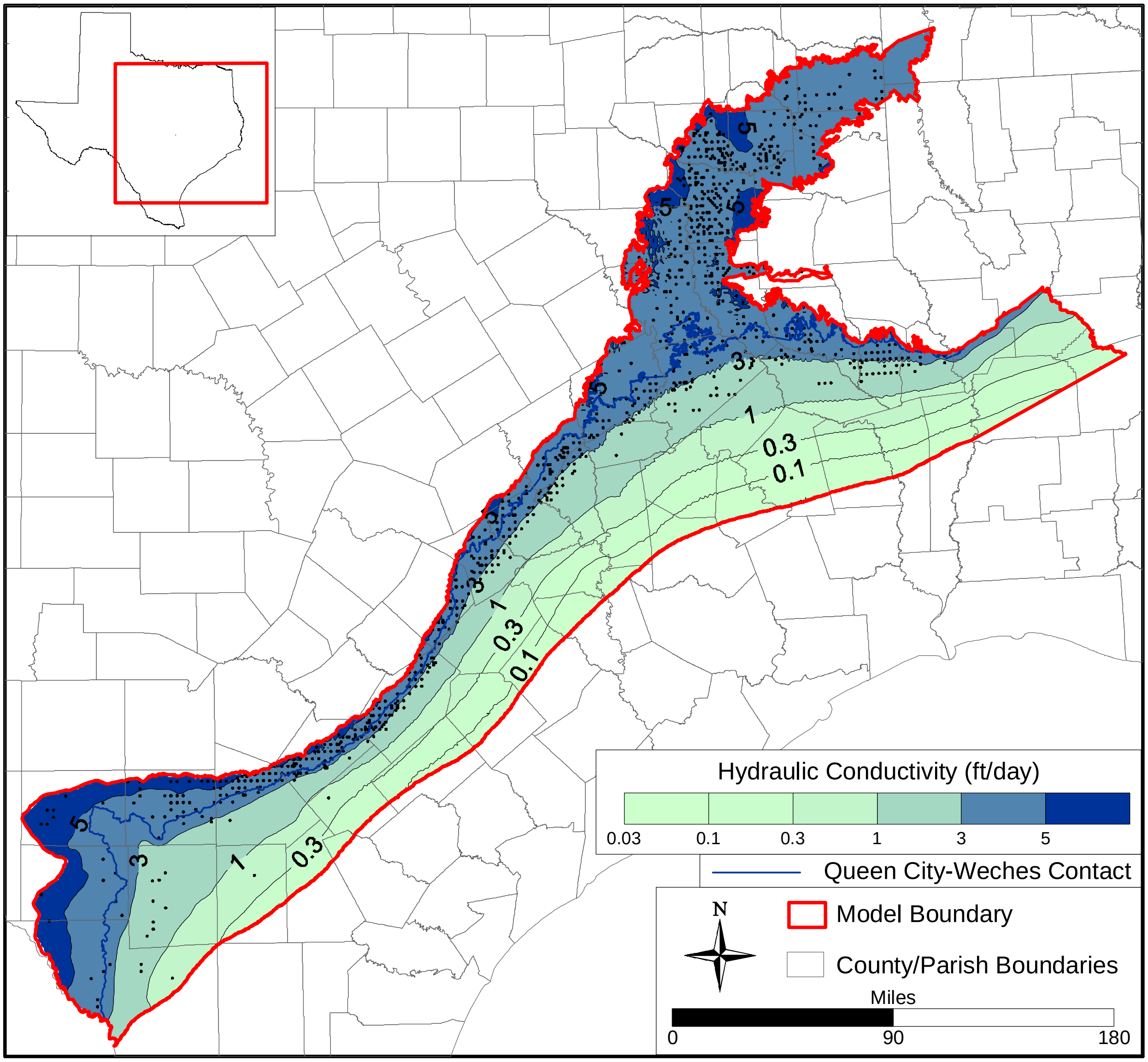


Figure 4.3.10 Queen City hydraulic conductivity estimated from depth correlation.

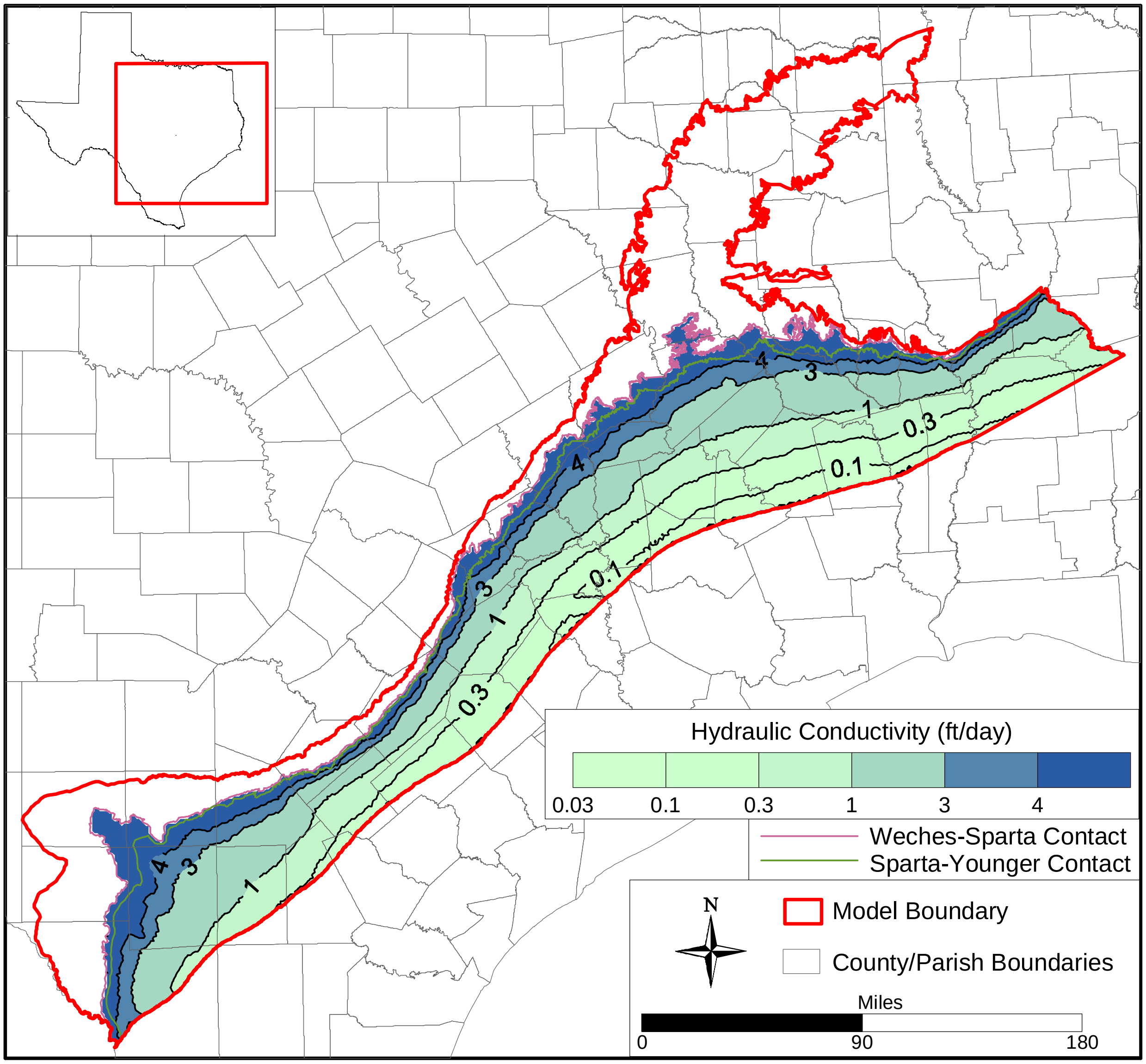


Figure 4.3.11 **Sparta hydraulic conductivity estimated from depth correlation.**

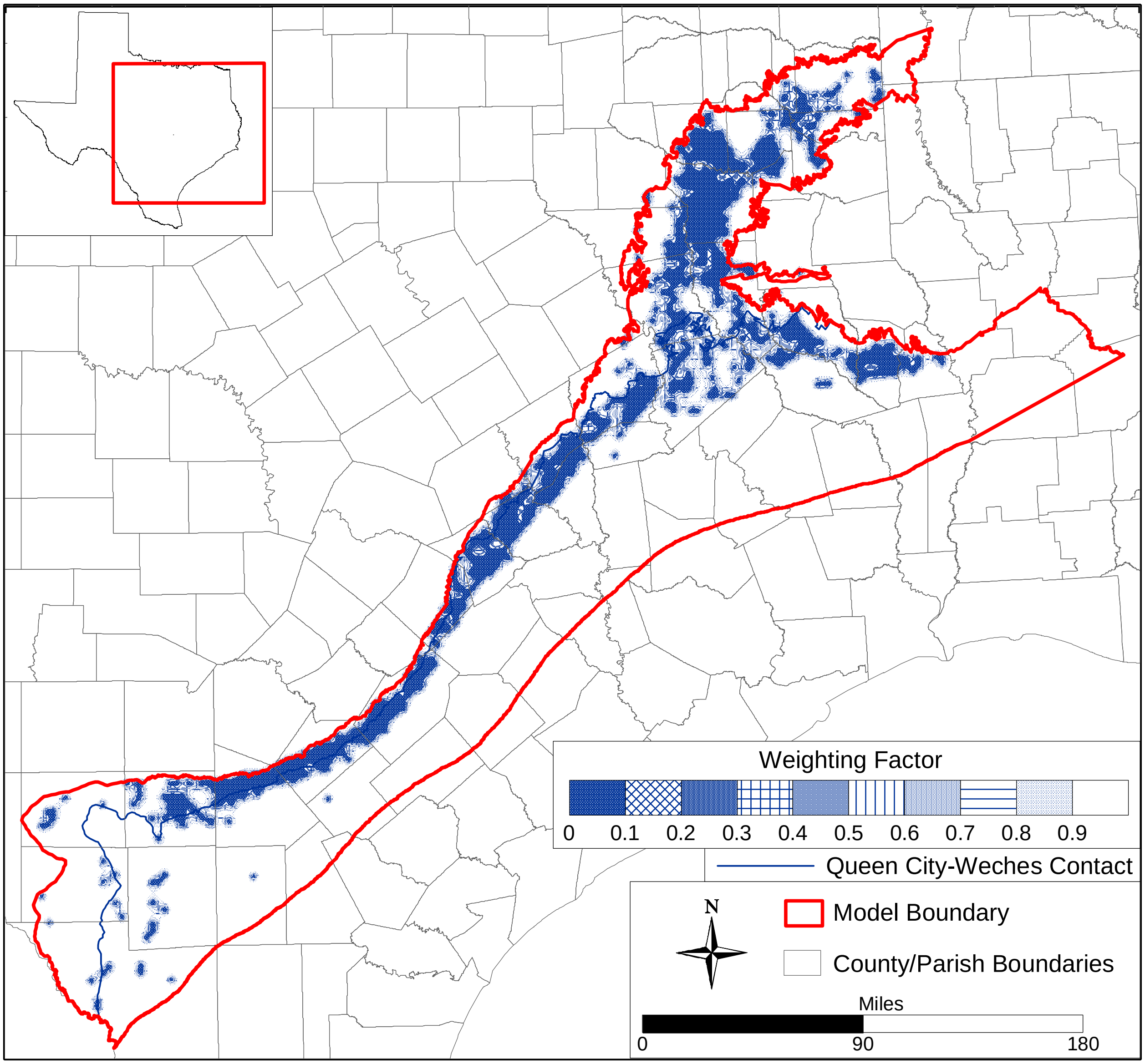


Figure 4.3.12 Weighting grid used to merge kriged and depth trend Queen City hydraulic conductivity fields.

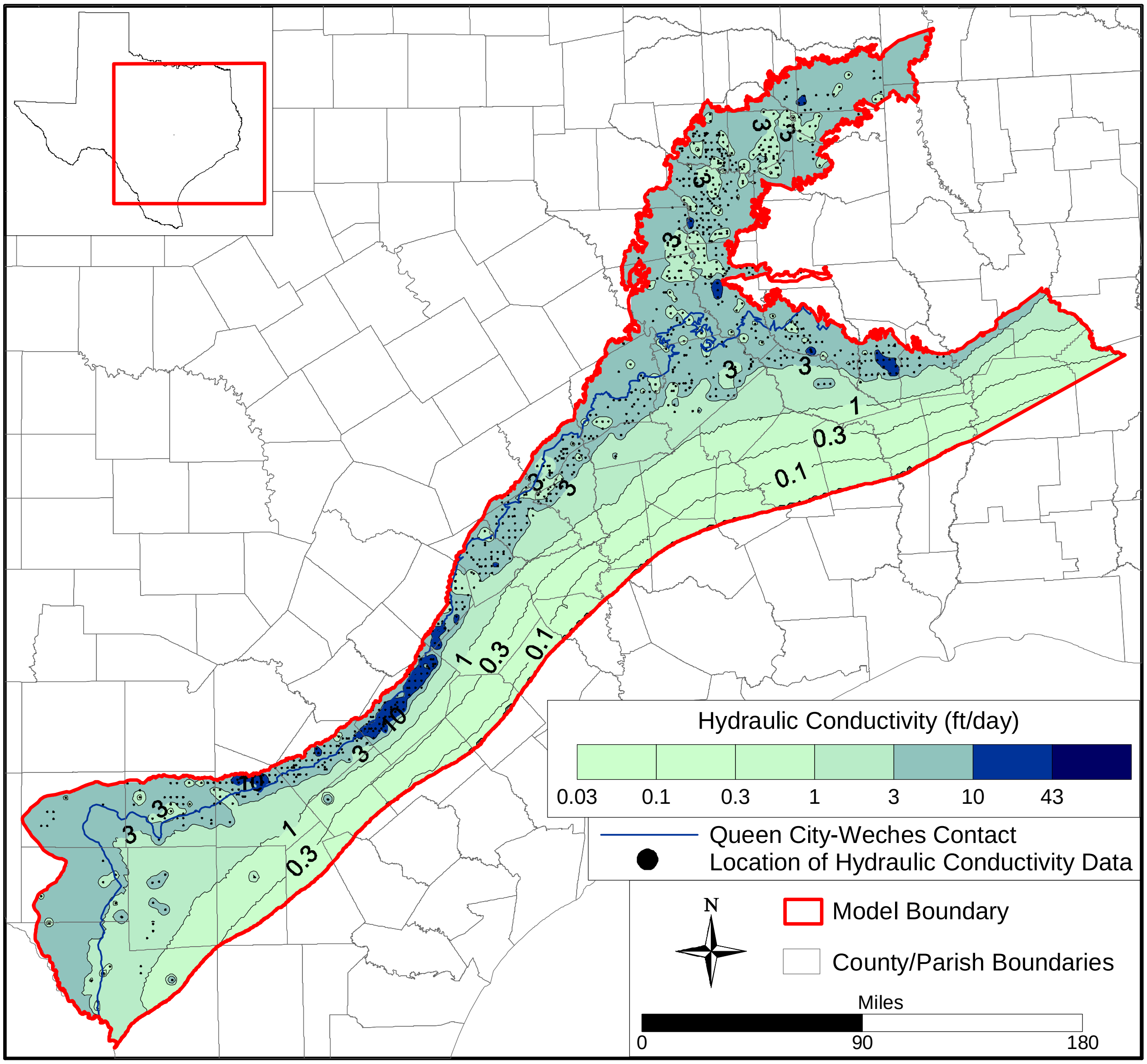


Figure 4.3.13 Merged Queen City hydraulic conductivity field.

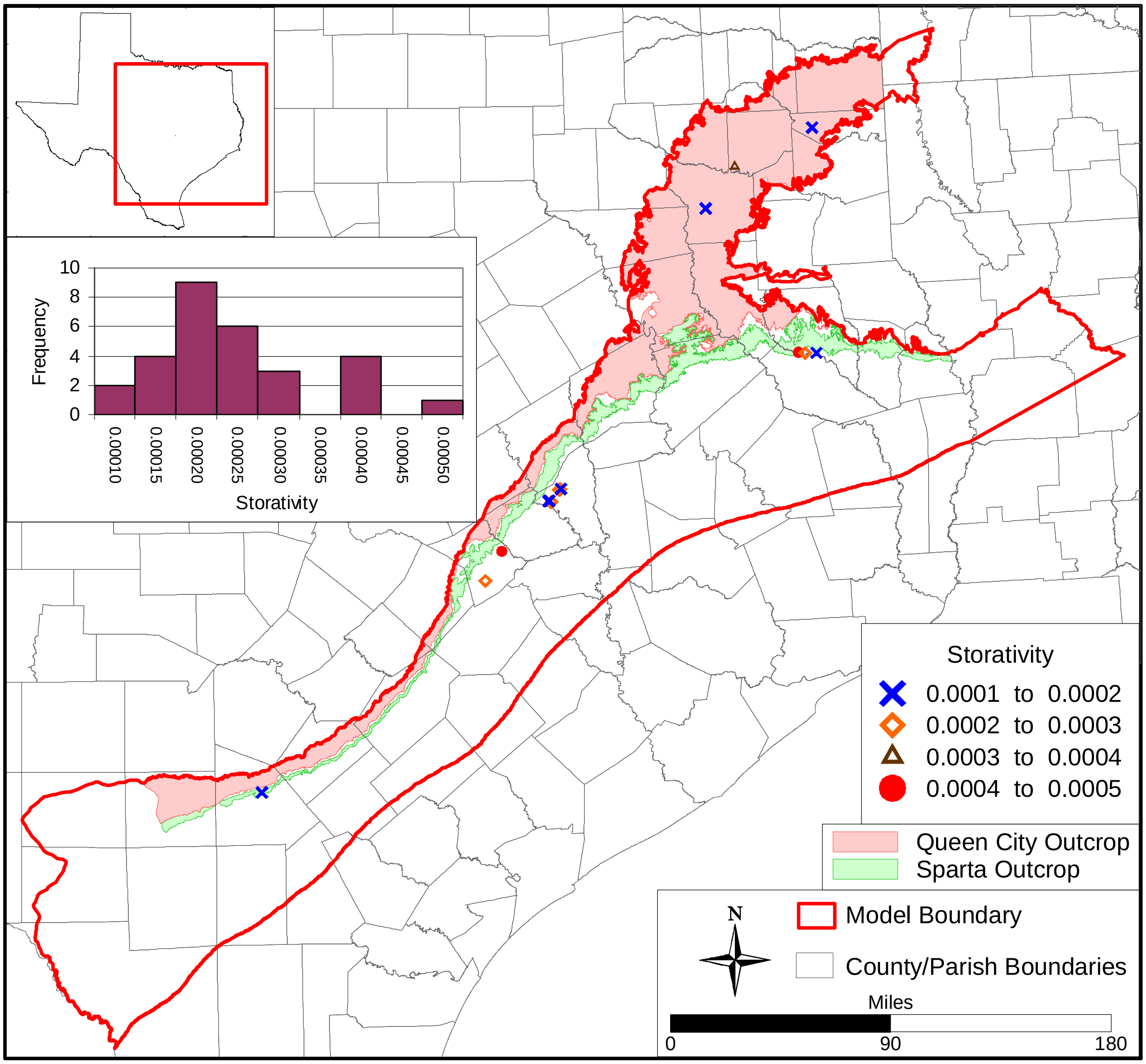


Figure 4.3.14 **Queen City and Sparta storativity estimates in the study area.**

4.4 Water Levels and Groundwater Flow

An extensive literature search was conducted to understand (1) regional groundwater flow in the Sparta and Queen City aquifers prior to extensive development of groundwater resources in the area and (2) the history of groundwater usage from the Sparta and Queen City aquifers. The literature search included a review of available county reports, historical USGS reports (predominately water-supply papers), and reports by the various Texas state agencies responsible for water resources (i.e., the Texas Board of Water Engineers, the Texas Water Commission, and the TWDB). In addition, water-level data provided by the TWDB on their website was used to (1) perform a pressure versus depth analysis, (2) develop water-level elevation contours corresponding to the start time for the transient model (January 1980), the end of the model calibration period (December 1989), and the end of the model verification period (December 1999), and (3) investigate transient water level conditions.

The water-level data found on the TWDB website[1] were used to investigate water-level elevations for this study. Aquifer codes were used to query data by hydrostratigraphic unit. Water-level elevations were calculated as the land surface datum elevation plus the depth to water, which is negative for depths below land surface.

In the Queen City aquifer as defined by the TWDB, approximately 4,450 water-level measurements have been made at about 1,000 different locations from the earliest measurement in 1915 through 1999. About 8 percent of those measurements were made prior to 1950. Figures 4.4.1 and 4.4.2a show the spatial and temporal distributions, respectively, of water-level measurements for the Queen City aquifer.

Based on the data found on the TWDB website, approximately 2,100 water-level measurements have been made in the Sparta aquifer, as defined by the TWDB, at about 440 different locations from the earliest measurement in 1901 through 1999. About 36 percent of those measurements were made prior to 1950, and, of those, 83 percent were taken in Nacogdoches County. Figures 4.4.3 and 4.4.2b show the spatial and temporal distributions, respectively, of water-level measurements for the Sparta aquifer.

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[1] rio.twdb.state.tx.us/publications/reports/GroundWaterReports/GWDatabaseReports/GWdatabaserpt.htm

4.4.1 Regional Groundwater Flow

Groundwater within the Queen City and Sparta aquifers occurs under water-table conditions in the outcrop areas and artesian conditions downdip of the outcrops where the aquifers are confined. Groundwater flow within the outcrop areas is essentially controlled by topography. For the Queen City aquifer in the East Texas Embayment located in the northern model area, the presence of ridges and valleys with significant elevation differences (see Section 2) results in the development of localized groundwater basins within the aquifer and the absence of a regionally coherent flow system (Fogg and Kreitler, 1982). In the outcrop belt of the Queen City and Sparta aquifers from Frio to Leon counties and from Frio to Sabine counties, respectively, groundwater moves from the higher elevations along drainage divides to lower elevations in creeks and rivers.

In the artesian portions of the aquifers, groundwater moves horizontally along the dip of the formations and vertically across formations (see Section 4.4.3) assuming no influences from pumpage. In general, the dip of the formations and land surface is toward the Gulf of Mexico resulting in groundwater flow in the southward and southwesterly directions in Nacogdoches, San Augustine, and Sabine counties and in the southeasterly direction in the counties from Houston County in the north to La Salle County in the south.

4.4.2 Predevelopment Conditions for the Queen City and Sparta Aquifers

Predevelopment conditions are defined as those existing in the aquifers prior to any disturbances of natural groundwater flow due to artificial discharge via pumping. The estimation of predevelopment conditions considered historical development within counties as discussed in county reports, dates at which wells were drilled in each county based on data on the TWDB website, dates at which first water-level measurements were taken in each county based on data on the TWDB website, and maximum water levels measured within the county and within individual wells. A summary of dates at which wells were first completed to the Queen City and/or Sparta aquifers and dates for the first water-level measurements are provided in Appendix A in brief descriptions of historical development in each county in the three model areas. The purpose for understanding predevelopment conditions was to enable generation of predevelopment water-level elevations contours. Those contours were used as general guidelines to calibration the steady-state models.

In general, the use of groundwater from the Queen City and Sparta aquifers in the northern model region is considered to be much less than is available based on discussions in the county reports. The only exception is Houston County where the Sparta aquifer is a primary source of groundwater. In the central model region, groundwater needs for all purposes are predominantly supplied by the Wilcox Group and/or the Carrizo Sand. The only exception is municipal pumpage in Brazos and Lee counties from the Queen City and/or Sparta aquifers. In the southern model area, groundwater needs for all purposes are predominantly supplied by the Carrizo Sand. Groundwater from the Queen City and Sparta aquifers is used by several small municipalities in this model area.

Queen City Aquifer

Pumping of the Queen City aquifer in the northern model area began in the mid to late 1800s, and the first water-level measurements were made in 1936 in Cherokee, Henderson, Freestone, Leon, Nacogdoches, and Rusk counties. Early water levels from measurements in the 1940s are available for Cass, Harrison, Upshur, and Wood counties. Due to the complex nature of the water table in the northern model area as a result of the irregular topography, the number and locations of the early water-level measurements are insufficient to develop water-level elevation contours across the model area. Therefore, these data were used as point targets in calibration of the steady-state model (Table 4.4.1). Only data for wells located within the boundary of the Queen City aquifer as defined by the TWDB were used as targets.

In order to understand general flow conditions in the Queen City outcrop across the entire northern model area, an approximation of the water-table surface was generated based on ground-surface elevations. A relationship between ground-surface elevation and water-level elevation was developed based on the 1936 data (Figure 4.4.4a). Development of this relationship assumed that the 1936 water-level data do not reflect affects of pumpage. In addition, all data identified for the Queen City Sand (aquifer code 124QNCT), even that for wells located outside of the aquifer boundary, were used. At the locations of the 1936 data, the difference between water levels calculated with the relationship and measured water levels ranges from a maximum of 83 feet to a minimum of 0.01 feet with an average of 0.45 feet (Figure 4.4.4b). Using the average DEM elevations, a water-level elevation was calculated for each grid block. Those elevations were then contoured to produce the estimated water-level elevation contours shown in Figure 4.4.5. Posted on the contours are the locations of the 1936 water-level data; measured values could not be posted due to the small scale of the figure. A scatter-plot comparison between calculated and measured water-level elevations for the 1936 data is provided in the insert on Figure 4.4.5. In general, the data show uniform scatter around the unit-slope line for measured water-level elevations of less than about 500 feet. Above that elevation, the calculated elevations are consistently lower than the measured values. This is due in part to the loss of the high ground-surface elevations on ridges as a result of the models requirement for an average ground-surface elevation at the center of each 1 mile by 1 mile grid block.

No attempt was made to determine predevelopment conditions in the artesian section of the Queen City aquifer in the northern model area. Water-level data are available only for Houston County in this section of the aquifer. In all other counties, the Queen City is not tapped by wells at this time.

Water-level data for as early as 1936 are available on the TWDB website for several counties in the central model region. Unfortunately, none of these early data are for Brazos or Lee counties which have experienced significant pumpage from the Queen City and Sparta aquifers. In Brazos County, wells tapping the Queen City and Sparta sands have provided groundwater for the city of Bryan since 1915 and for Texas A&M University and the city of College Station since 1951. Several towns in Lee County obtain all of their public supply needs from the Queen City and Sparta aquifers.

In generating predevelopment water-level elevations for the Queen City aquifer in the central model area, two methods were used. First, water-level data from early time periods were used if the number of wells drilled prior to that data was small. Second, average water levels for wells with stable hydrographs over many years were used. The water-level elevation contours for the predevelopment period for the central model region are shown in Figure 4.4.6 and the control data, which were used as calibration targets for the steady-state model, are given in Table 4.4.2. These contours end slightly north of the Brazos River due to two factors. First, predevelopment water levels for the northern model area will be used northeast of the Brazos-Madison county line due to the lack of data and the strong influence of the irregular topography on water-table elevations. Second, all measured water levels for Brazos County were determined to be affected by pumpage and not representative of predevelopment conditions. Therefore, there are no data with which to contour predevelopment water-level elevations in Brazos County. The contours north of the Brazos River in Figure 4.4.6 are not considered to be representative of actual conditions due to the lack of data in that area. In actuality, the contours should show groundwater flowing into the Brazos River on both sides of the river. The contours in Figure 4.4.6 indicate that predevelopment flow was generally from the topographic highs on the ridges to the topographic lows in the major river basins in the outcrop area and down the dip of the aquifer toward the Gulf of Mexico in the artesian portion of the aquifer. In the portion of the central model area that overlaps with the southern model area, predevelopment contours for the Queen City aquifer are identical.

In generating predevelopment water-level elevations for the Queen City aquifer in the southern model area, two methods were used. First, water-level data from early time periods were used if the number of wells drilled prior to that data was small. Second, average water levels for wells with stable hydrographs over many years were used. The water-level elevation contours for the predevelopment period for the southern model area are shown in Figure 4.4.7. These contours show that groundwater moved from the topographic highs in the outcrop to topographic lows in the artesian section of the aquifer. In the portion of the southern model area that overlaps with the central model area, predevelopment contours for the Queen City aquifer are identical. The point data used to generate the predevelopment contours are provided in Table 4.4.3. These points were used as calibration targets for the steady-state model.

Sparta Aquifer

Pumpage from the Sparta aquifer began in the late 1800s and the early 1900s across the three model areas. The first recorded water-level measurement available on the TWDB website was taken in 1900 in Fayette County. Significant numbers of water-level measurements are not available until about 1936 (see Figure 4.4.2b). In generating conditions representative of predevelopment for the Sparta aquifer in the three model regions, water-level data from early time periods, the number of wells completed to the aquifer prior to the first water-level measurements, the transient nature of water levels in individual wells, and maximum water levels measured were evaluated. The data were investigated on a county by county basis. See Appendix A for county summaries of historical development of the Sparta aquifer and how predevelopment water levels were selected. Water levels determined to be representative of predevelopment conditions for each county were contoured across the entire Sparta aquifer to ensure continuity between the three models. Several water-level measurements for the Sparta in Louisiana were used in the contouring. Water-Level data for Louisiana was obtained from a USGS website[2].

In general, groundwater from the Sparta aquifer is used predominantly for domestic and stock purposes, with two exceptions, and has not been significantly impacted by pumpage. The Sparta aquifer has been used as a primary source of groundwater in Houston and Brazos counties. In Brazos County, wells tapping the Queen City and Sparta sands have provided groundwater for the city of Bryan since 1915 and for Texas A&M University and the city of College Station since 1951. The Sparta aquifer is a primary source of water for two municipalities and a prison farm in Houston County. In these two counties and in several other areas, water levels from early measurements are lower than those taken at later times. In these cases, the maximum water level, regardless of time, was considered to be the most representative of predevelopment conditions.

Contours of water-level elevation created to represent predevelopment conditions in the Sparta aquifer are given in Figure 4.4.8. These contours show highest water levels in the outcrop area and lower water levels in the downdip direction. The shape and locations of the contours in the artesian portion of the aquifer are suspect due to a total lack of data control in this area of the aquifer. These contours were used as a general guideline in calibrating the steady-state model. Calibration targets for the steady-state model were the point data used to generate the predevelopment contours (Table 4.4.4).

4.4.3 Pressure Versus Depth Analysis

A study of pressure head versus screen-midpoint depth was conducted using wells having both water-level and screen-depth data on the TWDB website. The goal of the analysis was to evaluate vertical gradients between the various hydrostratigraphic units. The methodology used for the analysis is described in Fogg and Kreitler (1982). The locations of the wells used in the analysis and the unit in which they are completed are given in Figure 4.4.9. The youngest hydrostratigraphic unit considered in the analysis was the Sparta and the oldest unit considered

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[2] http://waterdata.usgs.gov/nwis/gw

was the Wilcox Group. In all cases, the analysis used the maximum water level measured in each well.

Table 4.4.5 summarizes the pressure-depth analysis results for data from each county. The analysis was conducted only for those counties in which the Queen City and/or Sparta aquifers are found based on the aquifer outlines as defined by the TWDB. A linear fit to the data was determined for two conditions; data for all dates and data for dates prior to 1950. For many counties, data prior to 1950 was not available for wells screened in the Sparta or Queen City aquifers. In other counties, insufficient screen data or no screen data were available for wells completed to the Sparta or Queen City aquifers. The results in Table 4.4.5 are tabulated by model area with the northern model area at the top, the central model area in the middle, and the southern model area at the bottom. A slope greater than one is indicative of upward hydraulic gradients and a slope less than one is indicative of downward hydraulic gradients. The results provided in Table 4.4.5 indicate that vertical flow conditions in the northern model area are different from those in the central and southern model areas. In general, slopes in the northern model area are less than one indicating downward flow. This is consistent with the fact that the Queen City is predominantly in outcrop across the East Texas Embayment and that the water-table elevation (i.e., Queen City head surface) would regionally be the highest heads. The heads indicate slight upward gradients to hydrostatic conditions in the central and southern model areas. In areas where the Carrizo-Wilcox aquifer has been significantly developed, near hydrostatic or downward gradients would be expected.

The fits through the data for the counties in the northern model area yield slopes ranging from a low of 0.48 in San Augustine County to a high of 0.89 in Houston County when data for all dates are considered. These slopes are less than one indicating downward flow. Use of data prior to 1950 results in a significant increase in the slope and correlation for the data from Angelina and Nacogdoches counties, and little change in the slope and correlation for data from Anderson and Wood counties. These results suggest significant depressurization of the deeper units relative to the shallower units between 1950 and 2000 for Angelina and Nacogdoches counties and little change in relative aquifer pressures from 1950 to 2000 in Anderson and Wood counties. The decrease in slope signifying an increase in downward gradient between results for data prior to 1950 and results for data for all dates in Angelina and Nacogdoches counties is most likely due to the large cone of depression created in the Carrizo Sand due to pumpage by the cities of Nacogdoches and Lufkin and by a paper mill (formerly the Southland Paper Mill) located on the Nacogdoches-Angelina county line. An example fit to data for counties in the northern model area is illustrated in Figure 4.4.10a. For the northern model area, the depth to screen midpoints ranges from about 12 to 2,119 feet.

With the exception of Bastrop County with a slope of 0.84, data for counties in the central and southern model areas have slopes equal to or slightly greater than one (see Table 4.4.5) when considering data for all dates. This indicates nearly hydrostatic to upward flow conditions. Data prior to 1950 is not available for any county in these two model areas. Because the data is temporally biased to post-development times, the upward gradients in predevelopment times are expected to be less evident than in post-development times. Example fits to data for counties in the central and southern model areas are shown in Figures 4.4.10b and 4.4.10c, respectively. For the central model area, the depth to screen midpoints ranges from about 72 to 3,898 feet. The range in screen-midpoint depths for the southern model area is about 70 to 5,260 feet.

An analysis of the combined data for all counties in each of the model areas was conducted considering three combinations of hydrostratigraphic units; (1) all units, (2) Sparta and Queen City only, and (3) Queen City and Carrizo only. For the northern model area (Figure 4.4.11), the slope of the fit to data with dates prior to 1950 is higher than the slope of the fit to all data. This indicates that depressurization of the deeper units occurred at a higher rate relative to depressurization in the shallower units throughout the entire area between 1950 and 2000, which is consistent with the production history in the region. In addition, all slopes are less than one indicating downward flow from the Sparta to the Queen City and from the Queen City to the Carrizo. In the central and southern model regions (Figures 4.4.12 and 4.4.13, respectively), the slopes of the fits are slightly greater than one indicating slight upward gradients. Figure 4.4.12a indicates a change from upward vertical flow prior to 1950 to essentially static flow after 1950 in the central model area.

In summary, vertical pressure gradients are generally upward to near hydrostatic in the central and southern model areas and are less than hydrostatic in the northern model area indicating downward flow gradients regionally. There is evidence for a decrease in upward gradients in the central model area from pre-1950 to post 1950 head measurements. There was a lack of measurements prior to 1950 in the southern model region form which to investigate temporal trends. The magnitude of the vertical gradient in the downward direction has increased in the northern model area with time.

4.4.4 Water-Level Elevations for Model Calibration and Verification

Model calibration considers the time period from January 1, 1980 to December 31, 1989 and model verification considers the time period from January 1, 1990 to December 31, 1999. Water-level data found on the TWDB website were used to develop water-level elevation contours for the start of calibration, the end of calibration, and the end of verification. Initialization of water levels in the transient model utilized the contours for the time corresponding to the start of calibration (January 1980). The contours for the end of calibration and the end of verification aided in assessing the transient model's ability to represent observed conditions.

Water-level data on the TWDB website 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. For example, Queen City water levels were measured in one well in January 1980 and in a total of 20 wells during all of 1980 in all three model areas combined. Since the amount of water-level data available for the times of interest were not sufficient to develop contours, 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.

Figures 4.4.14a-b show the water-level elevation contours for the Queen City and Sparta aquifers, respectively, at the start of calibration (January 1, 1980) for the entire aquifers (i.e., all model areas). The water-level elevations shown on these contour maps were used as the initial conditions for the transient models. The contours that were used to initialize the transient models for the remaining model layers can be found in the corresponding GAM reports for the Carrizo-Wilcox aquifer [Fryar et al., 2003 (northern model area); Dutton et al., 2003 (central model area); Deeds et al., 2003 (southern model area)].

The 1980 water-level elevation contours show several cones of depression in the Queen City aquifer in the northern model area. One is found in southeastern Wood County, another in northeastern Henderson County, and small ones in western Marion, southeastern Cass, and central Leon counties. In the central model region, a low in the water-level elevations is found in the vicinity of the Brazos River. The small cone of depression in Leon County is also located within the central model area. The only cone of depression found in the Sparta aquifer in 1980 is in the central model region in northwest Brazos County.

Figures 4.4.15a-b show the water-level elevation contours for the Queen City and Sparta aquifers, respectively, at the end of model calibration (December 31, 1989). The contours on these plots were used along with the transient water-level data to calibrate the transient models. The contours that were used to calibrate the transient models for the remaining model layers can be found in the corresponding GAM reports for the Carrizo-Wilcox aquifer [Fryar et al., 2003 (northern model area); Dutton et al., 2003 (central model area); Deeds et al., 2003 (southern model area)].

For the Queen City aquifer in the northern model area, the 1989 water-level elevation contours show that the cone of depression in southeastern Wood County is still present. The cone of depression in Marion County is significantly smaller in size. A cone of depression is found in south-central Henderson County that was not present in 1980 and the cone of depression in the northeastern corner of this county is no longer present. These differences in locations of cones of depression in Henderson County may be a function of where water-level measurements were taken for each time period rather than any significant changes in the character of aquifer pumpage. Several additional cones of depression are found in Smith and Cherokee counties. Again, this is most likely due to differences in locations of water-level measurements between the two time periods. In the central and southern model areas, the water-level elevation contours in the Queen City aquifer for 1989 are similar to those for 1980.

In the Sparta aquifer, a low in water-level elevations is present in northwestern Brazos County in 1989 as it was in 1980. However, the low is not as predominant in 1989 as it was in 1980. In the remaining portions of the aquifer, the 1989 water-level elevation contours are very similar to those for 1980.

Figures 4.4.16a-b show the water-level elevation contours for the Queen City and Sparta aquifers, respectively, at the end of model verification (December 31, 1999). The contours on these plots were used along with the transient water-level data to verify the transient models.

The contours that were used to verify the transient models for the remaining model layers can be found in the corresponding GAM reports for the Carrizo-Wilcox aquifer [Fryar et al., 2003 (northern model area); Dutton et al., 2003 (central model area); Deeds et al., 2003 (southern model area)].

The most significant change in the Queen City water-level elevations between 1989 and 1999 is the increase in the size and magnitude of the cone of depression in southeastern Wood County in the northern model area. A small cone of depression is found in Frio County in the southern model area in 1999 that was not present in 1980 or 1989. Another major difference in the 1999 contours versus both the 1980 and 1989 contours is the apparent overall decrease in pressures in the artesian portion of the aquifer in all three model areas. This decline may be real or it may be a function of differences in numbers and locations of water-level measurements. For example, the number of data points was fewer for 1999 (112 data points) than for 1989 (146 data points) and 1980 (175 data points).

The major differences in the Sparta aquifer between the 1999 contours and the contours for 1989 and 1980 are the apparent increase in water levels in the artesian portion of the aquifer in the northern model area and the apparent, and significant, decrease in the artesian portion of the aquifer in the southern model area. The decrease in the southern model area is probably explained by the reduced number of data points in Atascosa and Frio counties in 1999 than in 1989 and 1980. In particular, one well located in Frio County on the southern county line a little east of center is missing in the 1999 measurements and another well located in the Sparta outcrop in the south-central portion of this county is present in 1999 and missing in 1990 and 1980. The water level in the first well controls the southwest-northeast trend of the contours for 1989 and 1980 in La Salle County. For the second well, its low water level is causing the contours to be lower in La Salle County and oriented in an arc from southeast to northwest.

4.4.5 Transient Water Levels

Transient water-level data were used along with water-level elevation contours at specific time periods to both calibrate and verify the transient models. Figures 4.4.17a-b show the locations for which transient water-level data (hydrographs) are available for the Queen City and Sparta aquifers, respectively, based on data found on the TWDB website. Hydrograph data are available for over 200 wells completed to the Queen City aquifer and over 100 wells completed to the Sparta aquifer. In most cases, the hydrographs include data during the transient model calibration and verification time period of 1980 through 1999. Generation of the hydrographs assumes that the aquifer codes given on the TWDB website represent the aquifer within which the wells are completed.

Queen City Aquifer

In general, water levels have remained fairly stable with time in the Queen City aquifer in the northern model area during the time period of 1980 through 1999. Half of the about 90 hydrographs (51 percent) show less than a ± 20-foot water-level change over several decades with no apparent increasing or decreasing trend. Examples of such hydrographs are shown in Figure 4.4.18. A few hydrographs, about 11 percent, show declines in water levels over a period of about 15 years. Most of the declines are on the order of 10 to 35 feet, but one well shows a major decrease of 75 feet. This well is located in the southeast corner of Wood County at a location that coincides with the location of a large cone of depression in the water-level elevation contours as seen in Figures 4.4.14a, 4.4.15a, and 4.4.16a. An example water-level decline is illustrated in Figure 4.4.19. Increasing water-level elevations on the order of 10 to 25 feet are observed for about 10 percent of the hydrographs and erratic changes in water levels are observed in about 17 percent of the hydrographs. About 29 percent of the hydrographs show a change in trend (e.g., from increasing to decreasing) in the water levels over the transient record. Example hydrographs showing increases, erratic behavior, and changing trends are also shown in Figure 4.4.19.

Approximately 23 percent of the hydrographs for wells located in the central model area show stable water-level elevations for the time period of 1980 to 2000. Stable elevations are considered those that fluctuate within ± 20 feet and do not show an increasing or decreasing trend. Examples of such hydrographs are shown in Figure 4.4.20. About 37 percent of the hydrographs for the central model area show decreasing water-level elevations with time. The magnitude of the declines ranges from about 10 feet to about 70 feet over time periods from 5 to 40 years. The largest declines are observed for wells located in Leon County. Two examples of hydrographs with declining water-level elevations are illustrated in Figure 4.4.21. Water-level elevations in 21 percent of the wells located in the central model area increase with time. Most increases are between 5 and 20 feet. The largest increase is 50 feet over about 20 years in well

58-48-509 located in Lee County (see Figure 4.4.21). Hydrographs showing changes in trends over time make up about 19 percent of the hydrographs available for wells in the central model area. In one well located in Leon County, water-level elevations decreased about 60 feet over 25 years and then increased about 20 feet over 25 years (see Figure 4.4.21). Erratic changes in water-level elevation are observed in 6 percent of the wells with hydrographs. One such hydrograph is shown in Figure 4.4.21. In summary, water-level elevations in the Queen City aquifer have changed inconsistently in wells located in the central model area. The water level in some wells has remained fairly stable. Increases in water level have ranged from a low of 5 feet to a high of 50 feet. Likewise, a wide range in decreases in water levels has also been observed (5 to 70 feet). The trend in the water level has changed over time in some wells and erratic changes have been observed in several wells. The only wells showing substantial declines in water levels are located in Leon County and the only well showing a substantial increase in water levels is located in Lee County.

About 28 percent of the available transient water-level data for the southern model area cover the entire time period of 1980 through 1999. Of the remaining data, about 48 percent end prior to 1980 and about 24 percent either end or begin sometime between 1980 and 1999. Considering all available hydrographs, about half (55 percent) of the transient water-level data for wells located within the southern model area show a declining trend. The magnitude of the declines ranges from 5 to 130 feet with most falling between 5 and 20 feet. Water levels for two wells with declining hydrographs are shown in Figure 4.4.22. Wells with declining hydrographs are found in all counties within this model area. For about 24 percent of the wells, the transient data show a change in trend over time. In most cases, this change consists of increasing water levels followed by a decrease and then another increase. The hydrographs for three such wells are also shown in Figure 4.4.22. An increase in water-level elevations ranging from about 7 feet to approximately 20 feet over a 10 to 35-year time frame was observed for two wells in the southern model area. Unfortunately, the transient data for both wells ends during the 1960s and it is unknown whether the water levels continued to rise. Stable water levels are found in three wells and erratic water levels are found in one well in the southern model region. During the time period from 1980 to 1999, the transient water-level data indicate an overall decline in water levels in the Queen City aquifer in the southern model area.

The changes in Queen City water levels between the start of transient model calibration (January 1980) and the end of model calibration (December 1989) and the end of model verification (December 1999) are illustrated in Figures 4.4.23a and 4.4.23b, respectively. All water level measurements included are from the same well. In each scatter plot, if the head at a given well has decreased with time, it plots below the unit slope line. The data in Figure 4.4.23 show that heads have basically remained stable from 1980 through 1999 in the Queen City aquifer in Texas. However, there are areas where local drawdown has occurred such as in Fayette County between 1980 and 1999. In the majority of the aquifer in all three model regions, water levels varied little between 1980 and 1999 based on the available data from the TWDB website. This is consistent with the relatively small aquifer production in Texas relative to many of the major aquifers and to the extensive portion of the aquifer that is in outcrop in east Texas.

An attempt was made to analyze the transient water-level data for the Queen City aquifer with respect to seasonal fluctuations. This could not be performed because the frequency of data collection was sufficient for such analysis in only one well. With the availability of only a single data point, analysis of changes in water levels due to changes in seasons could not be conducted.

Sparta Aquifer

Transient water-level data for 31 wells completed in the Sparta aquifer and located within the northern model area were found on the TWDB website. Of these wells, nine have transient data during the entire period from 1980 through 1989, seven have data that either start or stop during this time period, and 15 have data only prior to 1980. Hydrographs of the data during either all or a portion of the period from 1981 through 1989 show declines in 38 percent of the wells, stable water levels in 25 percent of the wells, increases in 6 percent of the wells, and changing trends (e.g., decrease followed by increase) in 31 percent of the wells. The magnitude of the decline in water levels ranges from about 5 to 15 feet. The hydrograph for the well showing the largest decline (about 15 feet) over the longest time period (about 40 years) is provided in Figure 4.4.24. Only one well shows an increase in water level with time. That increase is about 20 feet over a period of about 40 years. The hydrograph for this well is also provided on Figure 4.4.24. Transient water-level elevations for one well in each of Anderson, Angelina, Cherokee, and Angelina counties show a stable trend for a period of several decades. Hydrographs for two of those wells can be found in Figure 4.4.24. Several wells (one each in

Anderson, Houston, Leon, Nacogdoches, and Sabine counties) show changing trends in water-level elevations. The hydrograph for the well located in Sabine County is provided in Figure 4.4.24. In summary, changes in water-level elevations in the Sparta aquifer in the northern model area have been, in general, relatively small, on the order of ±15 feet, based on the available data.

Transient water-level data for 34 wells completed to the Sparta aquifer and located within the central model area were found on the TWDB website. Of these wells, 23 have transient data during the entire period from 1980 through 1989, eight have data that either start or stop during this time period, and three have data only prior to 1980. In general, water-level elevations within these wells have varied within a range of about ±20 feet over the period from 1981 to 1989. The hydrograph data show an overall decline in water level in 26 percent of the wells, an overall increase in water level in 6 percent of the wells, a changing trend in 65 percent of the wells, and a stable water level in 3 percent of the wells. The observed decreases in water level range from a low of 10 feet to a high of 70 feet and the observed increases range from 25 to 100 feet. For the hydrographs showing changing trends, a predominantly downward trend is observed in 68 percent of the wells, a predominantly upward trend is observed in 14 percent of the wells, and a predominantly stable trend is observed in 18 percent of the wells. Figure 4.4.25 shows examples of the types of changes observed. The hydrograph data show a predominant declining trend in Burleson, Fayette, Lee, Madison, and Walker counties. The transient water-level data in two wells is substantially different from the general trend discussed to this point. For well 59-21-713 in Brazos County, the hydrograph shows an increase in water-level elevation of almost 100 feet over a time period of about 20 years (Figure 4.4.26). In Madison County, the hydrograph for well 60-03-202 shows a decrease of about 80 feet over about 20 years followed by an increase of over 40 feet over a few years and then another decrease of about 20 feet over 10 years (Figure 4.4.26). In summary, the transient water-level data for wells completed to the Sparta aquifer and located within the central model area show changes on the order of ±20 feet over the period from 1980 to 2000 in almost all cases. These changes have been on a downward trend in most wells.

Transient water-level data for 16 wells completed to the Sparta aquifer and located within the southern model area were found on the TWDB website. Of that, data from 1980 to 1989 are available for 50 percent of the wells, data either starting or stopping sometime between 1980 and

1989 are observed in 25 percent of the wells, only data prior to 1980 are available for 13 percent of the wells, and 12 percent of the wells have only recent data. The hydrographs show an overall decreasing trend in 6 percent of the wells, an overall increasing trend in 19 percent of the wells, changing trends in 69 percent of the wells, and a stable water level in 6 percent of the wells. Based on the available data, no general trend could be determined for any county within the southern model region. At least two different types of trends in water levels can all be found within each of the individual counties. For example, of the five hydrographs available for wells in Wilson County, two show an overall increasing trend and three show a stable trend. Examples of hydrographs showing increasing, decreasing, and changing trends are provided in Figure 4.4.27.

The changes in Sparta water levels between the start of the transient model calibration (January 1980) and the end of model calibration (December 1989) and the end of model verification (December 1999) are illustrated in Figures 4.4.28a and 4.4.28b, respectively. As was the case in the Queen City plots, each water level was measured in the same well at different times. In each scatter plot, if the head at a given well has decreased with time, then it will plot below the unit slope line. The majority of the points plot below the unit slope line indicating a slight decrease in Sparta aquifer heads since 1980.

An attempt was made to analyze the transient water-level data for the Sparta aquifer with respect to seasonal fluctuations. This analysis could not be performed because measurements of water levels at a frequency sufficient for evaluation of seasonal changes were not taken in any well completed in the Sparta aquifer.

Table 4.4.1 **Target values for calibration of the northern area steady-state model to predevelopment conditions in the Queen City aquifer.**

State Well Number	County	Measurement Date	Observed Water-Level Elevation (feet)	Source of Observed Water Level
3460601	Anderson	6/14/1944	412	TWDB (website)
1660601	Cass	12/9/1941	291	TWDB (website)
1664101	Cass	12/13/1941	306	TWDB (website)
1664203	Cass	12/13/1941	253	TWDB (website
3461603	Cherokee	3/9/1936	433	TWDB (website)
3461904	Cherokee	3/11/1936	409	TWDB (website)
3462304	Cherokee	3/13/1936	430	TWDB (website)
3462402	Cherokee	3/10/1936	440	TWDB (website)
3462603	Cherokee	3/4/1936	667	TWDB (website)
3462604	Cherokee	3/4/1936	641	TWDB (website)
3462805	Cherokee	3/10/1936	486	TWDB (website)
3463103	Cherokee	3/13/1936	422	TWDB (website)
3463104	Cherokee	3/13/1936	385	TWDB (website)
3463105	Cherokee	3/26/1936	383	TWDB (website)
3463206	Cherokee	3/26/1936	383	TWDB (website)
3463406	Cherokee	3/25/1936	413	TWDB (website)
3463603	Cherokee	3/27/1936	379	TWDB (website)
3463803	Cherokee	3/25/1936	408	TWDB (website)
3717402	Cherokee	6/19/1936	248	TWDB (website)
3717403	Cherokee	6/30/1936	246	TWDB (website)
3717704	Cherokee	6/19/1936	281	TWDB (website)
3805303	Cherokee	4/14/1936	586	TWDB (website)
3805604	Cherokee	4/14/1936	316	TWDB (website)
3805605	Cherokee	4/14/1936	434	TWDB (website)
3805906	Cherokee	4/14/1936	384	TWDB (website)
3806104	Cherokee	3/12/1936	453	TWDB (website)
3806105	Cherokee	4/14/1936	682	TWDB (website)
3806405	Cherokee	4/14/1936	401	TWDB (website)
3806406	Cherokee	4/10/1936	410	TWDB (website)
3806407	Cherokee	4/14/1936	407	TWDB (website)
3806803	Cherokee	4/17/1936	561	TWDB (website)
3806804	Cherokee	4/17/1936	450	TWDB (website)
3806902	Cherokee	4/20/1936	465	TWDB (website)
3807104	Cherokee	3/17/1936	367	TWDB (website)
3807304	Cherokee	4/13/1936	383	TWDB (website)
3807406	Cherokee	3/7/1936	476	TWDB (website)
3807407	Cherokee	3/7/1936	425	TWDB (website)
3807505	Cherokee	3/17/1936	347	TWDB (website)
3807702	Cherokee	3/7/1936	423	TWDB (website)
3807704	Cherokee	4/20/1936	620	TWDB (website)
3808106	Cherokee	3/23/1936	437	TWDB (website)
3808205	Cherokee	3/23/1936	530	TWDB (website)
3808303	Cherokee	3/23/1936	380	TWDB (website)

Table 4.4.1, continued

State Well Number	County	Measurement Date	Observed Water-Level Elevation (feet)	Source of Observed Water Level
3808505	Cherokee	4/3/1936	473	TWDB (website)
3814104	Cherokee	4/15/1936	356	TWDB (website)
3814105	Cherokee	4/16/1936	411	TWDB (website)
3814201	Cherokee	4/17/1936	664	TWDB (website)
3814203	Cherokee	4/10/1936	607	TWDB (website)
3814204	Cherokee	4/10/1936	601	TWDB (website)
3814305	Cherokee	4/20/1936	623	TWDB (website)
3814306	Cherokee	6/12/1936	598	TWDB (website)
3814404	Cherokee	4/17/1936	398	TWDB (website)
3814504	Cherokee	4/17/1936	406	TWDB (website)
3814505	Cherokee	5/6/1936	344	TWDB (website)
3814506	Cherokee	4/17/1936	641	TWDB (website)
3814602	Cherokee	6/12/1936	393	TWDB (website)
3814604	Cherokee	4/21/1936	431	TWDB (website)
3814802	Cherokee	5/27/1936	350	TWDB (website)
3814904	Cherokee	5/1/1936	640	TWDB (website)
3814905	Cherokee	5/1/1936	423	TWDB (website)
3814907	Cherokee	5/6/1936	397	TWDB (website)
3815103	Cherokee	4/20/1936	629	TWDB (website)
3815104	Cherokee	4/21/1936	415	TWDB (website)
3815301	Cherokee	4/23/1936	439	TWDB (website)
3815303	Cherokee	4/3/1936	436	TWDB (website)
3815404	Cherokee	4/21/1936	409	TWDB (website)
3815902	Cherokee	5/4/1936	443	TWDB (website)
3816404	Cherokee	4/29/1936	513	TWDB (website)
3816501	Cherokee	4/28/1936	366	TWDB (website)
3816703	Cherokee	4/30/1936	710	TWDB (website)
3816704	Cherokee	4/30/1936	682	TWDB (website)
3816906	Cherokee	4/28/1936	344	TWDB (website)
3822301	Cherokee	5/12/1936	302	TWDB (website)
3823104	Cherokee	5/11/1936	419	TWDB (website)
3823105	Cherokee	5/11/1936	355	TWDB (website)
3823107	Cherokee	5/11/1936	352	TWDB (website)
3823203	Cherokee	6/22/1936	385	TWDB (website)
3823204	Cherokee	5/11/1936	382	TWDB (website)
3823303	Cherokee	6/25/1936	455	TWDB (website)
3823304	Cherokee	5/5/1936	452	TWDB (website)
3823305	Cherokee	5/5/1936	409	TWDB (website)
3823403	Cherokee	6/22/1936	347	TWDB (website)
3823404	Cherokee	6/22/1936	292	TWDB (website)
3823405	Cherokee	6/6/1936	346	TWDB (website)
3823604	Cherokee	5/5/1936	410	TWDB (website)
3823704	Cherokee	6/22/1936	308	TWDB (website)
3823902	Cherokee	6/15/1936	296	TWDB (website)
3824201	Cherokee	5/8/1936	432	TWDB (website)
3824303	Cherokee	4/30/1936	359	TWDB (website)
3824402	Cherokee	6/17/1936	365	TWDB (website)
3824404	Cherokee	6/17/1936	314	TWDB (website)
3824602	Cherokee	5/8/1936	378	TWDB (website)

Table 4.4.1, continued

State Well Number	County	Measurement Date	Observed Water-Level Elevation (feet)	Source of Observed Water Level
3826104	Freestone	6/19/1936	429	TWDB (website)
3826105	Freestone	6/19/1936	424	TWDB (website)
3826106	Freestone	6/19/1936	419	TWDB (website)
3826108	Freestone	6/19/1936	403	TWDB (website)
3932502	Freestone	4/30/1936	390	TWDB (website)
3932503	Freestone	4/30/1936	366	TWDB (website)
3511901	Harrison	1/29/1942	306	TWDB (website)
3521403	Harrison	1/29/1942	264	TWDB (website)
3528101	Harrison	1/30/1942	281	TWDB (website)
3536201	Harrison	1/27/1942	356	TWDB (website)
3443105	Henderson	5/6/1936	445	TWDB (website)
3443506	Henderson	4/7/1936	445	TWDB (website)
3443507	Henderson	4/6/1936	486	TWDB (website)
3443605	Henderson	4/7/1936	443	TWDB (website)
3443606	Henderson	4/7/1936	508	TWDB (website)
3443607	Henderson	4/7/1936	434	TWDB (website)
3443703	Henderson	5/7/1936	424	TWDB (website)
3443704	Henderson	4/8/1936	391	TWDB (website)
3443705	Henderson	4/8/1936	413	TWDB (website)
3443706	Henderson	5/7/1936	448	TWDB (website)
3443805	Henderson	5/7/1936	419	TWDB (website)
3443903	Henderson	5/4/1936	377	TWDB (website)
3444204	Henderson	4/24/1936	455	TWDB (website)
3444407	Henderson	4/21/1936	469	TWDB (website)
3444501	Henderson	2/21/1936	409	TWDB (website)
3444502	Henderson	4/24/1936	428	TWDB (website)
3444503	Henderson	2/21/1936	363	TWDB (website)
3444504	Henderson	2/21/1936	342	TWDB (website)
3444704	Henderson	2/21/1936	463	TWDB (website)
3444705	Henderson	2/21/1936	463	TWDB (website)
3444905	Henderson	2/23/1936	496	TWDB (website)
3445101	Henderson	2/25/1936	473	TWDB (website)
3445405	Henderson	2/25/1936	467	TWDB (website)
3445703	Henderson	2/13/1936	437	TWDB (website)
3450304	Henderson	3/8/1936	399	TWDB (website)
3450305	Henderson	3/27/1936	387	TWDB (website)
3450604	Henderson	3/10/1936	414	TWDB (website)
3451105	Henderson	4/27/1936	465	TWDB (website)
3451106	Henderson	5/4/1936	460	TWDB (website)
3451206	Henderson	5/4/1936	534	TWDB (website)
3451207	Henderson	5/5/1936	424	TWDB (website)
3451303	Henderson	5/4/1936	471	TWDB (website)
3451304	Henderson	5/4/1936	458	TWDB (website)
3451505	Henderson	4/10/1936	525	TWDB (website)
3451606	Henderson	4/27/1936	344	TWDB (website)
3451703	Henderson	4/16/1936	353	TWDB (website)
3451704	Henderson	5/1/1936	413	TWDB (website)
3451804	Henderson	5/5/1936	359	TWDB (website)

Table 4.4.1, continued

State Well Number	County	Measurement Date	Observed Water-Level Elevation (feet)	Source of Observed Water Level
3451904	Henderson	4/10/1936	434	TWDB (website)
3451905	Henderson	5/5/1936	406	TWDB (website)
3452105	Henderson	5/4/1936	421	TWDB (website)
3452305	Henderson	4/20/1936	449	TWDB (website)
3452306	Henderson	4/21/1936	438	TWDB (website)
3452307	Henderson	4/23/1936	452	TWDB (website)
3452403	Henderson	4/27/1936	369	TWDB (website)
3452404	Henderson	5/5/1936	323	TWDB (website)
3452505	Henderson	5/5/1936	424	TWDB (website)
3452506	Henderson	4/20/1936	379	TWDB (website)
3452704	Henderson	5/5/1936	441	TWDB (website)
3452804	Henderson	4/21/1936	429	TWDB (website)
3458103	Henderson	4/19/1936	370	TWDB (website)
3458203	Henderson	2/12/1936	416	TWDB (website)
3458204	Henderson	4/29/1936	475	TWDB (website)
3458303	Henderson	4/30/1936	517	TWDB (website)
3458604	Henderson	4/30/1936	452	TWDB (website)
3458903	Henderson	2/24/1936	438	TWDB (website)
3459106	Henderson	5/1/1936	422	TWDB (website)
3459107	Henderson	5/1/1936	456	TWDB (website)
3459203	Henderson	4/16/1936	475	TWDB (website)
3459204	Henderson	4/16/1936	471	TWDB (website)
3459304	Henderson	4/16/1936	458	TWDB (website)
3459305	Henderson	4/16/1936	391	TWDB (website)
3459405	Henderson	4/30/1936	396	TWDB (website)
3459406	Henderson	4/30/1936	330	TWDB (website)
3459503	Henderson	4/17/1936	346	TWDB (website)
3459504	Henderson	4/17/1936	333	TWDB (website)
3459505	Henderson	4/30/1936	365	TWDB (website)
3460406	Henderson	4/20/1936	427	TWDB (website)
3460408	Henderson	4/20/1936	478	TWDB (website)
3461106	Henderson	4/18/1936	397	TWDB (website)
3461107	Henderson	4/18/1936	431	TWDB (website)
3461405	Henderson	4/18/1936	659	TWDB (website)
3849101	Leon	12/7/1936	283	TWDB (website)
3940905	Leon	11/30/1936	359	TWDB (website)
3520201	Marion	3/17/1942	274	TWDB (website)
3709902	Nacogdoches	9/8/1936	325	TWDB (website)
3710404	Nacogdoches	9/4/1936	369	TWDB (website)
3710405	Nacogdoches	9/8/1936	407	TWDB (website)
3710701	Nacogdoches	9/8/1936	323	TWDB (website)
3710702	Nacogdoches	9/8/1936	334	TWDB (website)
3710802	Nacogdoches	9/8/1936	292	TWDB (website)
3717202	Nacogdoches	8/27/1936	292	TWDB (website)
3717303	Nacogdoches	8/26/1936	365	TWDB (website)
3717304	Nacogdoches	8/27/1936	236	TWDB (website)
3717602	Nacogdoches	8/26/1936	327	TWDB (website)
3717603	Nacogdoches	8/26/1936	250	TWDB (website)
3717604	Nacogdoches	8/26/1936	405	TWDB (website)

Table 4.4.1, continued

State Well Number	County	Measurement Date	Observed Water-Level Elevation (feet)	Source of Observed Water Level
3717605	Nacogdoches	8/26/1936	425	TWDB (website)
3717606	Nacogdoches	8/27/1936	432	TWDB (website)
3717802	Nacogdoches	9/25/1936	410	TWDB (website)
3717903	Nacogdoches	9/25/1936	435	TWDB (website)
3717904	Nacogdoches	9/23/1936	428	TWDB (website)
3718103	Nacogdoches	9/3/1936	374	TWDB (website)
3718203	Nacogdoches	9/3/1936	364	TWDB (website)
3718204	Nacogdoches	9/3/1936	347	TWDB (website)
3718302	Nacogdoches	9/2/1936	385	TWDB (website)
3718303	Nacogdoches	9/2/1936	355	TWDB (website)
3718304	Nacogdoches	9/3/1936	453	TWDB (website)
3718402	Nacogdoches	8/25/1936	351	TWDB (website)
3718403	Nacogdoches	8/28/1936	441	TWDB (website)
3718501	Nacogdoches	9/2/1936	332	TWDB (website)
3718601	Nacogdoches	9/2/1936	306	TWDB (website)
3718802	Nacogdoches	8/25/1936	342	TWDB (website)
3719201	Nacogdoches	9/7/1936	340	TWDB (website)
3719302	Nacogdoches	8/31/1936	344	TWDB (website)
3719303	Nacogdoches	8/31/1936	357	TWDB (website)
3728305	Nacogdoches	9/14/1936	389	TWDB (website)
3728306	Nacogdoches	10/13/1936	386	TWDB (website)
3541101	Rusk	6/9/1936	418	TWDB (website)
3541706	Rusk	6/11/1936	471	TWDB (website)
3549102	Rusk	6/11/1936	438	TWDB (website)
3701202	Rusk	11/2/1936	384	TWDB (website)
3702401	Rusk	10/22/1936	483	TWDB (website)
3703503	Rusk	10/20/1936	508	TWDB (website)
3424901	Upshur	3/13/1942	412	TWDB (website)
3517701	Upshur	3/12/1942	379	TWDB (website)
3518201	Upshur	3/11/1942	326	TWDB (website)
3406602	Wood	2/16/1942	474	TWDB (website)
3406804	Wood	2/16/1942	488	TWDB (website)
3407702	Wood	2/10/1942	538	TWDB (website)
3407903	Wood	2/9/1942	441	TWDB (website)
3413801	Wood	2/3/1942	376	TWDB (website)
3413802	Wood	2/3/1942	414	TWDB (website)
3414102	Wood	2/18/1942	450	TWDB (website)
3414201	Wood	2/10/1942	460	TWDB (website)
3414203	Wood	2/16/1942	453	TWDB (website)
3414801	Wood	2/3/1942	414	TWDB (website)

Table 4.4.2 Target values for calibration of the central area steady-state model to predevelopment conditions in the Queen City aquifer.

State Well Number	County	Measurement Date	Observed Water-Level Elevation (feet)	Source of Observed Water Level
5855602	Bastrop	1/8/1938	522	TWDB (website)
5863909	Bastrop	1/1/1915	294	TWDB (website)
5918901	Burleson	9/2/1936	456	TWDB (website)
5919601	Burleson	9/1/1936	442	TWDB (website)
5926604	Burleson	10/9/1936	372	TWDB (website)
5926701	Burleson	9/22/1936	440	TWDB (website)
6713601	Caldwell	4/18/1946	457	TWDB (website)
6713901	Caldwell	4/16/1946	433	TWDB (website)
6714603	Fayette	1940	369	TWDB (website)
6728303	Gonzales	10/14/1938	309	TWDB (website)
6735502	Gonzales	11/22/1938	327	TWDB (website)
5848201	Lee	average(1)	397	TWDB (website)

(1) average water level for well which shows stable water-level elevations with time

Table 4.4.3 Target values for calibration of the southern area steady-state model to predevelopment conditions in the Queen City aquifer.

State Well Number	County	Measurement Date	Observed Water-Level Elevation (feet)	Source of Observed Water Level
6862702	Atascosa	1936	383	TWDB (website)
7804601	Atascosa	1929	393	TWDB (website)
7814203	Atascosa	5/16/1944	351	TWDB (website)
7729401	Dimmit	10/22/1929	473	TWDB (website)
7708407	Frio	1929	572	TWDB (website)
7732501	La Salle	average(1)	380	TWDB (website)
7746804	La Salle	10/17/1942	459	TWDB (website)
7827903	McMullen	4/14/1959	373	TWDB (website)
7828303	McMullen	4/15/1959	391	TWDB (website)
5919301	Milam	5/6/1936	300	TWDB (website)
8512601	Webb	8/1/1931	573	TWDB (website)
6742401	Wilson	6/15/1936	402	TWDB (website)
6750103	Wilson	average(1)	383	TWDB (website)

(1) average water level for well which shows stable water-level elevations with time

Table 4.4.4 Target values for calibration of the steady-state models to predevelopment conditions in the Sparta aquifer.

Well Number	County	Measurement Date	Observed Water-Level Elevation (feet)	Source of Observed Water Level
Northern Model Area				
3832802	Cherokee	5/13/1936	322	TWDB (website)
3846501	Houston	12/8/1975	270	TWDB (website)
3837901	Houston	12/7/1993	399	TWDB (website)
3828604	Houston	7/3/1987	417	TWDB (website)
3729903	Nacogdoches	9/29/1936	327	TWDB (website)
3729502	Nacogdoches	9/28/1936	418	TWDB (website)
3729203	Nacogdoches	10/13/1936	499	TWDB (website)
3727502	Nacogdoches	average(1)	288	TWDB (website)
3727307	Nacogdoches	1/24/1938	336	TWDB (website)
3718903	Nacogdoches	8/25/1936	467	TWDB (website)
NA-437	Natchitoches	8/7/1974	279	USGS (website)
R-617	Rapides	4/1/1957	36	USGS (website)
3633404	Sabine	11/18/1998	308	TWDB (website)
SA-459	Sabine	6/6/1971	290	USGS (website)
SA-343	Sabine	1/1/1957	320	USGS (website)
SA-303	Sabine	1/1/1959	270	USGS (website)
SA-108	Sabine	11/18/1954	351	USGS (website)
3740801	San Augustine	8/31/1960	275	TWDB (website)
Central Model Area				
5864404	Bastrop	1947	355	TWDB (website)
5923403	Brazos	12/31/1953	243	TWDB (website)
5913903	Brazos	7/15/1970	328	TWDB (website)
5906502	Brazos	7/23/1970	357	TWDB (website)
5937603	Burleson	7/9/1970	236	TWDB (website)
5936205	Burleson	6/4/1969	283	TWDB (website)
5935401	Burleson	1/1927	353	TWDB (website)
5934905	Burleson	3/22/1982	322	TWDB (website)
5927801	Burleson	9/25/1936	335	TWDB (website)
5927504	Burleson	4/14/1970	363	TWDB (website)
5926502	Burleson	3/23/1970	485	TWDB (website)
6723102	Fayette	10/9/1942	363	TWDB (website)
6715410	Fayette	1914	381	TWDB (website)
6714905	Fayette	1900	373	TWDB (website)
6708402	Fayette	2/17/1977	318	TWDB (website)
6736601	Gonzales	2/25/1986	309	TWDB (website)
6729501	Gonzales	1/26/1977	315	TWDB (website)
6729302	Gonzales	2/17/1989	330	TWDB (website)
5949501	Lee	1/8/1938	339	TWDB (website)
5941704	Lee	4/17/1975	346	TWDB (website)
5856901	Lee	1962	346	TWDB (website)
3956901	Leon	5/8/1963	362	TWDB (website)
6003201	Madison	11/18/1996	283	TWDB (website)
5916102	Madison	9/26/1972	260	TWDB (website)
5908201	Madison	6/22/1961	330	TWDB (website)
5913301	Robertson	5/4/1938	375	TWDB (website)

Table 4.4.4, continued

Well Number	County	Measurement Date	Observed Water-Level Elevation (feet)	Source of Observed Water Level
5906305	Robertson	7/24/2002	364	TWDB (website)
6003902	Walker	7/10/1973	230	TWDB (website)
Southern Model Area				
7818306	Atascosa	1929	418	TWDB (website)
7813701	Atascosa	2/24/1982	357	TWDB (website)
7811204	Atascosa	1/22/1991	413	TWDB (website)
7805717	Atascosa	9/2/1970	402	TWDB (website)
7817502	Frio	2/14/1975	440	TWDB (website)
7762704	La Salle	4/28/1959	447	TWDB (website)
7746803	La Salle	8/7/1963	439	TWDB (website)
7730301	La Salle	11/5/1962	520	TWDB (website)
6863207	Wilson	1/14/1976	432	TWDB (website)
6862607	Wilson	12/12/1990	443	TWDB (website)
6750104	Wilson	7/1/1998	383	TWDB (website)

(1) average water level for well which shows stable water-level elevations with time

Table 4.4.5 Results of pressure versus depth analysis by county.

County	All Data				Data Prior to 1950			
	Number of Data Points	Correlation	Slope	Intercept	Number of Data Points	Correlation	Slope	Intercept
Northern Model Area								
Anderson	128	0.95	0.86	-61.10	7	0.99	0.86	-28.40
Angelina	49	0.75	0.73	+1.85	12	0.98	0.87	+52.09
Camp	(1)							
Cass	(1)							
Cherokee	137	0.79	0.68	-35.87	(2)			
Freestone	(3)							
Gregg	(1)							
Harrison	(1)							
Henderson	87	0.87	0.85	-47.04	(2)			
Houston	12	0.94	0.89	-115.32	(2)			
Marion	(1)							
Morris	(1)							
Nacogdoches	85	0.74	0.85	-74.27	36	0.96	1.03	-70.78
Rusk	(1)							
Sabine	(3)							
San Augustine	4	0.88	0.48	+87.35	(3)			
Smith	164	0.82	0.73	-40.49	(2)			
Titus	(4)							
Trinity	(4)							
Upshur	62	0.81	0.83	-85.75	(2)			
Van Zandt	(3)							
Wood	118	0.93	0.86	-38.62	8	0.99	0.85	-18.10
Central Model Area								
Bastrop	63	0.94	0.84	-27.90	(2)			
Brazos	17	1.00	1.01	-70.77	(3)			
Burleson	22	0.99	1.04	-147.03	(2)			
Caldwell	(1)							
Fayette	(3)							
Grimes	(4)							
Gonzales	77	1.00	1.04	-48.70	(2)			
Lee	14	0.98	0.97	-119.10	(2)			
Leon	28	0.93	1.00	-126.77	(2)			
Madison	5	1.00	1.04	-136.11	(2)			
Milam	(3)							
Robertson	53	0.99	0.98	-75.52	(2)			
Walker	(4)							
Washington	(4)							
Southern Model Area								
Atascosa	56	0.99	1.04	-125.73	(2)			
Frio	15	0.94	1.03	-235.00	(2)			
La Salle	45	0.99	1.04	-185.67	(2)			
McMullen	(1)							
Webb	73	0.99	0.99	-132.35	(2)			
Wilson	35	0.99	1.03	-104.94	(2)			

(1) Screen data were not available for wells completed to the Sparta or Queen City sands.
(2) No Sparta or Queen City water-level data prior to 1950 for wells with screen data.
(3) Insufficient Sparta or Queen City screen data to conduct analysis.
(4) No Sparta or Queen City water-level data available.

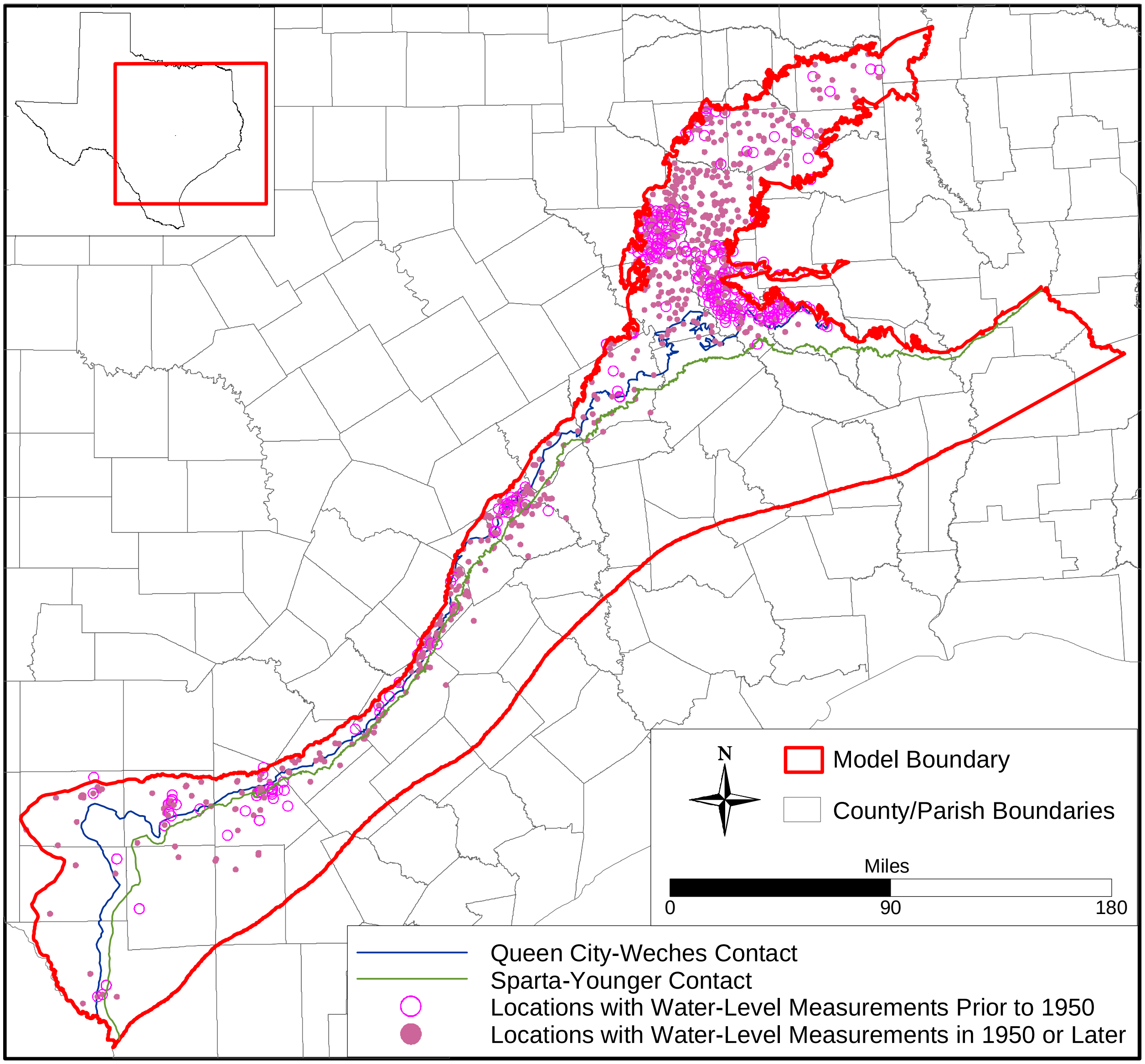

Figure 4.4.1 **Water-level measurement locations for the Queen City aquifer.**

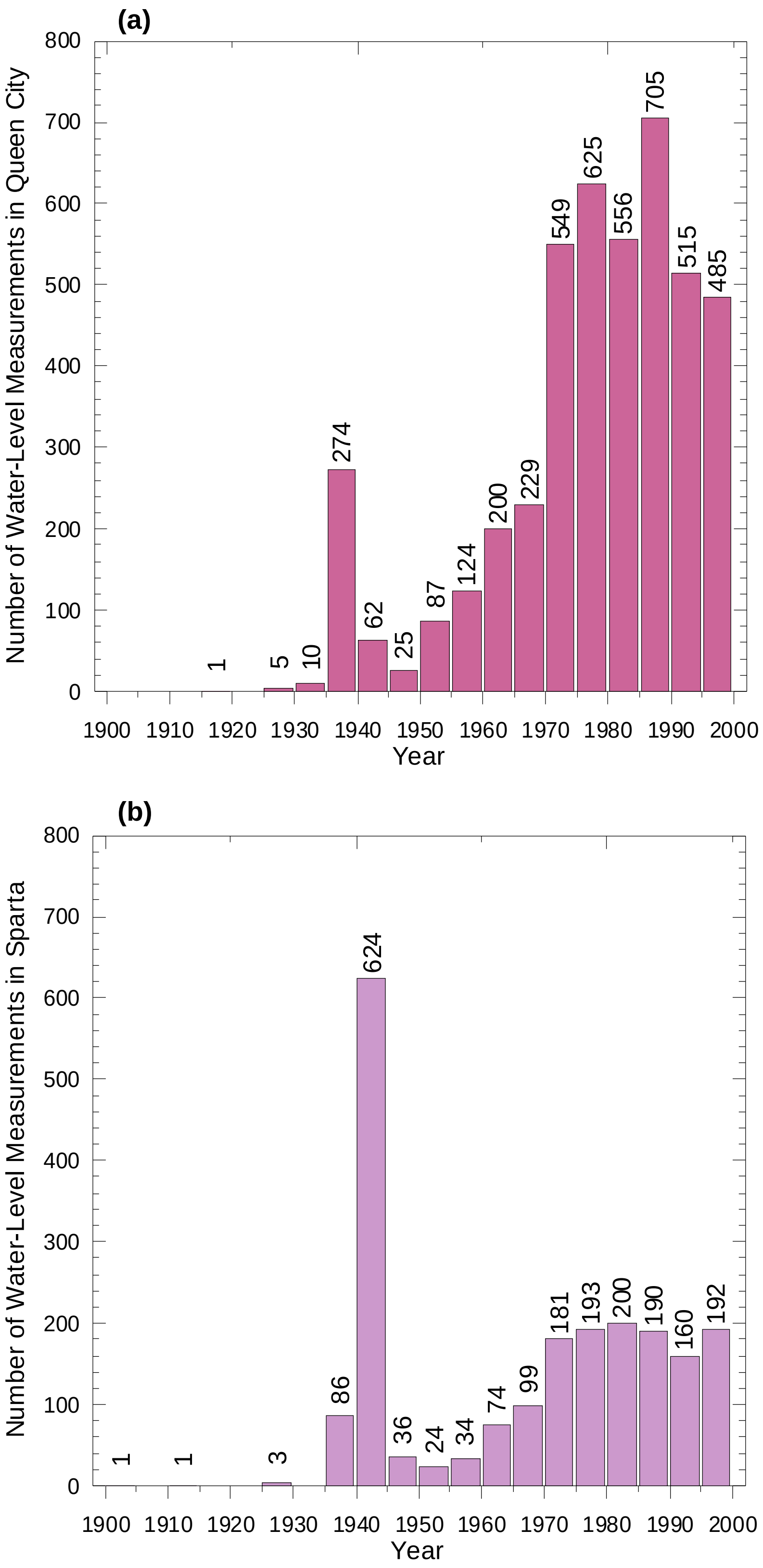

Figure 4.4.2 Temporal distribution of water-level measurements in the (a) Queen City aquifer and (b) Sparta aquifer.

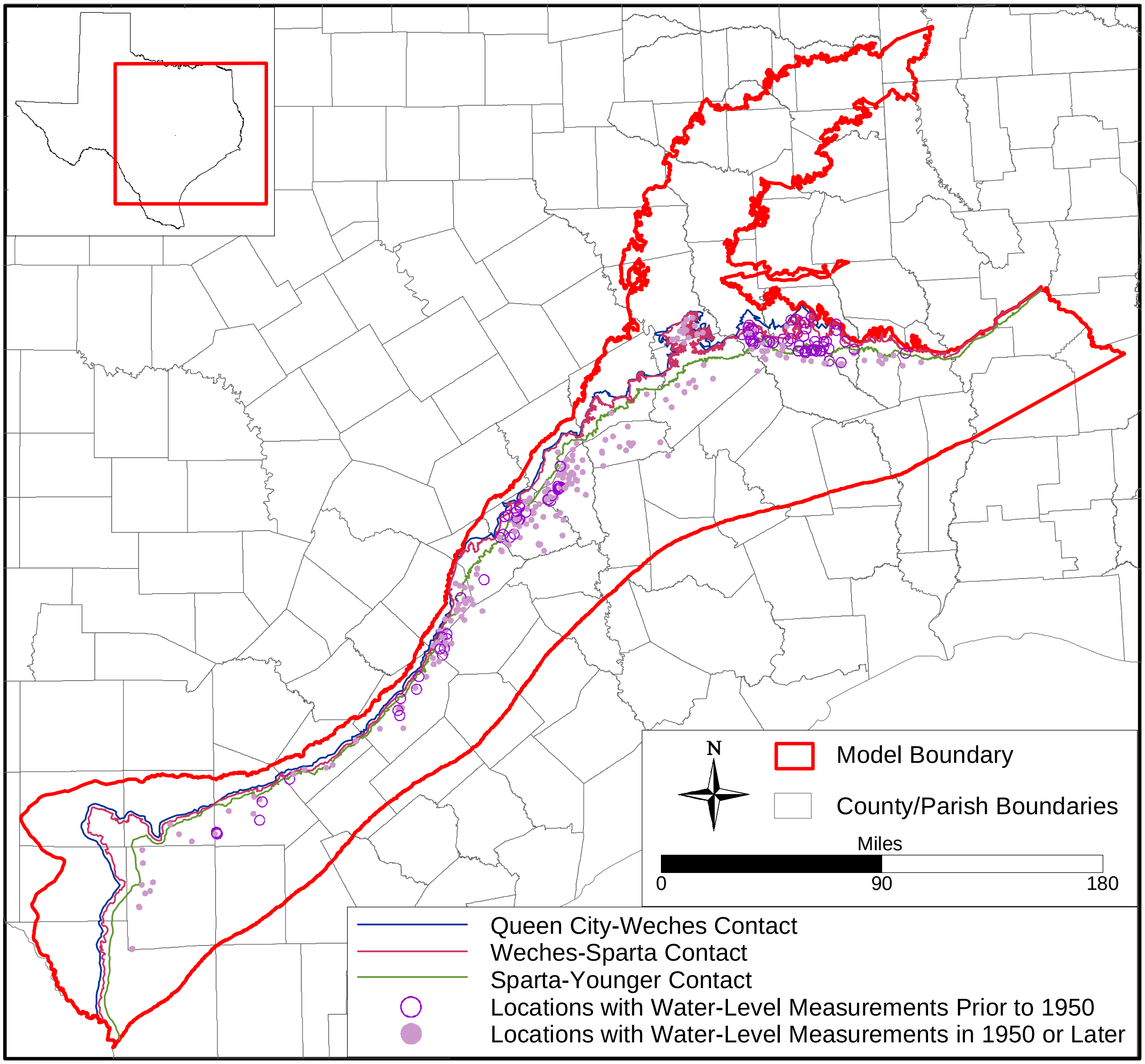

Figure 4.4.3 **Water-level measurement locations for the Sparta aquifer.**

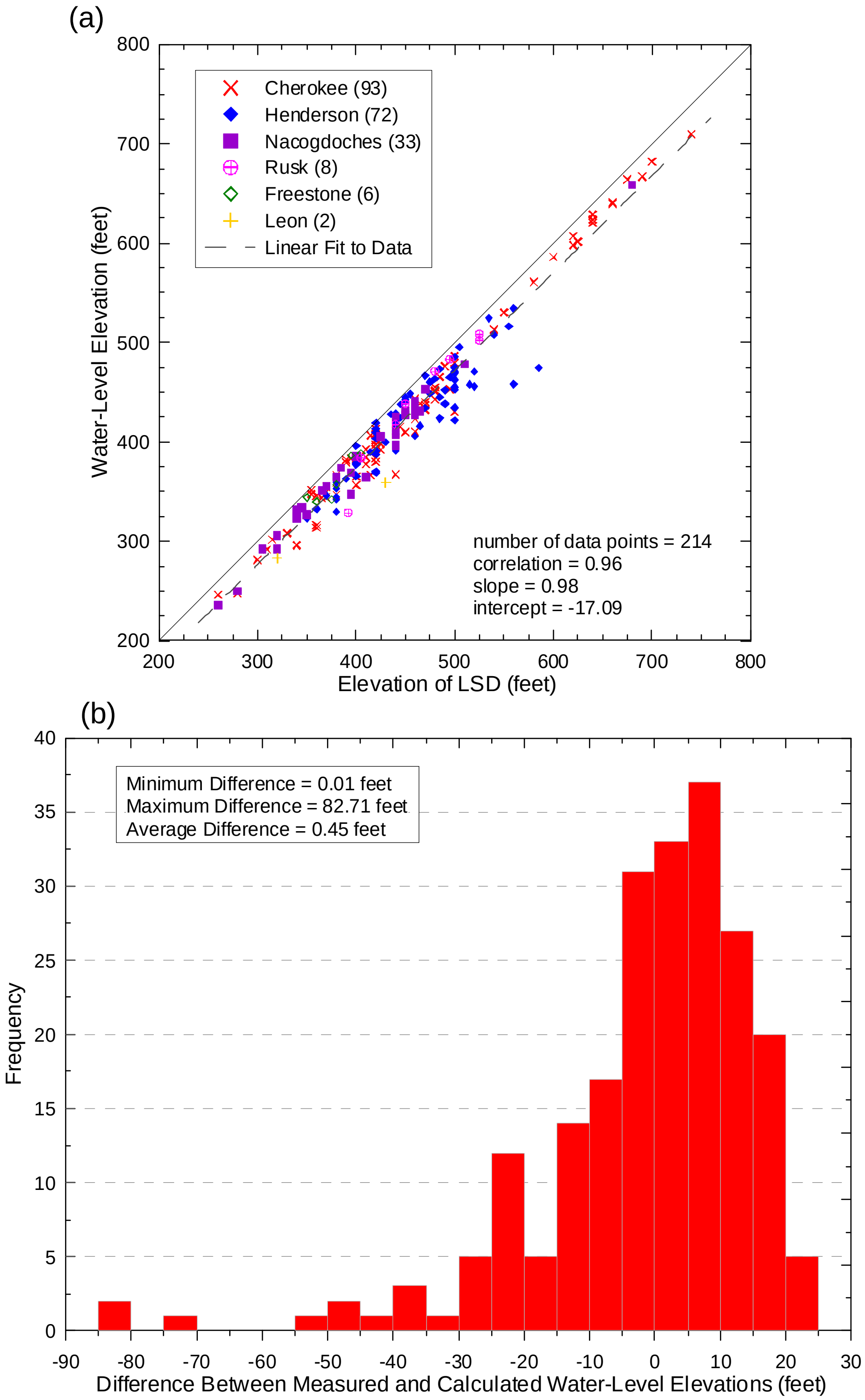

Figure 4.4.4 For the 1936 water-level measurements in the Queen City aquifer in the northern model area, (a) the relationship between ground-surface elevation and water-level elevation and (b) histogram of differences between observed and calculated water-level elevations.

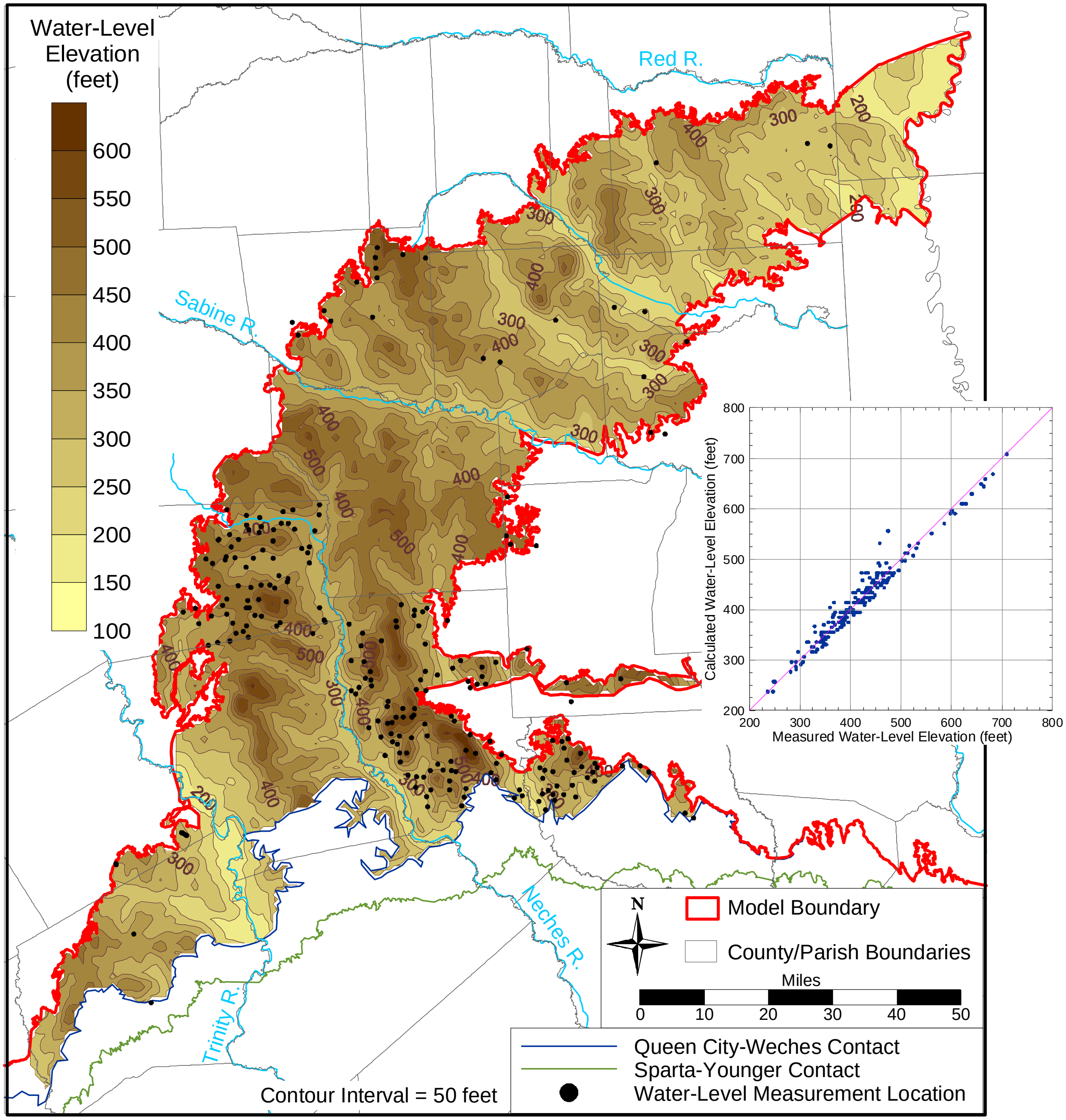

Figure 4.4.5 Estimated water-level elevation contours for predevelopment conditions in the Queen City aquifer in the northern model area with scatter-plot comparison between calculated and measured water-level elevations for the 1936 water-level measurements.

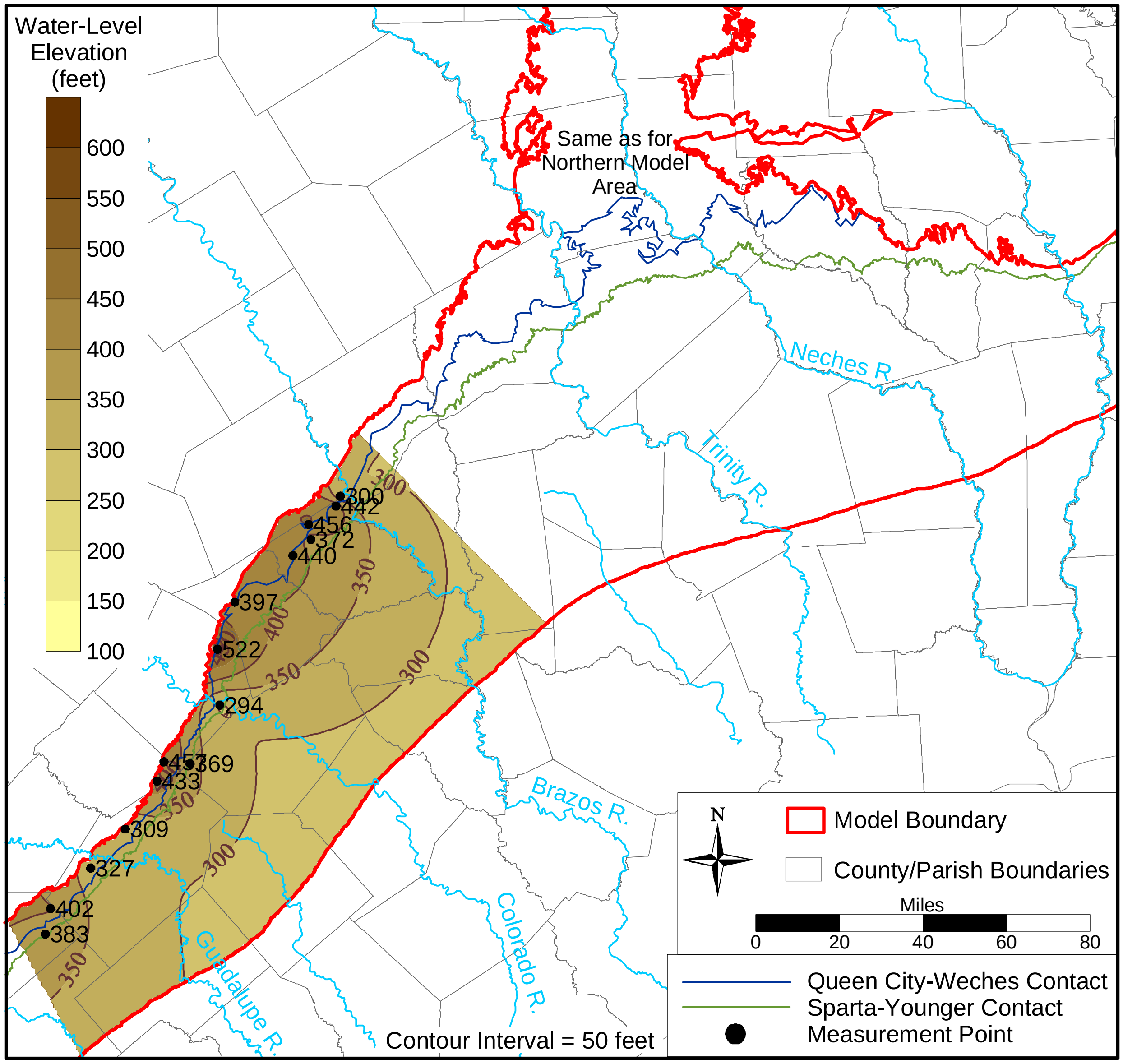

Figure 4.4.6 Estimated water-level elevation contours for predevelopment conditions in the Queen City aquifer in the central model area.

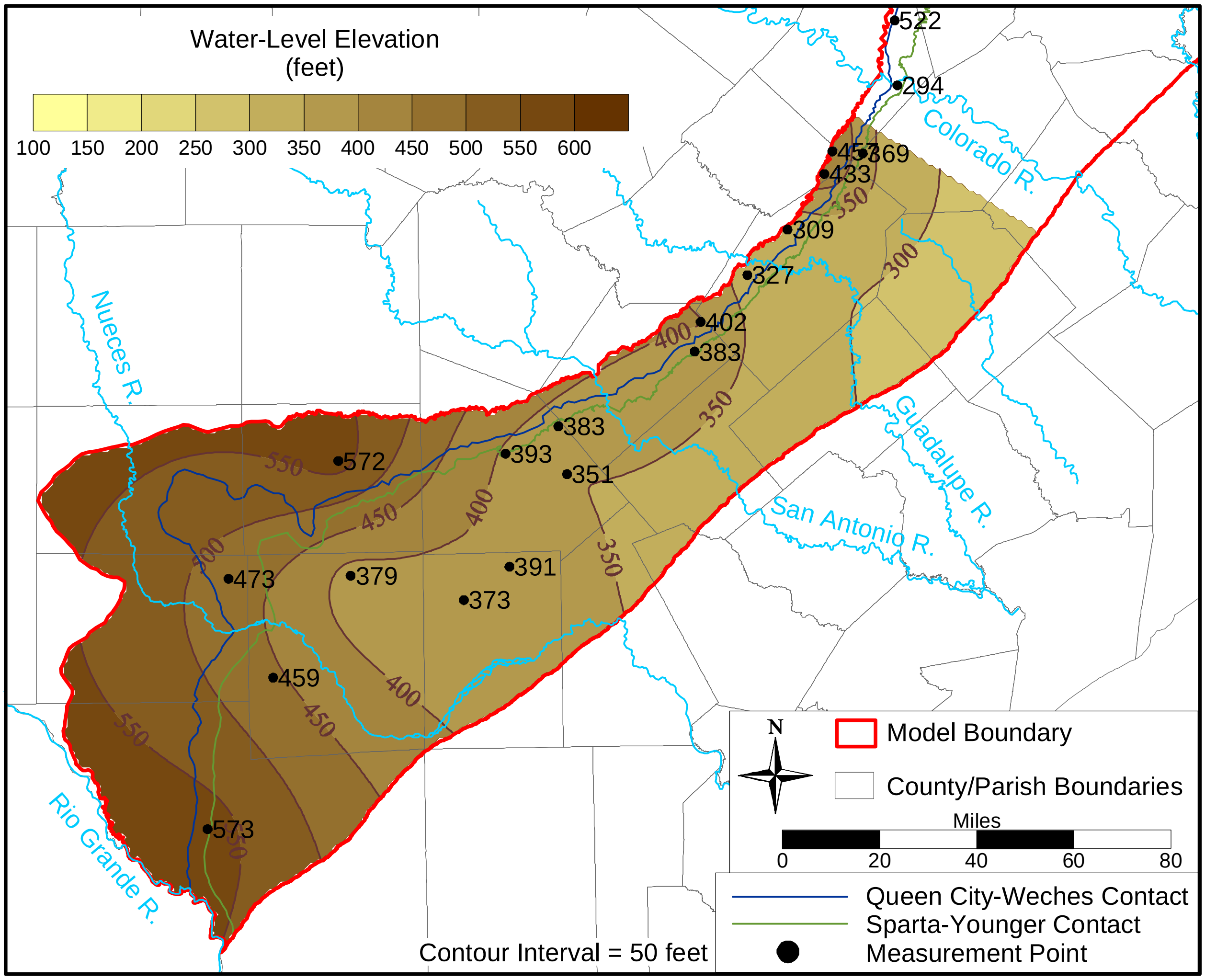

Figure 4.4.7 **Estimated water-level elevation contours for predevelopment conditions in the Queen City aquifer in the southern model area.**

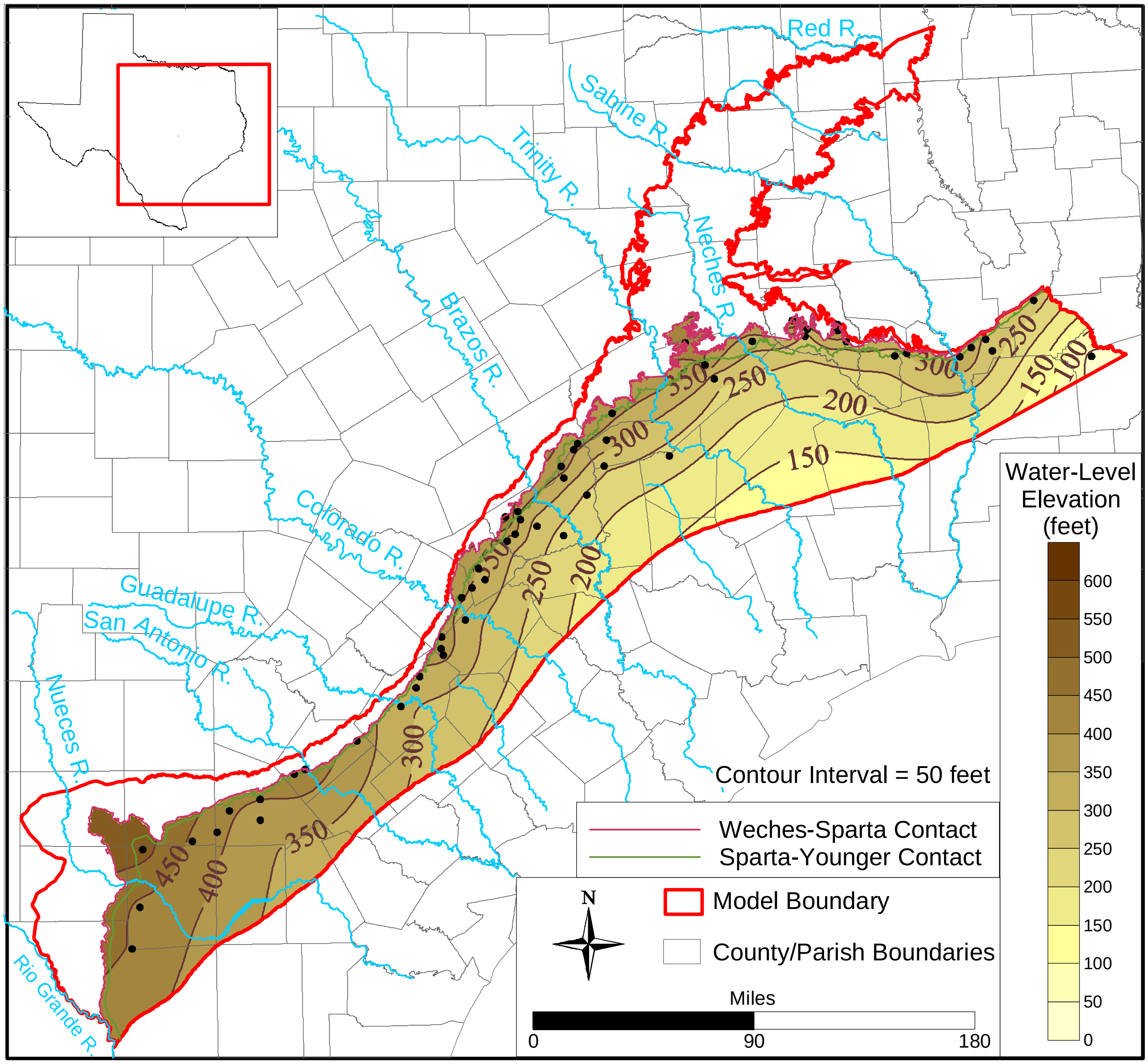

Figure 4.4.8 Estimated water-level elevation contours for predevelopment conditions in the entire Sparta aquifer.

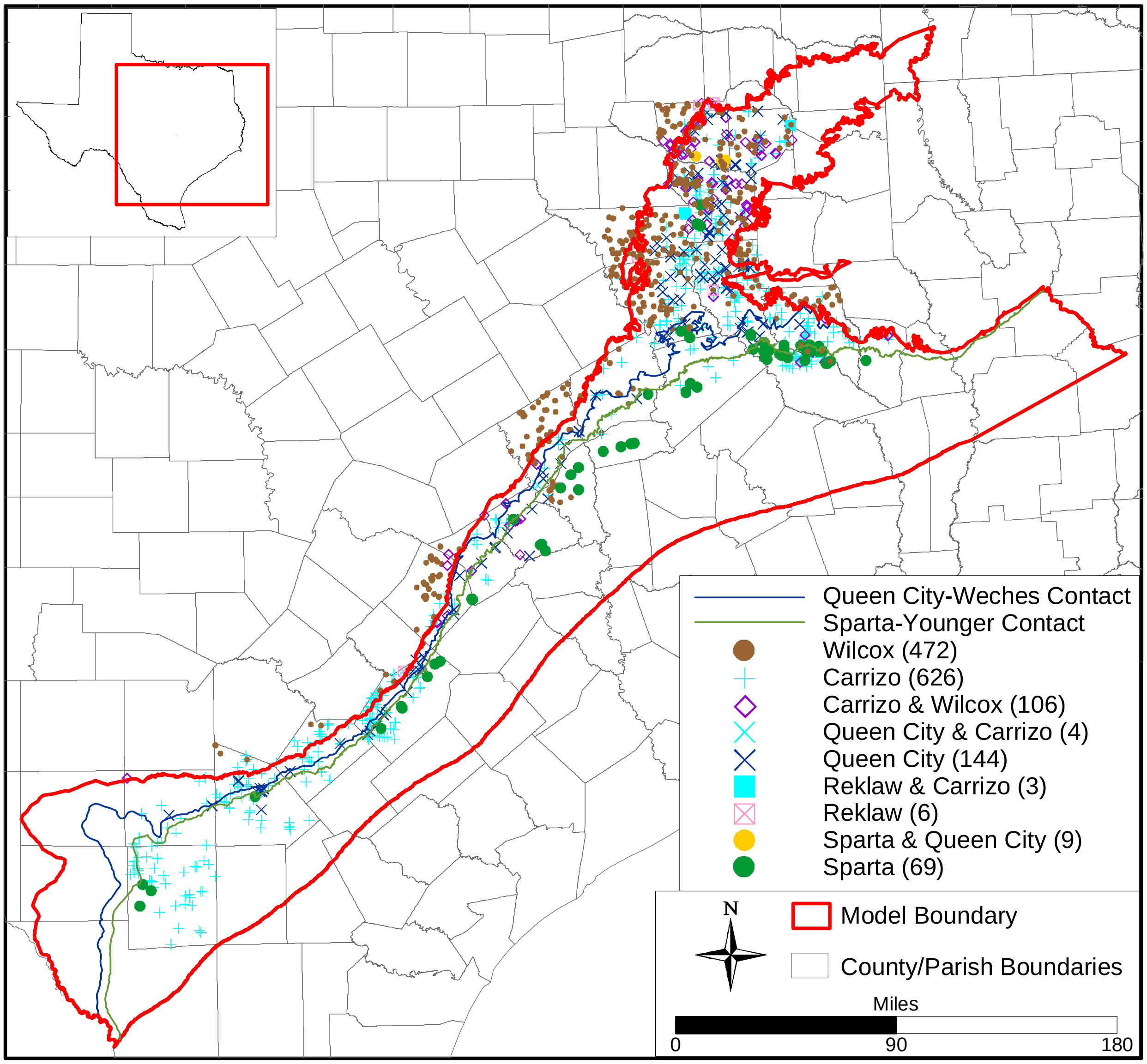

Figure 4.4.9 Water-level measurement locations used for the pressure versus depth analysis.

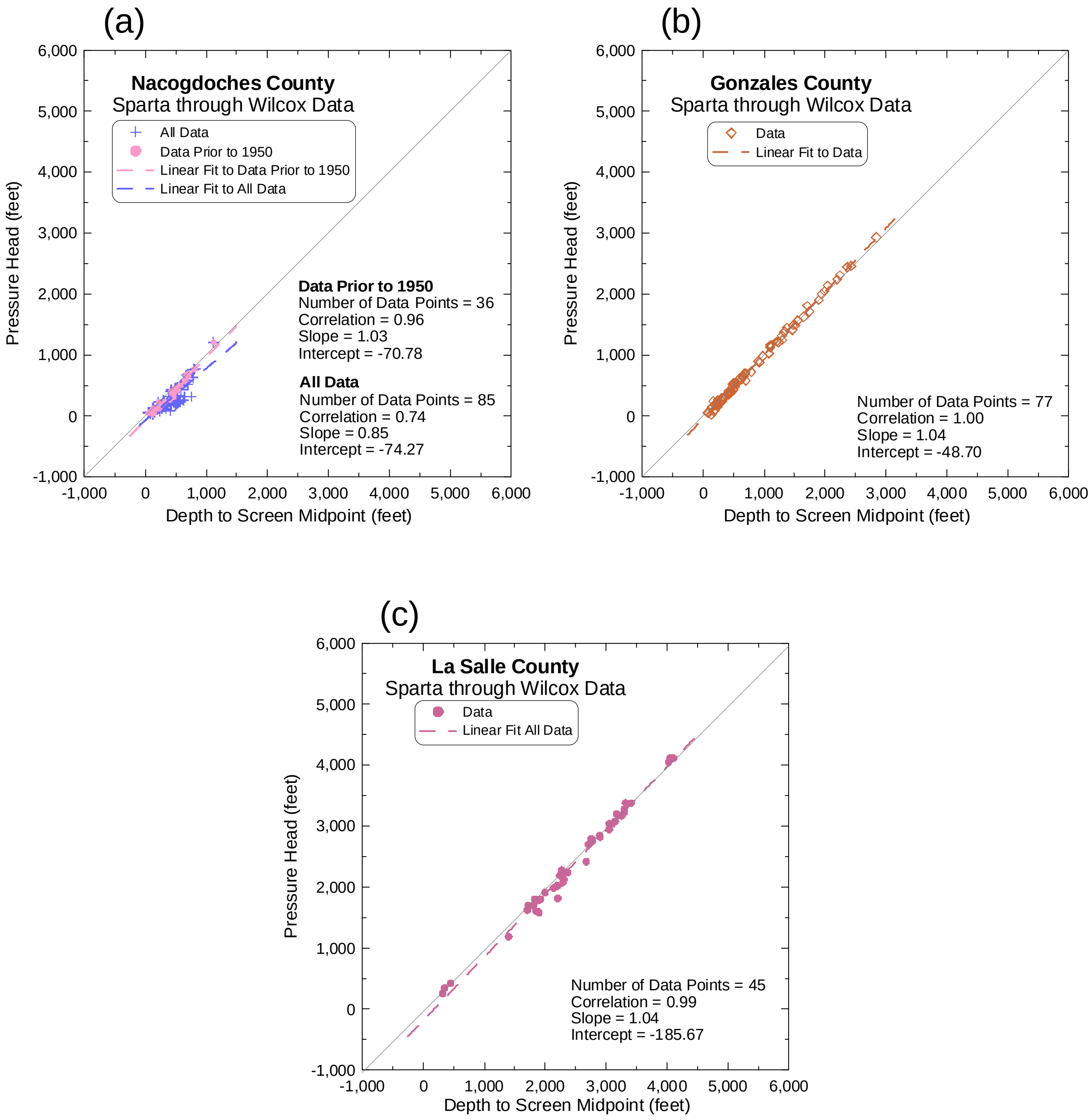

Figure 4.4.10 Example pressure versus depth analysis results for (a) the northern model area, (b) the central model area, and (c) the southern model area.

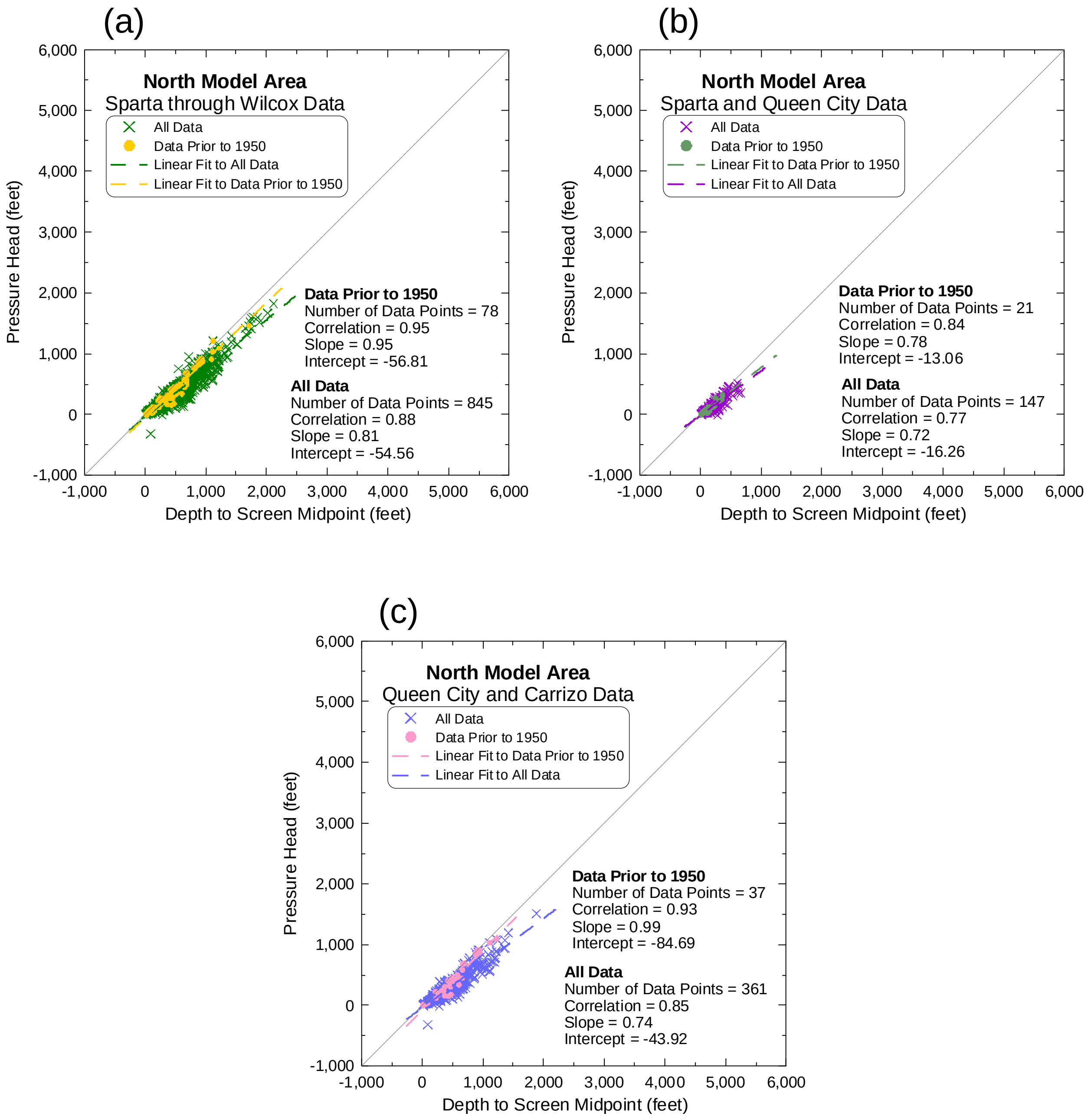

Figure 4.4.11 **Pressure versus depth analysis results for the northern model area considering (a) all hydrostratigraphic units from the Sparta Sand to the Wilcox Group, (b) the Sparta and Queen City aquifers, and (c) the Queen City and Carrizo aquifers.**

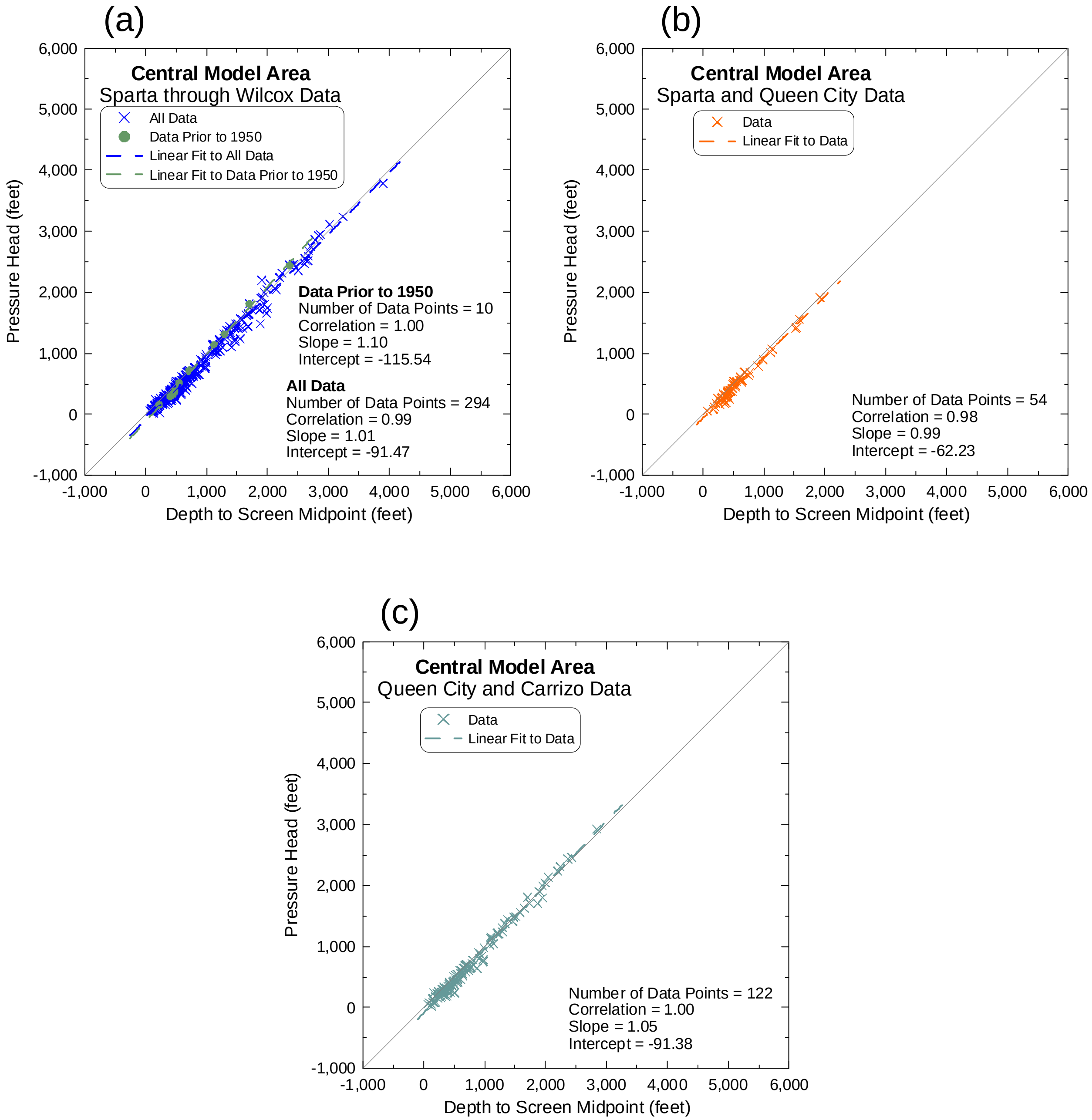

Figure 4.4.12 **Pressure versus depth analysis results for the central model area considering (a) all hydrostratigraphic units from the Sparta Sand to the Wilcox Group, (b) the Sparta and Queen City aquifers, and (c) the Queen City and Carrizo aquifers.**

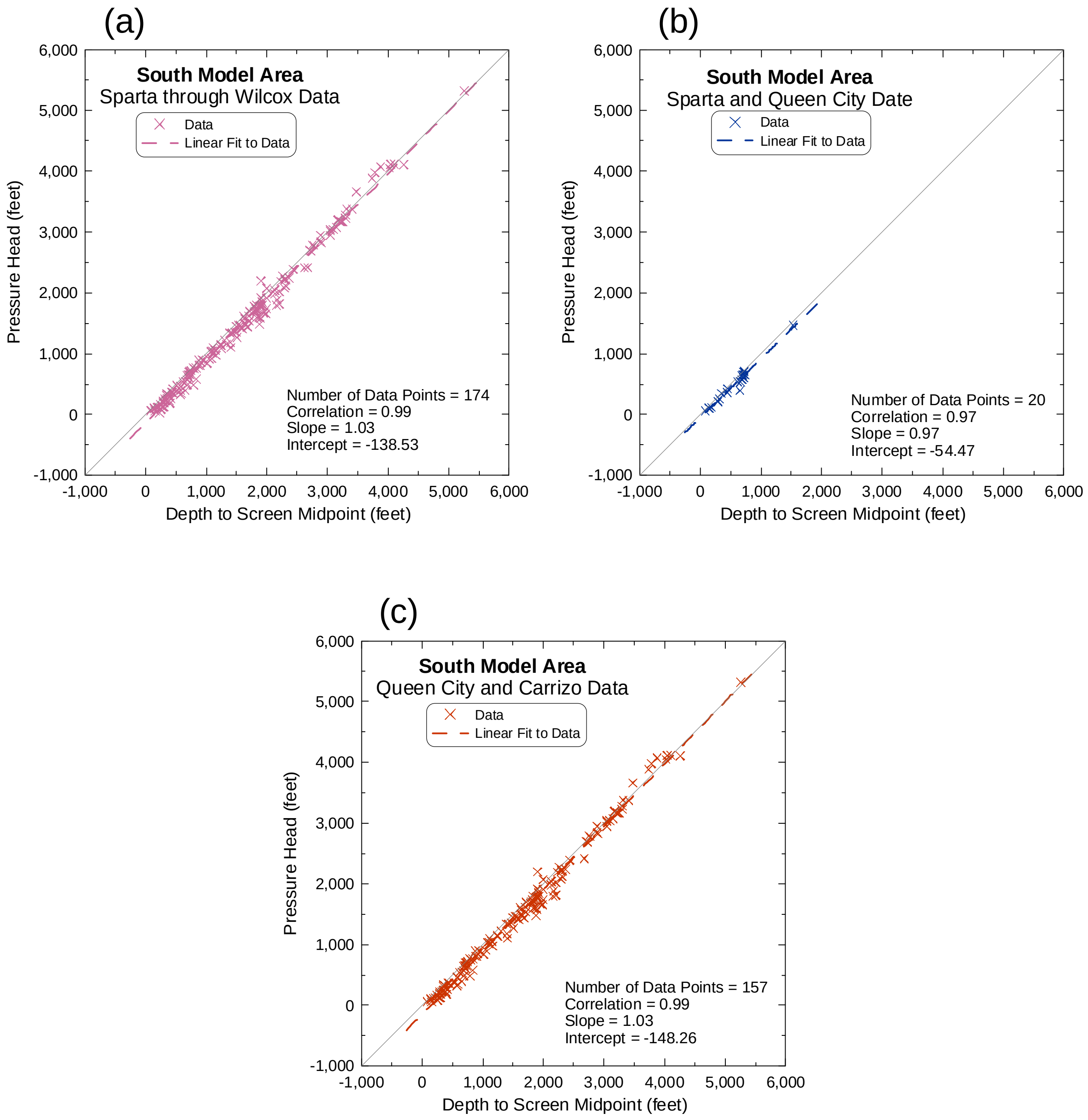

Figure 4.4.13 Pressure versus depth analysis results for the southern model area considering (a) all hydrostratigraphic units from the Sparta Sand to the Wilcox Group, (b) the Sparta and Queen City aquifers, and (c) the Queen City and Carrizo aquifers.

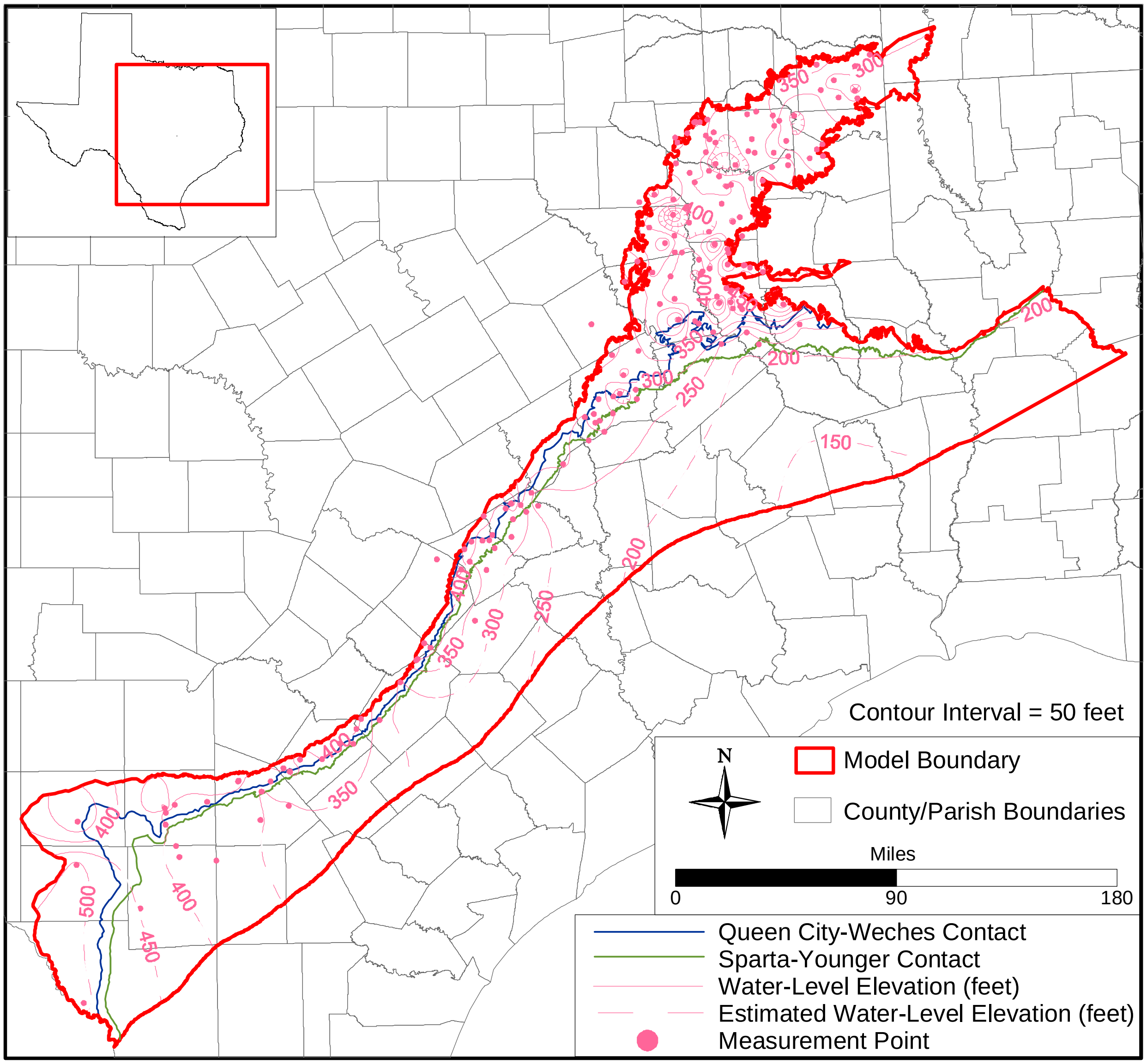

Figure 4.4.14a Water-level elevations contours for the Queen City aquifer at the start of model calibration (January 1980).

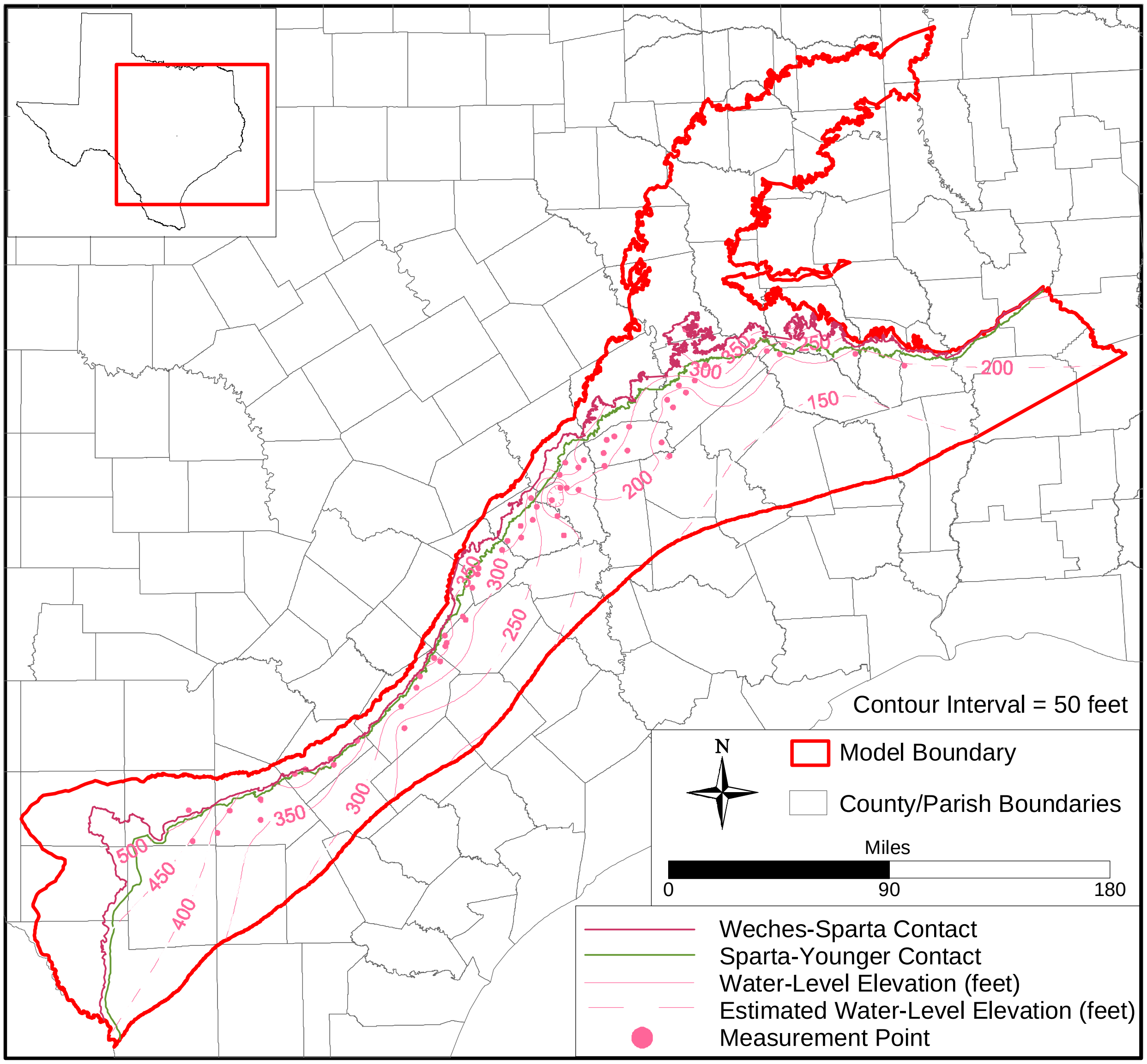

Figure 4.4.14b Water-level elevations contours for the Sparta aquifer at the start of model calibration (January 1980).

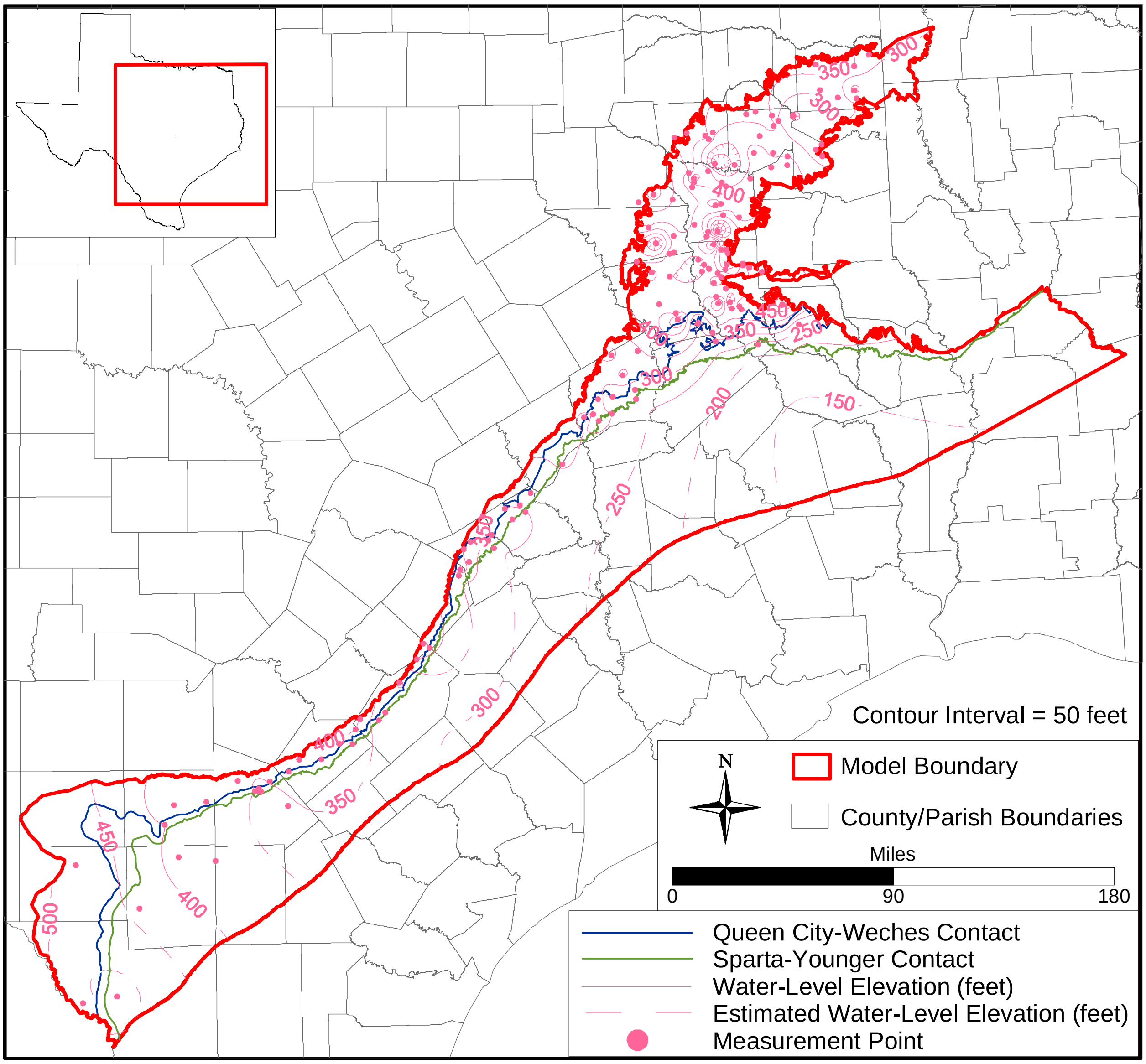

Figure 4.4.15a Water-level elevations contours for the Queen City aquifer at the end of model calibration (December 1989).

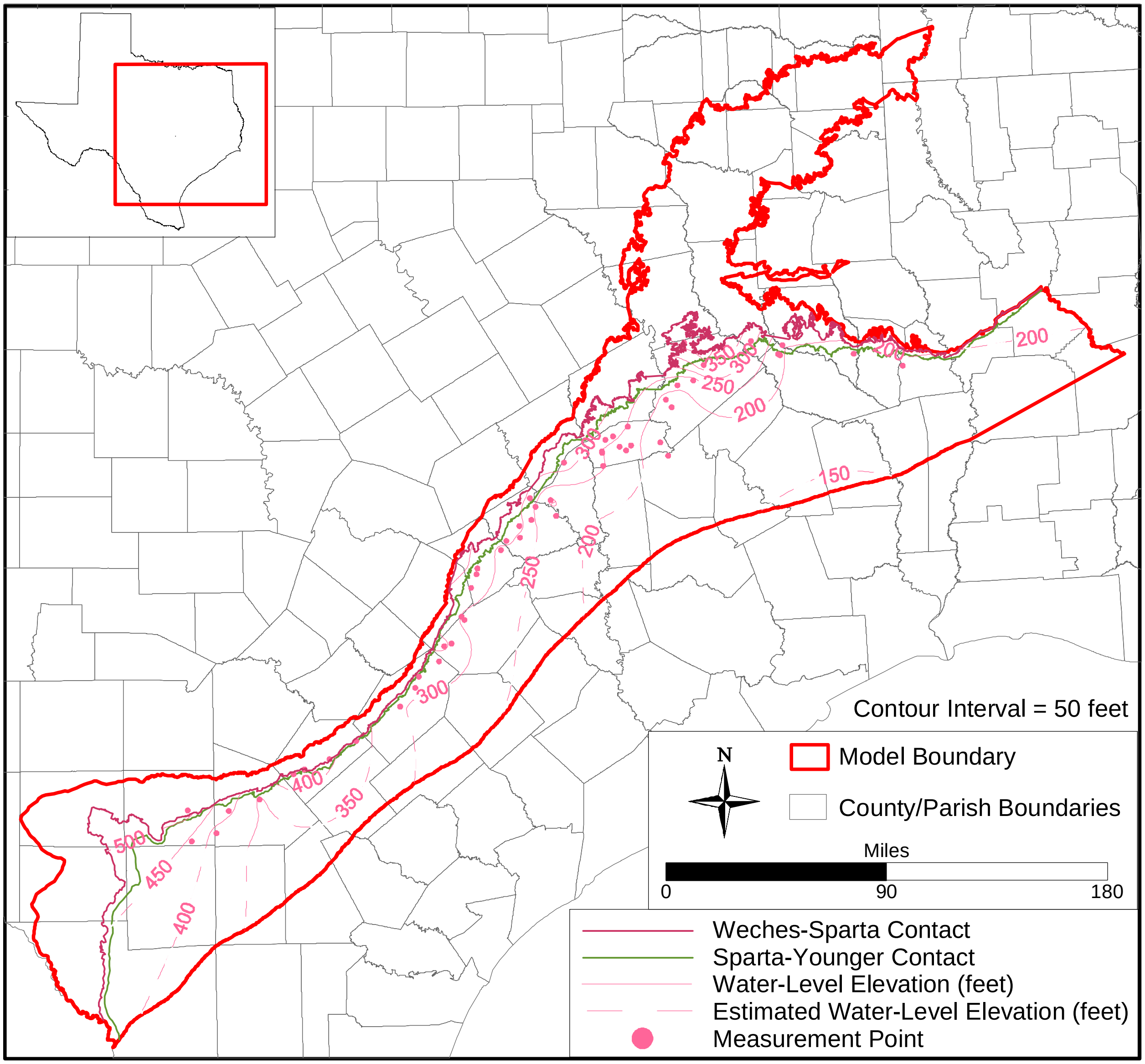

Figure 4.4.15b Water-level elevations contours for the Sparta aquifer at the end of model calibration (December 1989).

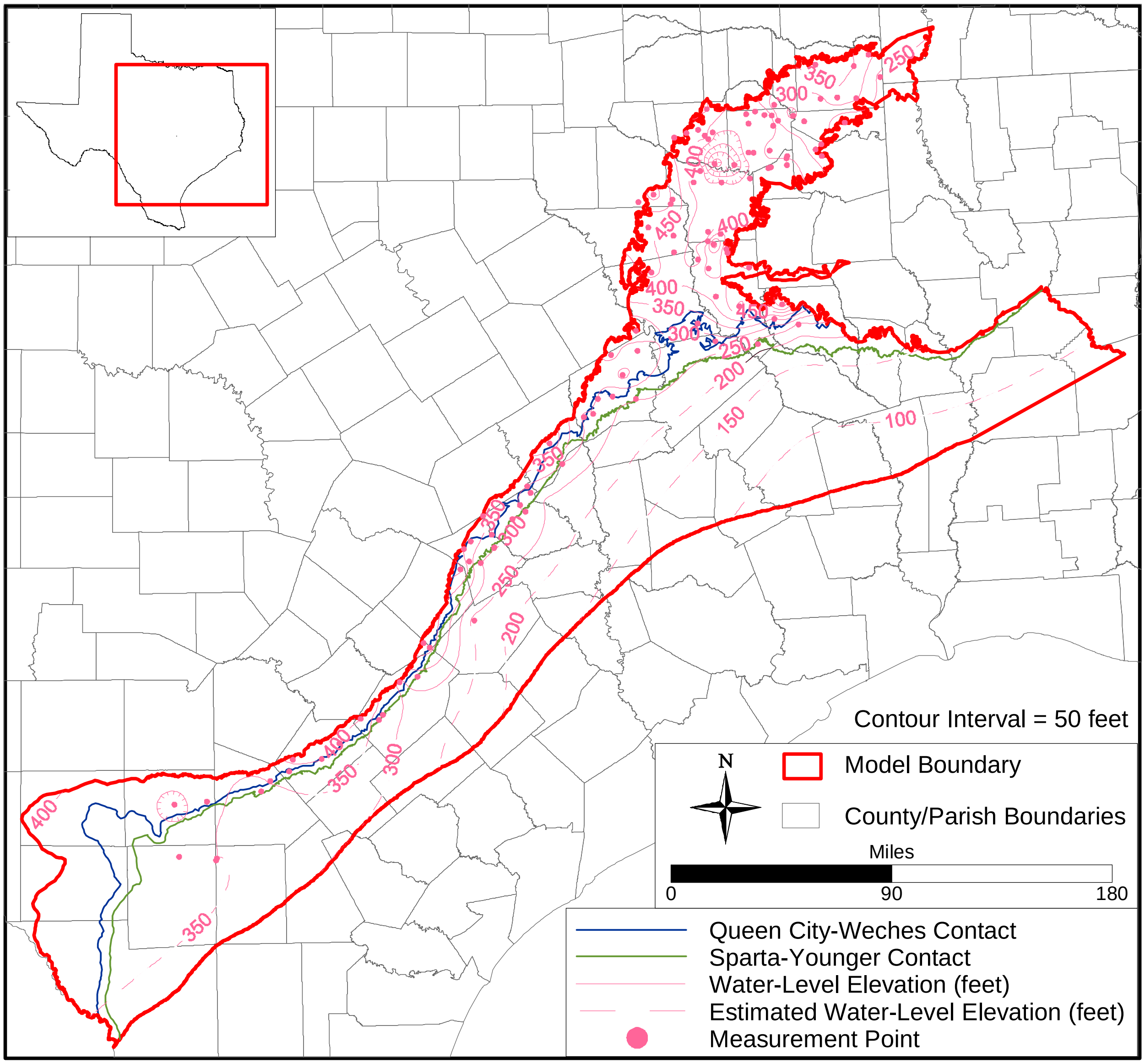

Figure 4.4.16a Water-level elevations contours for the Queen City aquifer at the end of model verification (December 1999).

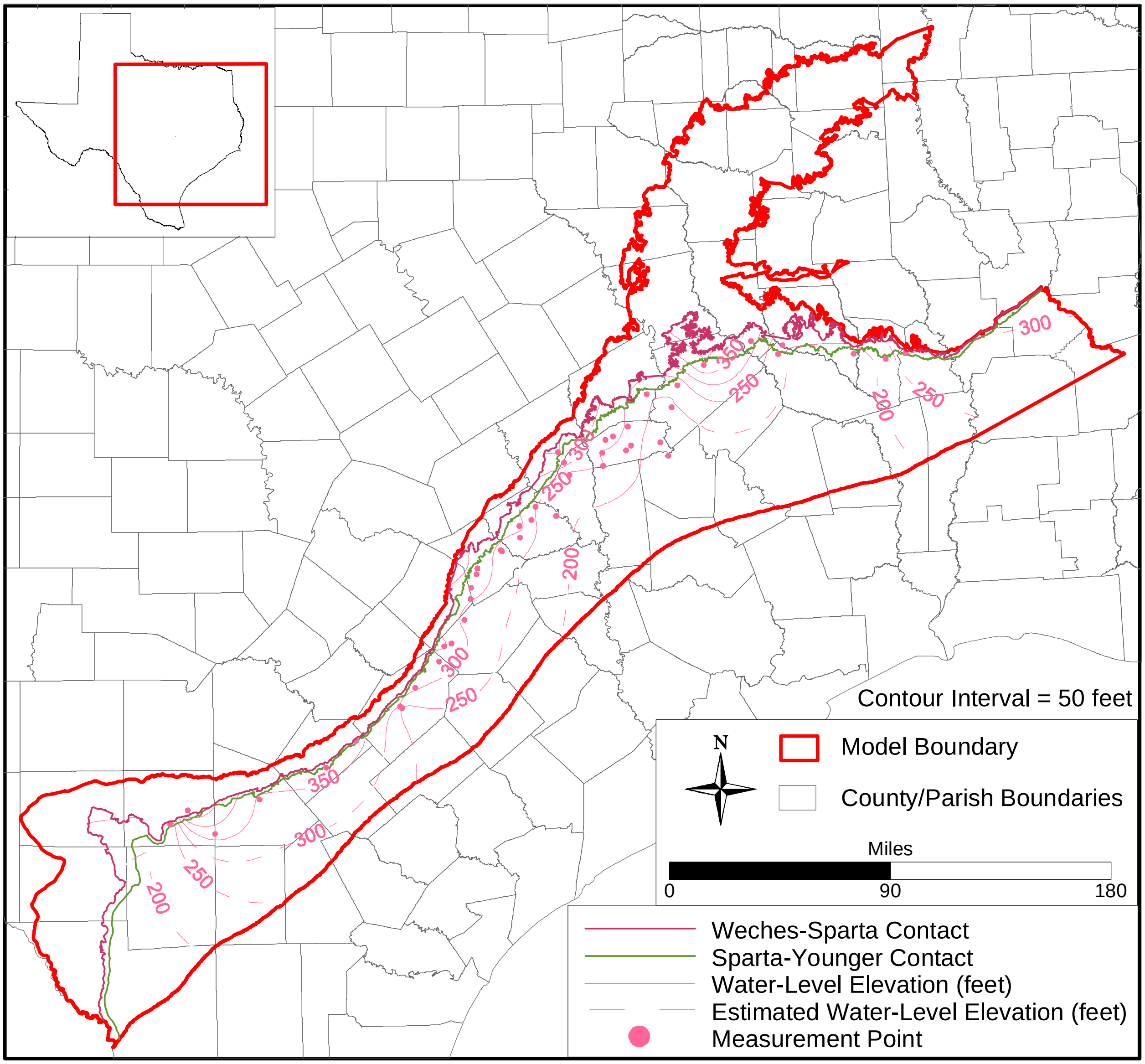

Figure 4.4.16b Water-level elevations contours for the Sparta aquifer at the end of model verification (December 1999).

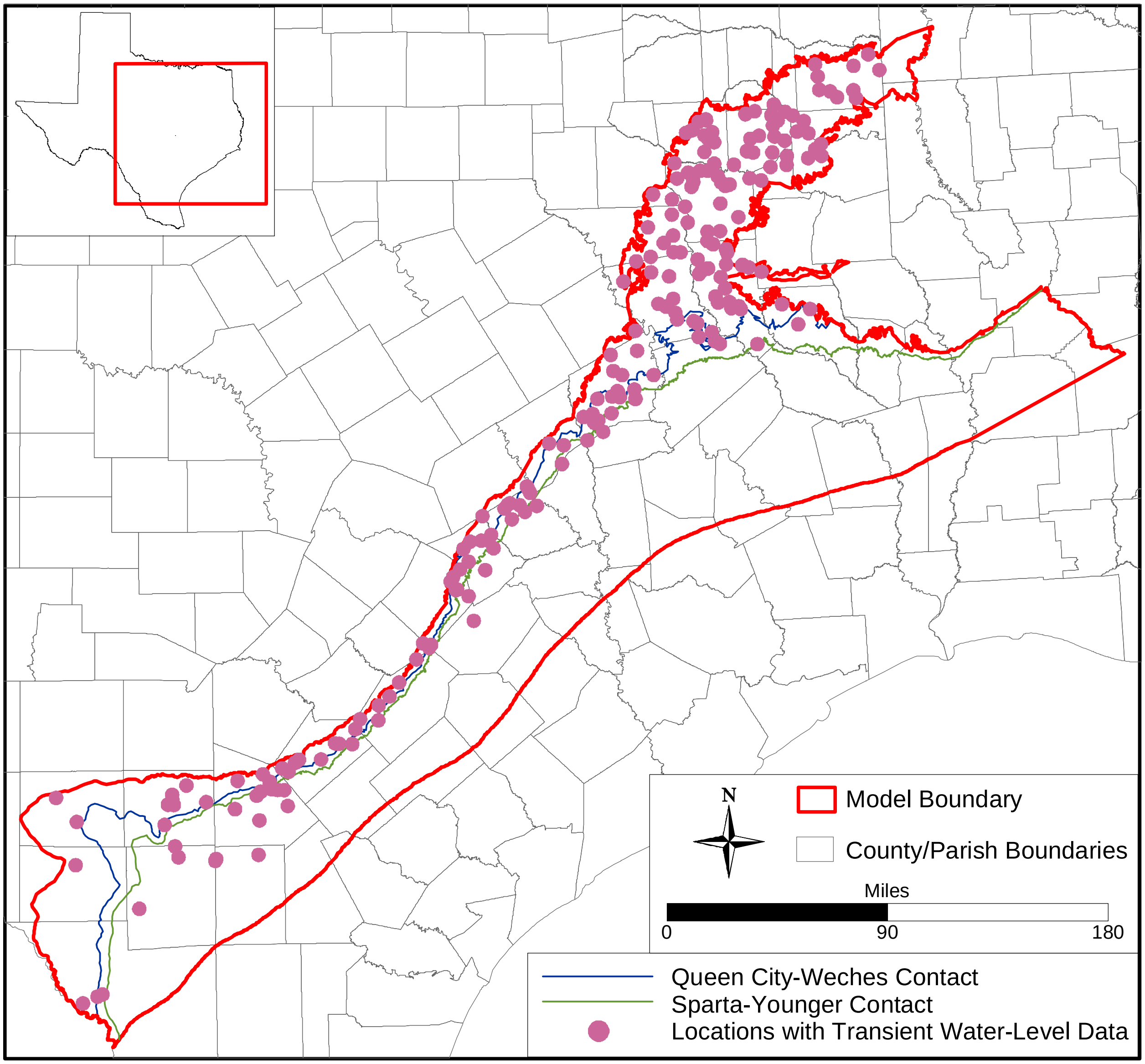

Figure 4.4.17a Locations with transient water-level data in the Queen City aquifer.

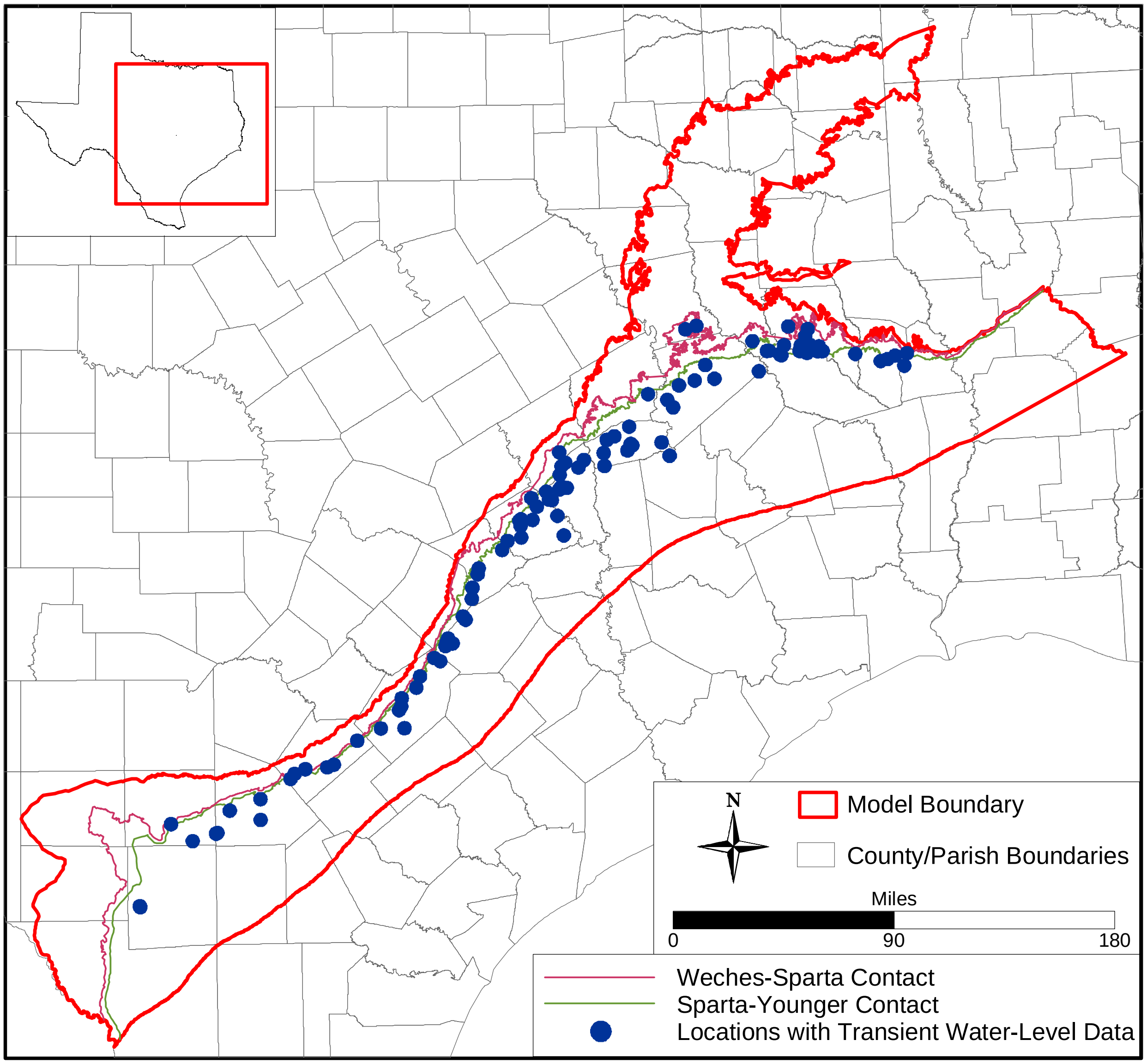

Figure 4.4.17b Locations with transient water-level data in the Sparta aquifer.

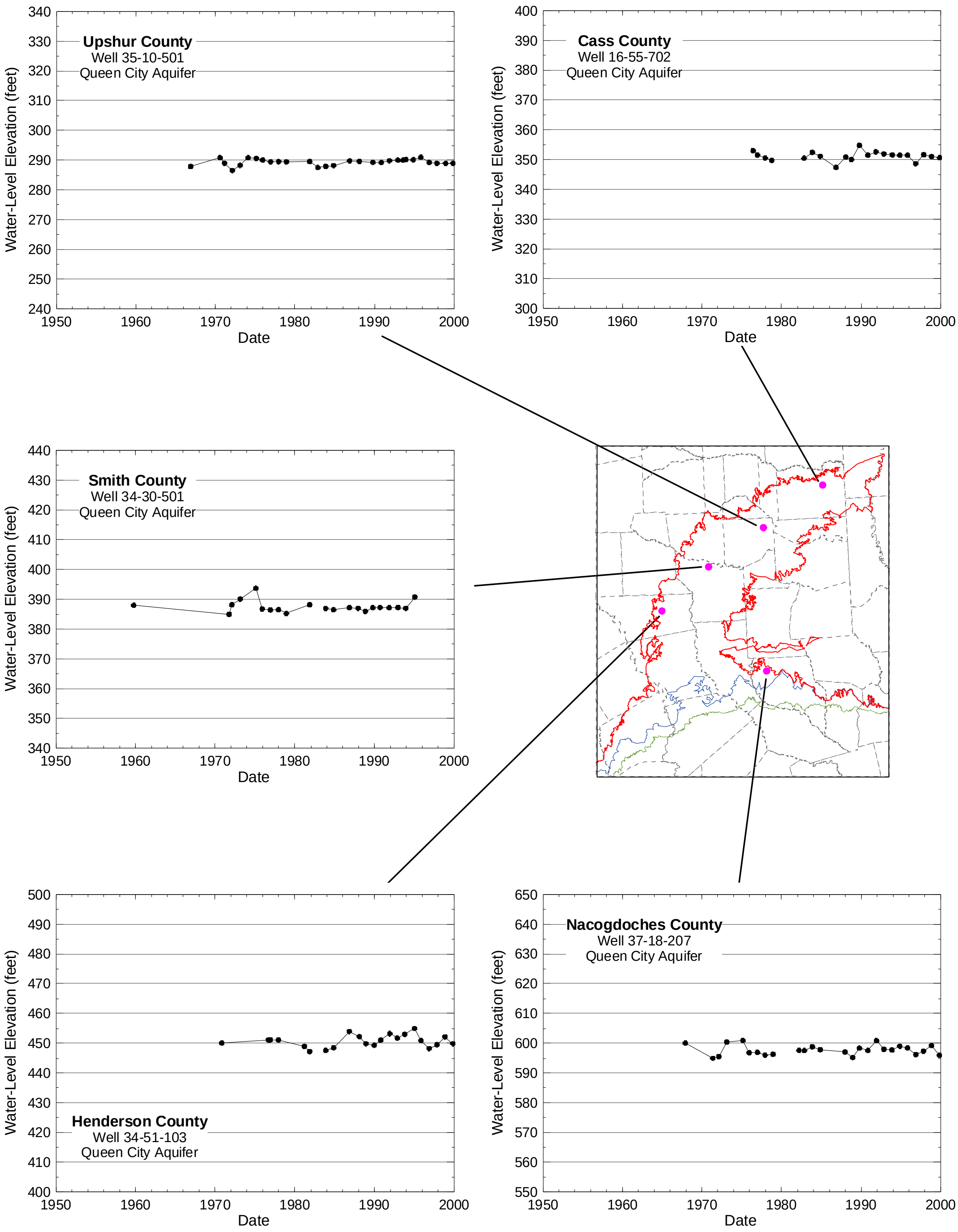

Figure 4.4.18 Example hydrographs for Queen City wells in the northern model area showing stable water-level elevations with time.

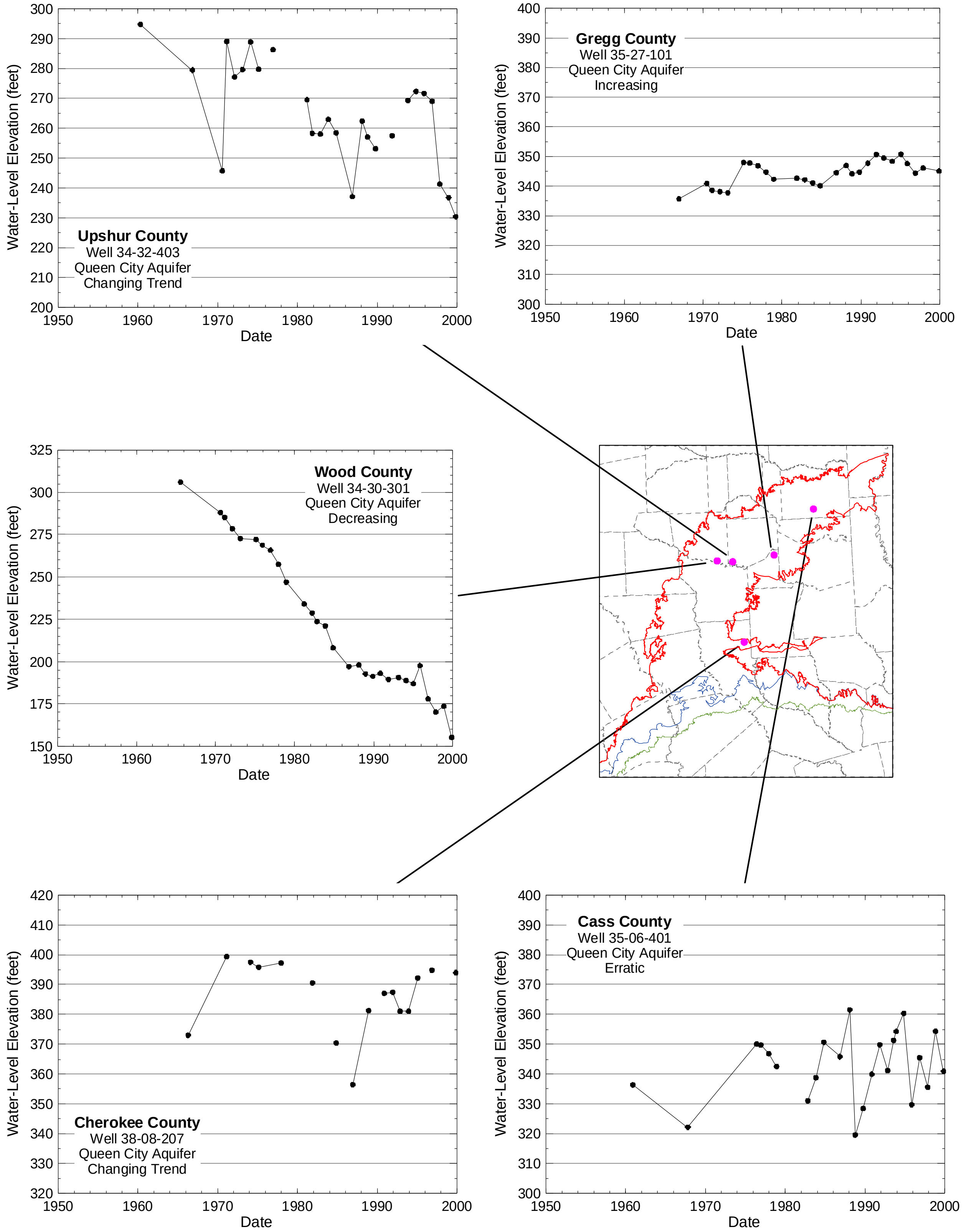

Figure 4.4.19 Examples hydrographs for Queen City wells in the northern model area showing changing water-level elevations with time.

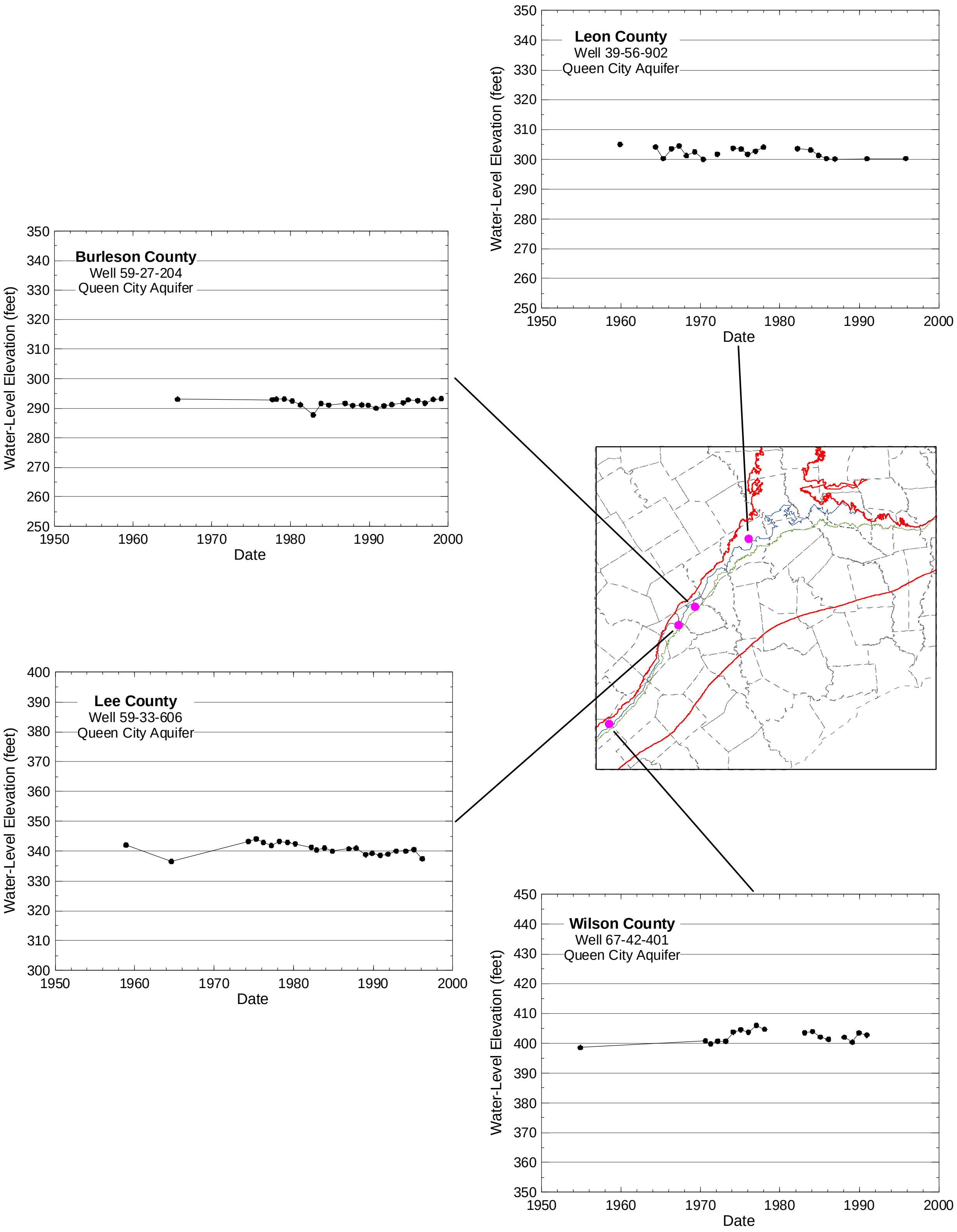

Figure 4.4.20 Example hydrographs for Queen City wells in the central model area showing stable water-level elevations with time.

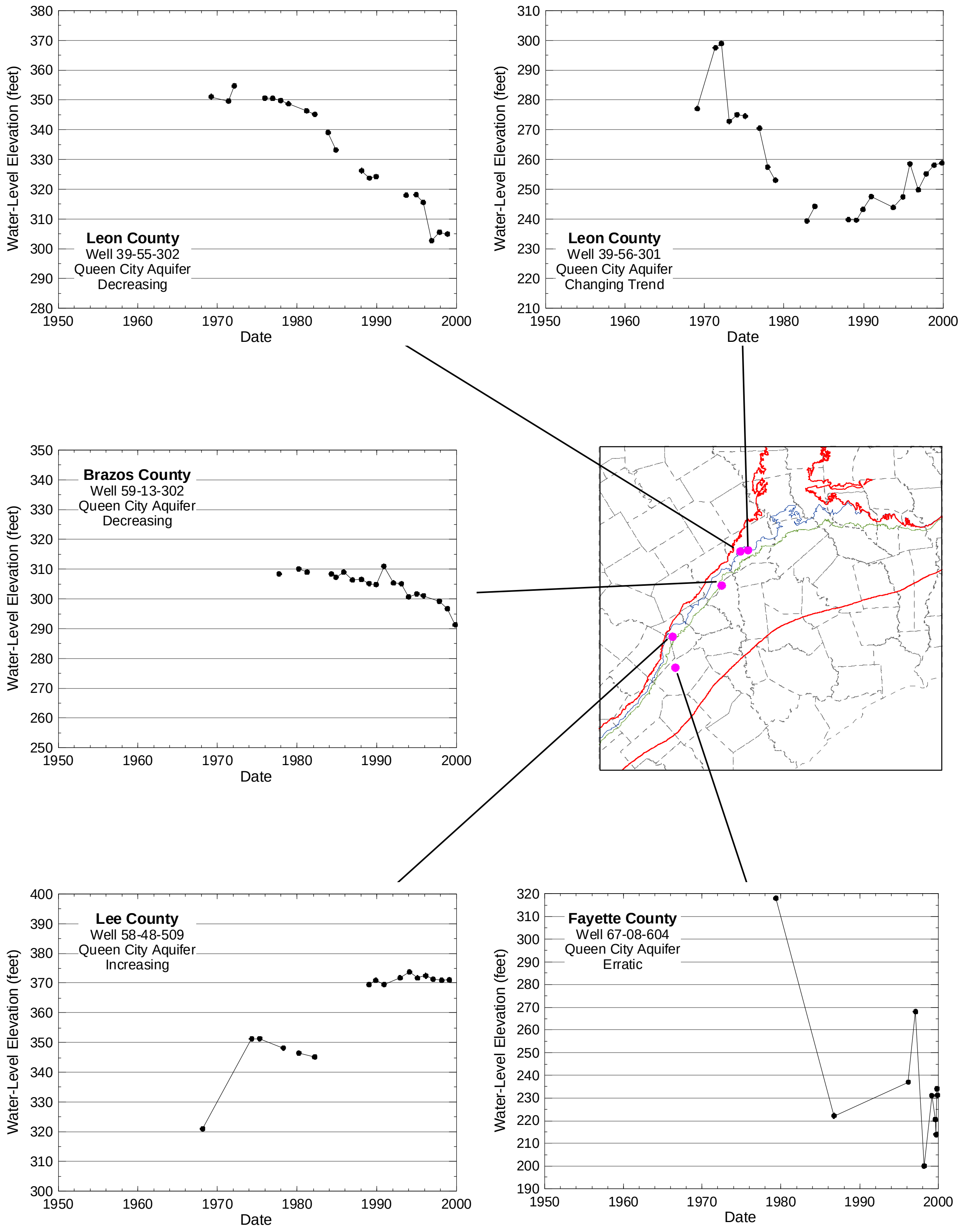

Figure 4.4.21 Examples hydrographs for Queen City wells in the central model area showing changing water-level elevations with time.

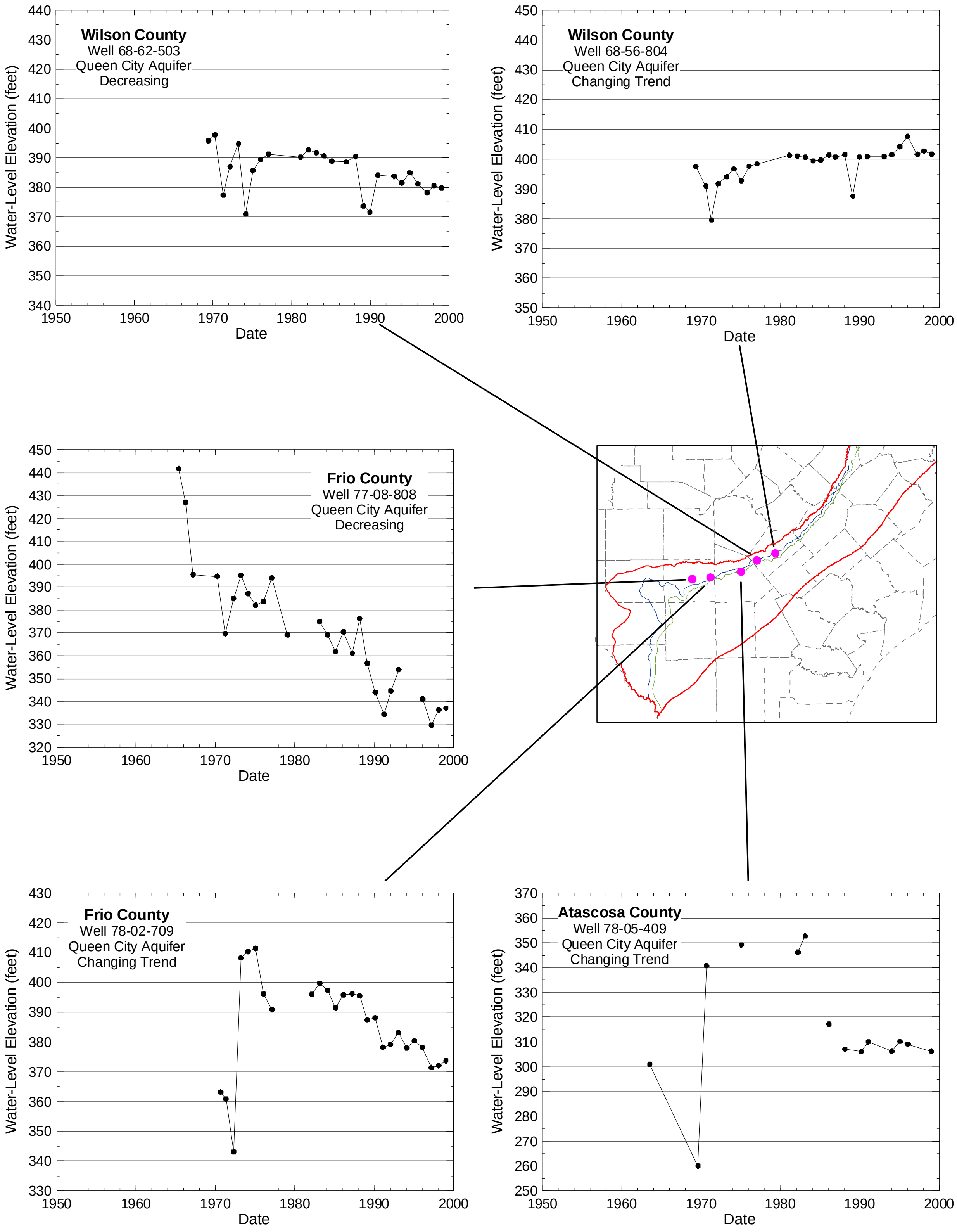

Figure 4.4.22 Example hydrographs for Queen City wells in the southern model area.

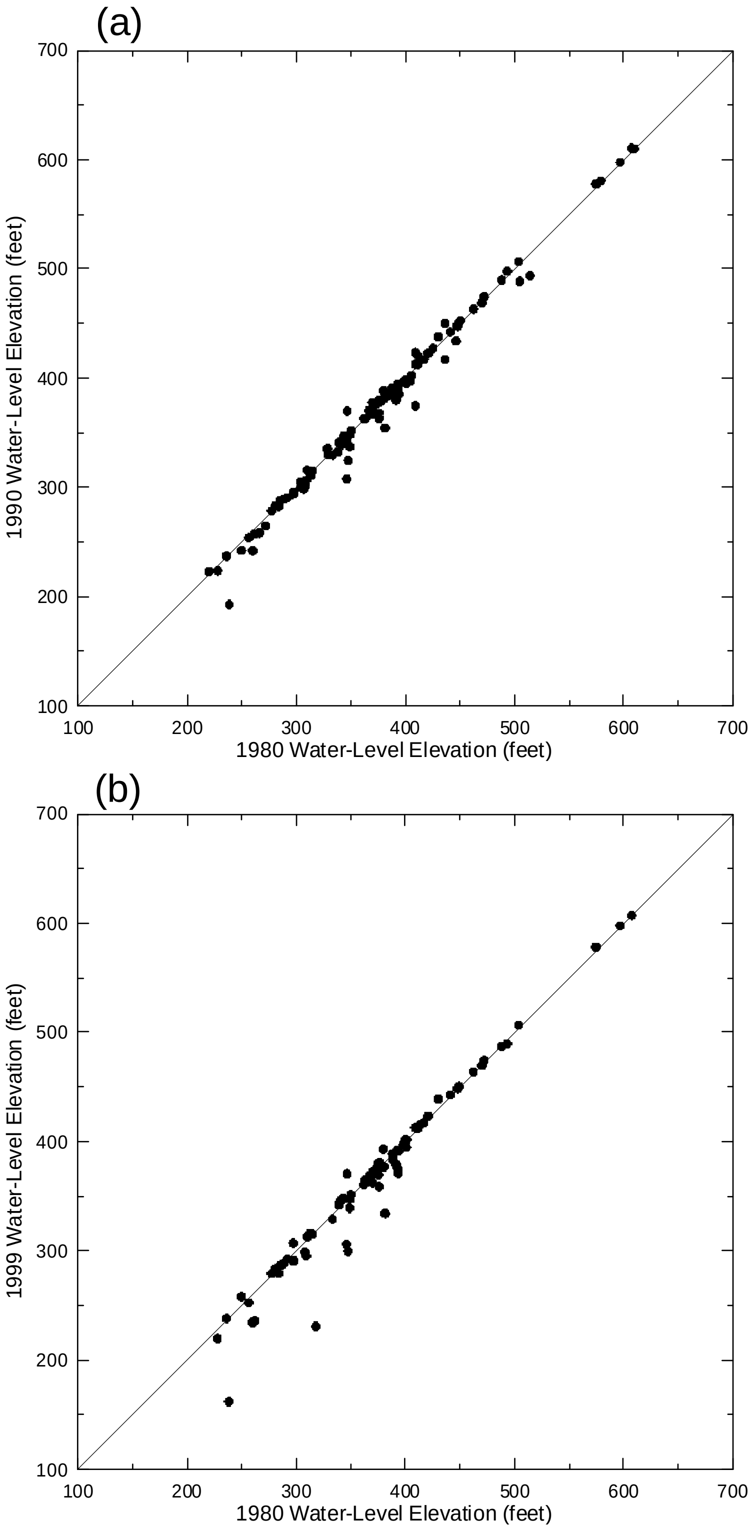

Figure 4.4.23 **Water-level change in the Queen City aquifer (a) from the start of model calibration (January 1980) to the end of model calibration (December 1989) and (b) from the start of model calibration (January 1980) to the end of model verification (December 1999).**

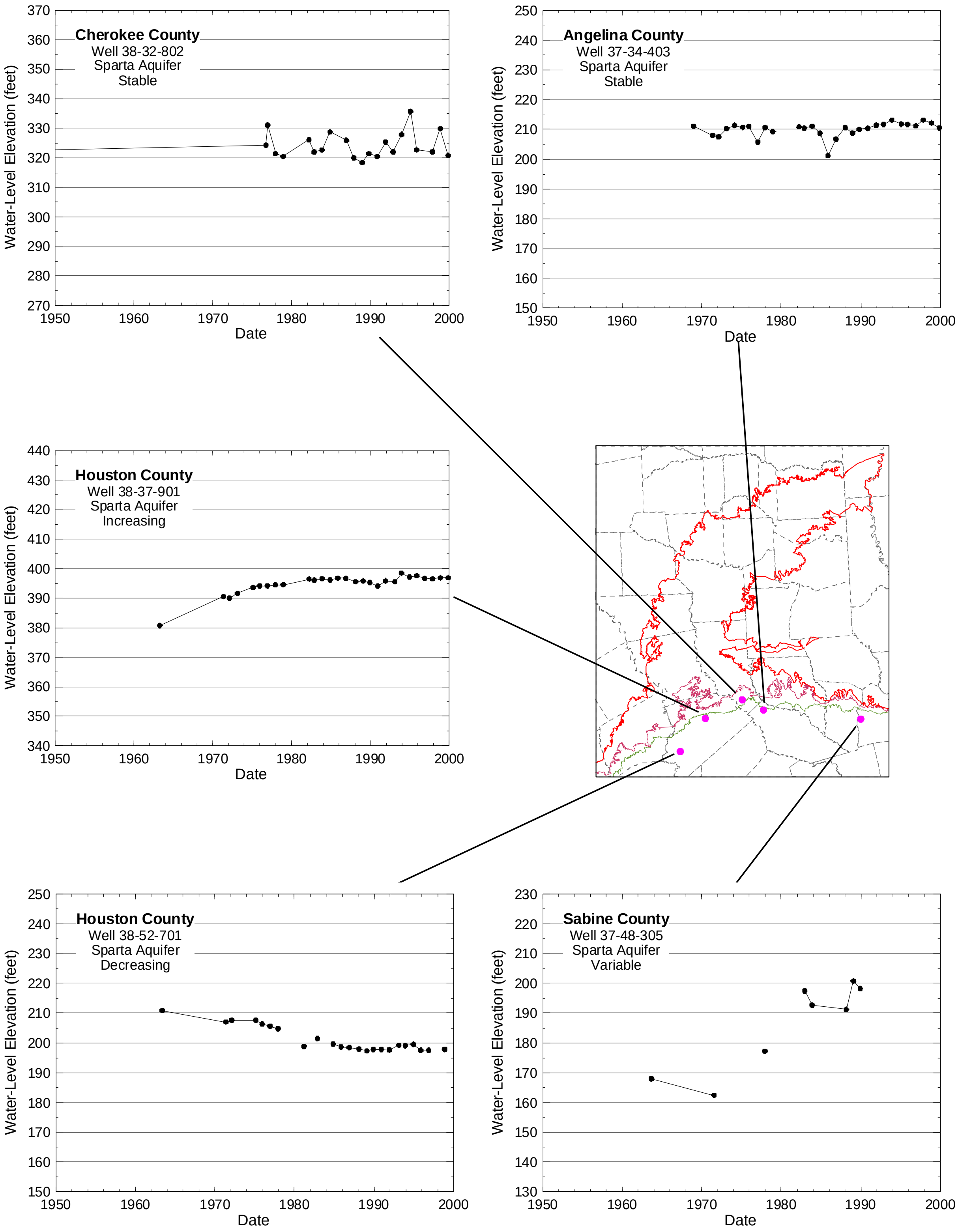

Figure 4.4.24 Example hydrographs for Sparta wells in the northern model area.

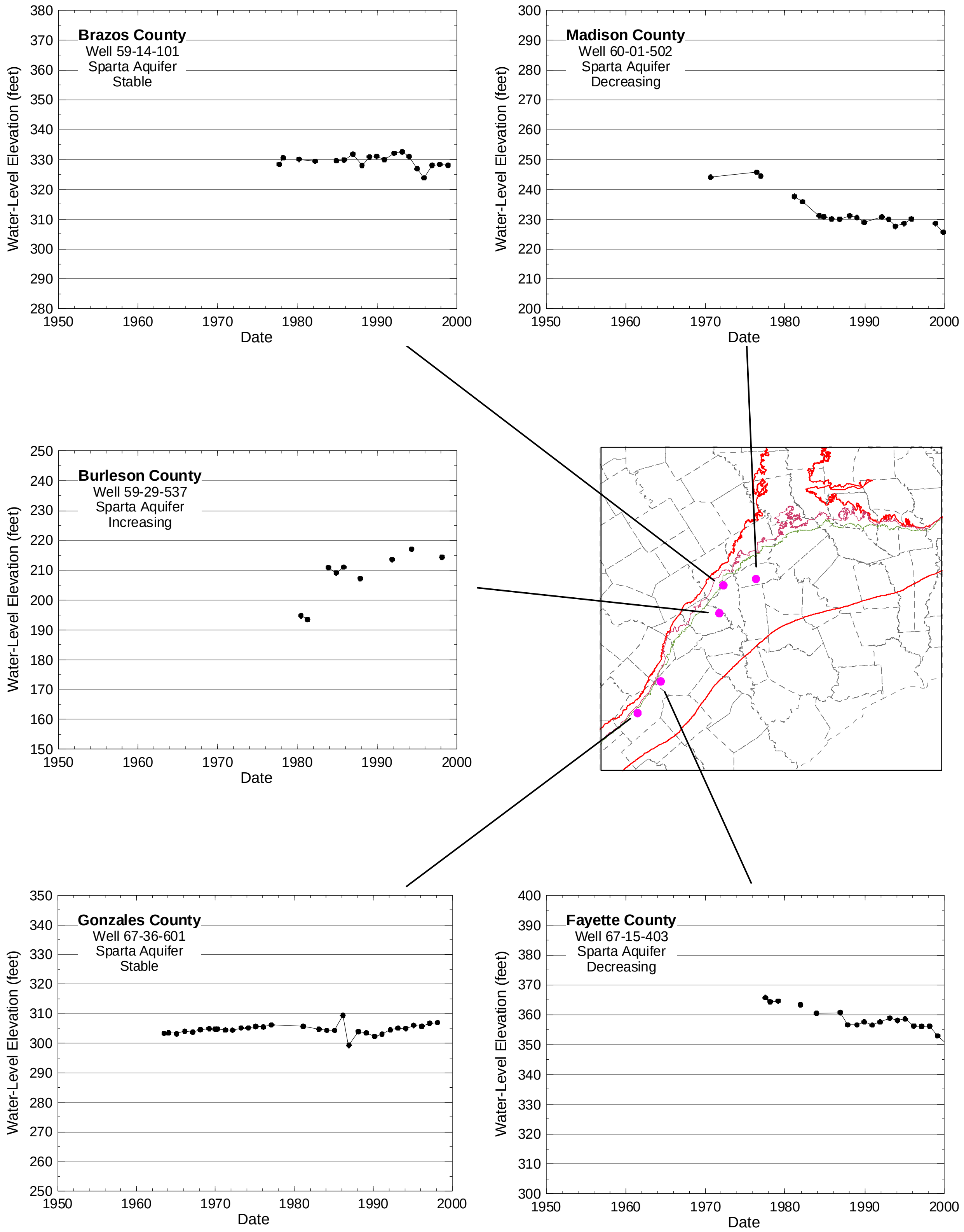

Figure 4.4.25 Example hydrographs for Sparta wells in the central model area showing small changes in water-level elevation with time.

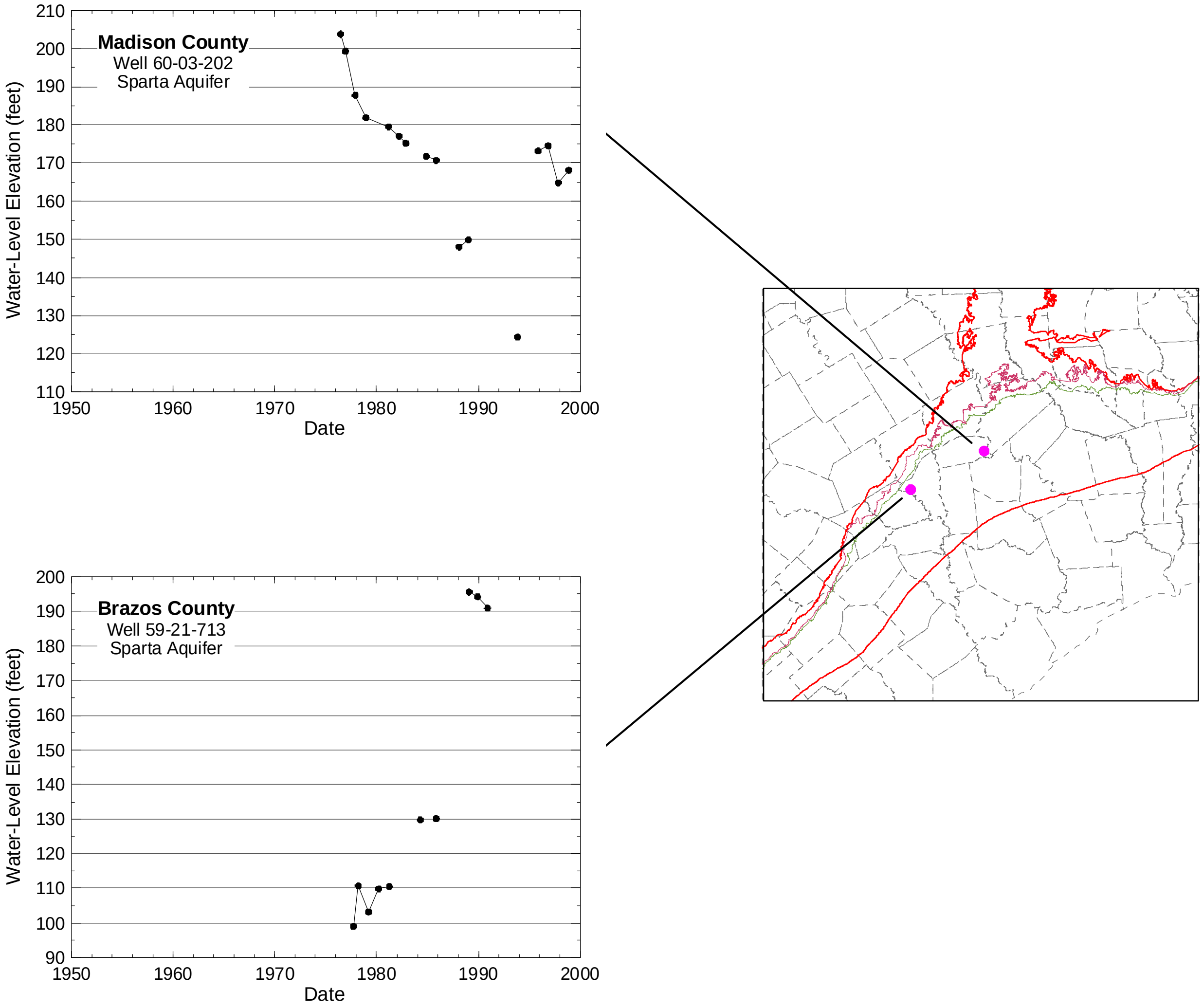

Figure 4.4.26 **Example hydrographs for Sparta wells in the central model area showing large changes in water-level elevation with time.**

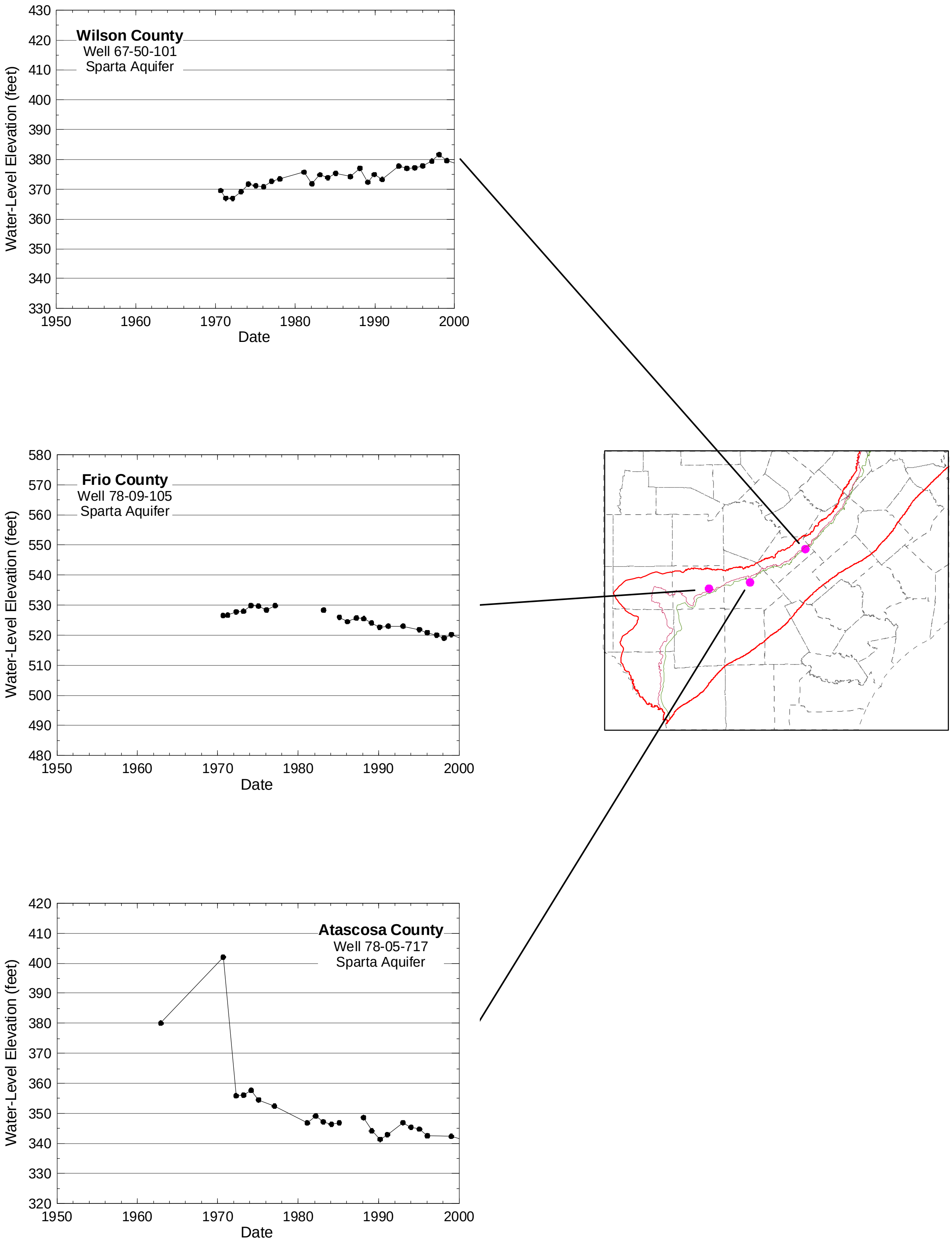

Figure 4.4.27 Example hydrographs for Sparta wells in the southern model area.

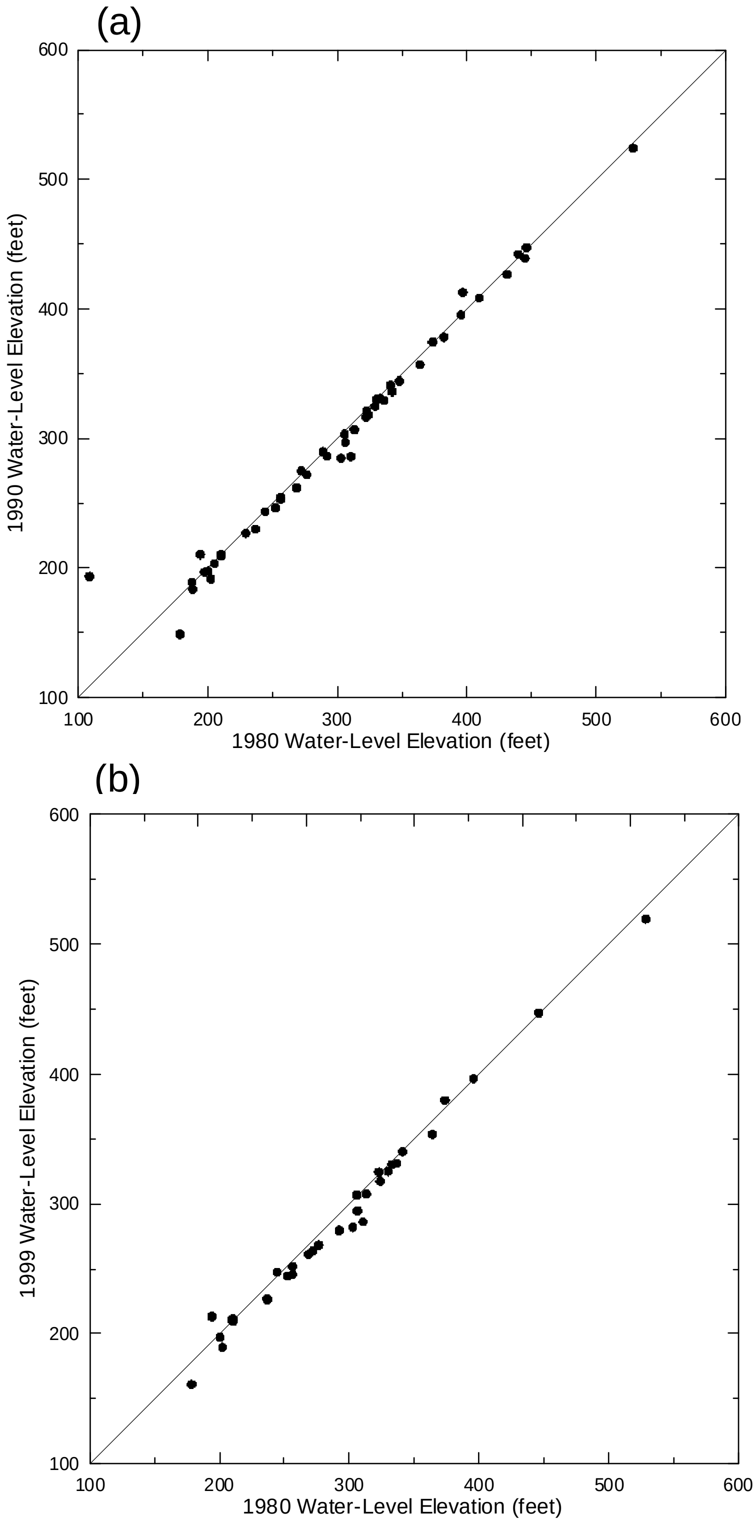

Figure 4.4.28 **Water-level change in the Sparta aquifer (a) from the start of model calibration (January 1980) to the end of model calibration (December 1989) and (b) from the start of model calibration (January 1980) to the end of model verification (December 1999).**

4.5 Water Quality

4.5.1 Previous Studies

Local variations in groundwater quality are summarized in a number of county-wide assessments of groundwater resources (Anders, 1957, 1960; Mason, 1960; Anders and Baker, 1961; Dillard, 1963; Harris, 1965; Peckham, 1965; Shafer, 1965; Alexander and White, 1966; Follett, 1966, 1970, 1974; Tarver, 1966; Thompson, 1966; Rogers, 1967; Broom, 1968, 1969, 1971; Guyton and Associates, 1970, 1972; White, 1973; Baker et al., 1974; McCoy, 1991; Beynon, 1992). Most report few water-quality problems in the Queen City or Sparta aquifers; a common complaint (including but not limited to Anderson, Bastrop, Brazos, Burleson, Caldwell, Cass, Cherokee, Gregg, Lee, Leon, Live Oak, Marion, Smith, Upshur, and Wood counties) is high iron concentration. Brown (1997) and Biri (1997) summarized regional water-quality trends in the Queen City and Sparta aquifers, respectively. They showed that there is a regional increase in salinity from north to south in both aquifers. In the downdip, confined part of the aquifers, sodium concentration tends to be elevated and there can be a sodium hazard for irrigation water.

Foster (1950) described major controls on chemical evolution of groundwater in typical aquifers beneath the Gulf Coastal Plain. Payne (1968) defined three provinces of water types in the Sparta aquifer in Texas: bicarbonate type in the northern part of the aquifer, sulfate type in the southern part, and a chloride type downdip in the aquifer. Payne (1968) also mapped total dissolved solids (TDS) between 200 and 10,000 mg/L using geophysical logs and found an inverse relation between sand thickness and TDS—thin beds have higher TDS and were thought to be less completely flushed. Grossman et al. (1986) and Zhang et al. (1998) demonstrated that subsurface bacteria in the Sparta aquifer have a significant geochemical effect on dissolved bicarbonate, sulfate, and methane concentrations. Based on these and other studies, the predominant processes common to the Queen City and Sparta aquifers and other Gulf Coastal Plain aquifers include:

1. incongruent solution of minerals including reaction of water with detrital rock fragments and feldspar in the unsaturated zone (Dutton, 1990) and in the unconfined aquifer to form dilute solutions (TDS ≤300 mg/L);

2. ionic exchange with dissolved calcium exchanging with sodium adsorbed on clay minerals, resulting in increasing ratio of sodium/calcium downdip in each aquifer;
3. bacterially mediated oxidation of dissolved or solid organic carbon and of methane, which raises the bicarbonate concentration in groundwater; and
4. diffusion of chloride-rich (brackish to slightly saline) water from clayey deposits into the more productive beds of the aquifer.

Downdip of the aquifer, that is, below the base of potable water in the Queen City and Sparta aquifers, the Claiborne Group has salty formation water (Payne, 1968) and hosts oil and gas fields (Guevara and Garcia, 1972; Ricoy and Brown, 1977). The chemical composition of Claiborne Group formation waters may be similar to that of other formation waters in the Gulf Coast Cenozoic section (Morton and Land, 1987; Land and Macpherson, 1992). Land and Macpherson (1992) defined three typical water types for the Cenozoic saline section beneath the Texas Coastal Plain: sodium-acetate, sodium-chloride, and calcium-chloride waters. The sodium-chloride water originated from dissolution of halite by groundwater whereas the sodium-acetate water derived from seawater by sulfate reduction and other mineralogic reactions, including dilution by water released from the smectite-to-illite change. The calcium-chloride water was derived from water moving up faults from the underlying Mesozoic section.

4.5.2 Data Sources and Methods of Analysis

Water-quality data from water-supply wells were compiled from TWDB internet files (http://www.twdb.state.tx.us/data/waterwell/well_info.html). TWDB water-quality data included records for more than 310 wells in the Queen City Formation and the El Pico Clay and more than 520 wells in the Sparta and Laredo formations. Of these, data were used for 243 wells in the Queen City aquifer and 418 wells in the Sparta aquifer that included (a) data for major ions, (b) an acceptable charge balance, and (c) locational information. Charge balance for freshwater chemical analyses was between ±5 percent. Where repeated samples were reported for a well, the most recent analysis was used for mapping. Data abundance was sufficient to allow regional mapping of water quality in the Queen City and Sparta aquifers, and in equivalent formations south of the Frio River.

To extend the TDS map downdip of the base of potable water, data from USGS internet files on chemical composition of co-produced formation waters from oil or gas wells in the downdip section of the Claiborne Group (Breit, 2002) were used. Charge balance for co-produced formation waters is variable, ranging from -13 to 30 percent; 67 percent of samples have a charge balance of ±5 percent. Sodium and potassium content of some formation-water samples may have been determined by setting charge balance to zero.

Data on TDS were posted and contoured using ArcGIS©. TDS numbers were contoured using the inverse distance weighted method. The gridded map was reclassified into nine zones with nonuniform contour intervals between 10 and >100,000 mg/L. Resulting maps were 'clipped' to the study area for each aquifer.

Hydrochemical facies (Piper, 1944), which describe the proportion of major dissolved cations and anions, also were calculated and mapped. Hydrochemical facies were calculated for this study using slightly different criteria than defined in Back (1966). In this study, the cation name is defined by the cation that makes up more than 50 percent of the total cationic charge of the water sample as summed in milliequivalents per liter (meq/L). For example, if sodium comprises 60 percent of the cationic charge, the sample would be called a sodium-type water. If no cation makes up more than 50 percent of the charge, the sample is called a mixed-cation type water. A similar calculation is made for major anions. Sodium and potassium are added together for the calculation and are referred to in this study simply as sodium. Dissolved carbonate and bicarbonate ions likewise are added together and referred to as bicarbonate. The hydrochemical facies type is named by combining cation and anion names. Hydrochemical facies were also posted using ArcGIS©.

4.5.3 Results

The Queen City and Sparta aquifers have similar chemical compositions and similar regional trends in water quality. Average TDS is essentially the same and is not statistically different between the Queen City (517 mg/L) and Sparta (610 mg/L) aquifers (Table 4.5.1).

Table 4.5.1 Average total dissolved solids (TDS) in the Queen City and Sparta aquifers in Texas (mg/L). Calculated from logarithm-transformed mean values.

Area	Queen City Aquifer	Sparta Aquifer
Overall	517	610
Unconfined	305	287
Confined	759	784
North	339	319
South	922	1,553

Average TDS statistically differs between the unconfined (outcropping) and confined parts of both the Queen City and Sparta aquifers (see Table 4.5.1). The unconfined parts of the aquifers have an average TDS of 305 and 287 mg/L whereas the confined parts have an average of 759 and 784 mg/L. Since TDS generally increases along the flowpath and with depth in the aquifers (Figures 4.5.1 and 4.5.2), average TDS is greater in the confined aquifer than in the unconfined aquifer.

The increase in TDS continues with depth beyond the freshwater or potable-water part of the formations. TDS of samples of formation waters compiled in this study from oil and gas fields in the Claiborne Group ranges from ~6,800 to >150,000 mg/L. This pattern of a downdip increase in TDS matches that described for the Carrizo-Wilcox aquifer in central Texas (Dutton et al., 2002; 2003).

This study statistically confirmed the finding of Biri (1997) and Brown (1997) that TDS is greater in the southern parts of both aquifers than in the northern parts. The difference in average TDS between 339 mg/L in the northern part and 922 mg/L in the southern part of the Queen City aquifer is statistically significant (0.95 confidence level). Likewise, the difference between the 319 mg/L in the northern part and the 1,553 mg/L in the southern part of the Sparta aquifer is statistically significant. The split between northern and southern parts of the aquifers was made in the middle of Lee County where a gap in data density (see Figures. 4.5.1 and 4.5.2) provided a convenient dividing line for the purpose of this statistical test.

The statistical difference between average TDS in the northern and southern parts of the Queen City aquifer may reflect the extent of the East Texas Embayment, where the unconfined aquifer has a low TDS (see Figure 4.5.1). The north-to-south difference also is significant in the

Sparta aquifer; however, it does not include many samples from the unconfined aquifer in the East Texas Embayment.

The downdip increase in TDS consists of several trends in concentrations of individual dissolved ions. First, sodium and chloride increase together (Figures 4.5.3a and 4.5.3b); their increase parallels the increase in TDS with depth in the aquifers. The groundwaters from the southern part of the Queen City and Sparta aquifers have, on average, greater sodium and chloride concentrations than those from the northern part of the aquifers, reflecting the overall greater TDS. Most of the ionic concentrations plot along a trend between seawater and dilute water. The sodium/chloride ratio is greater at chloride concentrations of less than 1,000 mg/L than at greater chloride concentrations, a pattern seen in other aquifers (Dutton and Simpkins, 1986; Richter et al., 1990).

The range in TDS and ionic concentration of sodium and chloride most likely reflect displacement of seawater from the aquifers (Mason, 1960). Seawater has long since been completely displaced near the recharge zone in well-interconnected deposits of permeable sandstone in the aquifers. Adjacent clayey beds of low permeability, however, may retain some amount of diluted seawater, even near the recharge zone (Dutton, 1985). Dissolved ions can move by diffusion from the clayey beds into the sandstone beds (Domenico and Robbins, 1985). The thickest and most permeable sand beds are the most completely flushed, at least near the outcrop (Payne, 1968). There is a downdip limit at which recharging water might no longer effectively displace seawater, even from permeable sandy beds that are hydrologically connected to the recharge zone (Domenico and Robbins, 1985). Thus, groundwater samples with higher TDS and higher sodium and chloride concentrations in the southern parts of the Queen City and Sparta aquifers may reflect less recharge moving downdip in the aquifers, or lower transmissivity and slower flow rates, or both.

Foster (1950) showed that incongruent solution of minerals and ionic exchange increase the ionic ratio of sodium/calcium in most Gulf Coast aquifers. At chloride concentrations of more than 10,000 mg/L, clay minerals show little preference or selectivity for sodium versus calcium ions; adsorption sites are saturated in proportion to ionic concentrations in solution. As TDS decreases, there is increasing selectivity for adsorption of charge-dense calcium ions, so concentration of dissolved sodium increases. This is reflected in an inverse variation of sodium and calcium ions (Figures 4.5.3c and 4.5.3d). Since sodium concentration is strongly correlated with TDS, the proportionate amount of sodium associated with diluted seawater was subtracted from total dissolved sodium in these figures. In seawater, the sodium/chloride ratio is 0.85 (in meq/L units).

Bicarbonate increases in the downdip flow direction along with sodium (Figures 4.5.3e and 4.5.3f). The increase in dissolved bicarbonate in the aquifers is attributable to dissolution of calcium carbonate by carbonic acid, which might be produced in the subsurface by bacterial degradation of organic matter such as lignite or dissolved organic carbon (Foster, 1950; Pearson and White, 1967; Kreitler et al., 1977). Oxidation of methane can also generate CO_2 and additional carbonic acid (Grossman et al., 1986; Zhang et al., 1998).

These main geochemical processes change the ratio of major dissolved ions in groundwater in the Queen City and Sparta aquifers. Most groundwaters in the Queen City and Sparta aquifers are of either of three types of hydrochemical facies: calcium-bicarbonate, sodium-bicarbonate, or sodium-mixed anion types (Figures 4.5.4 and 4.5.5). The single most prevalent type in either aquifer is the sodium-bicarbonate type (29 to 39 percent). A fourth type, the mixed-cation—mixed-anion water type, in which no single cation or anion accounts for more than 50 percent of the ionic charge, makes up an additional 9 to 11 percent of samples in the aquifers. Bicarbonate-type waters make up the greatest proportion of samples (~60 and ~38 percent in the Queen City and Sparta aquifers, respectively). Sulfate-type waters make up ~6 and ~11 percent of samples from the Queen City and Sparta aquifers, respectively.

The proportion of the three main hydrochemical facies types differs in both the Queen City and Sparta aquifers between (1) the unconfined and confined parts of the aquifers and (2) the northern and southern parts of the aquifers. A high percentage of water samples in the unconfined Queen City aquifer in the East Texas Embayment area have a calcium-bicarbonate water type. The calcium-bicarbonate water type makes up 14 percent of samples in the northern part of the Queen City aquifer and less than 4 percent in the southern part (Figure 4.5.4). The sodium-bicarbonate type makes up ~48 percent of samples in the northern part of the Sparta aquifer, but only ~3 percent in the southern part (Figure 4.5.5). The sodium—mixed anion type makes up ~40 percent of Sparta waters in the southern part of the study area.

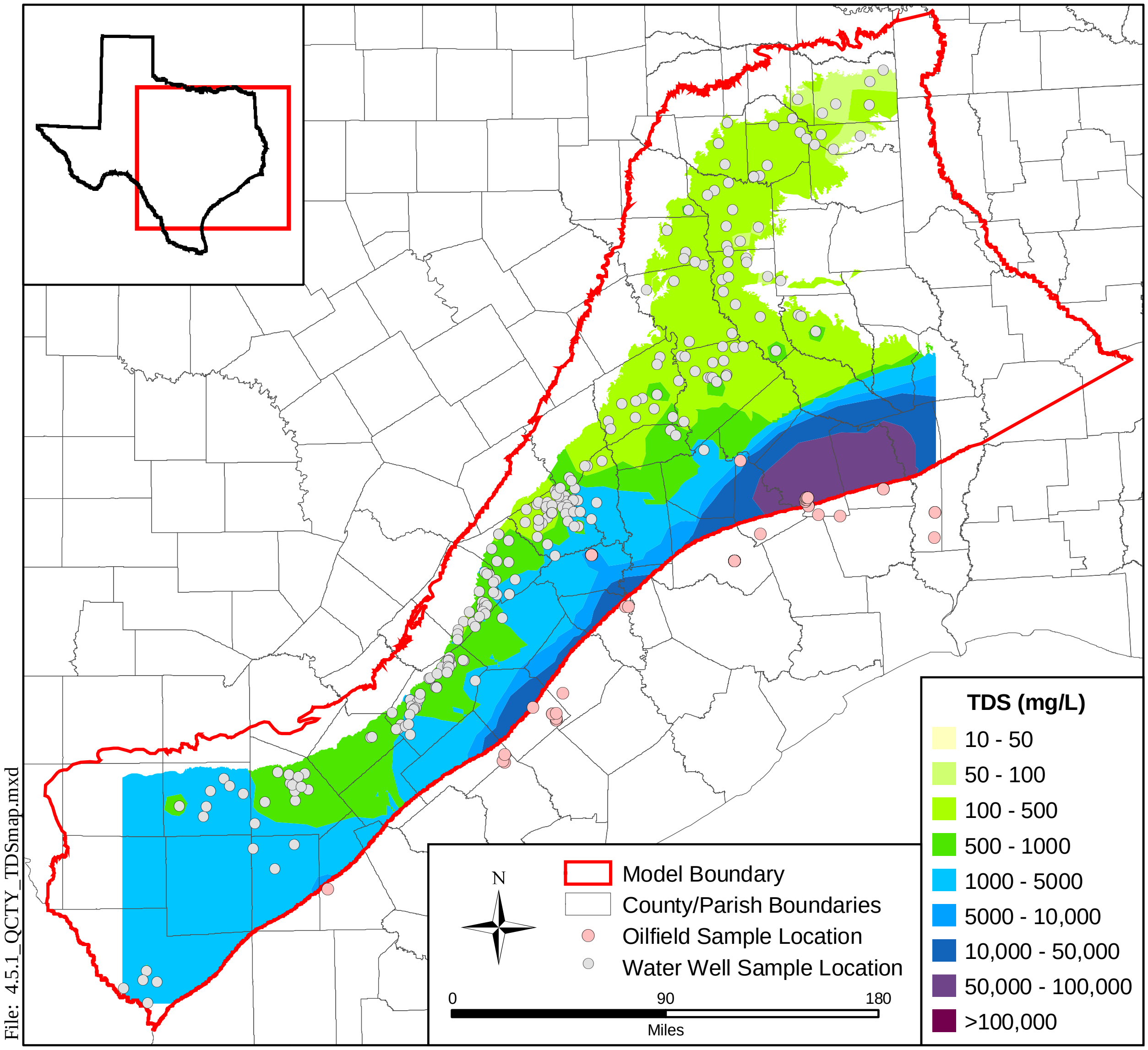

Figure 4.5.1 Map of total dissolved solids (TDS) in the Queen City aquifer and equivalent downdip section in Texas.

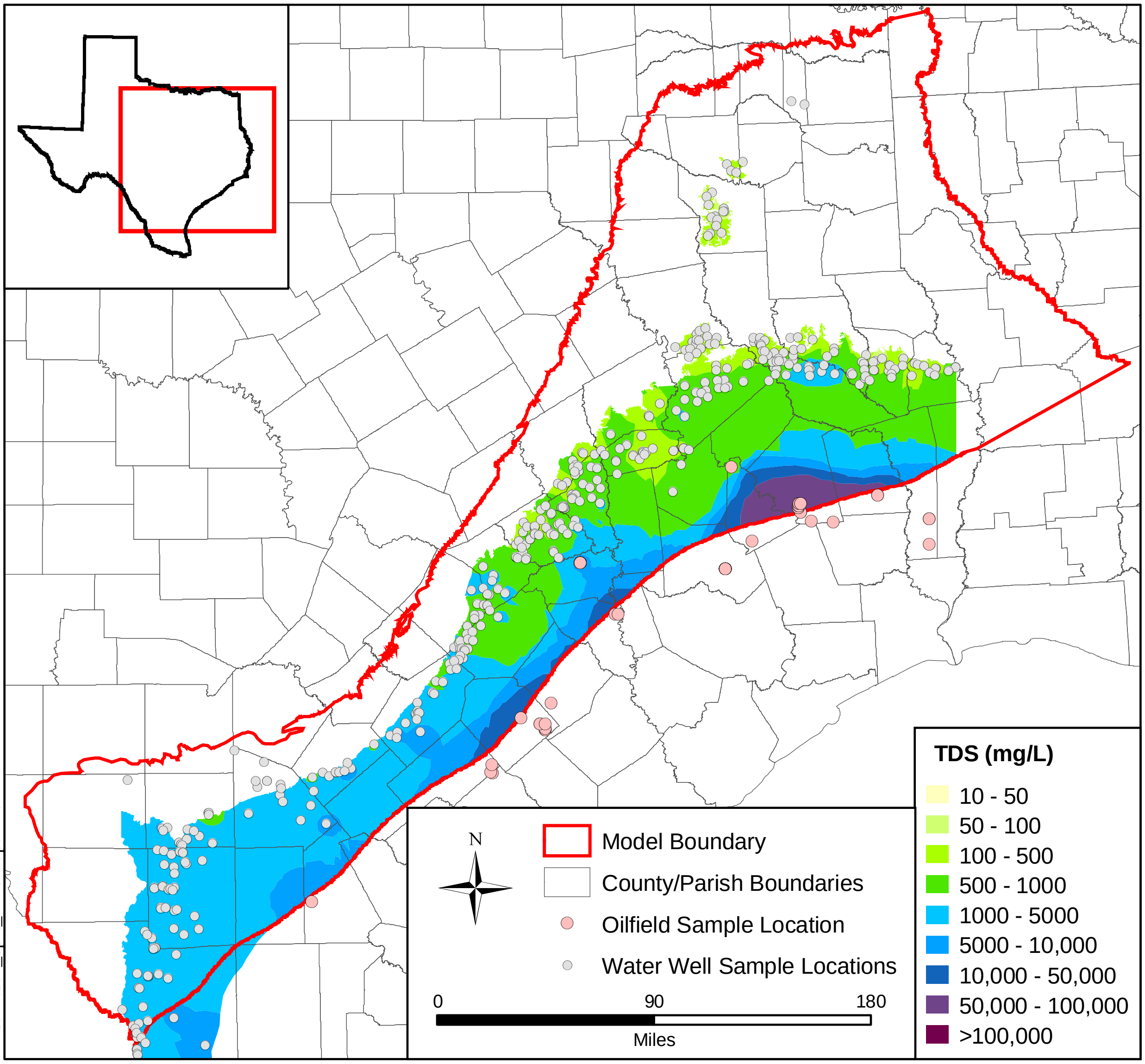

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Figure 4.5.2 **Map of total dissolved solids (TDS) in the Sparta aquifer and equivalent downdip section in Texas.**

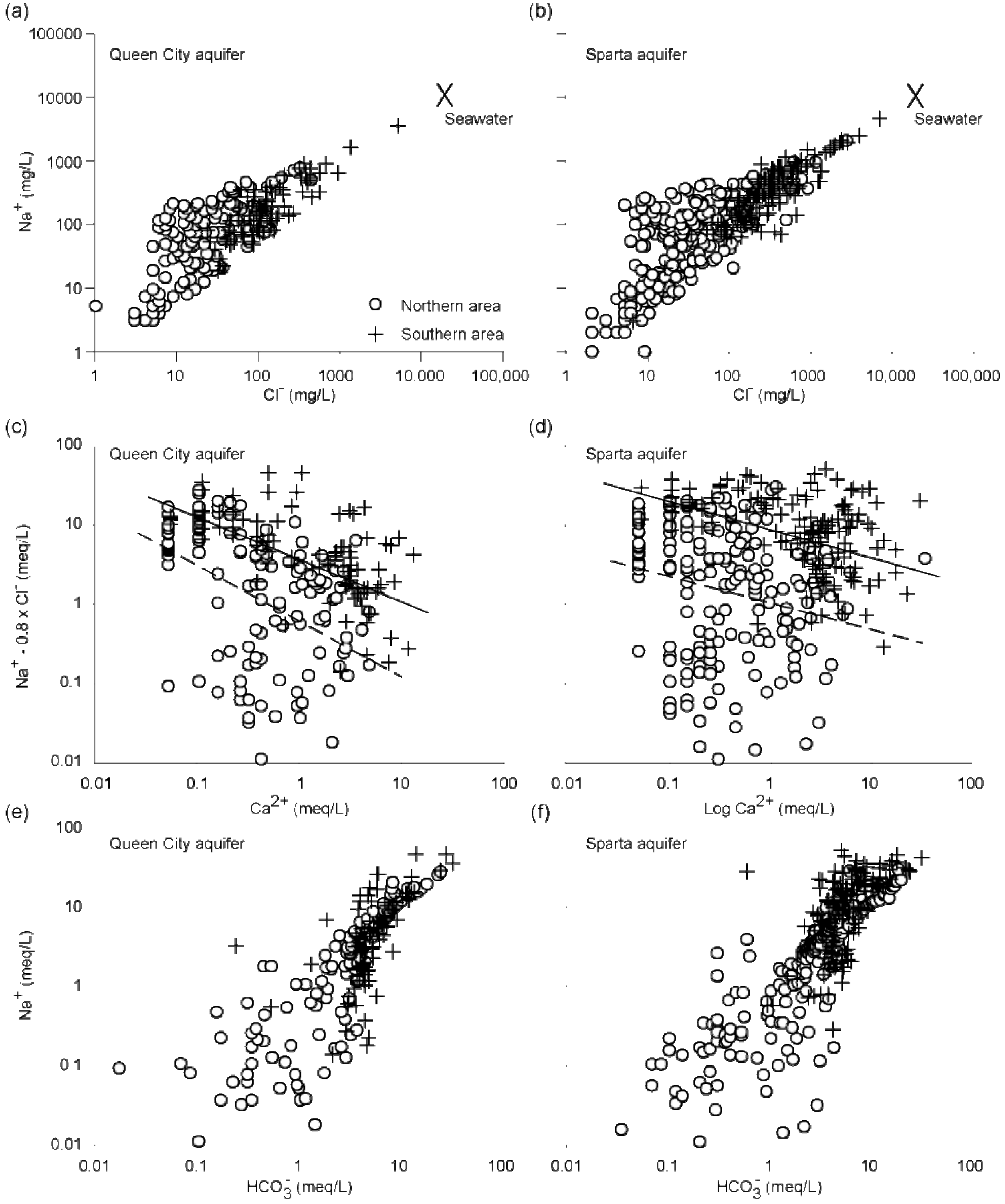

Figure 4.5.3 Graphs of ionic variation in the Queen City and Sparta aquifers.

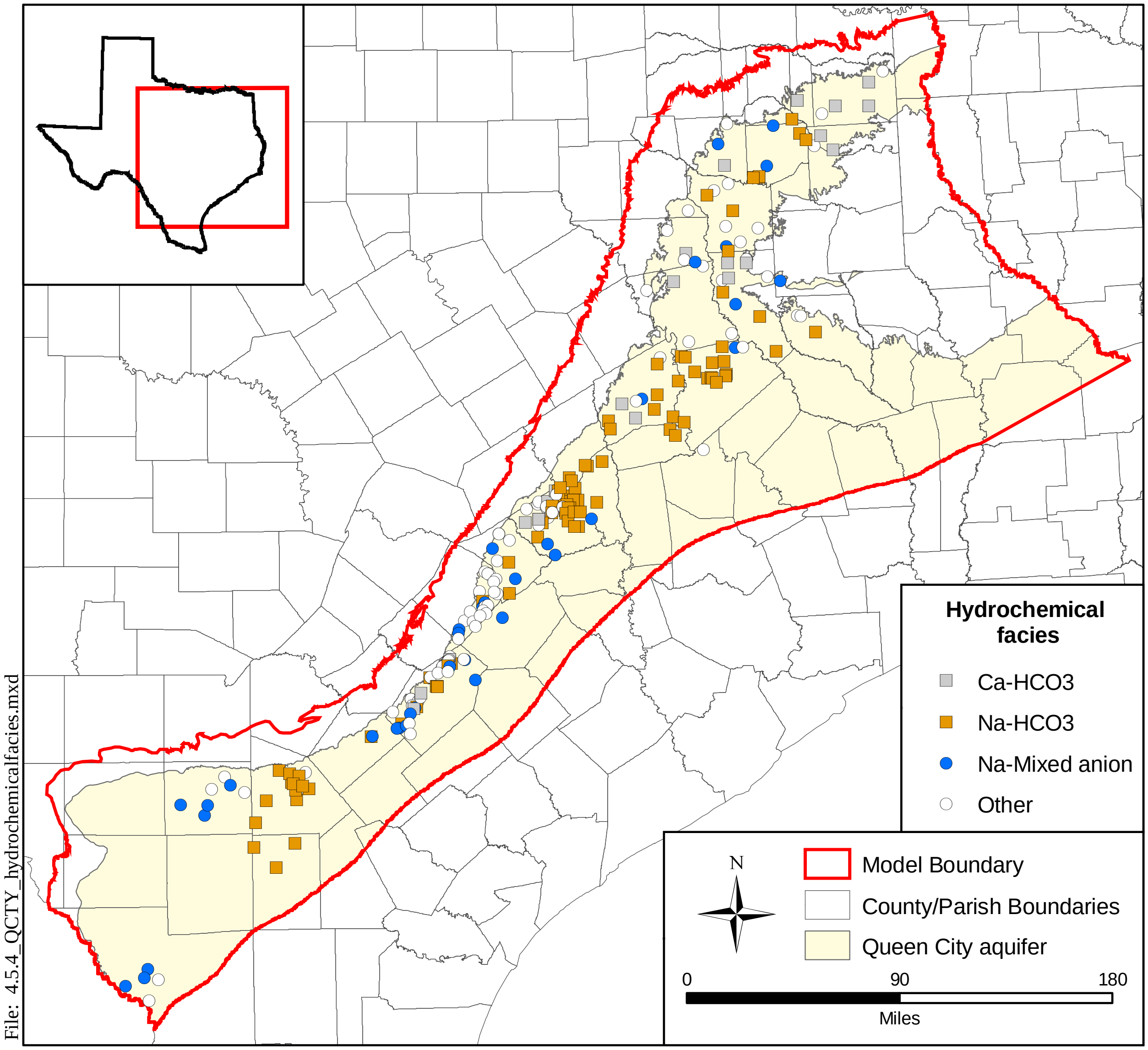

Figure 4.5.4 Map of hydrochemical facies in the Queen City aquifer in Texas.

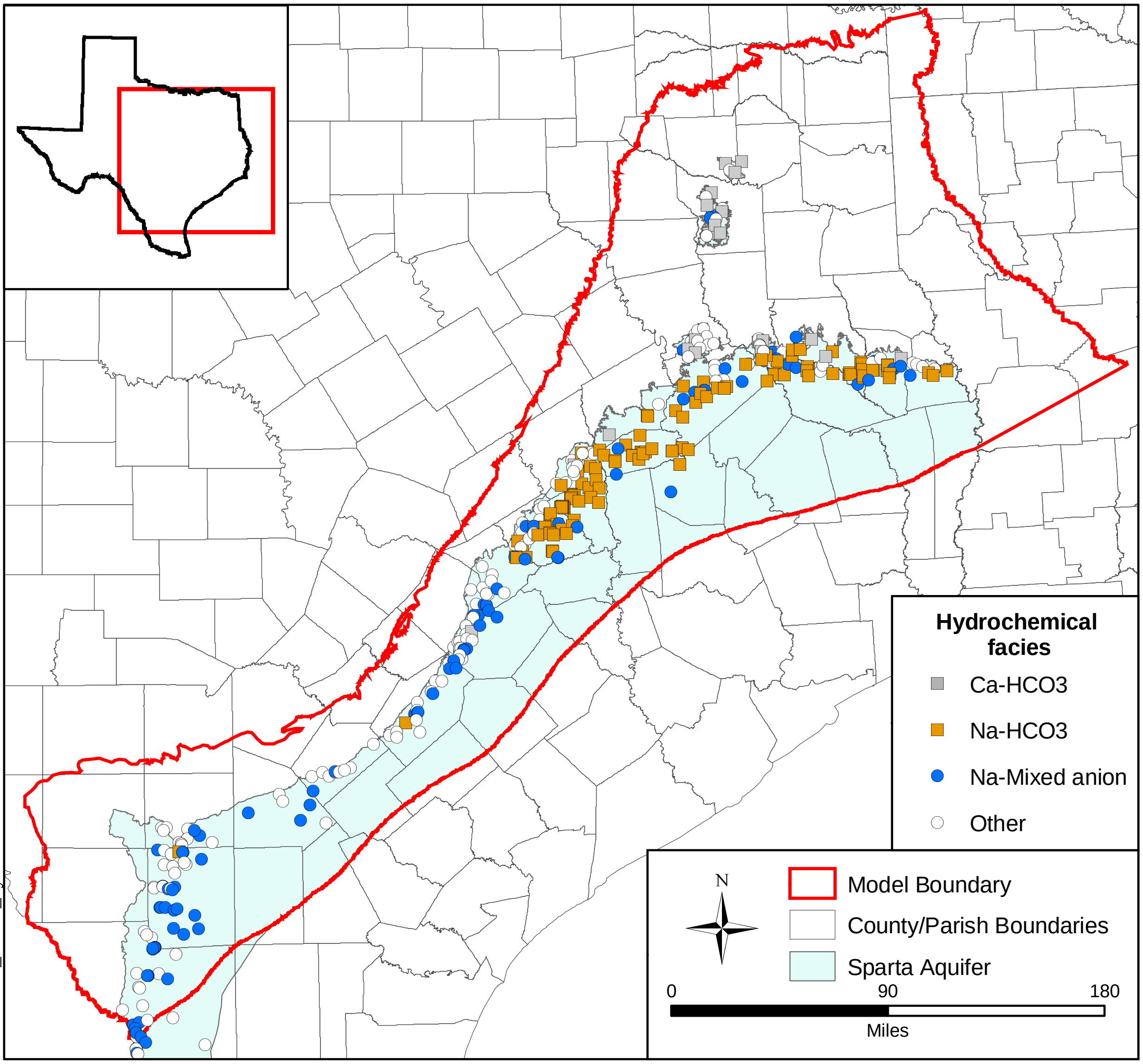

Figure 4.5.5 Map of hydrochemical facies in the Sparta aquifer in Texas.

4.6 Recharge

Recharge can be defined as water that enters the saturated zone at the water table (Freeze, 1969). Recharge is a complex function of rate and volume of precipitation, soil type, water level, soil moisture, topography, and ET (Freeze, 1969). Recharge is expected to vary seasonally. For example, winter and early spring is generally a high precipitation time. During this time, soil moisture would also be high while ET rates would be low. These conditions combine to increase the potential for recharge. In the heat of the summer, precipitation events tend to be more isolated and soil moisture is lower while ET is highest. These conditions combine to decrease the potential for recharge. The recharge estimates developed for these models (see Section 6.3.5) are yearly average estimates which integrate seasonal recharge variations.

Potential sources for recharge to the water table include precipitation, stream or reservoir leakage, or irrigation return flow. In the Queen City and Sparta aquifers, recharge is conceptualized to occur both as diffuse recharge in the outcrop and as focused recharge in areas where streams are predominantly losing (southern study area). Similarly, the amount of recharge occurring as diffuse recharge is expected to decrease from the wet humid northeast portions of the study area to the more arid southwest.

The following two sections discuss diffuse (or areal) recharge and focused recharge with published estimates from the literature. How recharge is implemented in the model, including the recharge and ET distributions, is provided later in Section 6.3.5.

4.6.1 Diffuse Recharge

Recharge in the major aquifers of Texas has been studied by many investigators. These studies have been summarized by Scanlon et al. (2002). Few estimates of recharge are available for the Queen City and Sparta aquifers in Texas. Muller and Price (1979) estimated groundwater availability for the aquifers of Texas. Their estimates were based upon a variety of means including consideration of an aquifer’s transmissivity and precipitation. Table 4.6.1 provides the estimates of recharge developed by Muller and Price (1979) for the Queen City, Sparta, and Carrizo-Wilcox aquifers by river basin.

Muller and Price (1979) estimate that the total Queen City recharge is approximately equal to the Carrizo-Wilcox recharge estimate. The Sparta is estimated to have significantly less recharge (24 percent) than the Queen City aquifer. This is largely a function of the difference in areas of the two aquifer outcrops with the Sparta outcrop area being approximately 20 percent of the Queen City outcrop area. Because modeling studies typically report recharge as a rate in inches per year, it is instructive to see what kind of areal recharge rates are implied by the recharge rates provided in Table 4.6.1 and reported in acre-feet per year.

Table 4.6.1 Estimated recharge rates (AFY) for the Carrizo-Wilcox, Queen City, and Sparta aquifers (after Muller and Price, 1979).

River Basin	Zone	Carrizo- Wilcox	Queen City	Sparta
Sulphur	1	4,000	7,000	
Cypress	1	15,000	234,500	
Sabine	1	40,000	137,800	
Sabine	2	4,000		7,400
Neches	1	124,600	253,200	30,700
Neches	2	25,400	8,100	23,700
Trinity	1	13,400	500	
Trinity	2	65,300	14,500	34,800
Trinity	3	300		200
Brazos	4	11,100		
Brazos	5	118,200	2,700	7,000
Colorado	3	49,200	3,700	10,000
Guadalupe	2	38,600	8,000	20,000
San Antonio	2	33,200	3,600	10,000
Nueces	1	78,700	8,500	20,000
Rio Grande	2	13,700		
TOTAL		634,700	682,100	163,800

AFY = acre-feet per year

Table 4.6.2 estimates recharge rates in acre-feet per year for the Carrizo-Wilcox, Queen City, and Sparta aquifers assuming a constant recharge rate in inches per year. This scoping calculation indicates that the recharge rate reported by Muller and Price (1979) for the Carrizo-Wilcox aquifer is roughly equivalent to one inch per year. Similarly, the Queen City aquifer would get approximately 1.5 inches of recharge a year based upon Muller and Price (1979). The Sparta recharge rate would be approximately 2 inches per year.

Table 4.6.2 Estimated recharge rates in AFY with assumed recharge rates in inches per year for the Carrizo-Wilcox, Queen City, and Sparta aquifers.

Aquifer	Outcrop Area (acres)	Recharge Rate 1 in/yr	Recharge Rate 2 in/yr	Recharge Rate 3 in/yr
Carrizo-Wilcox	7,203,119	600,260	1,200,520	1,800,780
Queen City	4,947,597	412,300	824,600	1,236,899
Sparta	991,344	82,612	165,224	247,836

AFY = acre-feet per year

The most recent recharge estimates for the Queen City aquifer are from the Northern and Southern Carrizo-Wilcox GAMs (Fryar et al., 2003 and Deeds et al., 2003). The Southern Carrizo-Wilcox GAM estimated an average recharge rate (before groundwater ET) of 0.8 inches per year. The Northern Carrizo-Wilcox GAM estimated an average recharge rate (before groundwater ET) of from 1 to 2.5 inches per year.

4.6.2 Reservoirs and Lakes

As stated earlier, reservoirs provide a potential site of focused recharge. There was only one natural lake in Texas, Caddo Lake, which was drained in the 1870s and later impounded in 1914. However, there are 48 reservoirs with surface areas greater than half a square mile in the study area that occur in the outcrop of the Queen City, Sparta, and Carrizo-Wilcox aquifers (Figure 4.6.1). Table 4.6.3 lists the names, owners, and year impounded for these reservoirs. Figure 4.6.2 shows the lake stage elevations of five of the reservoirs for the historical simulation period from 1980 to 1999. Because they are located in outcrop areas, these reservoirs provide potential areas of focused recharge to the underlying aquifers. Figure 4.6.2 shows that the reservoirs generally have stages that do not vary greatly over the time period of interest. Details regarding model implementation of reservoirs and lakes can be found in Section 6.3.3.

Table 4.6.3 Characteristics of reservoirs in study area.

Reservoir	Reservoir Name	Owner	Date Impounded
1	Alcoa Lake	Aluminum Company of America	1953
2	Black Bayou Lake	State of Louisiana	1955
3	Brandy Branch Cooling Pond	Southwestern Electric Power Company	1983
4	Caddo Lake	Caddo Levee District	1914
5	Calaveras Lake	City Public Service Board of San Antonio	1969
6	Camp Creek Lake	Camp Creek Water Co.	1948
7	Cedar Creek Reservoir	Tarrant County WCID #1	1965
8	Clear Lake	Information Unavailable	Information Unavailable
9	Cross Lake	City of Shreveport	1925
10	Eastman Lakes	Information Unavailable	Information Unavailable
11	Ellison Creek Reservoir	Lone Star Steel Company	1943
12	Fairfield Lake	Texas Utilities Generating Company	1969
13	Forest Grove Reservoir	Texas Utilities Generating Company	1980
14	Houston County Lake	Houston County WCID #1	Information Unavailable
15	Johnson Creek Reservoir	Southwestern Electric Power Company	1961
16	Lake Athens	Athens Municipal Water Authority	1962
17	Lake Bastrop	Lower Colorado River Authority	1964
18	Lake Bob Sandlin	Titus County FWSD #1	1977
19	Lake Cherokee	Cherokee Water Company	1948
20	Lake Cypress Springs	Franklin County Water District & TWDB	1970
21	Lake Fork Reservoir	Sabine River Authority	1979
22	Lake Gilmer	City of Gilmer	Information Unavailable
23	Lake Gladewater	City of Gladewater	1952
24	Lake Hawkins	Wood County	1962
25	Lake Holbrook	Wood County	1962
26	Lake Jacksonville	City of Jacksonville	1957
27	Lake Limestone	Brazos River Authority	1978
28	Lake Monticello	Texas Utilities Generating Company	1972
29	Lake Murvaul	Panola County GWSD #1	1957
30	Lake Nacogdoches	City of Nacogdoches	1976
31	Lake O' the Pines	U.S. Army Corps of Engineers	1957
32	Lake Palestine	Upper Neches River Authority	1962
33	Lake Quitman	Wood County	1962
34	Lake Striker	Angelina-Nacogdoches WCID #1	1957
35	Lake Tyler/Lake Tyler East	City of Tyler	1966
36	Lake Winnsboro	Wood County	1962
37	Martin Lake	Texas Utilities Generating Company	1974
38	Pinkston Reservoir	City of Center	1977
39	Richland-Chambers Reservoir	Tarrant County WCID #1	1987
40	Sibley Lake	State of Louisiana	1962
41	Smithport Lake	State of Louisiana	Information Unavailable
42	Toledo Bend Reservoir	Sabine River Authority	1966
43	Trinidad Lake	Information Unavailable	1925
44	Twin Oak Reservoir	Texas Utilities Generating Company	1982
45	Vidor Braunig Lake	City Public Service Board of San Antonio	1964
46	Wallace Lake	U.S. Army Corps of Engineers	1946
47	Welsh Reservoir	Southwestern Electric Power Company	1975
48	Wright Patman Lake	U.S. Army Corps of Engineers	1956

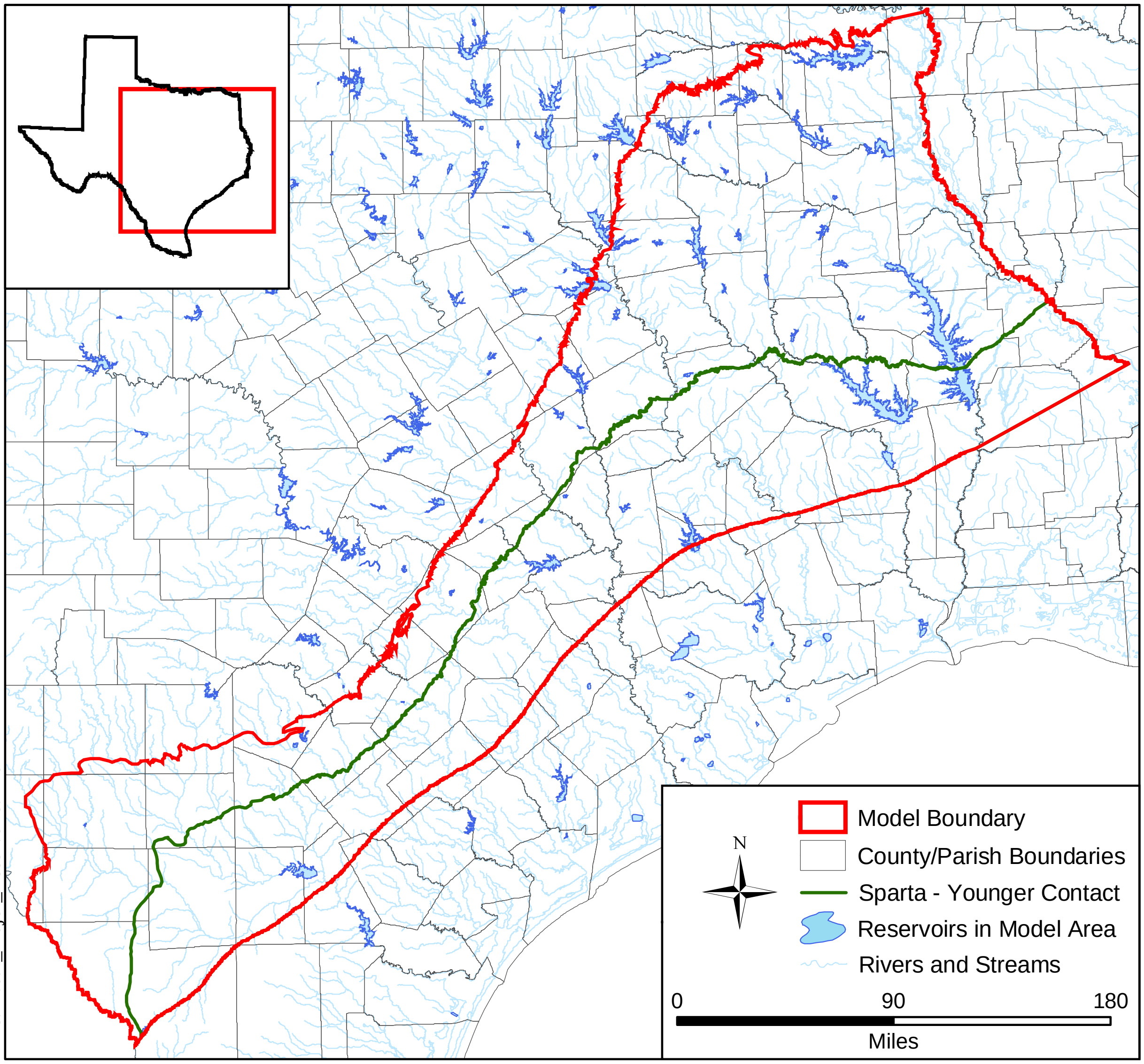

Figure 4.6.1 Major reservoirs in the study area.

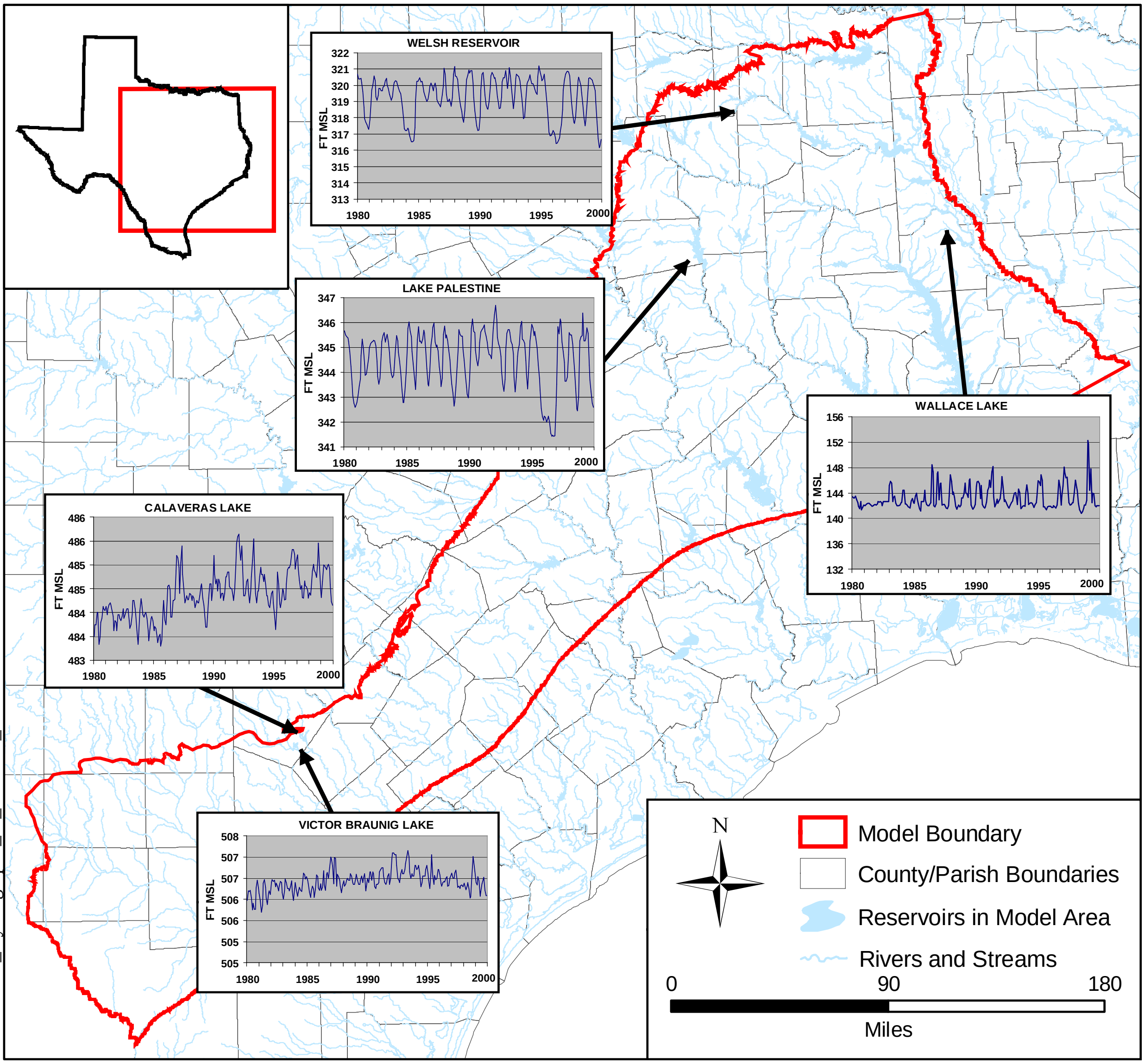

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Figure 4.6.2 Hydrographs for select reservoirs in the study area.

4.7 Natural Aquifer Discharge

Under predevelopment conditions, groundwater flow in the Queen City and Sparta aquifers is elevation driven from the higher elevation outcrops to the lower elevation stream valleys and to the confined sections of the aquifers. Prior to significant resource development, recharge occurring as a result of infiltration and stream loss was balanced by discharge to streams and springs in the outcrop, and through cross-formational flow. This section of the report focuses on aquifer-stream interaction and published accounts of springs in the model region. Details regarding how streams and springs were implemented in the models can be found in Section 6.3.3.

4.7.1 Rivers and Streams

The major streams intersecting the study area include the Rio Grande, Nueces, Frio, Atascosa, San Antonio, Guadalupe, Colorado, Brazos, Trinity, Neches, Sabine, Sulphur, and Red rivers and Cypress and Cibolo creeks. Numerous other smaller streams are included in the study area. Figure 4.7.1 plots the stream gages in the study areas where stream flow and elevation measurements are collected. The stream gage data can be used to characterize the flow rates in the streams and to determine aquifer-stream interaction, often referred to as stream gain or loss. Figure 4.7.2 plots stream hydrographs across the study region. These hydrographs show the yearly cyclical nature of stream flow in Texas with flows being greatest in late winter through early summer. In general, streams in the east and central study areas tend to flow year round (i.e., Big Cypress Creek near Pittsburg). In the far west of the study area, streams can cease flowing in dry times as can be seen in the Frio River gage near Derby.

Base flow is the contribution of groundwater to gaining reaches of a stream. After runoff from storm events has drained away, the natural surface-water flow that continues is predominately base flow from groundwater. Streams can have an intermittent base flow, which is usually associated with wet winters and dry, hot summers. Larger streams and rivers might have a perennial base flow. Direct exchange between surface and groundwater is limited to the outcrop. Prior to significant resource development, it is likely that most streams throughout the study area were gaining streams.

Stream-aquifer interaction can be quantified through several means including low flow studies, hydrograph separation studies, and by modeling studies. In the following pages, a series of studies is discussed that have characterized stream-aquifer interaction in the model study area. These include a low flow study survey performed by the USGS (Slade et al., 2002), a stream-aquifer interaction study performed using the Texas Water Availability Models (WAMs) performed by the R.J. Brandes Company as part of this study (see Appendix B of this report), a hydrograph separation study documented in Dutton et al. (2003), and a stream-aquifer interaction study documented in LBG-Guyton Associates and HDR Engineering, Inc. (1998).

4.7.1.1 USGS Low-Flow Study

Slade et al. (2002) compiled the results of 366 gain/loss studies since 1918 that included 249 individual stream reaches throughout Texas. They documented 41 gain/loss studies that intersect the Queen City and/or Sparta outcrop. Figure 4.7.3 shows the locations and survey numbers of the gain/loss studies in the model area. Table 4.7.1 provides the characteristics of the gain/loss studies that intersect the Queen City and/or Sparta formations. Characteristics for the other studies shown on Figure 4.7.3 are presented in either the Northern Carrizo-Wilcox GAM report (Fryar et al., 2003) or the Southern Carrizo-Wilcox GAM report (Deeds et al., 2003).

To the northeast in the area of the East Texas Embayment and the Sabine Uplift, gain/loss studies were performed on the Sabine River, Bowles Creek (Neches River Basin), Little Cypress and Sugar creeks (Red River Basin), Lake Fork Creek (Sabine River Basin), and Big and Little Elkhart creeks (Trinity River Basin). Three studies were performed on the Sabine River (345, 346, and 347). Studies 345 and 346 were performed in August and September of 1981 and both indicate gaining conditions with average gains of 592 and 3,847 AFY per mile of stream, respectively. Study 347 was performed along a 268-mile stretch of the Sabine River in September of 1963. The survey average gain for the Sabine River was 564 AFY/mile. Studies 244, 245, and 249 were performed in 1964 in tributary creeks to the Red River. Average gain estimates range from 96 to 431 AFY/mile. In 1942, a 6.5-mile length of Bowles Creek was surveyed and found to be gaining 335 AFY/mile (study 139). The only strongly losing stream study was performed on Lake Fork Creek in August and September of 1981. This study (342) estimated an average loss of -1,177 AFY/mile over a 1.6-mile stretch of stream. This study appears anomalous. The available gain/loss studies are consistent with our assumption that most major rivers and streams in the northeastern part of the Queen City and Sparta outcrop are gaining from the underlying aquifers.

In the central and southern portions of the study area, gain/loss studies were performed on Cibola Creek (San Antonio River Basin) and on the Rio Grande, Nueces, Leona, Frio, Atascosa, and Colorado rivers. Of the two studies (49 and 54) on the Colorado River, the one performed in 1918 was gaining and the one performed in 1985 was losing. There were, however, releases of large volumes of water from the Highland Lakes reservoirs during the 1985 study, so those results are not representative of low-flow conditions. Both studies on Cibolo Creek (349 and 350) indicated gaining conditions.

Studies 165 through 167, 169 through 171, 173, and 175 were performed on the Leona River in Zavala and Uvalde counties from as early as 1925 to as late as 1946. The Leona River was predominantly gaining over this period with average and median gain/loss estimates of 42 and 17 AFY/mile, respectively. There does seem to be a weak correlation between season and interaction with stream loss occurring more in summer and stream gain occurring more in winter.

Many of the relevant gain/loss studies were performed on the Nueces River. Studies 182 through 185 were performed on the same stretch of the Nueces River in four surveys from May 1940 through September 1940. The average and median gain/loss estimates for that time period were -814 and -898 AFY/mile of stream, respectively (negative indicated a losing stream). Studies 194, 197 through 202, 206, 207, 210, and 219 were performed as early as 1925 and as late as 1964. The Nueces River was predominantly losing during this period with average and median gain/loss estimates of -496 and -395 AFY/mile, respectively.

Three studies (325, 327, and 328) were performed on the Rio Grande River yielding average and median losses of -645 and -425 AFY/mile, respectively.

4.7.1.2 WAM Based Analysis of Groundwater-Surface Water Interaction

As part of this study, the R.J. Brandes Company developed estimates of stream gain loss for several streams and rivers across the study area. Their study is completely documented in Appendix B of this report. The interaction is quantified in terms of gains to the surface water body or losses from the surface water body. Quantifying the amount of gain or loss cannot be measured directly, so a method using naturalized flow data from the WAMs developed by the TCEQ was used to quantify the gains or losses in the majority of reaches crossing the aquifer. For the Colorado and Rio Grande rivers, a method using low flows was used to determine a percent loss for the specified reach.

Table 4.7.2 summarizes the results from the WAM-based stream-aquifer interaction study documented in Appendix B. The results from the analysis show that the streams in the north and central parts of Texas tend to be gaining across the Queen City and Sparta outcrops and the streams in the southern model region tend to be either slightly gaining or losing on average.

4.7.1.3 LBG-Guyton and HDR Stream-Aquifer Interaction Study

In a 1998 study by LBG-Guyton and HDR Engineering, they performed a detailed groundwater and surface water study in the southern GAM model area. The simulated period for which these GAMs and their modeling study overlap is the period from 1980 through 1990. Table 4.7.3 summarizes the gain/loss estimates derived from Figure 7-7 of the LBG-Guyton and HDR (1998) report. These gain/loss estimates were compared against the calibrated stream interaction for the southern Queen City and Sparta GAM as discussed later in this report.

4.7.1.4 HDR Central Carrizo-Wilcox GAM Study

Stream-aquifer interaction was also characterized for many central Texas rivers and streams as part of the Central Carrizo-Wilcox GAM (Dutton et al., 2003). In this study, HDR Engineering performed hydrograph separation studies on several streams within the Carrizo-Wilcox outcrop. From their analysis, they developed median base flow estimates for all of the modeled streams in the Central Carrizo-Wilcox GAM. The originally reported baseflow estimates were representative of cumulative flow across the watershed of a given stream, also equivalent to the baseflow in the most downstream cell of the model. To allow comparison to other gain loss estimates provided in this section, the Dutton et al. (2003) estimates were translated into units of acre-feet per year per mile of stream. This was done simply, in each watershed, by counting the numbers of stream cells located in the Reklaw to Lower Wilcox layers (layers 4 to 8) in the Queen City and Sparta model and dividing the central model HDR targets by that number of cells. The second step was to assume that baseflow in the Reklaw, Carrizo, and Wilcox layers is statistically similar to that of the Sparta, Weches, and Queen City layers. This is an appropriate assumption to make except in regions of the northern and central model overlap where the Queen City Formation crops out extensively. This limitation applies mainly to the Trinity River where the estimates are likely underestimated. These base flow estimates are summarized in Table 4.7.4 and were used as additional calibration targets as discussed later in this report.

4.7.2 Springs

Discharge also occurs in areas where the water table intersects the surface at springs or seeps. These springs usually occur in topographically low areas in river valleys or in areas of the outcrop where hydrogeologic conditions preferentially reject recharge. Figure 4.7.4 shows the results of a literature survey for springs located within the active model outcrop area. It should be noted that the primary source for spring locations (Brune, 1981) did not include spring surveys for counties from Angelina County southwest to Burleson County and from Gonzales County southwest to Atascosa County. It should also be noted that there are likely thousands of undocumented smaller springs and seeps, particularly in the northeastern part of the study area.

Of the more than 550 springs or groups of springs located, 40 were fourth magnitude [0.22 cubic feet per second (ft^3/s) or 100 gallons per minute (gpm) to 1 ft^3/s] or higher based on measured flow rates (Table 4.7.5). However, since flow rates were not provided for many of the documented springs, this number may be higher. The available measured spring flow rates range from less than 0.01 ft^3/s (<7 AFY) to a high of 3.4 ft^3/s (2,462 AFY) measured at Elkhart Creek Springs and originating from the Sparta Sand (Brune, 1975). Springs with multiple measurements over time show that fluctuations in precipitation can strongly influence spring flow.

Throughout much of the study area, spring flows have shown a general decline over time. Brune (1981) noted that declining groundwater levels due to pumping and flowing wells have resulted in thousands of smaller springs that no longer flow and reduced flows in many of the larger springs. The southern part of the study area has been most severely affected. Carrizo Springs, a large historically significant group of springs in Dimmit County, flowed constantly until 1929 (Brune, 1975). Because of free-flowing wells in Dimmit County from the late 1800s through the 1930s, Carrizo Springs quit flowing in 1929 and has flowed only intermittently since. Although pumping in the northern part of the study area has also resulted in reduced spring flows and dry springs, numerous springs still flow in that region due to the humid climate, dissected topography, and gently dipping aquifers of the East Texas Embayment.

4.7.3 Cross-Formational Flow

Cross-formational flow is also a natural mechanism for discharge of groundwater from the Queen City and Sparta aquifers. Fogg and Kreitler (1982) and Fogg et al. (1983) documented that in the East Texas Embayment, flow across the Reklaw is generally downward from the unconfined Queen City to the Carrizo. However, in the vicinity of the Trinity and Sabine rivers, hydraulic heads are reversed with the Carrizo-Wilcox discharging through upward leakage across the Reklaw into the Queen City. Estimates of these fluxes are lacking but Fogg et al. (1983) concluded that leakage across the Reklaw must be significant because of the effect of topography seen in large portions of the confined Carrizo aquifer. South and west of the East Texas Embayment and Sabine Uplift, the Queen City and Sparta aquifers dip steeply toward the Gulf of Mexico. Cross formational flow in this portion of the model area is expected to be generally upward. Payne (1968) noted that in the Sparta aquifer in Wilson County, upward leakage from the Sparta starts within a very short distance from the outcrop.

Table 4.7.1 Stream flow gain/loss studies in the study area (after Slade et al., 2002, Table 1).

Streamflow Study No.	Major River Basin	Stream Name	Reach Identification	Date of Study	Reach Length (river mi)	Total No. of Measurement Sites	No. of Measurement Sites on Main Channel	Aquifer Outcrop(s) Intersected by Reach		Total Gain or Loss (-) In Reach (ft^3/s)	Gain or Loss per Mile of Reach (ft^3/s per mile)	Gain or Loss per Mile of Reach (AFY per mile)
								Major Aquifers	Minor Aquifers			
49	Colorado	Colorado R	Austin (08158000) to near Bay City (08162500)	8/19-21/1985	257.6	19	12	Carrizo-Wilcox, Gulf Coast	Sparta	-1,634.2	-6.344	-4,596.0
54	Colorado	Colorado R	Robert Lee to mouth	8/7-14/1918	593	117	43	Carrizo-Wilcox, Edwards, Gulf Coast, Trinity	--	340.6	0.574	415.8
139	Neches	West Fk Bowles Cr - [Bowles Cr]	west of Old London to near Carlisle	10/28/1942	6.5	11	6	Carrizo-Wilcox	Queen City	3.0	0.462	334.7
140	Nueces	Atascosa, Frio, and Nueces R	3 mi southwest of Poteet to near Mathis	1/23-26/1951	103.8	29	14	Gulf Coast	Queen City, Sparta	4.83	0.047	34.0
165	Nueces	Leona R	1.7 mi southeast of Uvalde to 0.2 mi east of Zavalla-Frio Co line	2/5-8/1946	49.4	35	32	Carrizo-Wilcox	--	2.0	0.04	29.0
166	Nueces	Leona R	1.7 mi southeast of Uvalde to 35 mi southeast of Uvalde	6/11-12/1931	37.5	15	12	Carrizo-Wilcox	--	-3.1	-0.083	-60.1
167	Nueces	Leona R	1.7 mi southeast of Uvalde to 7.1 mi southeast of Batesville	8/7-9/1946	36.3	22	21	Carrizo-Wilcox	--	0.3	0.008	5.8
169	Nueces	Leona R	1.7 mi southeast of Uvalde to below Batesville	6/21-22/1934	34.6	13	10	Carrizo-Wilcox	--	-3.1	-0.09	-65.2
170	Nueces	Leona R	1.7 mi southeast of Uvalde to below Batesville	10/18-20/1934	34.6	14	11	Carrizo-Wilcox	--	2.4	0.069	50.0
171	Nueces	Leona R	1.7 mi southeast of Uvalde to below Batesville	7/5-6/1939	23	14	11	Carrizo-Wilcox	--	4.3	0.187	135.5
173	Nueces	Leona R	10 mi below Uvalde to below Batesville	6/8-10/1939	26	10	8	Carrizo-Wilcox	--	-3.8	-0.146	-105.8
175	Nueces	Leona R	Uvalde-Friotown Hwy to near Batesville	4/25-28/1925	33.5	14	11	Carrizo-Wilcox	--	15.89	0.474	343.4
182	Nueces	Nueces R	above Laguna (08190000) to 4.8 mi southeast of La Pryor	5/2-3/1940	46.9	14	13	Carrizo-Wilcox, Edwards	--	-63.8	-1.36	-985.3
183	Nueces	Nueces R	above Laguna (08190000) to 4.8 mi southeast of La Pryor	7/9-10/1940	46.9	14	13	Carrizo-Wilcox, Edwards	--	-66.7	-1.422	-1,030.2
184	Nueces	Nueces R	above Laguna (08190000) to 4.8 mi southeast of La Pryor	8/28-29/1940	46.8	14	13	Carrizo-Wilcox, Edwards	--	-52.3	-1.118	-809.9
185	Nueces	Nueces R	above Laguna (08190000) to 4.8 mi southeast of La Pryor	9/26-27/1940	46.9	14	12	Carrizo-Wilcox, Edwards	--	-27.9	-0.595	-431.1
194	Nueces	Nueces R	Laguna (08190000) to 3.8 mi southeast of Cinonia	6/14-30/1939	61.6	27	25	Carrizo-Wilcox, Edwards	--	-23.7	-0.385	-278.9

Table 4.7.1, continued

Streamflow Study No.	Major River Basin	Stream Name	Reach Identification	Date of Study	Reach Length (river mi)	Total No. of Measurement Sites	No. of Measurement Sites on Main Channel	Aquifer Outcrop(s) Intersected by Reach		Total Gain or Loss (-) In Reach (ft^3/s)	Gain or Loss per Mile of Reach (ft^3/s per mile)	Gain or Loss per Mile of Reach (AFY per mile)
								Major Aquifers	Minor Aquifers			
197	Nueces	Nueces R	Laguna (08190000) to Cinonia	4/30-5/8/1925	54.9	14	14	Carrizo-Wilcox, Edwards	--	-29.9	-0.545	-394.8
198	Nueces	Nueces R	Laguna (08190000) to Cinonia	5/16-17/1931	56.5	11	11	Carrizo-Wilcox, Edwards	--	-76.0	-1.345	-974.4
199	Nueces	Nueces R	Laguna (08190000) to Cinonia	6/4-6/1931	53	10	10	Carrizo-Wilcox, Edwards	--	-84.0	-1.585	-1,148.3
200	Nueces	Nueces R	Laguna (08190000) to Cinonia	6/15-17/1931	56.5	12	12	Carrizo-Wilcox, Edwards	--	-73.6	-1.303	-944.0
201	Nueces	Nueces R	Laguna (08190000) to Cinonia	6/22-24/1931	56.5	12	12	Carrizo-Wilcox, Edwards	--	-91.9	-1.627	-1,178.7
202	Nueces	Nueces R	Laguna (08190000) to Cinonia	7/2-4/1931	56.5	12	12	Carrizo-Wilcox, Edwards	--	-82.5	-1.46	-1,057.7
206	Nueces	Nueces R	Laguna (08190000) to near Cinonia	11/1-4/1932	56.5	14	14	Carrizo-Wilcox, Edwards	--	28.0	0.496	359.3
207	Nueces	Nueces R	Laguna (08190000) to near Cinonia	7/23-25/1933	56.5	14	14	Carrizo-Wilcox, Edwards	--	-8.7	-0.154	-111.6
210	Nueces	Nueces R	Uvalde (08204000) to Cinonia	7/13/1931	33.8	7	7	Carrizo-Wilcox	--	4.0	0.118	85.5
219	Nueces	Nueces R	US 90 to near Crystal City	11/23-25/1964	52.2	19	10	Carrizo-Wilcox	--	13.4	0.257	186.2
244	Red River	Little Cypress Cr	SH 155 to FM 134	6/10-13/1964	49.1	35	10	Carrizo-Wilcox	Queen City	6.52	0.133	96.4
245	Red River	Little Cypress Cr	northeast of Gilmer to near Jefferson	1/2-3/1964	40.5	7	7	Carrizo-Wilcox	Queen City	24.09	0.595	431.1
249	Red River	Sugar Cr	FM 1403 to SH 154	6/10-11/1964	0.8	3	2	--	Queen City	0.15	0.188	136.2
325	Rio Grande	Rio Grande	Eagle Pass to Laredo	2/22-4/12/1928	128	6	6	--	--	-10.0	-0.078	-56.5
327	Rio Grande	Rio Grande	Eagle Pass to Laredo	4/3-22/1928	128	6	6	--	--	-75.0	-0.586	-424.5
328	Rio Grande	Rio Grande	Eagle Pass to San Ygnacio	2/12-22/1926	167.5	22	17	Carrizo-Wilcox	--	-336.0	-2.006	-1,453.3
342	Sabine	Lake Fk Cr	SH 182 to US 80	8/31-9/1/1981	1.6	3	3	Carrizo-Wilcox	Queen City	-2.6	-1.625	-1,177.3
345	Sabine	Sabine R	FM 1804 to FM 2517	9/22-24/1981	156.4	11	10	Carrizo-Wilcox	Queen City	127.8	0.817	591.9
346	Sabine	Sabine R	Wills Point (08017410) to Smith-Upshur Co line at county road crossing	8/31-9/2/1981	80.5	8	6	Carrizo-Wilcox	Queen City	427.42	5.31	3,846.9

Table 4.7.1, continued

Streamflow Study No.	Major River Basin	Stream Name	Reach Identification	Date of Study	Reach Length (river mi)	Total No. of Measurement Sites	No. of Measurement Sites on Main Channel	Aquifer Outcrop(s) Intersected by Reach		Total Gain or Loss (-) In Reach (ft^3/s)	Gain or Loss per Mile of Reach (ft^3/s per mile)	Gain or Loss per Mile of Reach (AFY per mile)
								Major Aquifers	Minor Aquifers			
347	Sabine	Sabine R	northeast of Carthage to Ruliff (08030500)	9/4-5/1963	268	98	30	Carrizo-Wilcox, Gulf Coast	Sparta	208.72	0.779	564.4
349	San Antonio	Cibolo Cr	near Randolph AFB to mouth	3/5-7/1963	79.3	18	13	Carrizo-Wilcox, Gulf Coast	Queen City	16.68	0.21	152.1
350	San Antonio	Cibolo Cr	Selma (08185000) to mouth	3/4-8/1968	87.1	52	27	Carrizo-Wilcox, Gulf Coast	Queen City, Sparta	59.53	0.683	494.8
364	Trinity	Big Elkhart Cr	northwest of Grapeland to mouth	9/15-16/1965	25.7	9	7	--	Queen City	5.18	0.202	146.3
365	Trinity	Little Elkhart Cr	south of Grapeland to mouth	9/16/1965	17.5	11	5	--	Queen City, Sparta	-1.59	-0.091	-65.9

ft^3/s = cubic feet per second
AFY = acre-feet per year

Table 4.7.2 Gain/Loss estimates developed from WAMs for reaches crossing the Queen City and Sparta outcrop (see Appendix B).

River	Gain – Loss (ft^3/day per mile)	Gain – Loss (AFY per mile)
Angelina River	-32,639	-274
Atascosa River	18,064	151
Big Cypress Bayou	NA	NA
Black Cypress Bayou	64,198	538
Brazos River	159,763	1,340
Cibolo Creek	4,895	41
Colorado River	4,846	41
Frio River	12,926	108
Guadalupe River	28,038	235
Leona River	NA	NA
Navasota River	5,223	44
Neches River	153,851	1,290
Nueces River	-18,924	-159
Rio Grande	-8,344	-70
Sabine River	41,845	351
San Antonio River	25,690	215
San Marcos River	-33,111	-278
Sulphur River	-557	-5
Trinity River	202,366	1,697

ft^3/day = cubic feet per day
AFY = acre-feet per year

Table 4.7.3 LBG-Guyton and HDR Engineering(1998) simulated values (AFY per mile of stream).

Stream	1950		Historic Period 1980-1990	
	Gaining	*Losing*	*Gaining*	*Losing*
Cibolo Creek	200			100
Guadalupe River	180		50	
Nueces River	0			500
San Antonio River	540			325
San Marcos River	110		100	
San Miguel River		110		100
Frio River		100		500
Atascosa River	270			50

AFY = acre-feet per year

Table 4.7.4 HDR Stream Calibration Targets for Central Carrizo-Wilcox GAM (after Dutton et al., 2003).

River Name	Base Flow (AFY)	Base Flow (AFY per mile stream)
San Antonio River	13,700	269
Cibolo Creek	6,700	223
Guadalupe River	10,900	519
San Marcos River	11,100	150
Colorado River	26,100	242
Middle Yegua Creek	5,200	NA
East Yegua Creek	2,200	200
Brazos River	23,400	263
Navasota River	8,100	105
Trinity River	26,300	98

AFY = acre-feet per year

Table 4.7.5 Documented springs in the study area.

County	Spring	Formation	Flow Rate LPS	Flow Rate GPM	Flow Rate CFS	Date of Measurement	SOURCE
Bastrop	Springs in Sandy Creek	Wilcox	32.0	507	1.13	3-11-78	Brune (1981)
Bexar	Martinez Springs	Wilcox	45.3	718	1.60	3-5-63	Brune (1975)
Burleson	Sour or Spring Lake Springs	Sparta	11.3	180	0.40	1936	Brune (1975)
Camp	Couch or Lee Springs	Queen City	7.6	120	0.27	1-21-78	Brune (1981)
Cherokee	Rocky Springs	Weches	7.5	119	0.26	11-4-99	Brune (1981)
Cherokee	Springs	Weches	45.0	713	1.59	11-3-79	Brune (1981)
Dimmit	Carrizo Springs (1 of 2)	Carrizo	37.0	586	1.31	12-30-1901	Brune (1981)
Dimmit	Carrizo Springs (2 of 2)	Carrizo	7.4	117	0.26	1892	Brune (1981)
Franklin	Tanyard Springs	Reklaw	44.0	697	1.55	1898	Brune (1981)
Houston	Caney Creek Springs	Sparta	48.1	763	1.70	9-16-65	Brune (1975)
Houston	Elkhart Creek Springs	Sparta	96.3	1526	3.40	9-15-65	Brune (1975)
Houston	Hays Branch Springs	Sparta	51.0	808	1.80	9-16-65	Brune (1975)
Nacogdoches	Spring	Carrizo	14.2	225	0.50	3-1-42	County Reports
Nacogdoches	Tonkawa Springs (1 of 3)	Carrizo	14.0	222	0.49	3-31-42	Brune (1981)
Nacogdoches	Tonkawa Springs (2 of 3)	Carrizo	13.0	206	0.46	12-4-68	Brune (1981)
Nacogdoches	Tonkawa Springs (3 of 3)	Carrizo	11.0	174	0.39	2-11-78	Brune (1981)
Nacogdoches	Waterworks Springs (1 of 2)	Sparta	13.0	206	0.46	1914	Brune (1981)
Nacogdoches	Waterworks Springs (2 of 2)	Sparta	13.0	206	0.46	2-13-78	Brune (1981)
Rains	Springs	Wilcox	6.8	108	0.24	9-24-79	Brune (1981)
Rains	Springville Springs	Wilcox	14.0	222	0.49	9-24-79	Brune (1981)
Rusk	Spring	Queen City	14.4	228	0.51	11-17-78	TWDB well database
Smith	Spring Lake Springs	Queen City	36.0	571	1.27	10-31-79	Brune (1981)
Smith	Cool Springs and other nearby springs	Reklaw	6.8	108	0.24	11-1-79	Brune (1981)
Smith	Springs in Ray Creek	Sparta and Weches	23.0	365	0.81	10-30-79	Brune (1981)
Titus	Priefert Springs	Wilcox	9.6	152	0.34	12-16-77	Brune (1981)
Upshur	Hoover Springs and other nearby springs	Queen City	6.5	103	0.23	1-17-78	Brune (1981)
Upshur	Horn Springs	Queen City	14.0	222	0.49	1-20-78	Brune (1981)
Upshur	Valley Springs	Queen City	14.0	222	0.49	1-20-78	Brune (1981)
Van Zandt	Roher Springs (1 of 2)	Carrizo	14.0	222	0.49	9-27-79	Brune (1981)
Van Zandt	Roher Springs (1 of 2)	Carrizo	11.7	185	0.41	9-6-95	TWDB well database
Van Zandt	Cherokee Springs	Queen City	7.5	119	0.26	9-26-79	Brune (1981)
Van Zandt	Red Hill Springs	Queen City	7.2	114	0.25	9-26-79	Brune (1981)
Van Zandt	Jordan's Saline Springs	Wilcox	28.0	444	0.99	2-27-63	Brune (1981)
Van Zandt	Old Liberty Springs	Wilcox	12.0	190	0.42	9-28-79	Brune (1981)
Van Zandt	Riley Springs	Wilcox	17.0	269	0.60	9-28-79	Brune (1981)
Wilson	Sutherland Springs	Carrizo	42.5	673	1.50	1949	Brune (1975)
Wood	Dumas Spring	Carrizo and Wilcox	6.3	100	0.22	Estimated	TWDB well database
Wood	Big Woods Springs	Queen City	9.5	151	0.34	10-23-79	Brune (1981)
Wood	Gunstream Springs	Queen City	92.0	1458	3.25	1978	Brune (1981)
Wood	Holly Springs and other nearby springs	Queen City	55.0	872	1.94	10-22-79	Brune (1981)

Table 4.7.5, continued

County	Spring	Formation	Flow Rate LPS	Flow Rate GPM	Flow Rate CFS	Date of Measurement	SOURCE
Wood	Mill Race Springs	Queen City	9.2	146	0.32	10-22-79	Brune (1981)
Wood	Peach Springs	Queen City	11.0	174	0.39	10-22-79	Brune (1981)
Wood	Spring fed creek	Queen City	45.0	713	1.59	10-22-79	Brune (1981)
Wood	Springs	Queen City and Weches	6.5	103	0.23	10-1-79	Brune (1981)
Wood	Springs in Running Creek	Wilcox	60.0	951	2.12	10-23-79	Brune (1981)

LPS = liters per second
GPM = gallons per minute
CFS = cubic feet per second

File: Stream_Gage_Location

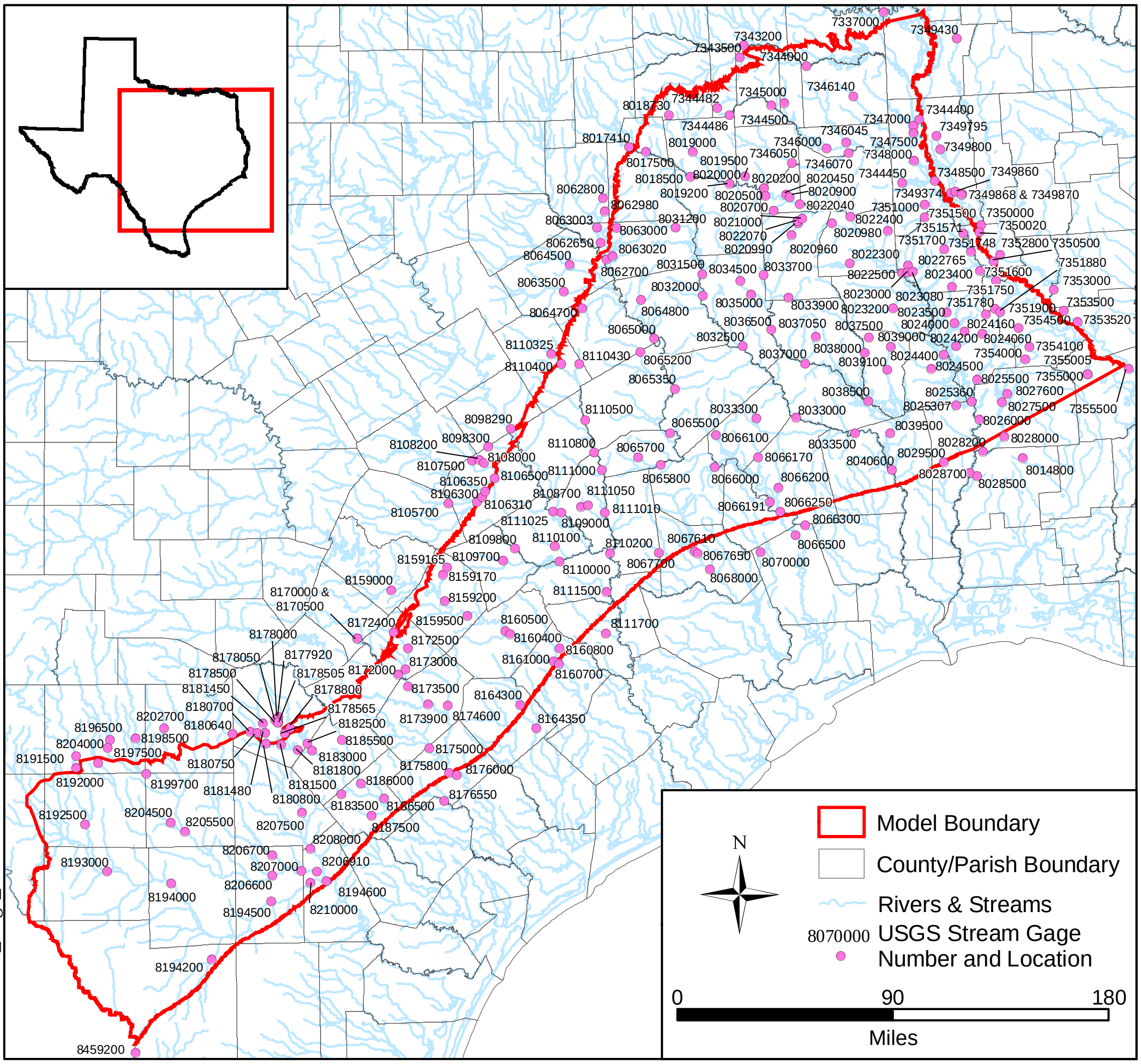


Figure 4.7.1 Stream gage locations in the study area.

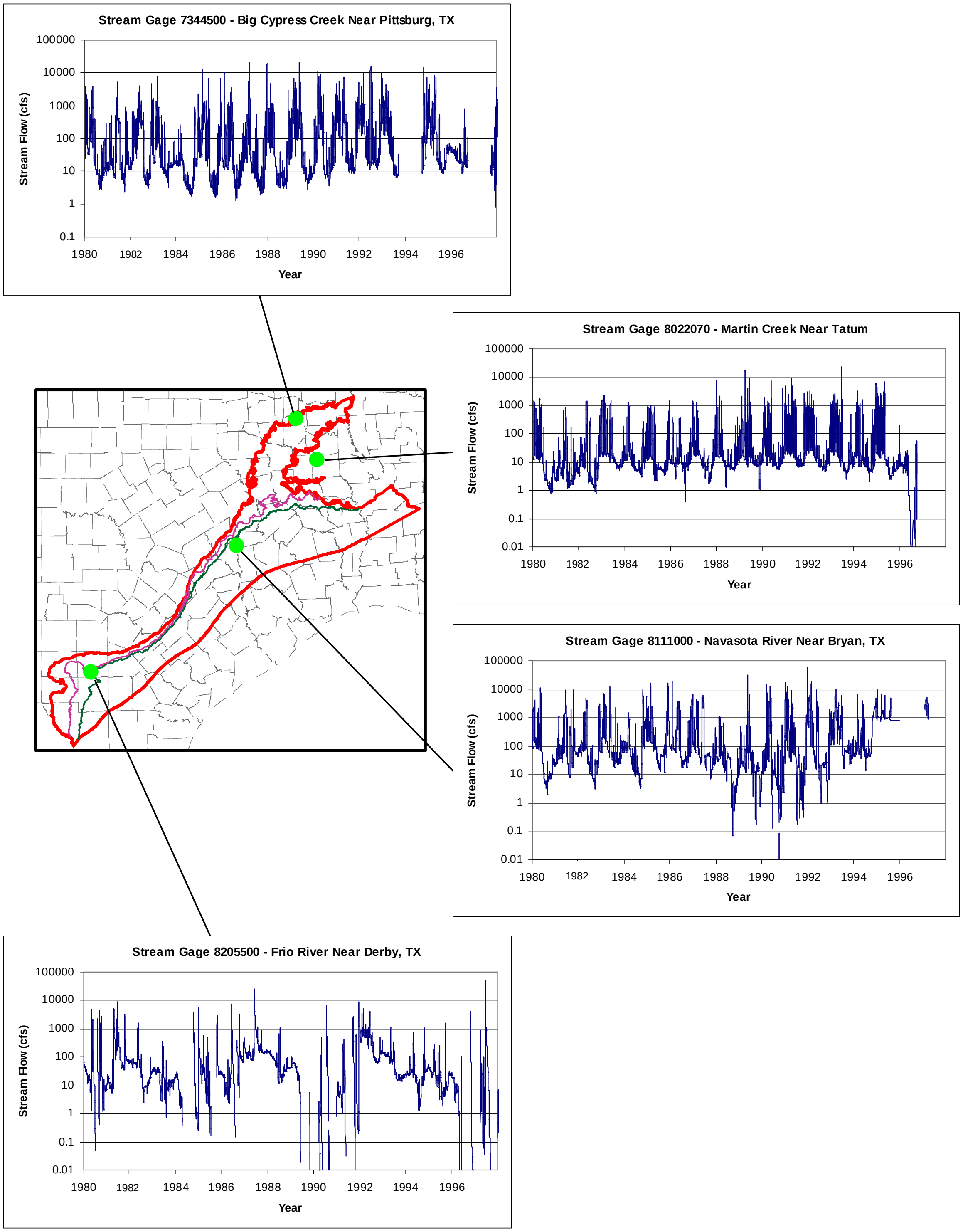


Figure 4.7.2 Stream hydrographs for selected streams in the study area.

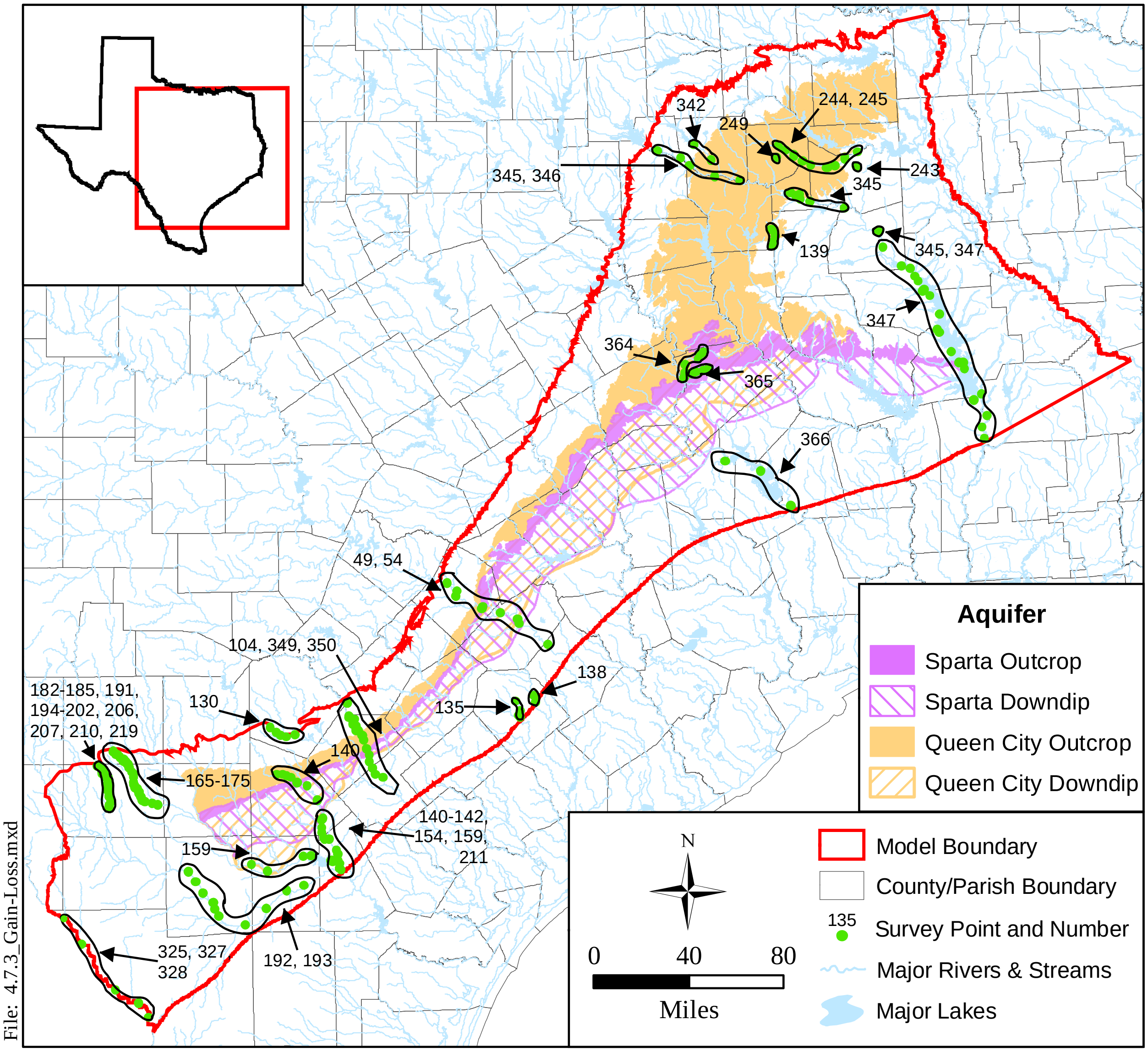


Figure 4.7.3 Stream gain/loss studies in the study area (after Slade et al., 2002).

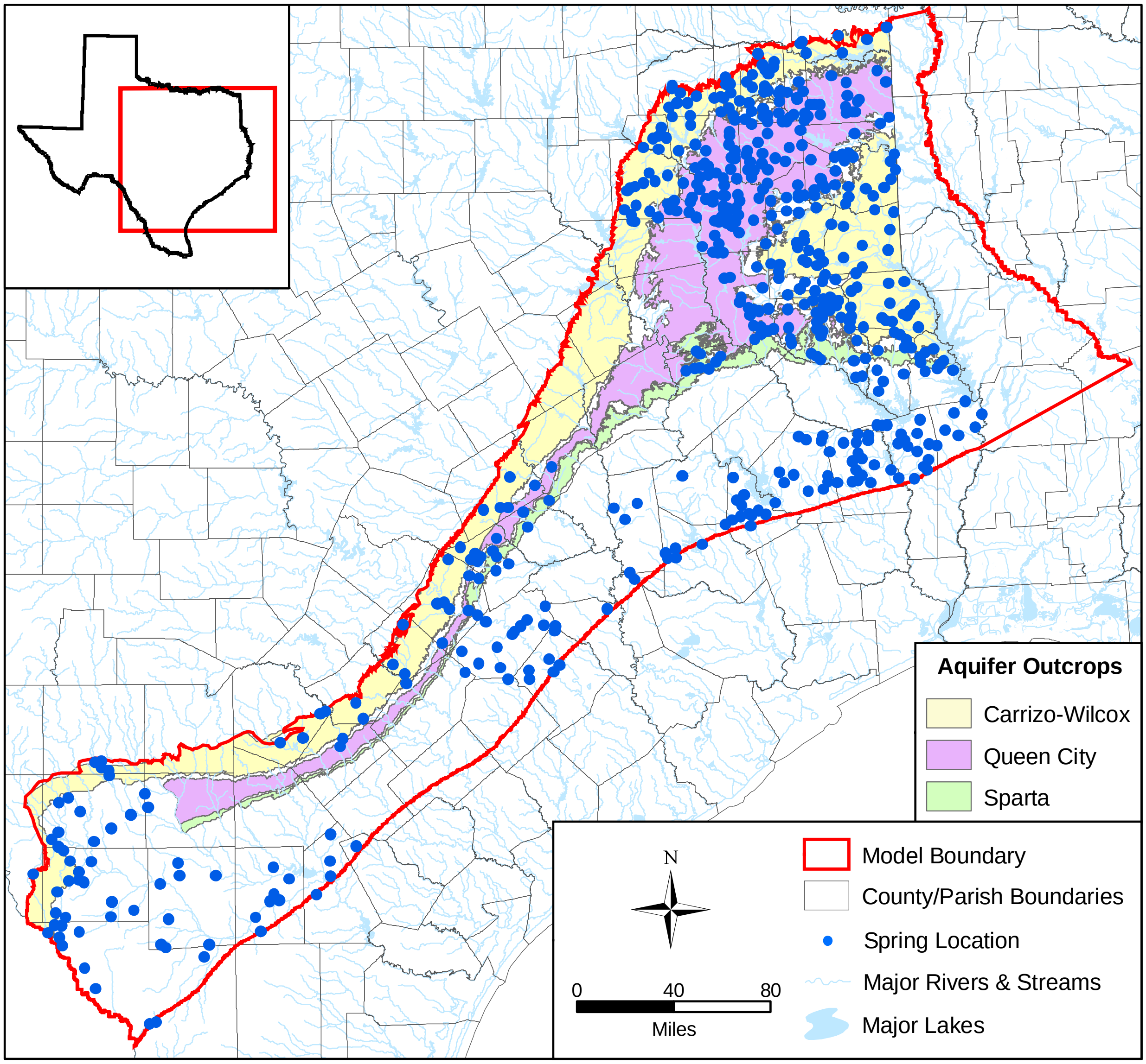


Figure 4.7.4 **Documented spring locations in the study area.**

4.8 Aquifer Discharge Through Pumping

Pumping discharge estimates for each model cell were developed for both the historical period (1980 to 1999) and for the predictive period (2000 to 2050). Historical estimates of groundwater pumping throughout Texas have been provided by the TWDB as a water use survey database. Each water use record in the database carries an aquifer identifier that was used to select pumping records for the Sparta and Queen City aquifers. Groundwater pumping estimates for the part of the study area in Arkansas were based upon data provided by the Arkansas Soil & Water Conservation Commission. The USGS provided groundwater pumping estimates for the Louisiana parishes in the study area.

The seven water use categories defined in the TWDB database are municipal (MUN), manufacturing (MFG), power generation (PWR), mining (MIN), livestock (STK), irrigation (IRR), and county-other (C-O), which consists primarily of unreported domestic water use. The methodology used to distribute the pumping estimates for each aquifer is described below. A detailed description of the procedures used to develop the historical and predictive pumping data sets can be found in Appendices C and D, respectively.

Municipal, manufacturing, mining, and power pumping estimates are actual water use records reported by the water user, which are available for 1980 through 2000. The water use survey also includes historical annual pumping estimates for livestock, irrigation, and county-other for the years 1980 through 1997 for each county-basin. A county-basin is a geographic unit created by the intersection of county and river basin boundaries. For example, Anderson County, which is intersected by both the Trinity River Basin and the Neches River Basin, contains two county-basins. Annual pumping estimates for the years 1998 and 1999 were developed by linear regression based on significant relationships between reported pumping and (1) average annual temperature, (2) total annual rainfall measured at the nearest weather station, and (3) the year, for each water use category.

Reported historical pumping for municipal, manufacturing, mining, and power water uses was matched to the specific wells from which it was pumped to identify the location in the aquifer from which it was drawn (latitude, longitude, and depth below mean sea level) based on the well’s reported properties. The well properties were obtained by compiling data from the

TWDB's state well database, the TCEQ's Public Water System database, the USGS's National Water Information System, the TWDB's follow up survey with water users, and various other minor sources. When more than one well was associated with a given water user, groundwater withdrawals were divided evenly among those wells.

Livestock pumping totals within each county-basin were distributed uniformly over the rangeland within the county-basin, based on land use maps, using the categories "herbaceous rangeland", "shrub and brush rangeland", and "mixed rangeland".

County-other pumping was distributed within each county-basin based on population density (Figure 4.8.1), after excluding urban areas which would generally be served by municipal water suppliers. The 1990 federal block-level census data was used for the years 1980 to 1990, and the 2000 census data was used for the years 1991 to 1999. The county-other pumping in the historical period was not assigned on an aquifer basis. Several methods for allocating county-other pumping between available aquifers were reviewed. A vertical aquifer allocation consistent with the predictive allocation was finally chosen for use. In some instances, the vertical allocation was adjusted from the predictive if the aquifer allocation was inconsistent with county reports or other information. The re-allocation of the county-other pumping required changes to the Carrizo-Wilcox aquifer pumping data sets for the county-other pumping category.

Irrigation pumping within each county-basin was spatially distributed across the land use categories "row crops", "orchard/vineyard", and "small grains". However, the pumping was not uniformly distributed across these land uses, but weighted based on proximity to irrigated farms mapped from the irrigated farmlands surveys performed in 1989 and 1994 by the Natural Resource Conservation Service of the U.S. Department of Agriculture. The 1989 irrigation survey was used for pumping between 1980 and 1989, while the 1994 survey was used for pumping from 1990 to 1999.

Predictive estimates of groundwater pumping throughout Texas have been provided by the TWDB in a form similar to the historical pumping database. As with the historical pumping database, pumping is provided for each of the seven use categories and each water use record carries an aquifer identifier. The TWDB predicted groundwater pumping for the period 2000 through 2050 based on projected water demand reported by RWPGs as part of Senate Bill 1 planning (TWDB, 2002). The RWPG water demand projections are available for the years 2000, 2010, 2020, 2030, 2040, and 2050. Projections for the intervening years were developed by linear interpolation. In some cases, the RWPGs identified new well field locations for developing new water supplies. In such instances, the specific locations of the future well fields were used to spatially distribute the groundwater pumping forecasts. However, in the absence of any data indicating otherwise, the most recent past spatial distribution of groundwater pumping was assumed to represent the best available estimate of the locations of future groundwater withdrawals.

Predicted municipal water use totals for each public water supplier were matched to the same wells used by that water user in 1999. Similarly, for manufacturing, mining, and power generation, predicted future water pumping totals by county-basin were distributed among the same wells and locations used by those water users in 1999. Irrigation, county-other, and livestock pumping estimates for each county-basin from 2000 to 2050 also used the 1999 spatial distribution within county-basins.

Estimates of projected Arkansas and Louisiana groundwater pumping for 2000 through 2050 are not available. Municipal and county-other pumping totals for future years were predicted by multiplying the per capita consumption for the period 1995 to 1999 by the projected future county/parish populations supplied by the state demographers. Predicted future pumping for other water use categories in Louisiana and Arkansas were not projected. Instead, pumping in future years was assumed to be equal to the average pumping for the period 1995 to 1999.

Pumping for the Sparta, Queen City, and Carrizo-Wilcox aquifers has been summed by county (or parish in Louisiana) for each aquifer and summed over the entire study area in Texas. Tables 4.8.1 through 4.8.3 list total groundwater withdrawals from the Sparta, Queen City, and Carrizo-Wilcox aquifers, respectively, by county or parish for the years 1980, 1990, 1999, 2000, 2010, 2020, 2030, 2040 and 2050. Figures 4.8.2 and 4.8.3 provide bar chart summaries of pumping totals for the Sparta and Queen City aquifers, respectively, in the model region in Texas, Arkansas, and Louisiana by year from 1980 through 2050. Pumping in both the Sparta and Queen City aquifers is projected to increase significantly from 2010 through 2050 with Sparta pumping reaching a maximum in 2050 of 32,777 AFY and the Queen City aquifer pumping reaching a maximum of 38,953 AFY in 2040.

Figures 4.8.4 and 4.8.5 post the Sparta total pumping distribution in acre-feet per year across the study area for the years 2000 and 2050, respectively. Figure 4.8.4 shows that the heaviest pumping for the Sparta aquifer is located in Atascosa, Frio, and Wilson counties in 2000. In 2050 (Figure 4.8.5), Frio and Wilson counties are projected to still be the locations of greatest pumping.

Figures 4.8.6 and 4.8.7 post the Queen City total pumping distribution in acre-feet per year across the study area for the years 2000 and 2050, respectively. Figure 4.8.6 shows that the heaviest pumping for the Queen City aquifer is located in Atascosa, Frio, Henderson, and Wilson counties in 2000. In 2050 (Figure 4.8.7), Frio, Henderson, Nacogdoches, and Wilson counties are projected to be the locations of greatest pumping.

Figures 4.8.8 and 4.8.9 plot total groundwater pumping by category for the Sparta and Queen City aquifers from 1980 through 2050, respectively. As can be seen in Figure 4.8.8, the projected large increase in Sparta pumping between 2000 and 2030 is related to irrigation use. After 2030, municipal, mining, power, and manufacturing pumping is projected to increase to levels in excess of the other pumping categories. Tables 4.8.4, 4.8.6, 4.8.8 and 4.8.10 summarize the groundwater withdrawals from the Sparta aquifer by point sources (municipal, mining, power, and manufacturing), county-other, irrigation, and livestock use categories, respectively.

Figure 4.8.9 shows that, for the Queen City aquifer, the projected increase in pumping after the year 2000 is largely driven by municipal, mining, power, and manufacturing production. Irrigation pumping is also projected to increase over historical production rates. Tables 4.8.5, 4.8.7, 4.8.9, and 4.8.11 summarize the groundwater withdrawals from the Queen City aquifer by point sources (municipal, mining, power, and manufacturing), county-other, irrigation, and livestock use categories, respectively.

Table 4.8.1 **Rate of groundwater withdrawal (AFY) from the Sparta aquifer for counties and parishes within the study area.**

County	1980	1990	1999	2000	2010	2020	2030	2040	2050
Anderson	87	137	157	333	337	339	341	341	345
Angelina	360	246	280	128	134	141	189	237	252
Atascosa	1,037	421	520	9,231	9,299	9,413	10,954	12,172	12,315
Bastrop	47	36	29	993	978	1,015	996	981	970
Brazos	359	510	569	1,233	1,304	1,382	1,395	1,325	1,247
Burleson	416	449	617	413	421	416	442	427	421
Caddo	12	23	42	24	24	24	24	24	24
Cherokee	251	158	223	153	148	148	149	149	149
Fayette	181	184	243	1,657	1,716	1,799	1,891	1,988	2,118
Frio	67	73	88	4,390	4,392	4,392	4,388	4,396	4,400
Gonzales	634	469	553	920	862	813	800	780	766
Grimes				80	80	80	80	80	80
Houston	580	662	708	914	1,222	1,585	1,961	2,318	2,773
La Salle	3,141	360	1,316	158	150	142	343	324	305
Lee	66	58	78	96	94	91	89	86	84
Leon	50	96	78	7	8	9	9	10	11
Madison	1,652	1,836	1,816	1,130	1,124	1,056	1,004	930	855
McMullen	0	0	0	20	8	4	3	1	1
Miller		0	35	1	1	1	1	1	1
Nacogdoches	271	280	340	205	205	191	198	194	204
Natchitoches	396	722	502	144	144	144	144	144	144
Robertson	85	83	111						
Sabine, TX	75	99	67	47	50	53	50	54	55
Sabine, LA	249	463	349	46	46	46	46	46	46
San Augustine	109	117	71	259	301	362	414	479	564
Trinity	9	13	15						
Wilson	224	372	505	3,386	3,282	3,436	4,758	4,675	4,647
Total	10,359	7,871	9,315	25,969	26,329	27,083	30,670	32,161	32,777

All withdrawals rounded to the nearest AFY.
AFY = acre-feet per year

Table 4.8.2 **Rate of groundwater withdrawal (AFY) from the Queen City aquifer for counties and parishes within the study area.**

County	1980	1990	1999	2000	2010	2020	2030	2040	2050
Anderson	553	682	777	797	808	813	819	817	828
Angelina	239	85	96	59	60	63	61	60	63
Atascosa	4,519	1,094	968	2,910	2,932	2,968	3,454	3,838	3,883
Bastrop	131	144	185	595	597	620	622	620	615
Brazos	268	363	432	424	512	604	634	587	533
Burleson	176	136	252	104	104	104	104	104	104
Caddo	13	20	31	31	31	32	32	33	35
Caldwell	48	62	133	123	118	114	136	121	106
Camp	196	211	254	117	117	117	117	117	117
Cass	547	507	528	1,444	1,180	1,132	1,092	1,062	698
Cherokee	709	737	906	1,072	1,040	1,286	1,562	1,695	1,852
Fayette	42	49	58	390	420	464	513	563	627
Freestone	30	21	40						
Frio	818	875	69	2,545	2,545	2,544	2,544	2,547	2,549
Gonzales	706	242	242	343	321	301	297	289	284
Grant				0	0	0	0	0	0
Gregg	302	280	292						
Harrison	396	392	409	152	72	33	26	26	26
Henderson	513	849	786	917	926	927	921	912	925
Houston	202	218	251	310	328	326	326	332	331
La Salle	2	2	2	49	46	44	104	98	93
Lee	296	235	392	36	36	37	37	38	38
Leon	646	862	765	150	160	172	184	197	213
Madison	45	52	63	96	95	107	103	100	105
Marion	131	143	149	156	156	156	156	156	156
McMullen	0	0	0	36	15	7	5	3	2
Milam	26	29	28						
Miller	1	1	1	1	1	1	1	1	1
Morris	184	189	207	4,561	4,546	4,542	4,540	4,540	4,541
Nacogdoches	253	265	315	259	552	1,055	1,434	1,950	2,366
Natchitoches	14	36	48	99	104	112	122	134	148
Rapides				0	0	0	0	0	0
Robertson	122	120	160						
Rusk	63	63	58	245	205	176	213	211	250
Sabine	2		1	134	144	156	168	181	195
Smith	1,119	1,265	1,174	771	524	524	524	524	525
Upshur	727	883	1,291						
Van Zandt	172	226	251						
Vernon				3	3	3	3	4	5
Wilson	76	127	172	1,313	1,256	1,593	1,813	1,885	1,928
Wood	3,075	1,588	1,445	1,200	16,682	16,442	16,205	15,205	3,739
Total	17,362	13,054	13,233	21,443	36,638	37,573	38,872	38,953	27,881

All withdrawals rounded to the nearest AFY.
AFY = acre-feet per year

Table 4.8.3 **Rate of groundwater withdrawal (AFY) from the Carrizo-Wilcox aquifers for counties and parishes in the study area.**

County	1980	1990	1999	2000	2010	2020	2030	2040	2050
Anderson	3,178	4,187	4,659	6,670	6,749	6,718	6,754	6,719	6,831
Angelina	21,092	18,456	19,642	13,957	12,239	11,616	12,505	13,158	14,336
Atascosa	72,076	55,763	55,032	17,303	17,753	18,281	8,828	10,947	17,059
Bastrop	5,778	6,274	8,857	10,393	19,183	22,938	21,620	25,452	33,520
Bee	60	67	77	80	81	80	82	84	88
Bexar	12,237	15,784	16,874	18,763	19,271	18,648	13,032	13,271	11,432
Bossier	114	66	97	95	98	102	108	115	123
Bowie	2,911	3,631	3,563	686	724	724	724	650	554
Brazos	18,813	23,693	29,414	29,518	39,967	45,339	44,783	49,020	52,693
Burleson	1,717	1,913	2,020	1,969	4,958	4,776	4,851	4,994	5,275
Caddo	5,009	3,802	4,628	5,094	5,243	5,534	5,970	6,549	7,223
Caldwell	2,876	3,912	3,639	7,118	7,526	7,895	8,237	8,293	8,323
Camp	1,368	1,669	1,324	1,535	1,831	1,856	1,886	1,907	1,922
Cass	3,639	3,987	2,758	789	799	804	810	862	866
Cherokee	6,781	7,339	7,866	8,325	4,169	4,265	4,448	4,633	4,872
De Soto	1,907	1,378	2,458	251	252	254	256	259	263
DeWitt	6	5	1	137	73	44	25	19	13
Dimmit	22,256	9,330	4,486	10,476	10,097	10,121	10,469	10,550	10,692
Falls	240	292	296	244	882	884	892	901	911
Fayette	7	4	3	1	0	0	0	0	0
Franklin	1,271	1,556	1,501	1,754	1,661	1,616	1,558	1,623	1,679
Freestone	2,328	2,645	2,967	2,868	3,245	3,226	3,255	3,287	3,314
Frio	77,177	83,182	110,016	20,503	20,606	20,661	5,599	5,708	5,793
Gonzales	3,304	4,309	2,615	17,937	19,046	23,457	32,759	34,874	36,788
Gregg	2,947	2,453	2,739	1,983	2,253	2,237	2,322	2,396	2,462
Grimes					1	1	1	1	1
Guadalupe	3,873	5,843	6,083	4,793	6,080	7,626	8,873	9,764	10,046
Harrison	3,408	4,163	4,006	3,095	3,163	3,457	3,540	3,624	3,662
Hempstead		13	20	21	21	21	21	21	21
Henderson	4,405	6,517	7,619	5,167	4,918	4,917	4,920	4,905	4,980
Hopkins	3,169	4,328	5,029	1,371	1,596	1,592	1,634	1,728	1,769
Houston	795	554	843	1,199	1,204	1,208	1,213	1,220	1,226
Karnes	1,559	718	473	2,003	1,714	1,538	1,274	1,179	1,085
La Salle	9,032	7,292	8,295	4,929	4,741	4,542	4,107	3,971	3,832
Lafayette		98	157	149	149	149	149	149	149
Lavaca	0	0		0	0	0	0	0	0
Lee	2,128	2,949	10,362	13,082	59,906	62,769	63,028	65,096	71,642
Leon	1,875	2,811	3,171	2,855	5,440	5,025	5,069	5,173	5,366
Limestone	1,572	3,094	2,817	2,506	11,446	11,507	11,642	11,830	12,140
Live Oak	114	77	85	170	170	170	170	170	170
Madison	80	93	97	170	1,634	1,589	1,543	1,491	1,454
Marion	842	932	1,105	721	710	711	716	720	738
Maverick	2,003	5,013	3,300	372	909	1,447	1,351	1,214	1,091
McMullen	420	1,554	123	2,134	2,058	2,018	516	813	2,175

Table 4.8.3, continued

County	1980	1990	1999	2000	2010	2020	2030	2040	2050
Medina	8,446	1,711	5,012	6,515	6,576	6,614	2,413	2,468	2,560
Milam	2,817	15,364	23,929	25,730	21,651	21,127	21,123	21,767	23,068
Miller	15	8,663	14,400	7,098	7,102	7,105	7,108	7,111	7,114
Morris	1,810	7,655	1,268	703	705	689	683	667	660
Nacogdoches	15,561	14,380	13,987	11,234	11,529	11,545	12,559	13,623	14,665
Natchitoches	496	519	700	946	974	1,013	1,062	1,122	1,187
Navarro	116	162	179	3	16	16	16	16	16
Panola	3,494	4,654	4,468	3,935	3,629	3,300	4,186	4,208	4,179
Rains	623	1,001	1,143	443	468	490	332	353	373
Red River	24	101	301	179	180	181	183	186	189
Robertson	7,067	8,409	22,788	22,723	26,645	27,219	30,912	32,056	33,306
Rusk	7,233	7,914	7,649	7,963	6,964	6,793	6,873	6,845	6,992
Sabine	1,319	1,274	2,526	3,268	3,505	3,752	4,011	4,288	4,517
San Augustine	590	601	635	498	495	488	495	493	498
Shelby	2,987	3,185	3,569	3,442	3,901	3,239	3,652	4,115	4,659
Smith	10,891	11,098	13,485	18,431	19,327	20,837	22,125	24,143	23,708
Titus	1,525	1,914	1,979	2,875	3,185	3,252	3,395	3,476	3,525
Trinity	15	22	25						
Upshur	3,386	3,814	4,588	3,347	3,546	3,548	3,602	3,599	3,645
Uvalde	4,925	588	596	4,422	4,363	4,321	1,537	1,526	1,505
Van Zandt	4,853	5,437	5,828	4,612	4,988	6,150	6,040	6,272	6,517
Walker					0	0	0	0	0
Webb	359	595	925	1,684	7,159	8,895	12,465	12,485	12,508
Williamson	1	1	1	1	7	7	7	7	7
Wilson	9,695	15,343	17,365	24,495	24,444	23,282	22,217	22,850	23,570
Wood	3,933	3,908	4,461	4,646	5,026	5,326	5,716	6,044	6,566
Zavala	85,453	80,158	48,776	26,585	26,660	26,632	7,447	7,692	7,995
Total	482,000	500,221	541,702	408,968	497,609	518,184	481,700	506,751	542,110

All withdrawals rounded to the nearest AFY.
AFY = acre-feet per year

Table 4.8.4 **Rate of municipal, mining, power, and manufacturing groundwater withdrawal (AFY) from the Sparta aquifer for counties and parishes within the study area.**

County	1980	1990	1999	2000	2010	2020	2030	2040	2050
Angelina				24	26	30	33	37	42
Atascosa				3,592	3,599	3,628	9,448	10,407	10,464
Bastrop				13	11	10	10	11	13
Brazos	7	0		27	27	28	30	32	34
Burleson	289	352	438	276	289	290	321	311	310
Caddo	12	11	18						
Fayette				658	711	786	870	954	1,060
Frio				78	66	62	116	114	113
Gonzales	206	192	276	221	235	246	263	281	298
Grimes				80	80	80	80	80	80
Houston				61	91	138	177	219	281
La Salle	88	117	133						
Madison	868	970	824						
McMullen				20	8	4	3	1	1
Miller			35						
Natchitoches	270	164	181						
Sabine, LA	153	311	303						
Wilson				53	39	34	44	48	51
Total	1,893	2,118	2,208	5,102	5,183	5,336	11,395	12,496	12,746

All withdrawals rounded to the nearest AFY.
AFY = acre-feet per year

Table 4.8.5 **Rate of municipal, mining, power, and manufacturing groundwater withdrawal (AFY) from the Queen City aquifer for counties and parishes within the study area.**

County	1980	1990	1999	2000	2010	2020	2030	2040	2050
Atascosa				1,133	1,135	1,144	2,979	3,281	3,299
Bastrop				12	9	7	5	4	6
Caldwell				2	2	2	3	3	3
Cass	3			1,209	945	897	857	827	463
Cherokee						242	515	646	800
Fayette				329	357	396	441	484	538
Frio				46	38	35	69	67	66
Gonzales				82	87	90	96	103	109
Gregg	3								
Harrison	1			126	46	7			
Lee				6	7	8	9	11	12
Leon	194	148	164						
Marion			3						
McMullen				36	15	7	5	3	2
Morris				4,414	4,399	4,395	4,393	4,393	4,394
Nacogdoches				79	85	95	161	176	192
Rusk				132	95	64	60	57	53
Smith	154			259	13	11	11	11	12
Upshur	141	194	224						
Wilson				19	16	14	19	22	24
Wood	2,493	731	223	974	16,456	16,216	15,979	14,979	3,513
Total	2,989	1,073	614	8,860	23,704	23,630	25,602	25,068	13,485

All withdrawals rounded to the nearest AFY.
AFY = acre-feet per year

Table 4.8.6 Rate of county-other groundwater withdrawal (AFY) from the Sparta aquifer for counties and parishes within the study area.

County	1980	1990	1999	2000	2010	2020	2030	2040	2050
Anderson	23	36	41	164	168	170	172	172	176
Angelina	150	202	230						
Atascosa	287	418	517	566	634	748	1,506	1,764	1,851
Bastrop									
Brazos	268	356	428	462	558	658	691	640	581
Cherokee	47	59	65	12	6	7	7	7	8
Fayette	145	172	177	190	196	210	227	247	278
Frio	63	71	87	104	106	106	214	221	225
Gonzales	144	179	188	271	258	249	253	255	258
Houston	265	285	280	353	465	525	599	652	701
La Salle	8	8	9	14	14	14	38	39	39
Leon	7	10	11	7	8	9	9	10	11
Madison	539	628	641	1,130	1,124	1,056	1,004	930	855
Nacogdoches	109	149	170	28	28	28	29	29	29
Sabine, TX	40	54	63	9	9	10	10	10	9
San Augustine	59	63	61	143	140	139	140	139	140
Trinity	9	13	15						
Wilson	224	372	505	715	931	1,024	1,812	2,194	2,569
Total	2,388	3,078	3,489	4,169	4,646	4,953	6,712	7,309	7,728

All withdrawals rounded to the nearest AFY.
AFY = acre-feet per year

Table 4.8.7 **Rate of county-other groundwater withdrawal (AFY) from the Queen City aquifer for counties and parishes within the study area.**

County	1980	1990	1999	2000	2010	2020	2030	2040	2050
Anderson	264	408	469	446	456	461	468	466	477
Angelina	30	40	46						
Atascosa	88	129	159	179	200	236	475	557	584
Bastrop	34	75	98	127	138	149	163	170	172
Brazos	254	337	405	424	512	604	634	587	533
Caddo	13	8	7	7	7	8	8	9	11
Caldwell	47	61	65	82	82	82	107	95	83
Camp	30	38	44						
Cass	296	347	362						
Cherokee	304	386	420	80	41	45	48	51	53
Fayette	41	49	50	61	63	68	73	79	89
Frio	36	41	50	60	61	60	124	128	130
Gonzales	54	67	71	101	96	93	95	95	96
Grant				0	0	0	0	0	0
Gregg	237	228	243						
Harrison	262	364	389						
Henderson	248	425	509	506	515	516	511	501	515
Houston	90	97	96	115	126	126	126	126	127
La Salle	2	2	2	5	5	5	12	12	12
Leon	112	175	190	150	160	172	184	197	213
Madison	45	52	53	96	95	107	103	100	105
Marion	91	101	104						
Miller	1	1	1	1	1	1	1	1	1
Morris	104	113	110						
Nacogdoches	109	149	170	24	24	24	25	25	25
Natchitoches	14	36	48	99	104	112	122	134	148
Rapides				0	0	0	0	0	0
Rusk	28	35	37	24	21	22	23	23	24
Sabine, LA	2		1	134	144	156	168	181	195
Smith	606	879	935	12	12	13	13	13	13
Upshur	222	288	314						
Van Zandt	71	104	111						
Vernon				3	3	3	3	4	5
Wilson	76	127	172	245	316	347	606	731	854
Wood	172	258	312						
Total	3,986	5,422	6,045	2,980	3,184	3,409	4,091	4,286	4,464

All withdrawals rounded to the nearest AFY.
AFY = acre-feet per year

Table 4.8.8 Rate of irrigation groundwater withdrawal (AFY) from the Sparta aquifer for counties and parishes within the study area.

County	1980	1990	1999	2000	2010	2020	2030	2040	2050
Angelina	186		0						
Atascosa	730			5,072	5,065	5,036			
Bastrop	18	8	0	118	105	143	124	109	95
Bossier		0	0	0	0	0	0	0	0
Brazos				508	483	460	438	417	397
Burleson				138	132	126	121	116	111
Caddo		12	24	24	24	24	24	24	24
Cherokee	0	0	3	2	2	2	2	2	2
Fayette	23	3	53	132	132	125	117	109	103
Frio				4,208	4,220	4,224	4,058	4,061	4,062
Gonzales	30	45	34	428	369	318	284	244	211
Houston	0	11	116	107	166	239	331	379	469
La Salle	3,012	207	1,159	144	136	128	305	285	266
Lee	0	0	0	96	94	91	89	86	84
Madison			11						
McMullen	0								
Miller		0	1	1	1	1	1	1	1
Natchitoches	63	27	140	140	140	140	140	140	140
Sabine, LA	1	60	15	15	15	15	15	15	15
San Augustine				29	29	29	29	29	29
Wilson				2,618	2,312	2,377	2,902	2,433	2,027
Total	4,063	375	1,556	13,780	13,424	13,478	8,979	8,450	8,034

All withdrawals rounded to the nearest AFY.
AFY = acre-feet per year

Table 4.8.9 Rate of irrigation groundwater withdrawal (AFY) from the Queen City aquifer for counties and parishes within the study area.

County	1980	1990	1999	2000	2010	2020	2030	2040	2050
Anderson	0	2	0	0	0	0	0	0	0
Angelina	186	0	0						
Atascosa	4,382	933	770	1,599	1,597	1,588			
Bastrop	22		8	71	65	79	69	60	52
Caddo		13	24	24	24	24	24	24	24
Caldwell	0	0	68	38	34	30	26	23	20
Camp		8	8						
Cass		0	16						
Cherokee	25	50	2	569	575	575	575	575	575
Fayette	0	0	9						
Frio	748	816	2	2,439	2,446	2,449	2,351	2,352	2,353
Gonzales	30	45	38	160	138	119	106	91	79
Houston		12	64	91	91	89	88	95	96
La Salle				44	41	39	92	86	81
Lee	85	53	153	30	29	29	28	27	26
Madison		0	10						
McMullen									
Miller		0	0	0	0	0	0	0	0
Morris			0						
Rusk				62	62	62	62	62	62
Smith	25	5	53	22	22	22	22	22	22
Upshur		2	1						
Wilson				1,048	924	1,232	1,188	1,133	1,050
Wood	0	54	0	226	226	226	226	226	226
Total	5,504	1,993	1,227	6,423	6,274	6,562	4,857	4,776	4,667

All withdrawals rounded to the nearest AFY.
AFY = acre-feet per year

Table 4.8.10 Rate of livestock groundwater withdrawal (AFY) from the Sparta aquifer for counties and parishes within the study area.

County	1980	1990	1999	2000	2010	2020	2030	2040	2050
Anderson	63	101	116	169	169	169	169	169	169
Angelina	24	44	50	104	108	112	156	199	210
Atascosa	20	3	3						
Bastrop	29	28	29	862	862	862	862	862	862
Brazos	84	154	141	236	236	236	236	236	236
Burleson	127	97	179						
Cherokee	204	99	156	140	140	140	140	140	140
Fayette	13	9	13	677	677	677	677	677	677
Frio	4	2	1						
Gonzales	254	53	54						
Houston	315	365	312	393	499	684	855	1,068	1,323
La Salle	33	28	15						
Lee	66	58	78						
Leon	43	86	67						
Madison	245	238	340						
McMullen	0	0	0						
Nacogdoches	162	131	170	177	177	163	169	165	176
Natchitoches	63	317	4	4	4	4	4	4	4
Robertson	85	83	111						
Sabine, TX	35	45	4	39	41	43	40	43	47
Sabine, LA	96	91	31	31	31	31	31	31	31
San Augustine	50	54	15	87	132	195	246	311	395
Wilson									
Total	2,015	2,086	1,890	2,919	3,075	3,316	3,585	3,906	4,269

All withdrawals rounded to the nearest AFY.
AFY = acre-feet per year

Table 4.8.11 Rate of livestock groundwater withdrawal (AFY) from the Queen City aquifer for counties and parishes within the study area.

County	1980	1990	1999	2000	2010	2020	2030	2040	2050
Anderson	289	272	308	351	351	351	351	351	351
Angelina	23	44	50	59	60	63	61	60	63
Atascosa	49	32	39						
Bastrop	75	69	79	385	385	385	385	385	385
Brazos	14	26	27						
Burleson	176	136	252	104	104	104	104	104	104
Camp	166	165	201	117	117	117	117	117	117
Cass	249	160	151	235	235	235	235	235	235
Cherokee	380	301	485	424	424	424	424	424	424
Fayette									
Freestone	30	21	40						
Frio	34	18	18						
Gonzales	622	130	133						
Gregg	62	52	49						
Harrison	133	28	20	26	26	26	26	26	26
Henderson	265	424	276	410	410	410	410	410	410
Houston	112	109	94	104	111	111	112	111	109
La Salle									
Lee	211	182	238						
Leon	339	539	411						
Marion	40	42	42	156	156	156	156	156	156
McMullen									
Milam	26	29	28						
Morris	80	76	97	147	147	147	147	147	147
Nacogdoches	144	116	144	156	443	936	1,249	1,749	2,149
Robertson	122	120	160						
Rusk	35	28	21	27	27	28	68	69	111
Smith	333	381	186	478	478	478	478	478	478
Upshur	364	399	752						
Van Zandt	101	122	141						
Wilson									
Wood	409	545	910						
Total	4,883	4,566	5,353	3,180	3,476	3,972	4,323	4,823	5,265

All withdrawals rounded to the nearest AFY.
AFY = acre-feet per year

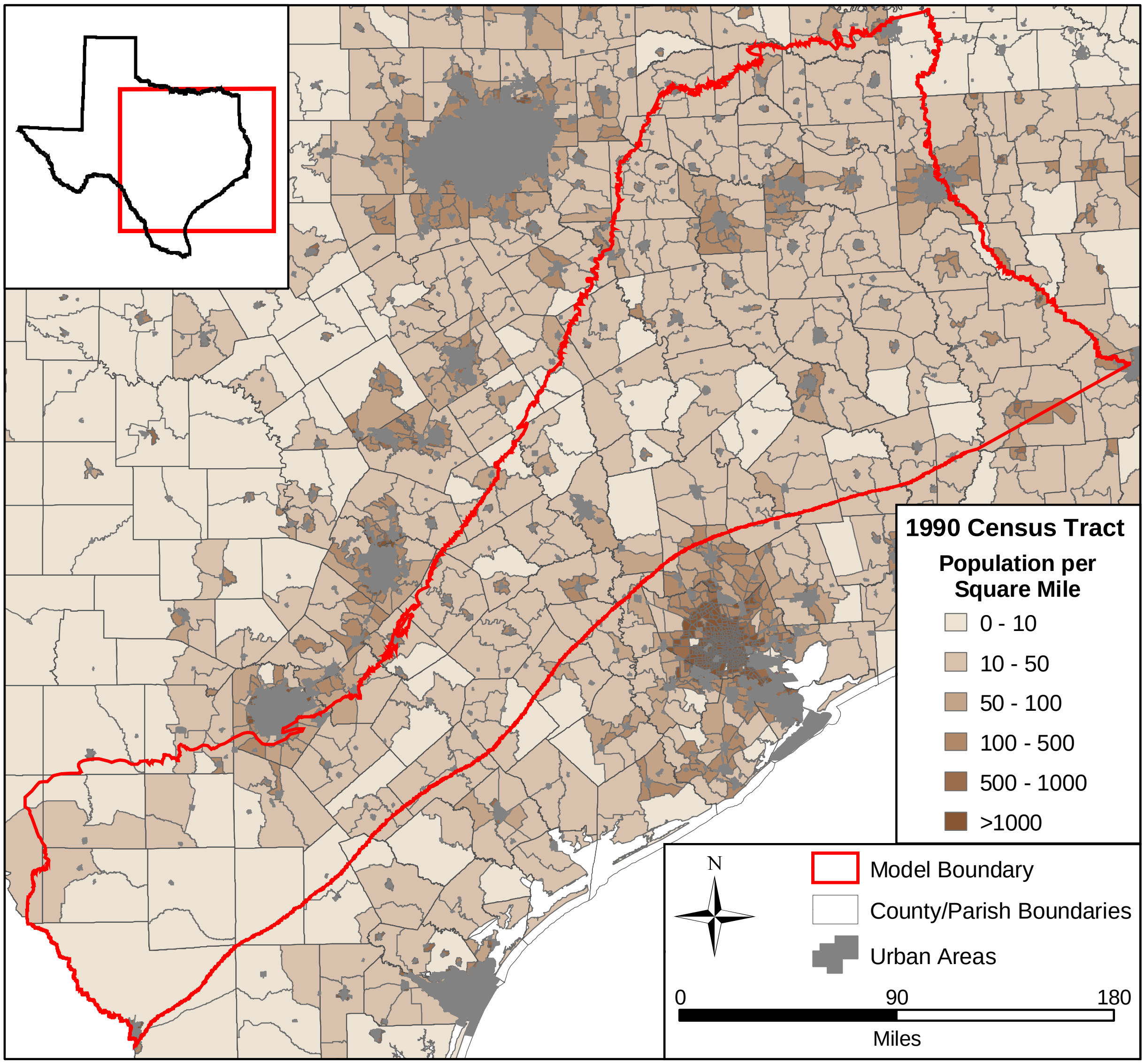


Figure 4.8.1 **Population density for the Queen City and Sparta GAM study area.**

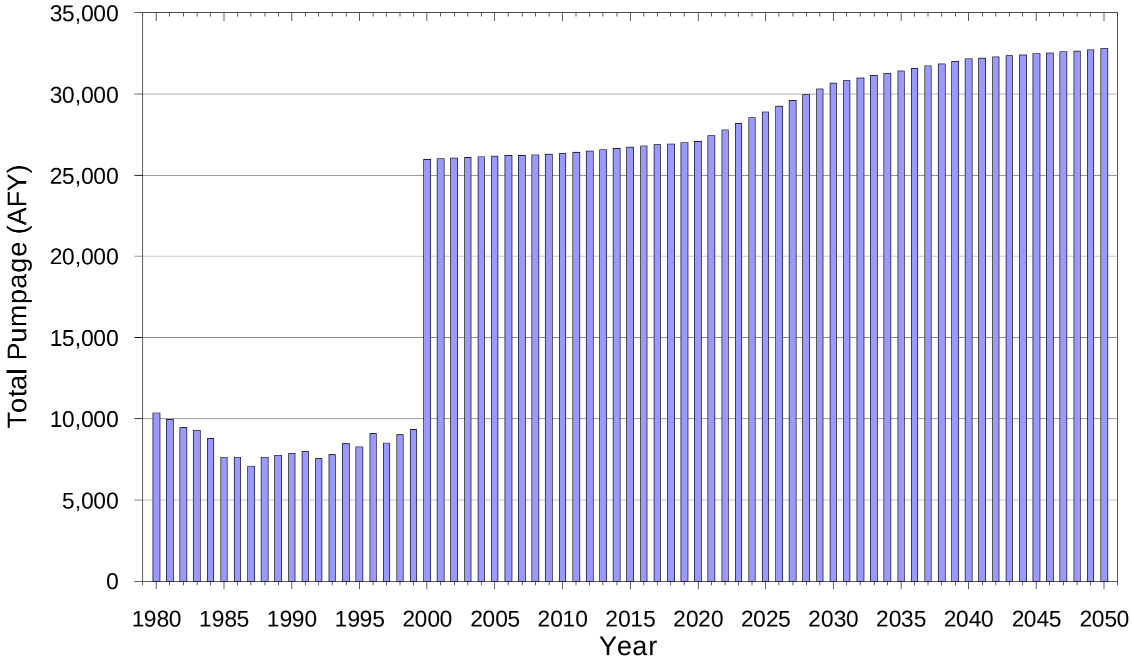


Figure 4.8.2 Total pumping (AFY) for the Sparta aquifer from 1980 through 2050.

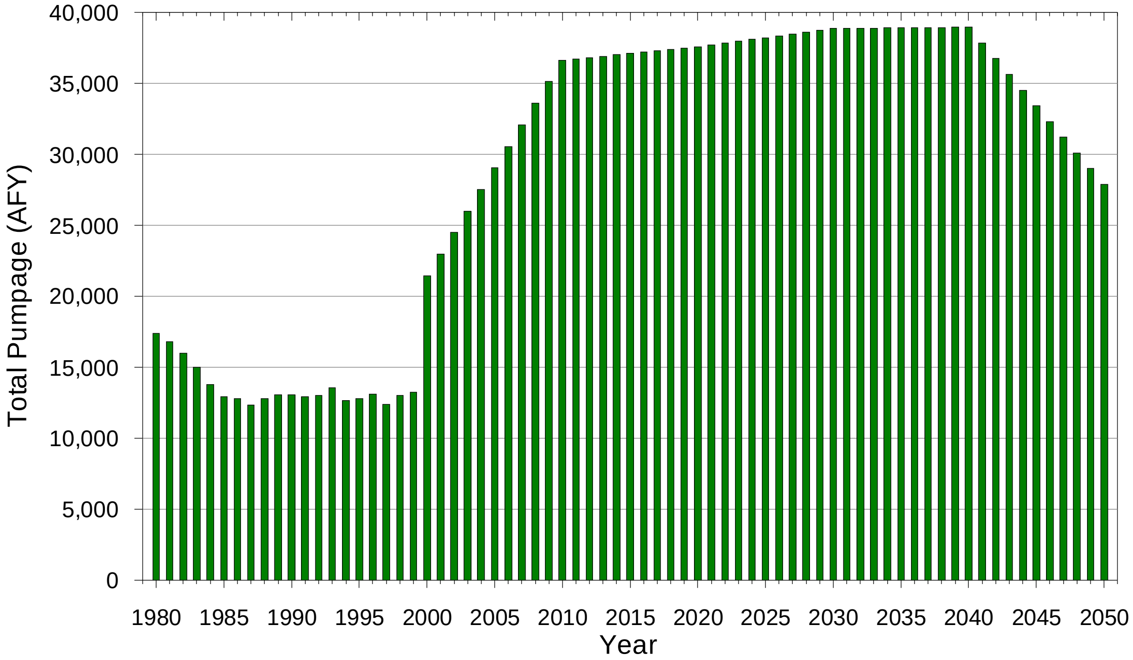


Figure 4.8.3 Total pumping (AFY) for the Queen City aquifer from 1980 through 2050.

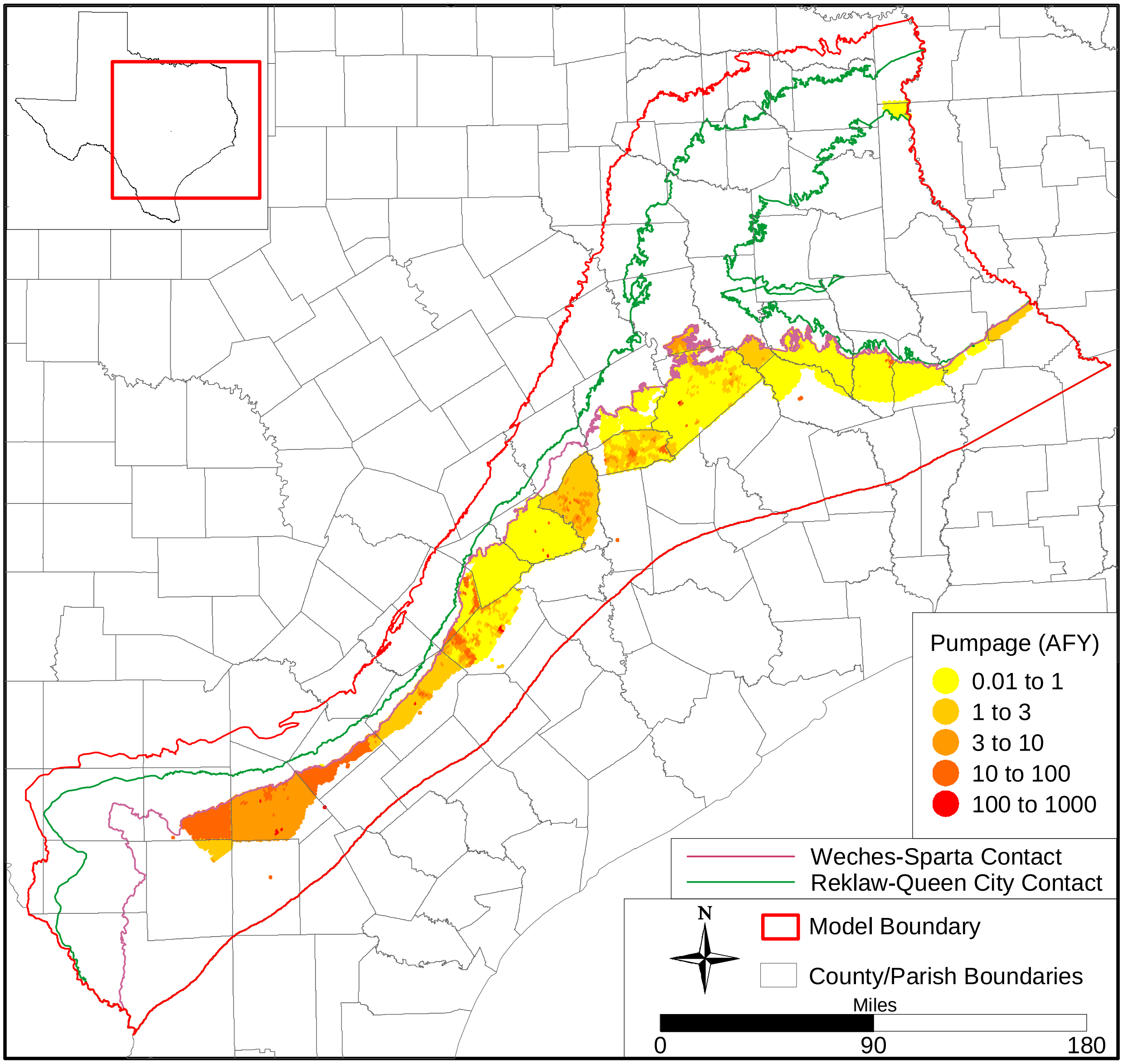


Figure 4.8.4 **Pumping rate for the Sparta aquifer for the year 2000.**

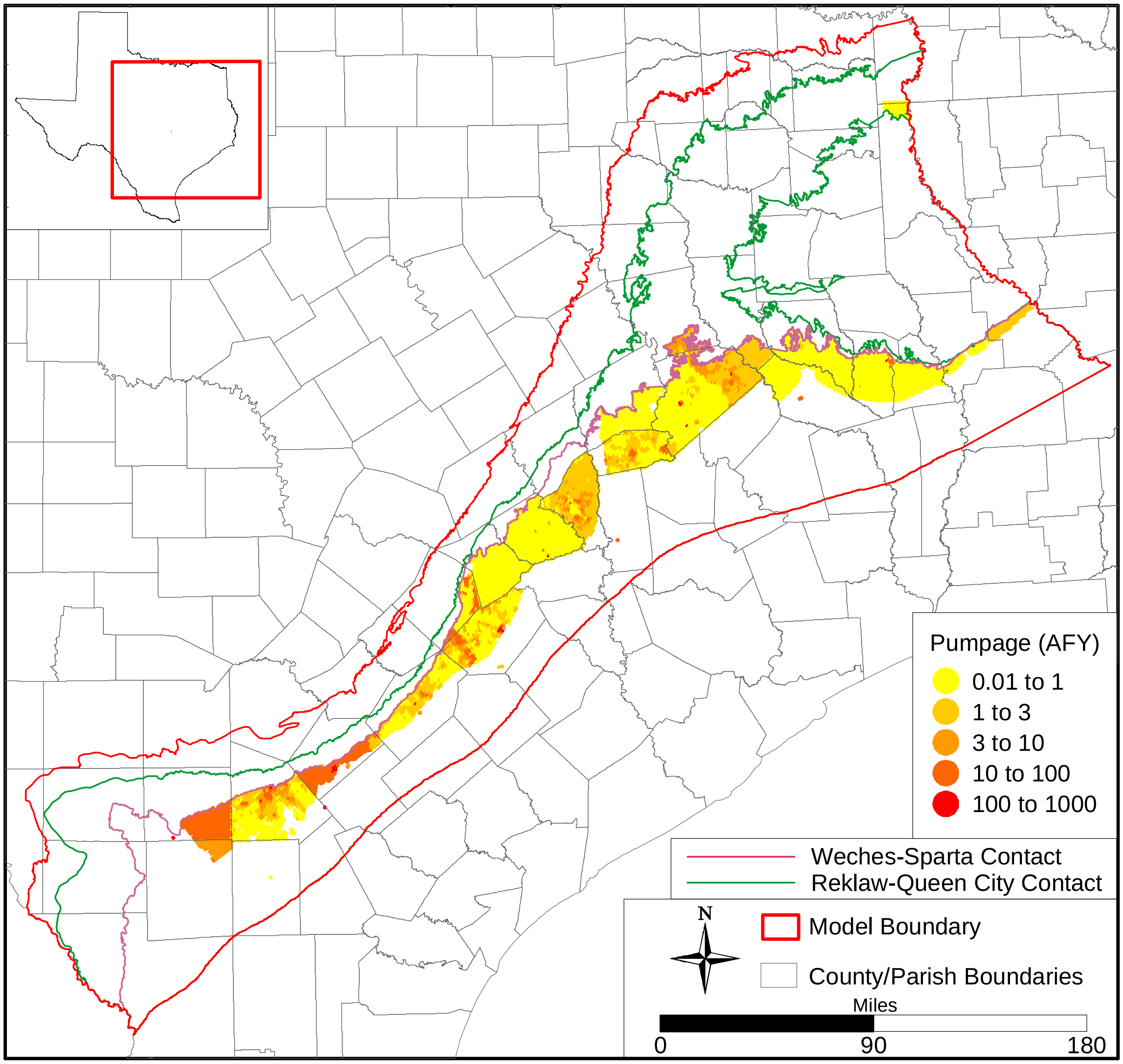


Figure 4.8.5 **Pumping rate for the Sparta aquifer for 2050.**

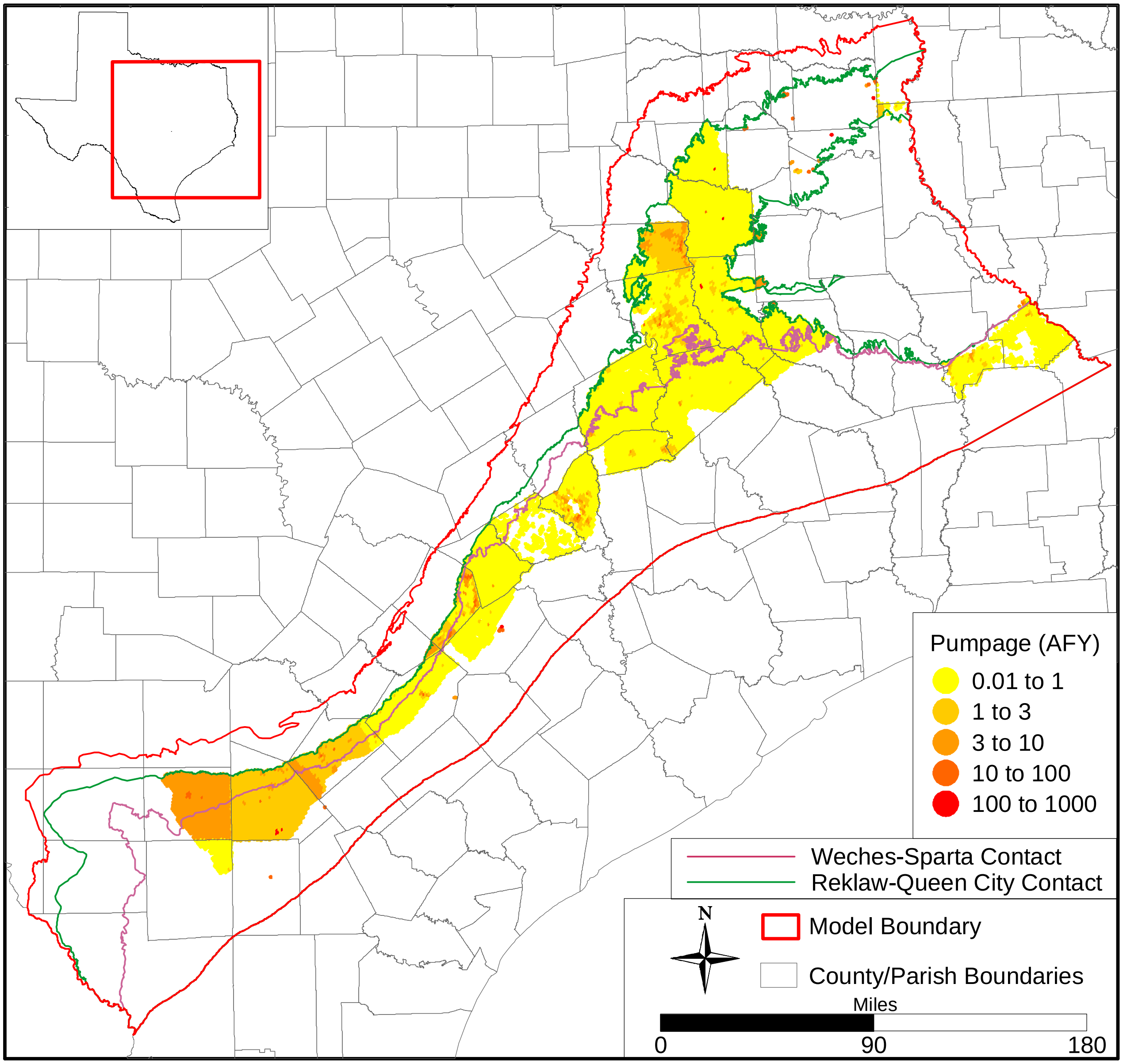


Figure 4.8.6 Pumping rate for the Queen City aquifer for 2000.

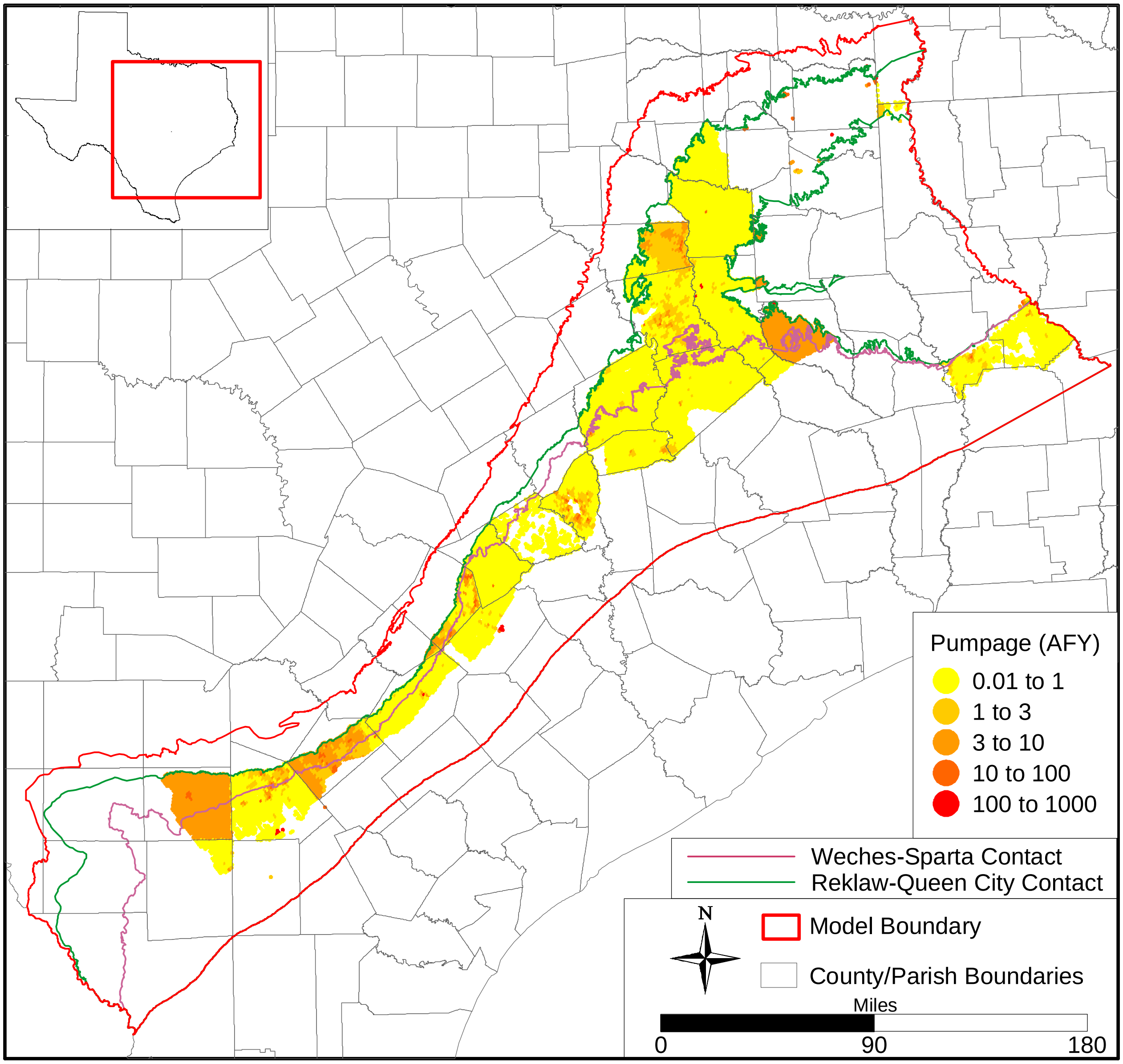


Figure 4.8.7 **Pumping rate for the Queen City aquifer for 2050.**

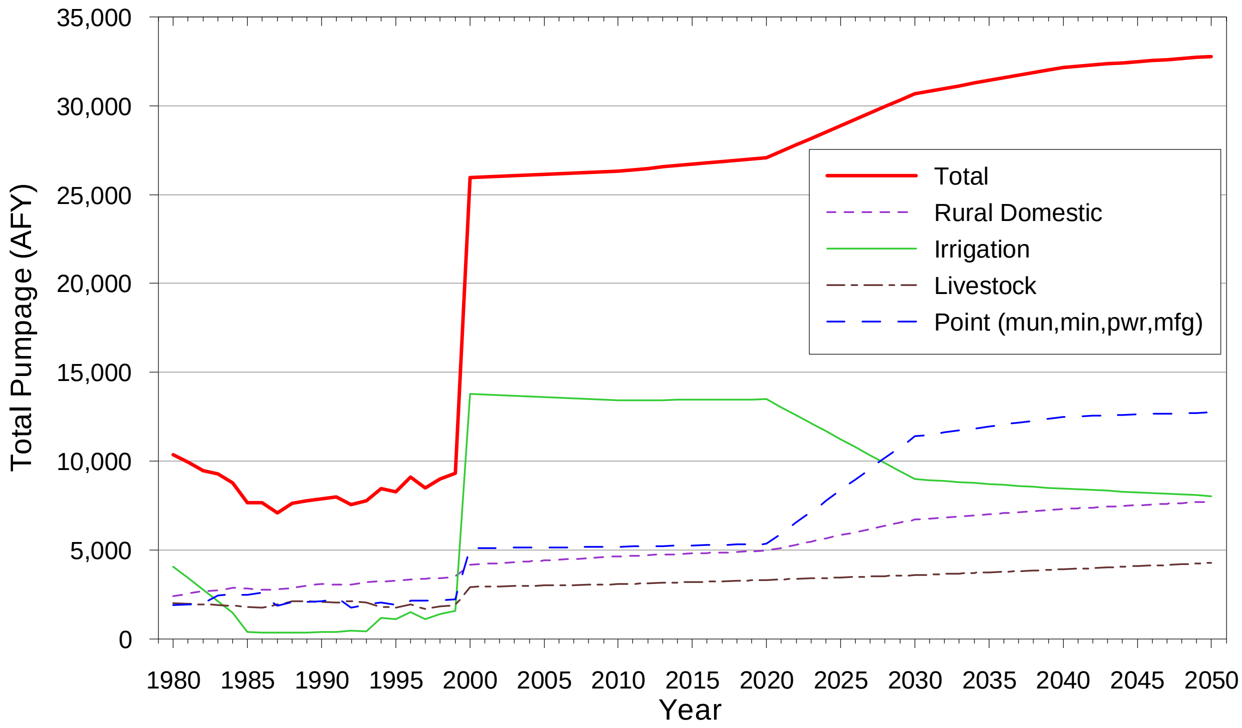


Figure 4.8.8 **Total groundwater withdrawals for the Sparta aquifer in Texas by category for 1980 through 2050.**

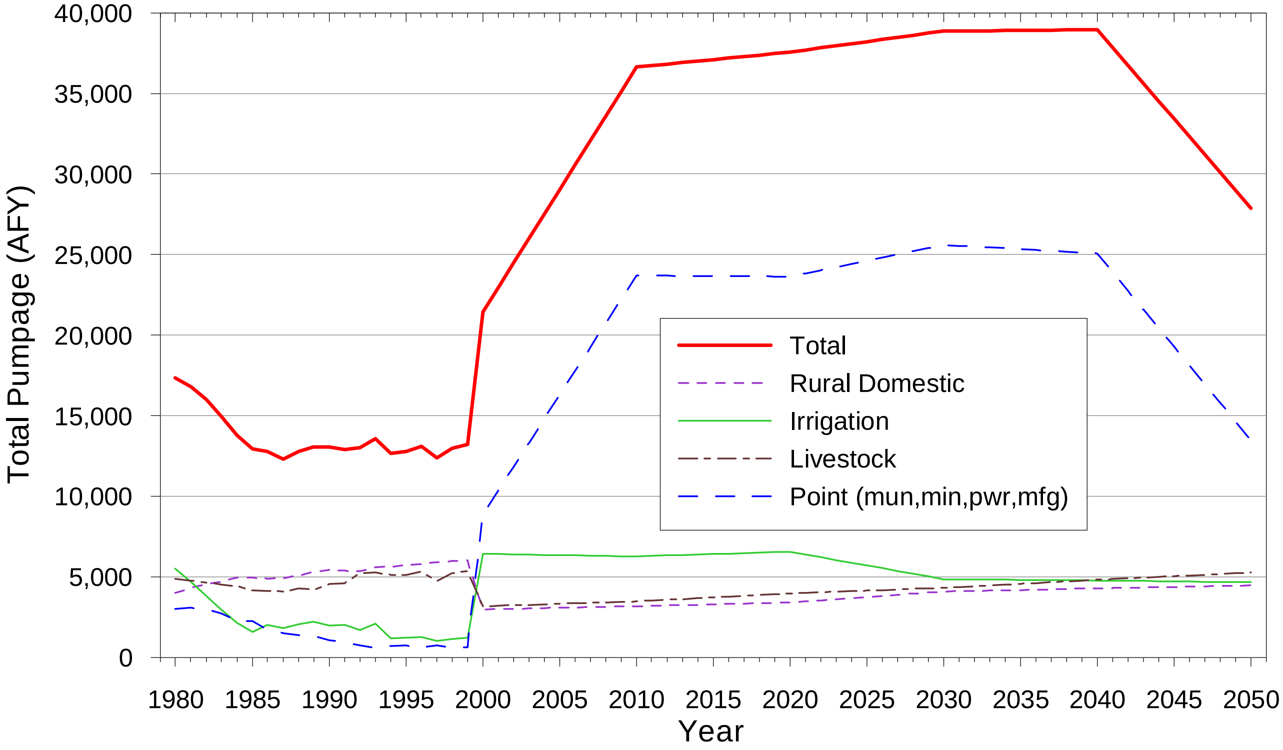


Figure 4.8.9 Total groundwater withdrawals for the Queen City aquifer in Texas by category for 1980 through 2050.

5.0 CONCEPTUAL MODEL OF GROUNDWATER FLOW IN THE AQUIFER

The conceptual model for groundwater flow in the Queen City and Sparta aquifers is based on the hydrogeologic setting, described in Section 4. The conceptual model is a simplified representation of the hydrogeological features that govern groundwater flow in the aquifers. These include the hydrostratigraphy, hydraulic properties, hydraulic boundaries, recharge and natural discharge, and anthropogenic stresses such as pumping. Each of the elements of the conceptual model are described below. The schematic diagram in Figure 5.1 depicts a simplified conceptual hydrogeologic model of groundwater flow in the Queen City and Sparta aquifers under predevelopment conditions. In this case, pumping is not considered and the aquifer recharge is equal to discharge on a long-term average. As the aquifer is developed, an additional flow component representing discharge from individual layers would be depicted in Figure 5.1 representing pumping of the aquifer.

The conceptual model for the Queen City and Sparta aquifers defines two productive layers, the Queen City Formation and the Sparta Formation, capable of producing groundwater to a well at adequate rates and quality for use. These two aquifers are divided by an aquitard, the Weches Formation. The Reklaw Formation separates the Queen City Formation from the underlying Carrizo-Wilcox aquifer and is also an aquitard regionally in Texas. In the southern and central parts of the study area, where all the layers dip toward the Gulf of Mexico, a wedge of younger sediments overlies the topmost model layer (Sparta aquifer). In this part of the study area, vertical flow between the aquifer and the shallow water table was approximated using general-head boundary conditions. In the northern model area in the East Texas Embayment, the Queen City aquifer, and the Sparta aquifer in isolated areas, is at ground surface and comprises the upper model boundary. In this portion of the model, these aquifers comprise the shallow water-table system which was actively modeled. South of the East Texas Embayment and the Sabine Uplift, the Queen City and Sparta aquifers again dip into the subsurface towards the Gulf Coast Basin and are overlain by younger sediments. In this portion of the study area, vertical flow between the aquifer and the shallow water table was approximated using general-head boundary conditions.

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. Recharge occurs mainly in the outcrop areas of the Queen City and Sparta layers. Conceptually, less recharge is expected to occur in the aquitards, which are the Weches and Reklaw formations. This is depicted by smaller recharge arrows in Figure 5.1. Additional recharge may occur by cross-formational flow from overlying or underlying layers (see Figure 5.1), which is discussed later in this section.

Precipitation falling on the outcrop either runs off as surface water, infiltrates and is lost to ET, or infiltrates into the subsurface and recharges the aquifer. Recharge is a small percentage of the average precipitation. For a typical surface-water basin in the model area, up to two thirds of the precipitation is expected to be removed via ET while about a quarter of the precipitation may run off as surface water. This leaves only 5 to 10 percent for recharge.

Recharge is a complex function of precipitation, soil type, geology, water level, soil moisture, topography, and ET. Precipitation, ET, water-table elevation, and soil moisture vary spatially and temporally, whereas soil type, geology, and topography vary spatially. In addition to natural phenomena, water levels are affected by pumpage and man-made surface-water reservoirs and lakes, which in turn affect recharge. Diffuse recharge occurs preferentially in topographically higher interstream areas within the outcrops. Focused recharge along streams can occur when the water table in the aquifer is below the stream-level elevation. If stream levels are lower than surrounding groundwater levels, groundwater discharges to the streams resulting in gaining streams. In this case, water levels in the valley are typically close to land surface and some of the shallow groundwater in this area can be lost to ET.

Groundwater flow within the aquifers is controlled by the topography, the structure, and the permeability variations within the different layers. Groundwater flow downdip into the confined portions of these aquifers is expected to be dominated by the high permeability sands relative to the lower permeability units. The low permeability units do retain the potential to be recharged at outcrop; however, flow in aquitards is dominantly vertical and any near-surface recharge would exit through ET, surface-water runoff, or cross-formational flow to higher permeability units.

Faults can affect groundwater flow patterns if they significantly displace hydrostratigraphic units or if the fault plane is altered as a result of clay smearing or hydrochemical alteration. There are very few fault zones within the Carrizo-Wilcox aquifer and Queen City and Sparta aquifers for which there is hydraulic evidence that the fault is a barrier to flow. However, some fault zones, such as the Elkhart-Mount Enterprise Fault Zone in the Sabine Uplift region, do appear to impact groundwater flow (Fogg and Kreitler, 1982). The Wilcox Growth Fault Zone is a barrier to flow and was used to delineate the downdip boundary of the aquifers modeled. Details regarding the implementation of faults in the models are described in Section 6.3.4.

Aquifer groundwater discharges to local creeks and major streams throughout the area, contributing to the baseflow of the major streams. In addition, discharge from the Queen City and Sparta aquifers occurs by cross-formational flow. In predevelopment times in the East Texas Embayment, where the Queen City and Sparta aquifers are unconfined, the dominant vertical hydraulic gradient would be expected to be downward with the exception of low river valleys where regional discharge may occur. Conceptually, vertical hydraulic gradients are expected to be upward in predevelopment times in the Queen City and Sparta aquifers in the southern portion of the northern study area and in the central and southern study areas where the aquifers outcrop in a narrow band and dip steeply into the subsurface. This predevelopment flow system is elevation driven similar to that in the Carrizo-Wilcox aquifer (Castro and Goblet, 2002). Cross-formational flow between the different layers within the Queen City and Sparta aquifers will redistribute groundwater that is recharged in the outcrops into different aquifer layers as a result of vertical gradients (see Figure 5.1).

Differences in average TDS and proportion of hydrochemical facies in the southern versus northern parts of the Queen City and Sparta aquifers have implications for the conceptual model of the movement of groundwater and recharge. The downdip increase in TDS along with sodium and chloride concentrations might reflect less displacement by meteoric water of connate water, according to a model developed by Domenico and Robbins (1985). The downdip extent of connate water displacement appears to be greater in the northern than in the southern parts of the aquifers. Recharge rate, breadth of the recharge area, and aquifer transmissivity control the displacement of the connate water (Domenico and Robbins, 1985). Geochemical data alone do not distinguish the relative influence of these three aspects. In the north, the Queen City aquifer is shallow and unconfined across much of the East Texas Basin which explains the observed lower TDS. Lower recharge rates, or lower transmissivity or both could account for less displacement of saline water and higher average TDS in the south than in the north. Cross-formational leakage also could play a role in regional variations. Depositional environments within the aquifers can be the factor controlling connectivity of sands from the outcrop areas to the deeper portions of the aquifer. Payne (1968) observed that in the south-central portions of the Sparta aquifer in Texas, the distance to bad water is small as a result of limited downdip sand thickness due to the strandplain depositional environment.

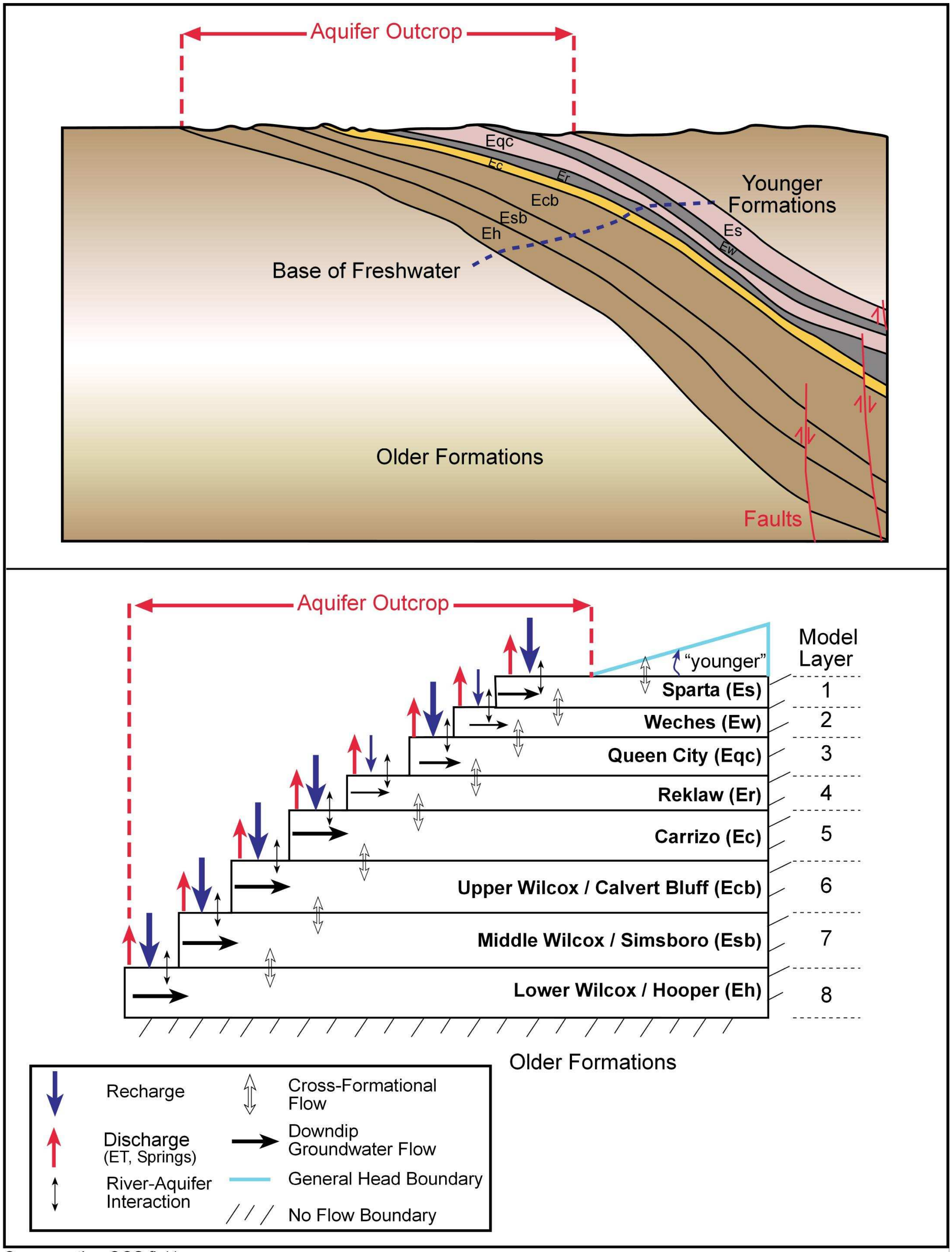
In a natural aquifer system unaffected by anthropogenic activities, the aquifer system is in a long-term dynamic equilibrium condition generally referred to as a steady-state condition (or predevelopment). In this predevelopment state, aquifer recharge is balanced by aquifer discharge resulting in no net change in groundwater storage. Recharge may include areal recharge from precipitation, cross-formational flow from adjacent water bearing formations, and potentially stream losses. Discharge includes stream base flow, spring flow, ET, and cross-formational flow. Muller and Price (1979) estimated that recharge in the Queen City and Sparta aquifers in Texas is approximately 634,700 and 163,800 AFY, respectively. Assuming these estimates are correct, these volumes can be equated to aquifer discharge under predevelopment (steady-state conditions).

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 et al., 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 reduced discharge or increased recharge, again the latter of which is usually negligible. Bredehoeft (2002) terms these two volumes as capture. The sources of discharge, which are ultimately captured by pumping, include stream base flow, spring flow, ET, and cross-formational flow.

Bredehoeft (2002) defined sustainable yield (i.e., a sustainable pumpage) as being equal to the rate of capture. In the situation of sustainable aquifer dynamics, the pumping rates in the basin are being matched by the capture in discharge with a net result of water levels becoming stable (albeit at a lower level than prior to development). It is important to note that a sustainable yield may not be a desirable future state of an aquifer, and therefore, may not represent an optimal yield. For example, a sustained yield could result in decreased discharge to streams (stream-flow capture) that would prove to be undesirable. If a basin is continually pumped at a rate (total pumpage) that is greater than the basins discharge rate (discharge capture), then water levels will continually decline and natural discharge will diminish. This condition was referred to as an unstable basin by Freeze (1969).

Pumping from the Queen City and Sparta aquifers to date has been small relative to their reported recharge rates with approximately 26,000 and 21,000 AFY of pumping projected for the Sparta and Queen City aquifers, respectively, for the year 2000. As a result, regional water levels reflect relatively stable heads indicative of limited development. Our conceptual model for the Queen City and Sparta aquifers is that of stable groundwater aquifers which are currently, on the regional scale, being developed sustainably. Large portions of the Queen City and Sparta aquifers are minimally impacted by pumping relative to predevelopment. However, some portions of these aquifers have experienced significant drawdown. In these regions, stream base flow, spring flow, ET, and cross-formational flow are expected to have been, or will be, decreased.

One of the aspects of aquifer development that is poorly defined is the amount of groundwater discharge, through natural cross-formational flow, that is captured by pumping. As a result of capture, vertical gradients within layered aquifer systems such as the Carrizo-Wilcox aquifer and the Queen City and Sparta aquifers are altered from their predevelopment conditions. Figure 5.2 shows the head difference, measured in feet, between the combined Queen City and Sparta aquifer head and the Carrizo-Wilcox aquifer head. The head surfaces used to make this difference plot are representative of 1980 and were developed as part of the USGS RASA program (Garza et al., 1987). A gray dot represents a location where the vertical hydraulic difference (gradient) is down from the Queen City and Sparta aquifers to the Carrizo-Wilcox aquifer. A red or pink triangle represents a location where the vertical head difference (gradient) is upwards from the Carrizo-Wilcox aquifer to the Queen City and Sparta aquifers. From the discussion above, in predevelopment time, primarily downward gradients in the East Texas Basin and dominantly upward gradients in areas where the aquifers are dipping into the Gulf Coast Basin are expected. Figure 5.2 is not representative of predevelopment conditions as it represents heads in 1980. However, this figure shows that gradients tend to be downward in east Texas, which is consistent with the conceptual model and the fact that the Queen City and Sparta aquifers are unconfined in that region. It does appear that gradients are interpreted by Garza et al. (1987) to be upward in the Cypress Creek valley. Moving from east Texas to central Texas, the gradients tend to become upward consistent with an elevation-driven system. This trend is reversed in areas where the Carrizo-Wilcox aquifer system has been significantly developed and has had significant head declines. Such a case can be observed around Brazos County where the Carrizo heads have been significantly lowered. This head reversal becomes dominant in the Wintergarden region where Carrizo-Wilcox heads have significantly decreased as a result of development. In this area, vertical gradients have been reversed from predevelopment times with flow directions now being downward from the Queen City and Sparta aquifers (and facies equivalents) to the Carrizo-Wilcox aquifer. This is a situation where natural vertical flow from the Carrizo to the Queen City in the Wintergarden region has been reversed as a result of cross-formational discharge capture caused by heavy pumping from the Carrizo in the region. The head reversals between the Queen City and the Carrizo also affect groundwater flow within the Queen City and Sparta impacting natural cross-formational flow within those aquifers. In the long term, development of the Carrizo-Wilcox aquifer and the Queen City and Sparta aquifers are coupled by capture hydraulics which requires predictive models such as the GAMs documented in this report.



Cross-section-QCS.fh11

Figure 5.1 Conceptual groundwater flow model for the Queen City and Sparta GAM.

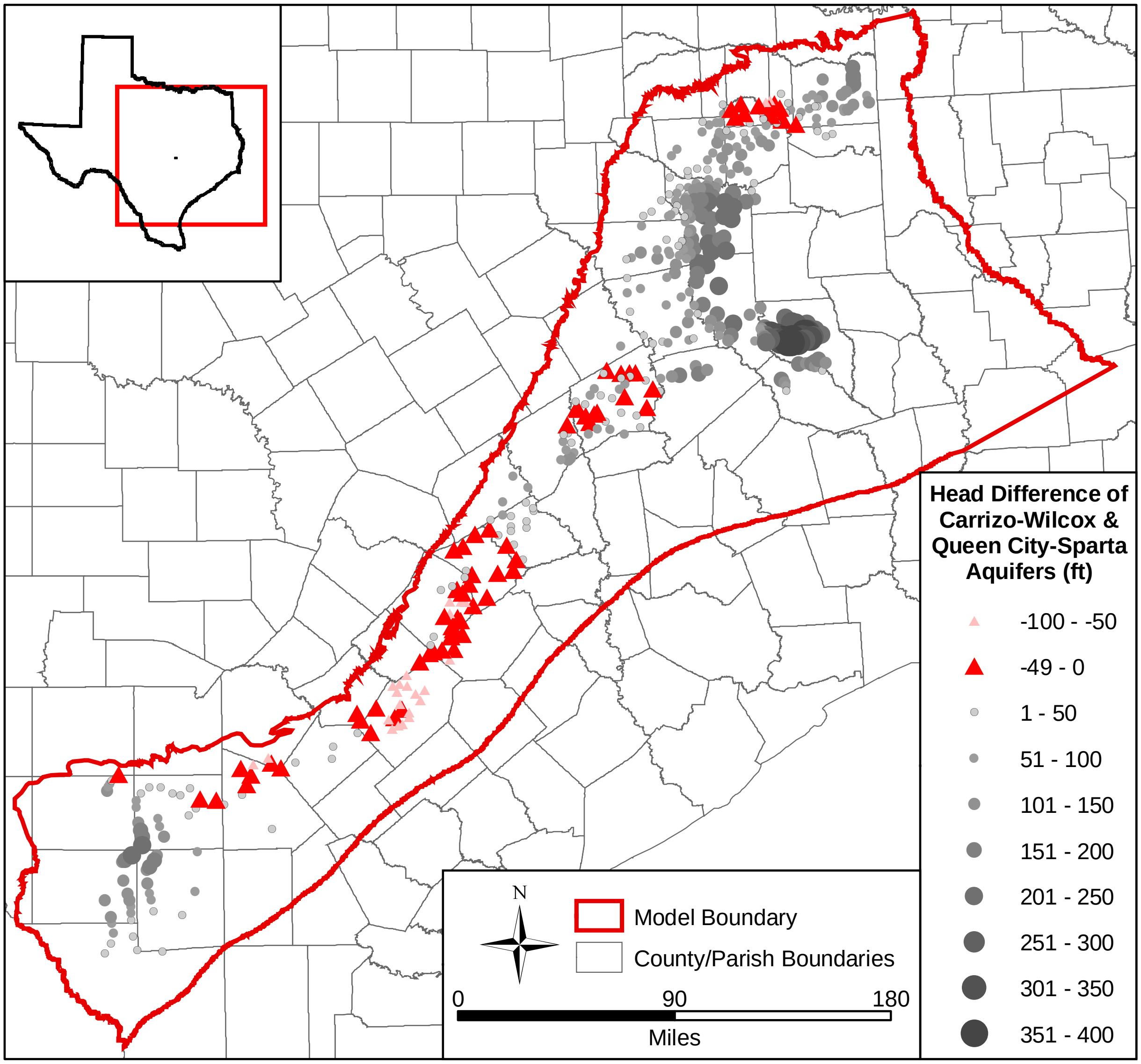


Figure 5.2 **Vertical head differences between the Queen City and Sparta aquifer system and the Carrizo-Wilcox aquifer system in 1980 (after Garza et al., 1987).**

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 for the code to be used. In addition to selection of the appropriate code, model design includes the definition of the model grid, layer structure, calibration time periods, the model boundary conditions, the model hydraulic parameters, and initial conditions. Each of these elements of model design and their implementation are described in this section.

6.1 Code and Processor

The code selected for all GAMs developed by or for the TWDB is MODFLOW-96 (Harbaugh and McDonald, 1996). MODFLOW-96 is a multi-dimensional, finite-difference, block-centered, saturated groundwater flow code which is supported by enhanced boundary condition packages to handle recharge, ET, streams (Prudic, 1988), and reservoirs (Fenske et al., 1996). The SIP solver was used for all steady-state simulations and the PCG2 solver was used for all transient simulations.

The benefits of using MODFLOW 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 USGS and is public domain, (4) MODFLOW is well documented (McDonald and Harbaugh, 1988; Harbaugh and McDonald, 1996), (5) MODFLOW has a large user group, and (6) there are multiple graphical user interface programs written for use with MODFLOW.

To the extent possible, the MODFLOW data sets have been developed to be compatible with Processing MODFLOW for Windows (PMWIN) Version 5.3 (Chiang and Kinzelbach, 1998). The size of the GAM and the complexity of our application (e.g., number of stream segments) precludes 100-percent compatibility with PMWIN, as well as many other interfaces.

The model was executed on x86 compatible (i.e., Pentium or Athlon) computers equipped with the Windows 2000 operating system. MODFLOW is not typically a memoryintensive application in its executable form. However, if any preprocessor (such as PMWIN) is used for this size and complexity of model, at least 256MB of RAM is recommended.

6.2 Model Discretization

Model discretization refers to the vertical model layers, the horizontal model grid, and the model simulation time periods. Each of these elements of model discretization are discussed in this section.

6.2.1 Model Layers

The Queen City and Sparta aquifers overlie the Carrizo-Wilcox aquifer. The Queen City and Sparta GAMs have been developed within the existing Carrizo-Wilcox GAMs documented in Deeds et al., 2003; Dutton et al., 2003; Fryar et al., 2003, and the model layers and stratigraphy used in the Carrizo-Wilcox GAMs still applies for the Wilcox aquifer. It is important to note that the alluvial aquifers modeled in the Central Carrizo-Wilcox GAM as model layer 1 have been removed from the Central Queen City and Sparta GAM.

The layering for the Queen City and Sparta aquifers is the same across all three GAMs with the Queen City, the Weches, and the Sparta each being modeled as individual model layers. MODFLOW-96 numbers layers from top (nearest to ground surface) to bottom and this is the order by which each layer is introduced. Layer 1 is the Sparta Formation, Layer 2 is the Weches Formation, and Layer 3 is the Queen City Formation (see Figure 5.1).

For all three Queen City and Sparta GAMs, the Carrizo-Wilcox is divided into five model layers; the Reklaw (Layer 4), the Carrizo (Layer 5), the Upper Wilcox (Layer 6), the Middle Wilcox (Layer 7), and the Lower Wilcox (Layer 8). In the Southern Queen City and Sparta GAM, Layer 4 is the Reklaw Formation east of the Frio River and the equivalent Bigford Formation west of the Frio River. In the Central Queen City and Sparta GAM, the Upper Wilcox (Layer 6) is the Calvert Bluff, the Middle Wilcox (Layer 7) is the Simsboro, and the Lower Wilcox (Layer 8) is the Hooper. The juxtaposition of these units can be seen schematically in Figure 2.9.

6.2.2 Model Grids

The lateral boundaries of the three Queen City and Sparta GAMs are similar to those of the Carrizo-Wilcox GAMs (Deeds et al., 2003; Dutton et al., 2003; and Fryar et al., 2003). The

Southern Queen City and Sparta GAM model area is bounded laterally on the northeast by the surface water basin divide between the Guadalupe and Colorado rivers and to the southwest by the Rio Grande River. The Central Queen City and Sparta GAM model area is consistent with the Central Carrizo-Wilcox GAM (Dutton et al., 2003) and is along an arbitrary line from the Wilcox-Midway contact at surface in Van Zandt County across the Sabine Uplift to the updip limit of the Wilcox growth-fault trend. The Northern Queen City and Sparta GAM model area is bounded laterally on the northeast by the Red River and in the southwest by the surface water basin divide between the Brazos and Trinity rivers.

The updip limit of all three Queen City and Sparta GAMs is defined by the outcrop of the Carrizo-Wilcox aquifer at the contact with the Midway Formation. The southern boundary of the active model is defined by the updip limit of the Wilcox growth-fault zone (Bebout et al., 1982). MODFLOW-96 requires a rectilinear grid and also requires an equal number of rows for all columns. As a result, the model area is constrained to being a rectangular grid. Typically, one axis of the model grid is aligned parallel to the primary direction of flow, which is slightly different for all three GAMs. The model areas were determined by imposing the preceding constraints with the additional constraint of minimizing the number of model grid cells.

Table 6.2.1 provides the details regarding the grid locations and sizes in rows and columns. The GAM standard requires that grid cells be square with a uniform dimension of no greater than 1 mile (area of 1 square mile). The Southern Queen City and Sparta GAM has 24,304 grid cells per layer, the Central Queen City and Sparta GAM has 48,321 grid cells per layer, and the Northern Queen City and Sparta GAM has 40,950 grid cells per layer. Not all of these grid cells are active in the model with the number of active cells varying between model layers.

Figure 6.2.1 shows the Southern Queen City and Sparta GAM grid. Included on this figure is an inset with an enlargement of Frio County to show the model grid at the county scale. Figure 6.2.2 shows the Central Queen City and Sparta GAM grid with an inset of Trinity County to show the model grid at the county scale. Figure 6.2.3 shows the Northern Queen City and Sparta GAM grid, again with an enlargement of an individual county (Rusk County) to provide a feeling for model scale as compared to a county.

To define the active area of each model layer and the active layer grid cells, each layer grid was intersected with the geologic map for the updip boundary and with the growth-fault boundaries for the southern downdip boundary. Cells extending past the outcrop or downdip of the growth-fault boundary were defined as inactive in the IBOUND array. If a cell was 50 percent or more in the outcrop, it was defined as active. Cells west of the Rio Grande River on the southwestern boundary of the Southern GAM were also made inactive on the assumption that the Rio Grande River represents a regional groundwater flow divide for the aquifers being modeled. Likewise, cells east of the Red River in the Northern GAM were made inactive on the assumption that the Red River represents a groundwater flow divide for the aquifers being modeled. Table 6.2.2 provides the number of active grid cells in each model layer for all three GAMs.

Table 6.2.1 Grid specifications for the three Queen City and Sparta GAMs.

GAM Grid	Grid Origin in GAM Coordinates (feet)	X-Axis Rotation (Bearing)	Number of Grid Rows	Number of Grid Columns
Southern GAM	5,062,000 E 18,280,000 N	E 36.727° N	112	217
Central GAM	5,382,716 E 18,977,220 N	E 58° N	177	273
Northern GAM	6,295,000 E 19,257,000 N	E 29.11° N	195	210

Table 6.2.2 Number of active model grid blocks per model layer for the three Queen City and Sparta GAMs.

Model Layer	Southern GAM	Central GAM	Northern GAM
Layer 1	8,514	16,398	11,983
Layer 2	8,892	16,952	12,419
Layer 3	12,263	20,561	18,747
Layer 4	12,848	21,585	20,491
Layer 5	13,871	22,299	21,434
Layer 6	13,911	24,444	24,844
Layer 7	14,910	25,006	30,001
Layer 8	15,674	26,012	30,614

6.2.3 Model Simulation Periods

The models were simulated for a predevelopment period and several transient periods. The predevelopment period is assumed to be a period where aquifer hydraulics are at steady state with aquifer recharge and discharge being both equal and constant. The predevelopment time period is representative of aquifer conditions prior to development, which is prior to the early 1900s.

The model is also simulated for calibration, verification, and predictive transient time periods. The transient model calibration period was from 1980 through the end of 1989. This transient simulation period was followed by a second transient simulation period, termed the verification period, which extends from 1990 through the end of 1999. The initial conditions for the transient simulation period (see Section 6.3.7) are poorly known for the entire model domain and for all modeled aquifers. As a result, for some time after the transient simulation begins, the model simulated heads will change from the initial heads and equilibrate with the model parameters, the model stresses, and the model boundary conditions. To account for this, an initial five year equilibration period was simulated to allow initial conditions to equilibrate prior to the calibration period.

Following the historical model simulation time period (1980 through 1999), the models were used to transiently simulate predictive conditions from the year 2000 through the year 2050.

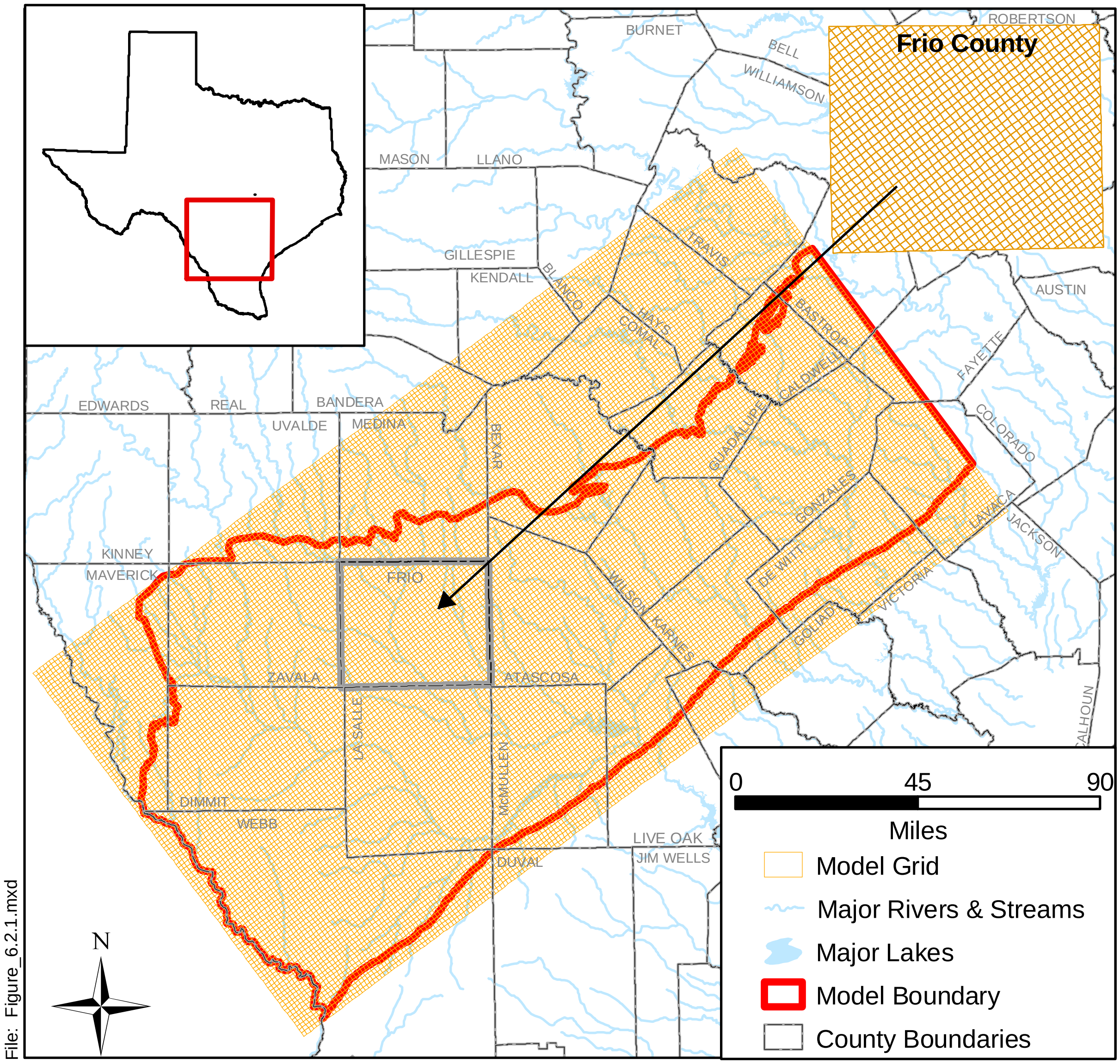


Figure 6.2.1 Southern Queen City and Sparta GAM model grid.

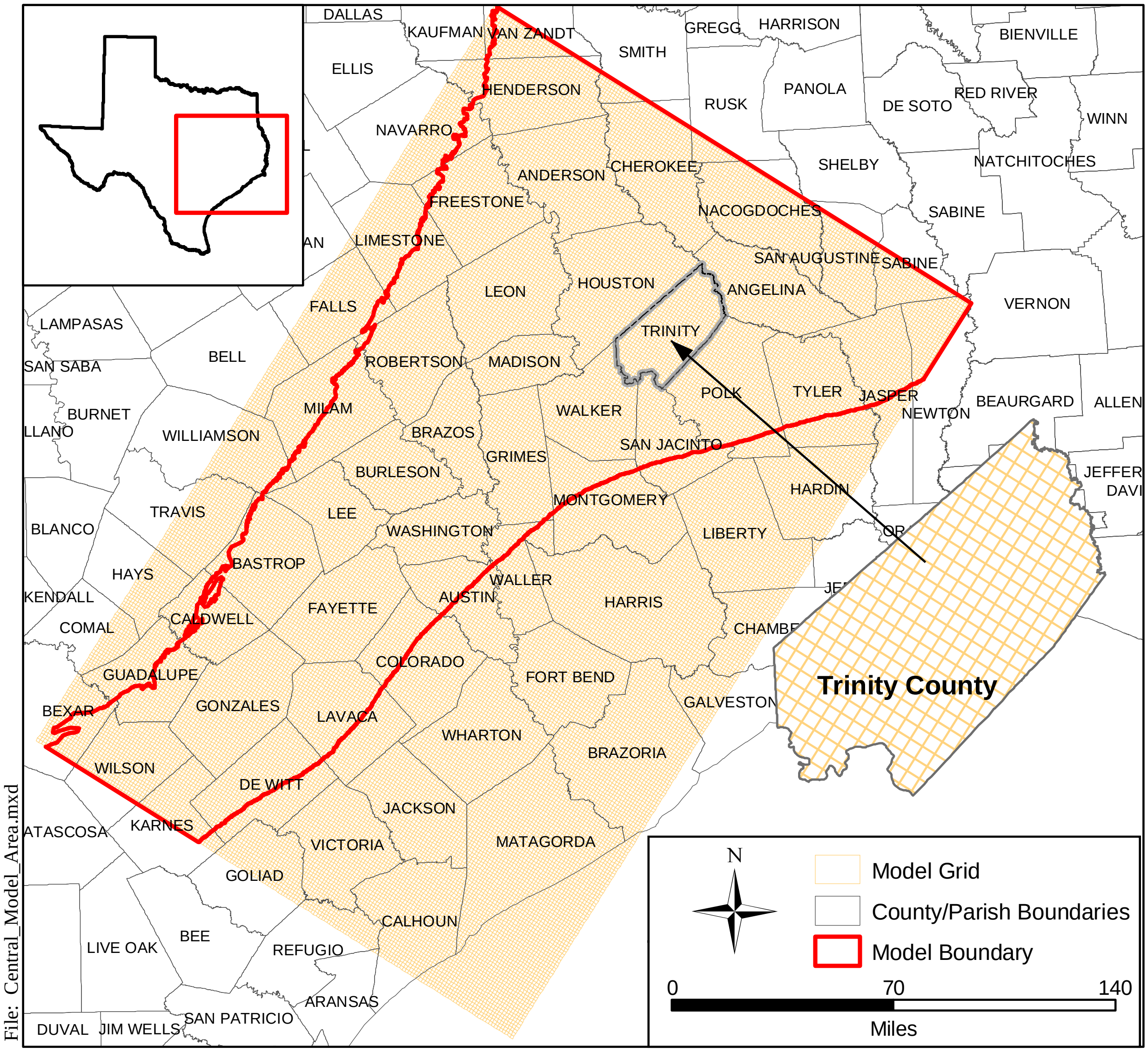


Figure 6.2.2 Central Queen City and Sparta GAM model grid.

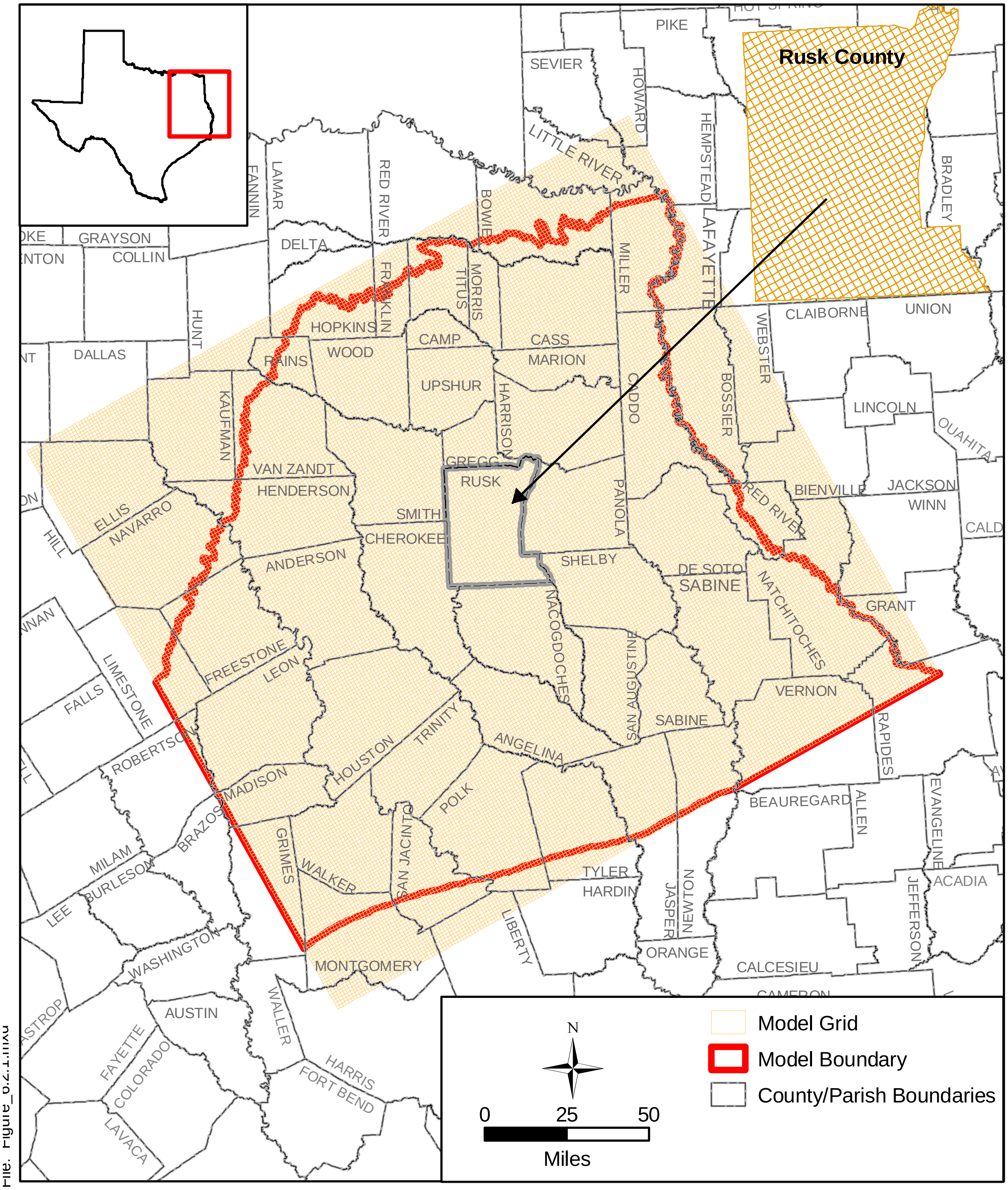


Figure 6.2.3 Northern Queen City and Sparta GAM model grid.

6.3 Boundary Condition Implementation and Initial Conditions

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 defined as being time independent or time dependent. An example of a time dependent boundary might be a pumping well or a reservoir. Because many boundaries require time dependent (transient) specification, the stress periods used by MODFLOW must be defined. A stress period in MODFLOW defines the minimum time period over which a boundary or model stress may remain constant. Each stress period may have a number of computational time steps, which are some fraction of the stress period but over which boundaries remain constant. For these models, the stress periods have been set at one year. Therefore, all transient boundaries in the model cannot change over a period of less than one year.

Boundaries requiring specification include: lateral and vertical boundaries, surface-water boundaries, recharge boundaries, and discharge boundaries caused by pumping. Lateral and vertical boundaries are a combination of specified flow (no-flow, Second Type) or head-dependent flow boundaries (general head boundaries, Third Type). Surface-water boundaries are head-dependent flow boundaries (Third Type). Recharge is a specified flow boundary (Second Type). ET is a head-dependent flow boundary (Third Type). Pumping discharge is a specified flow boundary (Second Type).

Figures 6.3.1 through 6.3.3 show the active and inactive grid cells for the Southern, Central, and Northern Queen City and Sparta GAMs, respectively. Implementation of the boundary conditions for the Queen City and Sparta GAMs are described below. Unless otherwise specified, the boundary between the active and inactive cells is a no-flow boundary.

6.3.1 Lateral Model Boundaries

The lateral model boundary extents for each GAM were described in Section 6.2. The southwestern boundary of the Southern GAM coincides with the Rio Grande River. This model boundary is specified as a no-flow boundary throughout all simulation periods from predevelopment through the predictive simulations. Similarly, the northeastern model boundary of the Northern GAM coincides with the Red River. This model boundary was also specified as a no-flow boundary condition throughout all simulated time periods. Both of these boundaries are assumed to be groundwater divides, which are equivalent to no-flow boundaries (Second Type).

The northeastern boundary of the Southern GAM, the southwest and northeast boundaries of the Central GAM, and the southeastern boundary of the Northern GAM are shared boundaries. A shared model boundary falls within the active grid of another GAM model. Shared model boundaries were specified in two different ways. For the predevelopment simulations, the shared lateral boundaries were assumed to be no-flow boundaries (Second Type). The assumption inherent in these boundaries is that, in predevelopment conditions, aquifer flow lines would be approximately parallel to our model boundaries and, therefore, model boundary fluxes would be small.

During the transient model period (1980 through 1999) and the predictive model period (2000 through 2050), the shared lateral boundaries were set as general head boundaries (Third Type). The procedure used to develop the transient and predictive lateral general head boundaries consisted of several steps. First, the three GAMs were simulated across the transient period with no-flow boundaries. Next, the heads for each shared model boundary were interpolated from the simulated heads within each GAM. These heads were then used to repeat the transient simulation. In the case of the transient calibration period (1980 through 1989), the heads were updated at least one more time as calibration and parameter changes between the three models were finalized.

6.3.2 Vertical Boundaries

Each Queen City and Sparta GAM has a no-flow boundary on the bottom of Layer 8 (the lower Wilcox) representing the marine shales of the Midway Formation. The upper model boundary is the water table calculated in the outcrops of Layers 1 through 8. In downdip portions of the model where younger sediments overlie the Sparta, these sediments are represented by a general head boundary condition (Third Type). The initial vertical conductances of the general head boundaries were based upon a harmonic average of the hydraulic conductivities of the overlying hydrostratigraphic units as mapped by Galloway et al. (1994). The sediments overlying the Sparta to the ground surface were divided into five stratigraphic classes from the four Galloway et al. (1994) cross sections. These are fluvial sandstone and mudstone, coastal plain mudstone, paralic sandstone and mudstone, marine-shelf sandstone, and marine mudstone. Vertical hydraulic conductivities were assigned to each lithologic class based upon typical values from the literature. For the five lithologic classes, the assumed hydraulic conductivities were $1x10^{-3}$, $1x10^{-4}$, $1x10^{-3}$, $1x10^{-2}$, and $1x10^{-4}$ ft/day, respectively. From the estimated lithologic thicknesses and the assumed hydraulic conductivities, the general head boundary vertical conductances were estimated assuming a harmonic law of composition. Figure 6.3.4 plots the vertical conductances estimated for the younger sediments across the model regions. Between the Galloway et al. (1994) cross sections, the conductances were interpolated using an anisotropic variogram with a large correlation along approximate depositional strike.

The hydraulic heads associated with the general head boundaries were set equal to the water table as estimated using the regression equations of Williams and Williamson (1989), which were developed as part of the USGS RASA program.

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 (outcrop). The MODFLOW stream package (Prudic, 1988) and reservoir package (Fenske et al., 1996) are head-dependent flow boundary conditions that offer a first-order approximation of surface water/groundwater interaction. The stream-routing package will allow for stream discharge during gaining conditions and for stream-related recharge to be induced during losing conditions. When pumping affects water levels near stream/aquifer connections, recharge will be included through stream loss.

The stream-routing 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, physical properties must be defined describing the hydraulic connection (conductance) between the stream and the aquifer. Stream flow rates are defined at the beginning of each segment for each stress period.

Figures 6.3.5 through 6.3.7 show the model grid cells which contain stream reaches in the model domain for all three Queen City and Sparta GAMs. Required physical properties of the reaches, including stream width, bed thickness, and roughness, were taken from the EPA River Reach (RF1) data set (http://www.epa.gov/region02/gis/atlas/rf1.htm). The hydraulic conductivity used to define the hydraulic conductance between the aquifer and the stream was initially approximated with a value of 0.1 ft/day.

Hibbs and Sharp (1991) studied the hydraulic connection between the Colorado River and the alluvium and Carrizo-Wilcox aquifer near a Bastrop well field. They concluded that the connection between the river and the aquifer was very good and did not see hydraulic evidence for a low permeability river bed. The initial approach for this study was to keep the hydraulic conductivity of the stream bed high and relatively constant and allow the stream width taken from the EPA RF1 data set to control the streambed conductance.

The stream-routing package also requires specification of the stream flow rate for each starting reach at each stress period. For predevelopment conditions and the historical period, no representative stream gage data exist for the majority of the stream segments. To handle this for the predevelopment simulations, mean flow rates from the EPA RF1 data set were used to specify the flow rate entering each model segment. The EPA RF1 data set contains mean flow rates estimated along the entire stream and coinciding with all of the modeled stream segments.

For the transient simulations, stream flows were based on historical records. However, because the stream gage coverage is sparse (see Figure 4.7.1), stream flow rates required estimation at the majority of stream segments. The approach employed to develop ungaged stream segment flow rates has the following assumptions: (1) gages in close proximity behave similarly, (2) the EPA RF1 average stream segment flow estimates are accurate, (3) a gage's distribution of monthly stream flow is lognormal, and (4) the standard deviation of the log of the monthly flow rate at an ungaged location is equal to the standard deviation of the log of the monthly flow rate at a nearby gaged location. Assumptions 1 through 3 have been checked and found to generally hold for the model region. Assumption 4 cannot be validated with the available data.

To calculate the ungaged stream segment flow rates at each yearly stress period, the yearly distribution of log flow rate at the gaged stream locations were constructed and the standard deviation of that distribution was calculated. From the EPA RF1 data set, the mean flow rates for all segments are available. For example, if for a given stress period the gaged yearly stream flow was equal to the 75th percentile of the distribution, the mean flow rate from the EPA RF1 data set with the standard deviation borrowed from the actual gaged flow distribution was used to estimate the 75th percentile flow rate at the ungaged segment. This technique maintains the proper magnitude of flows at ungaged locations as constrained by the EPA RF1 mean flow estimates while superposing the flow variability based upon the nearest gaged data. This statistical method of headwater flow definition for ungaged streams was tested against the Colorado River WAM and found that both methods provided very similar results.

The MODFLOW reservoir package (Fenske et al., 1996) has been used to model reservoirs and lakes. The selection of which reservoirs to include in the models was based upon the surface area of the reservoir. If a reservoir had a surface area that was greater that one-half of a square mile (i.e., one-half of a grid block), it was included. Figures 6.3.5 through 6.3.7 show reservoir cells for the three GAMs. Modeled reservoir properties include the hydraulic conductance between the lake and the aquifer and the reservoir stage as a function of stress period. Because reservoirs are in river valleys, the reservoir package must be integrated with the stream routing package. This is done by starting a new segment at the downstream side of each reservoir. The hydraulic conductivity used to estimate the reservoir/aquifer hydraulic conductance was initially set to a constant, approximately based on the hydraulic conductivity of the underlying formation. Lake stage records were developed by reviewing records in the literature and by contacting various river authorities in the study area. These stage histories are provided in the data model delivered with this modeling report.

Spring discharge records were reviewed for application in the Queen City and Sparta GAMs as drain boundary conditions (Type 3). The majority of the springs that are significant in terms of volumetric flow rates as compared to the volume of a one-square mile grid cell are in nearly every case coincident with stream cells. In these cases, the springs are handled as stream cell boundaries. To handle Dunne overland flow in stream valleys located in the humid climate zone, drains were assigned to low-lying stream valleys where the depth to water may be shallow. Drain cells were implemented as far south as the San Antonio River basin. Figures 6.3.8 through 6.3.10 show the location of the drain cells for the Southern, Central, and Northern GAMs, respectively.

6.3.4 Implementation of Faults

The Texas Gulf Coastal Plain sediments have numerous faults within them, many of which are syndepositional and in nearly all cases they are normal faults. As part of this study, the Bureau of Economic Geology digitized the faults which occur within the study area (see Figure 2.17). Faults can act as hydraulic flow barriers which may impact groundwater flow. In hydropressured zones of young extensional basins dominated by clastics, faults commonly displace but not seal.

In the three GAMs, all of the faults identified within the study region were implemented using the Horizontal Flow Barrier (HFB) package for MODFLOW (Hsieh and Freckleton, 1993). A low hydraulic conductivity was not assigned to all faults implemented in the model with the belief that making a fault seal without evidence added unsupported complexity to the model. Based upon that premise, the conductance was lowered for faults for which there was evidence that they were sealing or in the case where the model showed a strong sensitivity to the fault. All faults are included in the model so that future model user's can implement faults as additional hydraulic data come available. The grid cells with faults and the HFB boundary condition are shown in Figures 6.3.11 through 6.3.13 for the Southern, Central, and Northern GAMs, respectively.

6.3.5 Implementation of Recharge

Because an evaluation of groundwater availability is largely dependent upon recharge (Freeze, 1971), it is an important model input parameter warranting careful examination and meaningful implementation. In typical model applications, recharge is either homogeneously defined as a percentage of the yearly average precipitation or calibrated as an unknown parameter. Unfortunately, recharge and hydraulic conductivity can be correlated parameters preventing independent estimation when using only head data constraints. Another compounding problem is that recharge is a complex function of precipitation, soil type and underlying geology, water level, soil moisture, topography, and ET (Freeze, 1969). Precipitation, ET, water-table elevation, and soil moisture are areally and temporally variable. Soil type, geology, and topography are spatially variable. For the GAMs, recharge requires specification for steady-state conditions, for transient conditions from 1980 until 2000, and for the transient drought of record. Reliable tools for specification of recharge at watershed scale, or the regional model scale (1000s of square miles for the GAMs), do not currently exist.

In the Southern and Northern Carrizo-Wilcox GAMs, SWAT (Soil Water Assessment Tool) was used to estimate diffuse recharge rates. SWAT was developed for the USDA Agricultural Research Service by the Blacklands Research Center in Temple, Texas. SWAT is a public-domain model. The SWAT website where downloads and code-specific documentation can be found is http://www.brc.tamus.edi/swat/. SWAT provides a GIS-driven, watershed scale tool to estimate regional soil water balances, incorporating soils data (USDA/NRCS STATSGO) with the USGS Multi-Resolution Land Characteristics (MRLC) data. SWAT uses standard techniques to track water after it reaches the ground as precipitation. SWAT uses the NRCS Curve Number Method (accounting for antecedent moisture conditions) to partition precipitation into runoff and infiltration. Infiltrating water either increases the soil moisture, is lost through ET, or continues down to the water table.

Based on the experience using SWAT in the Carrizo-Wilcox GAMs, it was concluded that SWAT over-estimated recharge in areas with greater than 30 inches per year of rainfall. A post audit of the SWAT recharge simulations identified several potential factors which led to the overprediction of recharge in humid regions. First, SWAT only considers soil properties, which poorly correlate to the underlying aquifer lithology. Second, SWAT only simulates a shallow soil zone and does not provide vadose zone storage which might better reflect deep water tables (i.e., greater than 10 feet depth to water). Finally, limited evidence suggested that SWAT was underestimating ET in the Northern GAM study region, which would result in an overestimation of recharge. For these reasons, an alternative method for estimating recharge was developed for the Queen City and Sparta GAMs which was used for all three model areas and for all model layers. The method was used to develop recharge across all of Texas and then down-scaled to each GAM grid to force consistency in overlap zones. SWAT was used to estimate groundwater ET parameters required as input to the MODFLOW ET package as described below.

For estimation of diffuse recharge, a method based upon the conceptual model for recharge was used. This conceptual model assumes that recharge is a function of precipitation, underlying soil and geologic properties, and topography. Recharge has long been considered a function of precipitation. However, empirical relationships between precipitation and recharge are not available and could not be generically developed. Scanlon et al. (2003) performed a detailed analysis of recharge in Texas and the potential vulnerability of Texas aquifers to groundwater contamination from surface sources. In this study, they performed detailed unsaturated zone simulations using long-term weather data, STATSGO and SSURGO soils data (5 meter soil profile), and vegetation data for all the major aquifers in Texas. Their simulations considered expected vegetation types, surface evaporation and soil ET, and runoff. Scanlon et al. (2003) found a strong correlation between recharge and precipitation for average annual precipitation rates above 15 to 16 inches per year (Table 11 and Figure 10 of Scanlon et al., 2003). Figure 6.3.14 plots the data from Scanlon et al. (2003). The highest predicted recharge rate was from Liberty County (Gulf Coast aquifer) at greater than 4 inches per year. This estimate was assumed to be an outlier and not representative of the Queen City and Sparta GAM model areas. Also assumed was that a linear relationship between recharge and precipitation was not reasonable but, rather, recharge would asymptote at high values of precipitation in the GAM study regions. Therefore, a spherical model was used to fit the Scanlon et al. (2003) data excluding the highest recharge value. This results in a curve relating recharge to precipitation that caps recharge at 2 inches per year for annual average precipitation rates of greater than 45 inches per year and sets recharge equal to zero for annual average precipitation rates less than 16 inches per year. The equation of the spherical functional relationship and the model fit is provided on Figure 6.3.14. Figure 6.3.15 shows the recharge map developed for the model domain based upon the simple precipitation relationship. To develop this estimate, the average annual precipitation rates presented in Section 2 of this report were used. The estimated recharge varies from less than 0.5 inches per year in the southwest to a maximum of 2 inches per year in the northeast.

The next conceptual factor used to define recharge was topography. Investigators have determined that recharge is affected by topography with relatively higher recharge occurring in highlands relative to lowlands, which are more likely associated with discharge (Meyboom, 1966; Toth, 1966). The effects of topography on the flow system and the potential for recharge was noted in the Carrizo-Wilcox aquifer in east Texas by Fogg and Kreitler (1982). The objective for this study was to develop a topographic scale factor that could be applied to the precipitation based recharge estimates (Figure 6.3.15) to scale recharge up in local highlands and down in lowlands with the additional constraint of conserving the precipitation volume on an area basis as defined by precipitation after Scanlon et al. (2003). The topographic scalar grid was developed for the entire model outcrop area and was a maximum of 2 at elevation maximums and a minimum of 0.1 in regions identified as river valleys. The topographic scalar was applied to model regions north of the Guadalupe River because the relationship between topography and recharge might reverse in the southwest where the water table is relatively deep and most recharge may occur due to stream losses. Figure 6.3.16 shows recharge as estimated from the precipitation relationship and then scaled to account for elevation differences. As can be seen in this figure, recharge was increased on the higher elevations and reduced in the lowlands.

The final step in the estimation of diffuse recharge accounted for the underlying geology. This was done by simply applying a formation scalar that would account for the underlying geology and the relative formation hydraulic conductivities. Formations with relatively high conductivities were assigned a high formation scalar and vice versa. Table 6.3.1 summarizes the formation scalar factors for the eight model layers for the three models as initially developed. During calibration, recharge was modified through the alteration of the formation scale factors. This process of regularization reduced the number of parameters requiring estimation to describe model recharge. The final steady-state calibrated scale factors are provided in Table 6.3.2. Figure 6.3.17 shows the calibrated model estimate of diffuse recharge for the study region incorporating the effects of average precipitation rate, topography, and underlying geology. Table 6.3.3 presents the average annual recharge rate in acre-feet per year for the three Queen City and Sparta GAMs. Table 6.3.4 presents the steady-state calibrated average annual recharge rates in inches per year for the three Queen City and Sparta GAMs.

For transient simulations, recharge was varied yearly based upon calculation of an annual standard precipitation index (SPI). The method shows good consistency with regional precipitation trends. The recharge rate for a given year (*t*) was calculated by:

$$R(t) = ((SPI(t) \times 1/3) + 1) \times R_{ss} \tag{6.1}$$

where $R(t)$ is the recharge rate for year t, $SPI(t)$ is the calculated local standard precipitation index for year t, and R_{ss} is the calibrated steady-state recharge rate. The method reverts to the mean over long-time periods and variation in recharge rates was constrained consistent with the findings of Scanlon et al. (2003).

SWAT was used for groundwater ET because it provided a physically based method for developing regional estimates of groundwater ET and ET extinction depth (the rooting depth). SWAT uses the Hargreaves Method for estimating potential ET which requires only estimates of monthly mean minimum and maximum temperatures, which are readily available for the study area. The Hargreaves method is considered accurate for simulation periods equal to, or larger than, one month. This is consistent with one year stress periods and the assumptions underlying the NRCS curve-number method for estimating runoff. The potential ET is converted to an actual ET based on the vegetation size and type (determines maximum ET) and soil water availability (determines actual ET).

SWAT simulations were carried out using daily time steps and precipitation/temperature data. Daily time steps (or less) are necessary for approximating runoff during precipitation events. SWAT was simulated for the time period from 1975 through 1999. For each MODFLOW stress period, SWAT calculates the ET max and the extinction depth for the MODFLOW ET package. SWAT accounts for ET that may occur in the vadose zone. However, in the method of application for this study, SWAT did not account for groundwater transpiration. To account for groundwater ET, the “surplus” ET from SWAT (ET max – ET actual) was applied as ET max in the groundwater ET package in MODFLOW. For each month simulated, SWAT calculates a rooting depth representative of the season, vegetative cover, and soil type. This rooting depth was passed through to MODFLOW as the extinction depth required by the MODFLOW ET package. As a result, ET from groundwater occurred when the water table (as simulated by MODFLOW) was above the extinction depth and there was surplus ET potential for that particular stress period.

Figure 6.3.18 plots the average ET maximum rate estimated by SWAT and applied to the Queen City and Sparta GAMs. Figure 6.3.19 plots the ET extinction depth expressed in units of feet. The extinction depths range from 1 to 8 feet with large portions of the Central and Northern GAM regions having depths between 6 and 8 feet. These values compare well with the range in maximum rooting depths for temperate terrestrial biomes, which range to depths of 5 meters (16 feet) but average between 2 to 3 meters (7 to 10 feet) (Canadell et al., 1996).

6.3.6 Implementation of Pumping Discharge

Pumping discharge is not considered in the predevelopment model because that model is meant to be representative of times prior to significant resource use. However, pumping discharge is the primary stress on the model during the historical (1980 through 1999) and predictive (2000 through 2050) model periods. Pumping discharge is a cell dependent specified flow boundary.

The procedural techniques used to estimate and allocate pumping are provided in Section 4.7 and Appendices C and D. For details of how the historical or predictive pumping was derived, the reader is referred to those appendices. Once the pumping was estimated for each of the seven user groups, it was summed across all user groups for a given model cell (row, column) and a given model layer. This process was repeated for all active model cells in the model domain for each transient stress period. As discussed above, the stress period used in the transient simulations is one year. Therefore, the MODFLOW well-package data set has a specified flow boundary condition for each year of simulation, for each active grid cell within which pumping occurs. In the transient calibration equilibration period, well production rates were held at 1980 estimates.

Pumping distributions for the Carrizo-Wilcox aquifers were developed and documented for the Carrizo-Wilcox GAMs (Deeds et al., 2003; Dutton et al., 2003; Fryar et al., 2003). Reviewers of these reports and models identified pumping differences in the overlap county-basins. To correct this issue to the degree possible within the scope of the Queen City and Sparta GAMs, the pumping data sets for the three Carrizo-Wilcox GAMs were reviewed and the models which best reproduced the TWDB database pumping estimates were determined. In overlap counties, the model which best reproduced the TWDB's pumping estimates was used to define Carrizo-Wilcox pumping. Table 6.3.5 provides which model was used in which model county-basins. As discussed in Section 4 of this report, all county-other pumping was re-allocated by aquifer in these models.

6.3.7 Model Initial Conditions

Two sets of model initial conditions were required for the Queen City and Sparta GAMs. The first was the initial hydraulic heads for the steady-state simulations. The second was the initial hydraulic heads for the beginning of the transient simulation period (1980).

The choice of initial hydraulic heads for the steady-state model is generally not very important to the steady-state solution. However, it is important to initialize heads above the bottom of all model cells and advantageous to initialize heads higher than the expected model solution when modeling unconfined flow. Both of these constraints were used in initializing the steady-state heads to prevent numerical difficulties that result from the MODFLOW-96 BCF2 package.

For the beginning of the transient simulation, initial hydraulic heads were based upon average kriged head surfaces for 1980 detailed in Section 4.4.4. These heads were used as the initial heads at the beginning of the equilibration period.

Table 6.3.1 Initial recharge formation scalar factors.

Formation	Model Layer	Southern GAM	Central GAM	Northern GAM
Sparta	1	0.8	0.8	0.8
Weches	2	0.2	0.2	0.2
Queen City	3	0.5	0.5	0.5
Reklaw	4	0.2	0.2	0.2
Carrizo	5	1.2	1.2	1.2
U. Wilcox/Calvert Bluff	6	0.4	0.5	0.5
M. Wilcox/Simsboro	7	0.4	1.2	0.5
L. Wilcox/Hooper	8	0.5	0.4	0.4

Table 6.3.2 Calibrated steady-state recharge formation scalar factors.

Formation	Model Layer	Southern GAM	Central GAM	Northern GAM
Sparta	1	0.8	0.8	0.8
Weches	2	0.2	0.2	0.2
Queen City	3	0.5	0.5	0.4
Reklaw	4	0.2	0.2	0.2
Carrizo	5	1.2	1.2	1.2
U. Wilcox/Calvert Bluff	6	0.4	0.4	0.5
M. Wilcox/Simsboro	7	0.4	1.2	0.5
L. Wilcox/Hooper	8	0.5	0.3	0.3

Table 6.3.3 Calibrated steady-state recharge estimates for each model (AFY).

Formation	Southern GAM	Central GAM	Northern GAM
Sparta	24,486	126,400	140,025
Weches	4,714	12,700	10,815
Queen City	69,019	154,300	275,580
Reklaw	6,689	17,100	33,262
Carrizo	65,374	83,700	131,896
U. Wilcox/Calvert Bluff	1,130	83,300	166,745
M. Wilcox/Simsboro	22,849	53,300	274,089
L. Wilcox/Hooper	24,249	30,800	17,546
Total	218,510	561,600	1,049,957

Table 6.3.4 Calibrated steady-state recharge estimates for each model (in/year).

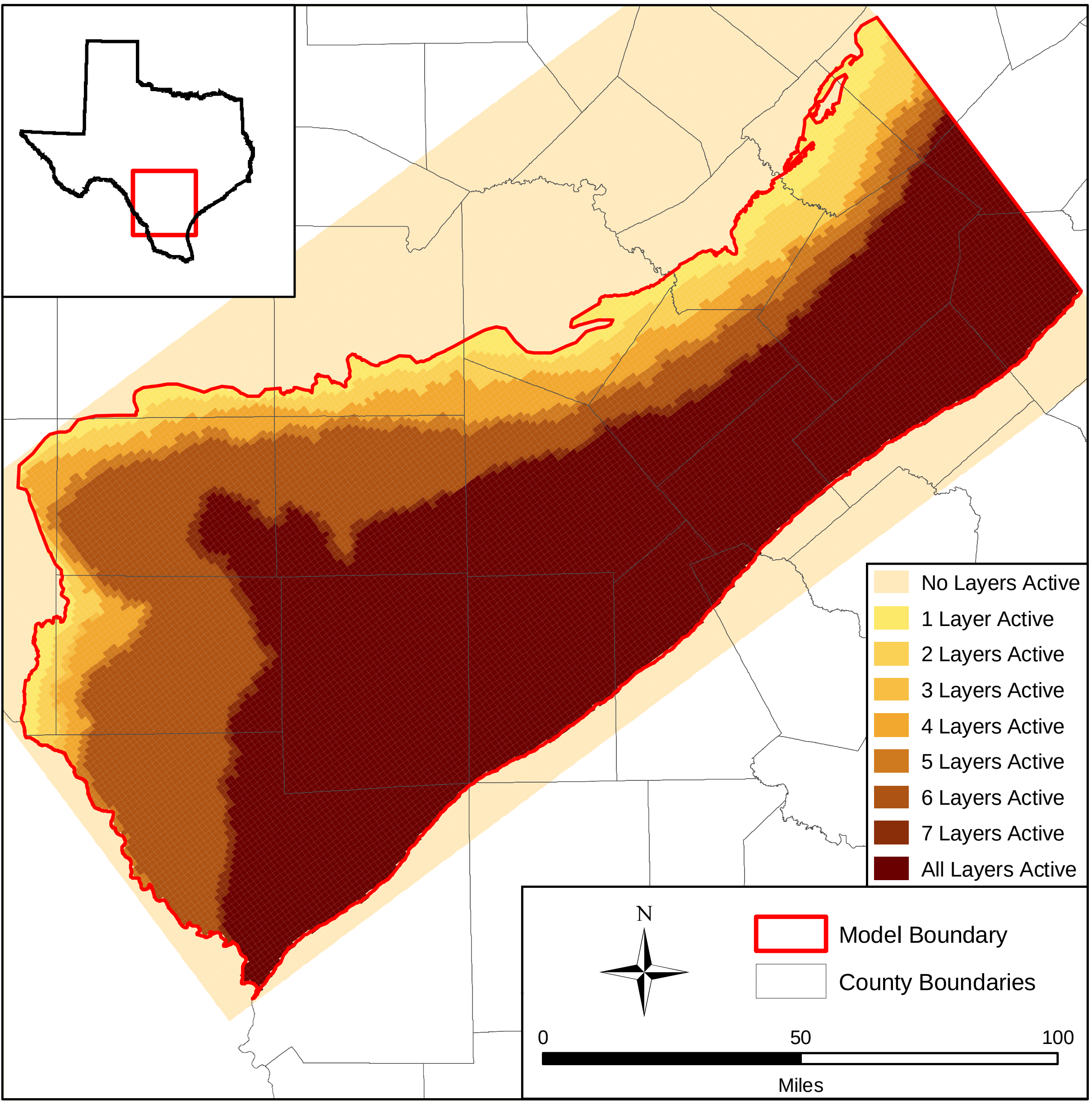
Formation	Southern GAM	Central GAM	Northern GAM
Sparta	0.6	1.6	1.7
Weches	0.2	0.4	0.5
Queen City	0.4	0.8	0.8
Reklaw	0.2	0.3	0.4
Carrizo	1.2	2.2	2.6
U. Wilcox/Calvert Bluff	0.5	0.7	0.9
M. Wilcox/Simsboro	0.4	1.8	1.0
L. Wilcox/Hooper	0.6	0.6	0.5

Table 6.3.5 **County-basin correlation table for defining pumping in the Carrizo-Wilcox aquifers of the Queen City and Sparta GAMs.**

County	Basin	Carrizo-Wilcox GAM Used for Pumping
Freestone	Trinity River Basin	Central
Freestone	Brazos River Basin	Central
Grimes	Trinity River Basin	Central
Grimes	San Jacinto River Basin	Central
Grimes	Brazos River Basin	Central
Leon	Trinity River Basin	Central
Leon	Brazos River Basin	Central
Limestone	Trinity River Basin	Central
Limestone	Brazos River Basin	Central
Madison	Trinity River Basin	Central
Madison	Brazos River Basin	Central
Montgomery	San Jacinto River Basin	Central
Navarro	Trinity River Basin	Central
Robertson	Brazos River Basin	Central
San Jacinto	Trinity River Basin	Central
San Jacinto	San Jacinto River Basin	Central
Walker	Trinity River Basin	Central
Walker	San Jacinto River Basin	Central
Bastrop	Colorado River Basin	Central
Fayette	Colorado River Basin	Central
Fayette	Lavaca River Basin	Central
Lavaca	Lavaca River Basin	Central
Anderson	Neches River Basin	Northern
Anderson	Trinity River Basin	Northern
Angelina	Neches River Basin	Northern
Cherokee	Neches River Basin	Northern
Henderson	Neches River Basin	Northern
Henderson	Trinity River Basin	Northern
Houston	Neches River Basin	Northern
Houston	Trinity River Basin	Northern
Jasper	Sabine River Basin	Northern
Jasper	Neches River Basin	Northern
Nacogdoches	Neches River Basin	Northern
Newton	Sabine River Basin	Northern
Newton	Neches River Basin	Northern
Polk	Neches River Basin	Northern
Polk	Trinity River Basin	Northern
Rusk	Neches River Basin	Northern
Sabine	Sabine River Basin	Northern
Sabine	Neches River Basin	Northern
San Augustine	Neches River Basin	Northern

Table 6.3.5, continued

County	Basin	Carrizo-Wilcox GAM Used for Pumping
Smith	Neches River Basin	Northern
Trinity	Neches River Basin	Northern
Trinity	Trinity River Basin	Northern
Tyler	Neches River Basin	Northern
Van Zandt	Neches River Basin	Northern
Van Zandt	Trinity River Basin	Northern
Bastrop	Guadalupe River Basin	Southern
Bexar	San Antonio River Basin	Southern
Caldwell	Colorado River Basin	Southern
Caldwell	Guadalupe River Basin	Southern
DeWitt	Lavaca River Basin	Southern
DeWitt	Guadalupe River Basin	Southern
DeWitt	San Antonio River Basin	Southern
Fayette	Guadalupe River Basin	Southern
Gonzales	Lavaca River Basin	Southern
Gonzales	Lavaca River Basin	Southern
Gonzales	Guadalupe River Basin	Southern
Guadalupe	Guadalupe River Basin	Southern
Guadalupe	San Antonio River Basin	Southern
Karnes	Guadalupe River Basin	Southern
Karnes	San Antonio River Basin	Southern
Lavaca	Guadalupe River Basin	Southern
Lavaca	Guadalupe River Basin	Southern
Wilson	Guadalupe River Basin	Southern
Wilson	San Antonio River Basin	Southern



File: Fig_6.3.1_SW_Active_Inactive.mxd

Figure 6.3.1 Southern GAM active and inactive cell coverage by layer.

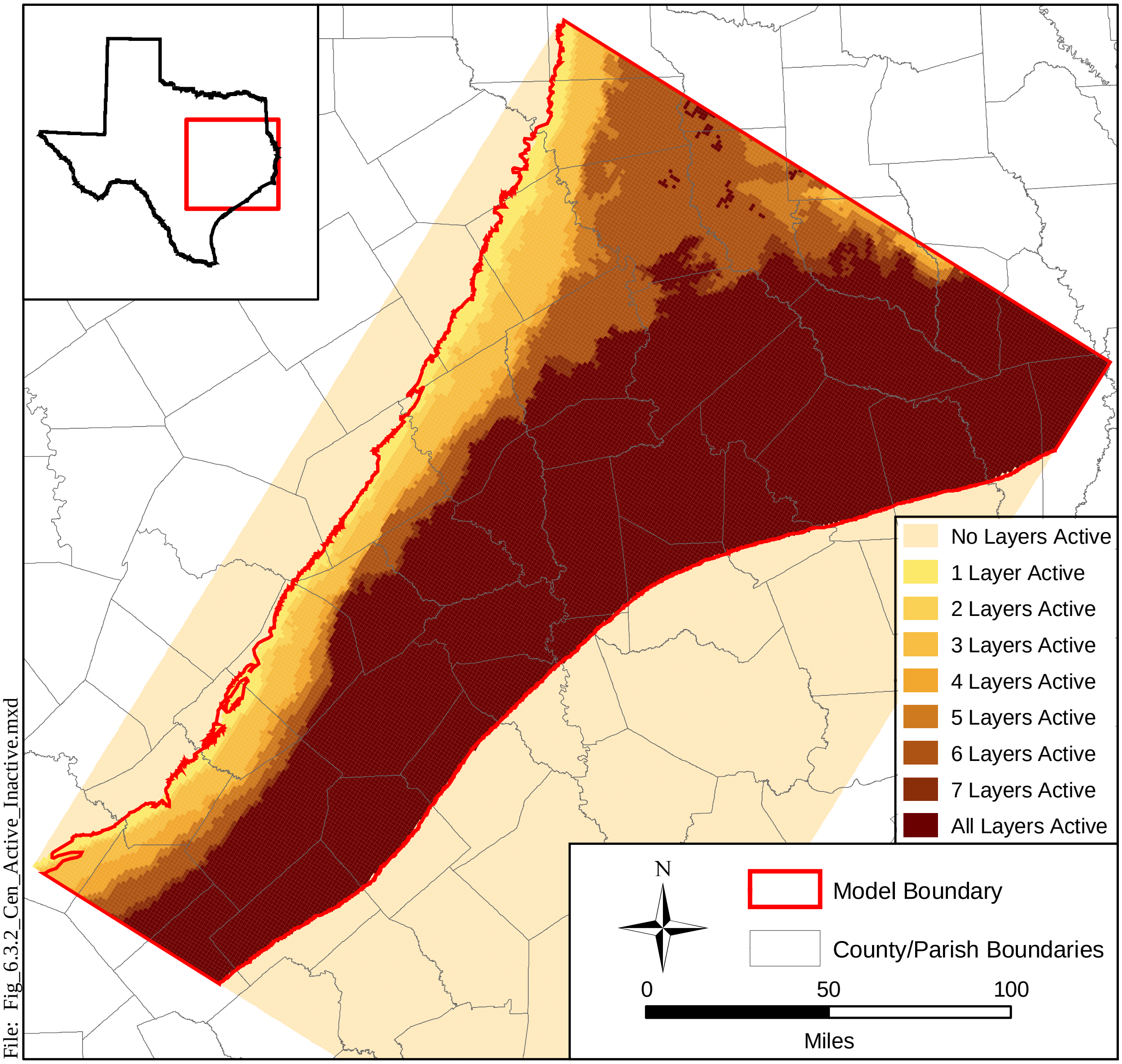


Figure 6.3.2 Central GAM active and inactive cell coverage by layer.

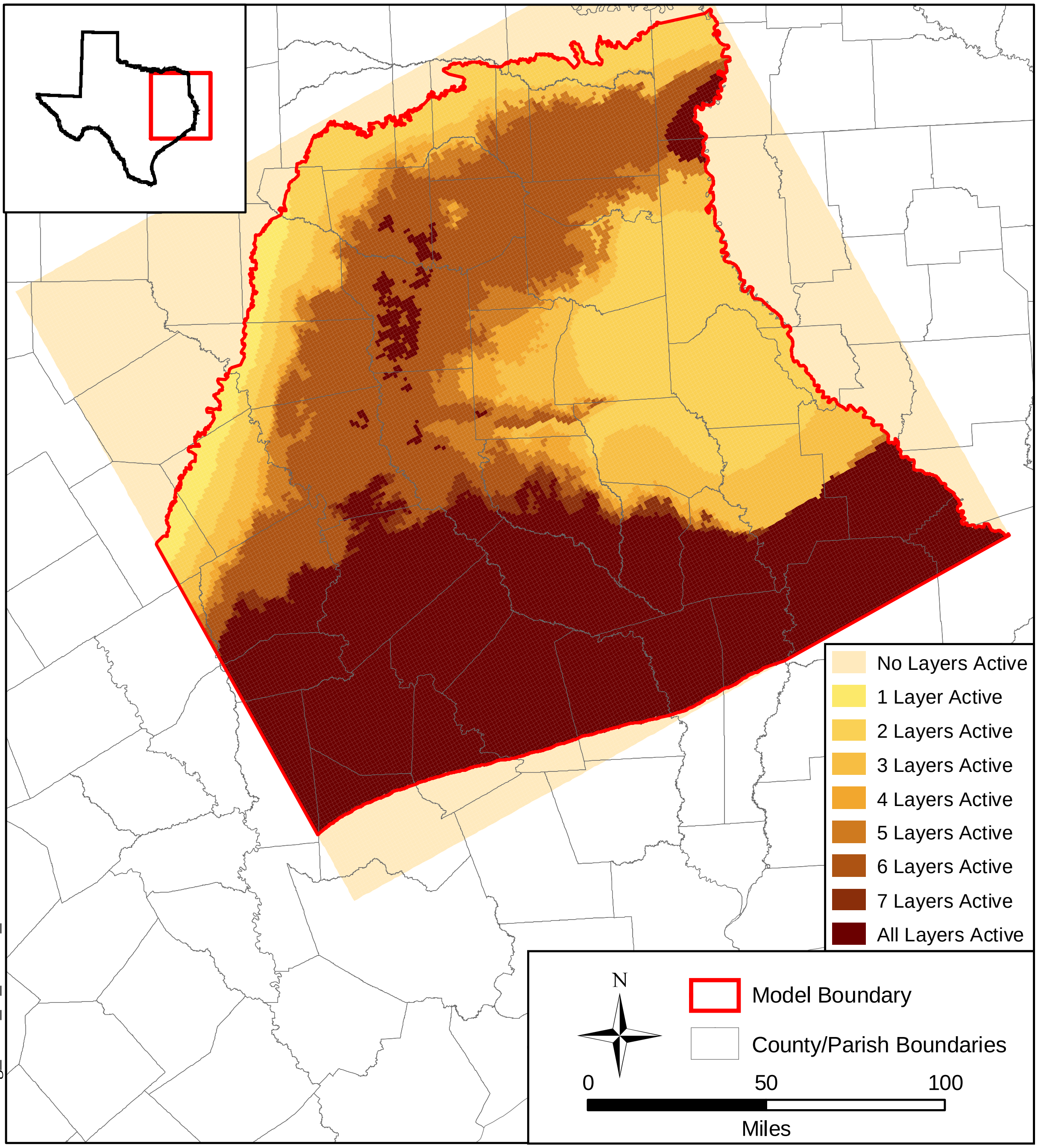


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Figure 6.3.3 Northern GAM active and inactive cell coverage by layer.

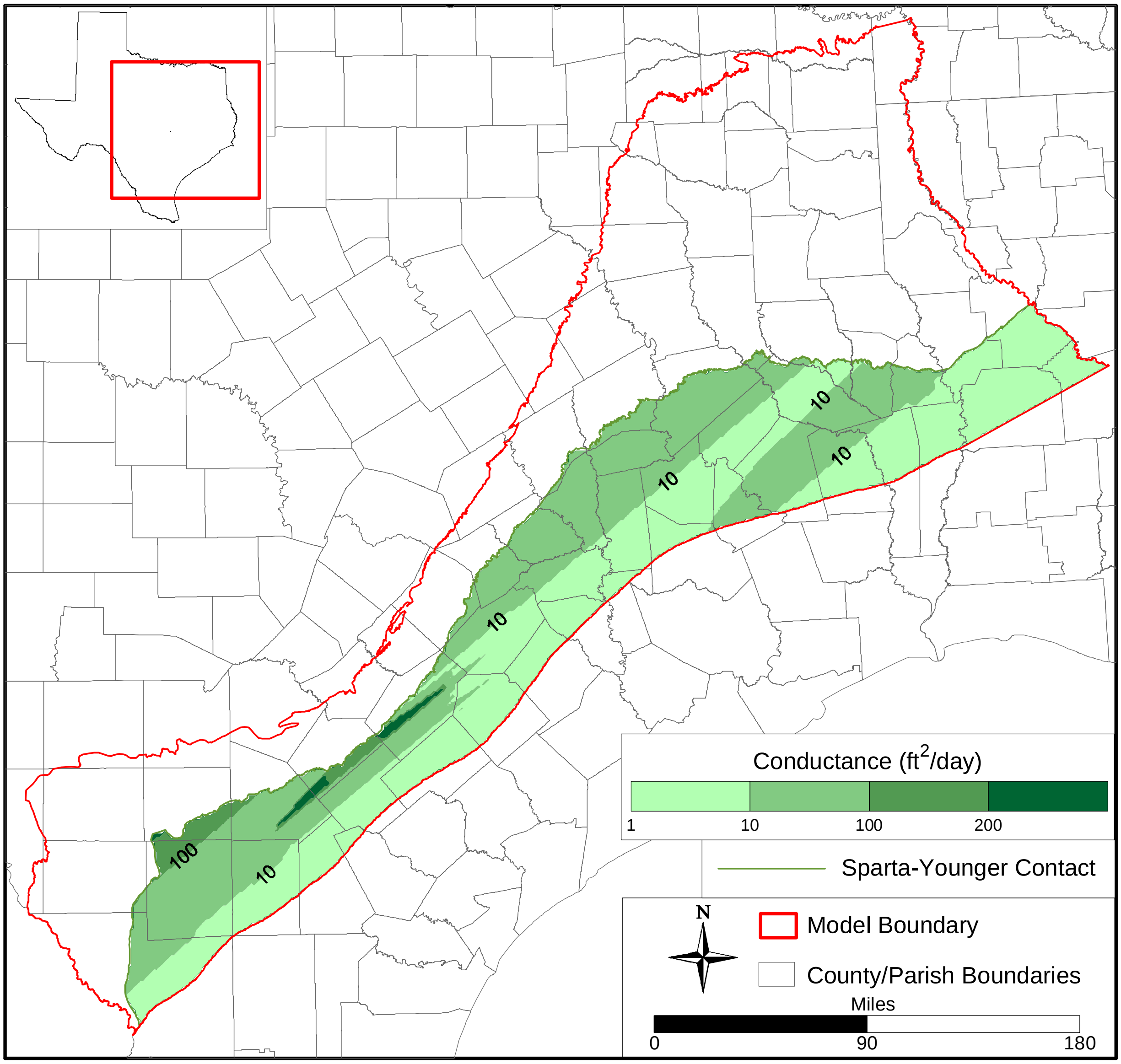

Figure 6.3.4 **Hydraulic conductance of the younger sediments applied to the vertical general head boundary.**

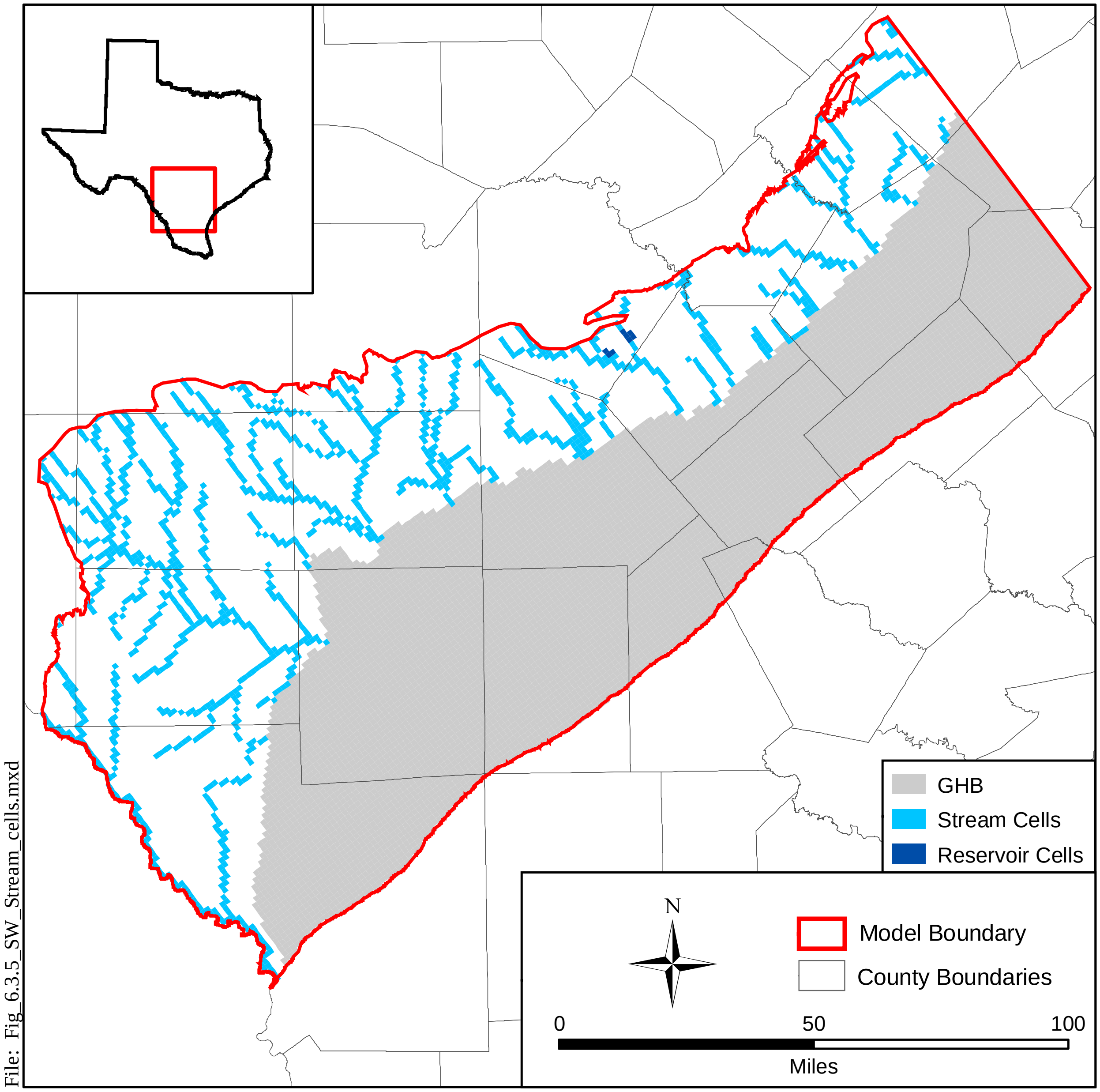

Figure 6.3.5 **Southern GAM stream and reservoir cell boundary conditions.**

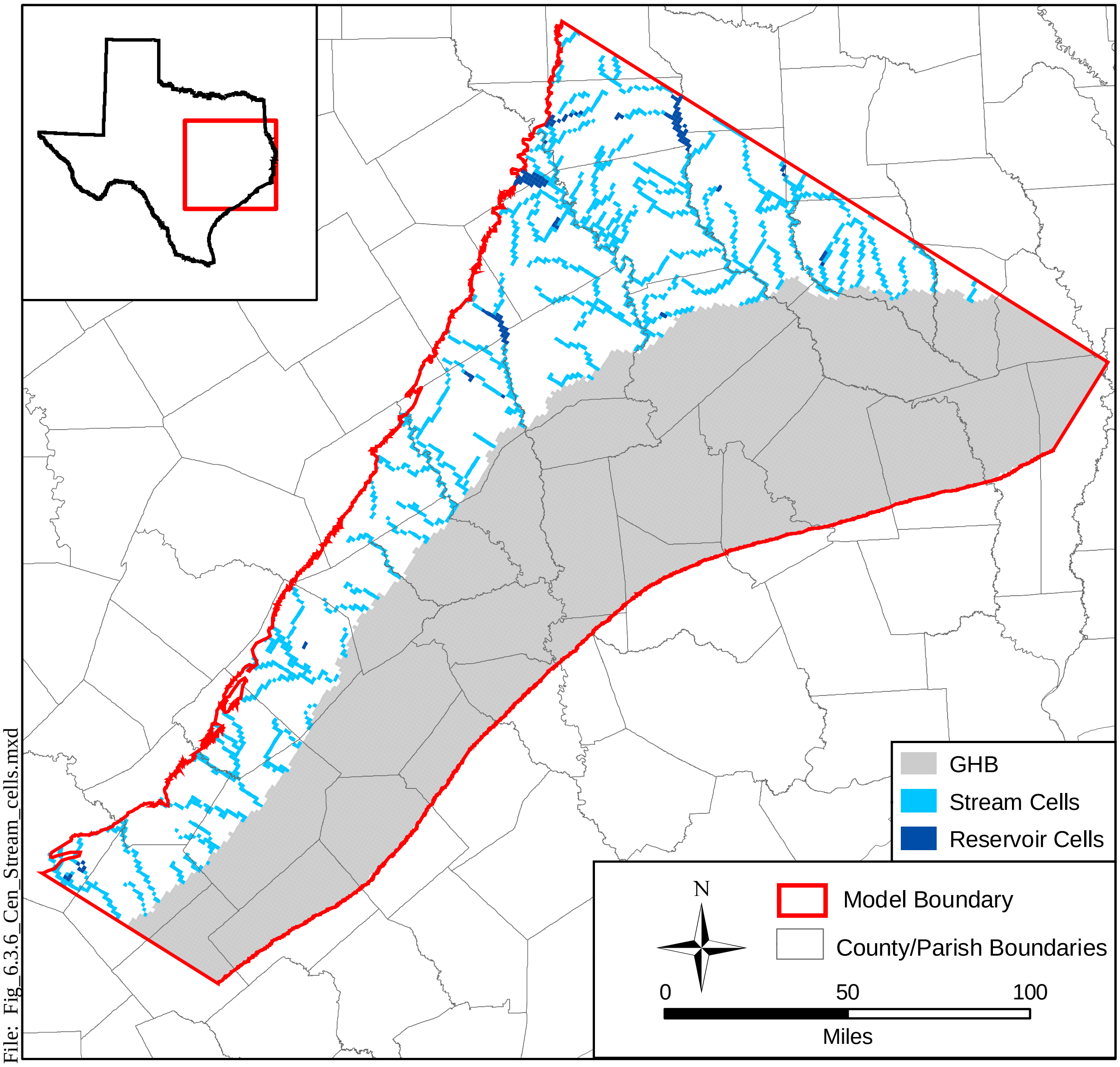

Figure 6.3.6 Central GAM stream and reservoir cell boundary conditions.

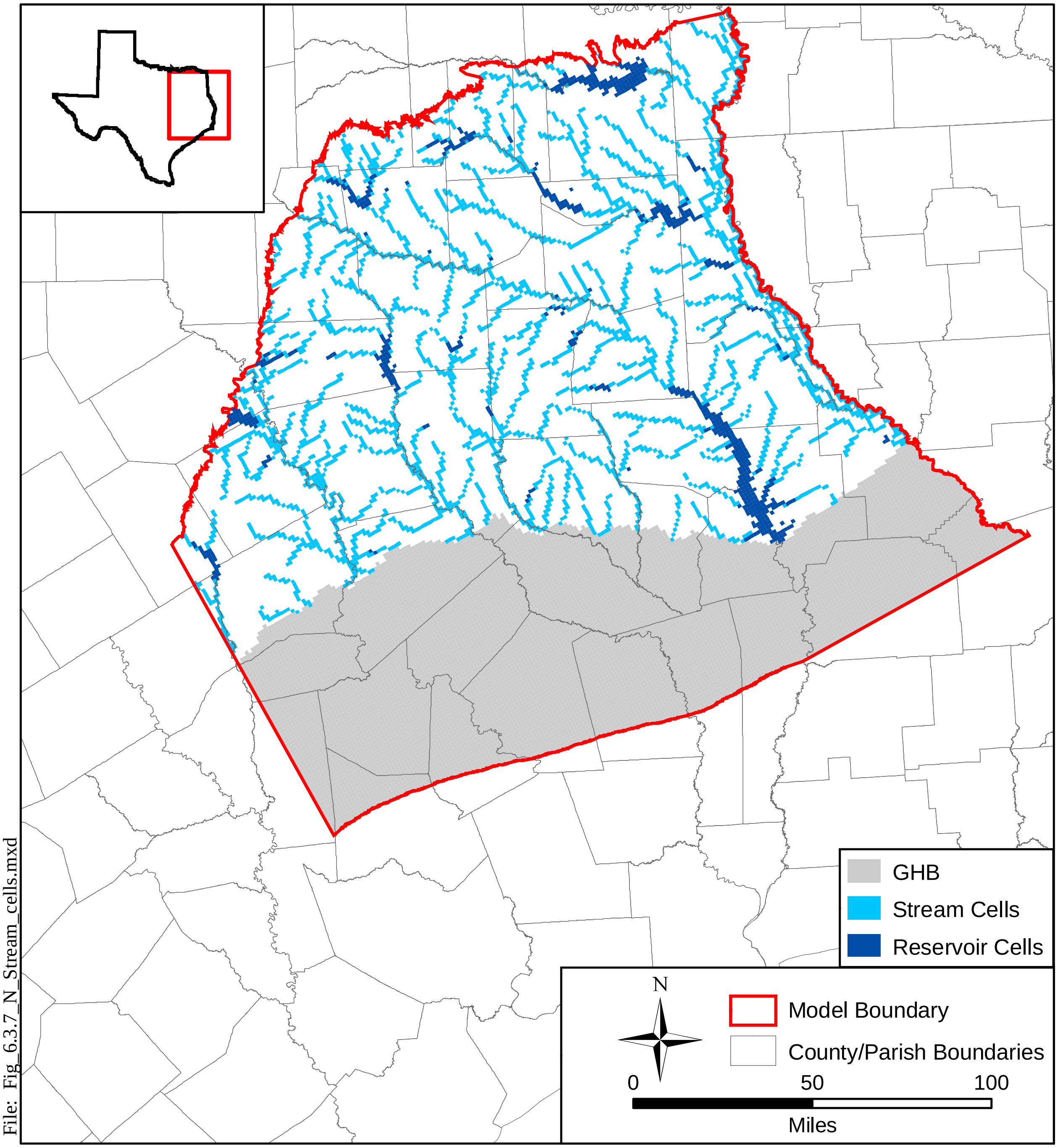

Figure 6.3.7 Northern GAM stream and reservoir cell boundary conditions.

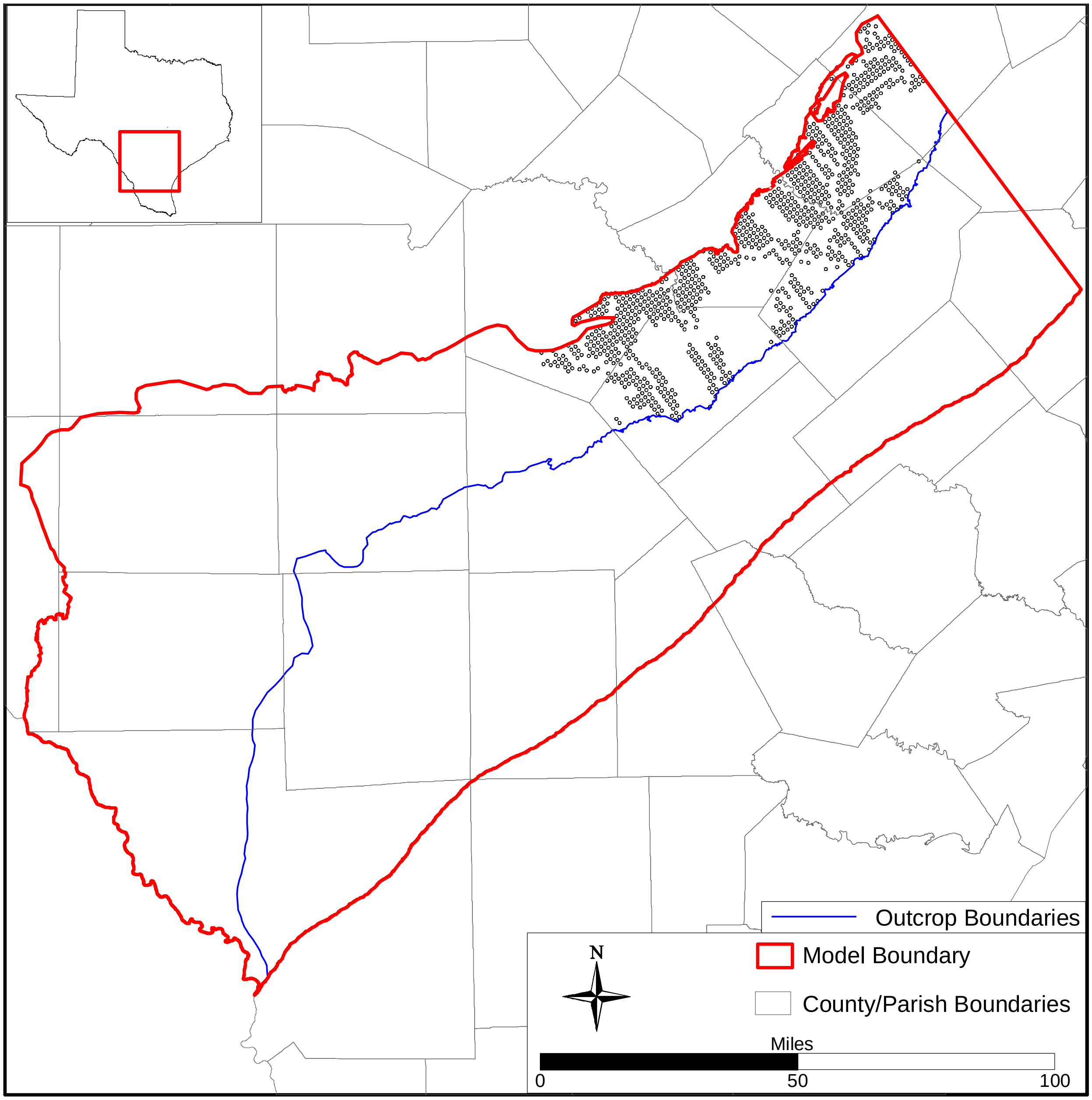

Figure 6.3.8 Southern GAM drain cells.

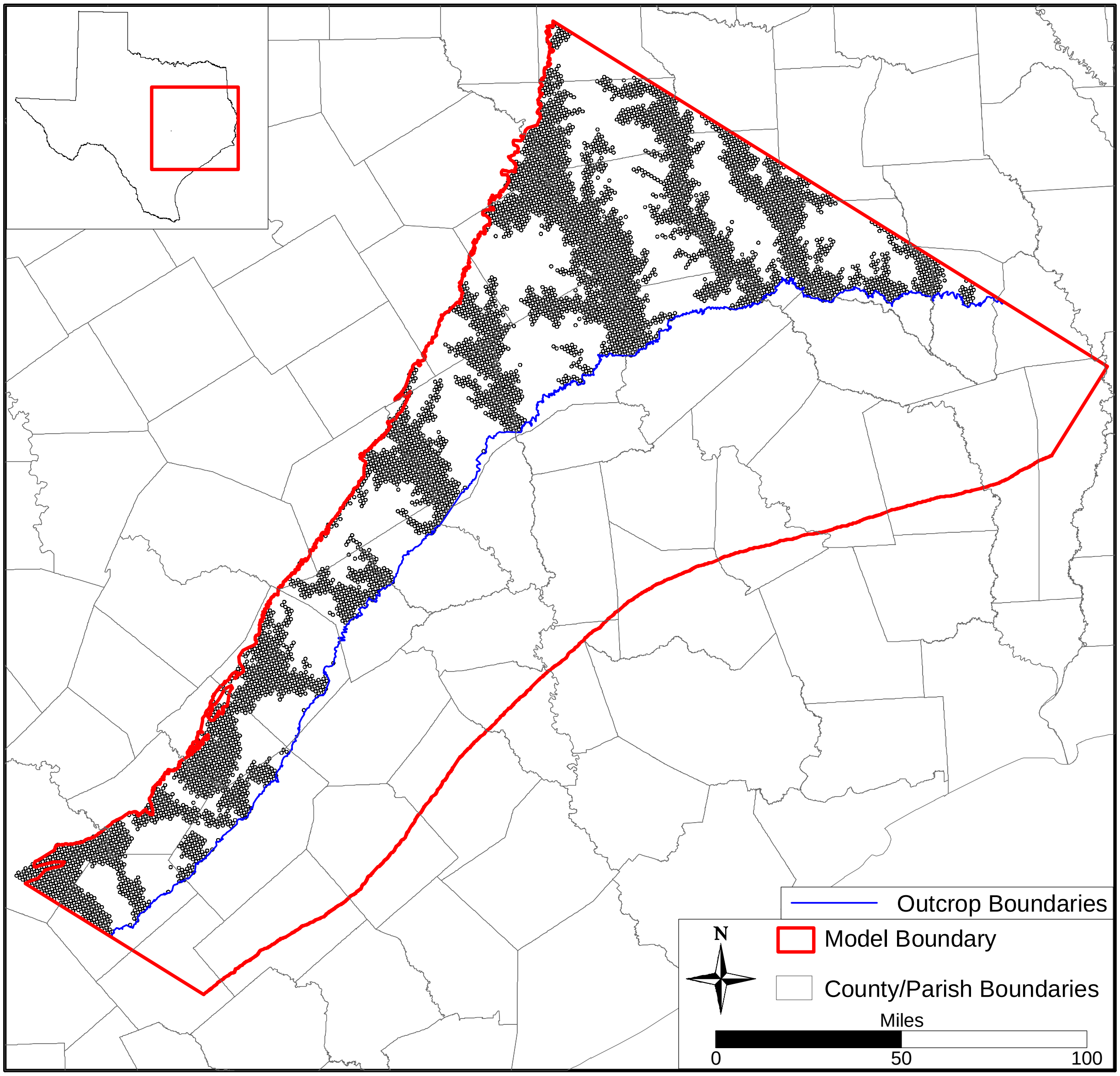

Figure 6.3.9 Central GAM drain cells.

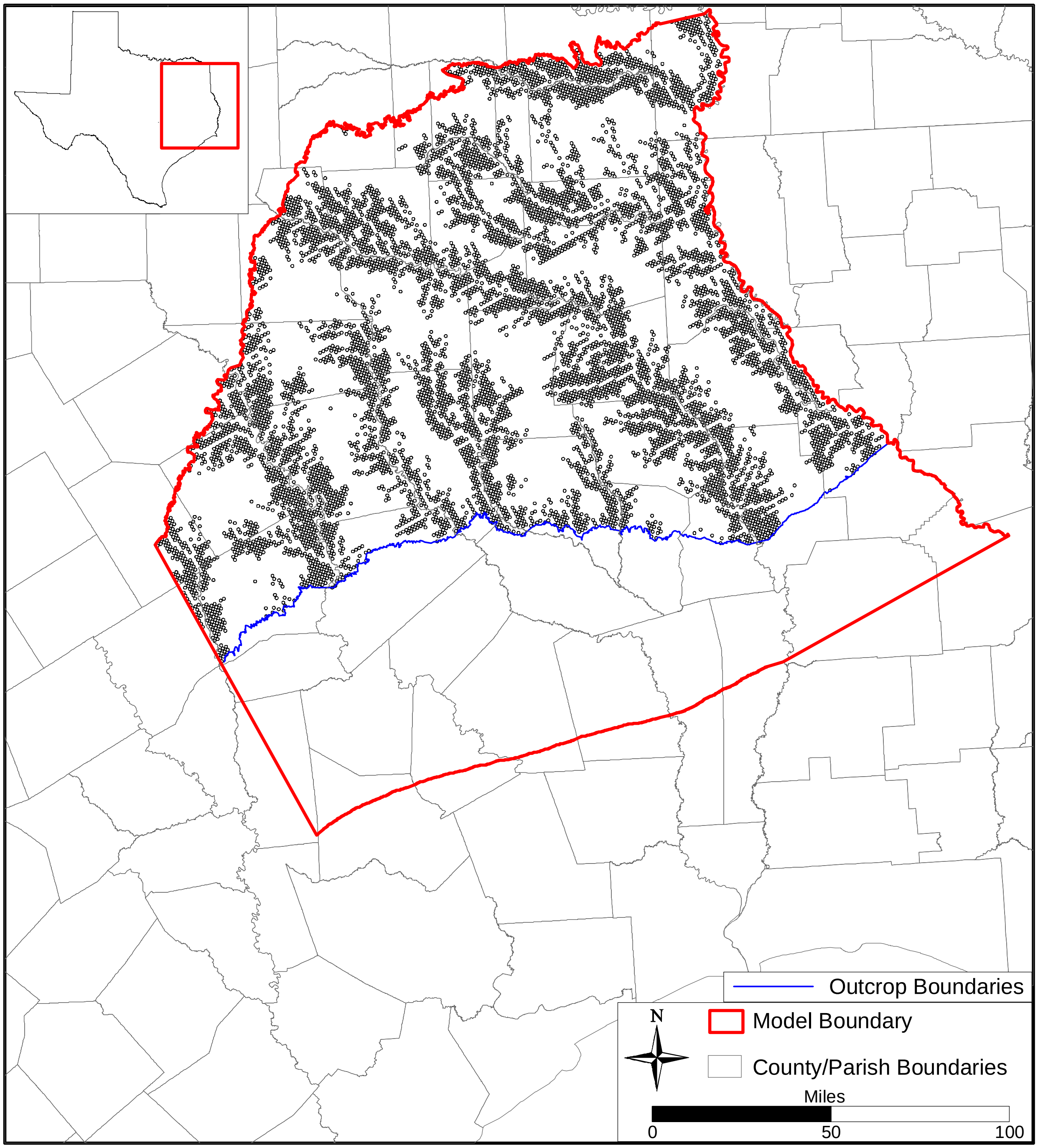

Figure 6.3.10 Northern GAM drain cells.

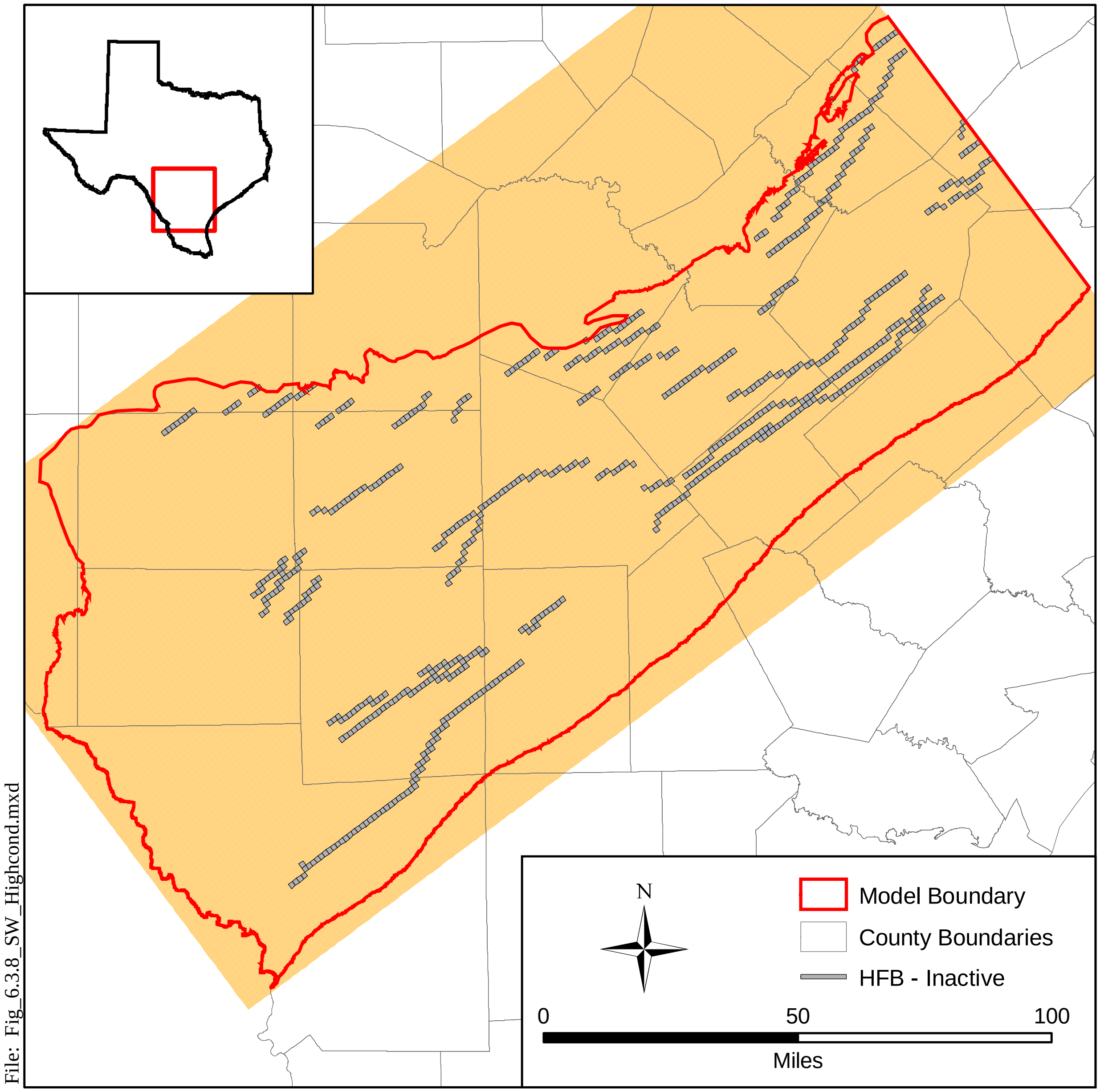

Figure 6.3.11 Southern GAM fault boundary cells.

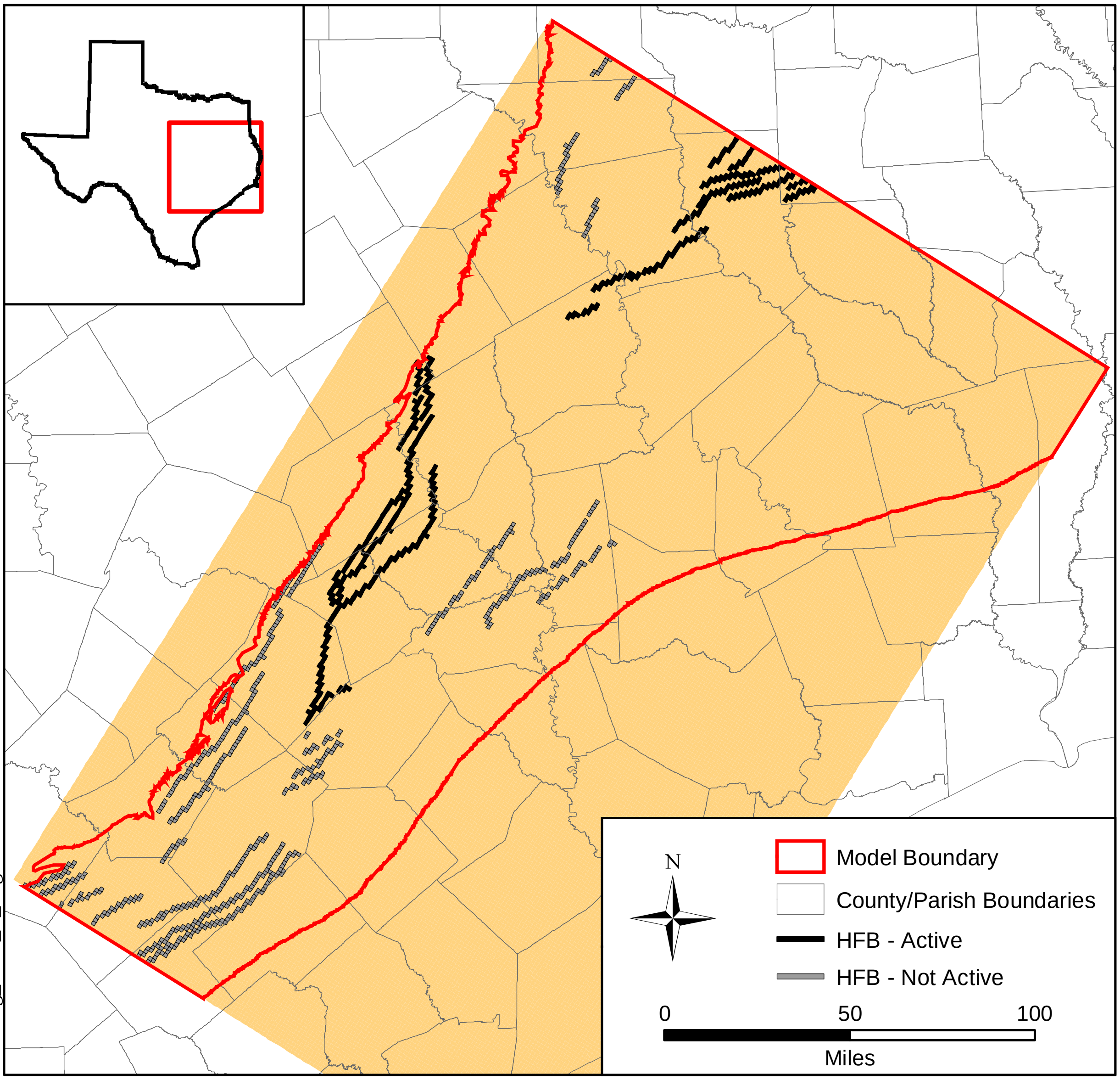

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Figure 6.3.12 Central GAM fault boundary cells.

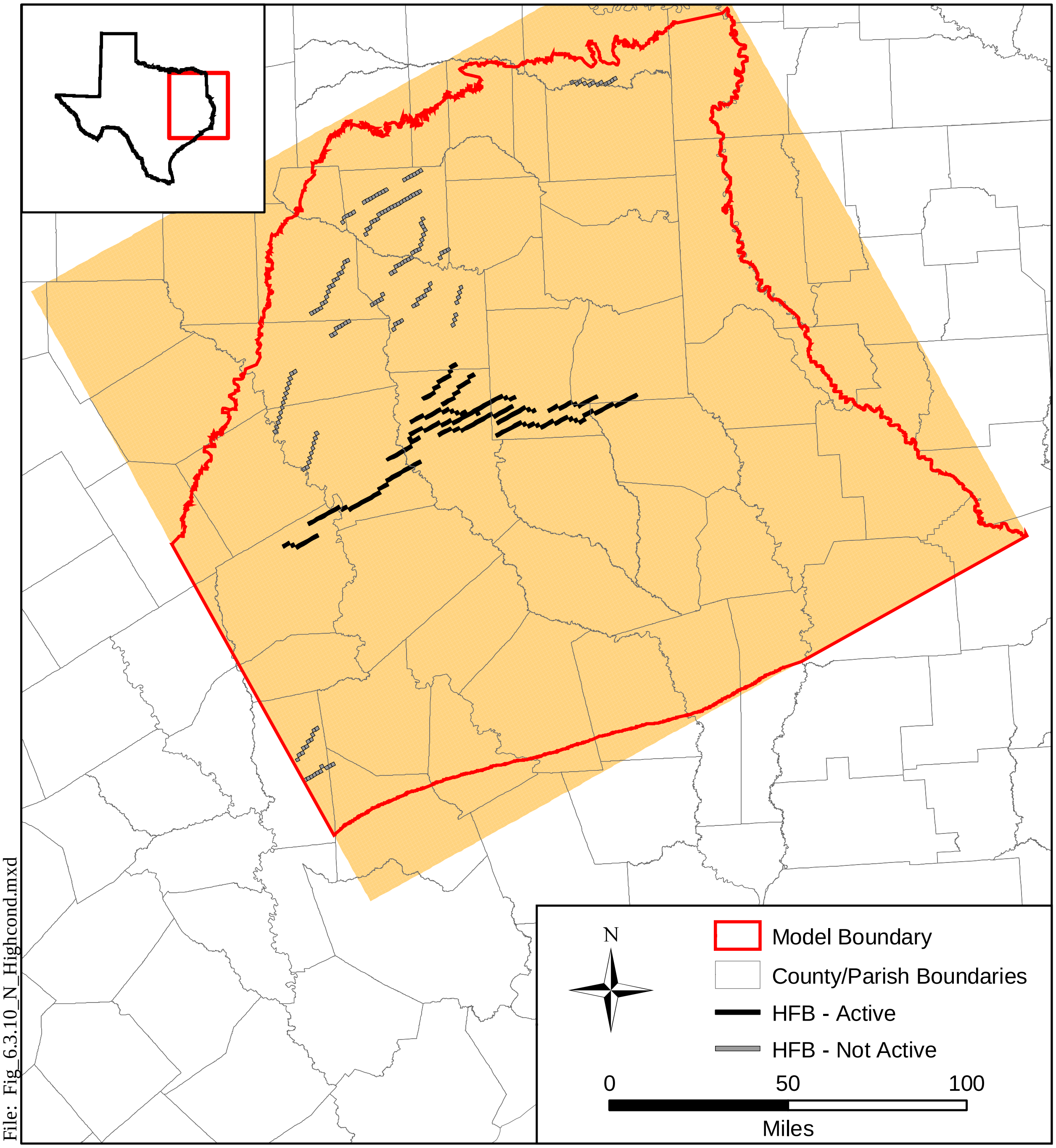
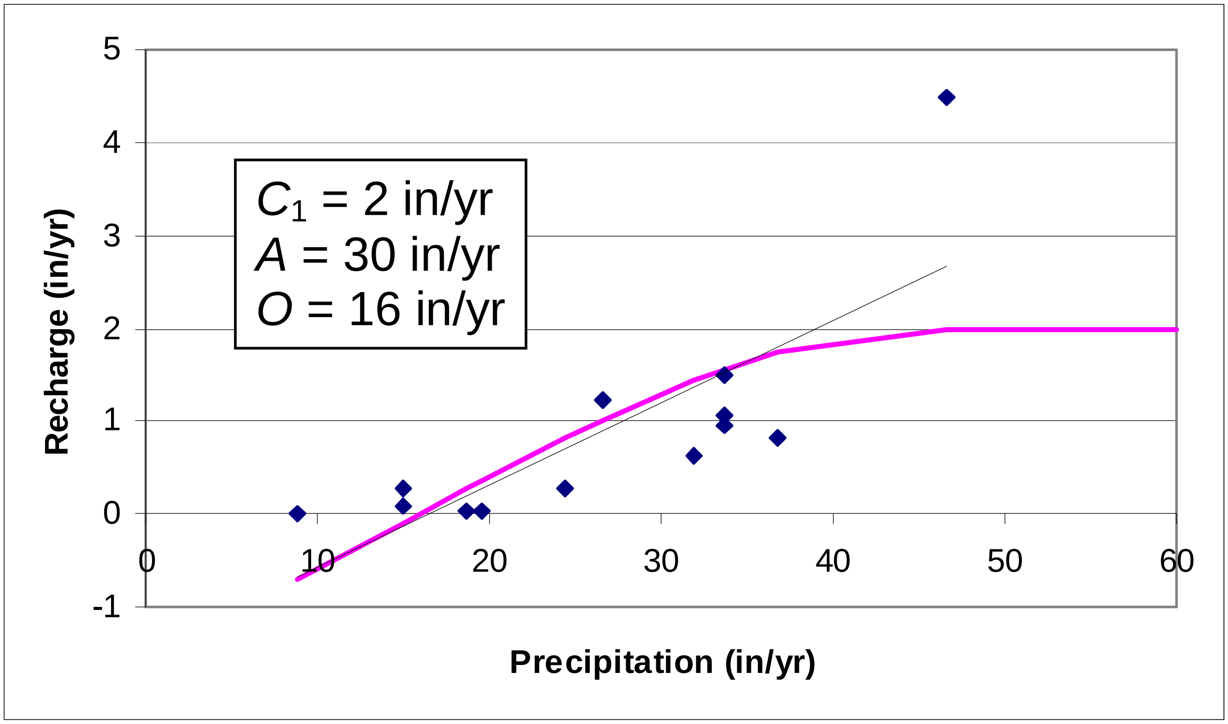


Figure 6.3.13 Northern GAM fault boundary cells.



$$R(P) = \left\{ \begin{array}{ll} C_1(1.5\frac{P-O}{A} - 0.5\left(\frac{P-O}{A}\right)^3) & (P-O) < A \\ C_1 & (P-O) \geq A \end{array} \right\}$$

Figure 6.3.14 Recharge as a function of precipitation (after Scanlon et al., 2003).

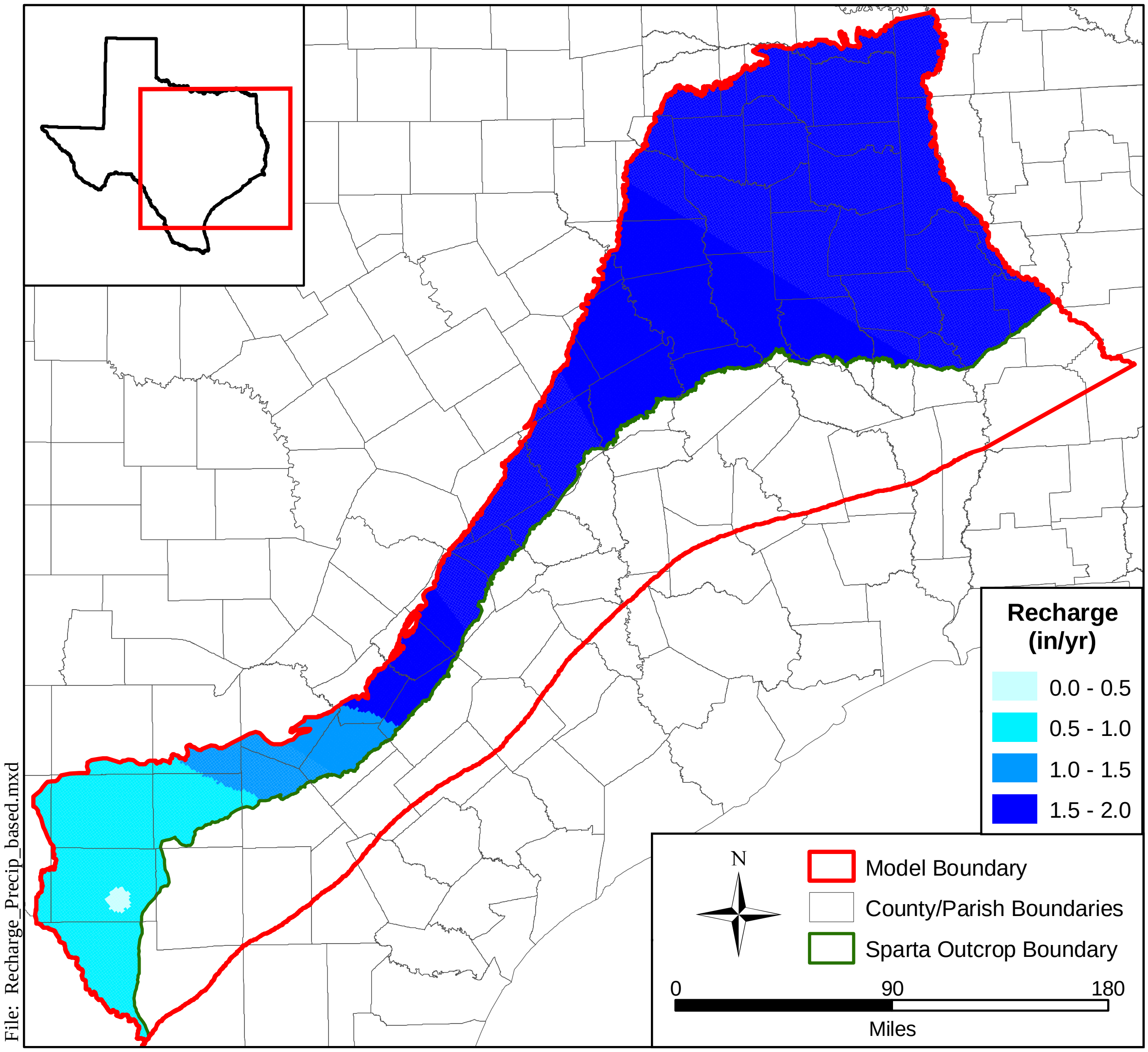


Figure 6.3.15 Recharge distribution based upon precipitation.

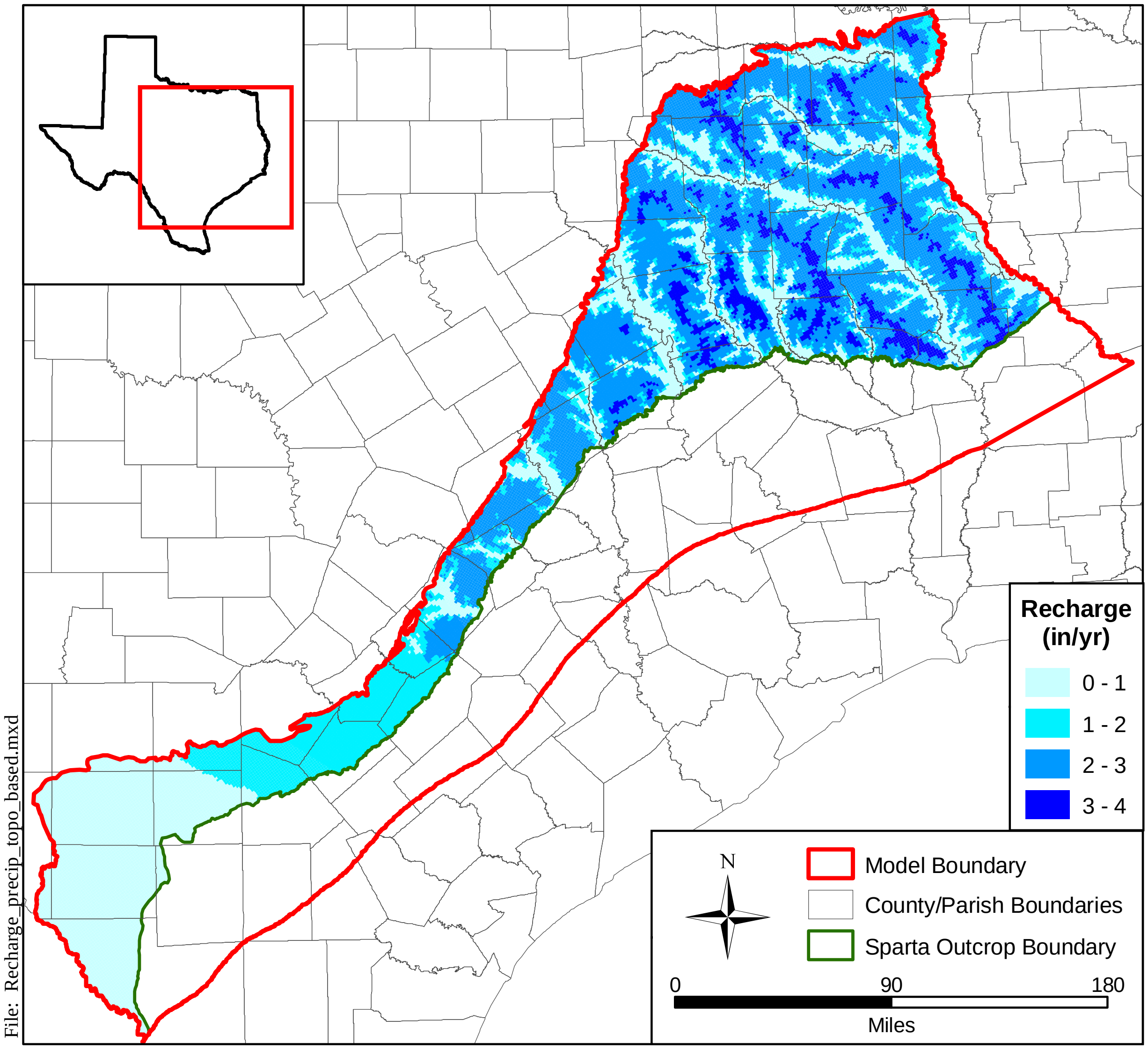
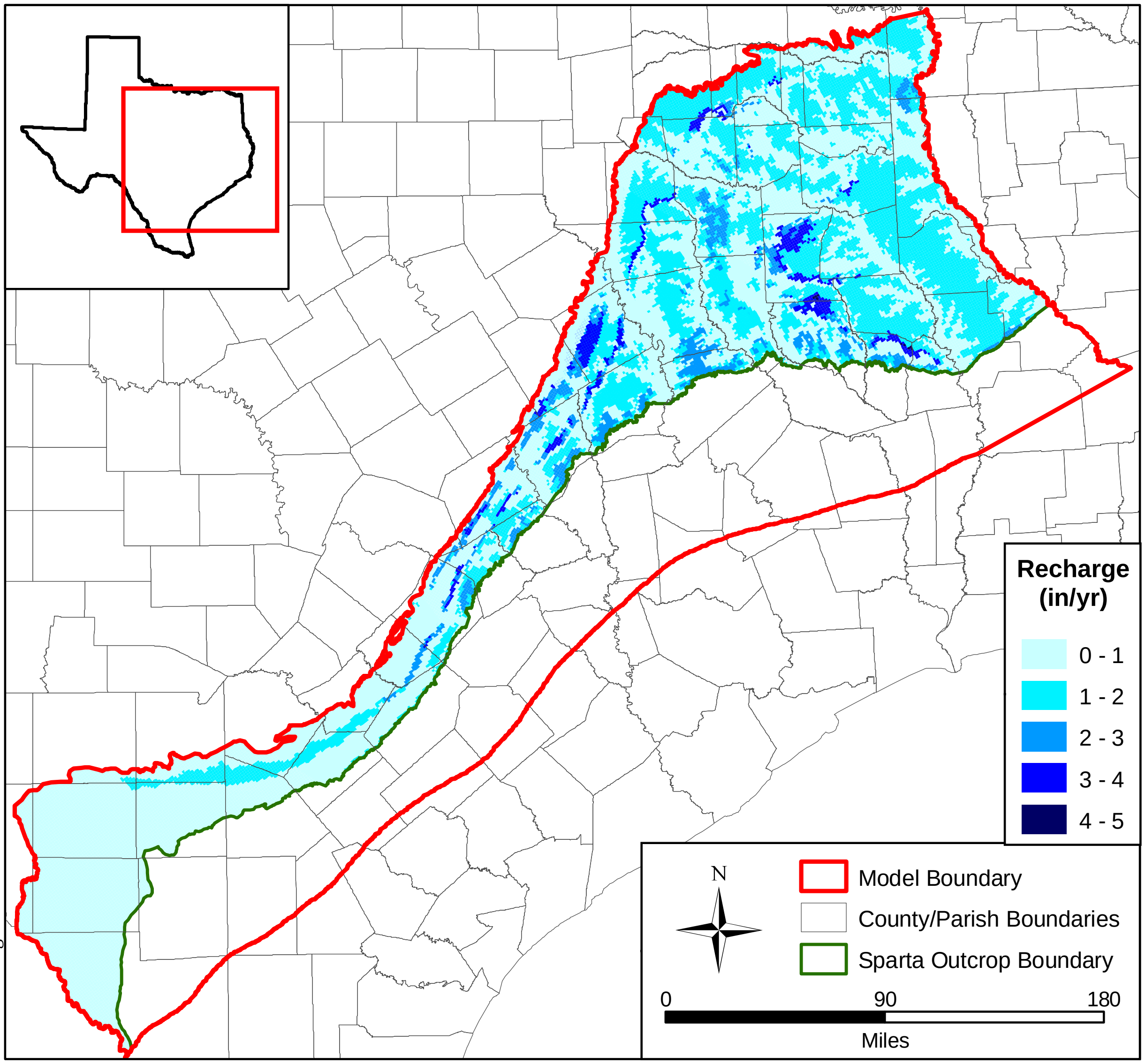


Figure 6.3.16 **Recharge distribution based upon precipitation and topography.**



File: Recharge.mxd

Figure 6.3.17 Calibrated recharge estimate based upon precipitation, topography, and geology.

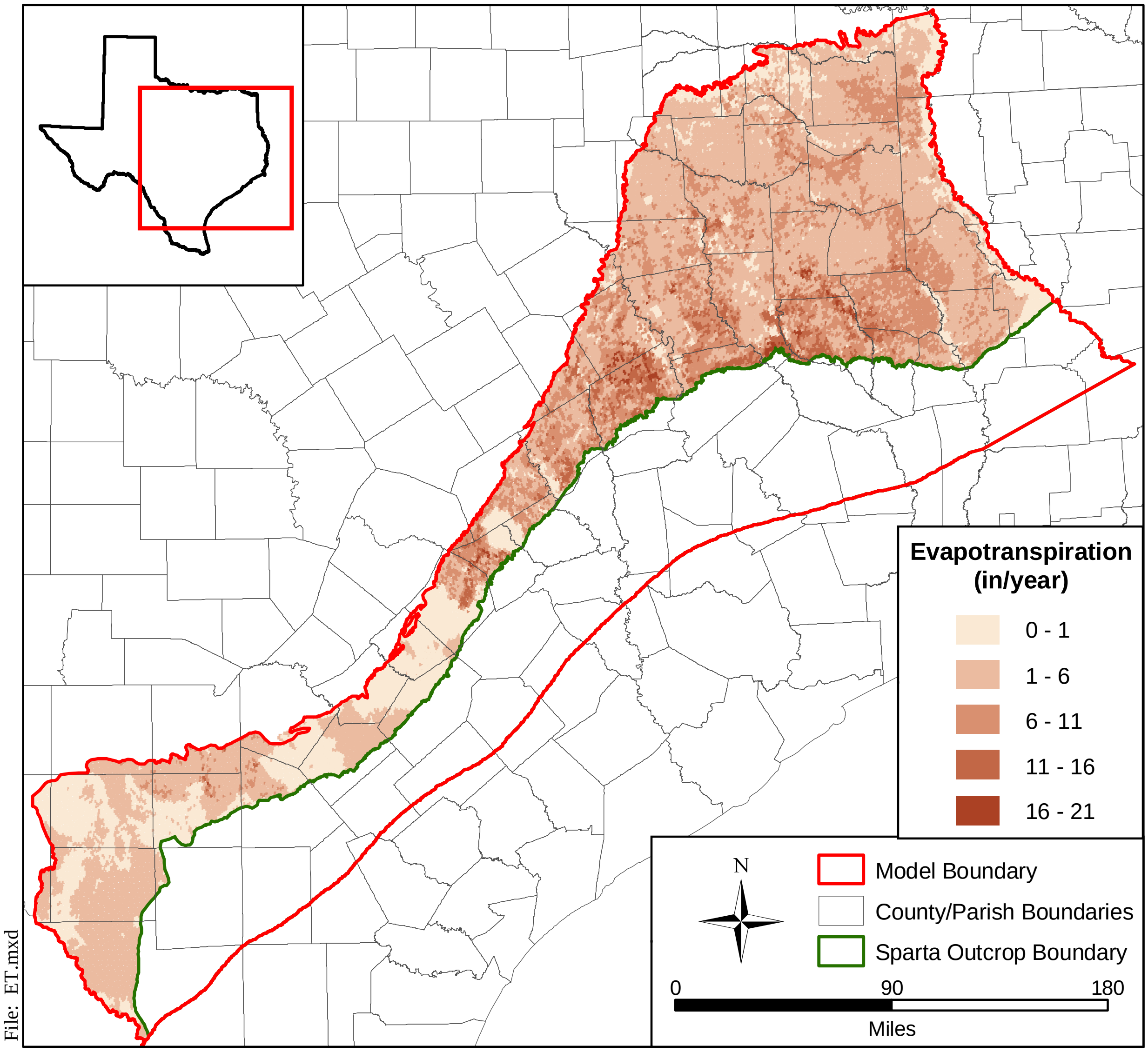


Figure 6.3.18 Average ET maximum estimated by SWAT.

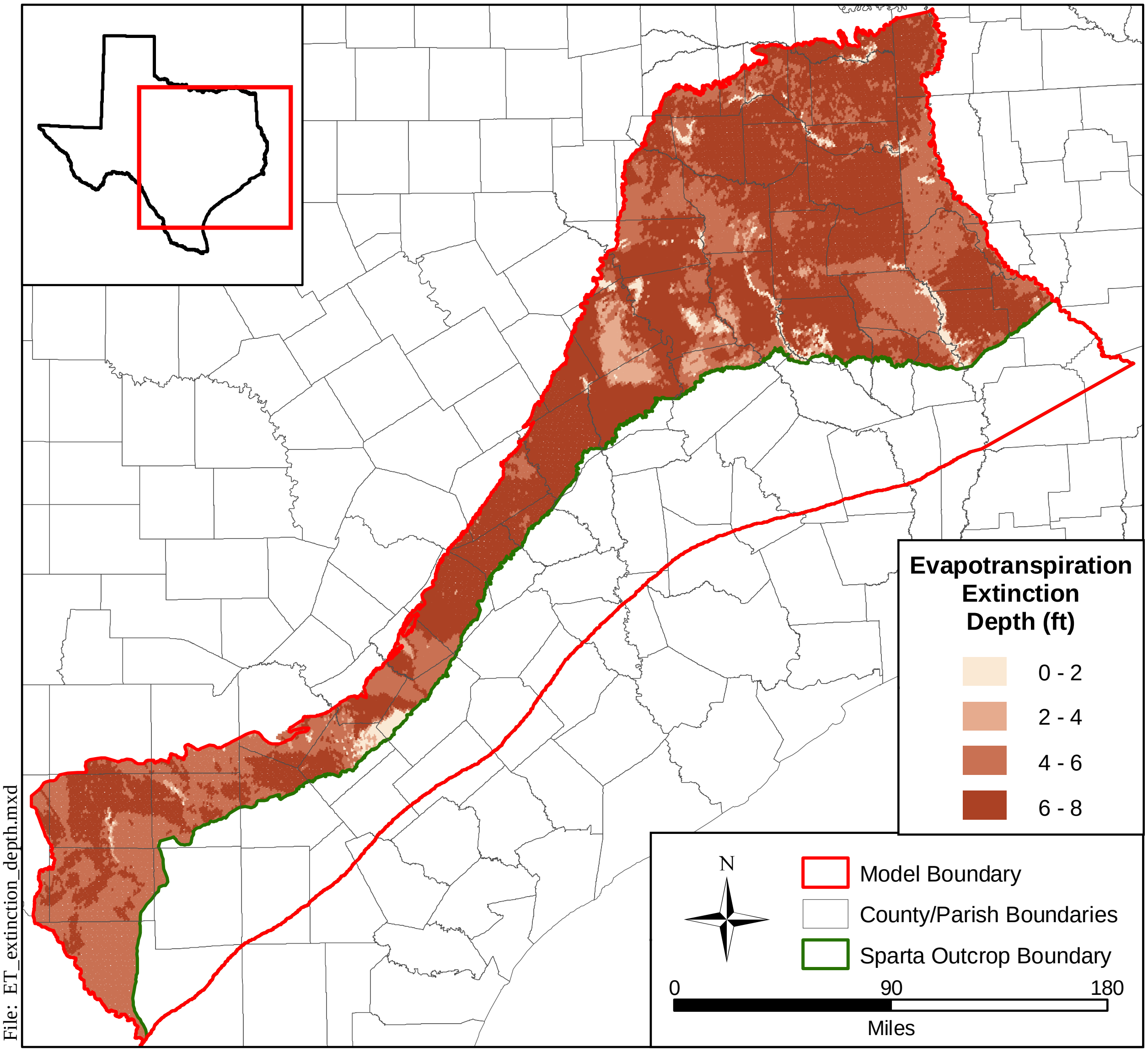


Figure 6.3.19 ET extinction depth estimated by SWAT.

6.4 Model Hydraulic Parameters

For the steady-state model, the primary parameter to be estimated and distributed across the model grid is hydraulic conductivity. For the transient model, the storage coefficient becomes important. The method used for distributing hydraulic conductivity and storage in the model domain is described in the following sections.

6.4.1 Hydraulic Conductivity

Section 4.3 discusses the distribution of hydraulic conductivity data collected for the Queen City and Sparta aquifers. Hydraulic parameterization of coastal plain sediments is often correlated to sand body thickness, geometry, and depositional facies (e.g., Payne, 1975; Henry et al., 1980; Fogg, 1986; Thorkildsen and Price, 1991). Previous investigators have also found, both theoretically and empirically, that the hydraulic conductivity of unconsolidated sediments decreases with depth (Helm, 1976; Prudic, 1991). This is thought to be a result of sediment compaction with increased overburden pressure.

In the GAM, model properties are constant within a given grid block which is one square mile in area and varies in thickness from a minimum of 20 feet to hundreds of feet. A challenge in constructing a regional model at this scale is the development of an accurate "effective" hydraulic conductivity that is representative of the grid block scale and, thus, represents the different lithologies present in each grid cell. The effective hydraulic conductivity depends on the geometry, hydraulic conductivity, and the correlation scale relative to the grid scale and simulation scale of the various lithologies present in the grid cell (Freeze, 1975). There have been many investigations on estimating an average effective hydraulic conductivity given assumptions for flow dimension, layer geometry, and correlation scales (Warren and Price, 1961; Gutjahr et al., 1978; Fogg, 1989). This process is generally termed upscaling.

In this study, a stream-tube technique, which is particularly suited to mixed sand/shale formations, was applied. In the direction parallel to the shale layering, that is, more or less horizontally, the average conductivity is equal to the arithmetic mean of the hydraulic conductivities which is dominated by the hydraulic conductivity of sandstone. In the direction orthogonal to the shale layering, the average conductivity is an expression of the geometry of the shale distribution and typically is equal to a weighted geometric to harmonic average.

The operational approach for scaling hydraulic conductivity used in this study was (1) determine the location of the top and bottom of the layers as well as the net sand thickness, (2) spatially locate the local measurements of hydraulic conductivity, (3) krige the discrete field, (4) apply a model describing hydraulic conductivity as a function of depth, and (5) assume a law of composition, which is related to the sand/clay ratio, or sand fraction (SF). Steps 1 through 4 have been discussed and presented in Section 4.3. The remainder of this section discusses the methodology used for developing an upscaled hydraulic conductivity with a sand fraction.

The SF of a formation is defined as the ratio of the cumulative thickness of sand layers and lenses to total formation thickness. As stated earlier, it is assumed that hydraulic conductivities which are derived from pump tests or specific capacity tests are representative of the sands within the completed test zone (K_{sand}). Using sand fraction and representative hydraulic conductivities for the sand and clay units, horizontal and vertical conductivity (K_H and K_V, respectively) were calculated by:

$$K_H = (SF)(K_{sand}) + (1 - SF) \times K_{clay} \tag{6.2}$$

$$\frac{1}{K_V} = \frac{SF}{K_{sand}} + \frac{1-SF}{K_{clay}} \tag{6.3}$$

$$K_V = \exp((SF)\ln(K_{sand}) + (1-SF)\ln(K_{clay})) \tag{6.4}$$

where K_{clay} is the hydraulic conductivity of the clay. The sensitive conductivity parameters of a layered model are typically horizontal conductivity of the aquifers, computed from arithmetic mean (equation 6.2), and vertical conductivity of the aquitards, computed from harmonic mean (equation 6.3). Equation 6.4, the geometric average, represents vertical hydraulic conductivity of aquifers with limited connectivity of both sand bodies and clay lenses.

Equation 6.2 was used to calculate the effective grid block hydraulic conductivity of the aquifers. Figures 6.4.1 through 6.4.3 present the effective horizontal hydraulic conductivity fields for the Sparta, Queen City, and Carrizo aquifers, respectively. The conductivity distributions preserve the measured data, impose a depth trend, and show the depositional texture evident in the Queen City and Sparta sand thickness maps (see Figures 4.2.12 and 4.2.13).

Vertical hydraulic conductivity is not measurable on a model grid scale and is, therefore, generally a calibrated parameter. Typical vertical anisotropy ratios are on the order of 1 to 1000 determined from model applications (Anderson and Woessner, 1992). However, Williamson et al. (1990) reported that vertical resistance to flow could be significant in the Gulf Coast Aquifer system in Texas and Louisiana which is composed of similar types of coastal plain sediments as encountered in the Carrizo-Wilcox, Queen City, and Sparta aquifers. Previous regional modeling studies in the Carrizo-Wilcox aquifer have documented vertical anisotropy ratios as high as 50,000 (Williamson et al., 1990).

Because the vertical hydraulic conductivity of an aquifer is expected to be controlled by depositional environment and lithofacies, a geometric mean (Equation 6.4) was used to determine the aquifer vertical hydraulic conductivity assuming a clay conductivity of $1x10^{-4}$ ft/day. For aquitards, a harmonic mean (Equation 6.3) was assumed to be representative and set the vertical hydraulic conductivity equal to $1x10^{-4}$ ft/day.

6.4.2 Storativity

For unconfined aquifer conditions, the storativity was assumed to be homogeneous and was assigned a value equal to 0.15 for aquifers and 0.1 for aquitards. Grid cells that represented outcrop (land surface) were modeled as either confined or unconfined depending upon the elevation of the simulated water table in that grid cell. The confined storativity assigned to outcrop cells was one to account for the condition of ponding water on the ground surface and to help prevent non-physical heads from being computed and used in the equations governing groundwater flow.

There are a limited number of available storativity measurements and estimates for the Queen City (a total of 5) and Sparta (a total of 18) aquifers (see Section 4.3.8). The underlying Carrizo-Wilcox aquifers, which are similar in architecture to the Queen City and Sparta aquifers, possess more storativity measurements with a total of 107 (Mace and Smyth, 2003). The data sets are statistically similar; the mean-sand specific storage of the Carrizo-Wilcox data set is $4.5x10^{-6}$ ft^{-1} (Mace and Smyth, 2003) whereas it is $3.1x10^{-6}$ ft^{-1} for the combined Queen City and Sparta aquifers (Table 6.4.1). The Carrizo-Wilcox GAMs assumed a constant specific storage of $3x10^{-6}$ and $4x10^{-6}$ ft^{-1} for the Carrizo layer in the southern model (Deeds et al., 2003) and northern model (Fryar et al., 2003), respectively. The central model used a distributed specific storage based on a storativity decreasing with sand content (Dutton et al., 2003). The storativity values of the three Carrizo-Wilcox GAMs were used in the Wilcox (Layers 6 to 8) of the Queen City and Sparta GAMs. The following discussion describes the assignment of storativity and specific storage for the Sparta through the Carrizo (Layers 1 through 5).

Storativity and specific storage measurements are too sparse to directly generate a spatial distribution by kriging or other mapping technique. However, the documented contrast in specific storage between clay and sand and the general observation that compaction increases with depth of burial allows the following description:

$$Ss = max\left[10^{-\frac{D_{up}-D}{D_{down}}}\left(SF \times Ss_{sand} + (1-SF)Ss_{clay}\right), Ss_{min}\right] \tag{6.5}$$

where Ss_{sand} and Ss_{clay} are the specific storage of sand and clay, respectively. The specific storage of sand is given by pump tests, whereas the clay specific storage is assumed to be larger than the sand specific storage. The function decreases specific storage with depth D. The parameter D_{up} is the average depth at which Ss_{sand} has been obtained, and D_{down} is the depth at which sand specific storage has decreased by one order of magnitude. Mace and Smyth (2003) suggest a decrease in specific storage by one to two orders of magnitude between ground surface and a depth of 4,000 feet for Carrizo-Wilcox sediments, although the trend is given by very few points and may not be adequate for this study. The lower limit of specific storage, Ss_{min}, represents the specific storage of a fissured, fully compacted or crystalline rock to which is added the water component of specific storage ($Ss_{min} \sim 1.3\text{x}10^{-6}$ ft^{-1}) which is no longer negligible.

Both Ss_{clay} and D_{down} were calibration parameters. A log-cycle decrease in specific storage between ground surface and 7,900 feet best fits the measurements. Similarly, the clay specific storage was assumed to be 7.5x10^{-6} ft^{-1}. The resulting average specific storage is between 2.8x10^{-6} and 5.5x10^{-6} ft^{-1} (Table 6.4.2). Formation thickness largely impacts the storativity value especially for the Queen City Formation where there is a three orders of magnitude change in thickness between the Louisiana state line and the Texas-Mexico border. Variations in thickness in the Sparta and Carrizo formations are less pronounced, translating into a less variable storativity map. The storativity distributions for the Sparta, Queen City, and Carrizo aquifers are shown in Figures 6.4.4 through 6.4.6, respectively. Distributed storativity of the Weches and Reklaw confining layers were computed similarly to the aquifers assuming a 5 percent sand fraction. In addition, specific yield was set to 0.15 for the aquifers and 0.10 for the aquitards.

Table 6.4.1 Storativity measurements whose average is used for model input.

Formation	Measured Storativity	Screen Length (ft)	Inferred Sc (ft^{-1})	Average Depth to Screen (ft)	Source
CY	1.4×10^{-4}	40	3.50×10^{-6}		Broom (1971)
CY	1.5×10^{-4}	137	1.09×10^{-6}		Broom et al. (1965)
QC	2.0×10^{-4}	160	1.25×10^{-6}		Thompson (1966)
QC	3.0×10^{-4}	125	2.40×10^{-6}	346.50	Broom (1969)
SP	2.8×10^{-4}	62	4.03×10^{-6}	493.50	Follett (1974)
SP	2.2×10^{-4}				
SP	2.3×10^{-4}	88	2.73×10^{-6}	479.00	Follett (1974)
SP	2.5×10^{-4}				
SP	1.5×10^{-4}	50	3.00×10^{-6}	467.00	Follett (1974)
SP	2.2×10^{-4}	90	2.52×10^{-6}	543.00	Follett (1974)
SP	2.3×10^{-4}				
SP	2.3×10^{-4}				
SP	1.5×10^{-4}	86	1.80×10^{-6}	444.00	Follett (1974)
SP	1.6×10^{-4}				
SP	1.7×10^{-4}	61	2.79×10^{-6}	442.25	Follett (1974)
SP	4.0×10^{-4}	75	5.33×10^{-6}		Thompson (1966)
SP	3.8×10^{-4}	92	4.62×10^{-6}		Guyton and Associates (1970)
SP	4.7×10^{-4}				
SP	2.6×10^{-4}	85	3.06×10^{-6}		Guyton and Associates (1970)
SP	1.7×10^{-4}	35	4.86×10^{-6}		Guyton and Associates (1970)
SP	1.7×10^{-4}	51	3.33×10^{-6}	136.75	Dillard (1963)
SP	1.7×10^{-4}	51	3.33×10^{-6}	185.75	Dillard (1963)
SP	2.0×10^{-4}	63	3.17×10^{-6}		LA
SP	1.0×10^{-4}				
Average			$\mathbf{3.11 \times 10^{-6}}$	**393**	

CY = Cypress Formation, SP = Sparta Formation, QC =Queen City Formation
Sc = specific storage

Table 6.4.2 Average specific storage and storativity by layer and model

Formation	Southern Model	Central Model	Northern Model
Sparta Formation	CS = 1.1×10^{-3} Sc = 3.7×10^{-6}	CS = 1.1×10^{-3} Sc = 3.1×10^{-6}	CS = 1.2×10^{-3} Sc = 3.0×10^{-6}
Weches Formation	CS = 3.4×10^{-4} Sc =5.3×10^{-6}	CS = 2.6×10^{-4} Sc = 4.4×10^{-6}	CS = 2.5×10^{-4} Sc = 4.5×10^{-6}
Queen City Formation	CS = 3.8×10^{-3} Sc =3.4×10^{-6}	CS = 1.2×10^{-3} Sc = 3.6×10^{-6}	CS = 7.3×10^{-4} Sc = 4.0×10^{-6}
Reklaw Formation	CS = 1.3×10^{-3} Sc = 4.5×10^{-6}	CS = 7.0×10^{-4} Sc = 4.6×10^{-6}	CS = 6.4×10^{-4} Sc = 5.5×10^{-6}
Carrizo Formation	CS = 1.3×10^{-3} Sc = 2.8×10^{-6}	CS = 8.6×10^{-4} Sc = 3.2×10^{-6}	CS = 4.9×10^{-4} Sc = 3.6×10^{-6}

CS = Storativity or Coefficient of Storage; Sc = Specific Storage

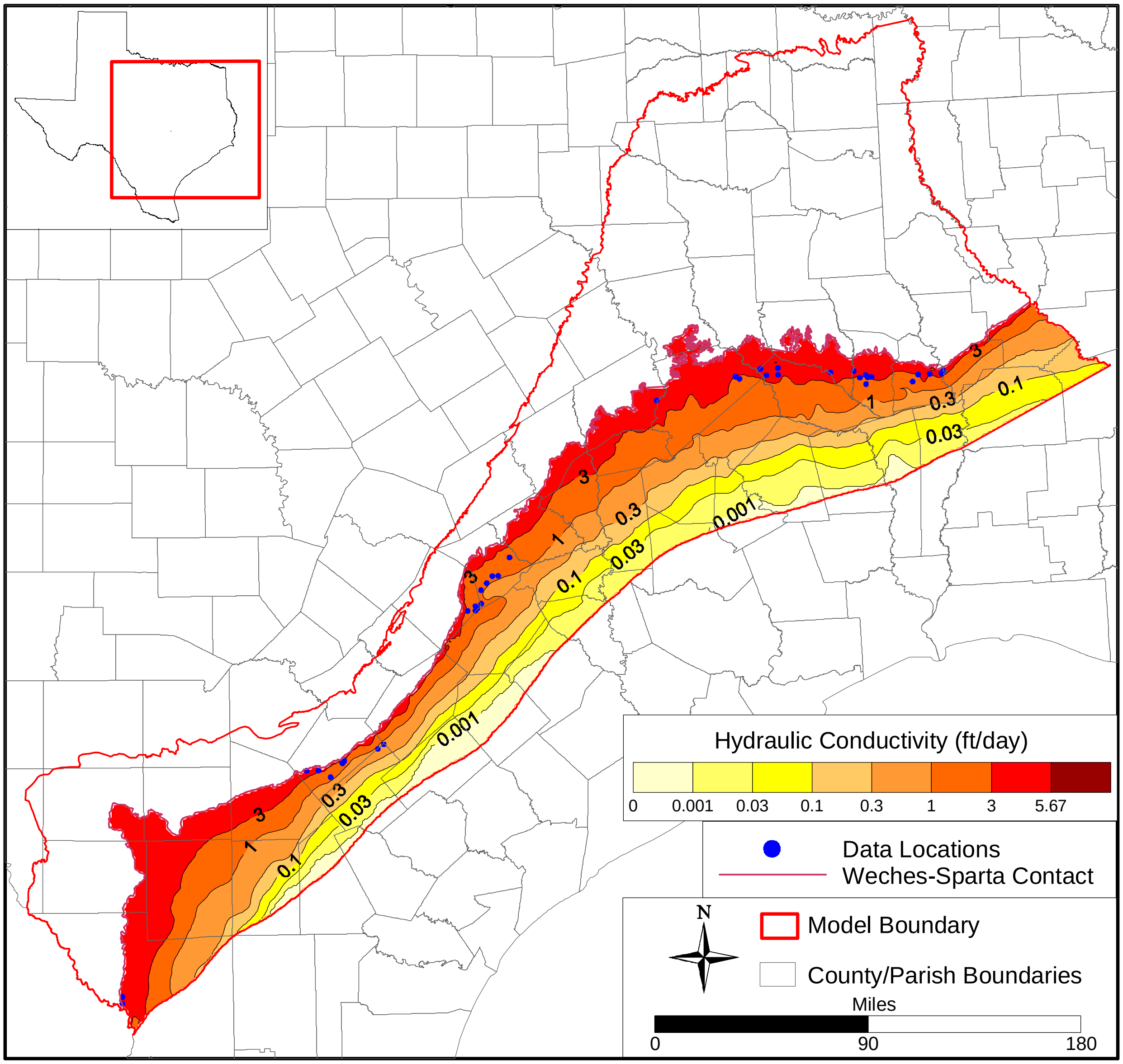


Figure 6.4.1 Effective hydraulic conductivity of the Sparta aquifer (Layer 1).

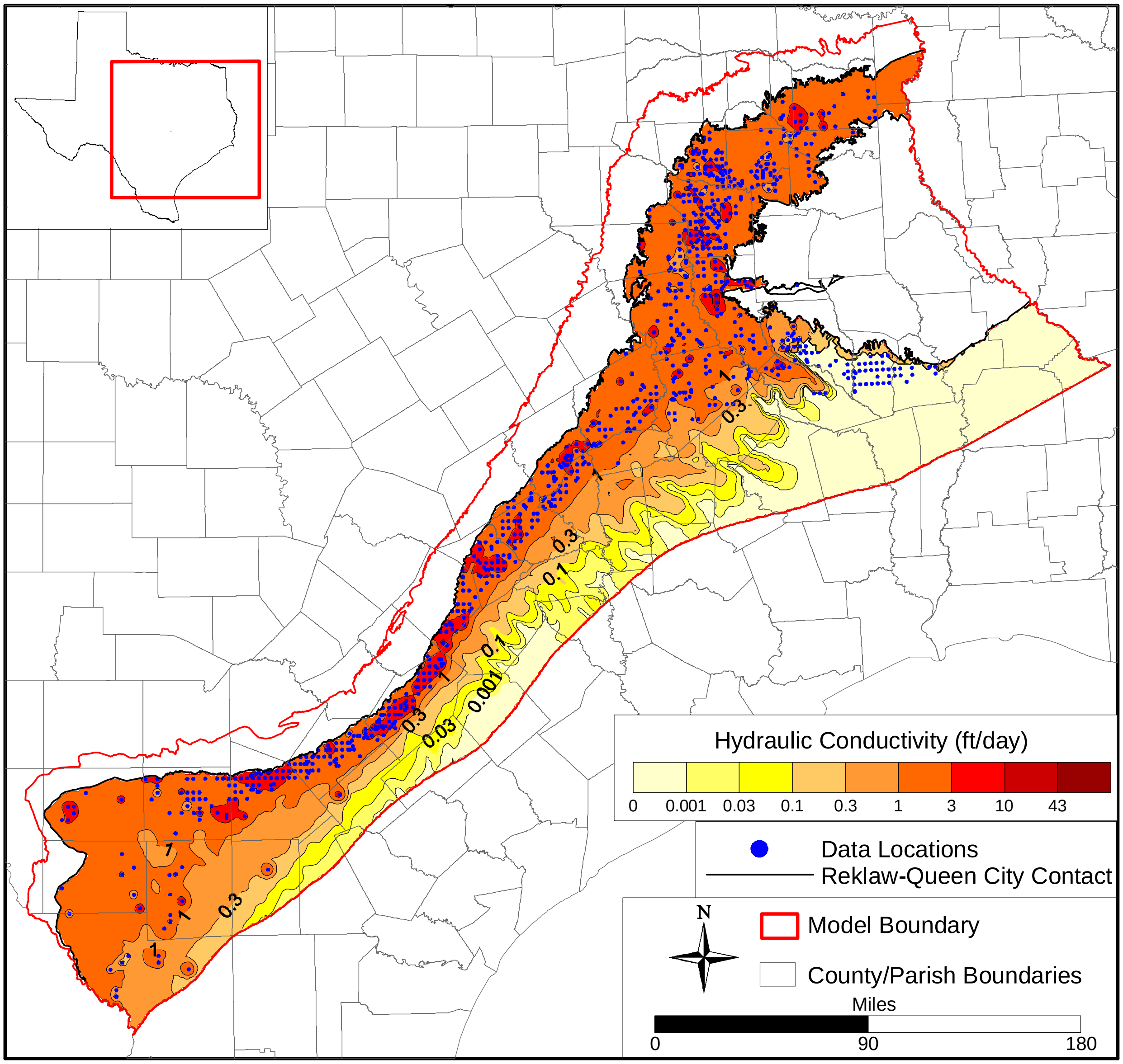


Figure 6.4.2 Effective hydraulic conductivity of the Queen City aquifer (Layer 3).

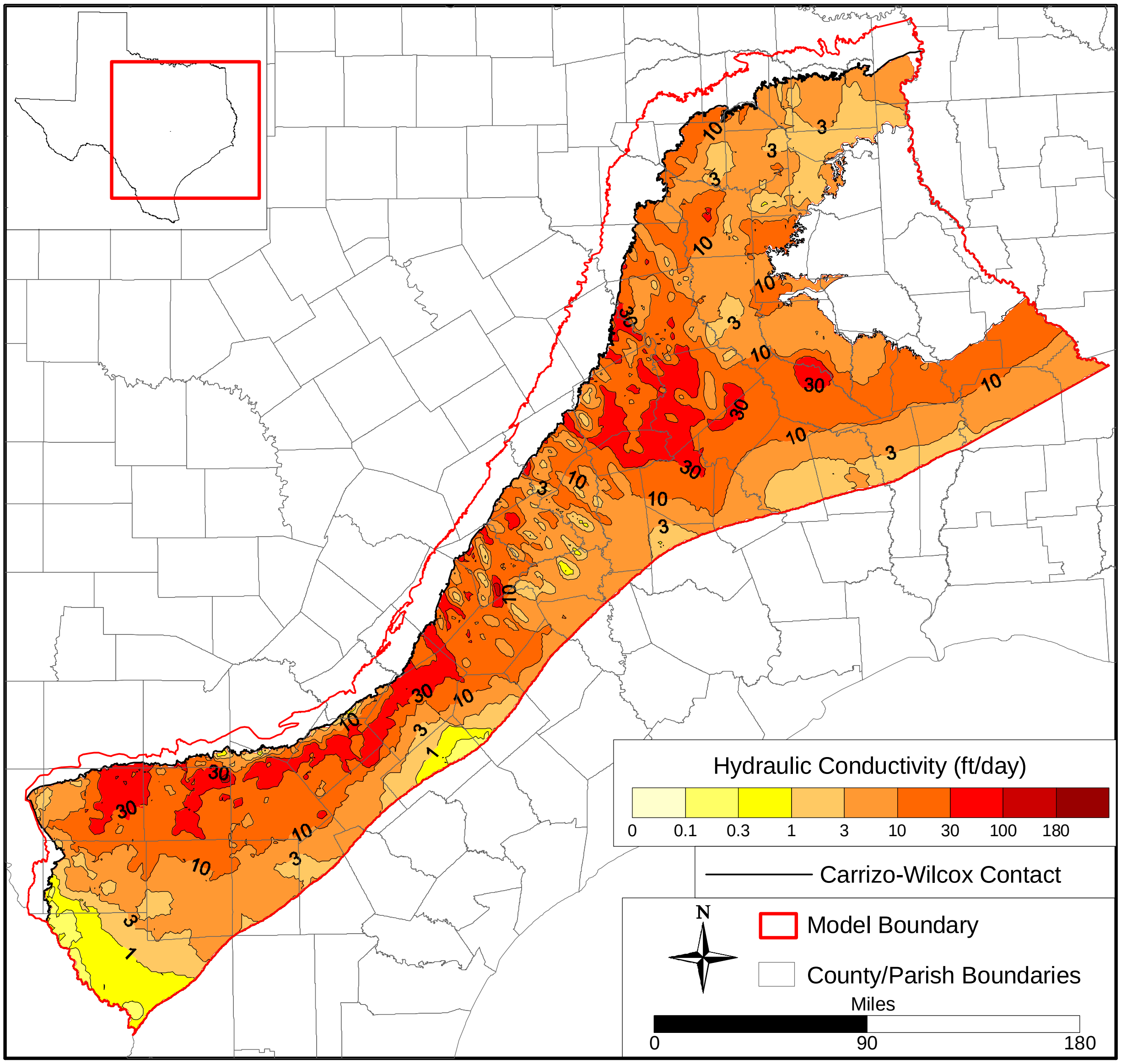


Figure 6.4.3 Effective hydraulic conductivity of the Carrizo aquifer (Layer 5).

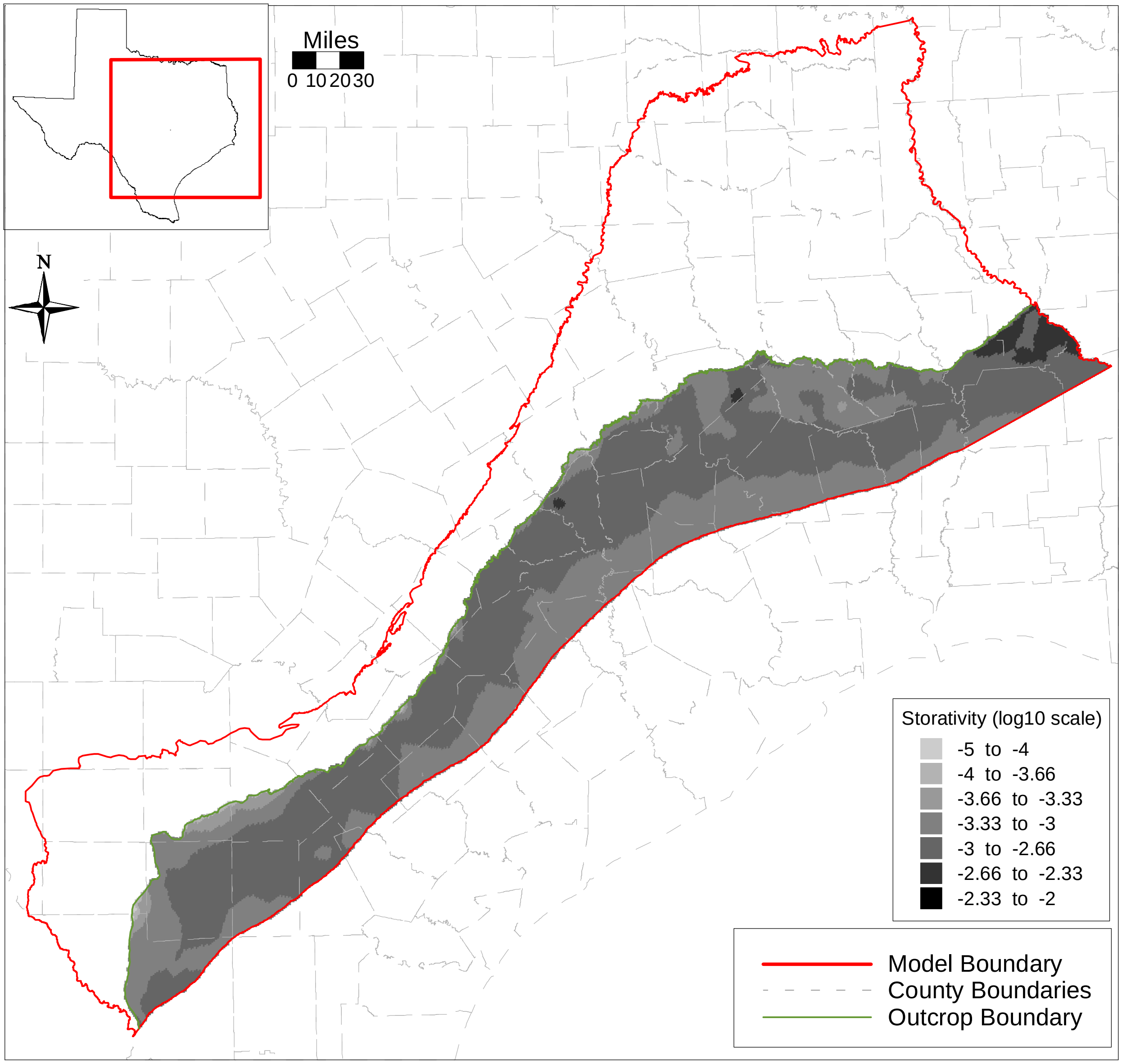


Figure 6.4.4 **Log_{10} storativity for the Sparta aquifer (Layer 1).**

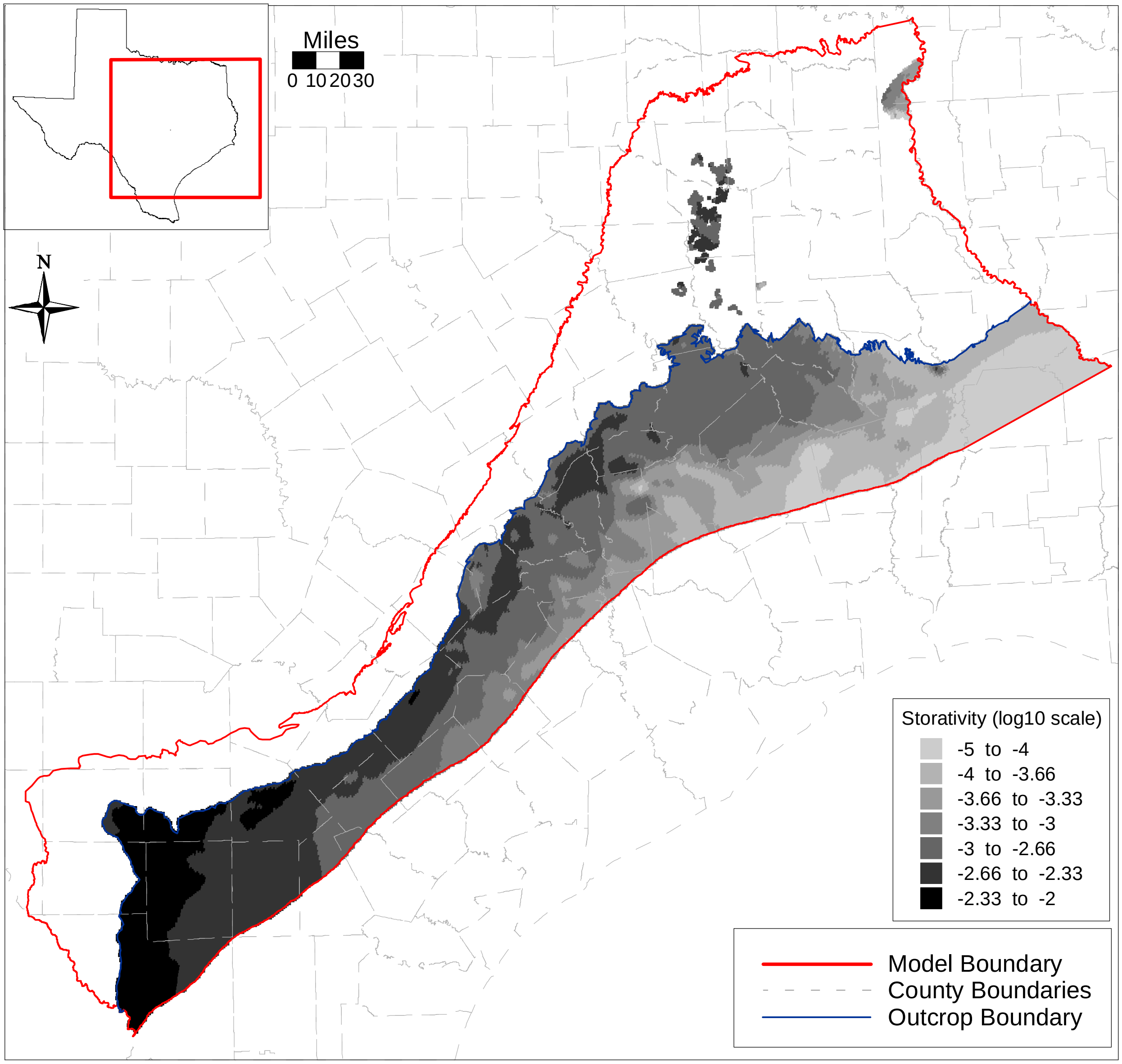


Figure 6.4.5 $\quad$ **Log_{10} storativity for the Queen City aquifer (Layer 3).**

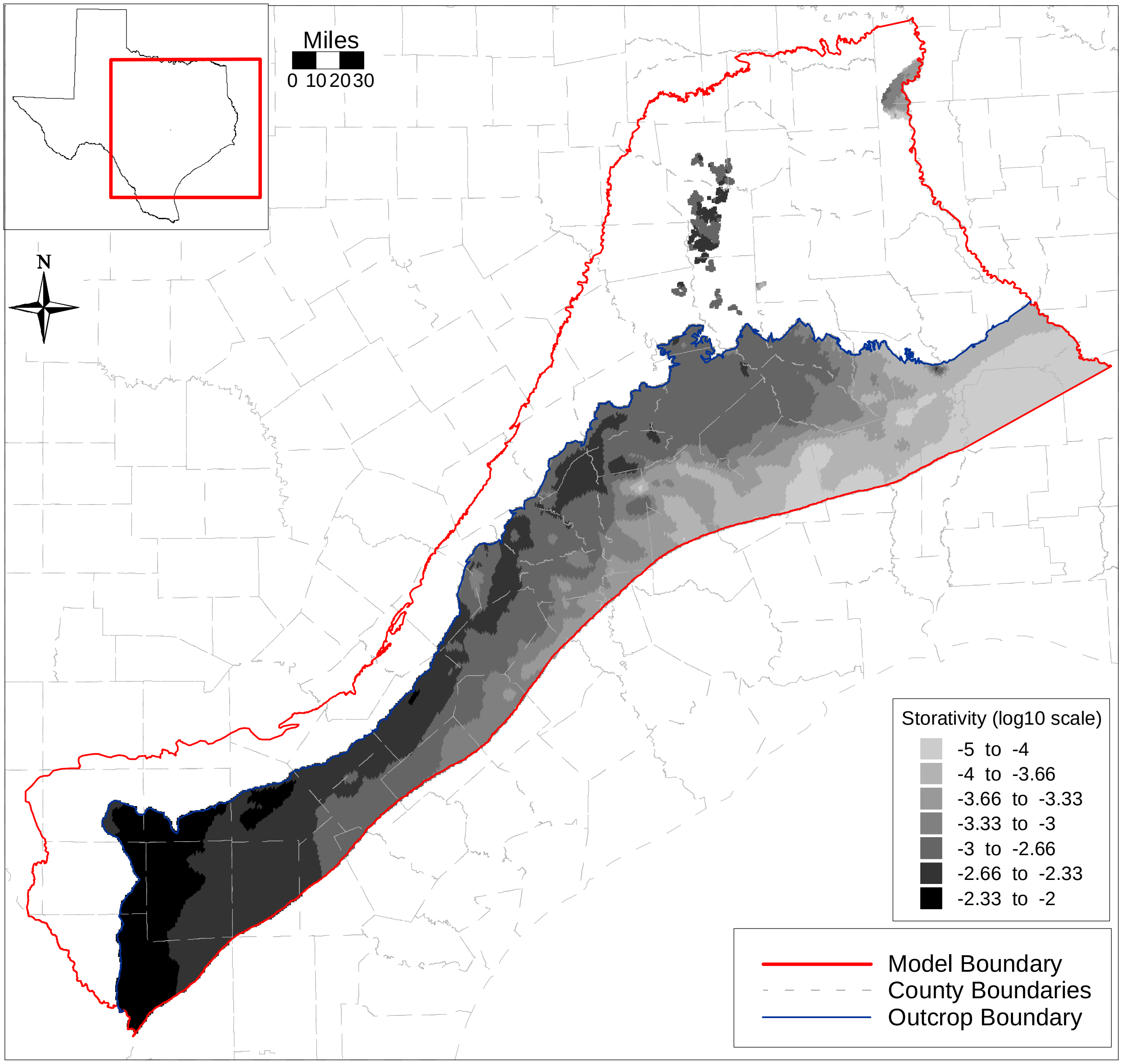


Figure 6.4.6 Log$_{10}$ storativity for the Carrizo aquifer (Layer 5).

7.0 MODELING APPROACH

In the context of groundwater modeling, model calibration can be defined as the process of producing agreement between model simulated water levels and aquifer discharge, and field measured water levels and aquifer discharge through the adjustment of independent variables (typically hydraulic conductivity, storativity, and recharge). Generally accepted practice for groundwater calibration usually includes performance of a sensitivity analysis and, if the model is going to be used for predictive purposes, a verification analysis. A sensitivity analysis entails a systematic variation of the calibrated parameters and stresses and the re-simulation of aquifer conditions. Those parameters which strongly change the simulated aquifer heads and discharges would be important parameters to the calibration. It is important to note that the "one-off" standard sensitivity analysis does not estimate parameter uncertainty as limited parameter space is investigated and parameter correlation is not accounted for. A verification analysis is a test to determine if the model is suitable for use as a predictive tool. This is performed by using the model to predict aquifer conditions during a period which was not used in the model calibration. Consistent with the approach outlined above, the models were calibrated and verified with the performance of a sensitivity analyses. The calibrated models were then used to perform predictive simulations.

7.1 Calibration

A discussion of model calibration should include a discussion of the calibration approach or calibration philosophy to address issues of uniqueness, the calibration targets and calibration performance measures by which calibration will be quantified, and some assessment of calibration target uncertainty to prevent over calibration of the model based upon uncertainty in the observations. These three issues are discussed below.

7.1.1 Calibration Approach

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 method described by Ritchey and Rumbaugh (1996) was employed. This method includes (1) calibrating the model using parameter values (i.e., hydraulic conductivity, storativity, and recharge) that are consistent with measured values,

(2) calibrating to multiple hydrologic conditions, and (3) using multiple calibration performance measures such as hydraulic heads and discharge rate to assess calibration. In addition, where available, prior information was used for definition of parameters and an attempt was to use methods of regularization to limit the number of parameters being calibrated. Each of these elements is discussed below.

The method used for model calibration was manual calibration, sometimes referred to as the “trial-and-error” method. In this approach, parameters which the model is sensitive to are adjusted to improve overall model agreement (fit) with observations. We considered using the automated calibration software package termed PEST (Doherty, 2002). However, because we needed to calibrate three models with two overlap zones using consistent parameters, automated calibration was impractical.

Measured hydraulic conductivity and storativity data were used for the initial estimated parameter fields. The analysis of hydraulic parameters in Section 4.3 of this report indicates that there is a small amount of hydraulic conductivity data available for use as initial model values for the Queen City and Sparta aquifers. However, additional knowledge (prior knowledge) regarding net sand thickness and hydraulic conductivity depth trends were used to better estimate hydraulic conductivity of the aquifers. Vertical hydraulic conductivity is not measurable at the model scale and thus, cannot be well constrained. However, literature estimates of clay hydraulic conductivity and net sand distributions were used to constrain initial vertical hydraulic conductivity. Unfortunately vertical hydraulic conductivity can be a function of grid scale. Storativity is a parameter which is not well defined on the scale of the model. Storativity was estimated from measured specific storage data in combination with the aquifer thickness and net sand thickness.

Recharge has not been directly measured in the study area and is arguably not measurable at the model scale. As described in Section 6, estimates of recharge were developed from a regionalization method which defined recharge as a function of precipitation, topography, and underlying geology. The initial recharge estimates are within plausible ranges based upon the available data and relevant literature.

A challenge in calibrating a model as complex as the GAMs is that there are approximately 170,000 active grid cells in one of the GAMs. Through the calibration process, horizontal and vertical hydraulic conductivity and storativity are being estimated for each GAM grid cell. This number of potential unknowns far exceeds the number of observations available to condition the solution resulting in an inherently non-unique calibration. To deal with this issue, the calibration approach uses the concept of regularization. For horizontal hydraulic conductivity, storativity, and recharge, interpolation functions were developed which rely on only a few calibrated parameters. During calibration, an attempt was made to limit adjustments to parameters to global adjustments rather than cell to cell adjustments. As a general rule, parameters that have few measurements were adjusted preferentially as compared to parameters that have a good supporting database. Finally, wholesale tweaking of parameters locally to improve local residuals was resisted. Local model over-calibration does not guarantee a better predictive model, especially when one has calibrated to levels below the error in the observations (Freyberg, 1988).

The model was calibrated over two time periods, one representing steady-state conditions and the other representing transient conditions. Predevelopment conditions were used for the steady-state model in hopes of recreating aquifer conditions prior to significant resource development. No pumping stresses were applied to the predevelopment model consistent with the assumption of steady-state conditions prior to significant resource development. The transient calibration period ran from 1980 through 1989 consistent with the GAM model requirements. The transient model was started five years prior to 1980 as a model equalization period to allow any initialization effects to dampen by 1980, the start of the calibration period. This equilibration period was not used for calibration. The initial heads used for the transient model were based upon head measurements averaged within a three year window centered on 1980. Section 4.4.4 describes the aquifer water levels and how they were derived to be used for the transient calibration period. Pumping estimates based upon historical records were applied on a yearly basis in the transient calibration period. Likewise, recharge, stream flow, and reservoir stage were estimated on a yearly integration time and set as input through the transient calibration period. The time period from 1990 through 1999 was used as the verification period to assess the predictive ability of the model. Like the calibration period, transient stresses or boundary conditions were determined on a yearly time step. Unlike the calibration period, parameters were not adjusted in the verification process.

The model was calibrated through a wide range of hydrological conditions. The steady-state predevelopment model represents a period of equilibrium where recharge and aquifer discharge through streams and cross-formational flow are in balance. Under these conditions, the amount of recharge to the aquifers is in equilibrium with the amount of discharge from the aquifer. The steady-state model is sensitive to recharge and also to the vertical hydraulic properties of the modeled aquifers and aquitards. The transient calibration and verification periods (1980 through 1999) represent significantly aquifer conditions as compared to the predevelopment period. By this time, portions of the aquifer have been extensively developed resulting in loss of storage, declining heads and capture of discharge. Some of the aquifer discharge observed under steady-state predevelopment conditions is captured as a result of reduced base flow, decreased cross-formational flow, and decreased ET. The calibration and verification periods also help constrain the model parameterization because a wide variety of hydrologic conditions are encountered and simulated. The transient model may be sensitive to parameters that are not sensitive for the steady-state model.

7.1.2 Calibration Targets and Calibration Measures

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). However, stream flows and gain-loss estimates were also used. Simulated heads were compared to measured heads at specific observation points through time (hydrographs) and head distributions (maps) for select time periods (see Section 4.4) to ensure that model head distributions were consistent with hydrogeologic interpretations and accepted conceptual models for flow within the aquifers.

Stream calibration targets were derived from two types of data. First, model simulated stream flow rates were compared to observed flow rates at key stream gages in the model area. Because stream flow rates greatly exceed aquifer/stream fluxes for local cells, available gain/loss estimates were also used for the major streams crossing the outcrop.

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

$$ME = \frac{1}{n} \sum_{i=1}^{n} \left(h_m - h_s\right)_i \tag{7.1}$$

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

$$MAE = \frac{1}{n} \sum_{i=1}^{n} \left|\left(h_m - h_s\right)_i\right| \tag{7.2}$$

where n is the number of calibration measurements. The root mean square (RMS) error is the square root of the average of the squared differences between measured heads (h_m) and simulated heads (h_s):

$$RMS = \left[\frac{1}{n} \sum_{i=1}^{n} \left(h_m - h_s\right)_i^2\right]^{0.5} \tag{7.3}$$

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 RMS was used as the basic measure of calibration for heads. The required calibration criterion for heads is an RMS that is equal to or less than 10 percent of the observed head range in the aquifer being simulated. To provide information on model performance with time, the RMS was calculated for the calibration period (1980 through 1989) and the verification period (1990 through 1999). The RMS 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 were used to check for spatial bias by indicating the magnitude and direction of mis-match between observed and simulated heads. Simulated head distributions were also compared to the head distributions developed from the field measurements. Finally, scatter plots were used to determine if the head residuals are biased based on the magnitude of the observed head surface.

For streams, the calibration target is defined in the GAM standards to be within 10 percent of the measured values. However, in most instances a much higher degree of uncertainty in stream flow gain-loss estimates than 10 percent of the value was observed.

An additional model calibration constraint that is useful, but rare, is groundwater velocity or groundwater age dating studies. A literature review was performed for these types of studies in the model study areas. The first study found to be relevant is a groundwater age dating study performed in Atascosa County using Carbon-14 age dating techniques (Pearson and White, 1967). In this study, a groundwater travel path was mapped through groundwater age dating and provides an integrated groundwater velocity profile from near the Carrizo outcrop to the deeper confined section. A second more recent study builds on the work of Pearson and White (1967) in Atascosa County using ^{4}He measurements to constrain an exploratory cross-sectional groundwater flow and transport model (Castro and Goblet, 2002).

7.1.3 Calibration Target Uncertainty

Calibration targets are uncertain. In order to avoid “over-calibrating” a model, which is a stated desire for the GAM models, calibration criteria should be defined consistent with the uncertainty in calibration targets. The primary calibration target in groundwater modeling is hydraulic head. Uncertainty in head measurements can be the result of many factors including, measurement error, scale errors, and various types of averaging errors, both spatial and temporal. The calibration criteria for head is an RMS less than or equal to 10 percent of head variation within the aquifer being modeled. Head differences across the aquifers in the study area are on the order of 300 to 500 feet. This leads to an acceptable RMS of between 30 and 50 feet. We can compare this RMS to an estimate of the head target errors and see what level of calibration the underlying head targets can support.

Measurement errors are typically on the order of tenths of feet, and at the GAM scale can be insignificant. However, measuring point elevation errors can be significant. In development of the Southern and Northern Carrizo-Wilcox GAMs (Deeds et al., 2003 and Fryar et al., 2003), differences between the reported land-surface datum (LSD) and the ground surface elevation as determined from a digital elevation map were analyzed. The average difference between LSD and the DEM was -5 feet with a standard deviation of 28 feet. Add to this error in averaging ground surface elevations available on a 30 m grid to a one mile grid, and the resulting errors can average 10 to 20 feet and may greatly exceed 20 feet in areas with higher topographic slopes. Additional error is caused by combining multiple lithologies into a single grid block representing one simulated head. Horizontal to vertical hydraulic conductivity ratios have been proven to be high in the Coastal Plain aquifers of Texas (Fogg et al., 1983; Williamson et al., 1990). As a result, significant vertical gradients can occur within individual model layers. Vertical gradients near pumping centers are quite large and approach 0.1 (Williamson et al., 1990). This implies that portions of the aquifer can have head variations within a single model cell on the order of 10 to 50 feet. A single model cell has one head. On average, in areas away from large pumping centers, this scale effect is expected to be on the order of 10 to 20 feet. Horizontal gradients relative to the grid scale also account for an additional one to five feet error with even greater errors near pumping centers. When these errors are added up, the average error in model heads could easily equal our calibration criteria of 30 to 50 feet. The nugget observed on kriged head maps within the modeled aquifers equals from 20 to 30 feet. This nugget captures both uncertainty and variability in the observed heads being rationalized above. Calibrating to RMS values less than 30 feet would constitute over calibration of the model and parameter adjustments to reach that RMS are not supported by the hydraulic head uncertainty.

7.2 Sensitivity Analyses

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 were unperturbed.

7.3 Predictions

Once the model satisfied the calibration criteria for both the calibration and verification periods, the model was used to make predictive simulations. The predictive simulations have different simulation periods. Simulations were run from 1999 to 2010, 2020, 2030, 2040, and 2050. Average climatic conditions were applied for each predictive simulation with the simulation ending with a drought of record. Pumping stresses were based upon the Regional Water Plans as described in Section 4.8 and Appendix D.

8.0 STEADY-STATE MODEL

The steady-state model is representative of predevelopment conditions. In predevelopment, aquifer inflow from recharge and streams is balanced by groundwater to surface-water discharge, ET, and cross-formational flow from the confined aquifers upwards to the younger overlying units. This section is divided into subsections that discuss calibration of the steady-state model and present the steady-state model results for each model region. Included in the subsection for each region are the results of a sensitivity analysis identifying the model parameters to which the steady-state model calibration is most sensitive.

8.1 Southern Queen City and Sparta GAM

8.1.1 Calibration

As discussed in Section 7, calibration is the process of adjusting model parameters to produce agreement between model simulated water levels and aquifer discharges and measured water levels and aquifer discharges. The calibration process for the steady-state model is described below.

8.1.1.1 Horizontal and Vertical Hydraulic Conductivities

Section 6.4.1 describes the determination of initial horizontal and vertical hydraulic conductivities for the model. The Sparta aquifer has very few measurements of horizontal hydraulic conductivity. The Queen City aquifer has more complete data coverage, especially in the updip section. During calibration, no compelling reason was found to modify the initial estimates of horizontal hydraulic conductivity in either of these aquifers. In the Sparta aquifer, heads are strongly affected by the GHBs that are attached to the majority of the active layer. In the Queen City aquifer, relatively good hydraulic conductivity control is available in the updip area, providing parameter constraint. In the downdip area, few targets exist to provide information about the accuracy of the simulated heads. In the Carrizo Formation, good control exists throughout and the horizontal conductivity field from the calibrated Southern Carrizo-Wilcox GAM was maintained, except in the overlap region as described in Section 6.4.1. The Weches and Reklaw formations are confining units, so their horizontal hydraulic conductivity has little effect on the overall flow system.

The vertical hydraulic conductivities of the aquifers are not expected to have much impact on the hydrology of the system, since vertical flow is limited by the Weches and Reklaw formations. Therefore, the vertical conductivity (K_v) of the Sparta, Queen City, and Carrizo formations was not varied from the initial estimate. For the confining units, the initial vertical conductivity estimate of approximately 10^{-4} ft/day represented about an order of magnitude decrease compared to the vertical conductivity of the Reklaw in the Southern Carrizo-Wilcox model, east of the Frio River. For the current model, this lower vertical conductivity improved the calibration. The change between the models was due primarily to differences in the overall recharge distribution and the improved representation of the Queen City aquifer in the current model. Further decreases in the vertical conductivity of the Reklaw resulted in unrealistically high heads downdip in the Carrizo Formation.

The vertical conductivity of the Weches affected the Queen City aquifer primarily in the downdip area, where few targets are available. Outcrop heads in the Queen City aquifer are less affected due to the extensive coverage of stream cells. Therefore, the vertical conductivity of the Weches is more poorly constrained than that of the Reklaw for the steady-state model. The transient model (described in Chapter 9) did not provide much additional information due to the lack of pumping stress in the Queen City and Sparta aquifers.

8.1.1.2 Recharge

The steady-state model is sensitive to recharge for two reasons: (1) recharge is the primary input source for water and (2) the model is at steady-state where inflow balances outflow with no change in storage or time dependence. In a transient model, recharge to the outcrop can be added to storage over decades without significantly affecting downdip heads. In a steady-state model, where there is no net change in storage, a balance must be found between the input recharge and all other flows in the model. This implies that the behavior of the whole model will be sensitive to the input recharge rate.

In the dipping aquifer flow system represented by the current model, recharge and the vertical conductivity of the confining units are directly correlated; that is, if recharge is increased, the vertical conductivity of the confining units must be increased to allow more water to leave the system under the same head gradient. Because the estimated recharge distribution allowed parameterization of the vertical conductivity of the confining units within reasonable limits, we were not compelled to modify recharge in the final calibrated model.

8.1.1.3 Groundwater Evapotranspiration

Steady-state groundwater ET was averaged from the SWAT transient results and applied as ET maximum in the MODFLOW ET package (see Section 6.3.5). Naturally, ET occurs above the ground surface, within the vadose zone, and within the saturated zone. Note that the ET maximum taken from SWAT and applied in MODFLOW is groundwater ET, not vadose zone ET (which was already considered in the SWAT recharge results). The maximum rooting depths were taken from the SWAT results and input as the extinction depth in the MODFLOW ET package. The ET surface was set to ground surface, so groundwater ET varied linearly starting from a maximum at ground surface and going down to the root depth. These parameters were fixed during calibration. The ET package in MODFLOW adds considerable instability to the steady-state model.

In the eastern portion of the model, where heads under predevelopment conditions were considered to be near ground surface, drains were added in the river valleys to emulate evaporation or seepage at the ground surface. As shown in the flow balance later in this chapter, these drains had little to no effect on flow.

8.1.1.4 General Head Boundaries

The heads assigned to the general head boundaries (GHBs) were estimated from the surficial water table (Section 6.3.2). The initial hydraulic conductances of the GHBs were estimated from the vertical conductivities of the younger sediments above the Sparta. Heads in the Sparta aquifer (Layer 1) were very sensitive to the conductance of the GHBs. The heads in the Sparta aquifer affect the gradient across the Weches Formation (Layer 2) to the underlying Queen City aquifer and, therefore, affect heads in the Queen City to a lesser extent.

During calibration, the GHB heads were reduced slightly to correct a bias in the heads of the Sparta aquifer (the simulated heads were generally higher than the measured heads).

8.1.1.5 Streams

Initial streambed conductances were set based on a constant sediment hydraulic conductivity of 0.1 ft/day, a bed thickness of 1 foot, and a streambed width as specified in the EPA RF1 dataset (Section 6.3.3). The initial stream bottom elevations were based on the average land surface elevation of the reach, derived from 30-meter DEMs. The stream bottoms were systematically lowered so that they were at least 20 feet below the land surface elevation of the cell. This allowed interaction between the stream and the aquifer without the aquifer head having to rise all the way to ground surface. A few adjustments were made to conductances in cells where extreme gain/loss values initially occurred, but no other model-wide adjustments were made. Because of the lack of well-constrained stream gain/loss targets (see Section 8.1.2.2), more local adjustments were not considered to be justified for this region.

8.1.2 Results

The steady-state model results are discussed in this section in terms of heads, stream flows, and the model water budget.

8.1.2.1 Heads

For head targets, a distinction was made between outcrop wells and wells located in the confined section. For wells in the outcrop, the water-level elevation was calculated based on the measured water-level depth using the grid-block averaged elevation from the model. For the confined section, the listed well elevation was used for calculating the water-level elevation. The adjustment in the outcrop was made to reduce potential errors induced by averaging ground-surface elevation over a 1-mile by 1-mile grid-block.

Figures 8.1.1 through 8.1.6 show the head surface results, residual plots, and scatterplots for the calibrated steady-state model. The residuals are defined as:

$$residual = head_{measured} - head_{simulated} \tag{8.1}$$

The RMSE (Equation 7.3) for Layer 1 (Sparta aquifer) in the steady-state model is 22 feet. The head range in this layer is 210 feet, giving an RMSE/range of 0.10. The RMSE in Layer 3 (Queen City aquifer) is 26 feet and the range in head is 288 feet, giving an RMSE/range of 0.091. The RMSE in Layer 5 (Carrizo Formation) is 22 feet and the range in head is 308 feet, giving an RMSE/range of 0.071. The head calibration statistics are summarized in the Table 8.1.1.

Figure 8.1.1 shows the steady-state simulated head for the Sparta aquifer. Most of the features in the contours are due to the GHBs that are attached to the layer. The heads in the GHBs are a smoothed expression of land surface, so the heads in the Sparta will follow a similar trend downdip. The outcrop of the Sparta is thin throughout most of the model region. A few dry cells are present in the western portion of the Sparta outcrop. This is the portion of the model where recharge is lowest, and the water table is expected to be deepest relative to the ground surface. Figure 8.1.2 shows that very few steady-state targets were available for the Sparta, and most were confined to near-outcrop. In general, the residuals show little spatial bias. A good distribution around the unit slope line is seen on the scatterplot supported by the small mean error (Table 8.1.1), indicating a good model fit to the data.

Figure 8.1.3 shows the steady-state simulated head for the Queen City aquifer. The features in the contours in the western region are due to the many streams in the outcrop of the formation. In general, the gradient is towards the southeast in the western portion of the model, with a relatively flat surface in the eastern portion of the model. Figure 8.1.4 shows the residuals in the Queen City aquifer. These are better distributed spatially than in the Sparta aquifer, and again show little spatial bias. The good distribution around the unit slope line on the scatterplot and small ME again indicate a good fit to the target values.

Figure 8.1.5 shows the steady-state simulated head for the Carrizo Formation. The Carrizo head surface indicates that the gradient in the steady-state model is mostly east-southeast, moving downdip consistent with the observed heads. In the eastern portion of the model, there is a depression in the head surface in Gonzales County. This depression is considered the result of a large number of streams running through that area, possibly enhanced by structural features. Note that heads increase moving from the Queen City to the Carrizo in the downdip portion, supporting the conceptual model of upward flow discussed in Section 5. Figure 8.1.6 shows the residuals for the Carrizo aquifer. In general, there is little spatial bias in the residuals. In the central portion of the model south of Atascosa County, there are three simulated heads that are higher than measured values, ranging from -14 to -31. These values are within the small group above the unit slope line on the scatterplot around the 400-foot mark. The magnitudes of these residuals are small compared to the intrinsic error in a regional model of this size, and the shift is less than 15 feet in that small region of the scatterplot. Combined with the very good mean error (-3.7 feet overall), this is not considered to be indicative of a significant bias.

Some cells went dry in the steady-state simulation. The rewetting option was not used in the steady state because it was unstable when combined with the ET package. Out of 7,944 outcrop cells, 233 were dry, or 2.9 percent. These dry cells can be indicative of model instability or actual subsurface conditions. Because no obvious discontinuities exist in the model predicted outcrop water table, these cells are likely indicative of actual subsurface conditions (i.e., small cell thickness, low water table). The small number of dry cells does not have a significant impact on model results.

8.1.2.2 Streams

Table 8.1.2 shows a summary of stream calibration targets from various sources (described in more detail in Section 4.7). The target sources are the R.J. Brandes Company study done for this report (see Appendix B), referred to as the Brandes targets; the 1950 and 1980 through 2000 targets from the LBG-Guyton Associates and HDR Engineering, Inc. (1998) study; the targets from the HDR Engineering work done for the Central Carrizo-Wilcox GAM (Dutton et al., 2003), referred to as the HDR targets; and the targets from Slade et al. (2002), referred to as the Slade targets. None of these targets are true predevelopment targets in this region, especially in the western portion of the model. The Brandes targets might be considered predevelopment because they use the “naturalized” streams from the WAM models in their derivation. The simulated values are also compared to the mid-century estimates from the various sources, keeping in mind that the simulated values should tend to be more gaining (or less losing) than the target estimates. For the Atascosa River, the simulated results for all layers agree well with the Brandes target. The simulated Carrizo-Wilcox flow rate is lower than the LBG-Guyton and HDR 1950 target but is similarly gaining. For Cibolo Creek, the simulated values are bracketed by the estimates from the various sources. For the Frio River, the Brandes target (all layers) is gaining while the LBG-Guyton and HDR 1950 target (Carrizo-Wilcox) is losing. In the model, the all layers result is similar to the Brandes target, while the Carrizo-Wilcox result is weakly gaining compared to the weakly losing target, perhaps because of the time discrepancy discussed above. For the Guadalupe River, the simulated results compare favorably to the various targets. For the Leona River, the simulated Carrizo-Wilcox result is weakly losing, compared to a more strongly losing target from Slade. Again, this is in the western portion of the model where drawdowns had already occurred during the time the Slade low-flow studies were completed. For the Nueces River, the steady-state model gives a weakly losing result in the Carrizo-Wilcox, while the targets range from neutral (LBG-Guyton and HDR) to losing (Brandes). Note that Slade has the Queen City strongly gaining and the Carrizo strongly losing for this river. Although the simulated trends are in the correct direction (i.e., the Queen City is losing and the Carrizo is gaining), the magnitudes are smaller. The Rio Grande River should not be considered to be properly simulated with this model, because it coincides with the western no-flow boundary. For the San Antonio River, the model gives a comparable gaining result to the various targets. The San Marcos simulated result seems somewhat high in the Carrizo-Wilcox portion, compared to the HDR target. In the model, this portion of the river acts as a site of significant discharge that helps define the "trough" in the heads in Gonzales County. The modeled river may be acting as a surrogate for some other real sources of discharge. The San Miguel River was not modeled for the Carrizo-Wilcox, so it cannot be compared to the given targets.

Figure 8.1.7 shows the gain/loss values for the stream reaches in the steady-state model. As would be expected, the larger stream segments are more likely to be gaining than the smaller tributaries which are typically higher in shallower channels and higher in overall elevation. Consistent with the conceptual model, the streams in the eastern portion of the model are more gaining than those in the west, partially due to the higher amount of recharge in that region and the shallower water table.

8.1.2.3 Water Budget

Table 8.1.3 summarizes the water budget for the model. The mass balance error for the steady-state model was -0.64 percent. As would be expected, the predominant input source is recharge. Water discharging from the model is split between the streams, GHBs, and ET in descending order. The majority of the water exiting the Sparta aquifer leaves through the GHBs. Because of the large outcrop area, much of the water entering the Queen City aquifer through recharge exits immediately through the streams. Although the Carrizo Formation has a smaller outcrop area, it receives about an equal amount of recharge as the Queen City, due to a higher recharge rate. The largest portion of water leaving the Carrizo goes out through the top, which is consistent with the conceptual model for the predevelopment case.

Table 8.1.4 gives the various sources and sinks as percentages of the total water entering or leaving the model. The highest percentage of recharge occurs in the Queen City, due to its large outcrop. Recharge makes up 81.5 percent of the inflow to the model, with streams contributing 15.4 percent. Sixty eight percent of the water leaving the aquifer exits through the streams, while 23.3 percent and 7.6 percent exit through the GHBs and groundwater ET, respectively.

In Atascosa County there is a study that allows us to check the Carrizo flow rates from the outcrop to the confined section. Pearson and White (1967) performed a groundwater age dating study in Atascosa County using Carbon-14 age dating techniques. Figure 8.1.8a shows their estimate of groundwater travel times from the outcrop to the confined section. Figure 8.1.8b is a plot of the travel times to all points in the simulated Carrizo Formation. These travel times were calculated by placing particles in all of the model cells and tracking them backwards to the source. The model travel times show good agreement (see, for example, the location of the 10,000 year contour) with the results of Pearson and White (1967) providing a good validation measure for flow in that portion of the model.

The simulated water ages are also in agreement with the general conceptual model of the flow system. In the western portion of the model, where the bad water line is farthest downdip, the 10,000 year contour extends more than 40 miles from the outcrop. In the eastern portion of the model where the bad water line is much closer to the outcrop (Gonzales County for example), the 10,000 year contour is generally 20 miles or less from the outcrop.

Table 8.1.1 Head calibration statistics for the Southern steady-state model.

Layer	Count	ME (ft)	MAE (ft)	RMSE (ft)	Range (ft)	RMSE/ Range
1	15	-3.8	18	22	210	0.10
3	16	-7.4	22	26	288	0.091
5	31	-3.7	16	22	308	0.071

RMSE=Root Mean Square Error; ME=Mean Error; MAE=Mean Absolute Error

Table 8.1.2 Summary of measured and simulated stream gain/loss values for the Southern model (AFY).

Source ->	Brandes	LBG-Guyton & HDR		HDR	Slade		Simulated			
Time Period ->	**N/A**	**1950**	**1980-2000**	**~1950**	**~1930-1960**		**Predevelopment**			
Aquifer->	**All**	**Carrizo-Wilcox**	**Carrizo-Wilcox**	**Carrizo-Wilcox**	**QCSP**	**Carrizo**	**QCSP**	**Carrizo-Wilcox**	**All Layers**	**All Layers w/Trib.**
Atascosa River	151	270	-50				181	60	139	
Cibolo Creek	41	200	-100	223	215	486	116	257	160	207
Frio River	108	-100	-500				185	20	116	
Guadalupe River	235	180	50	519			184	192	174	174
Leona River					-204	-469	153	-21	106	
Nueces River	-159	0	-500		825	-828	145	-68	119	
Rio Grande	-70				-1406		-33	73	-1	
San Antonio River	215	540	-325	269			364	917	660	286
San Marcos River	-278		100	150			268	985	726	396
San Miguel River		-110	-100				175	N/A	175	

Brandes: see Appendix B
LBG-Guyton & HDR: LBG-Guyton Associates and HDR Engineering, Inc. (1998)
HDR: Dutton et al. (2003)
Slade: Slade et al. (2002)

Table 8.1.3 Water budget for the Southern steady-state model (AFY).

IN						
Layer	**Drains**	**Recharge**	**GHBs**	**Streams**	**Top Flow**	**Bot. Flow**
1	0	24,486	8,307	3,388	0	51,482
2	0	4,714	0	925	10,419	51,726
3	0	69,019	0	18,539	13,390	49,628
4	0	6,689	0	5,479	7,782	47,758
5	0	65,374	0	4,662	8,705	17,142
6	0	1,130	0	14	9,217	11,405
7	0	22,849	0	6,951	3,371	15,451
8	0	24,249	0	1,314	5,483	0
Sum	0	218,510	8,307	41,272	58,367	244,591

OUT						
Layer	**Drains**	**ET**	**GHBs**	**Streams**	**Top Flow**	**Bot. Flow**
1	-175	-3,577	-62,766	-10,671	0	-10,419
2	-5	-489	0	-2,380	-51,482	-13,390
3	-360	-7,428	0	-83,212	-51,726	-7,782
4	-171	-2,325	0	-7,022	-49,628	-8,705
5	-831	-2,072	0	-37,123	-47,758	-9,217
6	0	-254	0	-1,242	-17,142	-3,371
7	-310	-1,368	0	-30,086	-11,405	-5,483
8	-1,313	-2,886	0	-11,751	-15,451	0
Sum	-3,165	-20,398	-62,766	-183,488	-244,591	-58,367

Table 8.1.4 Water budget for the Southern steady-state model expressed as a percent of total inflow or outflow.

IN				
Layer	**Drains**	**Recharge**	**GHBs**	**Streams**
1	0.0	9.1	3.1	1.3
2	0.0	1.8	0.0	0.3
3	0.0	25.7	0.0	6.9
4	0.0	2.5	0.0	2.0
5	0.0	24.4	0.0	1.7
6	0.0	0.4	0.0	0.0
7	0.0	8.5	0.0	2.6
8	0.0	9.0	0.0	0.5
Sum	0.0	81.5	3.1	15.4
OUT				
Layer	**Drains**	**ET**	**GHBs**	**Streams**
1	0.1	1.3	23.3	4.0
2	0.0	0.2	0.0	0.9
3	0.1	2.8	0.0	30.8
4	0.1	0.9	0.0	2.6
5	0.3	0.8	0.0	13.8
6	0.0	0.1	0.0	0.5
7	0.1	0.5	0.0	11.2
8	0.5	1.1	0.0	4.4
Sum	1.2	7.6	23.3	68.0

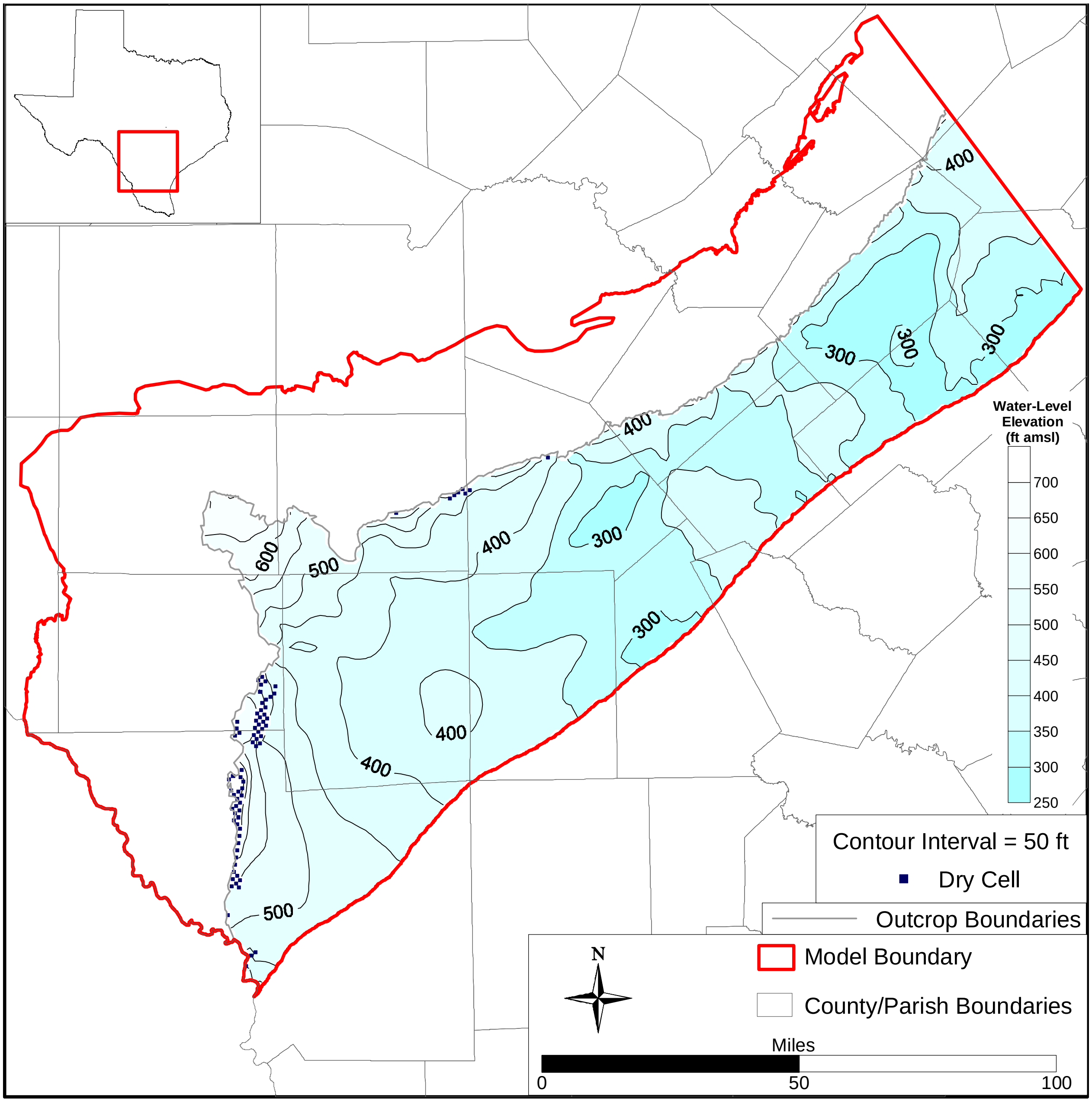
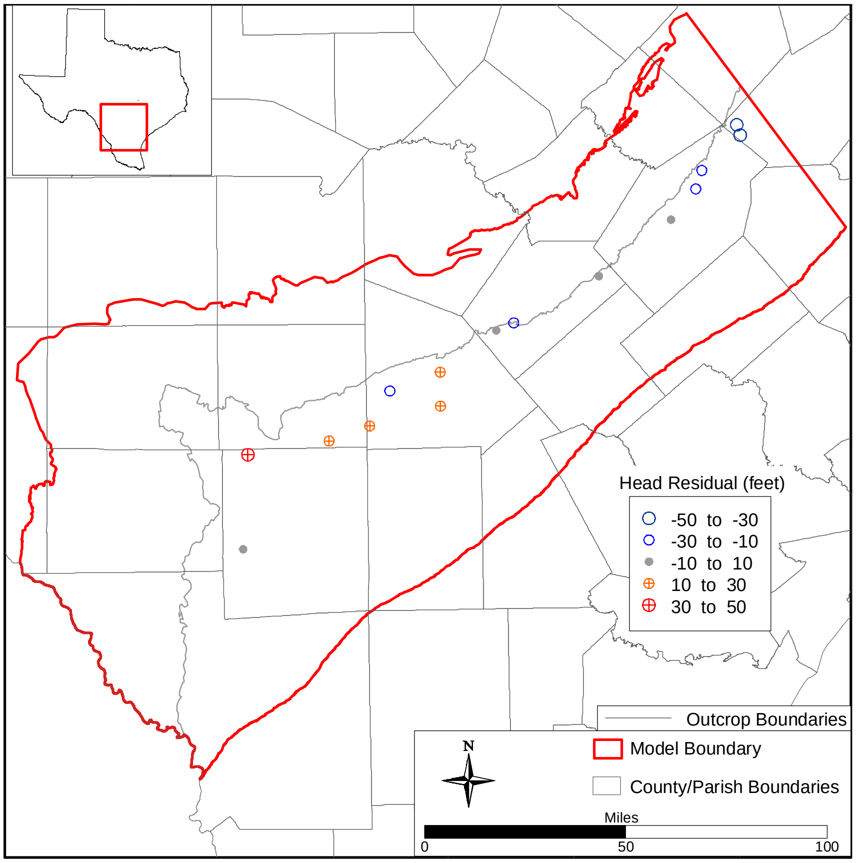
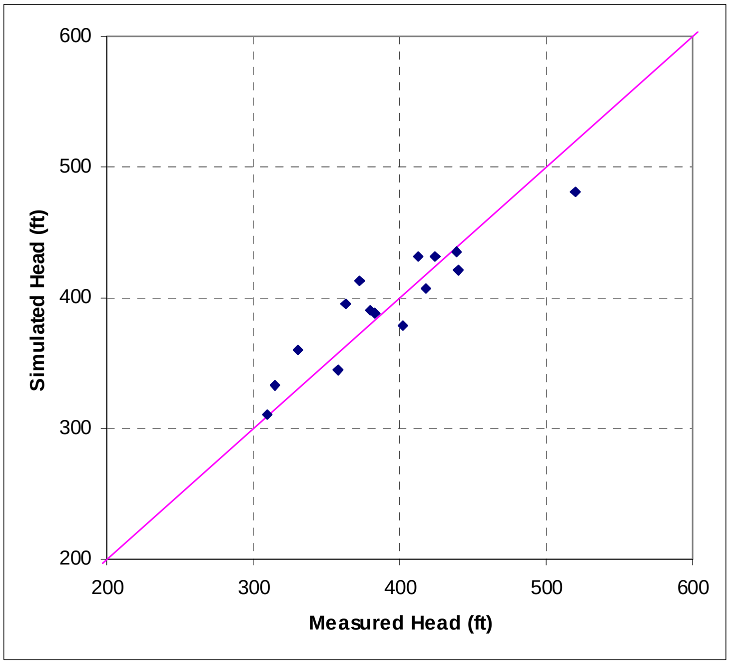


Figure 8.1.1 **Simulated steady-state head surface for the Sparta aquifer (Layer 1).**



a.



b.

Figure 8.1.2 Head residuals (a) and scatterplot (b) of simulated and measured heads for the Sparta aquifer (Layer 1).

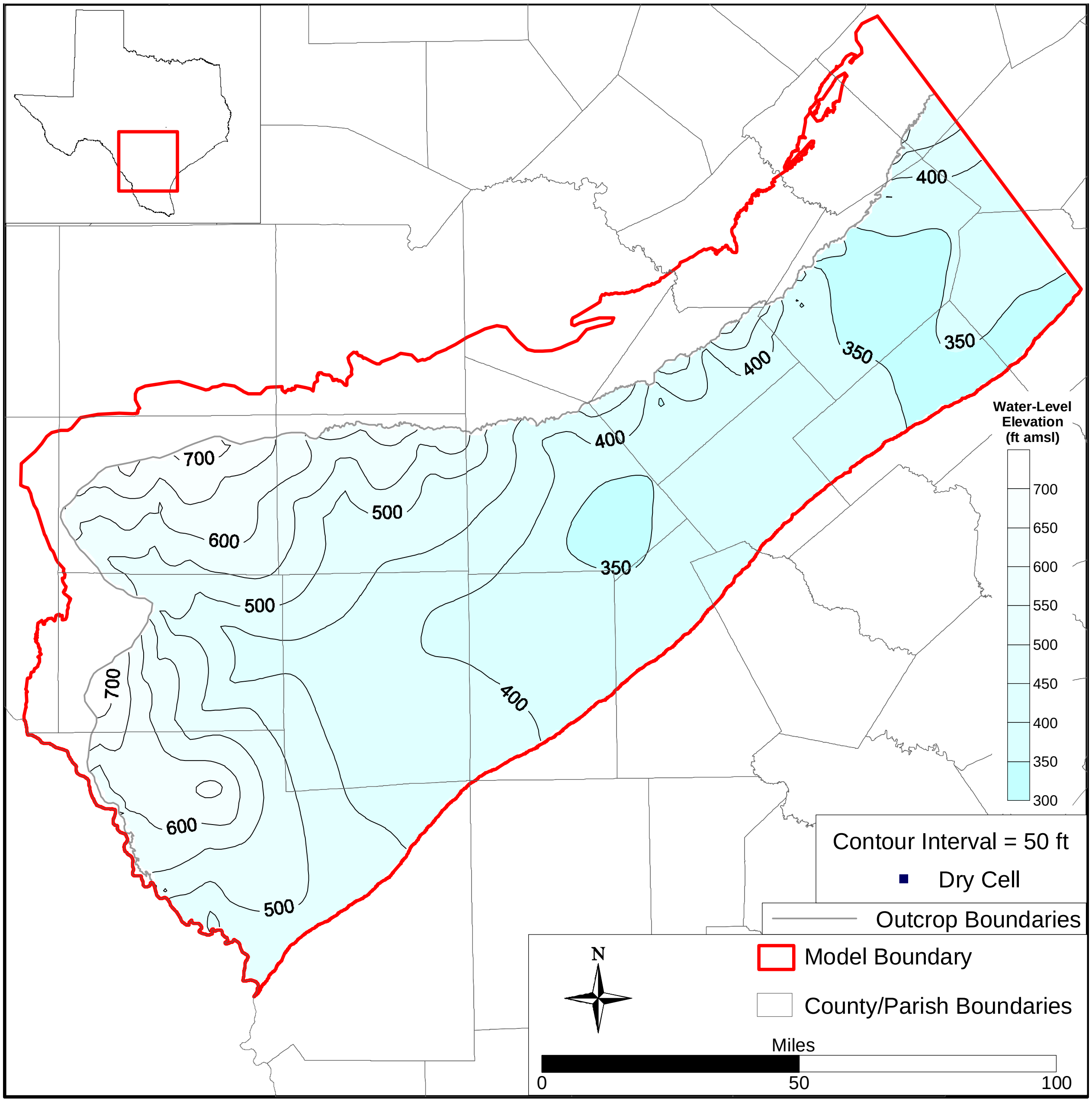


Figure 8.1.3 Simulated steady-state head surface for the Queen City aquifer (Layer 3).

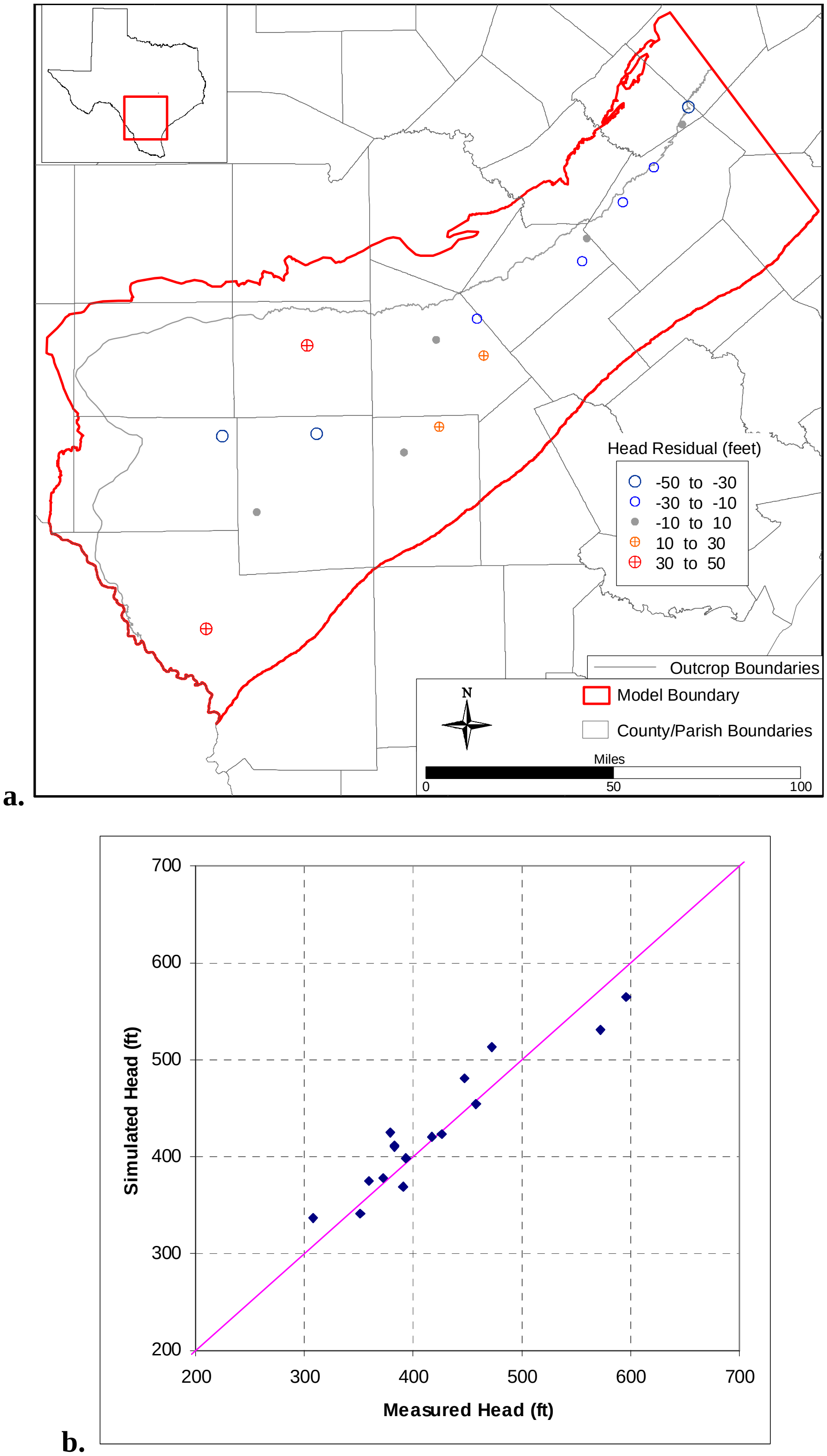


Figure 8.1.4 Head residuals (a) and scatterplot (b) of simulated and measured heads for the Queen City aquifer (Layer 3).

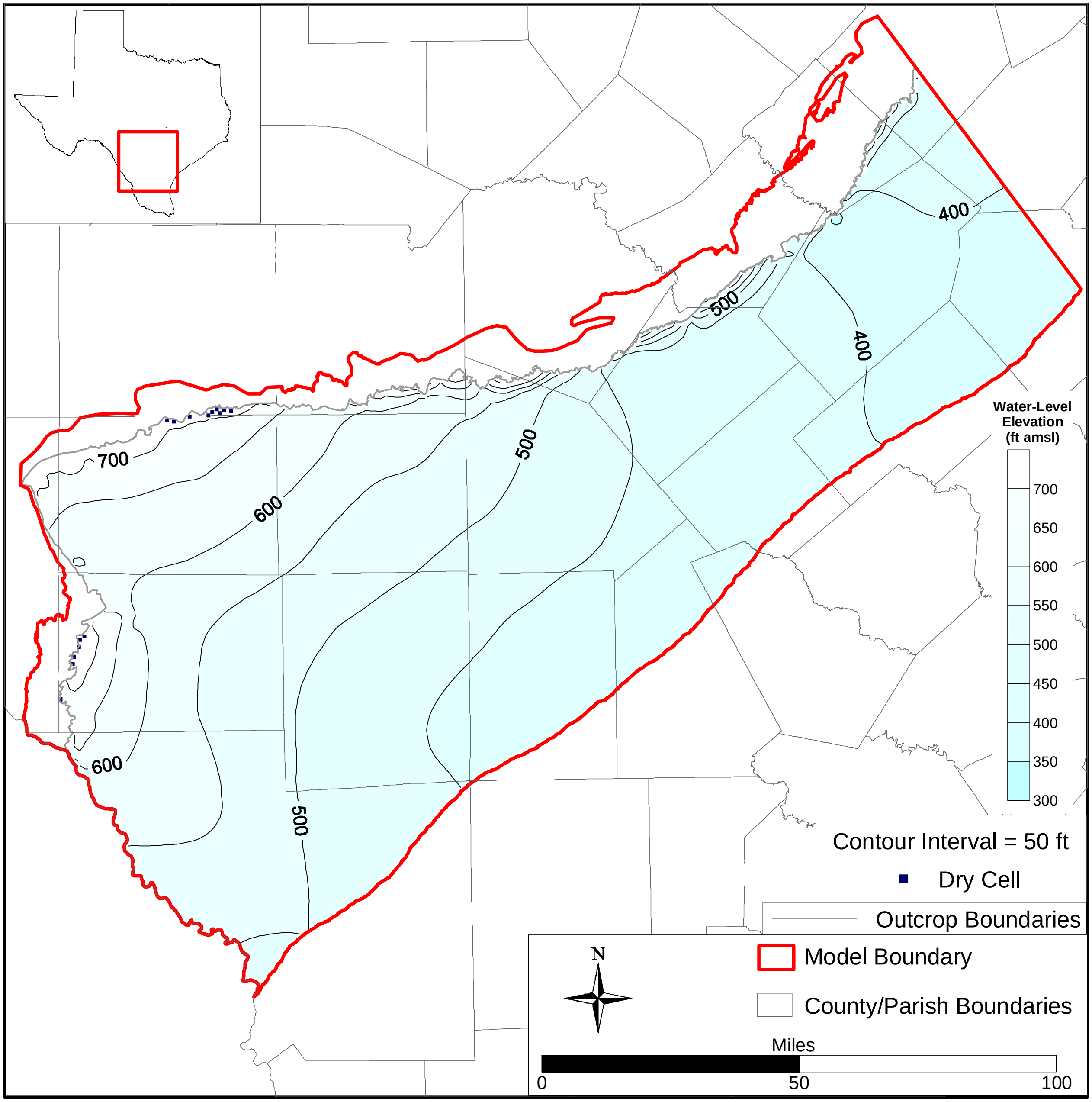


Figure 8.1.5 Simulated steady-state head surface for the Carrizo Formation (Layer 5).

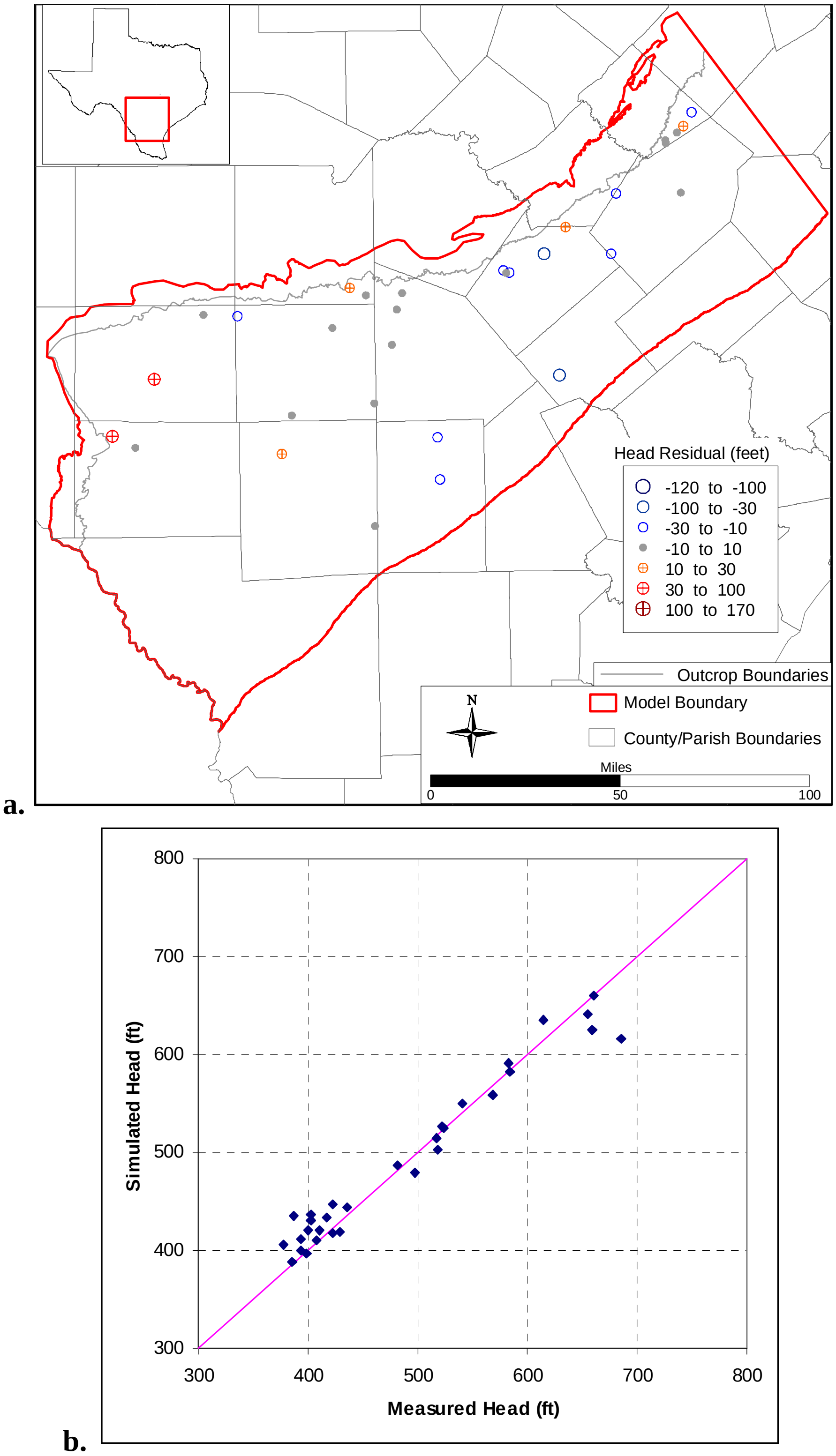


Figure 8.1.6 Head residuals (a) and scatterplot (b) of simulated and measured heads for the Carrizo Formation (Layer 5).

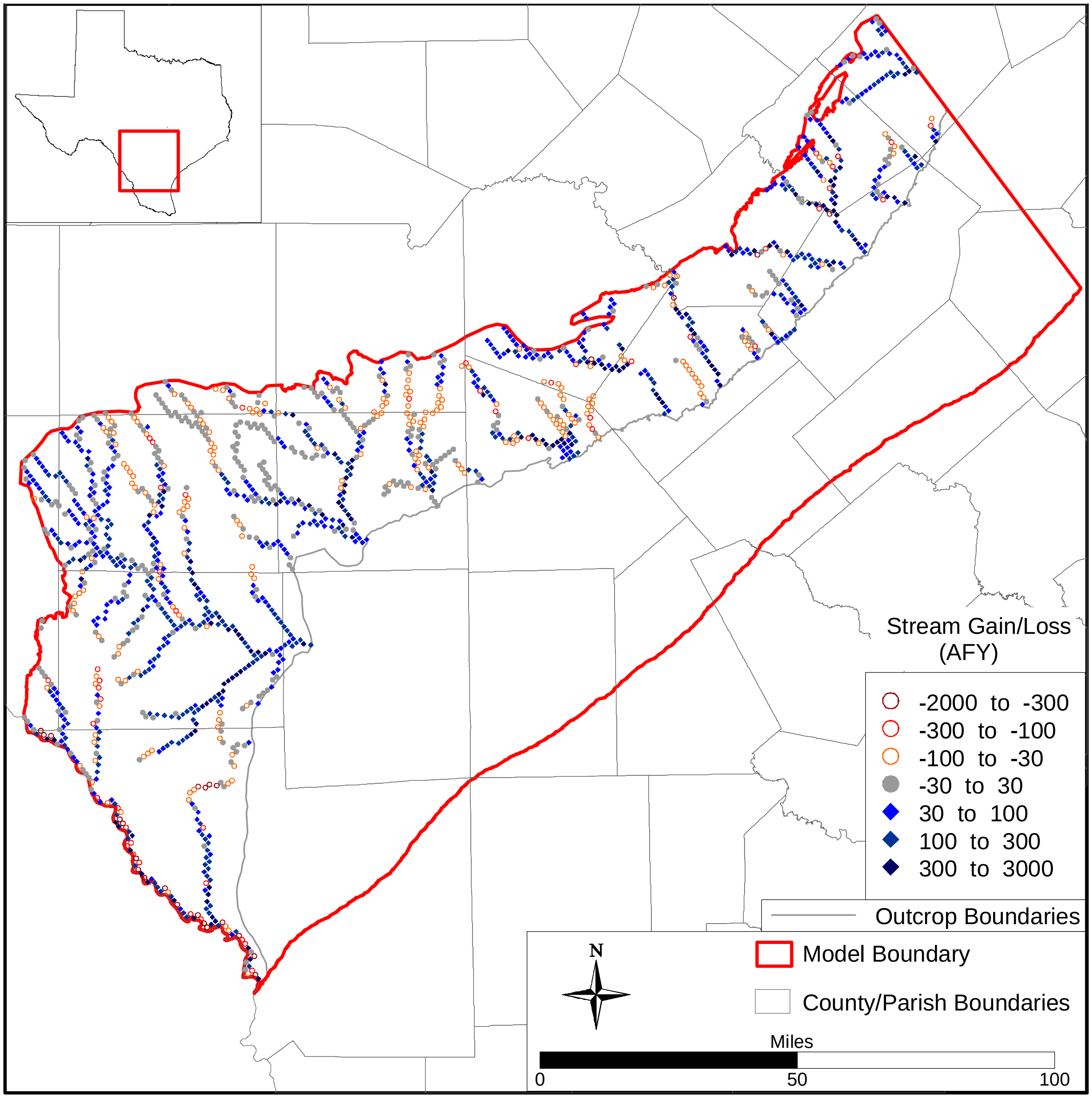


Figure 8.1.7 **Steady-state model stream gain/loss (positive value denotes gaining stream).**

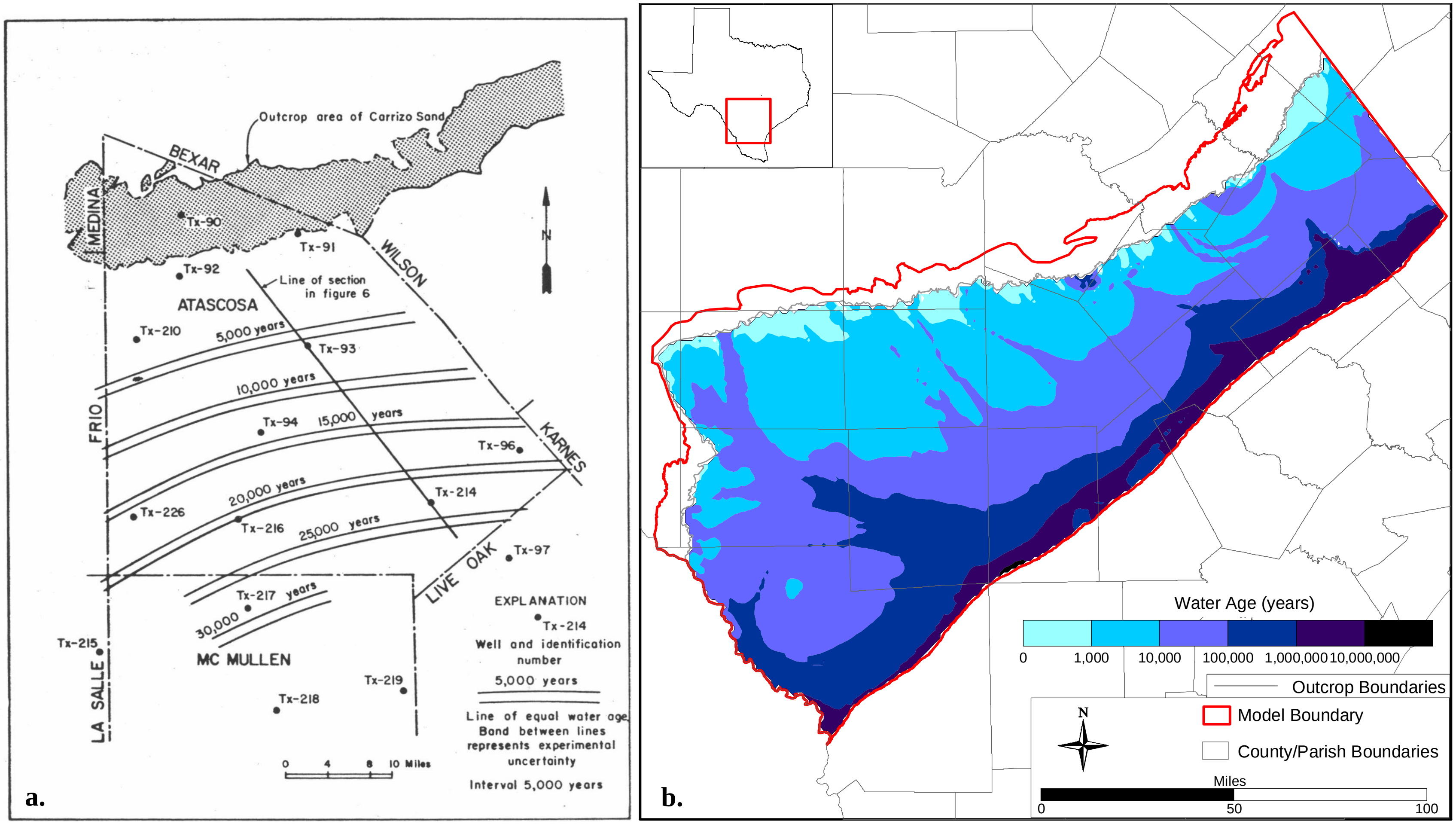


Figure 8.1.8 Water age results from Pearson and White (1967) (a) and steady-state model water age based on particle travel times from the outcrop (b).

8.1.3 Sensitivity Analysis

A sensitivity analysis was performed for 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 head was recorded. Four simulations were completed for each parameter varied, where the input parameters were varied either according to:

$$sensitivity\,value = (calibrated\,value)(factor) \tag{8.2}$$

$$sensitivity\,value = (calibrated\,value)\left(10^{factor-1}\right) \tag{8.3}$$

and the factors were 0.8, 0.9, 1.1, and 1.2. For parameters such as hydraulic conductivity, which typically vary by orders of magnitude and are usually lognormally distributed, Equation (8.3) was used. Parameters such as recharge were varied linearly using Equation (8.2). Also, for varying GHB and stream heads, these factors were not appropriate, and linear factors of 0.96, 0.98, 1.02, and 1.04 were used. For the output variable, we calculated the mean difference (*MD*) between the base simulated head and the simulated head calculated for the sensitivity simulation for each layer. The equation for calculating the *MD* is:

$$MD = \frac{1}{n}\sum_{i=1}^{n}\left(h_{sens,i} - h_{cal,i}\right) \tag{8.4}$$

where

$h_{sens,i}$ = sensitivity simulation head at active gridblock i

$h_{cal,i}$ = calibrated simulation head at active gridblock i

n = number of gridblocks compared

We considered two approaches to applying Equation 8.4 to the sensitivity of output heads. First, we compared the heads in all active gridblocks between the sensitivity output and the calibrated output. Second, we compared the heads only at gridblocks where measured targets were available (i.e., n = number of targets in that layer). A comparison between these two methods can provide information about the bias in the target locations, (i.e., a similar result suggests adequate target coverage). However, a drawback to the second method is that sensitivity results will not be available in layers containing an insufficient number of targets.

For the steady-state analysis, 14 parameter sensitivities were completed:

1. Horizontal hydraulic conductivity, Sparta (Kh-Sparta)
2. Horizontal hydraulic conductivity, Queen City (Kh-Queen City)
3. Horizontal hydraulic conductivity, Carrizo (Kh-Carrizo)
4. Horizontal hydraulic conductivity, Wilcox (Kh-Wilcox)
5. Vertical hydraulic conductivity in the Weches (Kv-Weches)
6. Vertical hydraulic conductivity in the Reklaw (Kv-Reklaw)
7. Vertical hydraulic conductivity in the Wilcox (Kv-Wilcox)
8. Recharge, model-wide (Rch - All)
9. Streambed conductance, model-wide (Str - K)
10. Stream head, model-wide (Str - Head)
11. GHB conductance, model-wide (GHB - K)
12. GHB head, model-wide (GHB - Head)
13. Fault conductance (Fault - K) – note that faults are transparent in this model so no effect is expected for this sensitivity.
14. Drain conductance (Drain - K)

Figure 8.1.9 shows the sensitivity results for the Queen City aquifer (Layer 3), with *MDs* calculated from just the grid blocks where targets are available. Figure 8.1.10 shows the sensitivity results for the Queen City aquifer, with *MDs* calculated from all active cells in the layer. Note that the two figures indicate a similar order of the most important variables, with Kh-Sparta and Kv-Weches being the most important negative trending and Kv-Reklaw and Kh-Carrizo being the most important positive trending. The two figures are less consistent for the *MD*s that were close to zero. The good agreement for the significant *MD* values indicates adequate target coverage in the Queen City aquifer. However, because the target coverage in the Sparta aquifer is less complete than in the Queen City aquifer, *MD*s calculated from all grid blocks will be primarily discussed to avoid a bias towards updip effects.

Figure 8.1.11 indicates that the change in head in the Sparta aquifer for the steady-state model is most positively correlated with GHB head and most negatively correlated with GHB-conductance. This is expected since the GHBs are attached to the majority of the Sparta layer. Figure 8.1.12 shows the impact of varying GHB conductance and head on all of the model layers. As expected, the impact of the GHBs decreases in lower layers. However, the GHBs do affect all layers in the steady-state model because, as discussed previously, they are the primary outlet for water to exit the downdip portions of the aquifers.

Figure 8.1.13 indicates that the change in head in the Queen City aquifer for the steady-state model is most positively correlated with stream heads and most negatively correlated with GHB conductance. This correlation with stream heads is due to the large outcrop area in the Queen City aquifer with many stream cells. Also, the heads in the Queen City aquifer are negatively correlated with the conductivity of the Weches, again because the Weches restricts upward flow in the downdip section of the aquifer.

Figure 8.1.14 shows that the heads in the Carrizo Formation are negatively correlated to the vertical conductivity of the Reklaw, because the Reklaw restricts upward flow in the downdip section of the Carrizo. The figure also shows that heads in the Carrizo are positively correlated with recharge. Figure 8.1.15 shows the sensitivity in all layers to the conductance of the Weches and to recharge. This balance between recharge and the vertical conductance of the confining units (as well as the vertical conductance of the younger sediments represented by the GHBs) is the most important aspect of steady-state model calibration. Increased recharge must be balanced by a decrease in vertical conductivity and vice-versa. Although the combination of these variables is relatively well constrained, the strong correlation makes it difficult to constrain one or the other with the steady-state model. This is why calibrating with multiple hydrologic conditions (i.e., both steady-state and transient) can be so valuable.

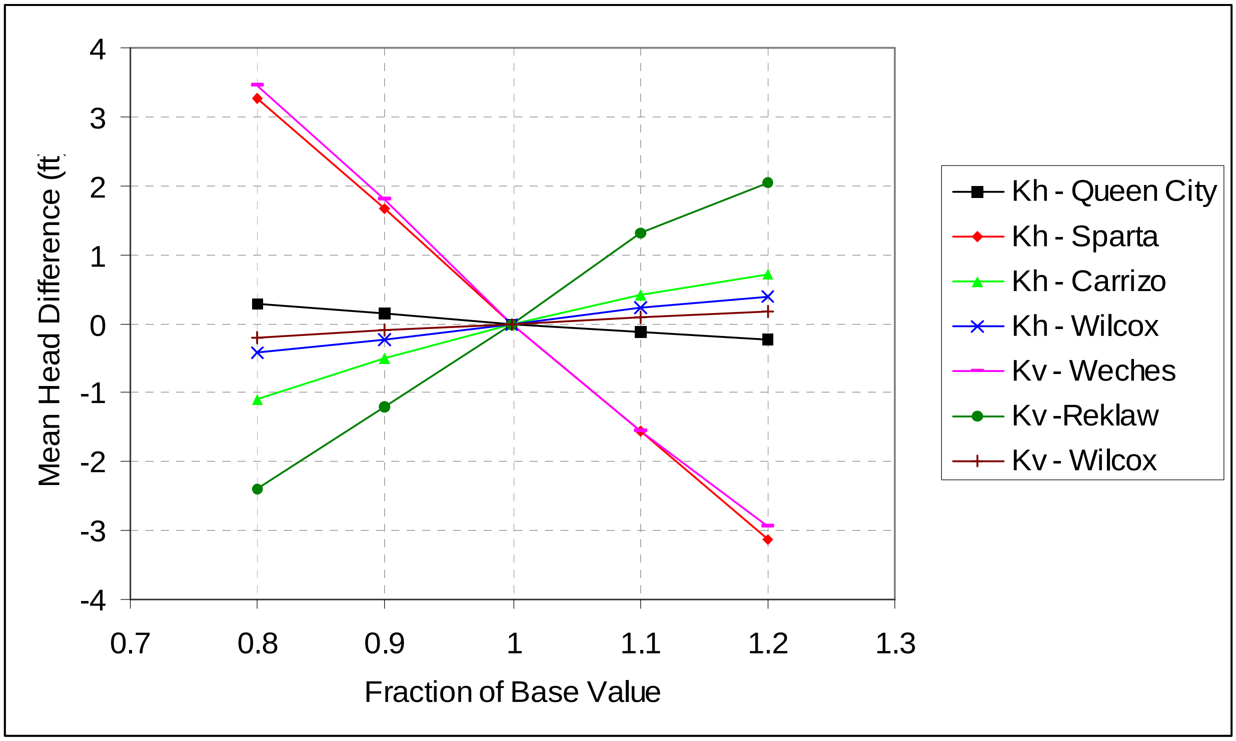


Figure 8.1.9 Steady-state sensitivity results for the Queen City aquifer (Layer 3) using target locations.

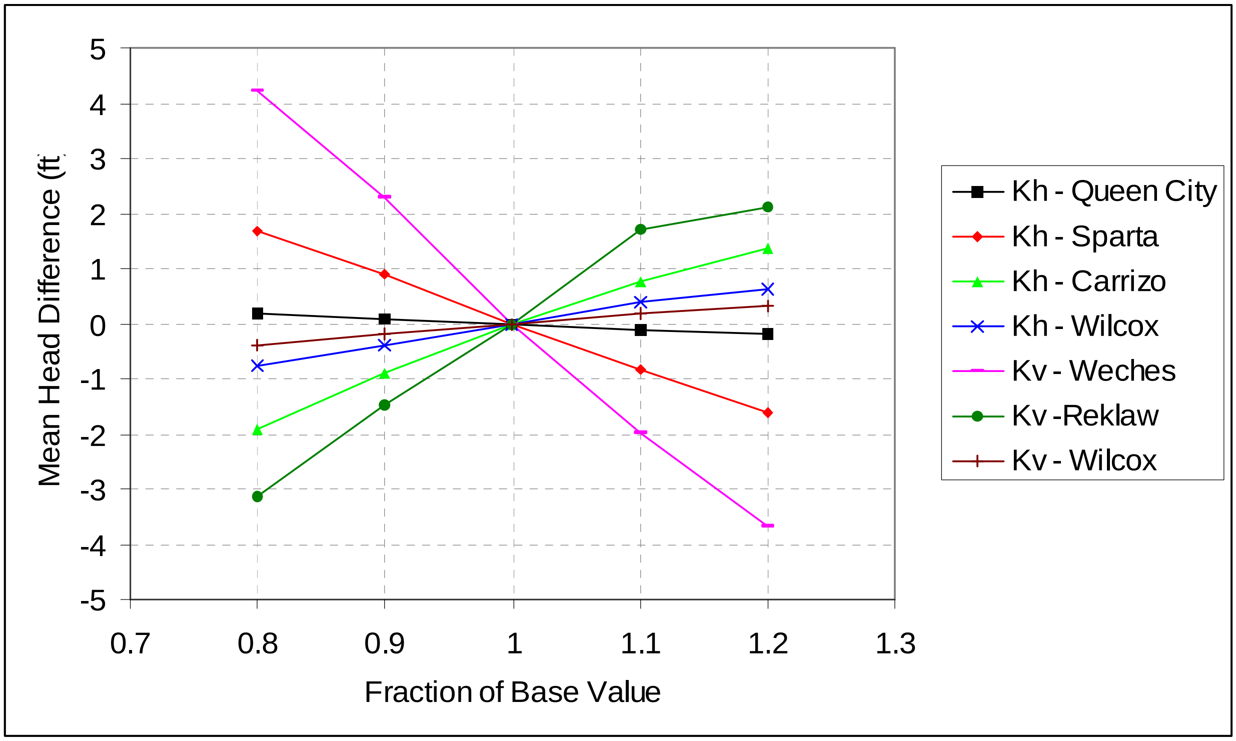
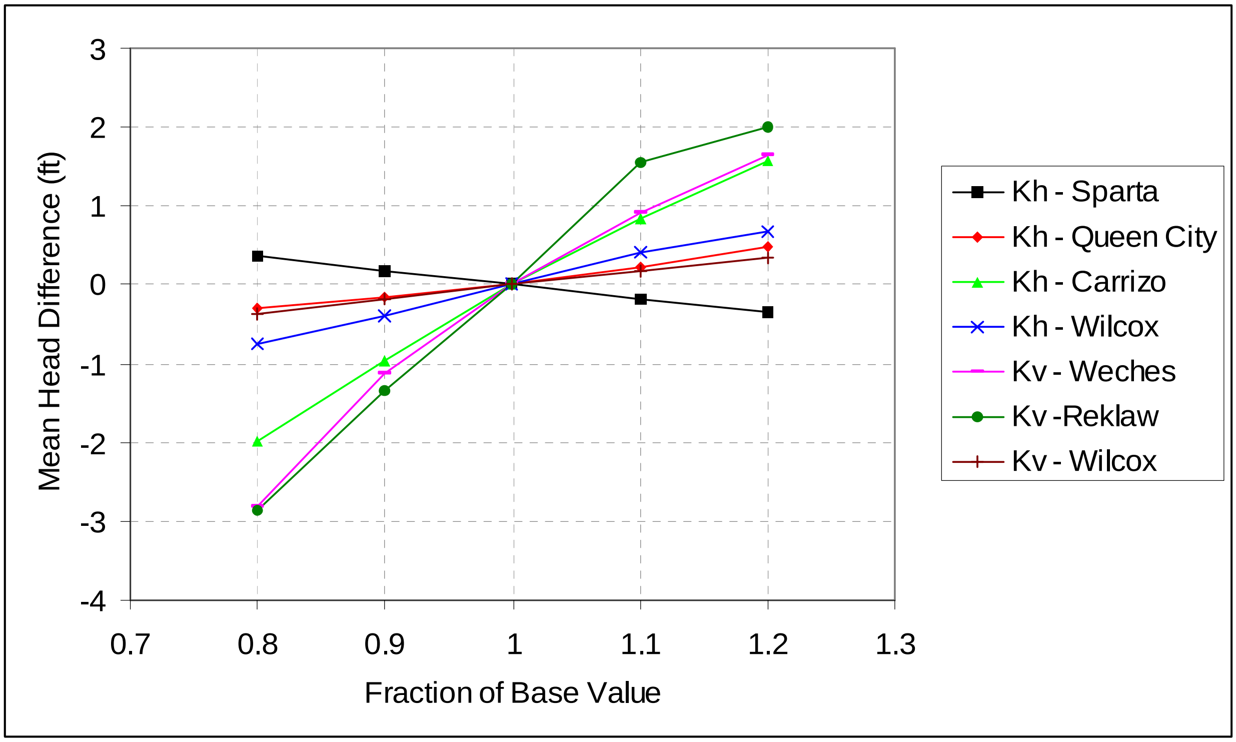


Figure 8.1.10 Steady-state sensitivity results for the Queen City aquifer (Layer 3) using all active grid blocks.



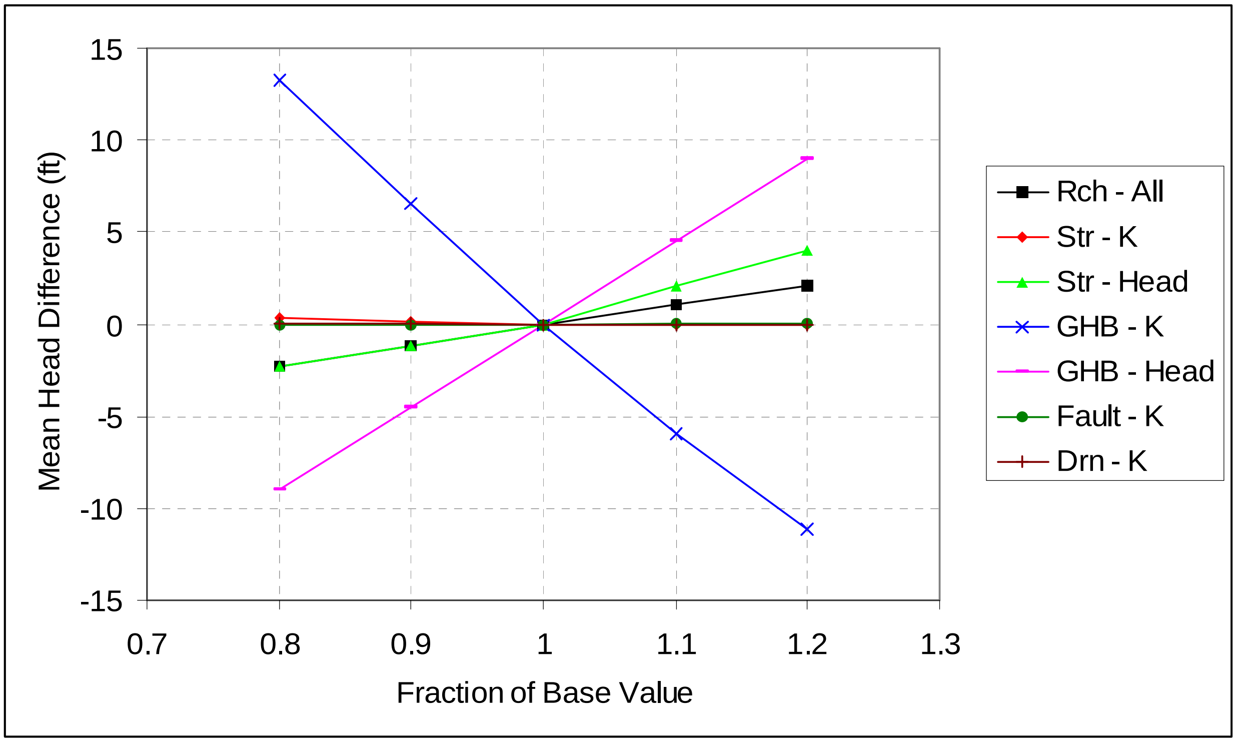
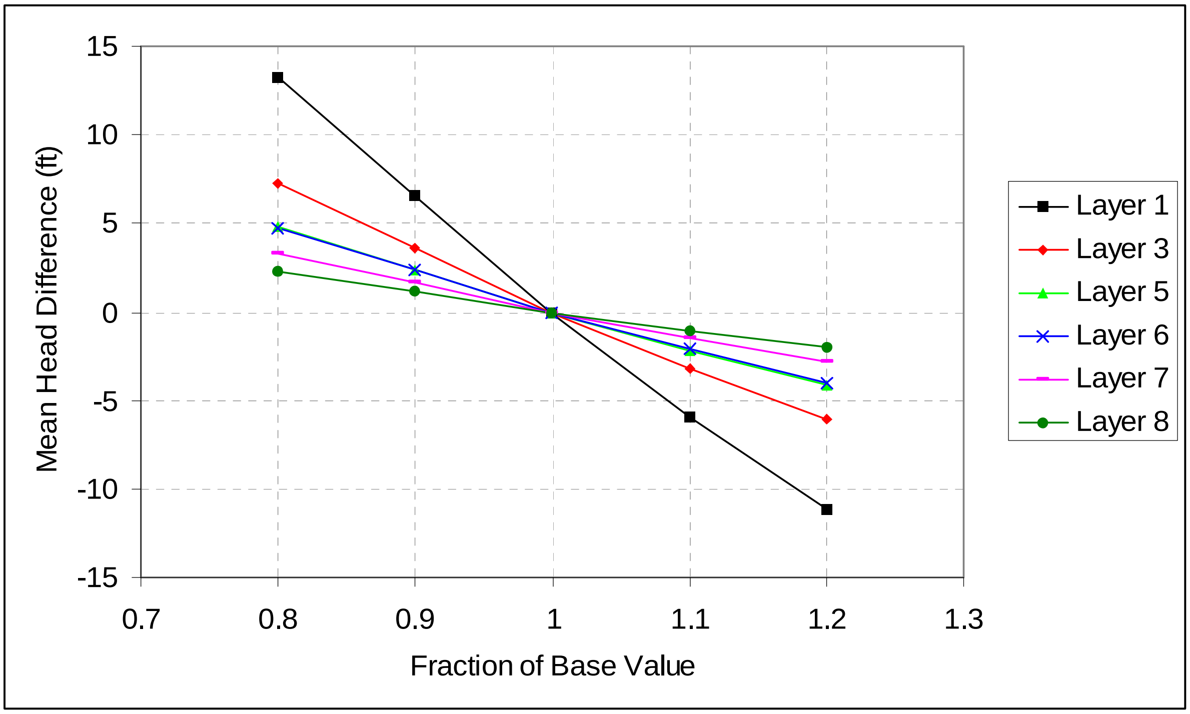
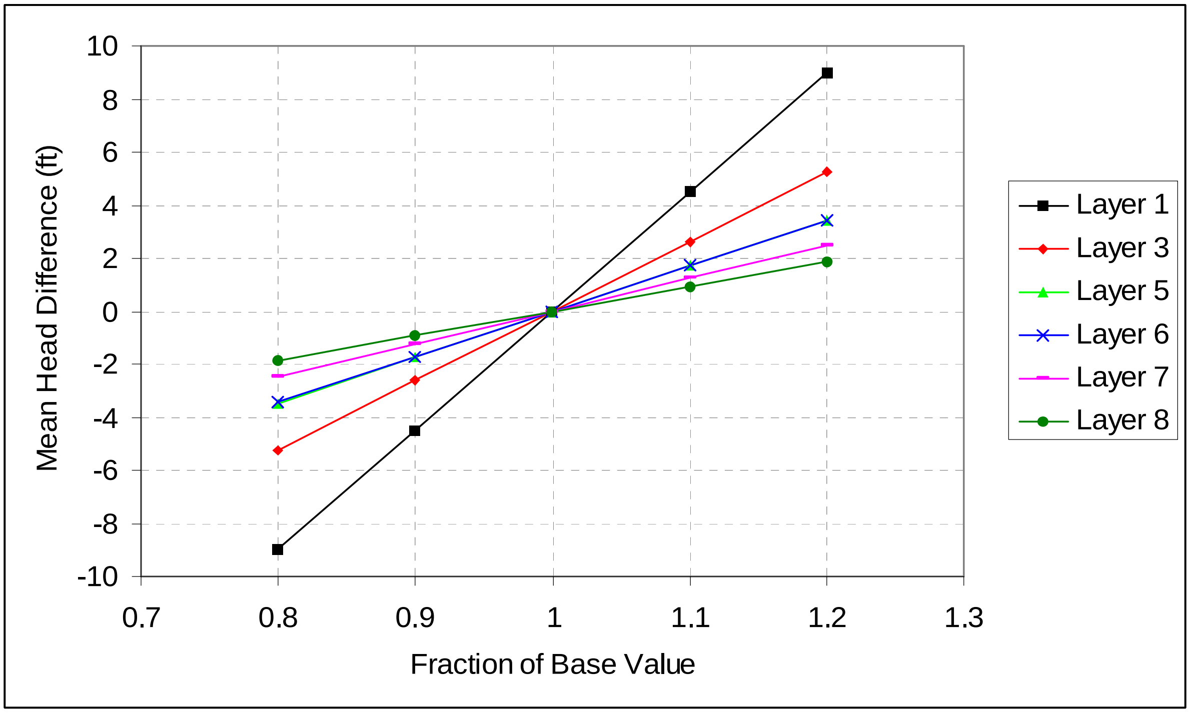


Figure 8.1.11 Steady-state sensitivity results for the Sparta aquifer (Layer 1) using all active grid blocks.

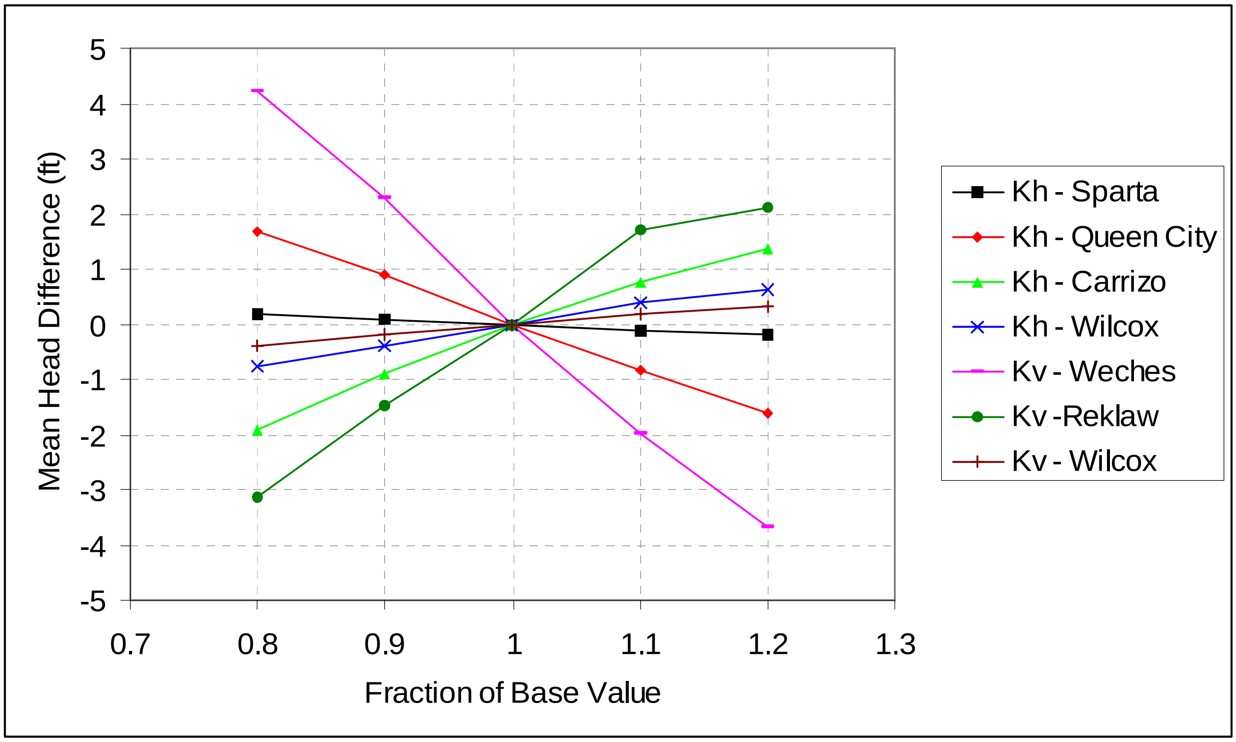


a.



b.

Figure 8.1.12 Steady-state sensitivity results where GHB conductivity (a) and head (b) is varied.



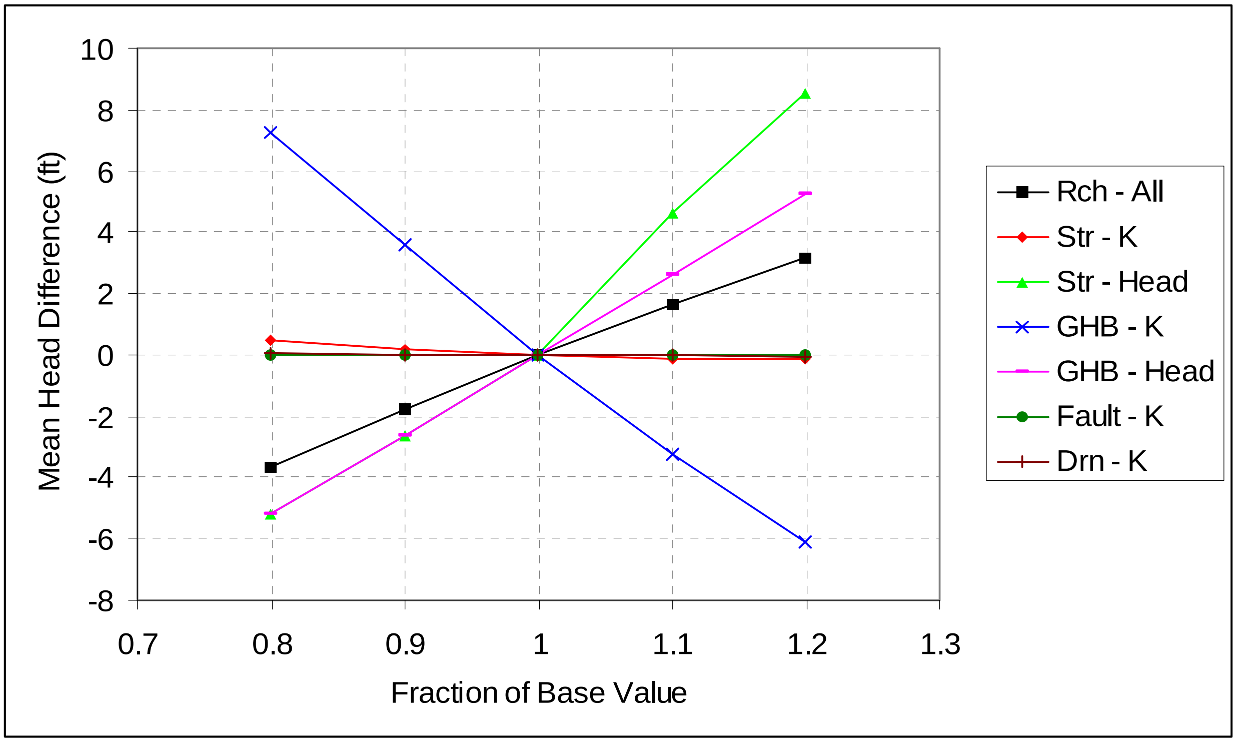
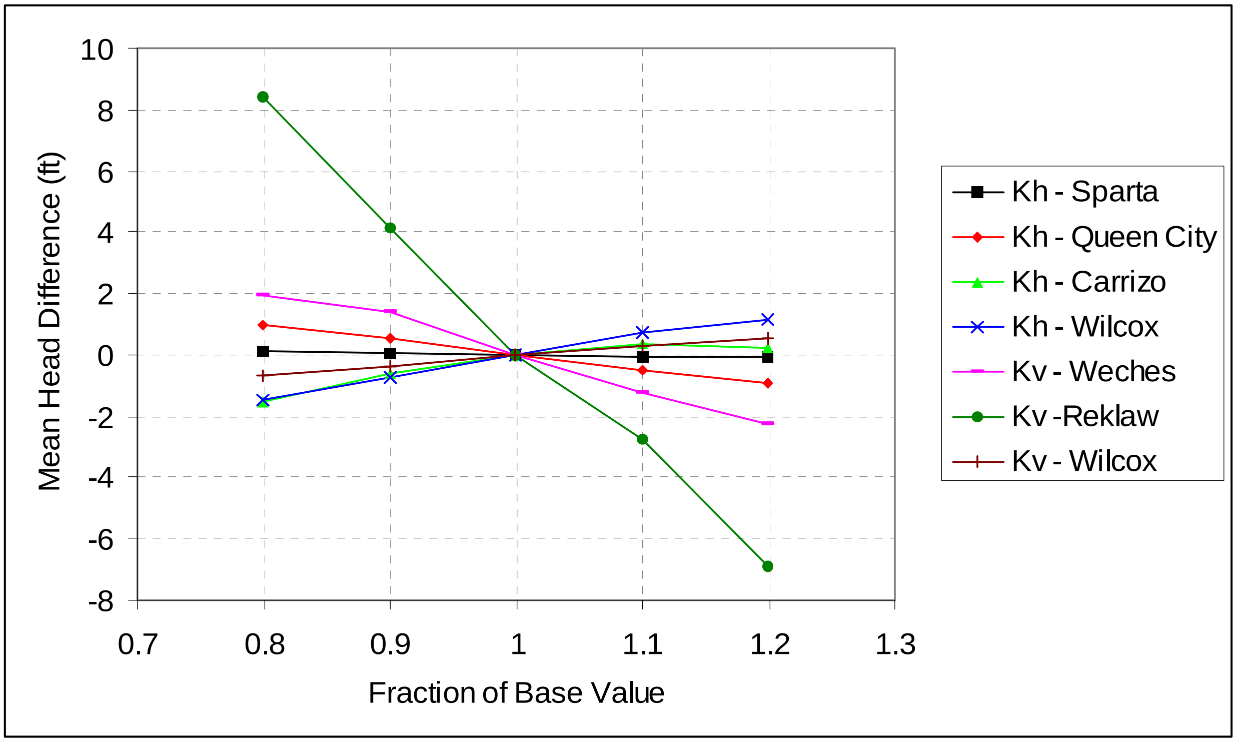


Figure 8.1.13 **Steady-state sensitivity results for the Queen City aquifer (Layer 3) using all active grid blocks.**



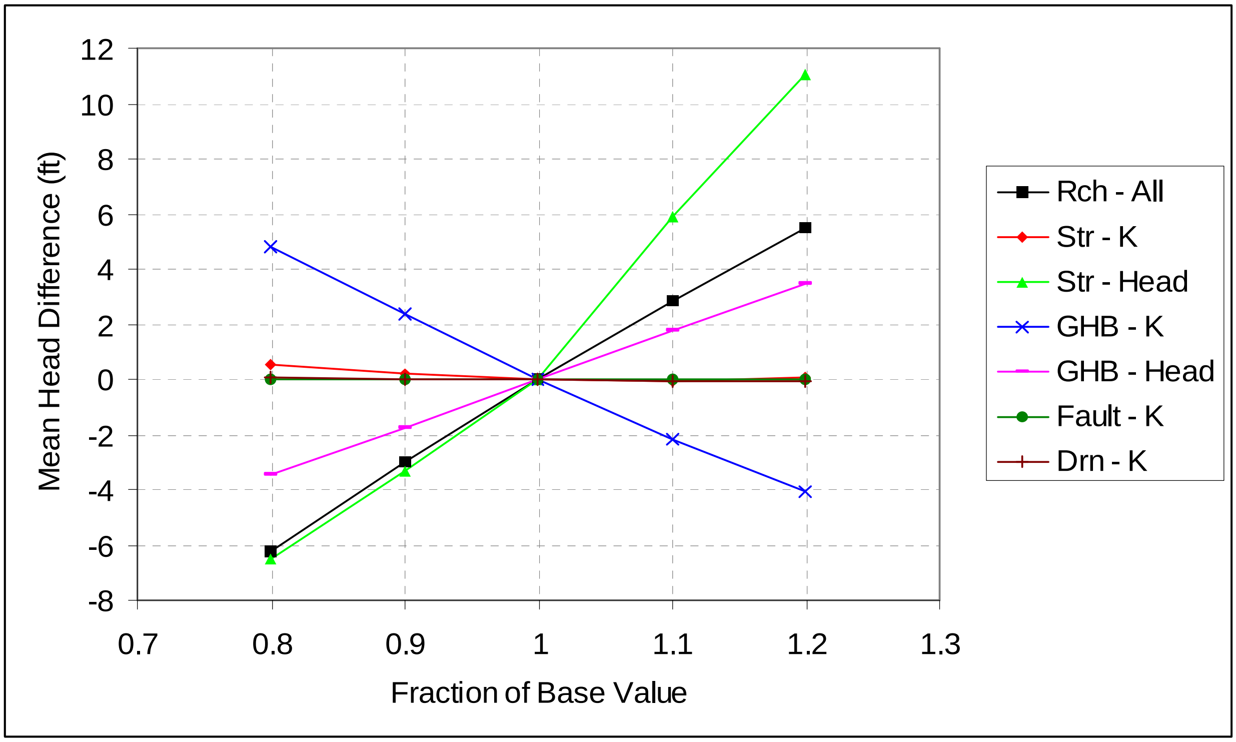
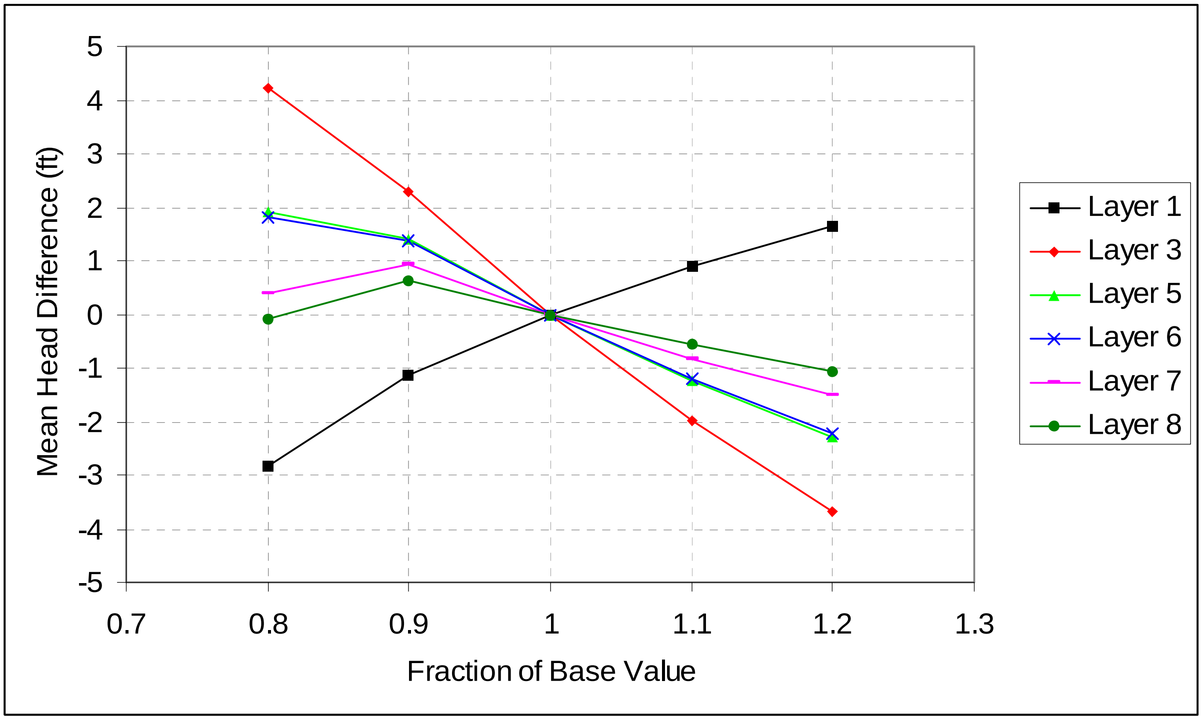
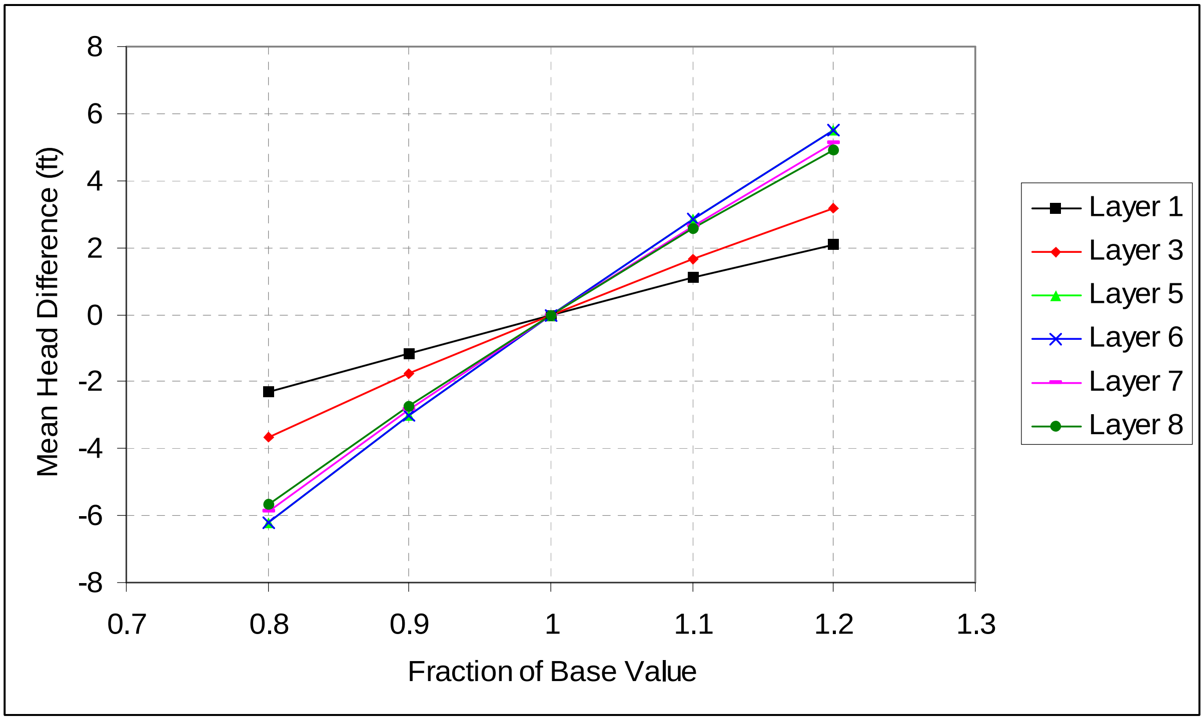


Figure 8.1.14 Steady-state sensitivity results for the Carrizo Formation (Layer 5) using all active grid blocks.



a.



b.

Figure 8.1.15 Steady-state sensitivity results where Kv of Weches (a) and recharge (b) is varied.

8.2 Central Queen City and Sparta GAM

This section describes the steady-state calibration targets and calibrated parameters including horizontal and vertical hydraulic conductivity, recharge, ET, stream conductance, and vertical conductance for younger sediments overlying the Queen City Formation.

8.2.1 Calibration

Water-level measurements are needed as targets for steady-state calibration. However, where there is a well, water levels have often been affected by groundwater pumpage. As a result, valid targets for predevelopment conditions were limited, because wells were typically drilled for pumpage.

During the calibration process, the adjusted parameters were mainly vertical conductivity and recharge. In the final calibrated model, the horizontal conductivity field was kept similar to initial estimates since this parameter was better constrained than recharge and vertical conductivity. As demonstrated by the sensitivity analyses, the GHB heads and conductance have a large impact on the model, particularly on the Sparta and Queen City aquifers. The heads were adjusted across the three models to allow for a better fit for Layers 1 and 3.

8.2.1.1 Horizontal and Vertical Hydraulic Conductivities

Few changes were made to the initial estimates of horizontal and vertical hydraulic conductivity fields. However, some changes were made in the overlap area between the Central and Northern models. The horizontal conductivity was locally decreased in the Carrizo Formation in Upshur and Smith counties and in the vicinity of the Lufkin well field as described in Section 8.3.1.1. The vertical conductivity was modified in the Reklaw Formation from the blanket value of $1x10^{-4}$ (as in the Weches Formation) to $1x10^{-5}$ and even $1x10^{-6}$ over a small fraction of the East Texas Basin straddling Cherokee and Anderson counties. The Central Carrizo-Wilcox GAM required the same tightening of the Reklaw Formation over the same area. Sensitivity analyses show that the Reklaw Formation vertical conductivity is important to the model.

8.2.1.2 Recharge

Recharge was not modified from the values presented in Section 6.3.5. After multiple trials and exchanges with the Northern and Southern models, it was recognized that the present recharge field represented the best compromise across the three models.

8.2.1.3 Groundwater Evapotranspiration

Several adjustments to groundwater ET were tried, such as a model-wide increase in extinction depth or an increase in ET maximum. However, none of these adjustments had a positive effect on the calibration, so the final model contains the initial estimate of ET from Section 6.3.5. Similar to the southern region (Section 8.1.1.3), drains were added in the river valleys to emulate evaporation or seepage at the ground surface.

8.2.1.4 General Head Boundaries

A general head boundary was assigned to the top of Layer 1. The head was computed as a fraction of the head of the water table aquifer located above that particular cell. The conductance field was obtained as described in Section 6.3.2. Contrary to the Central Carrizo-Wilcox GAM, no downdip GHB boundary was used in the current model. Instead, a no-flow boundary was implemented. Sensitivity analyses on the Central Carrizo-Wilcox GAM showed that, although the feature is realistic, it had little effect on the calibration because the low conductance acts nearly as a no-flow boundary.

8.2.1.5 Streams

Stream flows were computed external to MODFLOW (see Section 6.3.3). The steady state stream flow is the average of a 25 year-long gage record (1975 to 1999). Stream elevations were initially set up as described in Section 6.3.3. They were then systematically lowered ("incised"), if necessary, so that the bottom elevation of the stream was 20 feet below ground surface. During calibration, they were further incised in the northern half of the Central model where the topography is more varying. All stream cells north of and including the Brazos River were incised. The incision is a function of the stream width. It was assumed that a larger stream will be incised more into the general topography than a smaller stream. The incision was not allowed to go over 100 feet, except for the Trinity River where the maximum is 120 feet. The incision variable, Is, was not permitted to go deeper than the bottom of the formation in a given stream cell and is given by:

$$Is = \max(0.1833Ws + 30,100) \tag{8.5}$$

where *Ws* is the stream width (in feet), except for Trinity River where:

$$Is = \max(0.1833Ws + 50,120) \tag{8.6}$$

The new elevation E_{new} of the top of the stream bed was then:

$$E_{new} = \max(E_{form\,bot}, E_{old} - Is) \tag{8.7}$$

where $E_{form\ bot}$ is the cell bottom of the formation onto which the stream is flowing and E_{old} is the initial elevation. Because stream width varies from nearly zero to almost 300 feet (Trinity River) and other constraints, the change in elevation of the top of the stream bed varied from nearly zero to approximately 80 feet.

8.2.2 Results

8.2.2.1 Heads

The calibration statistics for the Sparta and Queen City layers are excellent overall (Table 8.2.1) and they present a relatively even distribution of the residuals. The root mean square error (RMSE) is 29.9 feet for the Sparta aquifer, 37.7 feet for the Queen City aquifer, and 25.7 feet for the Carrizo Formation. However, most of the targets are located in or close to the outcrop leaving the downdip area with little control. Results are graphically presented in Figures 8.2.1 through 8.2.6. The simulated head map of the Sparta aquifer is dominated by the GHB head field. In the outcrop area of the model, the shape of the potentiometric surfaces reflects the topography, particularly in the northern part of the Queen City aquifer where the formation crops out. The impact of large streams can also be seen in the downdip area of the model where heads are higher than in surroundings areas, because of the nature of the regional flow system with discharge in low-lying areas. Out of a total of 11,070 outcrop cells, including 1,460 and 3,609 for the Sparta and Queen City aquifers, respectively, about 38 (0.3 percent), including 9 and 0 for the Sparta and Queen City aquifers, respectively, went dry during the steady-state period.

The Carrizo and Simsboro aquifer calibrations are similar to that presented in Table 11 of Dutton et al. (2003) demonstrating that the changes made to the Carrizo Formation do not have a detrimental impact on the Wilcox Formation. Because of some data clustering in the calibration targets of the Queen City aquifer in Nacogdoches, Cherokee and Anderson counties, results are presented with and without the cluster. Results are not significantly different in both cases.

8.2.2.2 Streams

Figures 8.2.7 and 8.2.8 show the estimated simulated base flow to the streams and rivers included in the study. Drains, set up in all cells of lower elevation, mimic springs and seeps and help in increasing the simulated discharge near the streams. Two sets of targets were used to compare modeled stream base-flow to simulated values. One (“Brandes targets”) was specifically developed for this Queen City and Sparta GAM (see Section 8.1.2.2) while the other (“HDR targets”) was adapted from the Central Carrizo-Wilcox model (Dutton et al., 2003). Processing to the 2003 HDR targets is detailed in Section 4.7.1.4. Although most of the streams are gaining, the model generally underpredicts the estimated flow of the different targets. The Brandes target for the Angelina and San Marcos rivers show losing streams. This is probably inaccurate given the results of the model and the location of the rivers. A shortage of gage data may explain the discrepancy. The Brandes study also suggests very strongly gaining Brazos, Trinity, and Neches rivers on a AFY/mile basis. The model and HDR data suggest that there is not such a large difference in gain between rivers. Most of the average gains displayed by the model are between 50 and 250 AFY/mile. Such a large range in the targets demonstrates the large uncertainty involved in base-flow studies.

8.2.2.3 Water Budget

Tables 8.2.2 and 8.2.3 summarize the water budget calculated for the steady state. The water balance error for the steady-state model, which is the difference between inflow and outflow for the model, is approximately 0.2 percent. Recharge provides the bulk of the inflow. Simulated groundwater ET removes approximately one third of total gross recharge whereas streams and drains removes most of the rest. Net recharge, the portion of the recharge that flows to the deep confined sections of the aquifers, can be estimated by the GHB flow. It amounts to about 44,000 AFY for the 8 modeled layers.

Table 8.2.1 Head calibration statistics for the Central steady-state model.

	RMSE (ft)	Range (ft)	%	ME (ft)	MAE (ft)	#Points
Layer 1 (Sparta)	29.9	378.6	7.9%	-4.3	25.4	43
Layer 3 (Queen City) All	37.7	429.0	8.8%	2.6	27.0	201
Cluster	37.7			1.6	26.9	178
Remainder	37.7			10.0	28.1	23
Layer 5 (Carrizo)	25.7	230.1	11.2%	6.2	21.0	42
Layer 7 (Simsboro)	32.4	270.0	12.0%	19.3	30.1	14

RMSE=Root Mean Square Error; ME=Mean Error; MAE=Mean Absolute Error

Table 8.2.2 Water budget for the Central steady-state model (AFY).

IN	Layer	GHBs	Recharge	Streams	Top	Bottom	Drains
	1	20,009	126,354	1,319	0	47,128	0
	2	0	12,680	1,356	31,362	44,436	0
	3	0	154,348	7,590	33,519	31,764	0
	4	0	17,085	1,649	14,363	31,399	0
	5	0	83,690	5,140	15,080	10,263	0
	6	0	83,337	5,137	7,025	18,972	0
	7	0	53,275	5,590	16,739	7,489	0
	8	0	30,787	2,063	3,202	0	0
	Sum	20,009	561,556	29,845			0
OUT	**Layer**	**GHBs**	**ET**	**Streams**	**Top**	**Bottom**	**Drains**
	1	63,896	45,221	53,937	0	31,362	776
	2	0	4,114	4,910	47,128	33,519	283
	3	0	67,633	99,188	44,436	14,363	2,414
	4	0	6,054	11,010	31,764	15,080	692
	5	0	24,060	49,887	31,399	7,025	1,296
	6	0	23,997	60,448	10,263	16,739	3,030
	7	0	15,380	45,428	18,972	3,202	281
	8	0	4,970	21,978	7,489	0	1,945
	Sum	63,896	191,429	346,786			10,718
Net Results							
Layer	**GHBs**	**Recharge**	**ET**	**Streams**	**Top**	**Bottom**	**Drains**
1	-43,887	126,354	-45,221	-52,618	0	15,766	-776
2	0	12,680	-4,114	-3,554	-15,766	10,917	-283
3	0	154,348	-67,633	-91,599	-10,917	17,401	-2,414
4	0	17,085	-6,054	-9,361	-17,401	16,319	-692
5	0	83,690	-24,060	-44,746	-16,319	3,238	-1,296
6	0	83,337	-23,997	-55,310	-3,238	2,232	-3,030
7	0	53,275	-15,380	-39,838	-2,232	4,286	-281
8	0	30,787	-4,970	-19,915	-4,286	0	-1,945
Sum	-43,887	561,556	-191,429	-316,941			10717.6

Table 8.2.3 **Water budget for the Central steady-state model with values expressed as a percentage of inflow or outflow.**

IN	Layer	GHBs	Recharge	Streams	Drains
	1	3.3	20.7	0.2	0.0
	2	0.0	2.1	0.2	0.0
	3	0.0	25.2	1.2	0.0
	4	0.0	2.8	0.3	0.0
	5	0.0	13.7	0.8	0.0
	6	0.0	13.6	0.8	0.0
	7	0.0	8.7	0.9	0.0
	8	0.0	5.0	0.3	0.0
	Sum	3.3	91.8	4.9	0.0
OUT	**Layer**	**GHBs**	**ET**	**Streams**	**Drains**
	1	10.5	7.4	8.8	0.1
	2	0.0	0.7	0.8	0.0
	3	0.0	11.1	16.2	0.4
	4	0.0	1.0	1.8	0.1
	5	0.0	3.9	8.2	0.2
	6	0.0	3.9	9.9	0.5
	7	0.0	2.5	7.4	0.0
	8	0.0	0.8	3.6	0.3
	Sum	10.5	31.3	56.7	1.8

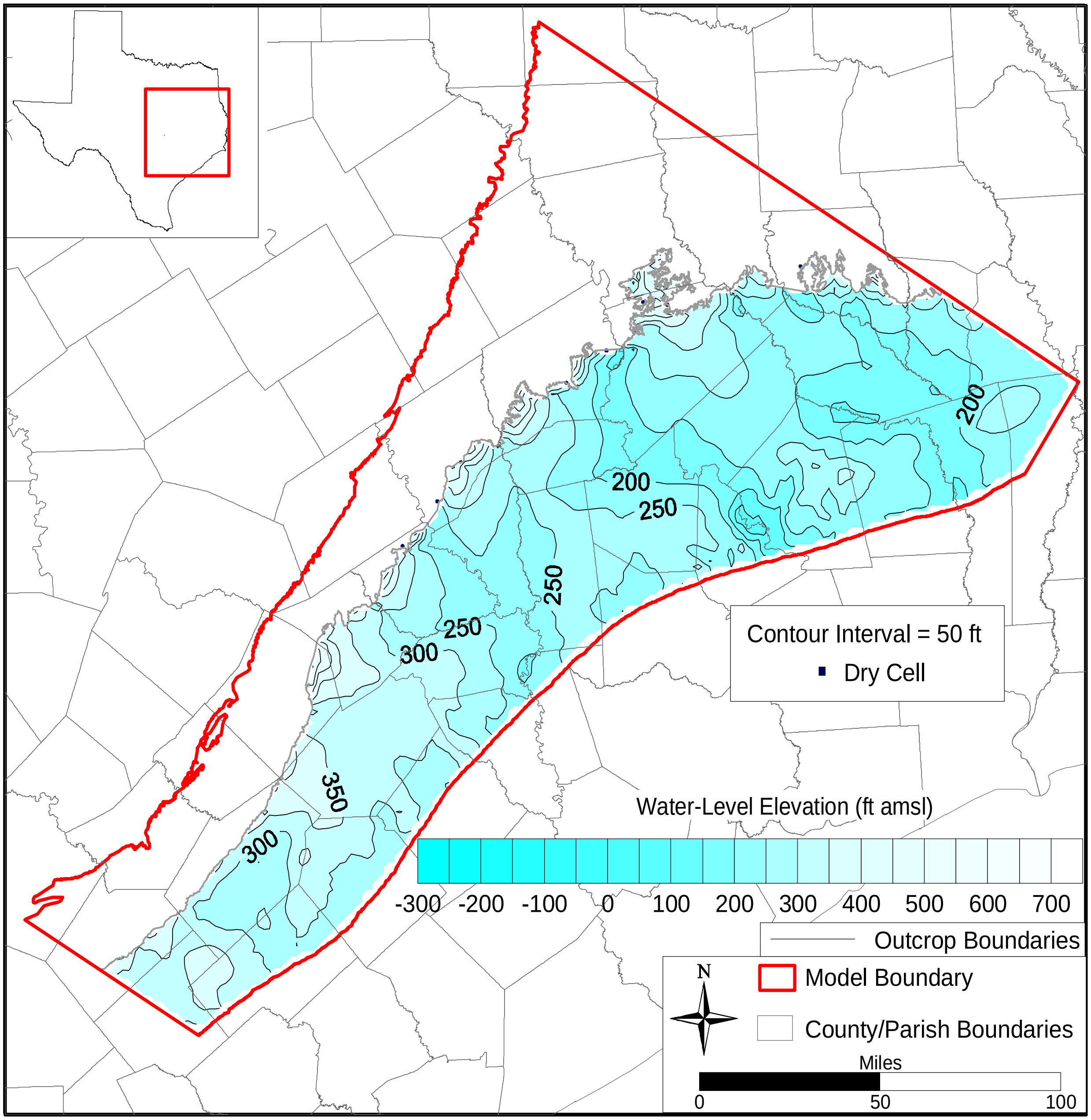
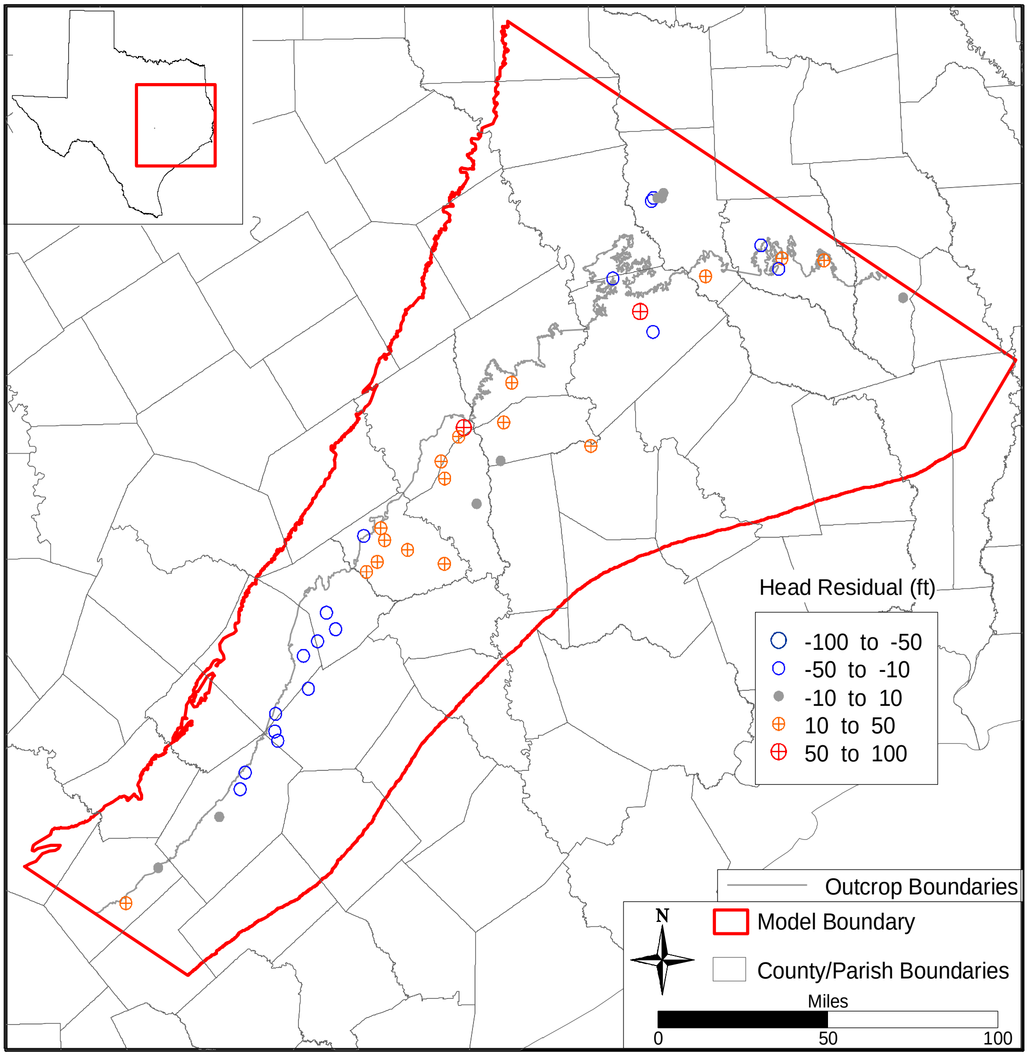


Figure 8.2.1 Simulated steady-state head surface for the Sparta aquifer (Layer 1).



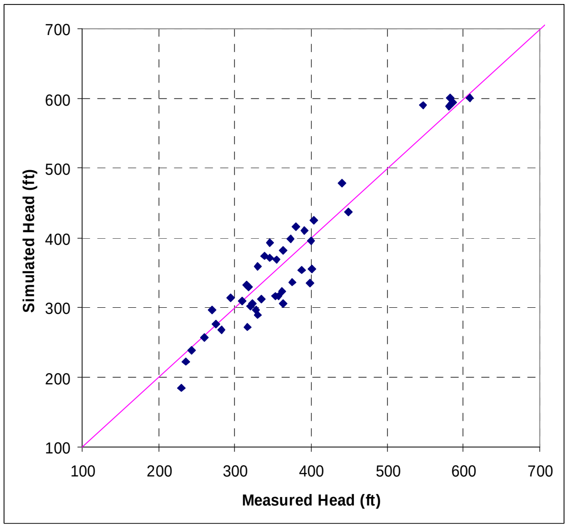


Figure 8.2.2 Head residuals (a) and scatterplot (b) of simulated and measured heads for the Sparta aquifer (Layer 1).

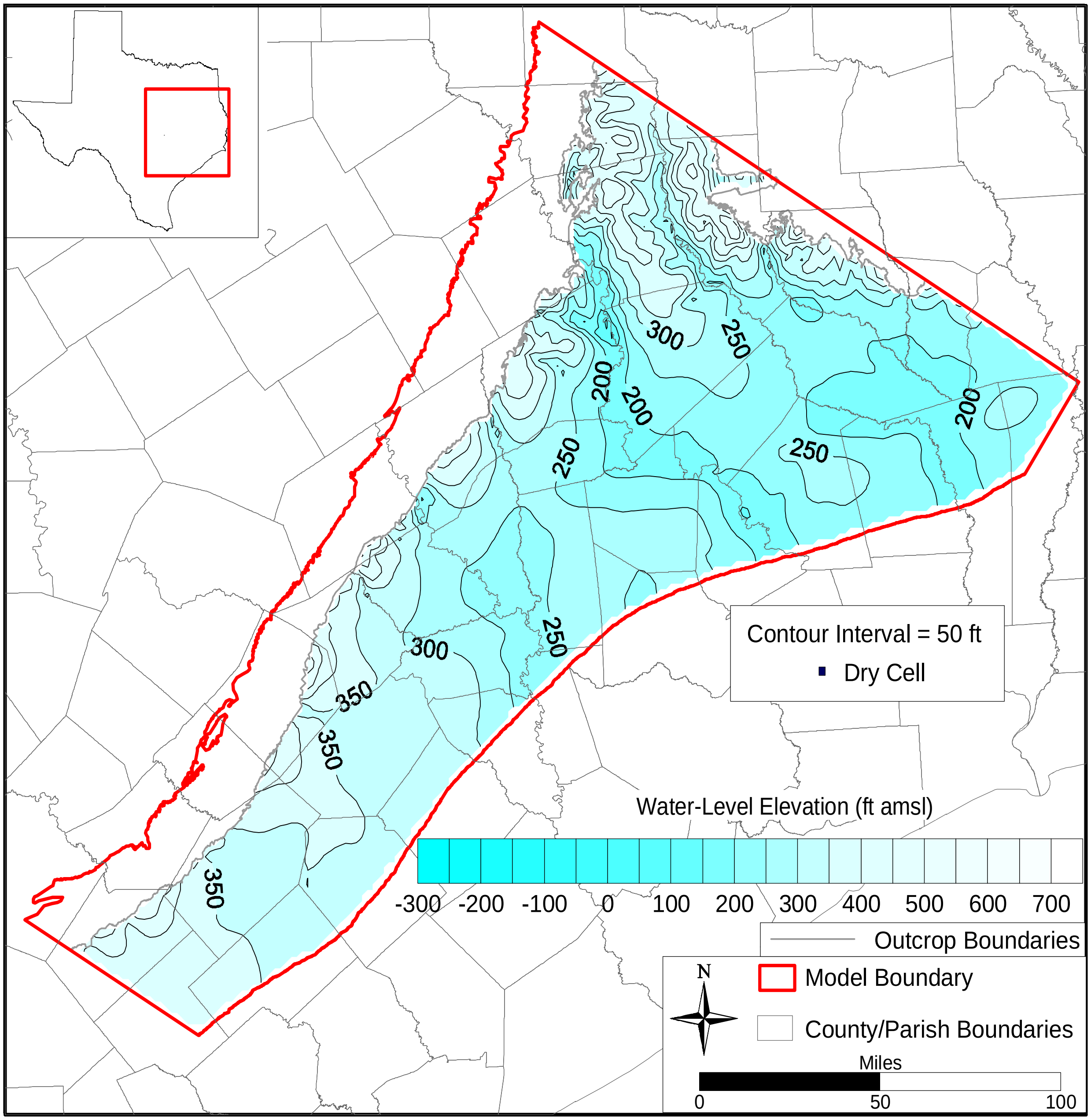


Figure 8.2.3 Simulated steady-state head surface for the Queen City aquifer (Layer 3).

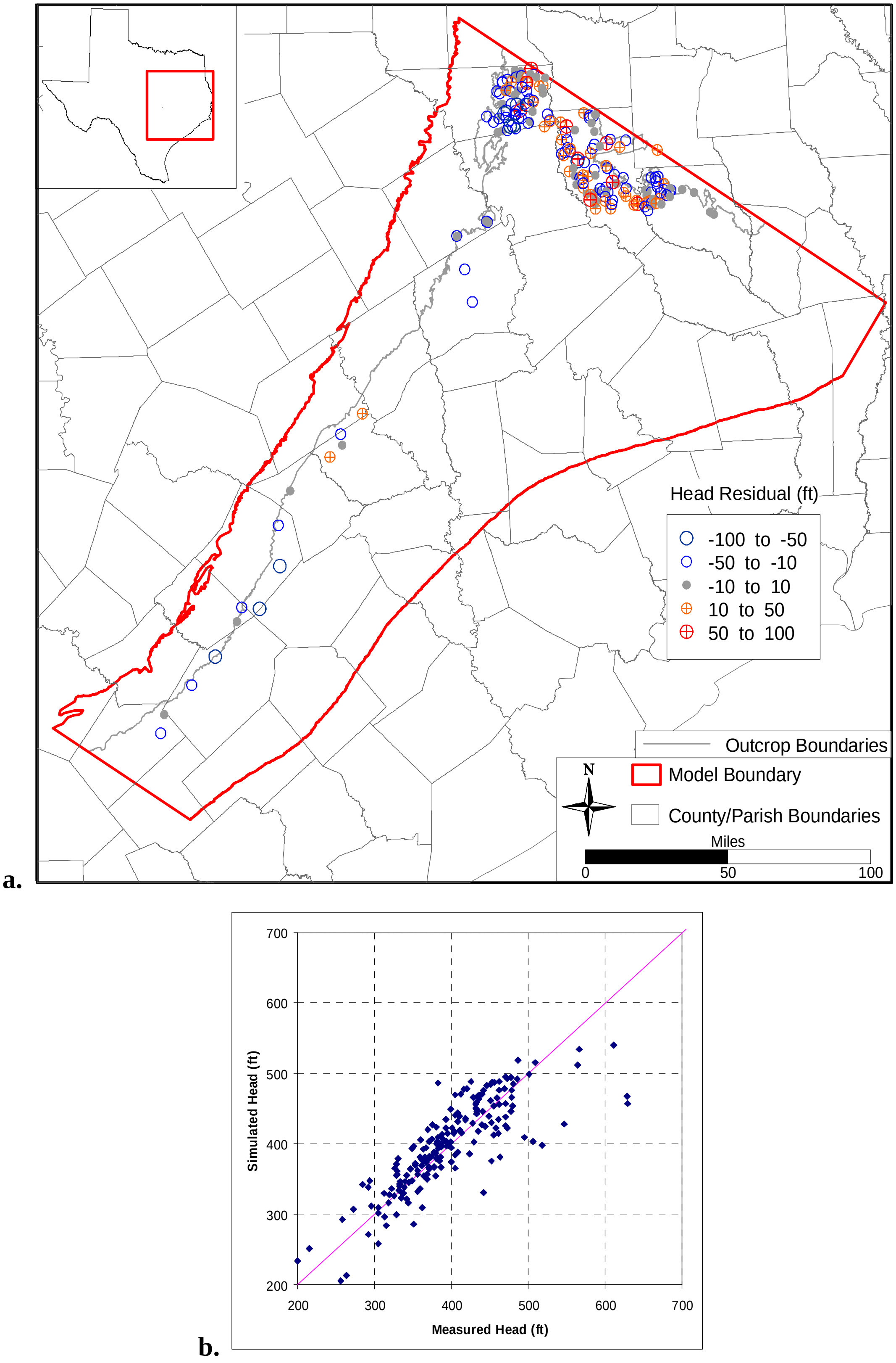


Figure 8.2.4 **Head residuals (a) and scatterplot (b) of simulated and measured heads for the Queen City aquifer (Layer 3).**

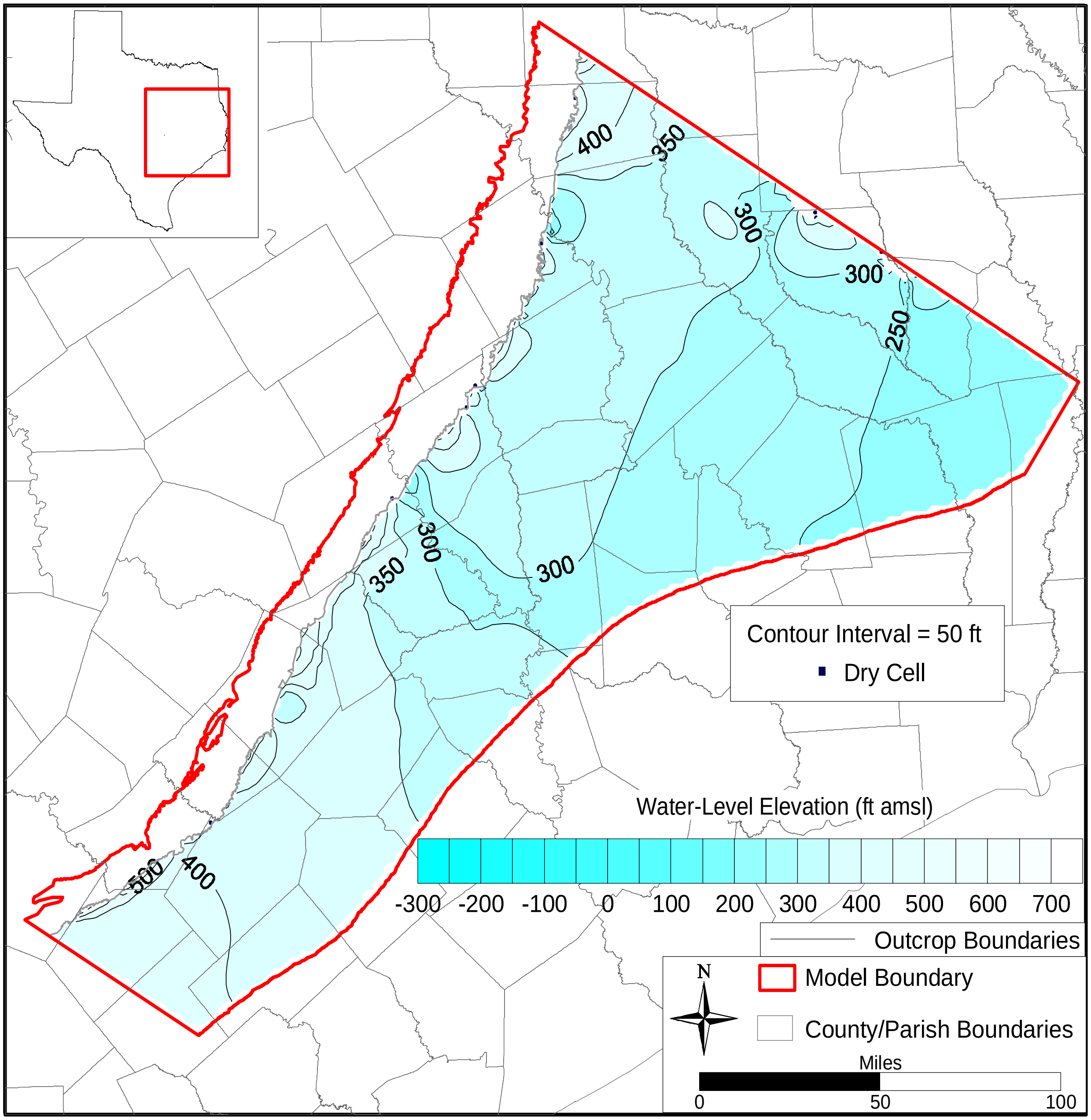


Figure 8.2.5 Simulated steady-state head surface for the Carrizo Formation (Layer 5).

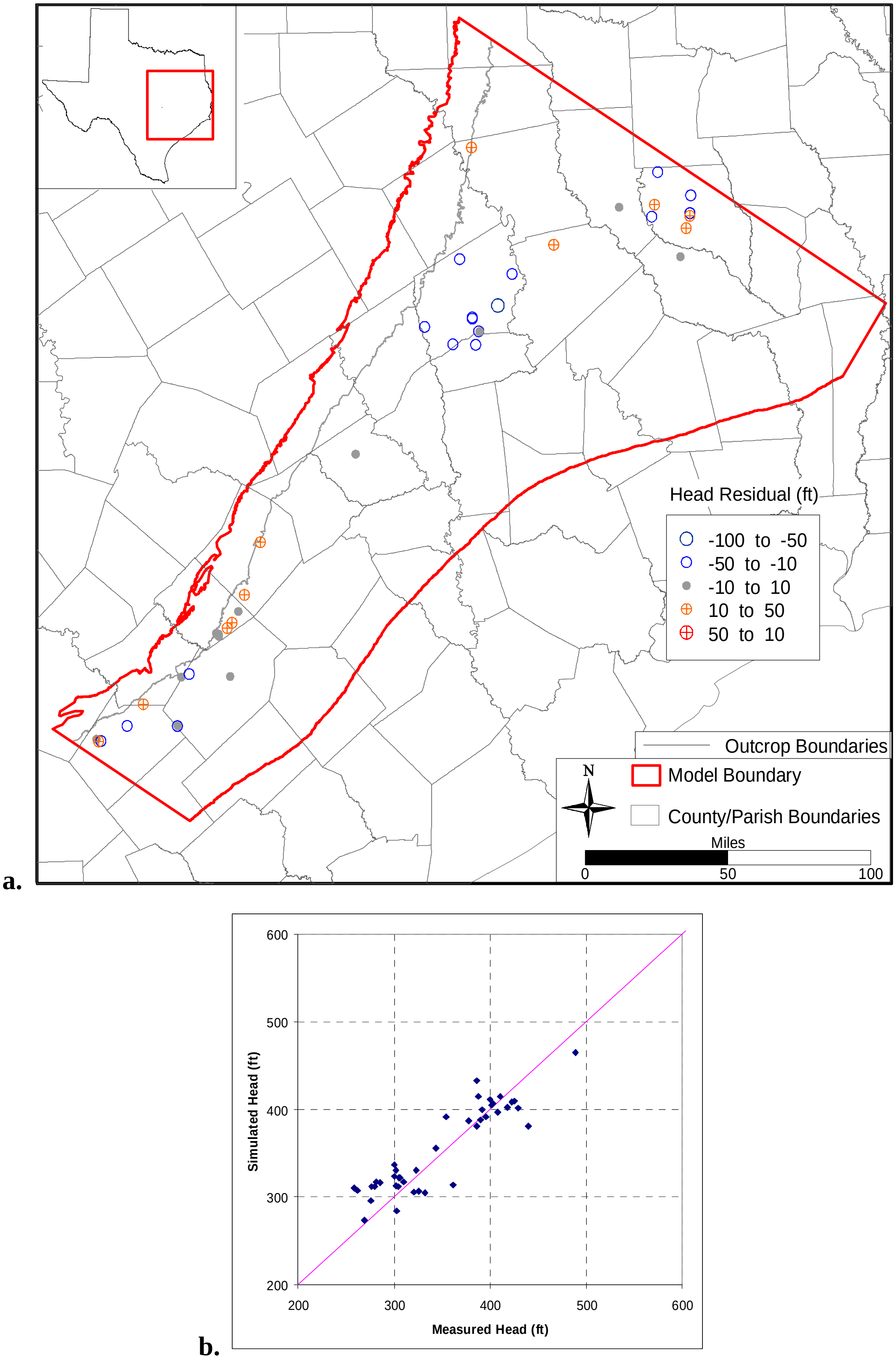


Figure 8.2.6 Head residuals (a) and scatterplot (b) of simulated and measured heads for the Carrizo Formation (Layer 5).

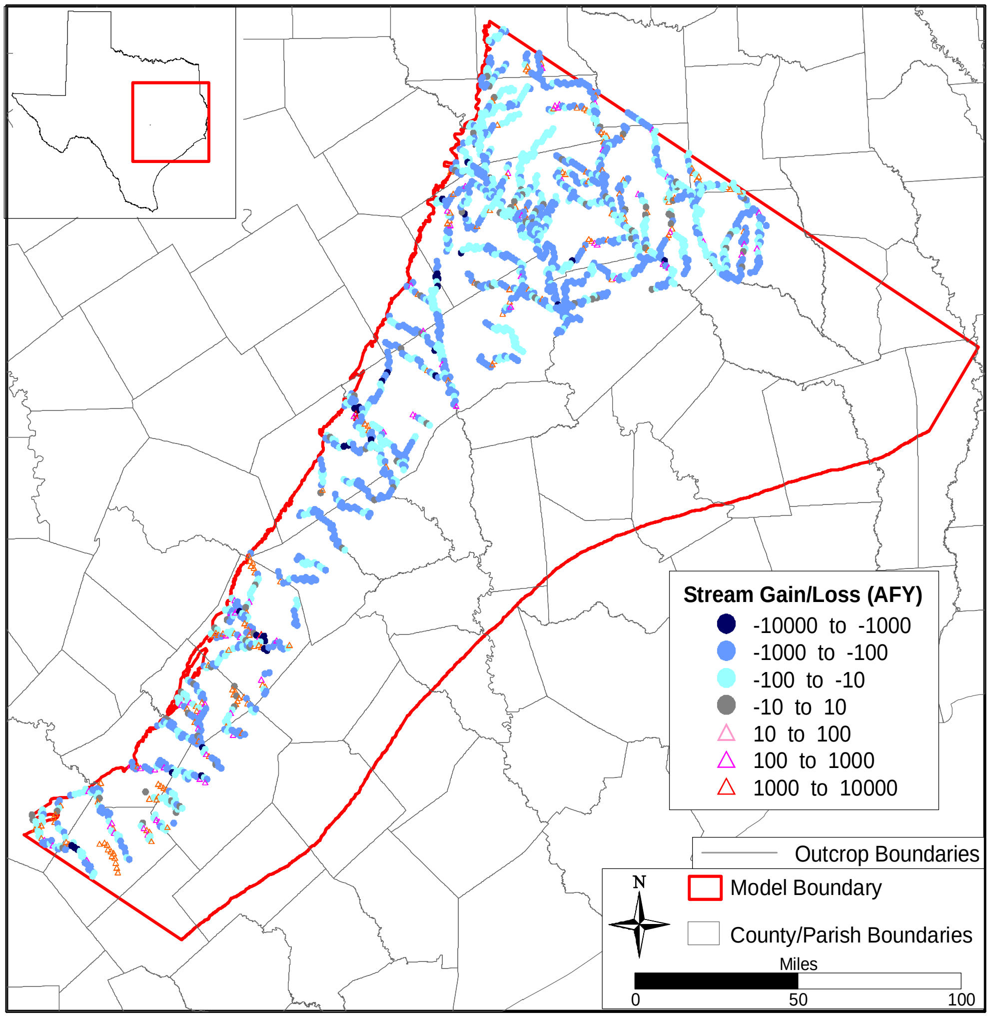


Figure 8.2.7 **Steady-state model stream gain/loss (positive value denotes a gaining stream)**

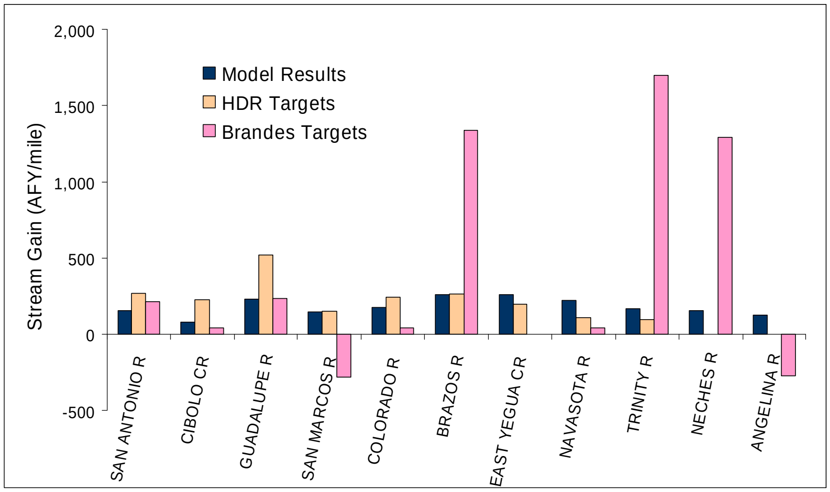


Figure 8.2.8 **Comparison of steady state model stream gain/loss to measurements.**

8.2.3 Sensitivity Analysis

The application of the sensitivity analysis was completed in a similar fashion to the Southern model (Section 8.1.3).

Results of the sensitivity analysis indicate that the steady-state simulation of the Sparta aquifer is most sensitive to the GHB imposed on the top of the layer (Figure 8.2.9). Results are also sensitive to the vertical hydraulic conductivity of the Reklaw Formation and to the recharge rate. Parameters of lesser impact are vertical hydraulic conductivity of the Weches Formation (Layer 2) and the stream conductance. Sensitivity to other parameters is smaller.

Sensitivity results for the Queen City aquifer (Figure 8.2.10) follow a similar pattern. The GHB heads and conductance on top of Layer 1 are the parameters with the largest impact. Similarly to the Sparta aquifer, results are also sensitive to the vertical hydraulic conductivity of the Reklaw Formation and to the recharge rate. Stream conductance is also important. The vertical hydraulic conductivity of the Weches Formation also has a significant impact on the Queen City aquifer, in the opposite direction compared to vertical conductivity of the Reklaw.

Sensitivity results for the Carrizo Formation (Figure 8.2.11) show a slightly different pattern than the results for the Queen City and Sparta aquifers. The GHB head and conductance are still important but the vertical hydraulic conductivity of the Reklaw Formation and recharge are more important. The sensitivity of the model to the GHB heads and conductance and vertical conductivity of the Reklaw disappear in Layers 6 to 8 while recharge stays relevant (Figures 8.2.12 through 8.2.14).

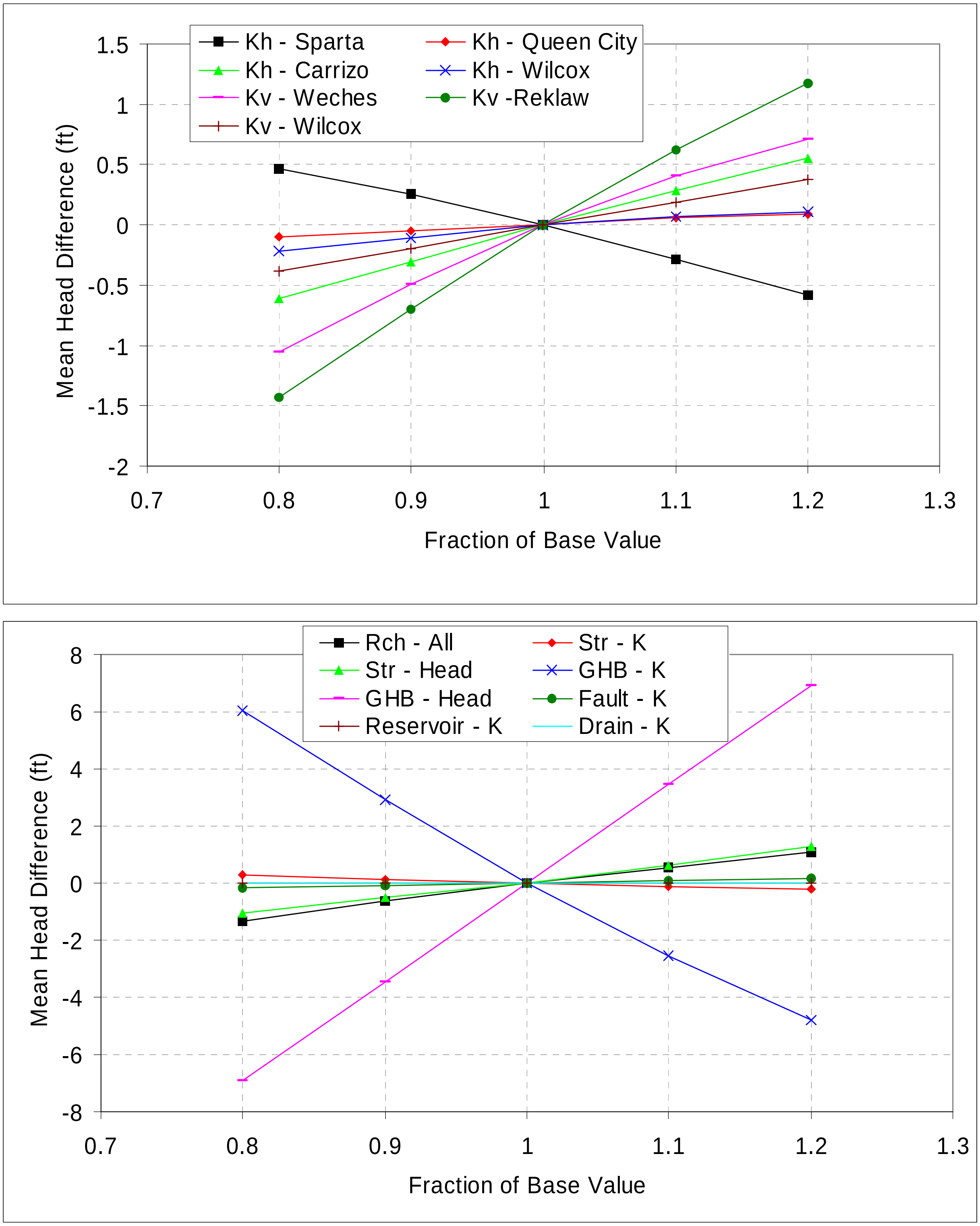
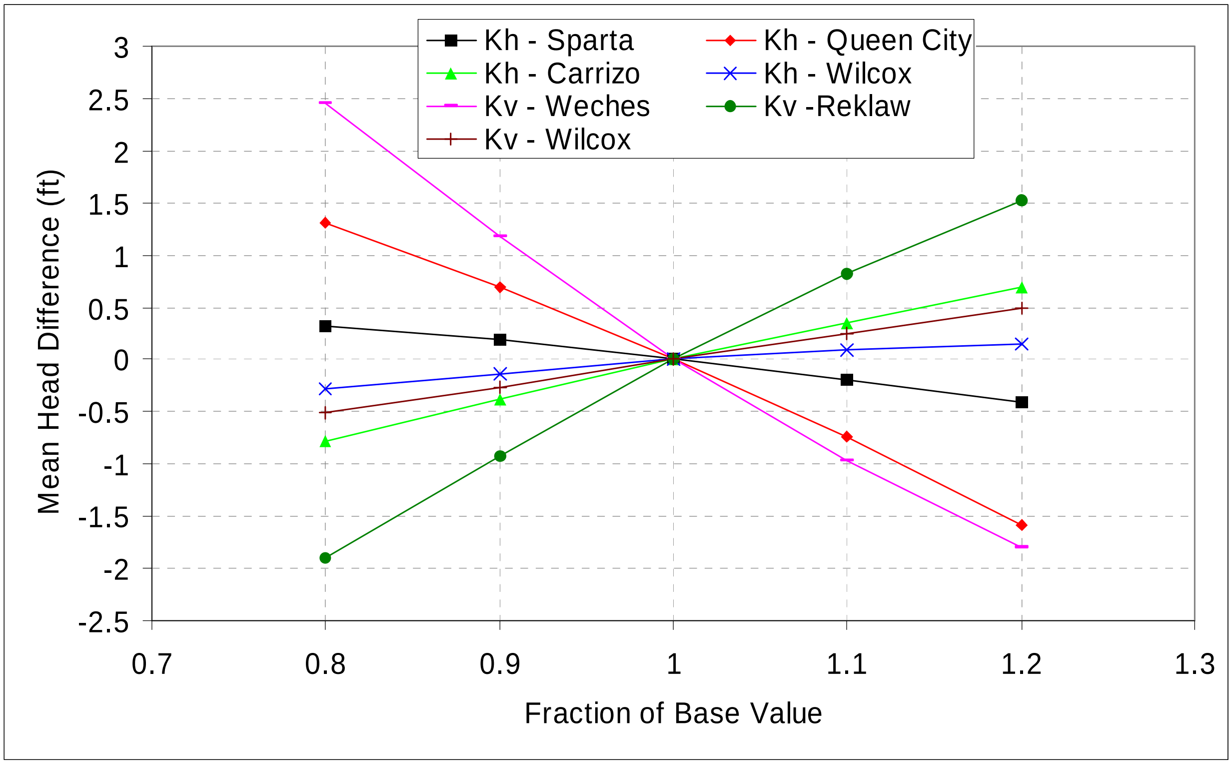


Figure 8.2.9 **Steady-state sensitivity results for Layer 1 (Sparta) using all active grid blocks.**



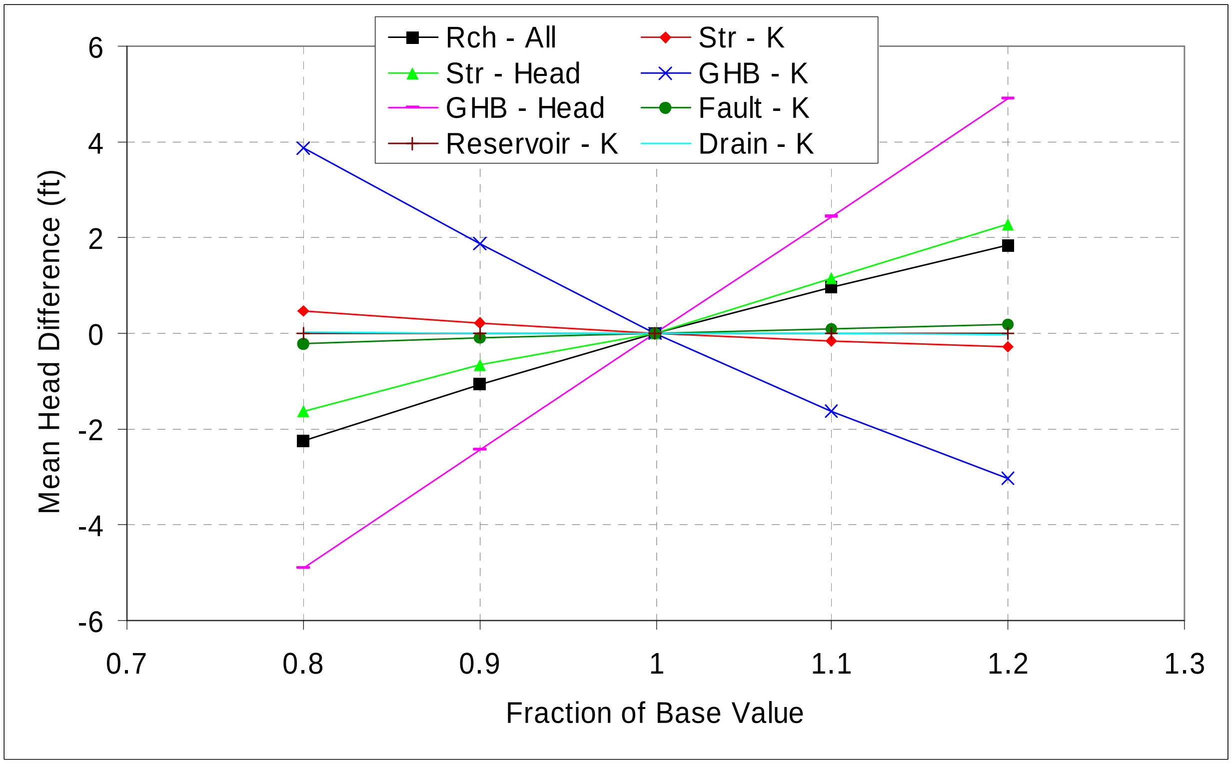
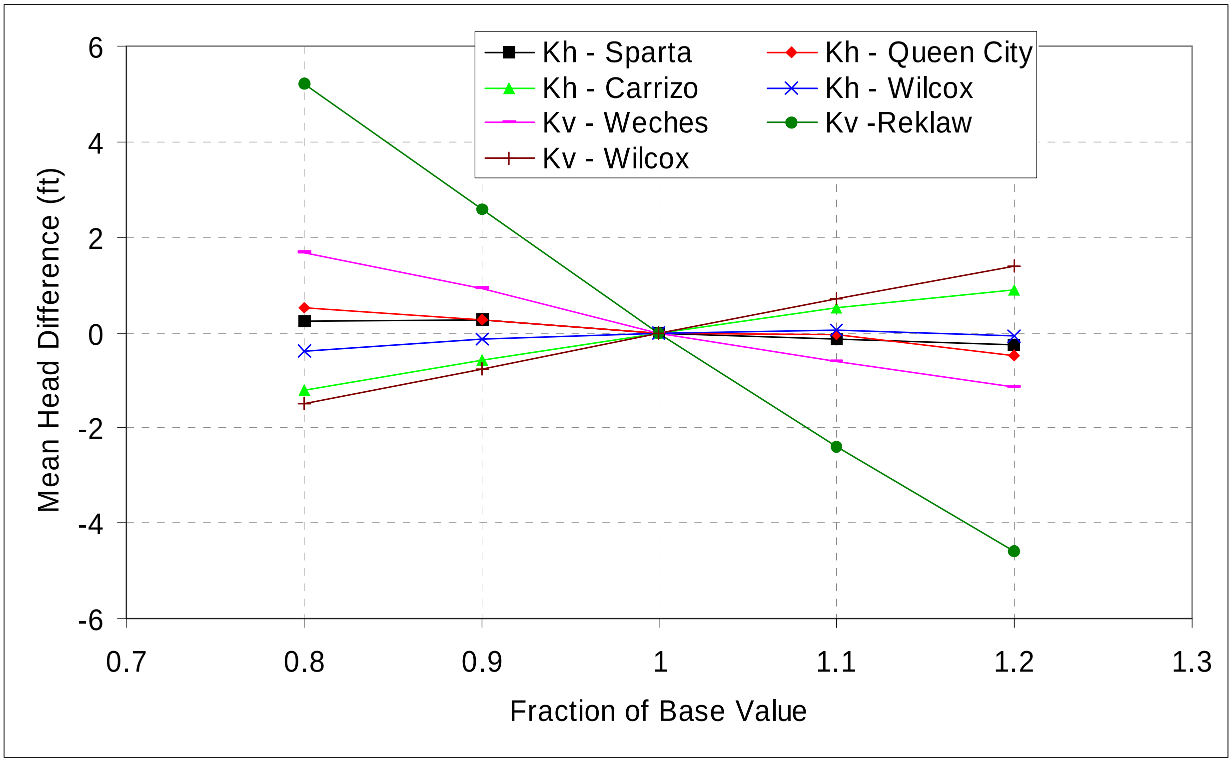


Figure 8.2.10 Steady-state sensitivity results for Layer 3 (Queen City) using all active grid blocks.



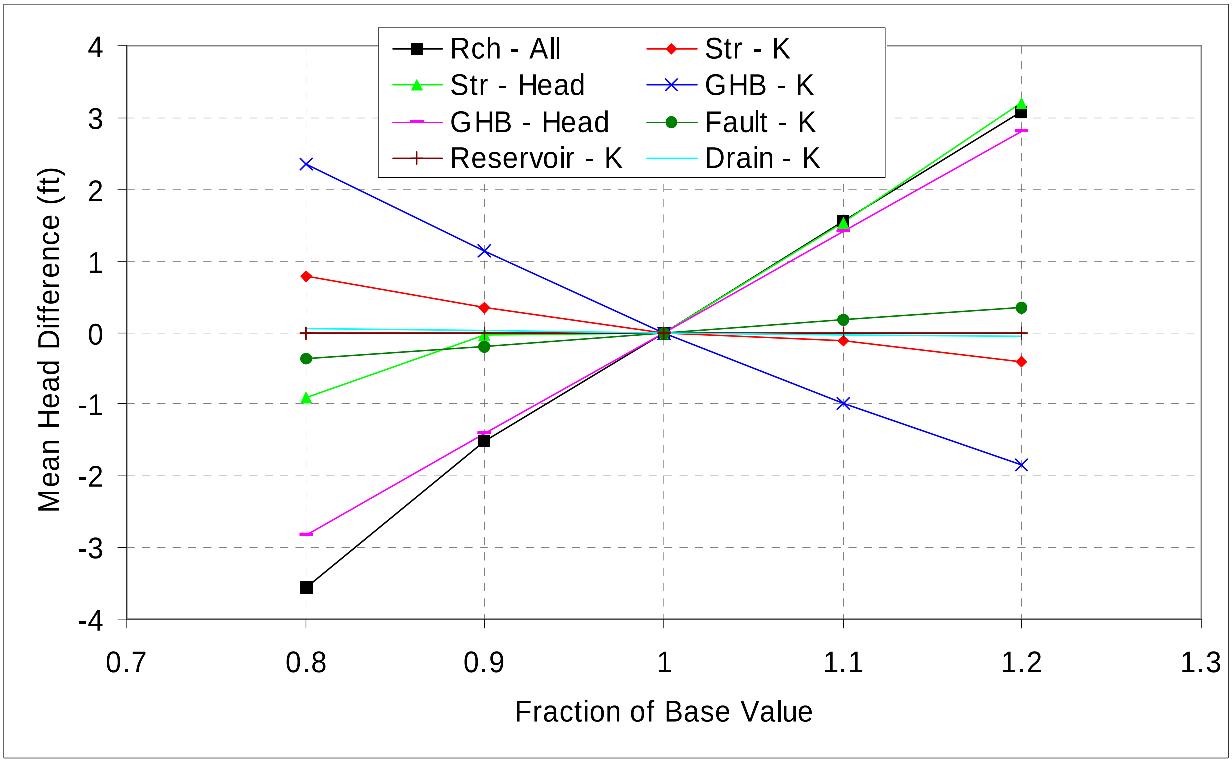


Figure 8.2.11 Steady-state sensitivity results for Layer 5 (Carrizo) using all active grid blocks.

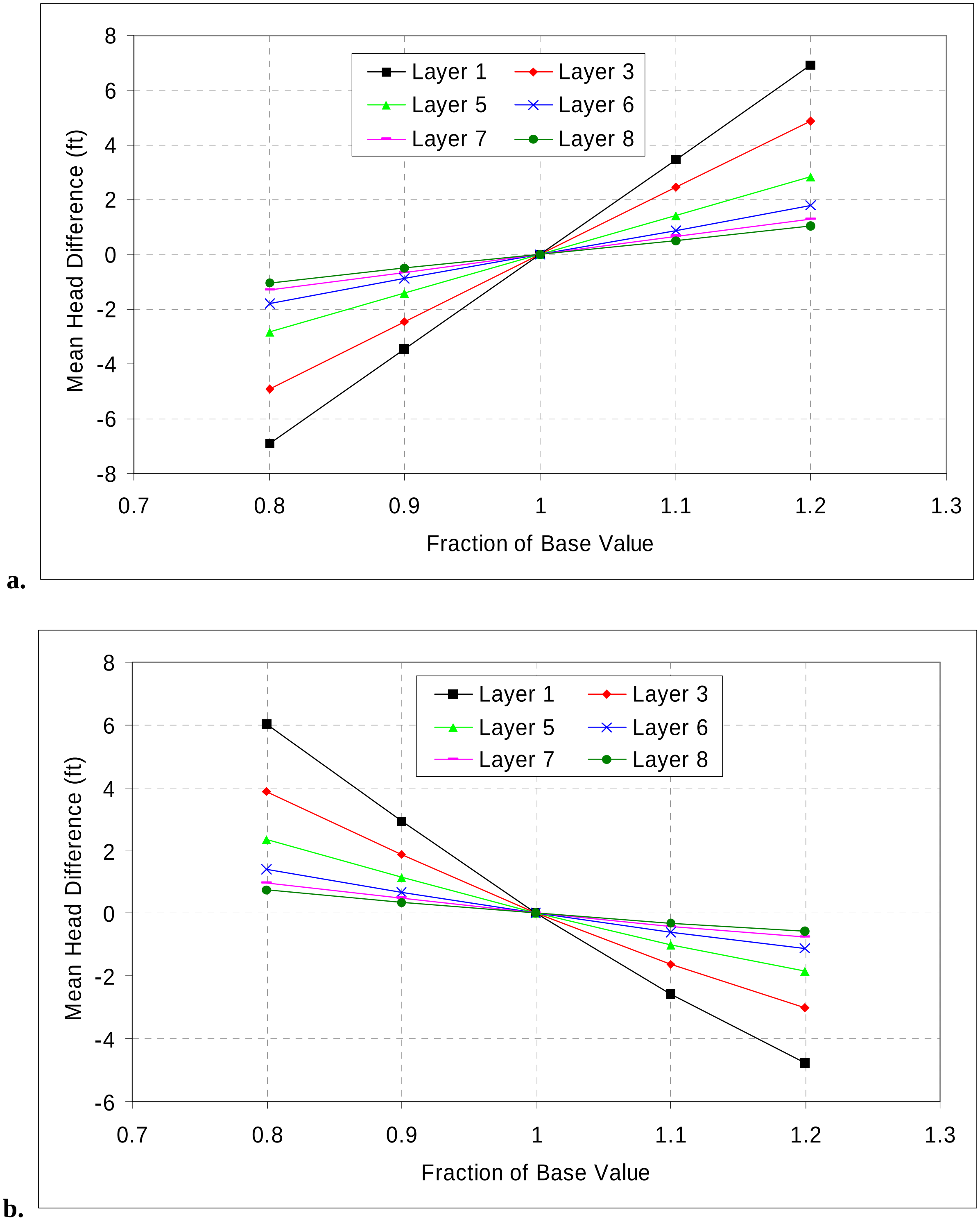


Figure 8.2.12 Steady-state sensitivity results using all active grid blocks where GHB heads (a) and conductance (b) are varied.

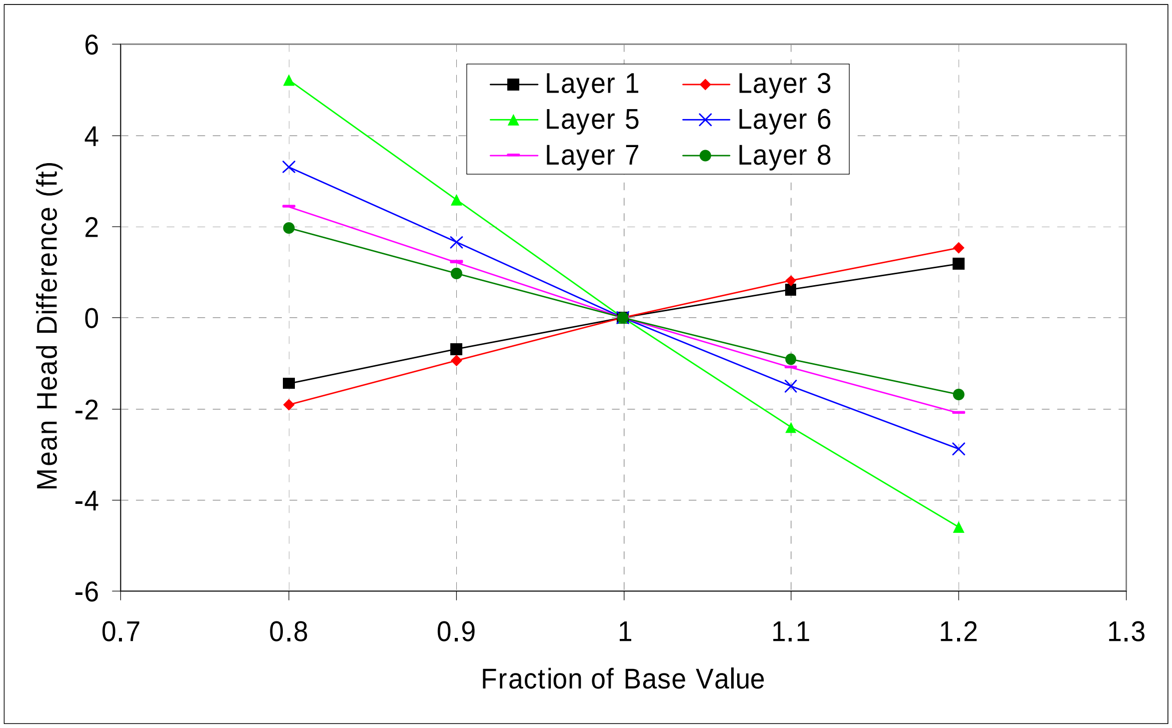


Figure 8.2.13 **Steady-state sensitivity results using all active grid blocks where Reklaw Formation vertical conductivity is varied.**

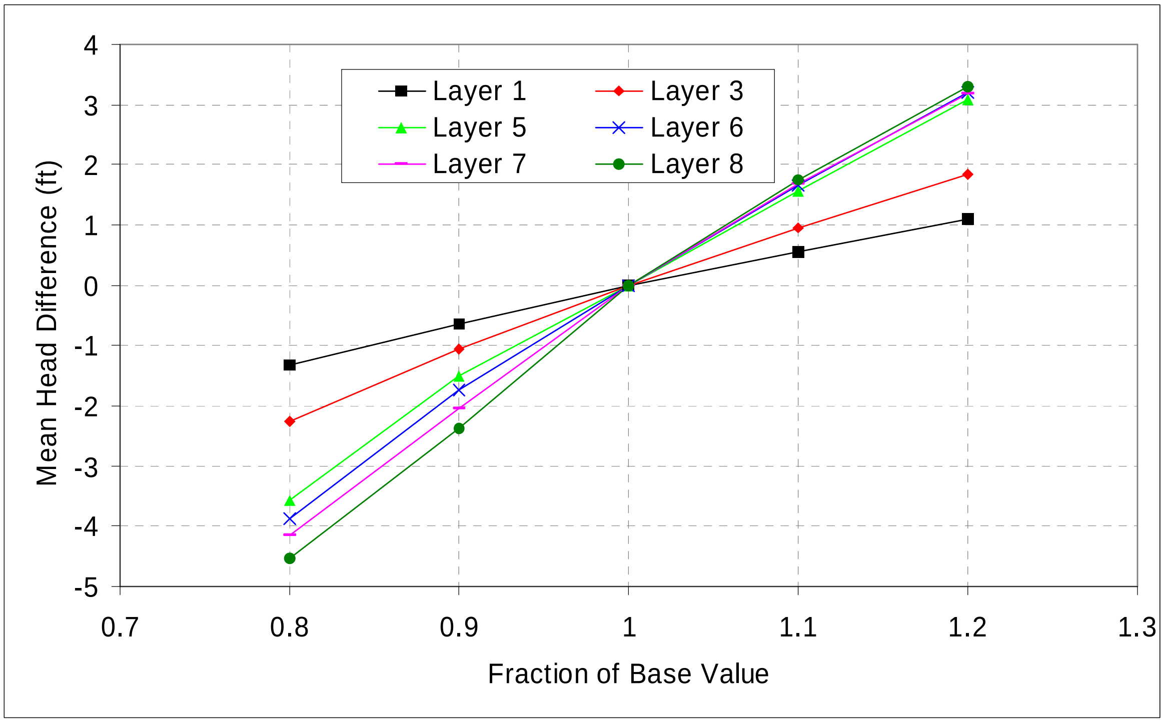


Figure 8.2.14 **Steady-state sensitivity results using all active grid blocks where recharge is varied.**

8.3 Northern Queen City and Sparta GAM

This section details the calibration of the Northern Queen City and Sparta GAM steady-state model and presents the steady-state model results. This section also describes analyses of model sensitivity to various hydrologic parameters.

8.3.1 Calibration

The calibration process for the Northern model was iterative. First, an initial steady-state calibration was developed. Although the initial steady-state calibrated model met the calibration criteria, the subsequent transient model calibration indicated that the vertical hydraulic conductivity of the Reklaw Formation was too high. It was necessary to jointly calibrate the steady-state and transient models to achieve a consistent calibration to both steady-state and transient water-level data.

8.3.1.1 Horizontal and Vertical Hydraulic Conductivities

Section 6.4.1 describes the determination of initial horizontal and vertical hydraulic conductivities for the model. During calibration, some adjustment of these conductivity fields was required to calibrate the model. Based on the transient calibration, the vertical hydraulic conductivity of the Reklaw Formation had to be lowered over much of the model area. Some modification of the Carrizo Formation horizontal hydraulic conductivity field was also required. All other hydraulic conductivity fields were unchanged during calibration.

Figure 8.3.1 shows the final calibrated horizontal hydraulic conductivity (K_h) field for the Carrizo Formation (Layer 5). During transient calibration, it was determined that the Carrizo Formation hydraulic conductivity values in an area running from Upshur County through Smith County and into northern Cherokee County needed to be lowered to maintain Carrizo drawdowns in that area. The hydraulic conductivity in a small area around the city of Lufkin in Angelina County was also reduced slightly to reduce the rebound that occurs in the Carrizo head surface in the Lufkin area.

Figure 8.3.2 shows the calibrated vertical hydraulic conductivity (K_v) field for the Reklaw Formation (Layer 4). The initial estimate of $1x10^{-4}$ ft/day for the Reklaw vertical hydraulic conductivity was too high to maintain some of the Carrizo drawdowns during the transient calibration. The overall field was lowered to $1x10^{-5}$ ft/day, with an area of $1x10^{-6}$ ft/day trending north-south through parts of Upshur, Wood, Smith, Henderson, Cherokee, and Anderson counties. An area in Nacogdoches, southern Rusk, and eastern Cherokee counties was left at $1x10^{-4}$ ft/day. There is no clear geologic or hydrologic information that can be used to support these spatial changes in vertical hydraulic conductivities of the Reklaw Formation. However, similar conductivities were required to calibrate the Northern Carrizo-Wilcox GAM (Fryar et al., 2003). The potential limitations of the steady-state model are discussed in Section 11.

8.3.1.2 Recharge

Recharge was not modified from the values presented in Section 6.3.5. After numerous calibrations runs, it was determined that the present recharge field represents the best compromise across the three models.

8.3.1.3 Groundwater Evapotranspiration

Groundwater ET was not changed from the initial estimate discussed in Section 6.3.5.

8.3.1.4 General Head Boundaries

General head boundaries for the steady-state model were not changed from the initial estimate discussed in Section 6.3.2.

8.3.1.5 Streams

Streams were adjusted in a similar fashion to the Central model, discussed in Section 8.2.1.5.

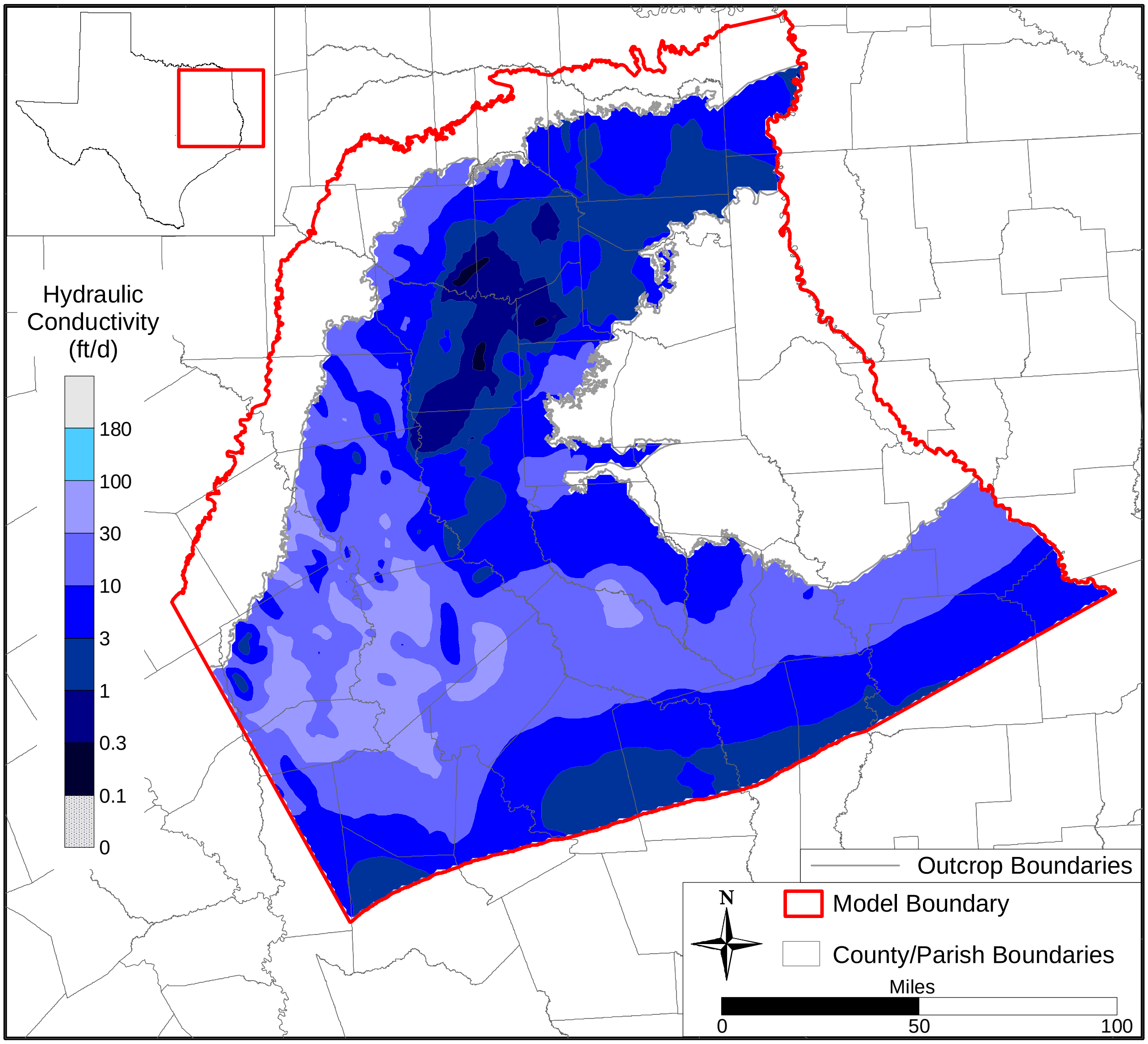


Figure 8.3.1 **Calibrated horizontal hydraulic conductivity field for the Carrizo Formation (Layer 5).**

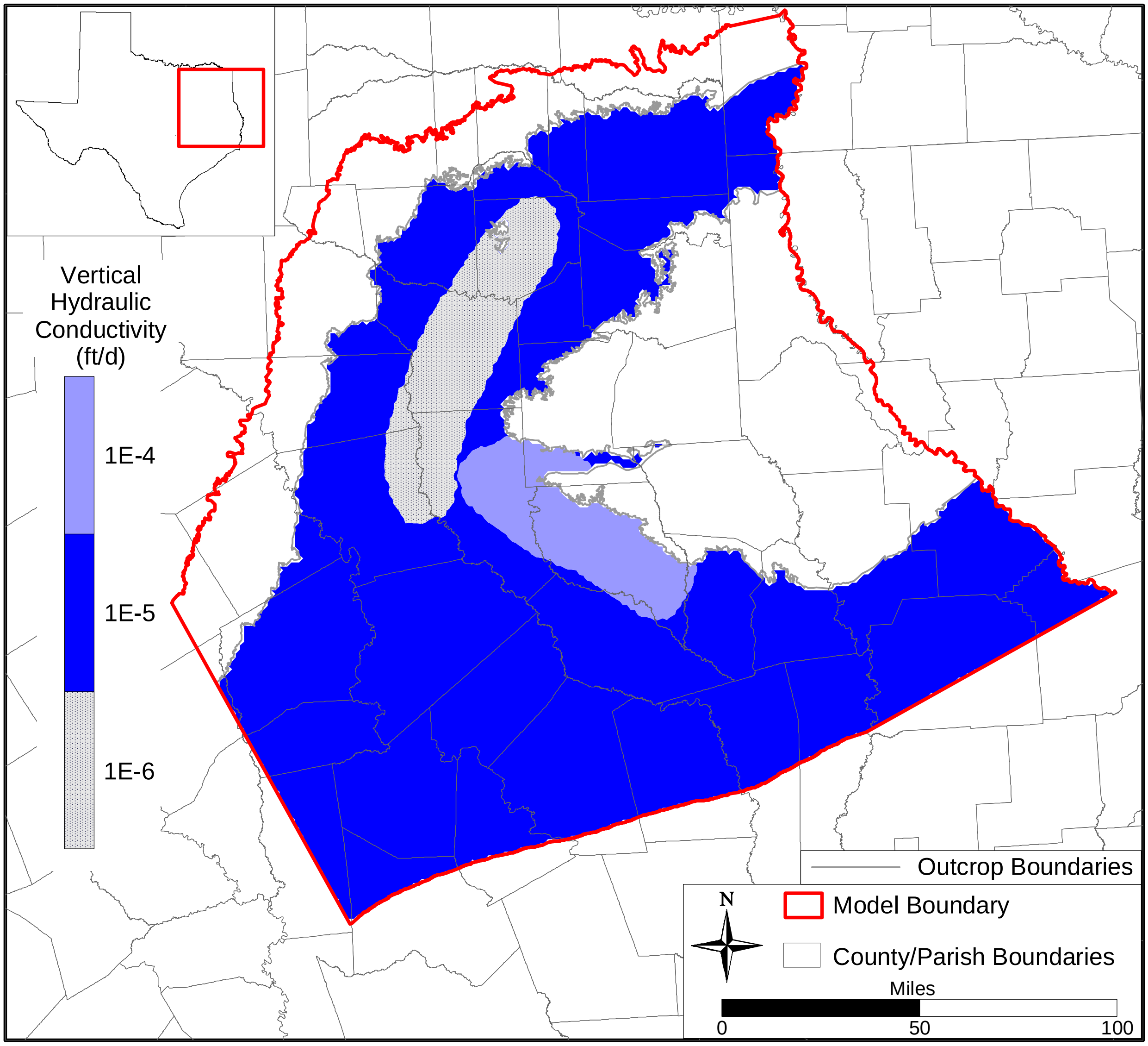


Figure 8.3.2 **Calibrated vertical hydraulic conductivity field for the Reklaw Formation (Layer 4).**

8.3.2 Results

8.3.2.1 Heads

Head targets were adjusted in the outcrop as described in Section 8.1.2.1. Figures 8.3.3 through 8.3.8 show the head surfaces for the calibrated steady-state model and the residuals for the target wells in the individual layers. A positive residual indicates that the model has underpredicted the hydraulic head, while a negative residual indicates overprediction. The calibration statistics for the individual layers are summarized in Table 8.3.1. The RMS errors for the layers range between 25.5 and 36.5 feet, well within the range of elevation error associated with the one-mile grid cell averaging (see Section 7.1.3).

Figure 8.3.3 shows the simulated hydraulic heads for Sparta aquifer (Layer 1). The simulated hydraulic heads for Sparta aquifer range from about 100 to 450 feet amsl and generally decrease to the south and beneath the major river valleys. Hydraulic heads were not plotted in the isolated Sparta outcrops in the East Texas Basin north of the main Sparta outcrop. These islands of Sparta sediments contain relatively few grid cells and are not large enough to contour at the model scale. Figure 8.3.4 shows the posted residuals and a scatterplot of residuals for the Sparta aquifer. Since Sparta production does not extend very far downdip in east Texas, most of the targets are in or near the outcrop. A few of the target wells in the western part of the model are farther downdip. No spatial bias is seen in the posted residuals. The scatterplot shows that the residuals are distributed around the unit-slope line, indicating that the simulated Sparta aquifer heads are not biased high or low. The calibration statistics show an RMSE/range of 7 percent for the Sparta aquifer.

Figure 8.3.5 shows the simulated hydraulic heads for Queen City aquifer (Layer 3). The simulated hydraulic heads for the Queen City aquifer range from about 100 to 600 feet amsl and generally decrease to the south and beneath the major river valleys, reproducing the water table as a reflection of the general topography in the Queen City outcrop. Figure 8.3.6 shows the posted residuals and a scatterplot of residuals for the Queen City aquifer. Although the posted residuals do not show a spatial bias, the layer as a whole is biased slightly high. During calibration, Queen City recharge was lowered from the initial estimate, but the need for additional reduction is indicated by the model. However, further reduction would put the Queen City recharge at levels well below the literature values. The RMSE/range for the Queen City aquifer is 6.5 percent. Many of the predevelopment Queen City targets are clustered in two groups, one in eastern Henderson County and one in Cherokee and Nacogdoches counties. In order to determine if these large groups produced a bias in the results, the statistics were recalculated for the Queen City residuals using only wells outside of these clusters. Removing the wells in the clusters cut the mean error by one half and reduced the RMS error significantly.

The simulated head surface for the Carrizo Formation (Layer 5) is shown in Figure 8.3.7. The steady-state hydraulic head surface shows an approximate west-east groundwater divide from Van Zandt County through Smith County to Rusk County. North of this divide, the hydraulic gradients in the confined portion of the Carrizo are to the east, indicating groundwater flow to the east toward the Red River in Louisiana. South of the divide, groundwater flow in the confined section is to the south and further downdip to the southeast. The overall head distribution and general flow pattern agrees reasonably well with that shown in Figure 13 of Fogg and Kreitler (1982), considering that the simulated heads represent steady-state predevelopment conditions and Fogg and Kreitler (1982) included pumping effects on their constructed potentiometric surface for the Carrizo-Wilcox aquifer. The calibration statistics for the Carrizo show an RMSE/range of 8.7 percent based on a relatively even distribution of the residuals throughout the confined and unconfined part of the aquifer (Figure 8.3.8a). The scatterplot of simulated and measured hydraulic heads indicates a uniform distribution around the unit-slope line (Figure 8.3.8b).

The calibration statistics for upper and middle Wilcox layers are comparable to those determined for the Northern Carrizo-Wilcox GAM (Fryar et al., 2003). The mean errors are slightly higher as a result of the effort to maintain consistent recharge rates between the steady-state and transient models. There were no calibration points identified in the lower Wilcox.

Some cells went dry in the steady-state simulation. Out of 20,167 outcrop cells, 36 cells or less than 1 percent, were dry. These dry cells can be indicative of model instability or actual subsurface conditions. Because no obvious discontinuity exists in the outcrop water table, these cells likely are indicative of actual subsurface conditions (i.e., small cell thickness, low water table). The small number of dry cells does not have a significant impact on model results.

8.3.2.2 Streams

Figure 8.3.9 shows the gain/loss values for the stream cells in the steady-state model. As would be expected, most of the stream segments are gaining. Only the upper reaches of some tributaries and a few isolated cells show losing conditions. Losses in some cells are due to streams intersecting only the edge of a cell which has a higher elevation than the surrounding stream cells.

Stream leakances were compared to stream gain/loss data from three sources. The stream targets were taken from Slade et al. (2002), the work done by HDR Engineering for the Central Carrizo-Wilcox GAM (Dutton et al., 2003), and a study done for this report by the R.J. Brandes Company (Table 4.7.2). The targets from Slade et al. (2002) and Dutton et al. (2003) are shown in Tables 4.7.1 and 4.7.4 of this report, respectively. Two of the ten Slade gain/loss studies that fall within the model outcrop area were not used. Sugar Creek is a minor stream that was not included in the model due to its small size. Lake Fork Creek was not used because the loss estimated for the study reach exceeded the average stream flow for Lake Fork Creek. The remaining Slade gain/loss studies were conducted between 1942 and 1981 and covered reaches of the Sabine River, Little Cypress Bayou, Bowles Creek, Big Elkhart Creek, and Little Elkhart Creek. For the Sabine River and Little Cypress Creek, Slade listed more than one estimate. These multiple estimates were averaged on a per mile basis to develop targets for those streams. Brandes gain/loss estimates for the Navasota River, Trinity River, Neches River, Angelina River, Sabine River, and Big Cypress Bayou intersect the outcrop area of the north model. Of the Dutton et al. (2003) gain/loss studies, only those for the Navasota and Trinity rivers intersect the north model.

Because the steady-state model simulates predevelopment conditions based on average recharge, ET, and stream flows, stream gain/loss studies conducted under a particular set of conditions may or may not agree with the steady-state results. Figure 8.3.10 shows a plot of the measured gain/loss values and those derived from the model. The data comparison shows agreement in the direction of flow (gain or loss) between the targets and simulated leakances for most of the streams. The Slade target for Little Elkhart Creek and the Brandes targets for the Angelina and Sulphur rivers indicate losing conditions while the model shows gaining conditions. The difference for Little Elkhart Creek and the Sulphur River are small with both the measured and simulated leakances comparatively low. The large loss estimated by Brandes for the Angelina River is probably not accurate since the gage data used was not ideal for the analysis. Based on the location of the Angelina River and estimated gains in surrounding streams, it is likely that the Angelina River is a gaining stream.

The remaining streams show reasonable agreement between measured and simulated leakances, with the exception of the Brandes estimates for the Trinity and Neches rivers and the Slade estimate for the Sabine River. However, other estimates for the Trinity and Sabine rivers show good agreement with the simulated leakances. These wide variations in estimated gain/loss indicate the large uncertainty in stream targets.

Slade et al. (2002) note that the potential error in stream flow measurements is typically about 5 to 8 percent. Since this error is possible at both ends of a gain/loss subreach, the potential error in gain/loss can equal a significant fraction of the total flow in the subreach. Comparing the Slade gain/loss values discussed in the previous paragraphs to mean stream flows from the EPA RF1 data set shows that almost all of the gain/loss values are less than 5 percent of the mean stream flow. This suggests that the gain/loss values are uncertain and can be used only qualitatively.

8.3.2.3 Water Budget

Tables 8.3.2 and 8.3.3 summarize the water budget for the model in terms of total volume and as a percentage of total inflow and outflow. The overall mass balance error for the steady-state simulation was -0.1 percent, well under the GAM requirement of one percent. The predominant input source is recharge, which accounts for 97 percent of the total inflow to the model. Water discharging from the model is mainly through ET (48 percent), followed by streams (47 percent), GHBs (2 percent), and drains (2 percent) in descending order.

The average recharge over the entire model region is 0.98 inches/yr. ET in the steady-state model averaged 0.49 inches/yr. The net recharge to the aquifer (i.e., recharge minus ET) for the steady-state simulation was 0.49 inches/yr. For comparison, the 20-year average net recharge in the transient model was 0.81 inches/yr, based on the average recharge rate of 1.0 inches/yr and an average ET rate of 0.19 inches/yr. In general, the estimated recharge rates are within the range reported in the various studies that are summarized in Table 4.6.1.

Table 8.3.1 Head calibration statistics for the Northern steady-state model.

Layer	ME (ft)	MAE (ft)	RMSE (ft)	Range (ft)	RMSE/Range
Layer 1 (Sparta)	-5.11	22.16	27.64	394	0.070
Layer 3 (Queen City)	-12.81	20.03	25.54	395	0.065
Layer 5 (Carrizo)	-7.68	25.78	29.50	340	0.087
Layer 6 (upper Wilcox)	13.33	31.44	36.44	264	0.138
Layer 7 (middle Wilcox)	16.10	29.07	36.34	444	0.082

ME = mean error
MAE = mean absolute error
RMSE = root mean square error

Table 8.3.2 Water budget for the Northern steady-state model. All rates reported in AFY.

IN	Layer	Recharge	Streams		GHBs	Top	Bottom
	1	140,025	228		22,499	0	20,008
	2	10,815	155		0	39,214	16,613
	3	275,580	2,954		0	38,381	12,757
	4	33,262	452		0	15,105	13,411
	5	131,896	34		0	13,802	7,678
	6	166,745	2,393		0	22,206	11,749
	7	274,089	3,827		0	17,407	13,013
	8	17,546	91		0	14,353	0
	Sum	1,049,957	10,134		22,499		
OUT	**Layer**	**ET**	**Streams**	**Drains**	**GHBs**	**Top**	**Bottom**
	1	-63,543	-49,390	-3,865	-26,755	0	-39,214
	2	-4,506	-3,865	-40	0	-20,008	-38,381
	3	-158,813	-134,876	-4,264	0	-16,613	-15,105
	4	-19,789	-15,476	-408	0	-12,757	-13,802
	5	-62,336	-52,785	-2,887	0	-13,411	-22,206
	6	-81,331	-89,566	-7,258	0	-7,678	-17,407
	7	-120,216	-155,502	-7,235	0	-11,749	-14,353
	8	-10,649	-8,115	-257	0	-13,013	0
	Sum	-521,182	-509,575	-26,215	-26,755		

Table 8.3.3 Water budget for the Northern steady-state model with values expressed as a percentage of inflow or outflow.

IN	Layer	Recharge	Streams		GHBs
	1	13	0		2
	2	1	0		
	3	25	0		
	4	3	0		
	5	12	0		
	6	15	0		
	7	25	0		
	8	2	0		
	Sum	97	1		2
OUT	**Layer**	**ET**	**Streams**	**Drains**	**GHBs**
	1	6	5	0	2
	2	0	0	0	
	3	15	12	0	
	4	2	1	0	
	5	6	5	0	
	6	8	8	1	
	7	11	14	1	
	8	1	1	0	
	Sum	48	47	2	2

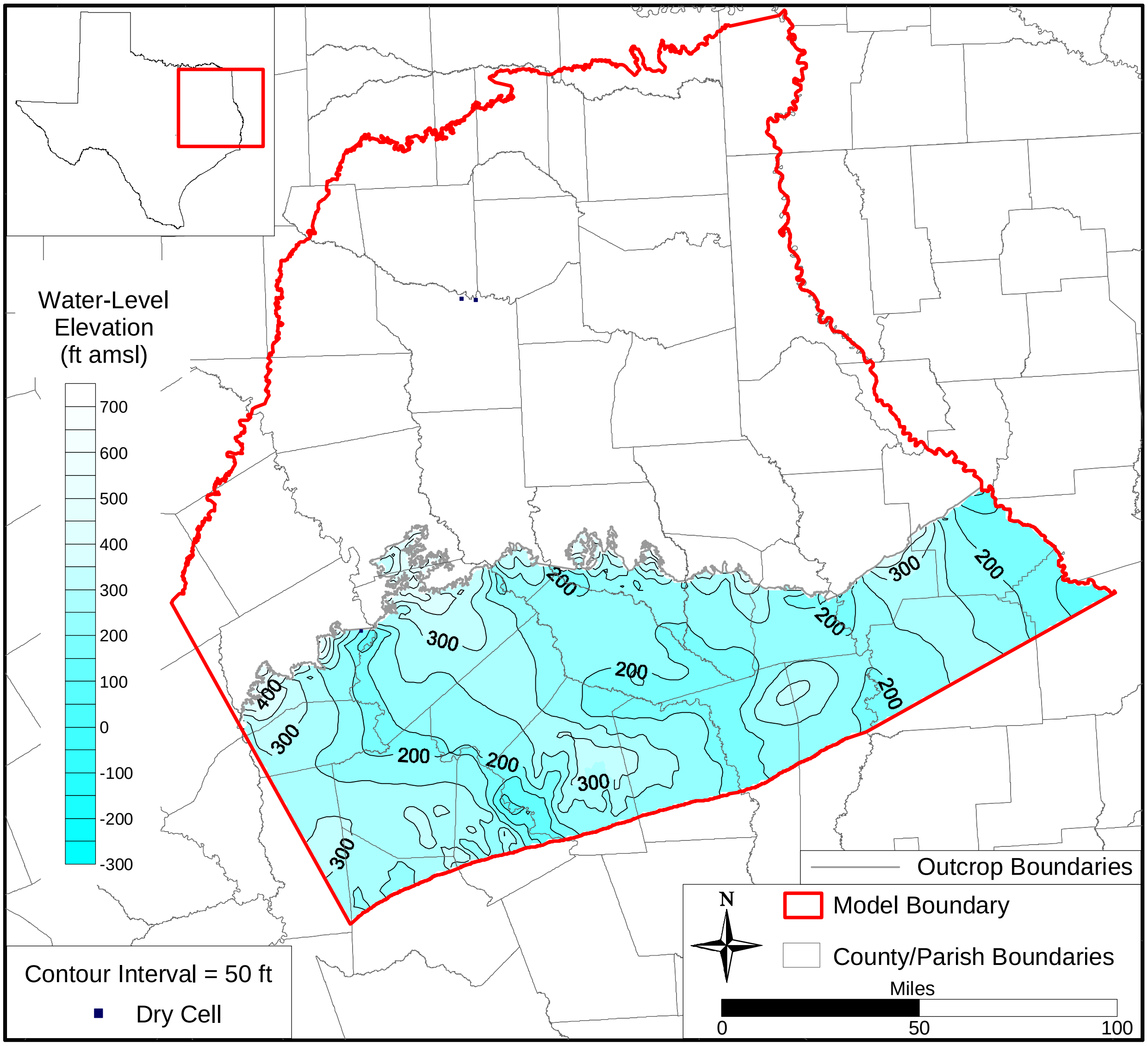
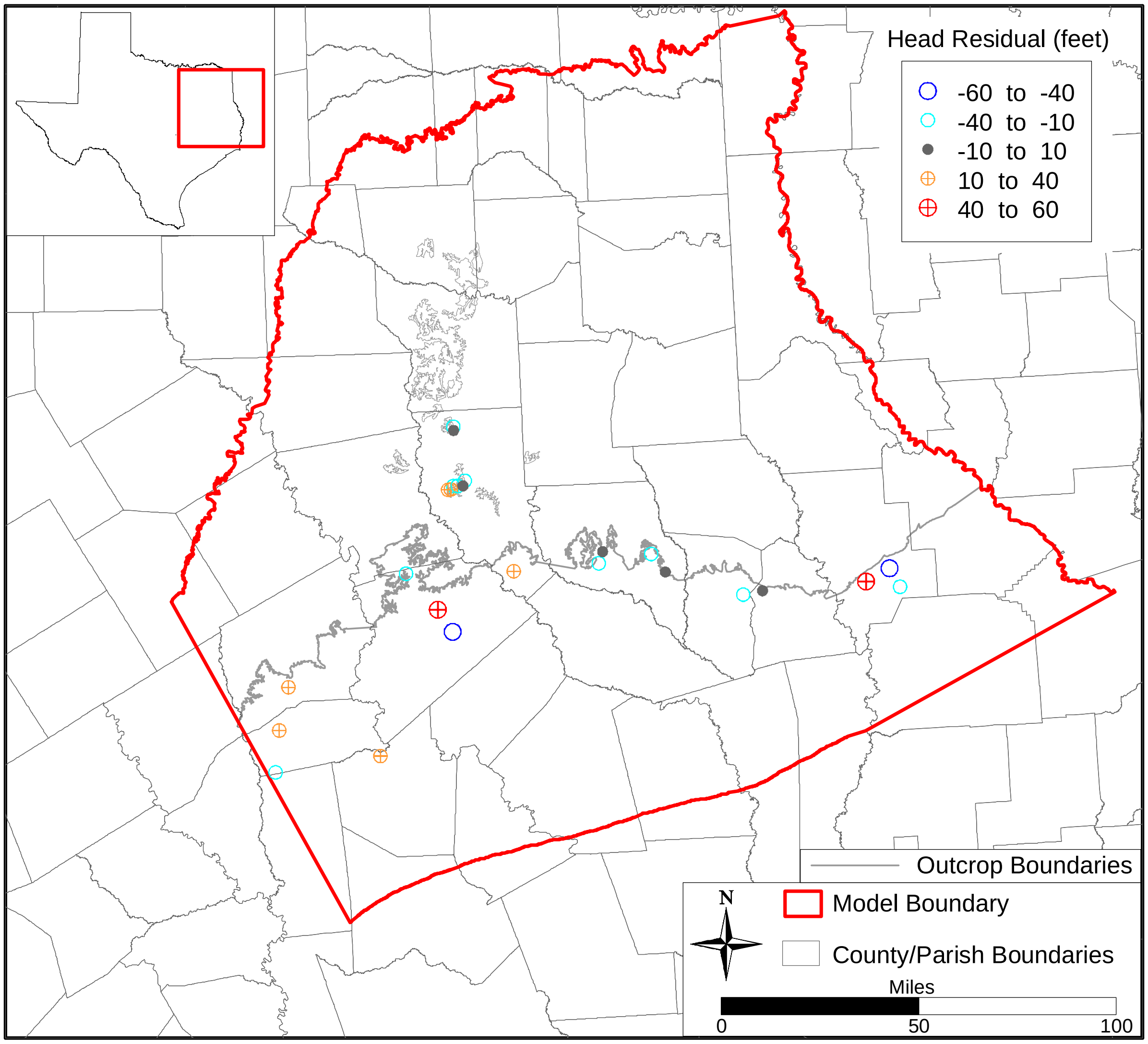


Figure 8.3.3 Simulated steady-state hydraulic heads for the Sparta aquifer (Layer 1).

a.



b.

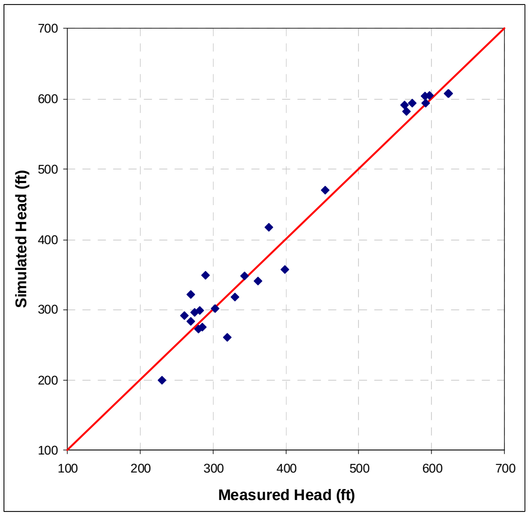


Figure 8.3.4 Head residuals (a) and scatterplot (b) of simulated and measured heads for the Sparta aquifer (Layer 1).

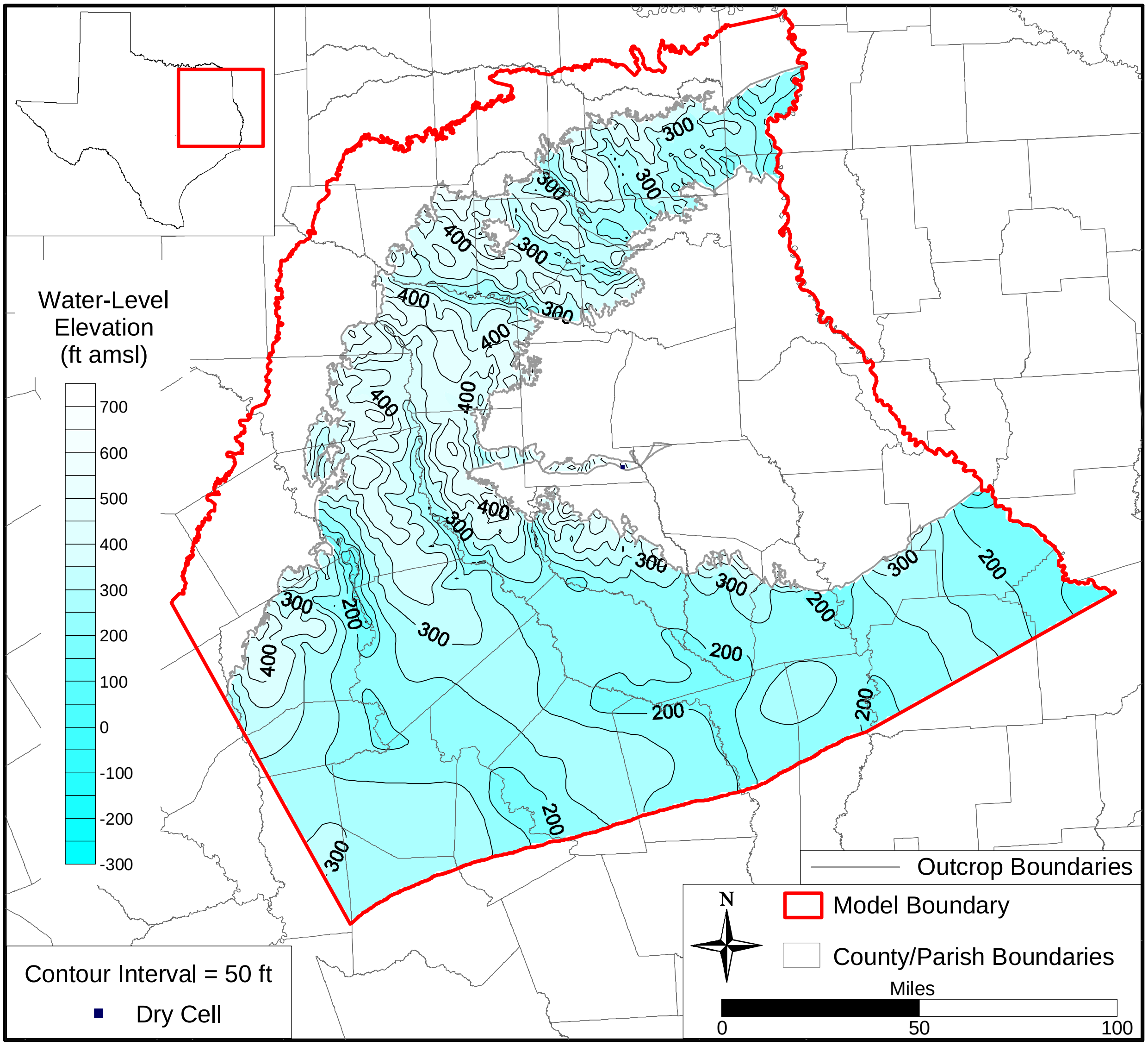
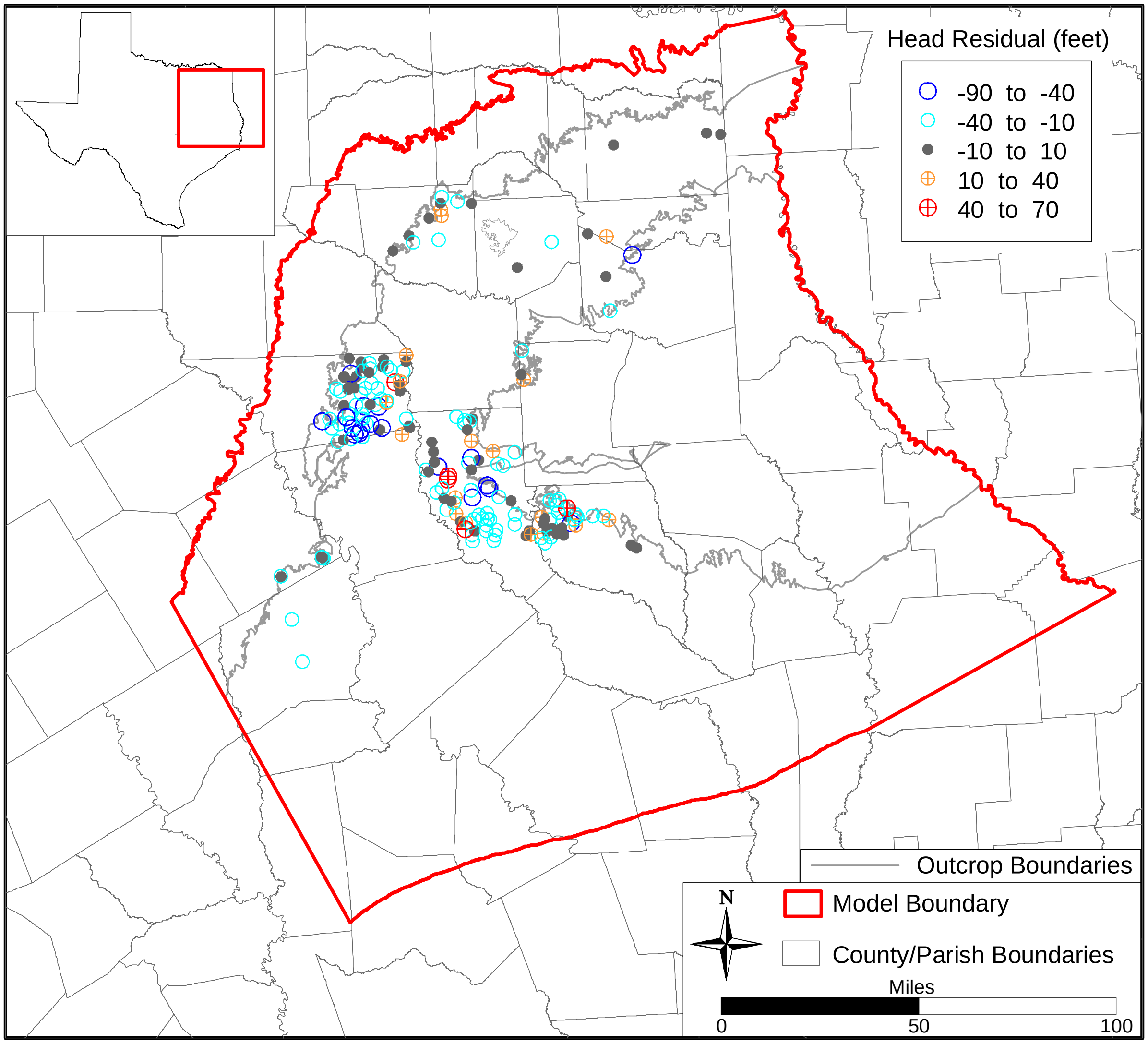
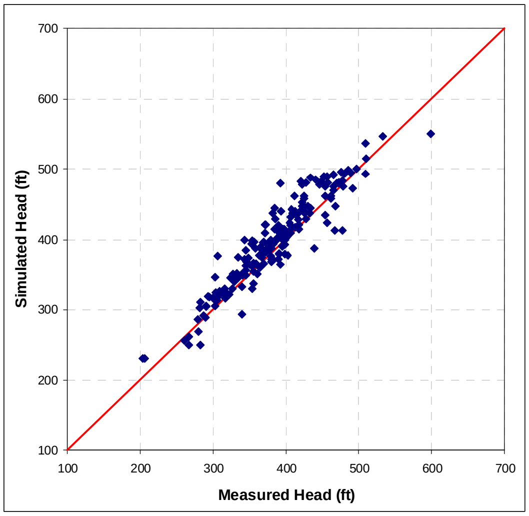


Figure 8.3.5 Simulated steady-state hydraulic heads for the Queen City aquifer (Layer 3).



a.



b.

Figure 8.3.6 Head residuals (a) and scatterplot (b) of simulated and measured heads for the Queen City aquifer (Layer 3).

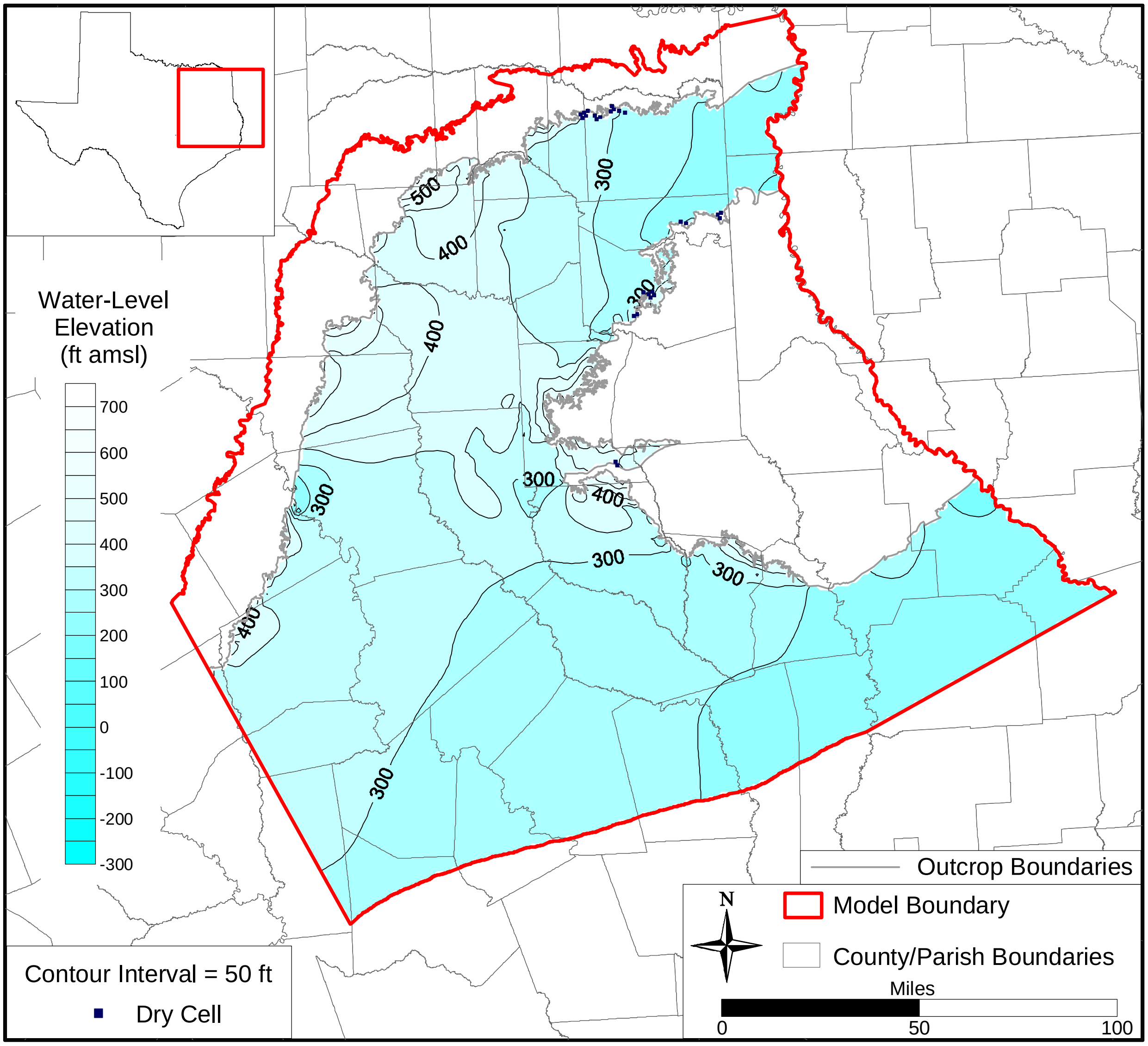


Figure 8.3.7 **Simulated steady-state hydraulic heads for the Carrizo Formation (Layer 5).**

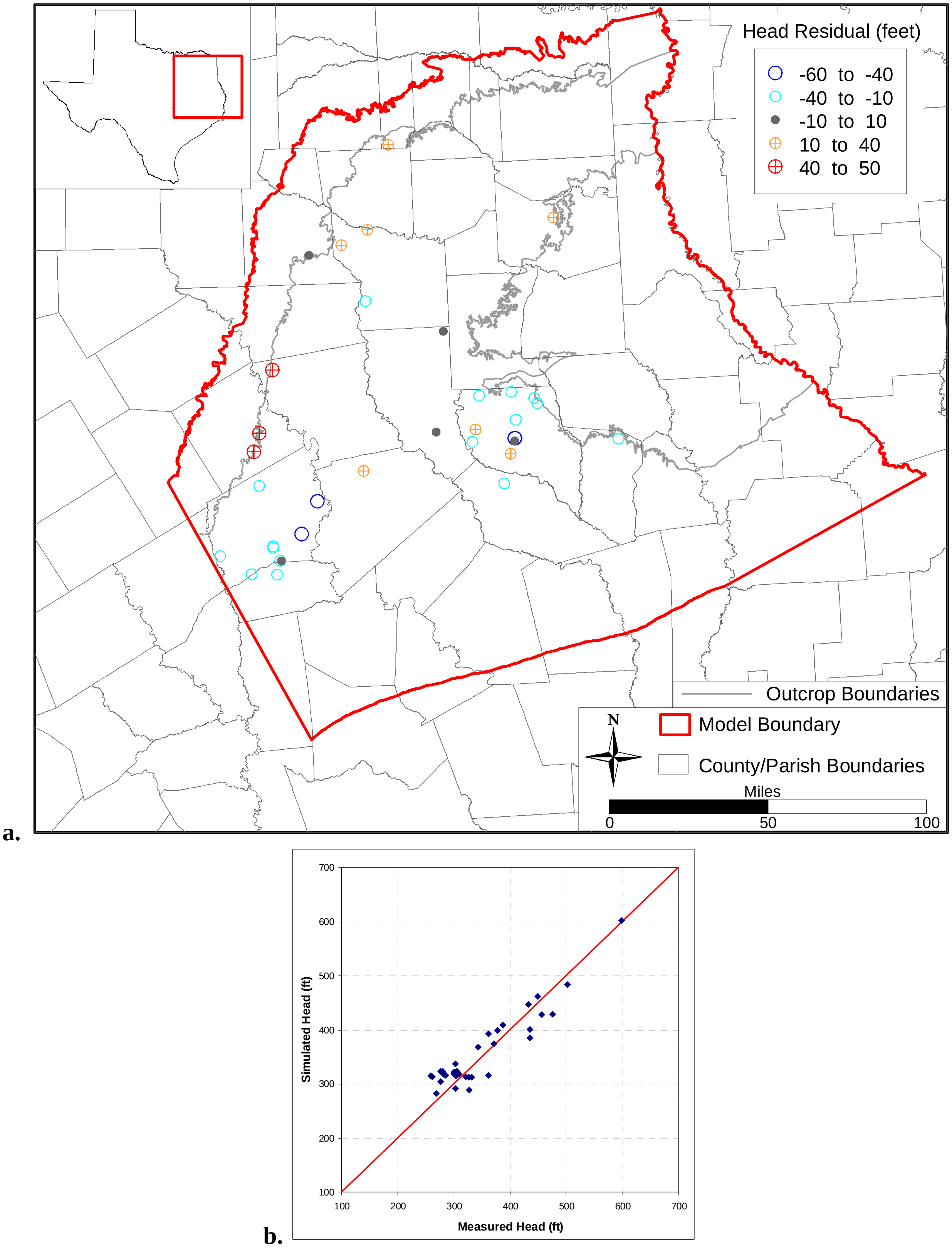


Figure 8.3.8 **Head residuals (a) and scatterplot (b) of simulated and measured heads for the Carrizo Formation (Layer 5).**

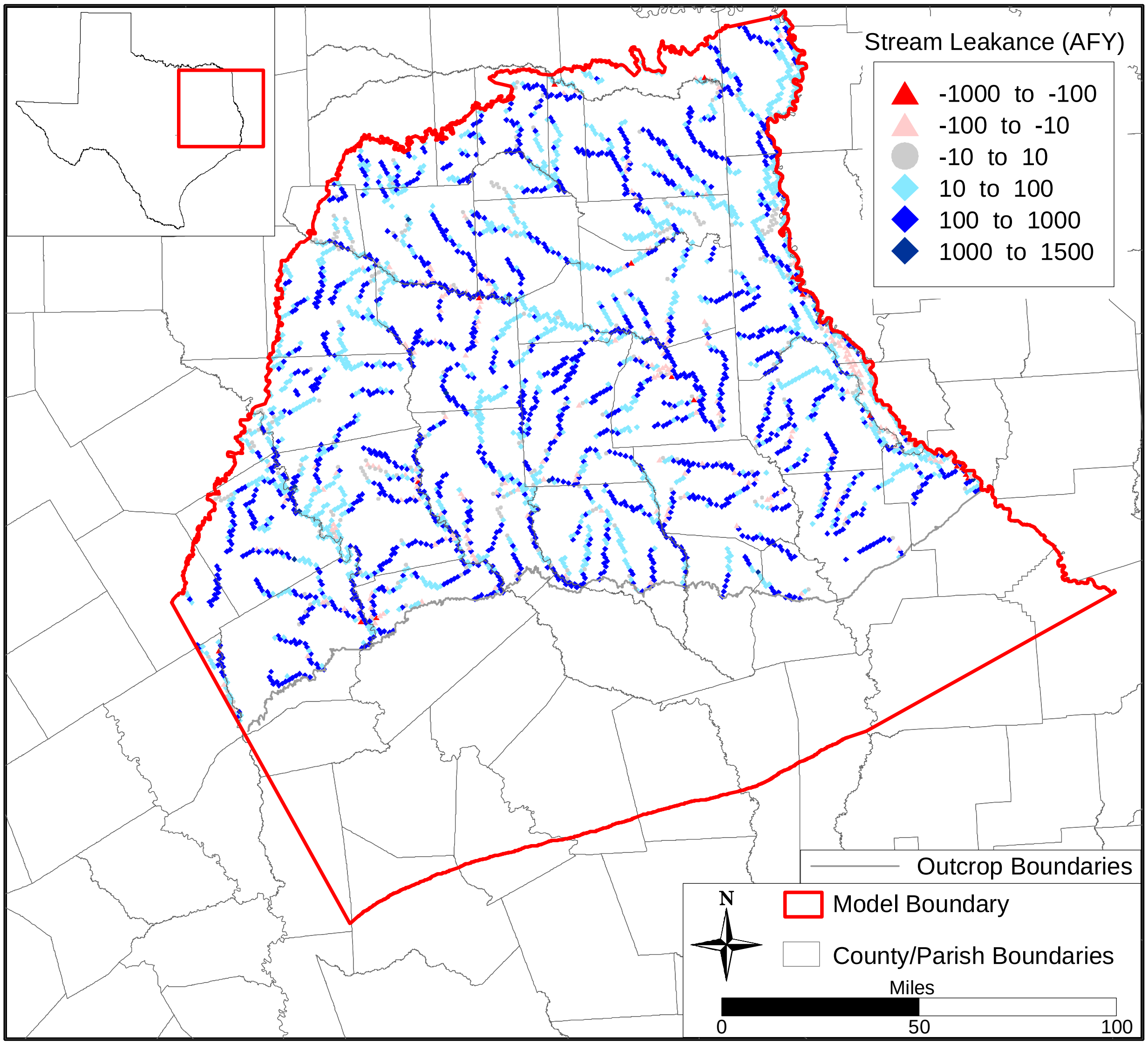


Figure 8.3.9 Steady-state model stream gain/loss (positive values indicate gaining streams).

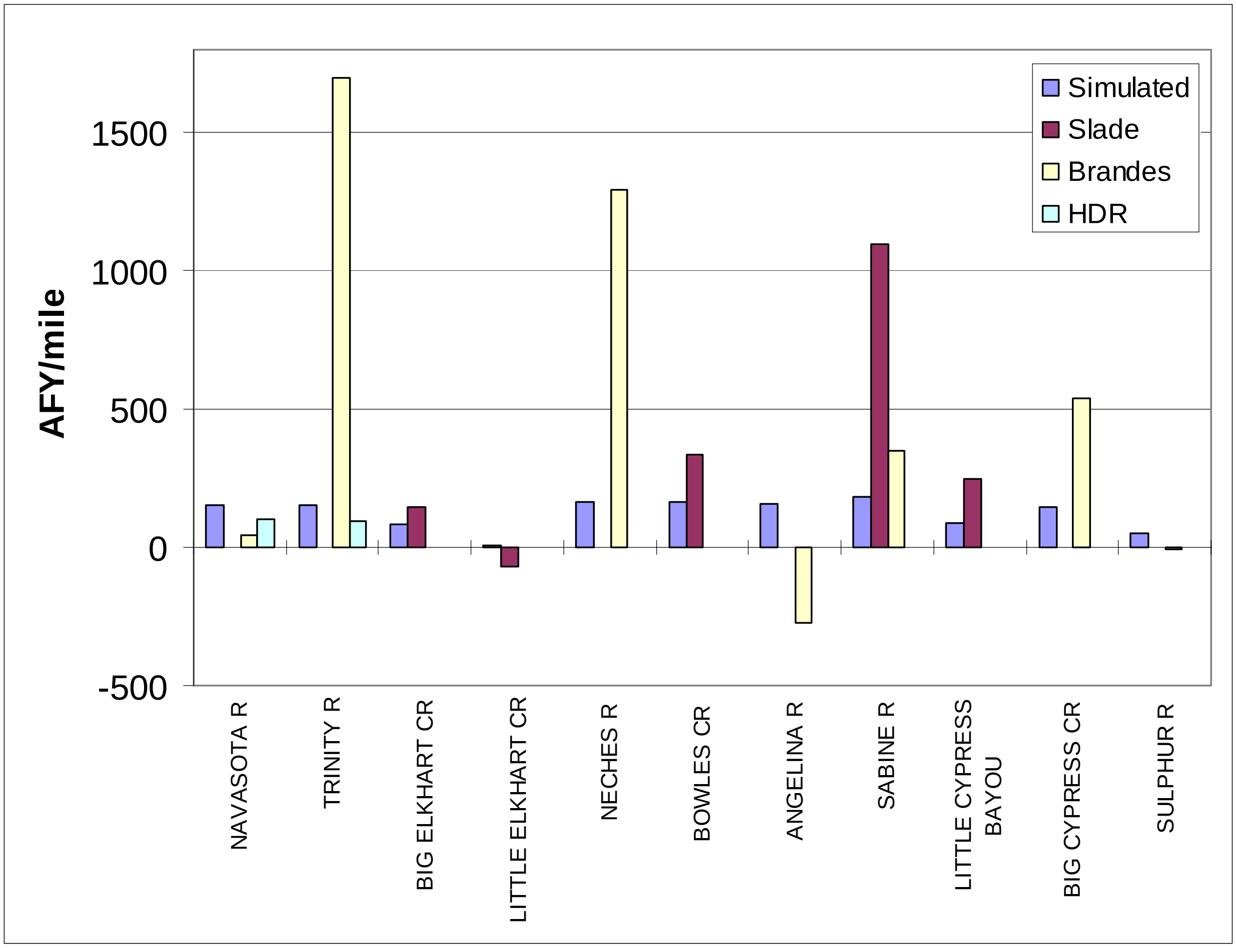


Figure 8.3.10 Simulated stream gain/loss compared to measured values.

8.3.3 Sensitivity Analysis

The application of the sensitivity analysis was the same as that of the Southern model, described in Section 8.1.3. Figure 8.3.11 shows the results of the sensitivity analyses for the Queen City aquifer (Layer 3) with *MDs* calculated from only the grid blocks where targets were available. In comparison, Figure 8.3.12 shows the corresponding sensitivity results with *MDs* calculated from all active cells in the layer. Note that the two figures indicate similar trends in sensitivities, with the exception of those affecting the GHBs. The GHB sensitivities show a greater effect for the case where all grid blocks were used to calculate the *MDs*. This is to be expected since most of the targets (and groundwater production from the Queen City and Sparta aquifers in east Texas) are in or near the outcrop and, therefore, less affected by the GHBs. The sensitivities that were calculated from all grid blocks are more affected by the GHBs since a large portion of the gridblocks are in the confined section. In general, most of the other parameters show reasonable agreement between sensitivities calculated using only target cells and those calculated using all active cells. Because the sensitivities calculated using all active cells are more representative of the entire model, only those sensitivities using all active cells are shown for the remaining sensitivities.

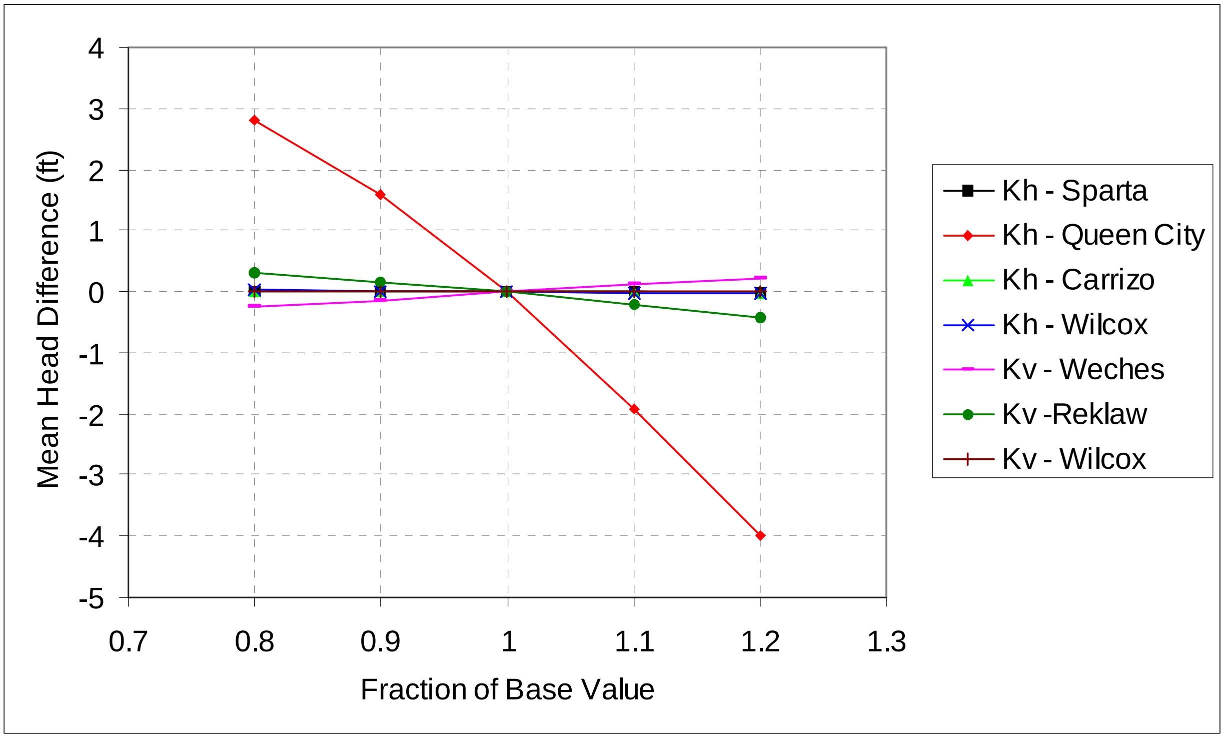
Figure 8.3.13 indicates that the change in head in the Sparta aquifer for the steady-state model is most positively correlated with GHB head, followed by recharge. Similar *MD* trends are shown in Figure 8.3.12 indicating that hydraulic heads in the Queen City aquifer are also strongly influenced by GHB heads and recharge. For the Sparta aquifer, the most negatively correlated parameters are GHB conductance and the horizontal hydraulic conductivity of the Sparta aquifer. The remaining parameters varied less than one foot from the base case.

As with the Sparta aquifer, the change in head in the Queen City aquifer is most positively correlated with GHB head, followed by recharge (Figure 8.3.12). The stream head sensitivity also shows some positive correlation. The most negatively correlated parameters are the horizontal hydraulic conductivity of the Queen City aquifer and GHB conductance. The remaining parameters varied less than one foot from the base case.

For the Carrizo Formation (Figure 8.3.14), recharge shows the strongest positive correlation, followed by stream head, GHB head, and the horizontal hydraulic conductivity of the Carrizo Formation. Significant negative correlations were demonstrated for the vertical hydraulic conductivity of the Reklaw Formation and the horizontal hydraulic conductivity of the Wilcox layers. The remaining parameters varied less than one foot from the base case.

Sensitivity to recharge, shown in Figure 8.3.15, indicates a similar positive trend for all layers, with the Carrizo-Wilcox layers showing slightly higher *MDs*. As expected, increasing recharge increases heads. Figure 8.3.16 shows the sensitivity to the vertical hydraulic conductivity of the Reklaw Formation. Lowered Reklaw vertical hydraulic conductivities increase heads in the Carrizo-Wilcox layers and decrease heads in the Sparta and Queen City layers.

Sensitivity to GHB heads and conductances are shown in Figures 8.3.17 and 8.3.18, indicating a positive correlation to heads and a negative correlation to conductances for all layers. Higher GHB heads are translated to higher model heads in all layers, with the effect decreasing from the Sparta to the Wilcox. Lower GHB conductances results in decreased discharge from the confined section of the Sparta aquifer and concomitantly increased hydraulic heads. As with GHB heads, the effect decreases from the Sparta to the Wilcox layers. Stream heads and conductivities show very similar effects, but with the greatest effect on the Wilcox layers and less effect on the Sparta.



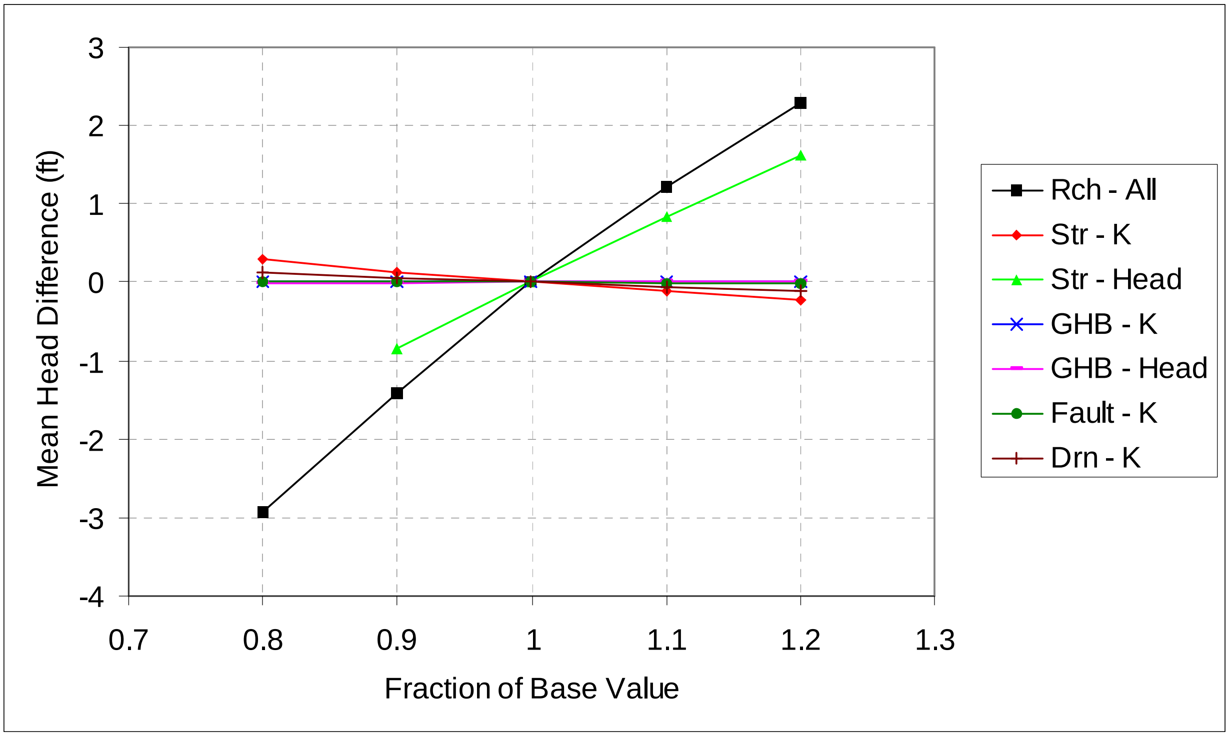
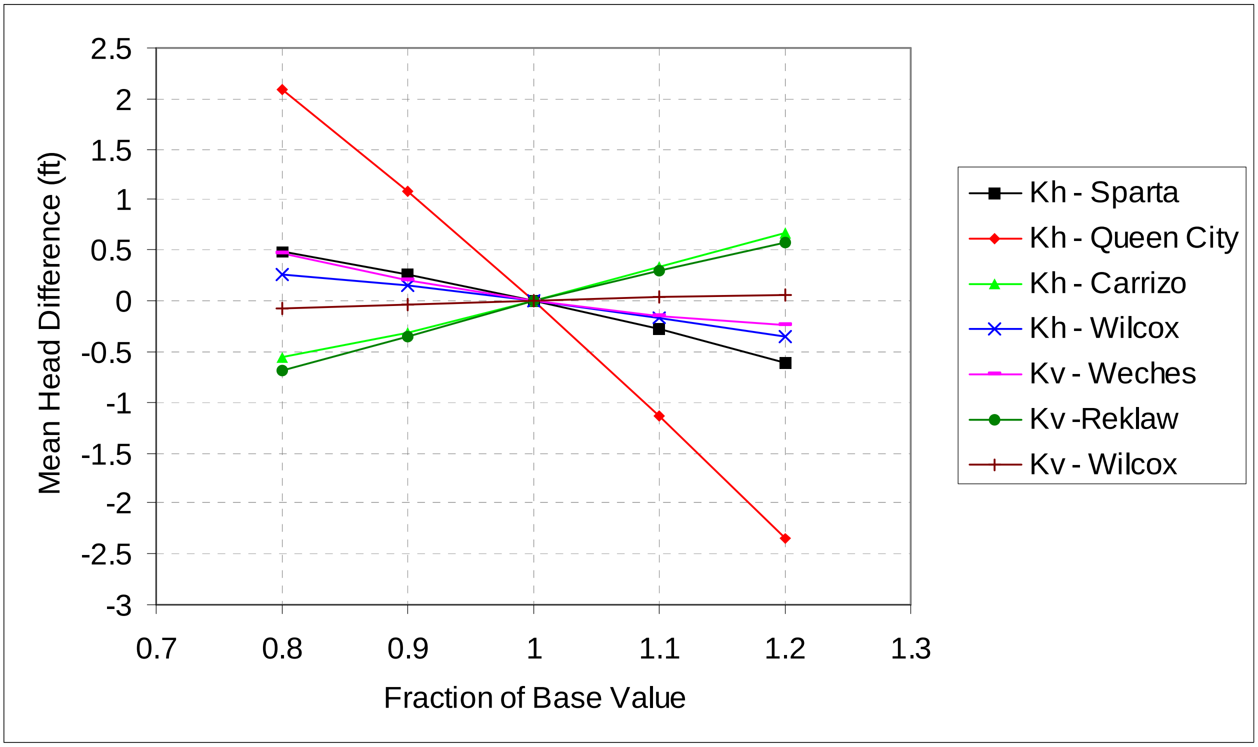


Figure 8.3.11 **Steady-state sensitivity results for the Queen City aquifer (Layer 3) using target locations.**



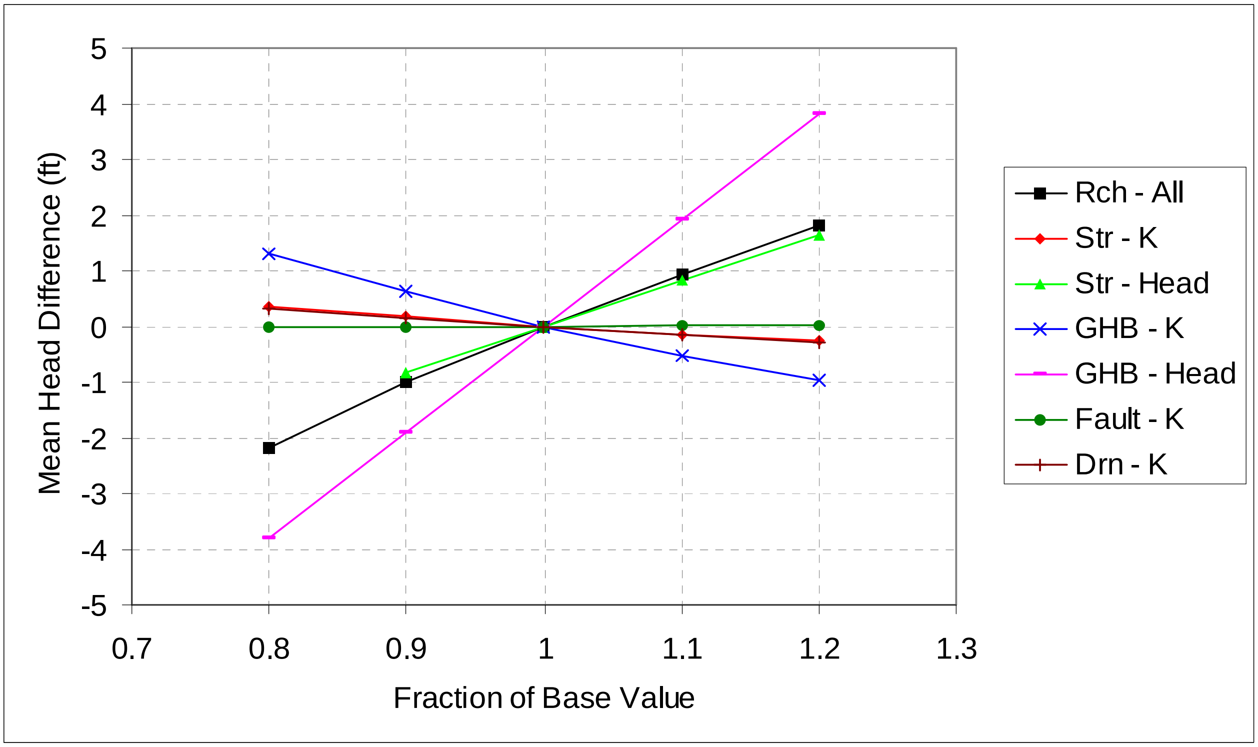
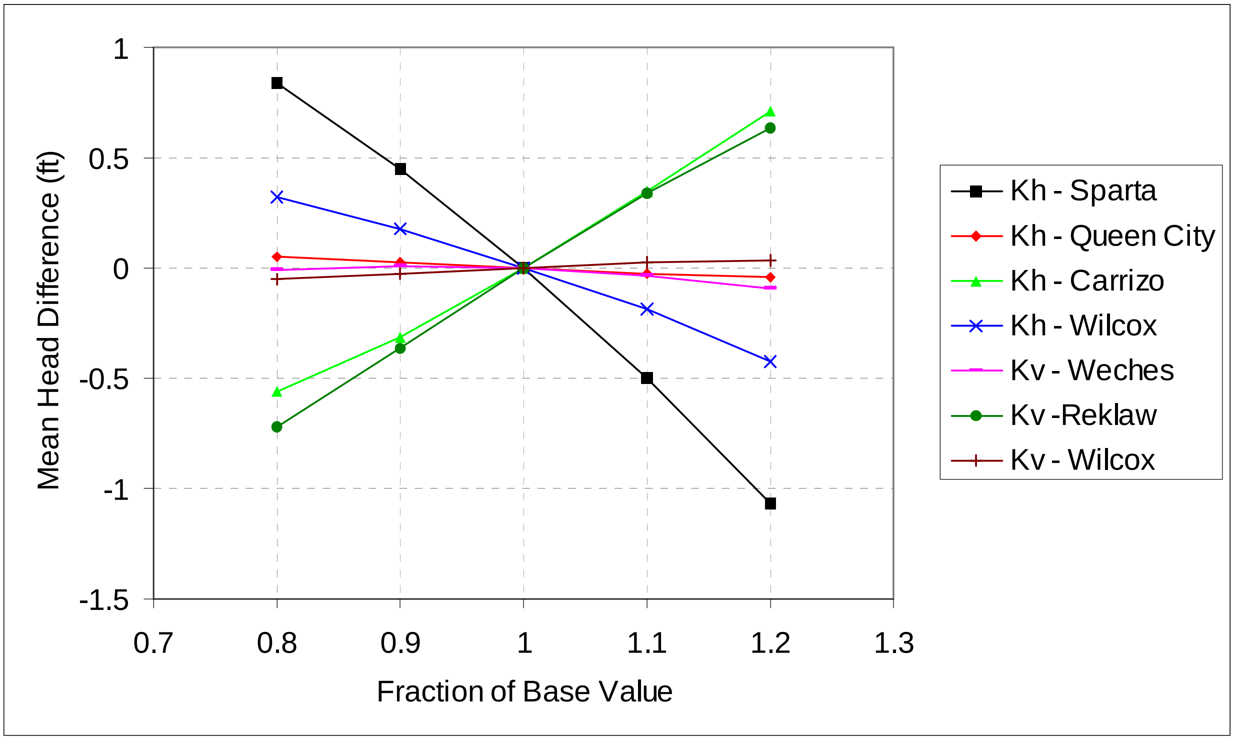


Figure 8.3.12 Steady-state sensitivity results for the Queen City aquifer (Layer 3) using all active grid blocks.



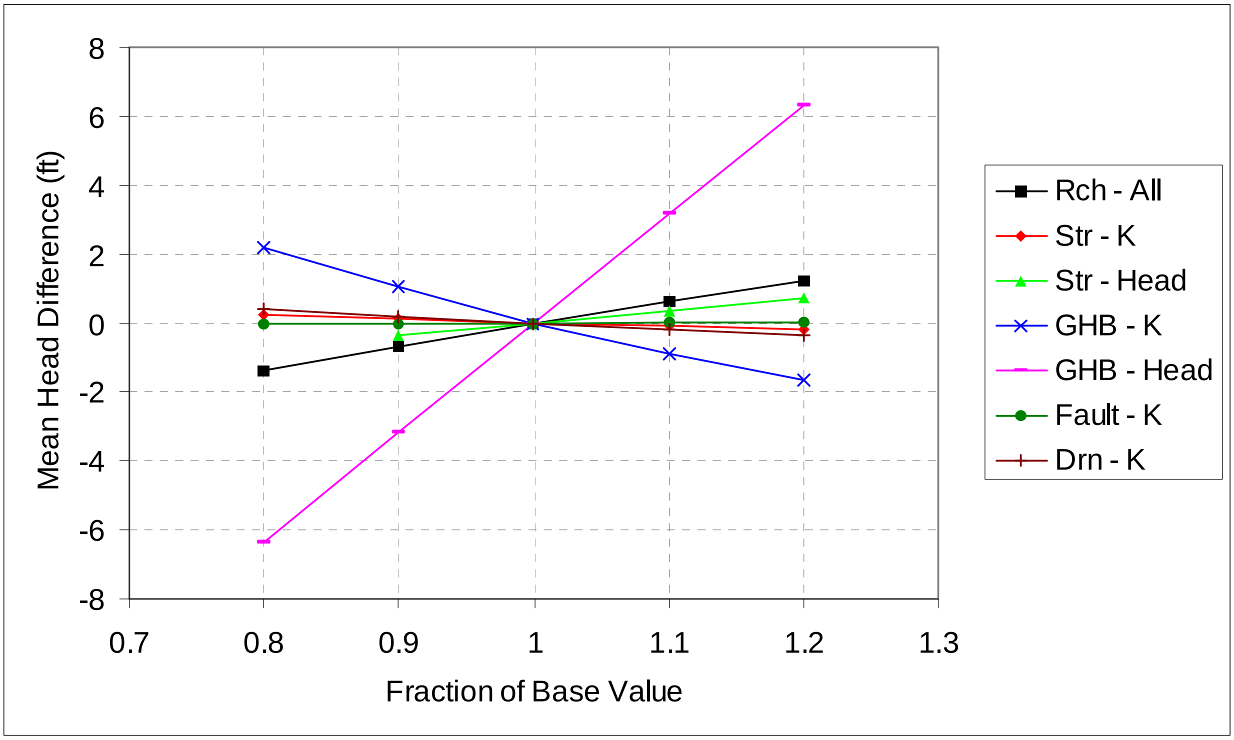


Figure 8.3.13 Steady-state sensitivity results for the Sparta aquifer (Layer 1) using all active grid blocks.

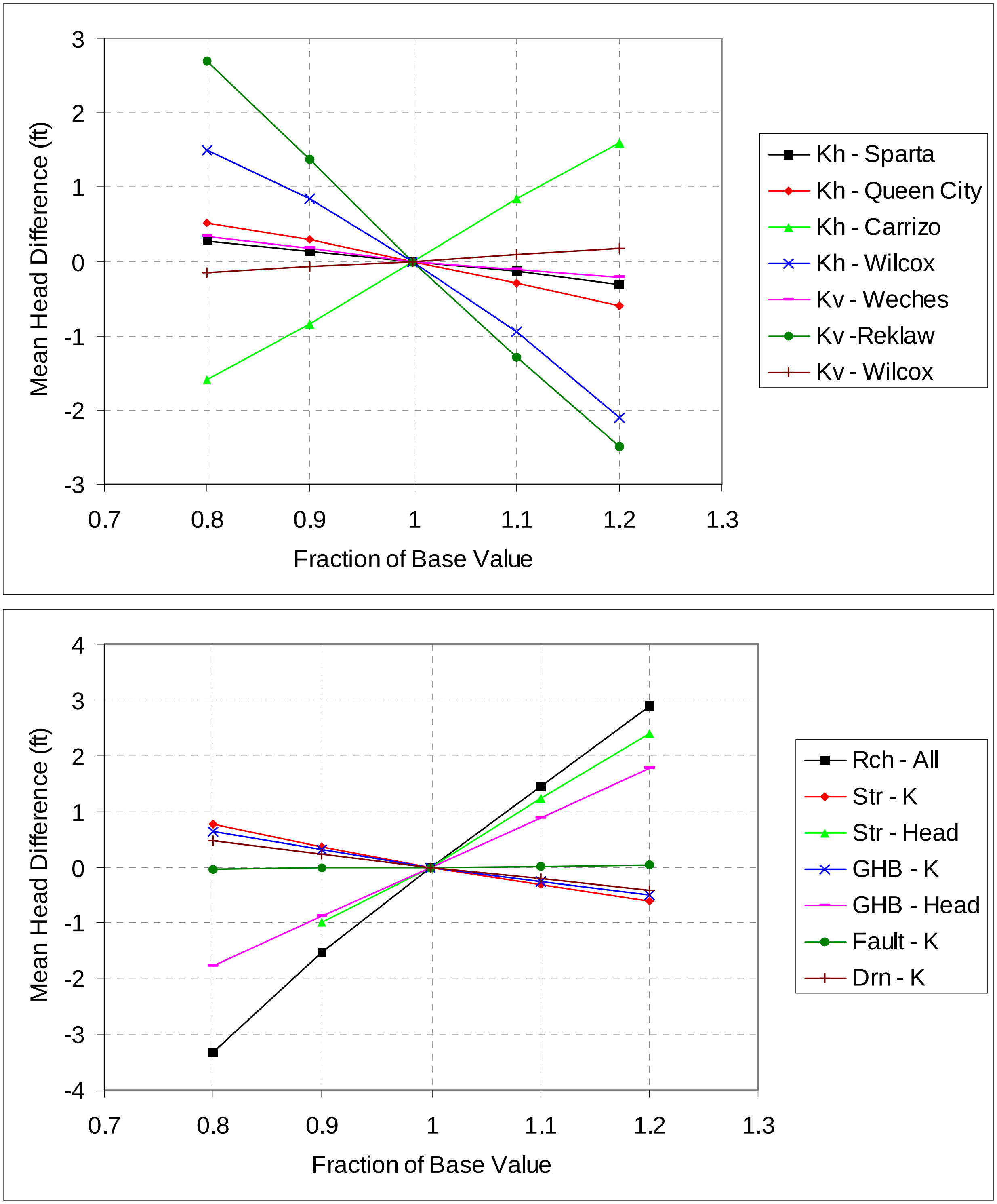


Figure 8.3.14 **Steady-state sensitivity results for the Carrizo Formation (Layer 5) using all active grid blocks.**

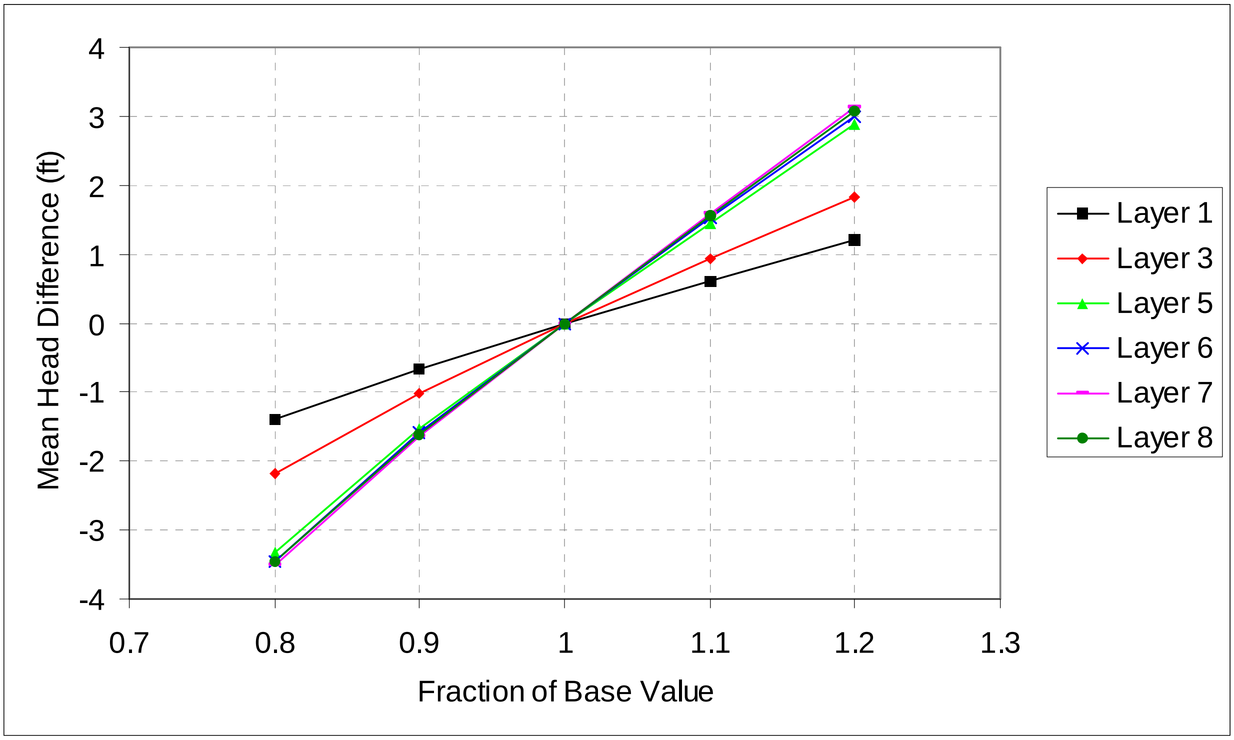


Figure 8.3.15 Steady-state sensitivity results where recharge is varied model wide.

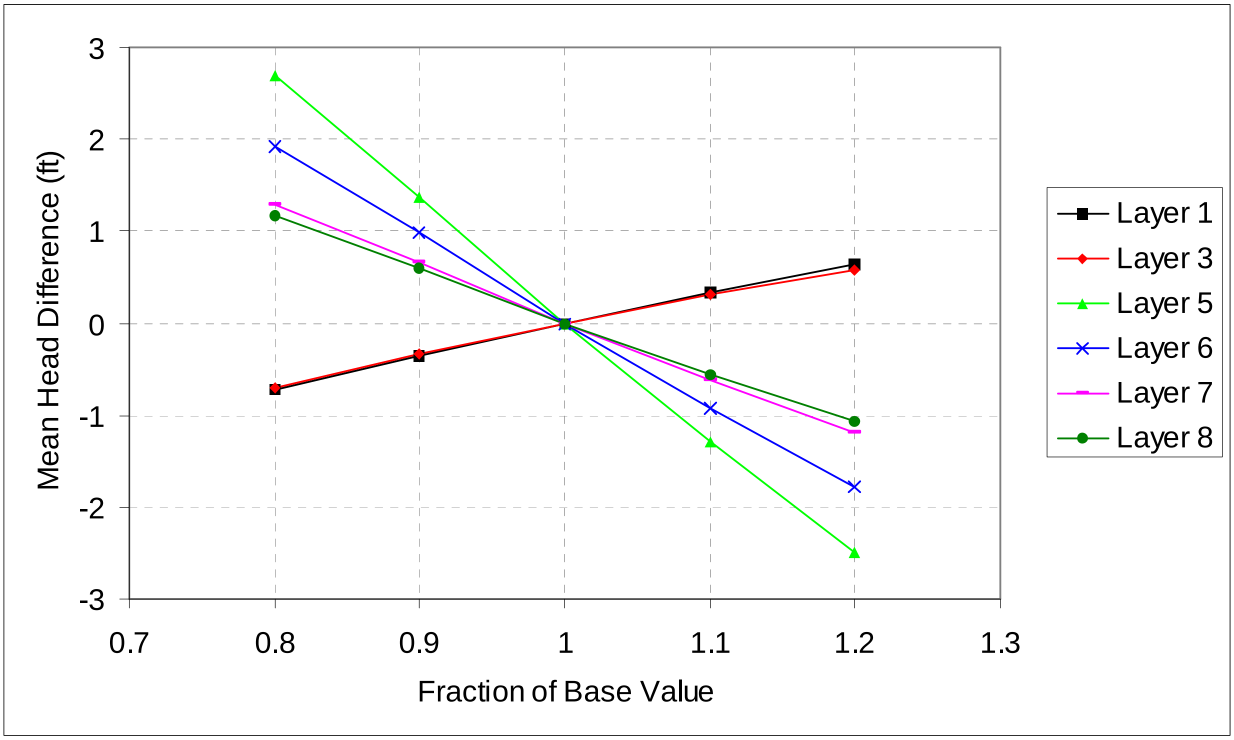


Figure 8.3.16 Steady-state sensitivity results where the vertical hydraulic conductivity of the Reklaw Formation is varied.

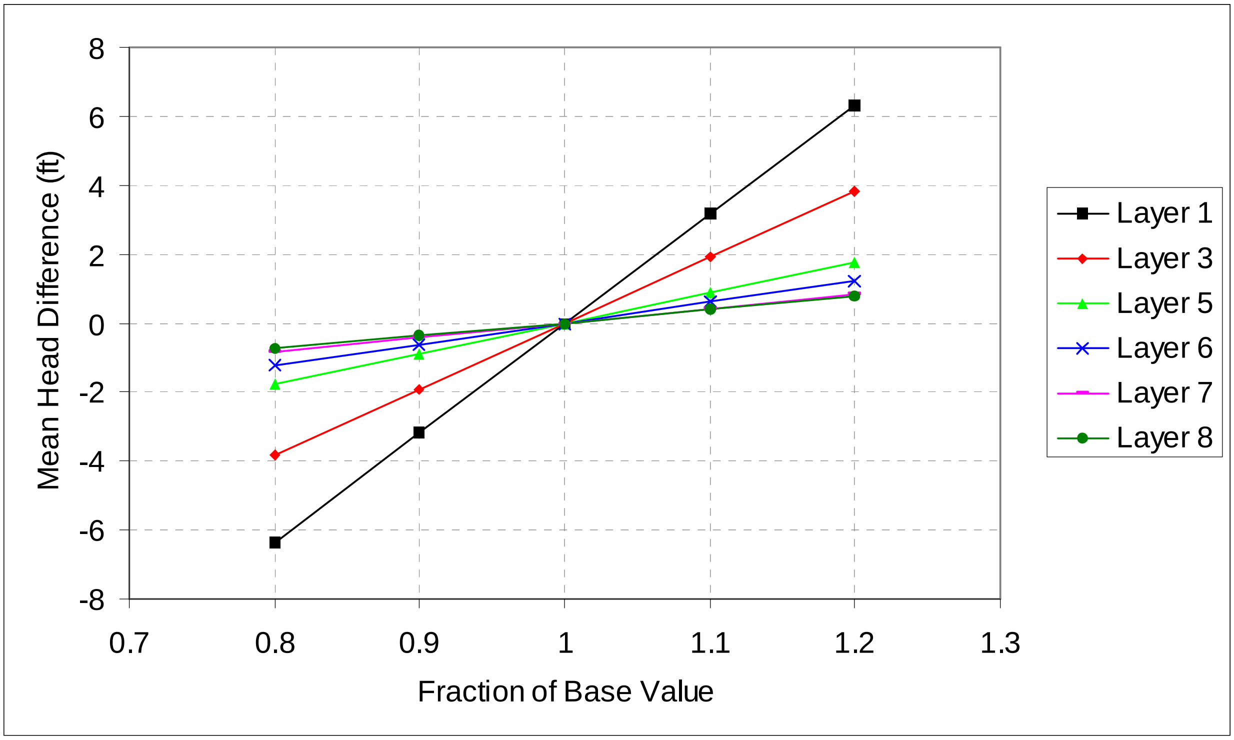


Figure 8.3.17 Steady-state sensitivity results where the GHB head is varied.

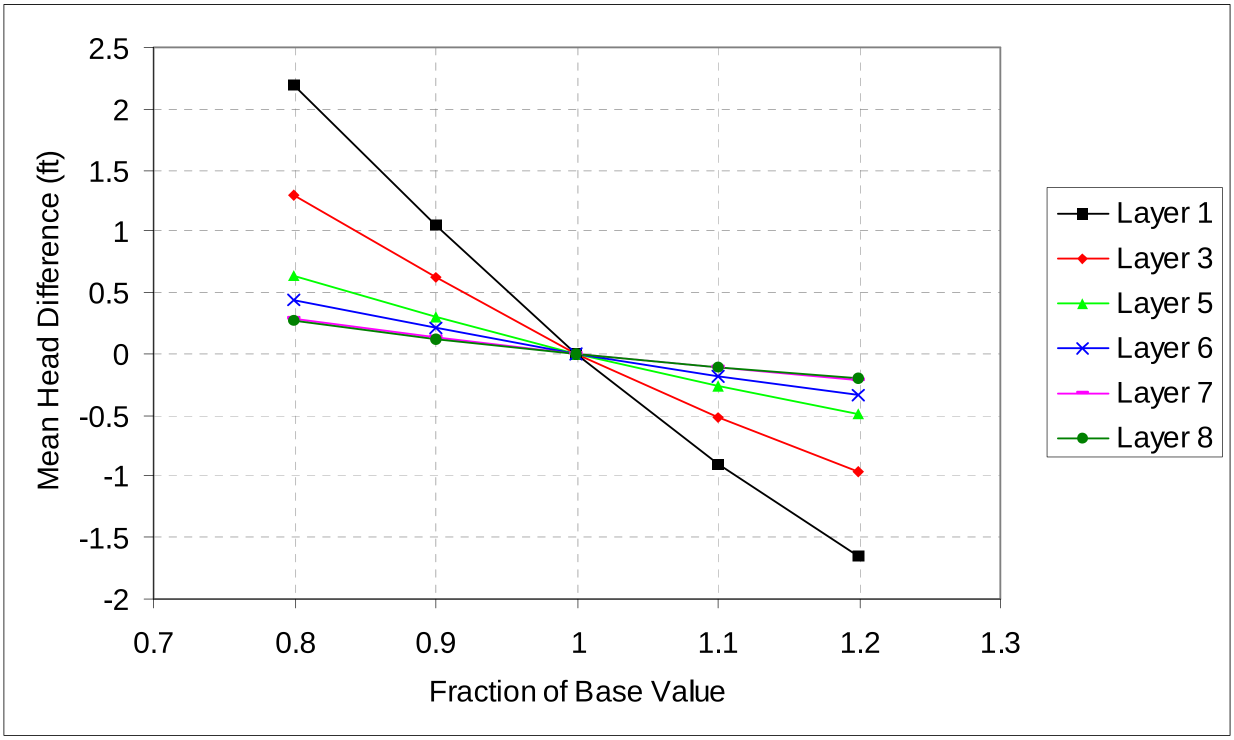


Figure 8.3.18 Steady-state sensitivity results where the GHB conductance is varied.

9.0 TRANSIENT MODEL

This section describes the calibration and verification of the transient models and presents the transient model results for each region in a separate subsection. Each subsection also describes a sensitivity analysis for the transient model for that region. The transient model was started with a five year equilibration period to allow any initialization effects to dampen by 1980, the start of the calibration period. This period is considered a "ramp up" period, and was not used for calibration. The model was calibrated for the time period from 1980 through 1989. The model was verified for the time period from 1990 through 1999.

9.1 Southern Queen City and Sparta GAM

This section details the calibration and verification of the Southern Queen City and Sparta transient model and presents the transient model results. Section 9.1.1 describes the calibration approach, and Section 9.1.2 presents the results of the transient calibration and verification together with the examination of residuals, hydrographs, and stream flow. A formal sensitivity analysis with the calibrated transient model can be found in Section 9.1.3.

9.1.1 Calibration

Because the groundwater model must be calibrated to steady-state and transient conditions using the same physical hydraulic properties, calibration is an iterative process between the conditions. As a result, the physical properties that are common between the steady-state model and the transient model are the same, as presented in Section 8.1. In addition, a transient model requires storage estimates for the aquifers.

Primary and secondary storage (also called storativity and specific yield) are properties of a transient model that are not required in a steady-state model. In the Carrizo-Wilcox GAM, specific storage was defined as 3.0×10^{-6} ft^{-1} in all layers based upon a review of published data, prior models, and considering the lithologies of the formations. Specific storage was then multiplied by layer thickness to provide the storativity at each grid cell. In the current model, storativity was derived as described in Section 6.4.2, which resulted in a change in storativity values in the Queen City aquifer, Reklaw Formation, and Carrizo aquifer from the Carrizo-Wilcox GAM. Although storativity has an impact upon the amplitude of head variation due to pumping, hydrograph trends were not found to be strongly sensitive to storativity. In the final calibrated model, storativity was not changed from the initial estimates.

Reservoirs are features that exist in the transient model, but not the steady-state model. Because there are only two reservoirs in the Southern model area, reservoirs did not play a significant role in the calibration. A hydraulic conductivity of $1x10^{-4}$ ft/day was initially assumed in the reservoir conductance calculation. These are no targets for reservoir leakance rates. Because the reservoirs' percent of the initial flow balance seemed reasonable, reservoir conductance was not varied during the calibration.

Only coarse adjustments were made to streambed conductivity during the calibration. The streams exchange significant volumes of water with the aquifer, so they are important in the outcrop area. However, in the transient model, the hydrology of the outcrop has little effect on downdip regions during the simulation period. Comparisons between simulated stream leakances and some general reported estimates are discussed in Section 9.1.2.

Transient recharge is consistent with the steady-state model recharge. That is, an average of the transient recharge will approximately reproduce the steady-state recharge. The transient model is insensitive to recharge, because of the large storage capacity in the outcrop. Therefore, the transient model does not show the correlation between recharge and vertical conductivity that is present in the steady-state model. In general, the transient model provides good information about conductivity ranges where significant stress is applied (such as in the Carrizo Formation). Where no significant stress has been applied (such as in the Sparta and Queen City aquifers), the conductivities will be poorly constrained by the transient model.

As described in Section 6.3.1, lateral GHBs were added to the transient model. The GHB heads were set by sampling heads at the boundary from the adjoining model with which the overlap region is shared. Iteration of the head exchange was completed until stability was reached.

9.1.2 Results

The results of the transient calibrated model are compared to the available calibration targets in this section. The calibration measures are also applied to the verification period to provide an indication of the model's predictive capability.

9.1.2.1 Hydraulic Heads

Outcrop head targets were adjusted as described in Section 8.1.2.1. Table 9.1.1 shows the calibration statistics for each aquifer for the calibration and verification periods. Note that because most of the targets had incomplete records over the simulated time period, calibration statistics have been calculated using all of the available data in time and space for the calibration and verification periods. For the Sparta aquifer (Layer 1), the RMSE is 22.7 feet for the calibration period. This RMSE decreases slightly to 18.9 feet in the verification period, indicating that the model calibration is relatively stable throughout the historical period. For both periods, the RMSE/range is less than 0.1. Figure 9.1.1 shows a comparison between the simulated and estimated 1990 heads for the Sparta aquifer. The Sparta aquifer simulated heads reflect the damped topographic effect of the GHBs, which cannot be reflected in the simple kriged surface from the measured data points. Figure 9.1.2 shows the residual and scatterplots for the Sparta aquifer in the calibration period. The residuals show little spatial bias, and this lack of bias is supported by the scatterplot, which has good distribution around the unit slope line, and the small magnitude of the ME at -2.9 feet. Figure 9.1.3 shows a comparison between the simulated and estimated 1999 heads for the Sparta aquifer. Again, the lack of control points in the estimated surface causes the contours to lack the features of the simulated surface. Figure 9.1.4 shows the residual and scatterplots for the Sparta aquifer in the verification period. Again, the residuals show little spatial bias. This is supported by the scatterplot, which has good distribution around the unit slope line, and the ME of -2.1 feet, which is smaller in absolute magnitude than in the calibration period.

For the Queen City aquifer (Layer 3), the RMSE increases slightly from 18.1 to 21.6 feet from calibration to verification, but this small increase does not signal any problems with calibration in the historical period. For both the calibration and verification periods, the RMSE/range is less than 0.1 for the Queen City aquifer. Figure 9.1.5 shows a comparison between the simulated and estimated 1990 heads for the Queen City aquifer. The Queen City aquifer simulated heads show the gentle southeast gradient that is expected in this aquifer. The measured heads, due to lack of control, do not provide a realistic head surface. However, the general magnitude of the contours are similar in similar areas of the two surfaces. Figure 9.1.6 shows the residual and scatterplots for the Queen City aquifer in the calibration period. The residuals show little spatial bias, and this is supported by the scatterplot, which has good distribution around the unit slope line, and the small magnitude of the ME at -0.7 feet. Figure 9.1.7 shows a comparison between the simulated and estimated 1999 heads for the Queen City aquifer. Here the increased number of control points in the estimated surface provides a result that is more comparable to the simulated surface. In the updip western region, the two surfaces differ, with the model showing approximately a 450-foot contour, and the measured surface showing a 400-foot contour. However, no control exists in this region for the measured surface, so it is considered to be approximate. Figure 9.1.8 shows the residual and scatterplots for the Queen City aquifer for the verification period. Again, the residuals show little spatial bias. This is supported by the scatterplot, which has good distribution around the unit slope line, and the ME of -5.7 feet, which is more than in the calibration period, but is still quite small. Some of the change in ME can be attributed to the target seen in the lower left portion of the scatterplot, which might be considered an outlier. This target was kept in the dataset because the ME is still within reasonable limits.

For the Carrizo aquifer (Layer 5), the RMSE increases from 33.1 to 47.6 feet from calibration to verification. This trend is similar to that in the previous Southern Carrizo-Wilcox GAM, although the RMSE has improved by about 3 feet in the current model verification period. The RMSE increase from calibration to verification is due to the inability of the model to sustain drawdowns in parts of the Wintergarden area, including the northeastern part of Dimmit County and the northern part of LaSalle County (see Figure 9.1.9). As with the Southern Carrizo-Wilcox GAM, without modifying either horizontal hydraulic conductivity or pumping, the model cannot sustain the large drawdowns in this area. Because a good distribution of well test data exist for the Carrizo aquifer throughout most of the problem area, it seemed arbitrary to modify horizontal hydraulic conductivity in this local area. Similarly, objective evidence for re-distributing the pumping does not exist, even though the distribution of pumping is known to be uncertain. Figure 9.1.9 shows a comparison between the simulated and estimated 1990 heads for the Carrizo aquifer. The general characteristics of the two surfaces are the same, with the exception of drawdown in the Wintergarden area in the western portion of the model, and the natural trough in Gonzales County. Figure 9.1.10 shows the residual and scatterplots for the Carrizo aquifer in the calibration period. Most of the area shows a good distribution of residuals, with the exception of the Wintergarden region mentioned previously, which is starting to show the effects of the non-sustained drawdown. The scatterplot shows points fairly well distributed around the unit slope line. Figure 9.1.11 shows a comparison between simulated and estimated 1999 heads for the Carrizo aquifer. Although the general trends are similar between the two surfaces, higher simulated heads are again seen in the Wintergarden area. This is evident in the residual plot and scatterplot shown in Figure 9.1.12. Note especially the "tailing" in the lower left corner of the scatterplot.

Figure 9.1.13 shows the results of a simulation that includes the effects of Schertz-Seguin pumping in Gonzales County for September 2002 to September 2003. Note that the predictive pumping dataset from 2000 through 2002 was not used, but rather the 1999 pumping was propagated forward to the point where the well field became active. This was done to avoid the discontinuity between the Carrizo-Wilcox historical and predictive datasets. The simulated drawdown contours are shown with the measured drawdowns at various wells in the area. In the center of the well field, the simulated drawdown of 17 feet is similar to the 18 to 19 feet measured at the wells. The 10-foot simulated contour is between the measured 7.4-foot value and the measured 10.9-foot value. The 5-foot contour runs through several points that are measured from 3 to 4 feet. In general the simulation compares well to measured results. However, two measured points in the southeastern part of the figure indicate no drawdown (near Smiley, Texas), while the model simulation shows that some drawdown should occur. This discrepancy could be due to some geologic feature (such as a fault) that is not well described in the model, or the Smiley wells could be completed in a strata that is relatively discontinuous with the sands being pumped at the Schertz-Seguin well field.

Figures 9.1.14 through 9.1.21 show selected hydrographs by layer for the transient model. All hydrographs in this section are shown on a 100-foot vertical scale for consistency, unless the data range exceeds 100 feet. Figure 9.1.14 shows hydrographs for wells completed in the Sparta aquifer in Frio and LaSalle counties. In general, both the measured and simulated hydrographs are flat. In LaSalle County, there is a slight downward trend in one of the simulated hydrographs, but it is less than 10 feet over 20 years. Figure 9.1.15 shows hydrographs for wells completed in the Sparta aquifer in Atascosa and Webb counties. Again, the simulated and measured hydrographs have very little trend. There is a slight upward trend in the hydrograph for one of the wells in Webb County that is matched by the model. Figure 9.1.16 shows hydrographs for wells completed in the Sparta aquifer in Wilson and Gonzales counties. Again, the measured and simulated hydrographs are flat, with no more than 5 feet of upward or downward trend over the course of the 20 year simulation. The lack of stress in the Sparta aquifer makes it difficult to evaluate the models predictive ability for this aquifer.

Figure 9.1.17 shows hydrographs for wells completed in the Queen City aquifer in Atascosa, Dimmitt, and Frio counties. In general, the measured and simulated hydrographs show very little trend. In the measured hydrograph for the well in Frio County that has a downward trend, the model is flat due to a lack of pumping in that area. This is an indication of a localized pumping effect, or a pumping well for which public information is not available. Figure 9.1.18 shows hydrographs for wells completed in the Queen City aquifer in LaSalle, McMullen, and Wilson counties. The slight downward trend in the measured hydrographs for wells in LaSalle County is reflected in the simulated hydrographs. Figure 9.1.19 shows hydrographs for wells completed in the Queen City aquifer in Caldwell, Gonzales, and Wilson counties. In all of these hydrographs, the measured and modeled trends are flat. As with the Sparta aquifer, a lack of significant pumping stress in the Queen City aquifer makes it difficult to evaluate the models predictive capabilities.

Figure 9.1.20 shows hydrographs for wells completed in the Carrizo aquifer in Gonzales, Wilson, Atascosa, and LaSalle counties. The model does a good job of reflecting the flat measured trend in the well in Gonzales County and the slightly downward measured trend in the well in Wilson County. The well in Atascosa County has a more significant measured downward trend that is again matched by the simulated results. As with the Southern Carrizo-Wilcox GAM, the measured hydrograph for the well in LaSalle County has a more significant downward trend than is simulated by the model. This is discussed earlier, where drawdowns in this part of the model are not sustained through the transient period. Figure 9.1.21 shows hydrographs for wells completed in the Carrizo aquifer in Frio, Zavala, Dimmit, and McMullen counties. The strong downward trend in the measured hydrographs for the wells in Frio and Zavala counties are correctly simulated by the model, as is the slight downward trend in the well in this part of Dimmit County. However, the simulated hydrograph for the well in Dimmit County suffers from the same offset and lack of drawdown that is observed in many of the hydrographs for wells in LaSalle County.

A few less cells went dry in the transient simulation compared to the steady-state simulation. Dry cells in the transient model are typically thin cells located at the farthest updip edge of layer outcrops. Because some of these cells are only 20-feet thick, the cells go dry if the water table is more than 20 feet below ground surface. The MODFLOW rewetting package is active, allowing these cells to resaturate given a subsequent increase of the water-table elevation. The activity of the rewetting package is the likely explanation for why the transient model has fewer dry cells than the steady-state model. Out of 7,944 outcrop cells, about 99 were dry at the end of the verification period. The drying of these thin edge cells is a physically correct condition and does not have an adverse impact on model results.

9.1.2.2 Stream-Aquifer Interaction

Direct comparisons of simulated streamflow to stream gages in the model area showed good agreement. However, this is expected because headwater streamflow rates were defined based upon the available gage data. The more important metric for aquifer-stream interaction is the gain/loss estimate. Table 9.1.2 shows a summary of stream calibration targets from various sources (described in more detail in Section 4.7). As expected, more streams are losing in the transient model than in the steady-state model. For example, the San Antonio River is now losing in the Carrizo-Wilcox aquifer, whereas it was gaining in the steady-state model. This switch is consistent with the LBG-Guyton and HDR estimates for 1950 and 1980-2000. Also, the Nueces River in the Carrizo-Wilcox aquifer went from losing 68 AFY/mile in the steady-state model to losing 222 AFY/mile in the transient model. This is also consistent with the LBG-Guyton and HDR estimates for 1950 and 1980-2000, although the simulated magnitude is less than estimated in the historical period. So the trend in river gain/loss is consistent with expectation for the steady-state and transient models.

For the Atascosa River, the simulated Carrizo-Wilcox result is consistent with the LBG-Guyton and HDR estimate for 1980-2000. The simulated result for all layers is gaining, which is consistent with the Brandes estimate, although smaller in magnitude. The simulated results for Cibolo Creek agree favorably with the Brandes (all layers) and the HDR estimate (all layers with tributaries), and are lower in magnitude than the Slade estimates. The all layers with tributaries simulated result was used to compare to the HDR estimate to be consistent with the approach of the Central region. LBG-Guyton and HDR has the Cibolo Creek as a losing stream in the Carrizo-Wilcox aquifer in the historical period (1980-2000), which contradicts all other sources in the table. For the Frio River, Brandes has a gaining estimate while LBG-Guyton and HDR has a losing estimate. The model simulated result is losing, but is bracketed by the two other estimates in magnitude. The simulated value for the Guadalupe River is similar to the LBG-Guyton and HDR estimate for 1980-2000, but is less in magnitude than the Brandes and HDR estimates. In the Leona River, the simulated result is losing, but is less in magnitude than the only measured estimate made by Slade. Similar to the Frio River, the simulated Nueces River result is bracketed by the Brandes and LBG-Guyton and HDR estimates, all of which are smaller in magnitude than the Slade estimate. As in the steady-state model, the magnitude of the simulated result for the San Marcos River is considerably larger than the target values. However, the amount of discharge in this area is necessary to maintain the correct head surface. The simulated river may be acting as a surrogate for other discharge mechanisms not being modeled.

Figures 9.1.22 and 9.1.23 show the stream gains/losses for years 1989 and 1996, respectively. As with the steady-state model, the streams are more typically losing in the western portion of the model and typically gaining in the eastern portion of the model. A comparison of the two figures shows that during drier times (1989) the streams have less flow and lower stages, so they lose less total water.

9.1.2.3 Water Budget

Table 9.1.3 shows the water budget for the transient model totaled for years 1980, 1988 (lowest annual precipitation in the calibration period), 1990, and 1999. Figure 9.1.24 shows the change in model-wide rates over the period from 1980 through 1999. In the overall model, the greatest influx of water consistently occurs from recharge, and the greatest outflow of water consistently occurs from pumping. Stream leakance and storage account for large amounts of influx or outflow, depending on climatic conditions for the model. Most of the pumping is from the Carrizo Formation. Pumping in the Sparta and Queen City aquifers is not significant in the flow balance.

In 1980, for example, pumping accounts for approximately 324,000 AFY of water extracted from the model, while recharge adds 178,000 AFY of water and 88,000 AFY of water is lost through the streams. Groundwater ET and flow from GHBs are not as significant. The outcrop and downdip sections operate nearly independently over the simulation time period. The streams and recharge dominate outcrop hydrogeology. Pumping and storage are the main components of downdip hydrogeology. Throughout the time period, recharge increases and decreases, affecting the amount of water going in and out of the streams and, to a lesser extent, groundwater ET. Downdip, pumping mostly removes water from storage. The effect of pumping on storage is sometimes masked in the flow balance table by the large exchange of water that occurs in the outcrop during a given period.

The Carrizo layer as a single unit is most affected by pumping. Pumping in the Carrizo aquifer draws water from storage in the layer and from cross-formational flow from above and below. The net flow of water from the Reklaw Formation to the Carrizo aquifer indicates that some of the gradients seen in the steady-state model, where water was flowing up and out of the Carrizo aquifer through the Reklaw Formation, have been reversed by pumping in the Carrizo aquifer.

Table 9.1.1 Calibration statistics for the Southern transient model for the calibration and verification periods.

<table>
<tr><th colspan="7">Calibration period (1980-1989)</th></tr>
<tr><th>Layer</th><th>Count</th><th>ME (ft)</th><th>MAE (ft)</th><th>RMSE (ft)</th><th>Range (ft)</th><th>RMSE/ Range</th></tr>
<tr><td>1</td><td>204</td><td>-2.9</td><td>18.0</td><td>22.7</td><td>285.6</td><td>0.079</td></tr>
<tr><td>3</td><td>189</td><td>-0.7</td><td>15.5</td><td>18.1</td><td>228.9</td><td>0.079</td></tr>
<tr><td>5</td><td>1325</td><td>0.7</td><td>24.6</td><td>33.1</td><td>509.5</td><td>0.065</td></tr>
<tr><td colspan="7"></td></tr>
<tr><th colspan="7">Verification period (1990-1999)</th></tr>
<tr><th>Layer</th><th>Count</th><th>ME (ft)</th><th>MAE (ft)</th><th>RMSE (ft)</th><th>Range (ft)</th><th>RMSE/ Range</th></tr>
<tr><td>1</td><td>133</td><td>-2.1</td><td>14.8</td><td>18.9</td><td>207.4</td><td>0.091</td></tr>
<tr><td>3</td><td>111</td><td>-5.7</td><td>18.3</td><td>21.6</td><td>221.5</td><td>0.098</td></tr>
<tr><td>5</td><td>883</td><td>4.3</td><td>35.1</td><td>47.6</td><td>564.8</td><td>0.084</td></tr>
</table>

Table 9.1.2 **Comparison of simulated stream leakance to various estimates for the Southern region (AFY per mile of stream).**

Source ->	Brandes	LBG-Guyton and HDR		HDR	Slade		Simulated			
Time Period ->	**N/A**	**1950**	**1980-2000**	**~1950**	**~1930-1960**		**1980-1999**			
Formation->	**All**	**Carrizo-Wilcox**	**Carrizo-Wilcox**	**Carrizo-Wilcox**	**QCSP**	**Carrizo**	**QCSP**	**Carrizo-Wilcox**	**All Layers**	**All Layers with tributaries**
Atascosa River	151	270	-50				63	-82	13	
Cibolo Creek	41	200	-100	223	215	486	93	87	80	212
Frio River	108	-100	-500				-62	-61	-55	
Guadalupe River	235	180	50	519			65	40	48	50
Leona River					-204	-469	-28	-16	-21	
Nueces River	-159	0	-500		825	-828	22	-222	-5	
Rio Grande	-70				-1406		57	94	0	
San Antonio River	215	540	-325	269			430	-41	70	17
San Marcos River	-278		100	150			170	667	488	301
San Miguel River		-110	-100				-61	N/A	-51	

Table 9.1.3 Water budget for the Southern transient model. All rates reported in AFY.

Year	Layer	Reserv.	ET	Drains	Rech.	GHBs	Streams	Storage	Wells	Bot. Flow	Top Flow
1980	1	0	-7,476	-1,409	21,220	-15,926	-39,315	45,759	-5,214	2,362	0
	2	0	-1,199	-541	3,168	-33	-4,079	10,336	0	-5,291	-2,362
	3	0	-5,773	-238	55,769	-238	-14,493	2,125	-6,270	-36,176	5,291
	4	0	-441	-223	5,846	-61	-1,214	-4,147	0	-35,937	36,176
	5	0	-4	0	53,020	-4,113	-4,055	185,261	-237,787	-28,262	35,937
	6	0	0	0	490	926	-415	-1,712	-32,638	5,086	28,262
	7	1,675	-118	-226	20,078	3,454	-20,839	24,198	-22,234	-904	-5,086
	8	0	-104	-615	18,265	5,036	-3,217	-179	-20,094	0	904
	Sum	1,675	-15,115	-3,252	177,856	-10,955	-87,627	261,641	-324,237	-99,122	99,122
1988	1	0	-5,683	-1,141	14,935	-14,108	-42,710	51,712	-1,495	-1,510	0
	2	0	-974	-444	2,270	-39	-4,196	9,539	0	-7,666	1,510
	3	0	-1,674	-125	36,780	-392	-66,386	65,430	-2,236	-39,066	7,666
	4	0	-241	-189	3,979	-85	-29,126	30,937	0	-44,344	39,066
	5	0	-3	0	33,918	-4,641	-5,312	161,118	-211,031	-18,395	44,344
	6	0	0	0	373	585	-3,144	2,574	-26,548	7,765	18,395
	7	1,708	-37	-137	12,698	1,967	-18,219	29,848	-23,349	3,282	-7,765
	8	0	-303	-328	11,476	2,710	-4,334	6,794	-12,735	0	-3,282
	Sum	1,708	-8,915	-2,364	116,429	-14,002	-173,427	357,951	-277,394	-99,935	99,935

Table 9.1.3, continued

Year	Layer	Reserv.	ET	Drains	Rech.	GHBs	Streams	Storage	Wells	Bot. Flow	Top Flow
1990	1	0	-2,881	-1,077	29,379	-13,458	46,669	-54,673	-1,775	-2,188	0
	2	0	-202	-419	4,397	-41	15,403	-13,152	0	-8,179	2,188
	3	0	-694	-114	75,209	-406	142,475	-180,474	-2,495	-41,700	8,179
	4	0	-518	-182	7,791	-85	92,627	-89,880	0	-51,457	41,700
	5	0	-21	0	70,378	-4,715	12,657	107,278	-221,986	-15,056	51,457
	6	0	0	0	817	528	2,794	-3,960	-25,605	10,368	15,056
	7	1,673	-70	-157	26,116	1,594	-9,933	10,205	-23,985	4,919	-10,368
	8	0	-297	-378	24,505	2,289	-9	-6,238	-14,958	0	-4,919
	Sum	1,673	-4,683	-2,326	238,594	-14,295	302,682	-230,893	-290,804	-103,294	103,294
1999	1	0	-4,018	-845	14,364	-10,181	-71,664	80,185	-3,042	-4,805	0
	2	0	-871	-341	2,121	-41	-16,278	20,695	0	-10,094	4,805
	3	0	-3,897	-62	39,176	-518	-59,051	63,505	-1,676	-47,592	10,094
	4	0	-2,719	-148	4,294	-85	-102,440	110,599	0	-57,097	47,592
	5	0	-29	0	40,061	-4,910	-9,551	144,310	-221,645	-5,339	57,097
	6	0	-4	0	472	303	-824	89	-18,870	13,493	5,339
	7	1,652	-280	-116	14,628	491	-11,656	25,763	-22,594	5,600	-13,493
	8	0	-1,724	-82	13,651	1,091	-1,761	10,661	-16,379	0	-5,600
	Sum	1,652	-13,544	-1,593	128,767	-13,850	-273,224	455,807	-284,206	-105,834	105,834

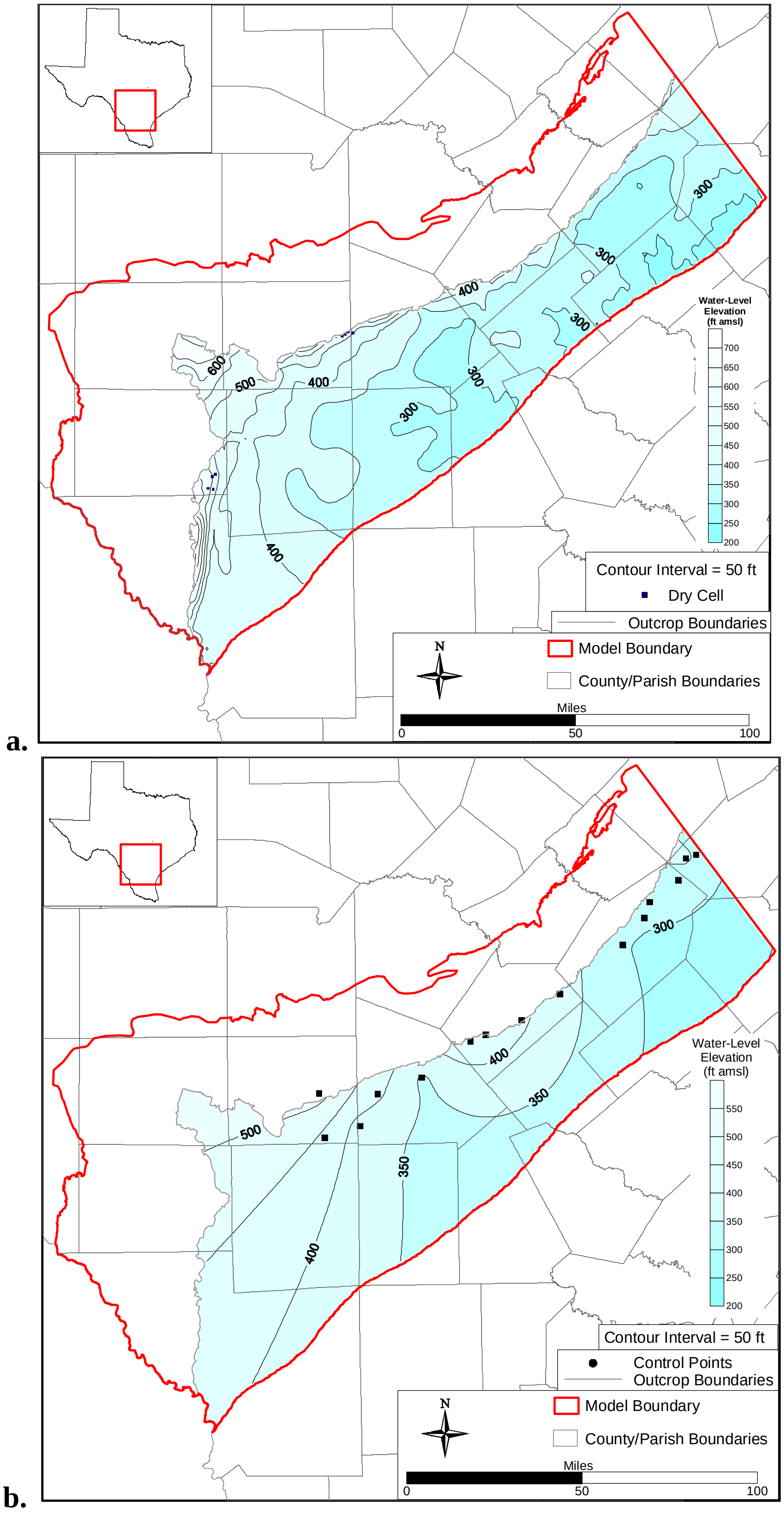


Figure 9.1.1 Comparison between simulated (a) and estimated (b) Sparta aquifer (Layer 1) heads for 1990 (the end of the calibration period).

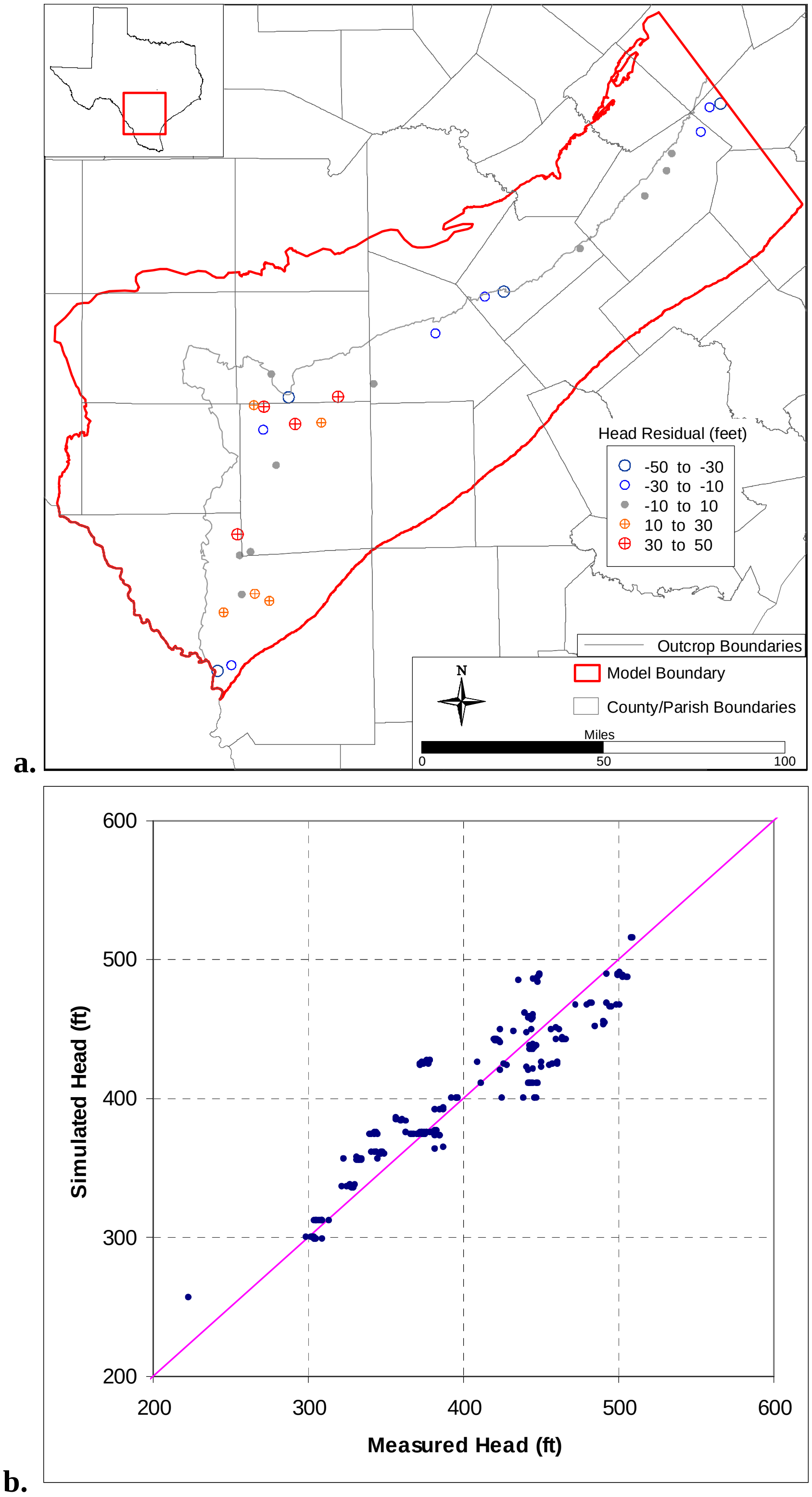


Figure 9.1.2 Residuals (a) and scatterplot (b) for the Sparta aquifer (Layer 1) in the calibration period.

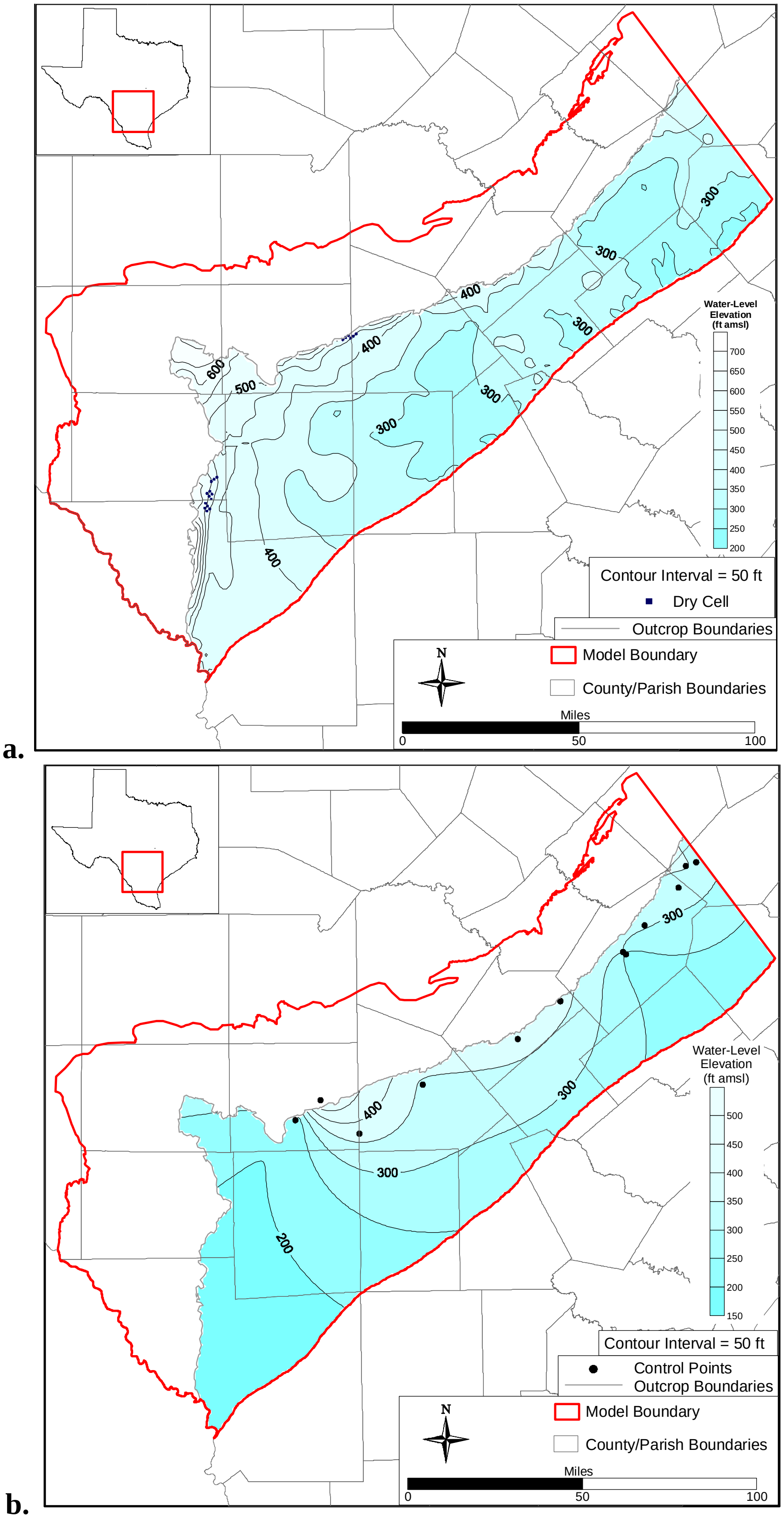


Figure 9.1.3 **Comparison between simulated (a) and estimated (b) Sparta aquifer (Layer 1) heads for 1999 (the end of the verification period).**

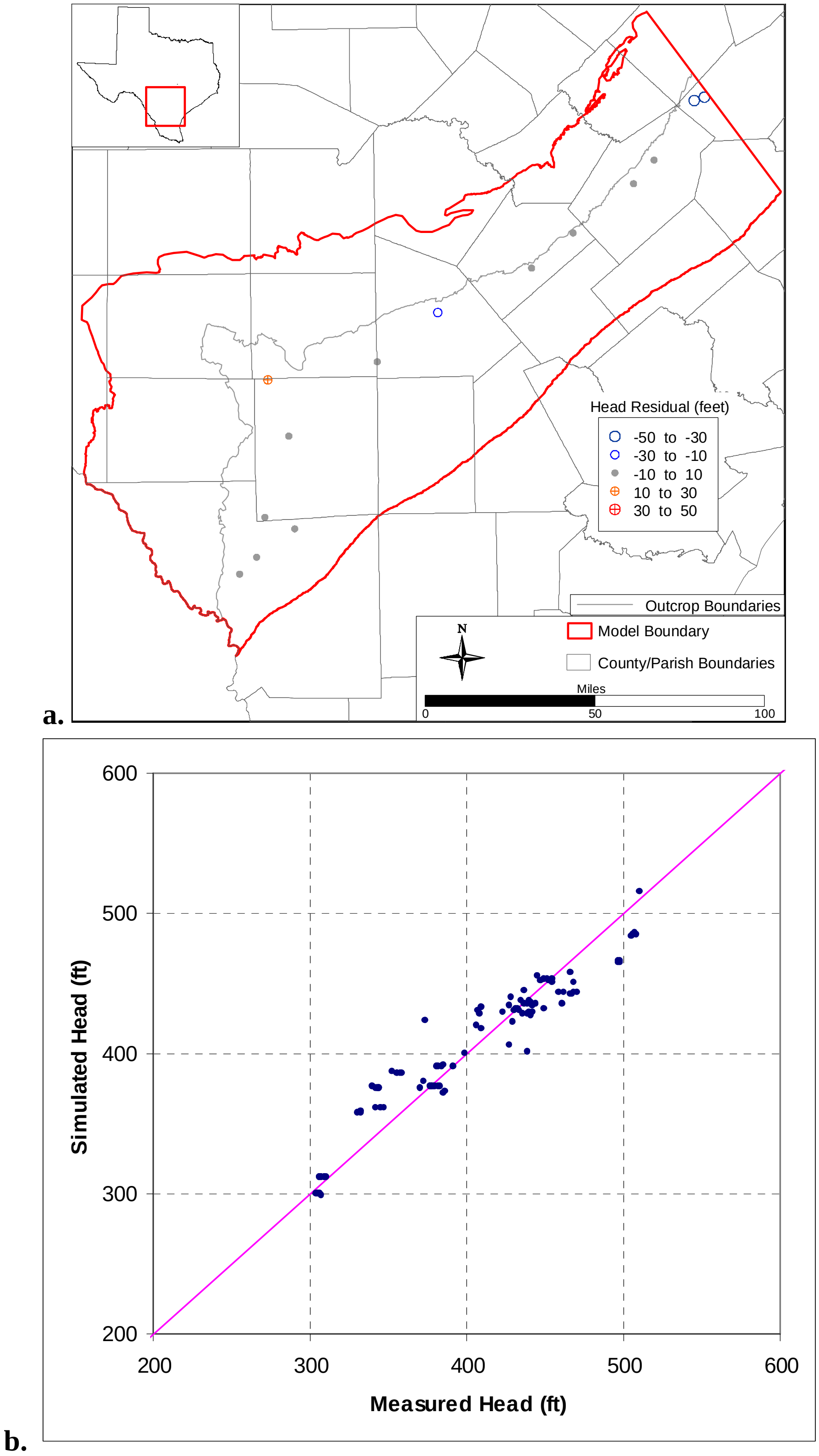


Figure 9.1.4 Residuals (a) and scatterplot (b) for the Sparta aquifer (Layer 1) in the verification period.

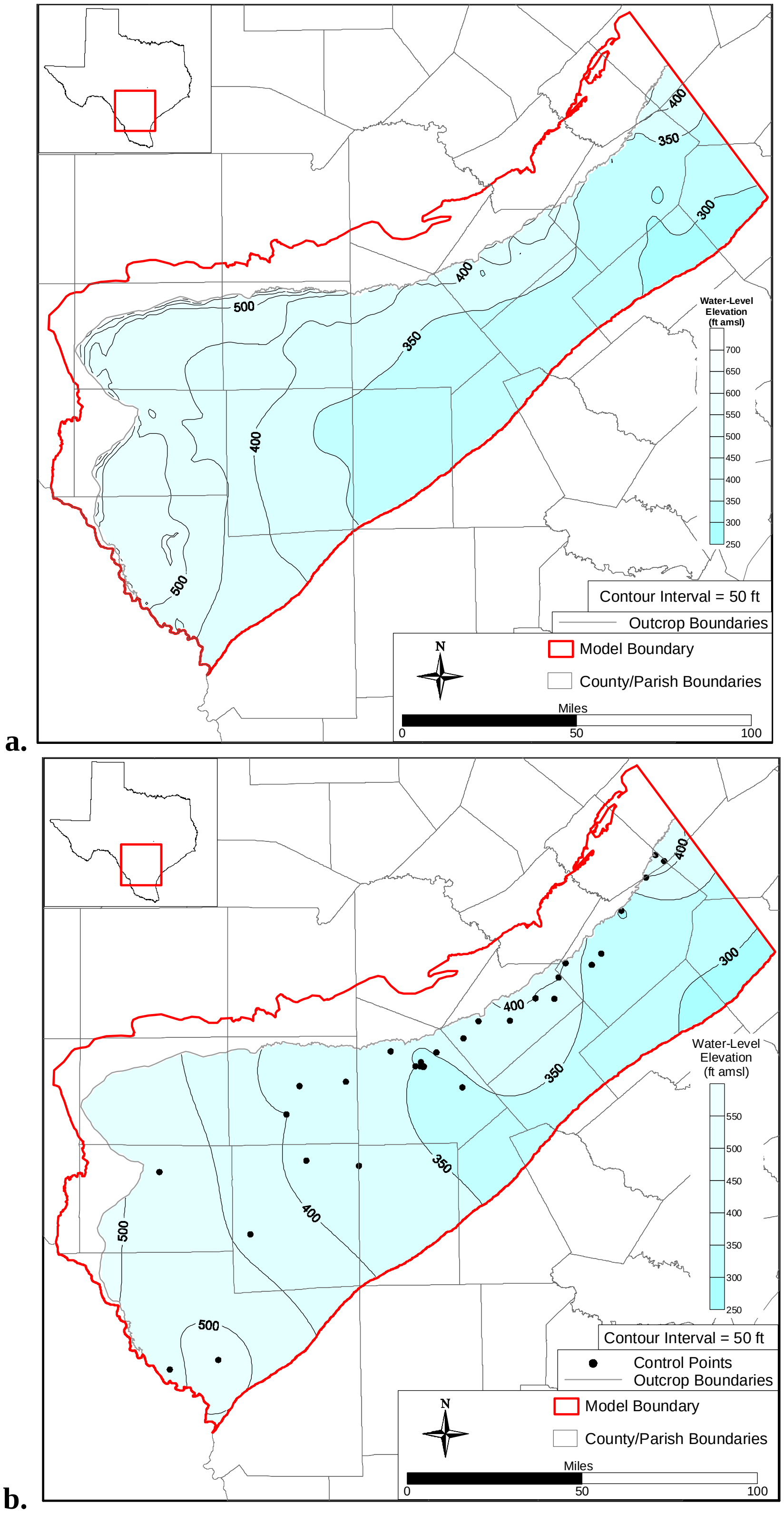


Figure 9.1.5 Comparison between simulated (a) and estimated (b) Queen City aquifer (Layer 3) heads for 1990 (the end of the calibration period).

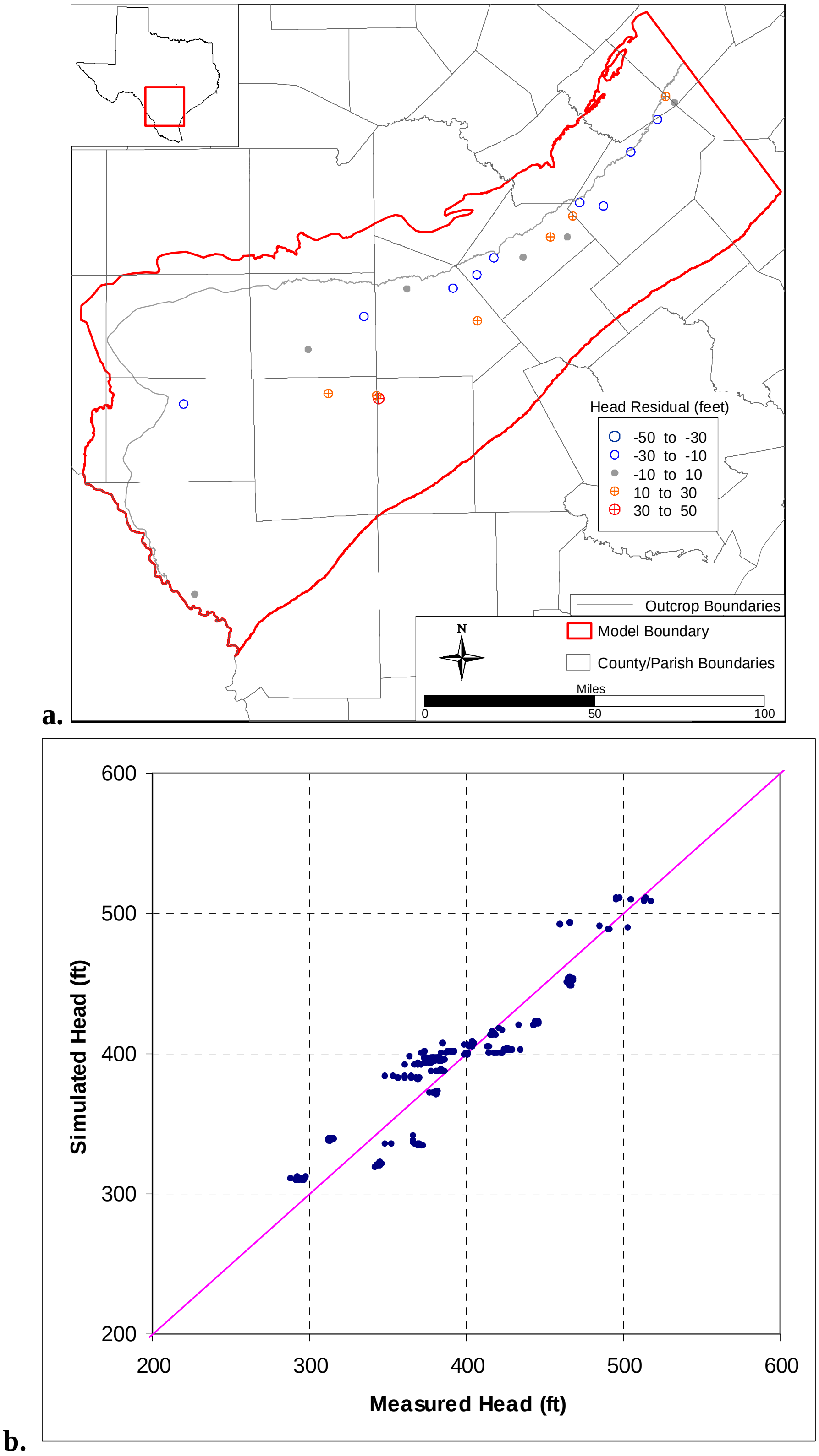


Figure 9.1.6 Residuals (a) and scatterplot (b) for the Queen City aquifer (Layer 3) in the calibration period.

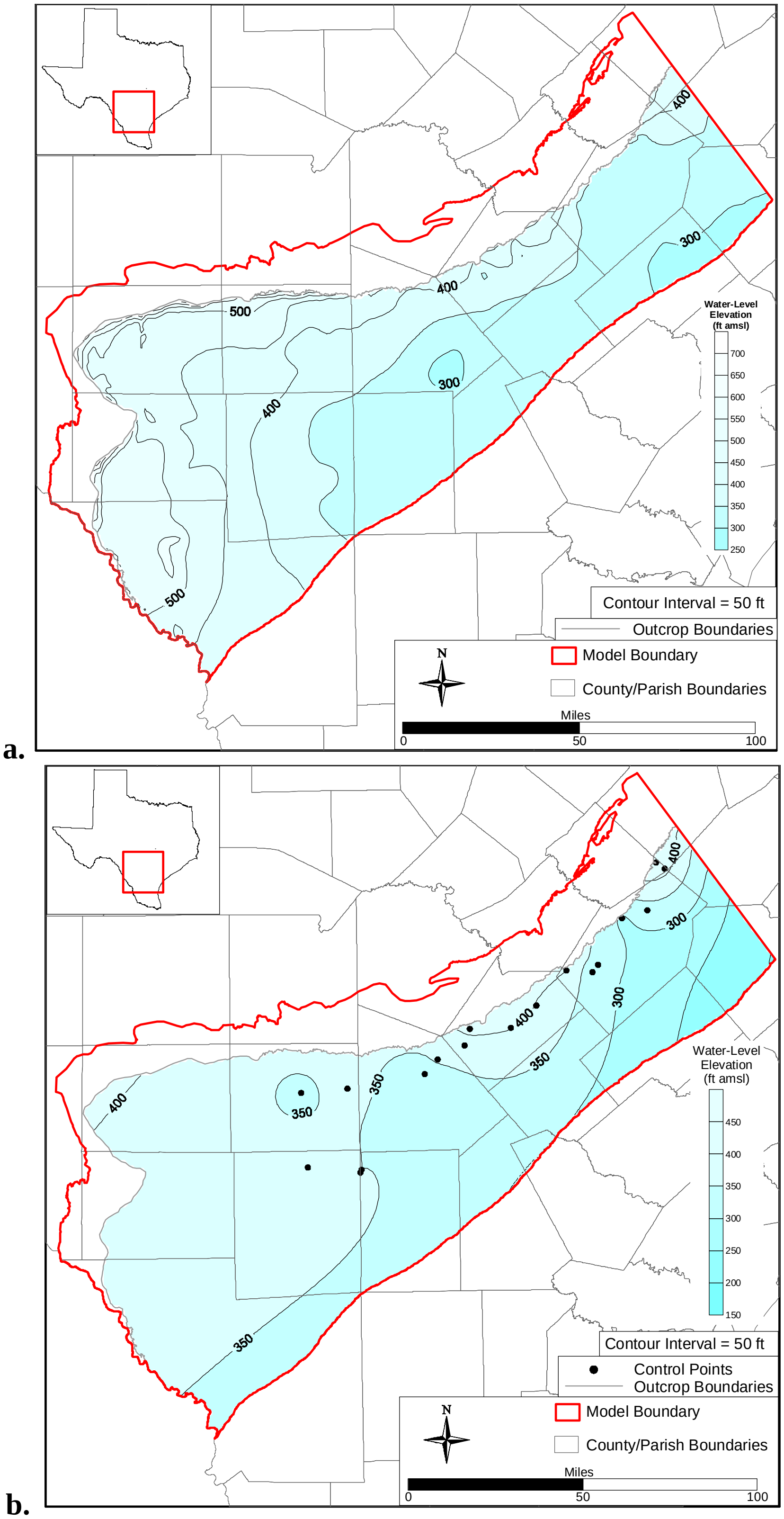


Figure 9.1.7 **Comparison between simulated (a) and estimated (b) Queen City aquifer (Layer 3) heads for 1999 (the end of the verification period).**

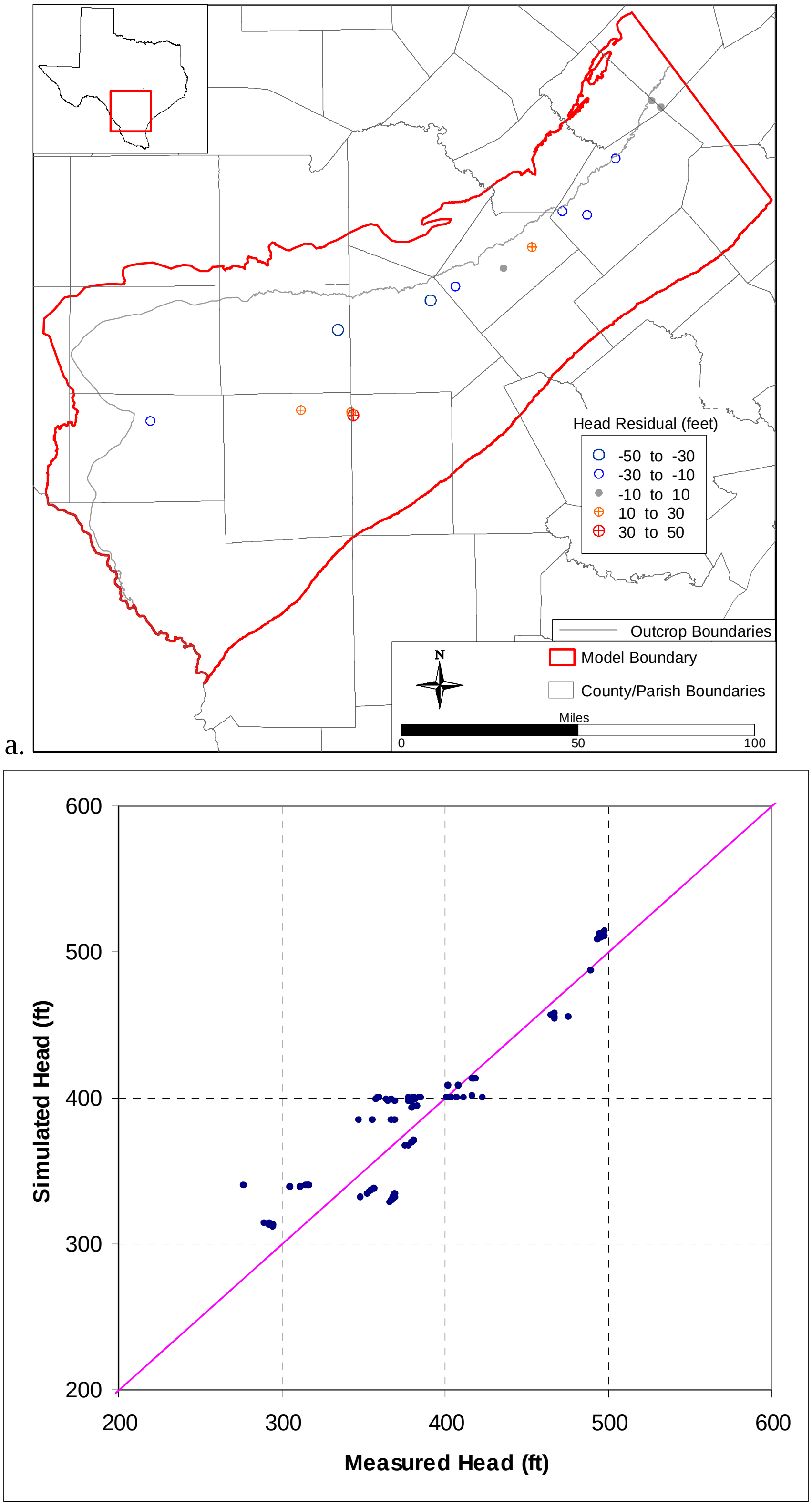


Figure 9.1.8 **Residuals (a) and scatterplot (b) for the Queen City aquifer (Layer 3) in the verification period.**

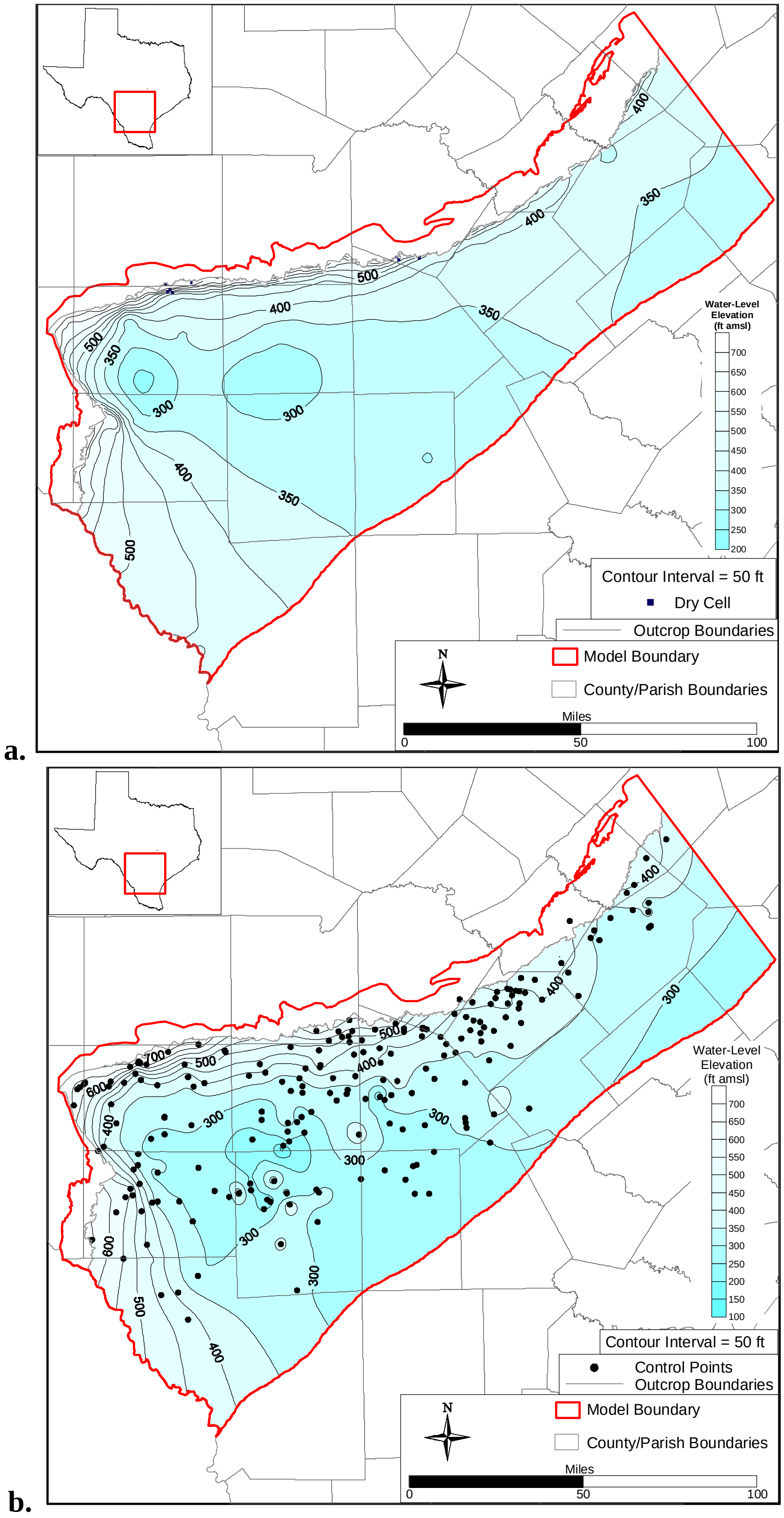


Figure 9.1.9 **Comparison between simulated (a) and estimated (b) Carrizo aquifer (Layer 5) heads for 1990 (the end of the calibration period).**

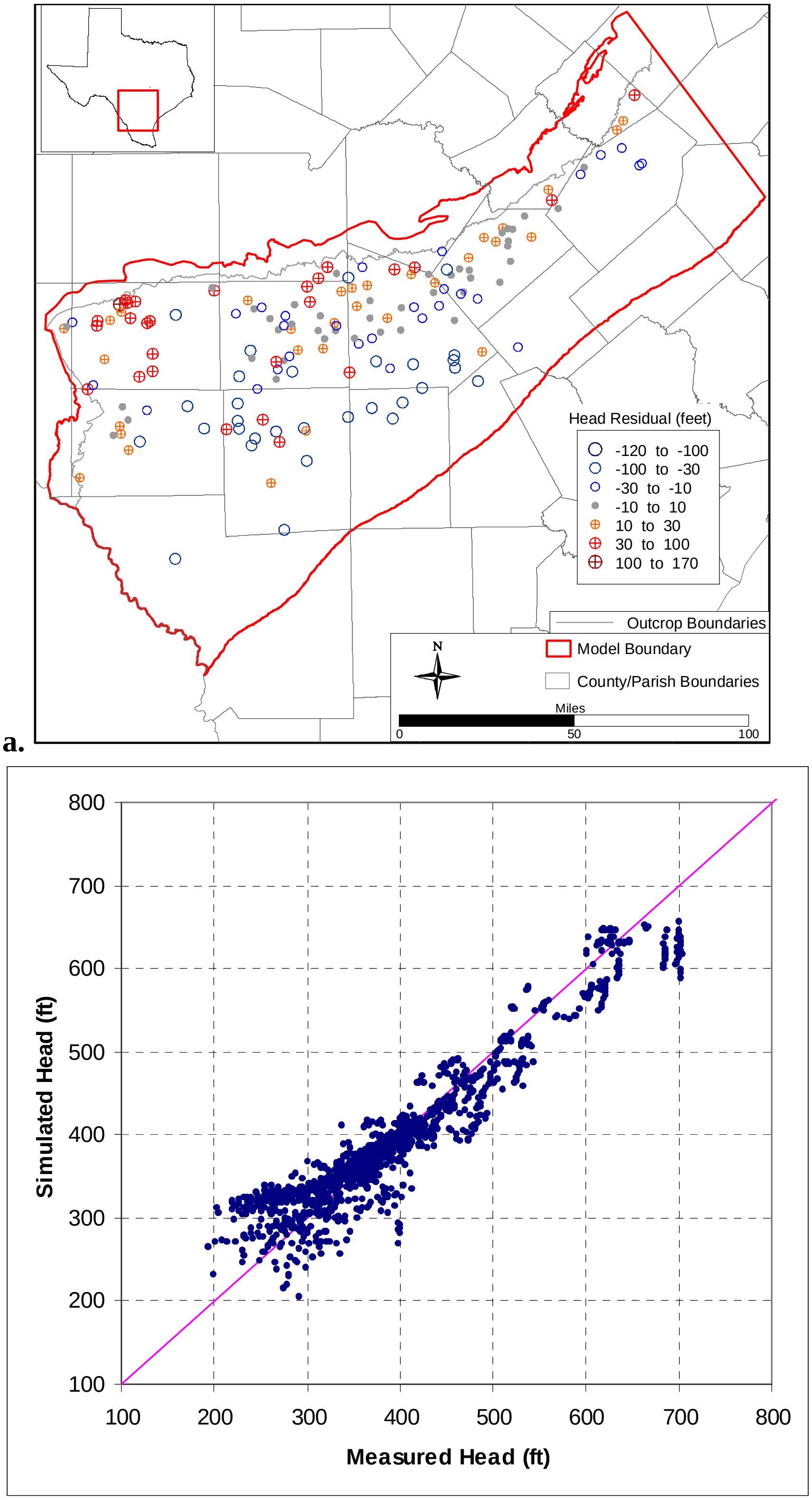


Figure 9.1.10 Residuals (a) and scatterplot (b) for the Carrizo aquifer (Layer 5) in the calibration period.

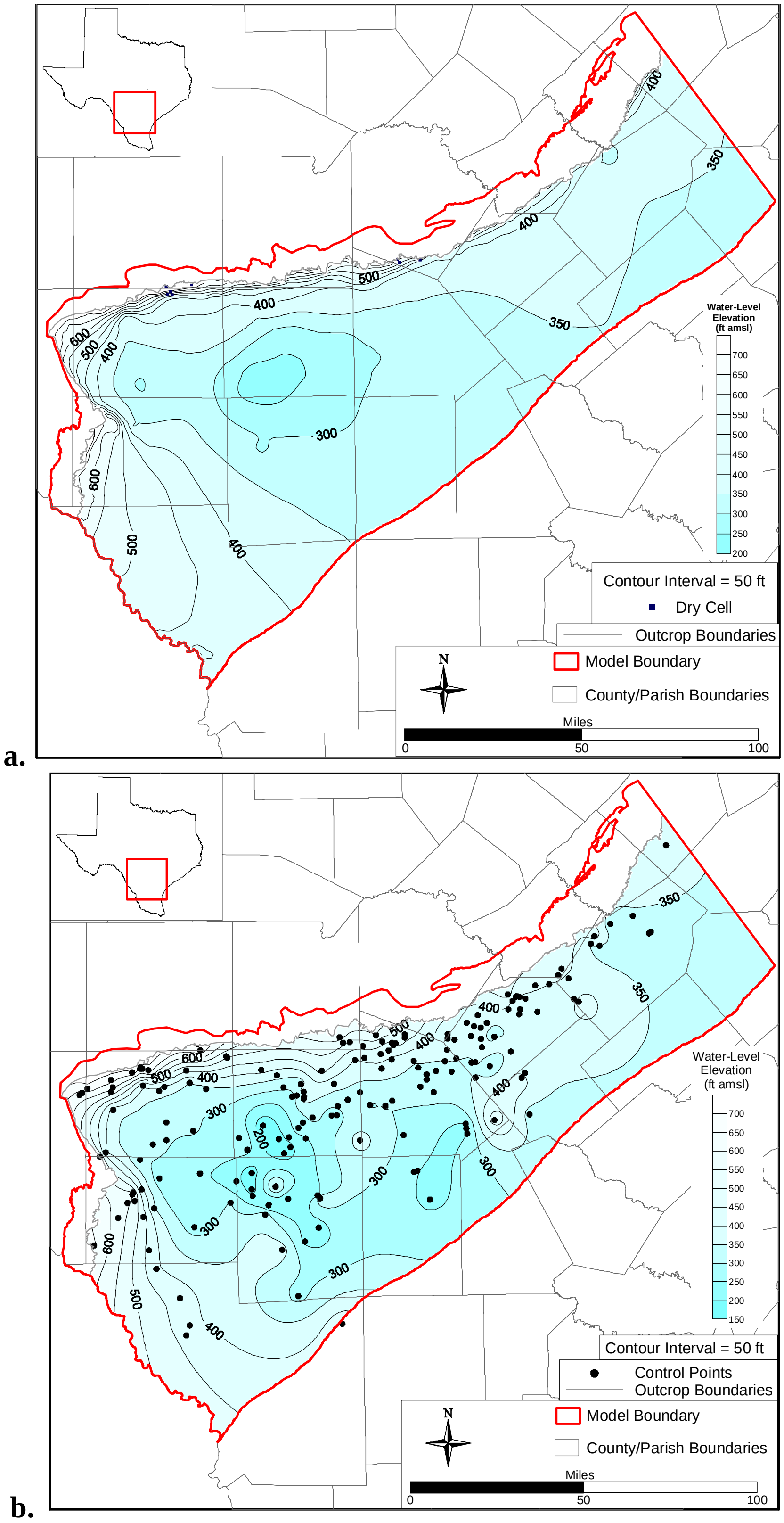


Figure 9.1.11 Comparison between simulated (a) and estimated (b) Carrizo aquifer (Layer 5) heads for 1999 (the end of the verification period).

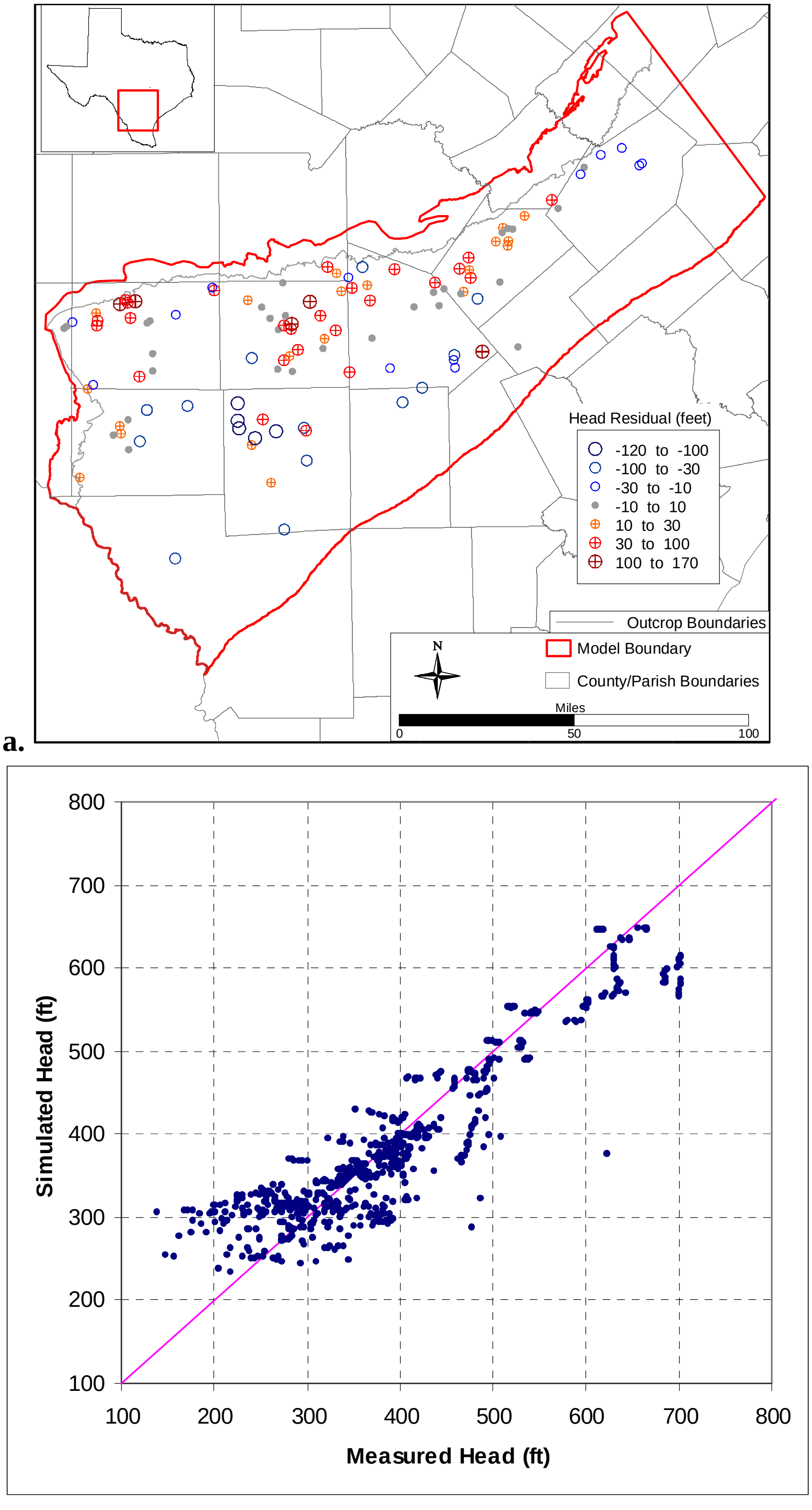


Figure 9.1.12 Residuals (a) and scatterplot (b) for the Carrizo aquifer (Layer 5) in the verification period.

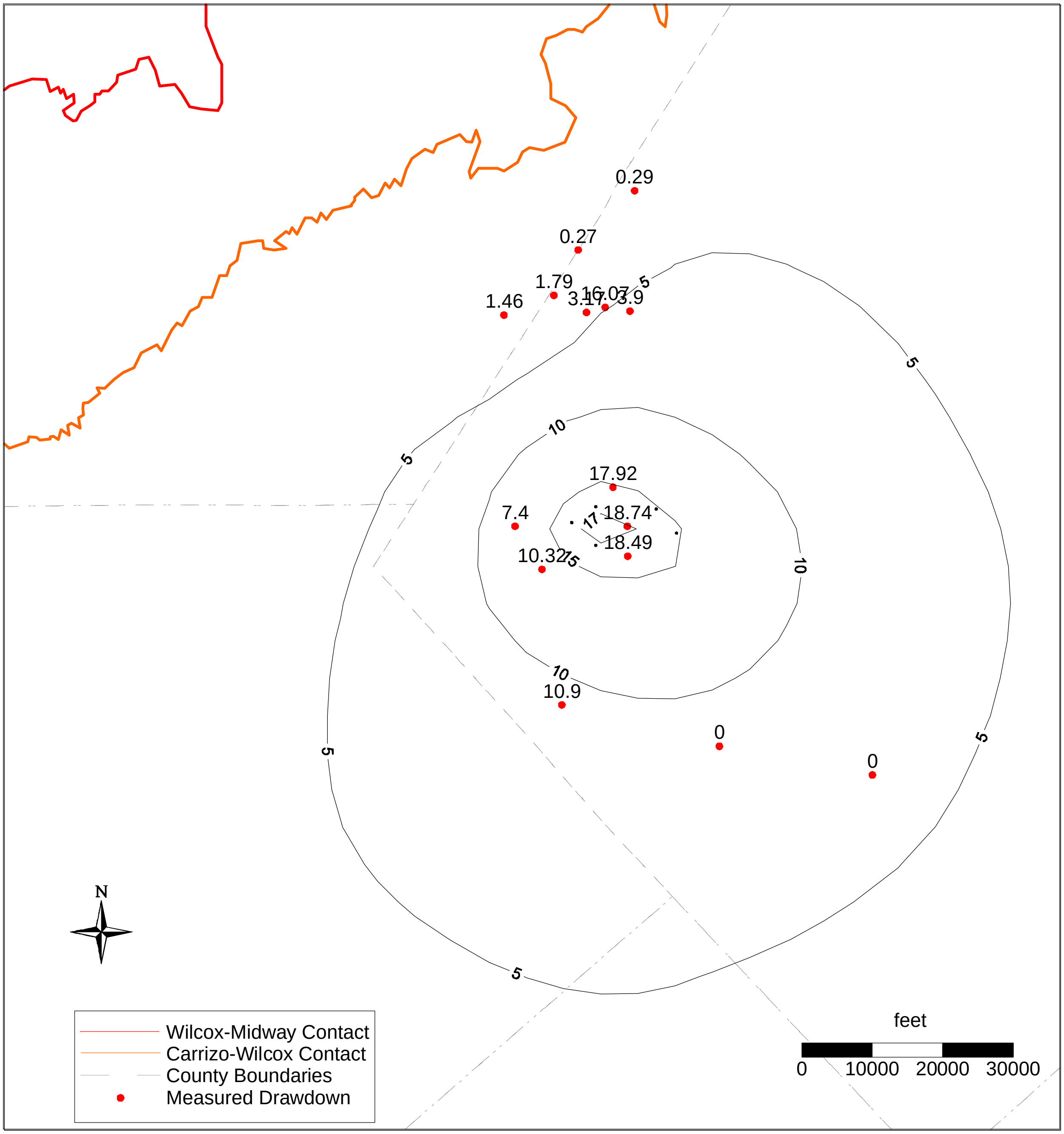


Figure 9.1.13 Comparison of simulated Schertz-Seguin drawdown with measured drawdown values for the first year of production.

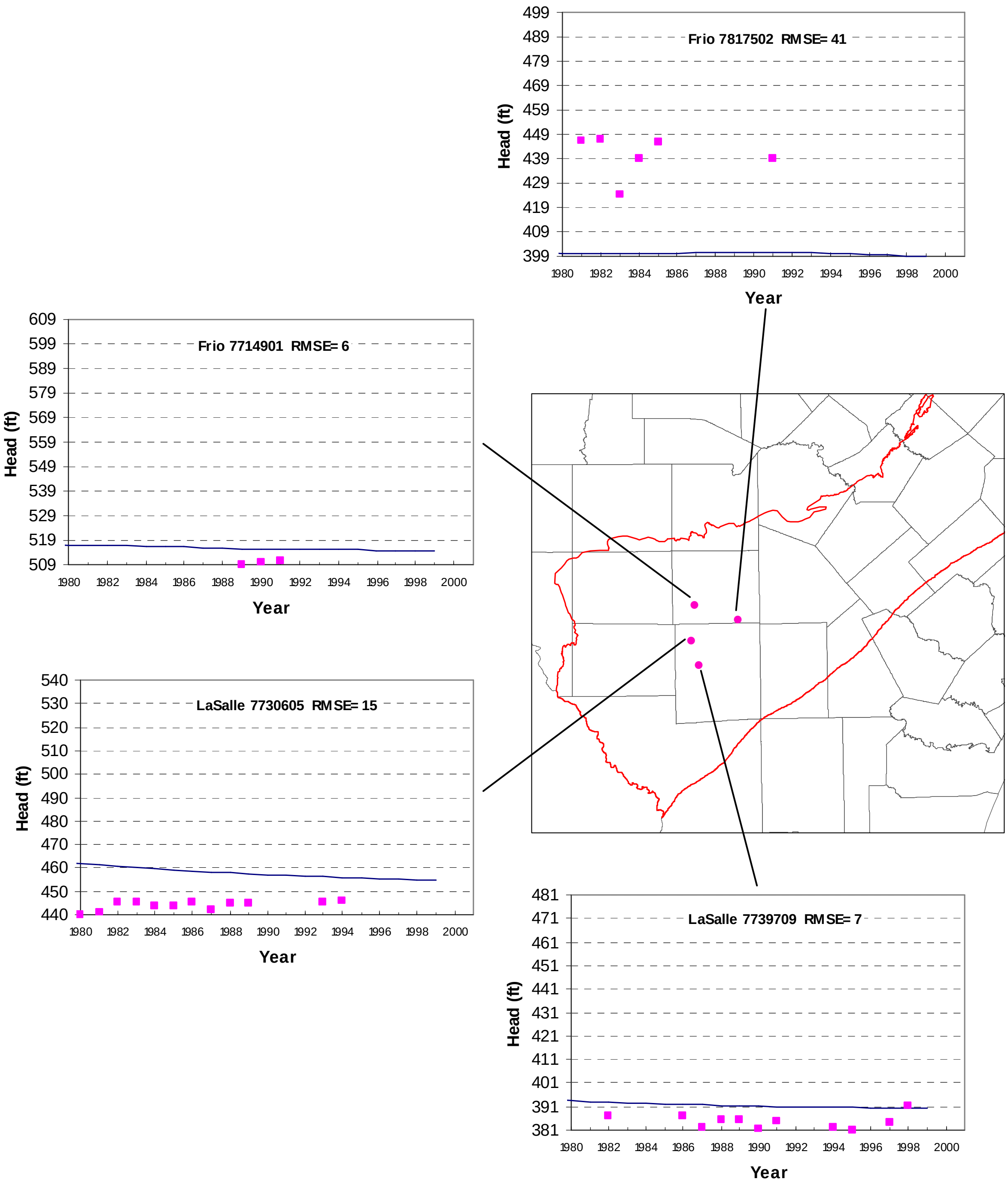


Figure 9.1.14 Selected Sparta aquifer (Layer 1) hydrographs of simulated (lines) and measured (points) hydraulic heads in Frio and LaSalle counties.

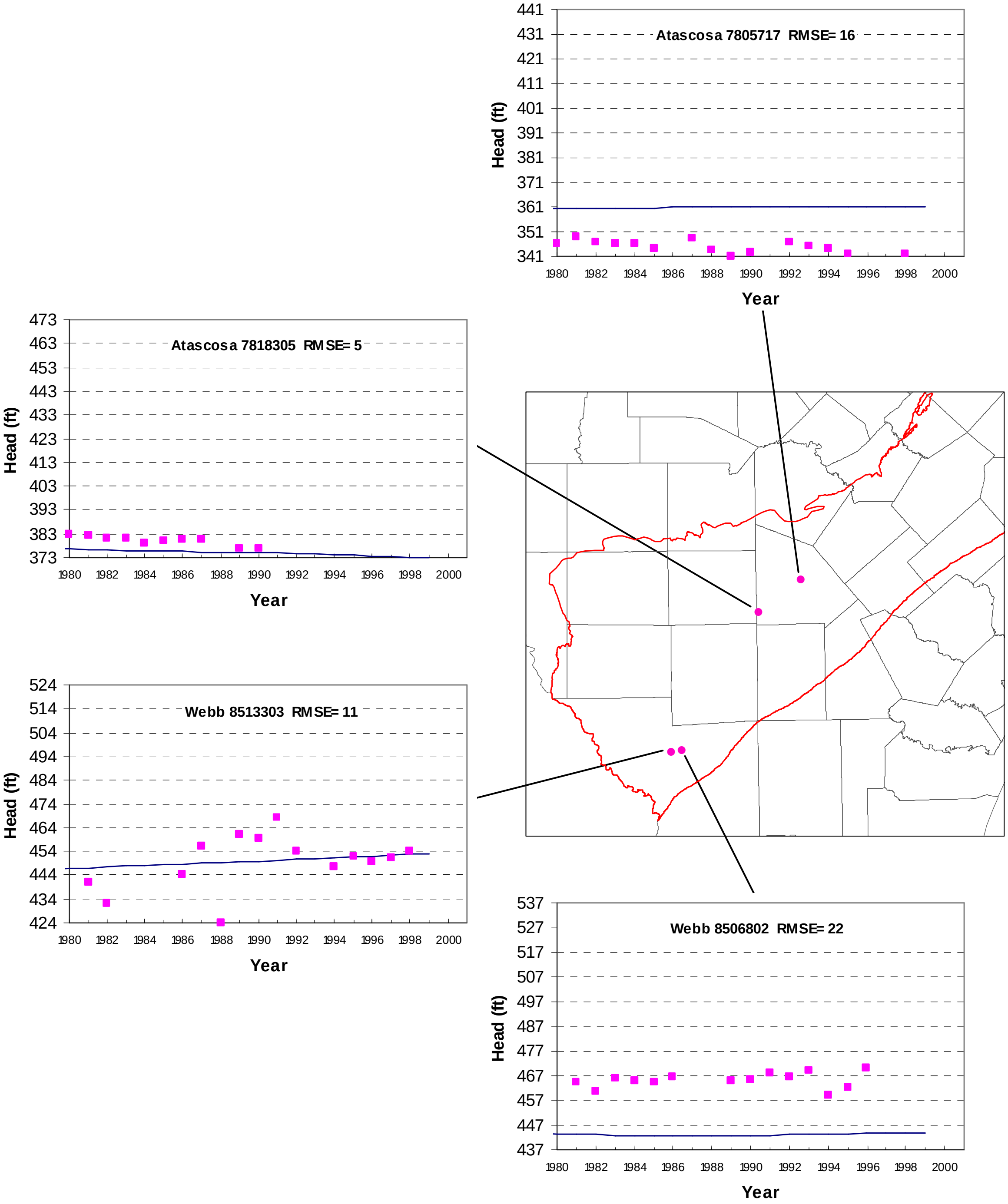


Figure 9.1.15 Selected Sparta aquifer (Layer 1) hydrographs of simulated (lines) and measured (points) hydraulic heads in Atascosa and Webb counties.

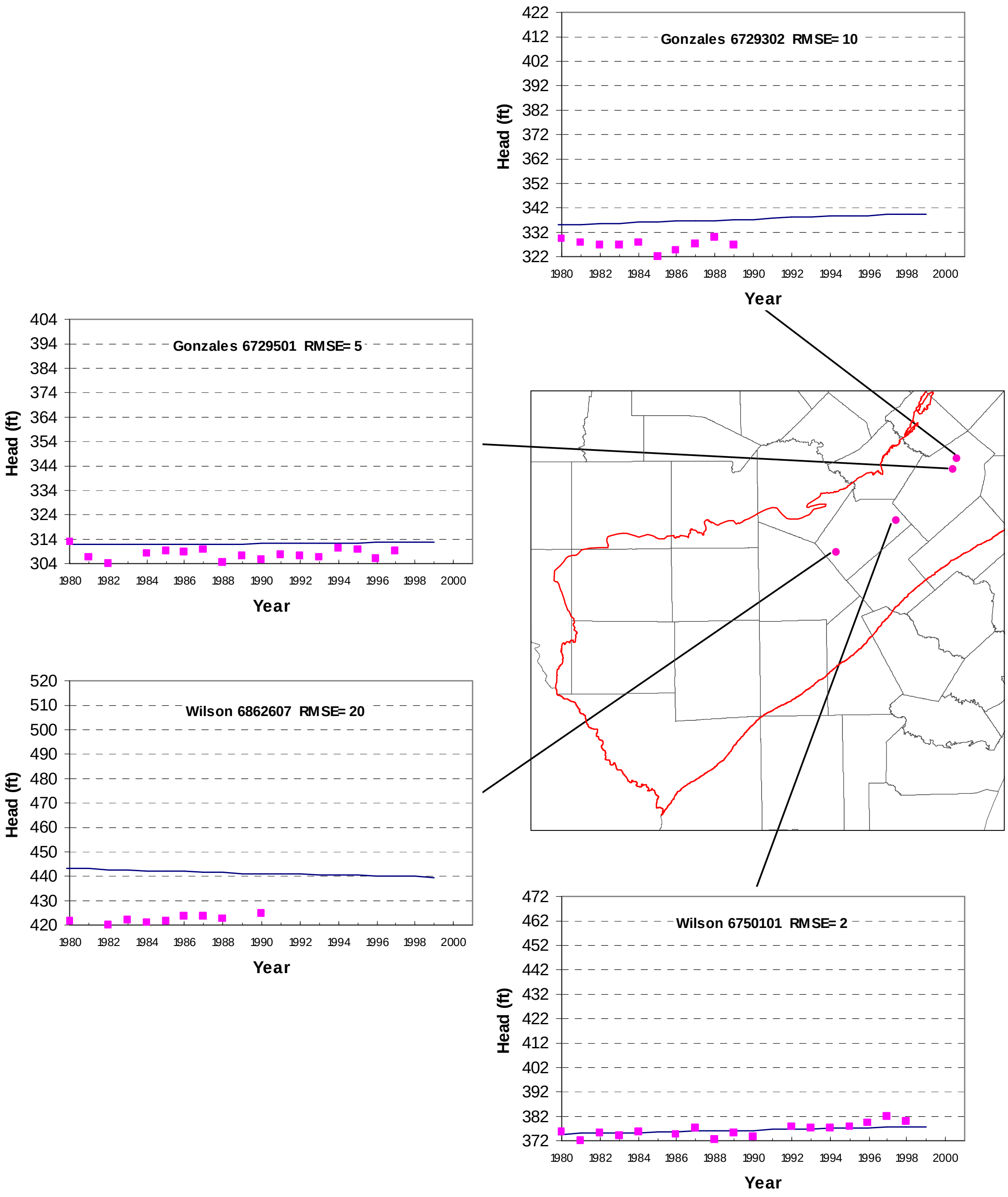


Figure 9.1.16 Selected Sparta aquifer (Layer 1) hydrographs of simulated (lines) and measured (points) hydraulic heads in Gonzales and Wilson counties.

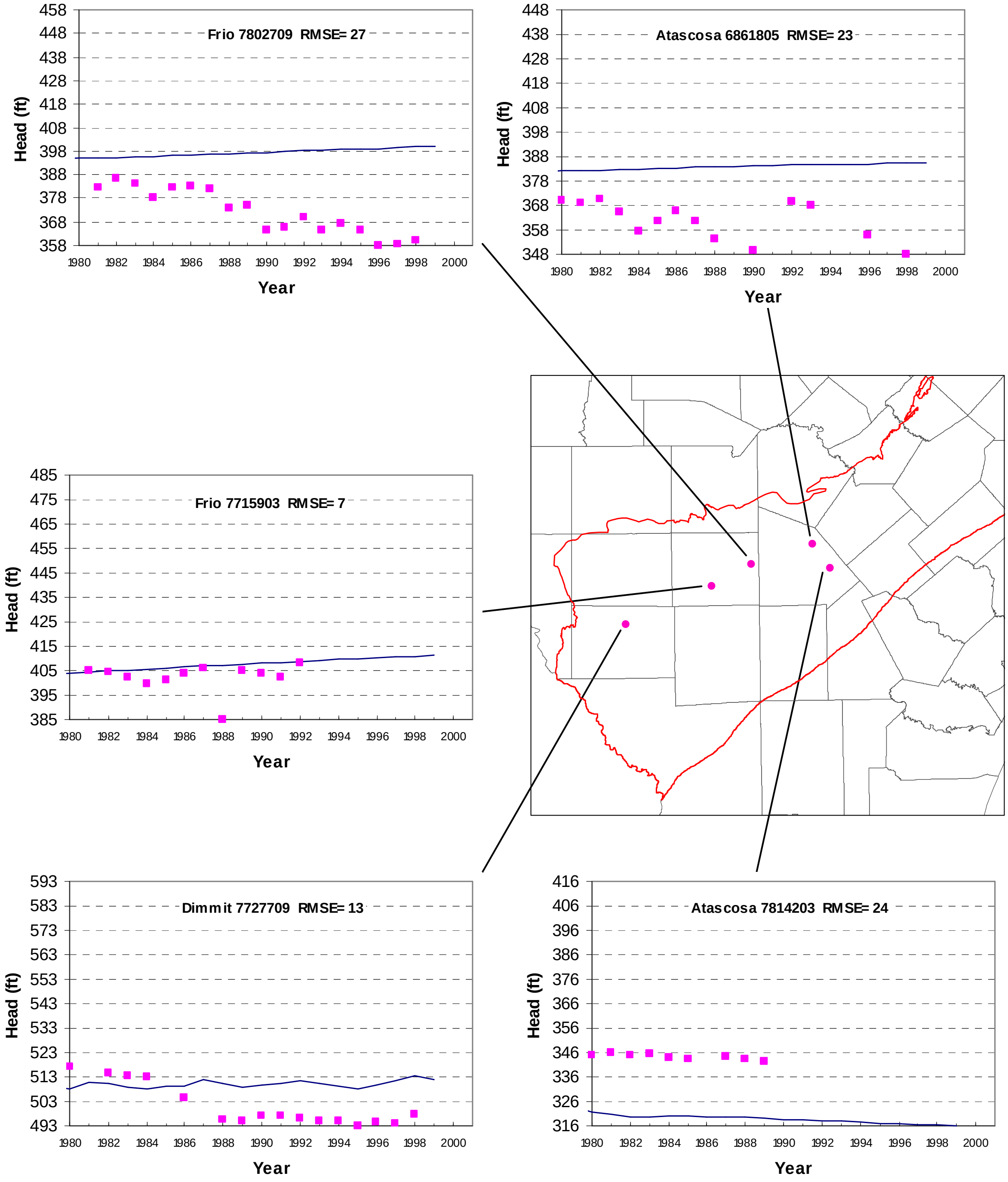


Figure 9.1.17 Selected Queen City aquifer (Layer 3) hydrographs of simulated (lines) and measured (points) hydraulic heads in Atascosa, Dimmit, and Frio counties.

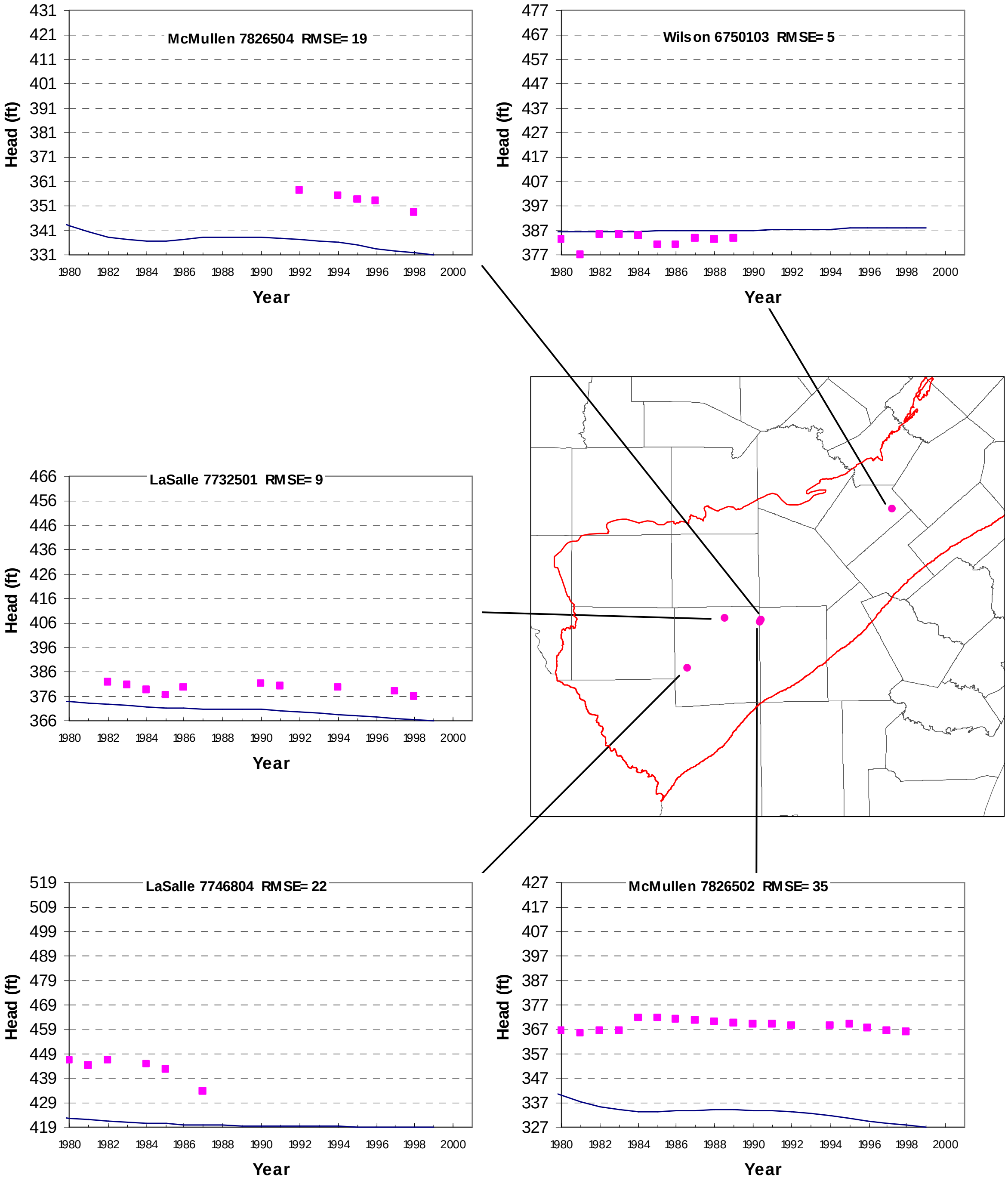


Figure 9.1.18 Selected Queen City aquifer (Layer 3) hydrographs of simulated (lines) and measured (points) hydraulic heads in LaSalle, McMullen, and Wilson counties.

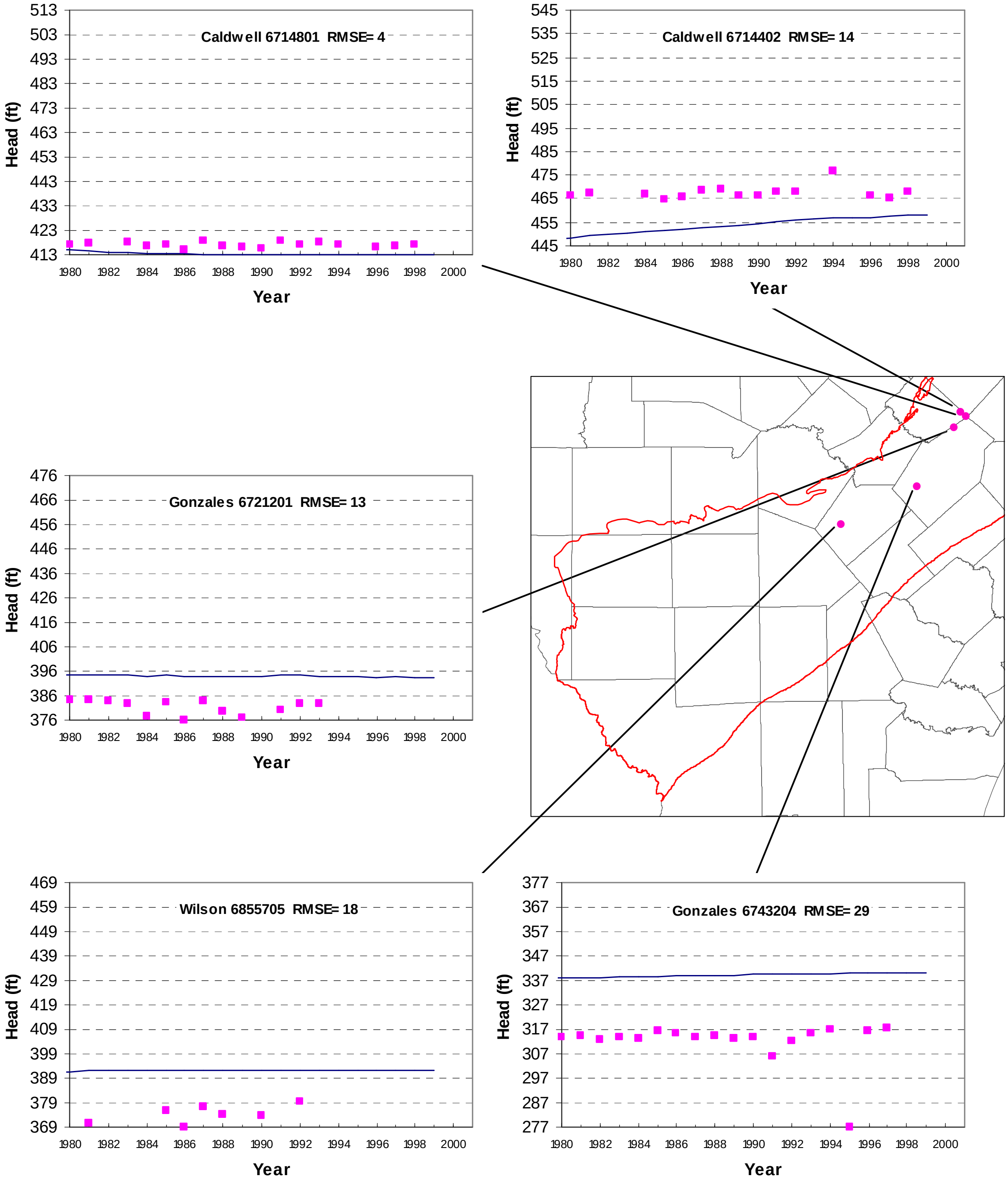


Figure 9.1.19 Selected Queen City aquifer (Layer 3) hydrographs of simulated (lines) and measured (points) hydraulic heads in Caldwell, Gonzales, and Wilson counties.

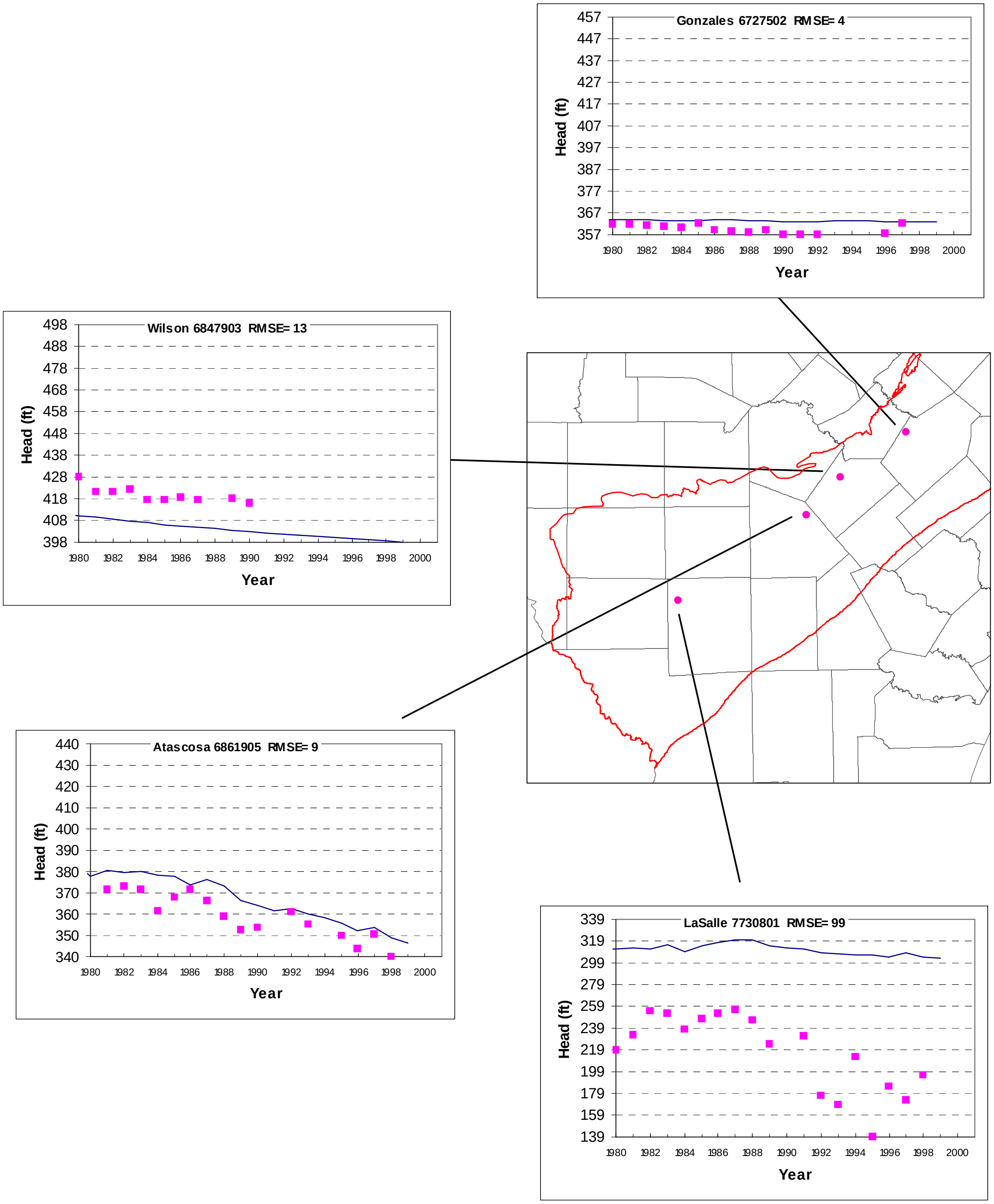


Figure 9.1.20 Selected Carrizo aquifer (Layer 5) hydrographs of simulated (lines) and measured (points) hydraulic heads in Atascosa, Gonzales, LaSalle, and Wilson counties.

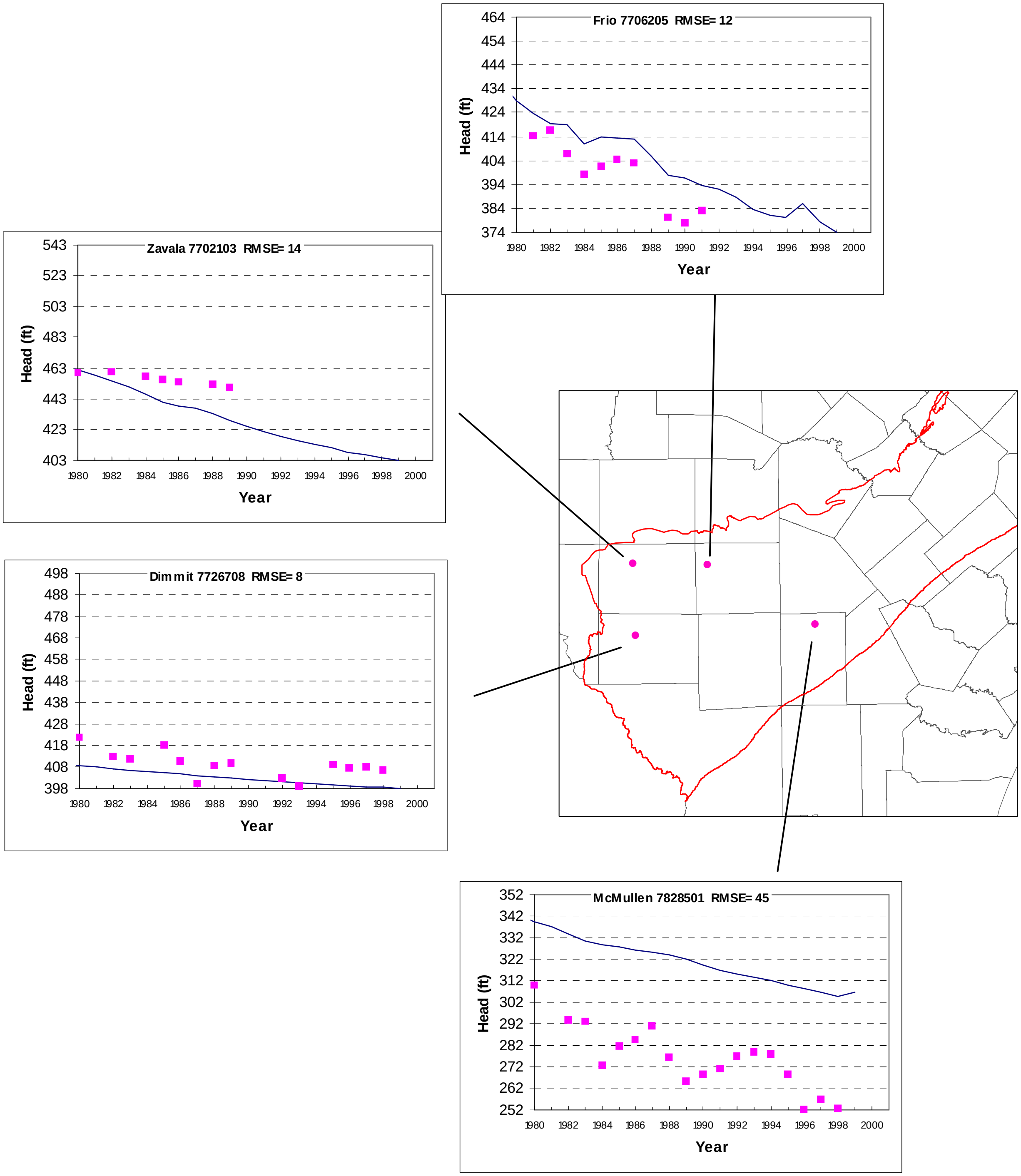


Figure 9.1.21 Selected Carrizo aquifer (Layer 5) hydrographs of simulated (lines) and measured (points) hydraulic heads in Dimmit, Frio, McMullen, and Zavala counties.

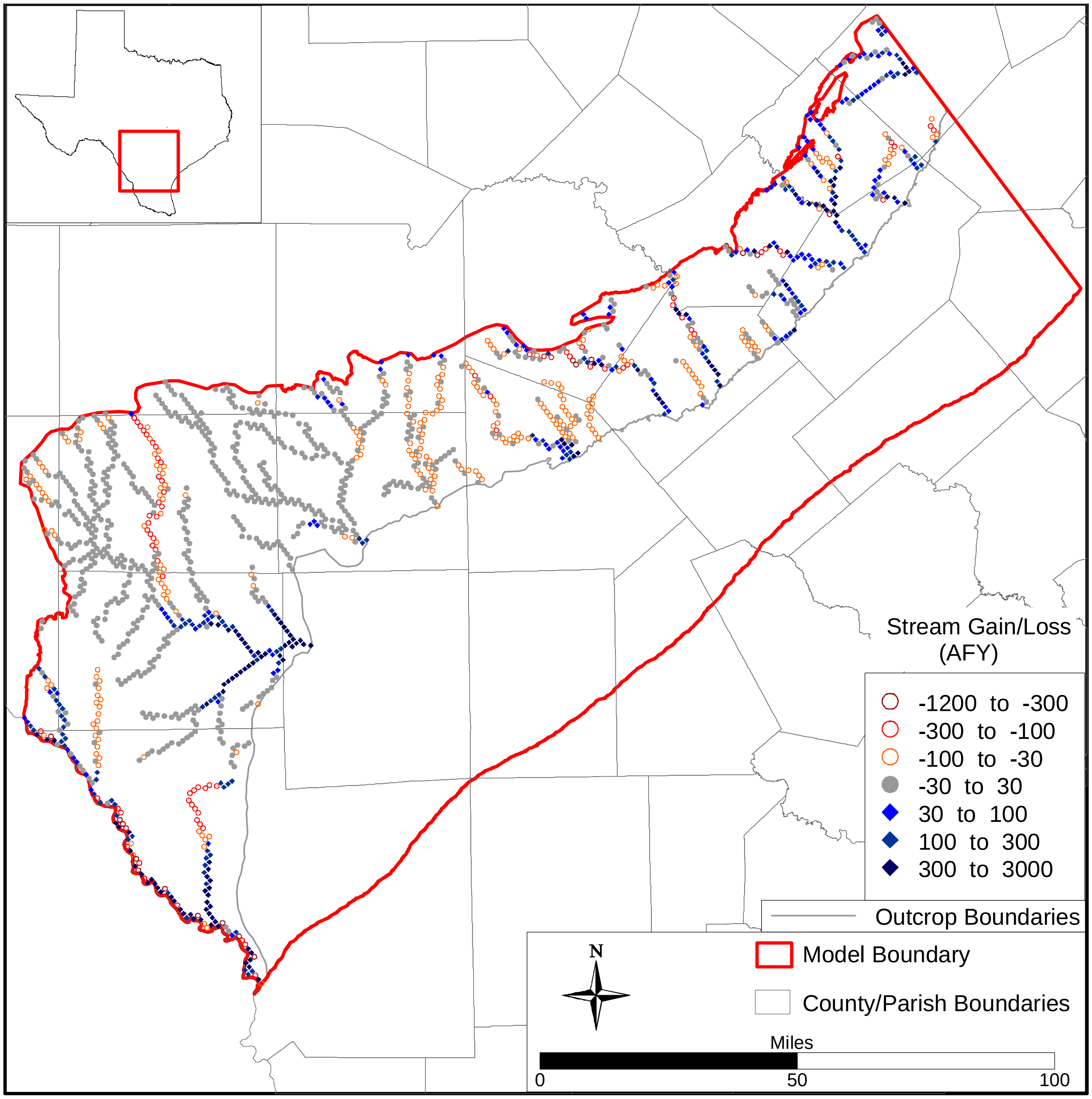


Figure 9.1.22 Transient model stream gain/loss in 1989 (positive value denotes a gaining stream).

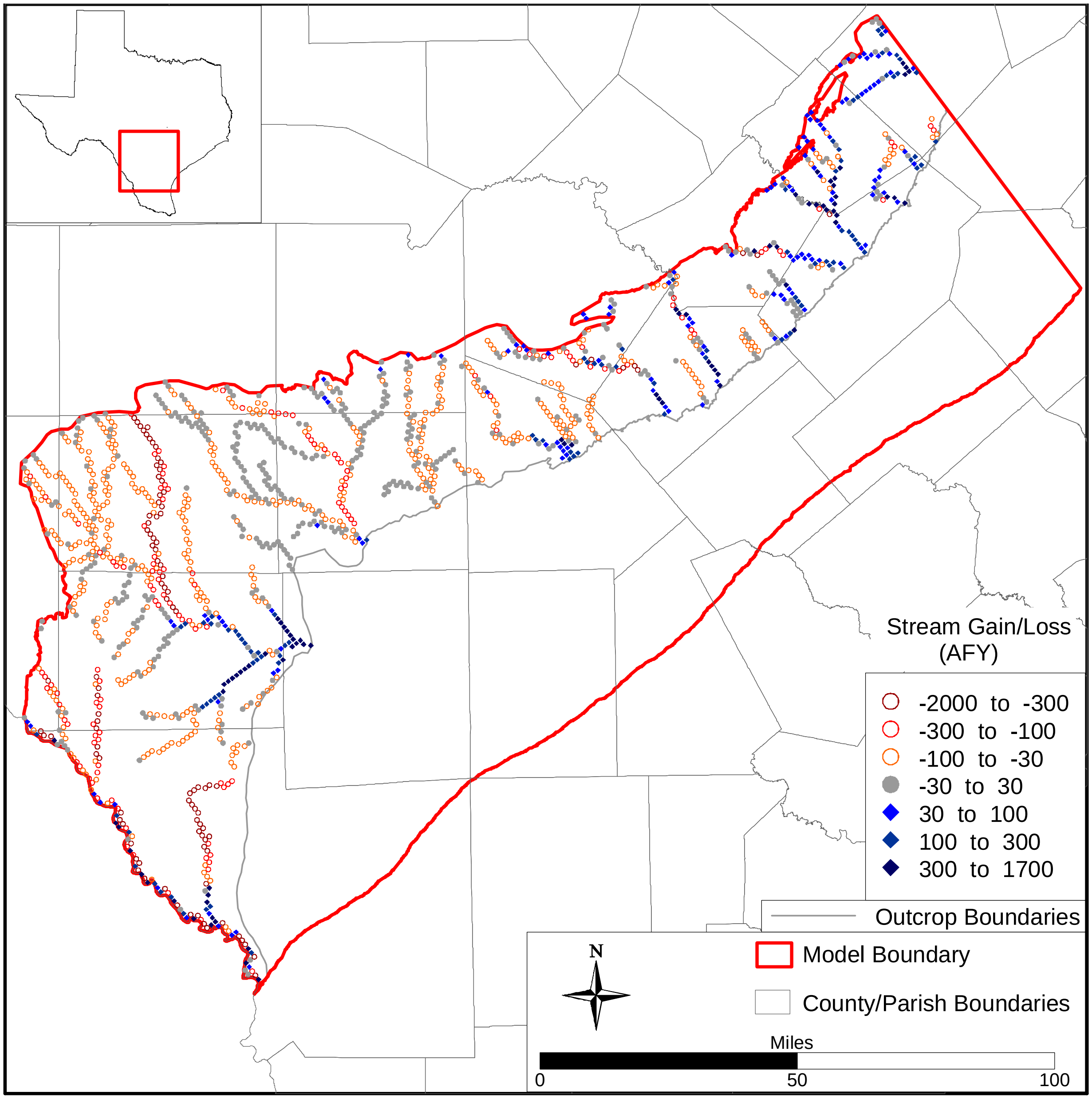


Figure 9.1.23 Transient model stream gain/loss in 1996 (positive value denotes a gaining stream).

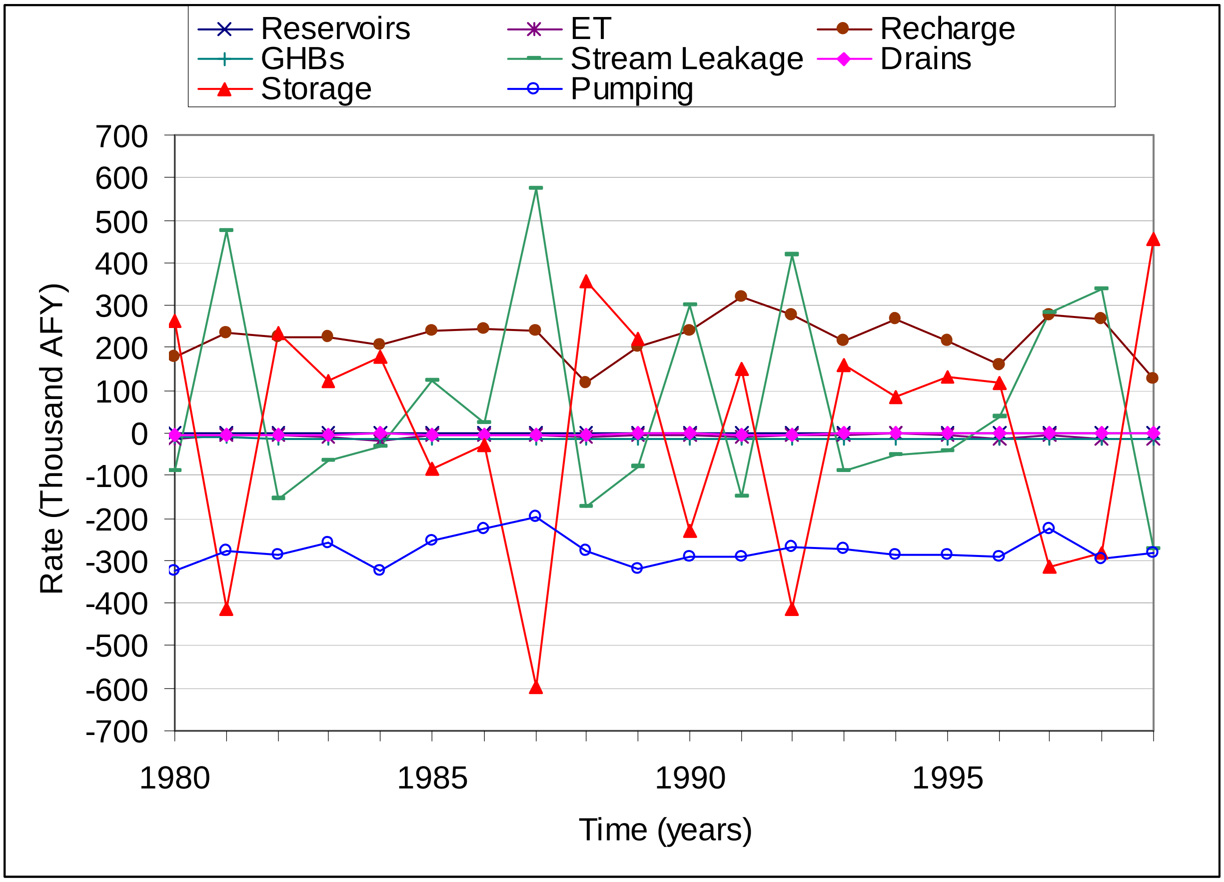


Figure 9.1.24 **Change in model-wide rates through time for the transient model.**

9.1.3 Sensitivity Analysis

Section 8.1.3 discusses the approach for the sensitivity analysis for the steady-state model. The sensitivity analysis for the transient model was performed in a similar fashion to that for the steady-state model. However, some additional sensitivity simulations were added for the transient model to account for the addition of storage and pumping as model parameters.

Eighteen parameter sensitivity simulations were performed for the transient model. These are:

1. Horizontal hydraulic conductivity, Sparta (Kh-Sparta)
2. Horizontal hydraulic conductivity, Queen City (Kh-Queen City)
3. Horizontal hydraulic conductivity, Carrizo (Kh-Carrizo)
4. Horizontal hydraulic conductivity, Wilcox (Kh-Wilcox)
5. Vertical hydraulic conductivity in the Weches (Kv-Weches)
6. Vertical hydraulic conductivity in the Reklaw (Kv-Reklaw)
7. Vertical hydraulic conductivity in the Wilcox (Kv-Wilcox)
8. Recharge, model-wide (Rch-All)
9. Streambed conductance, model-wide (Str-K)
10. Stream head, model-wide (Str-Head)
11. GHB conductance, model-wide (GHB-K)
12. GHB head, model-wide (GHB-Head)
13. Storativity, model-wide (S)
14. Specific yield, model-wide (Sy)
15. Pumping, model-wide
16. Fault conductance (Fault-K) – note that faults are transparent in this model so no effect is expected for this sensitivity.
17. Reservoir conductance (Res-K)
18. Drain conductance (Drain-K)

Equation 8.2 (varying linearly) was used for sensitivities 8, 14, and 15, and Equation 8.3 for the rest of the sensitivities listed above, with the exception of the stream and GHB heads, which were treated similarly to the steady-state model. Three of the 18 sensitivities had maximum *MD*s of less than 0.1 feet for all layers: the fault conductance, the reservoir conductance, and the drain conductance. The faults are not active in this model, so this is an expected result. The drains and reservoirs have very little interaction with the model so they also have little effect. Figure 9.1.25 shows Queen City aquifer sensitivities to various conductivities when the *MD* is calculated at target locations. Figure 9.1.26 shows Queen City aquifer sensitivities to various conductivities when the *MD* is calculated at all grid blocks. In both figures, the Queen City aquifer head is most positively correlated with the horizontal conductivity in the Carrizo aquifer. However, for the target locations the most negatively correlated parameter is the vertical conductivity of the Reklaw. For all grid blocks, the most negatively correlated parameter is the vertical conductivity of the Weches Formation. The Weches affects the Queen City aquifer most strongly in the downdip portion of the aquifer, where upward flow occurs. The Reklaw Formation affects the Queen City aquifer most strongly in the updip portion of the aquifer where gradients are more naturally downward. Also, where there are target locations there is often pumping, so these are the locations where lowered Carrizo aquifer heads might have more influence on the Queen City aquifer. The difference between the two plots indicates that the target coverage is biased in certain ways for calculating sensitivities. For the remainder of the plots, the *MD*s calculated for all grid blocks will be shown, since this will be more generally representative of the model.

Figure 9.1.27 shows that the most positively correlated parameter for the Sparta aquifer is GHB head and the most negatively correlated parameter is the vertical conductivity of the Reklaw Formation. As with the steady-state model, the connection of the GHBs to the majority of the Sparta layer causes them to have a large impact on Sparta heads. Figure 9.1.28 shows that heads in the Queen City aquifer are positively correlated with both the GHB heads and the horizontal hydraulic conductivity in the Queen City and Carrizo layers. The horizontal hydraulic conductivity affects the Queen City aquifer heads due to the pumping stress in the model. When hydraulic conductivity is increased, drawdown is decreased, and vice versa. Although the drawdown in the Queen City aquifer is small, the drawdown in the Carrizo aquifer is very large and the Carrizo aquifer has some affect on the Queen City aquifer through the Reklaw Formation. Figure 9.1.29 shows that, similar to the Southern Carrizo-Wilcox GAM, heads in the Carrizo aquifer are most positively correlated to the hydraulic conductivity in the Carrizo aquifer, and most negatively correlated to pumping. These are most important because of the large pumping stresses on the Carrizo aquifer. Contrast this with the steady-state model where recharge and the vertical conductivity of the Reklaw Formation were most important.

Figure 9.1.30 shows the transient sensitivity results for all layers when the vertical conductances of the confining units are varied. The Weches plot (Figure 9.1.30a) shows that the head in the Sparta aquifer is positively correlated to the Weches conductivity, while the head in the rest of the layers are negatively correlated with the Weches conductivity. An increase in Weches conductivity eases flow through the confining unit, which allows pressure support from the layers below to increase heads in the Sparta aquifer. This hydraulic diffusivity provides pressure relief in layers below the Weches, so heads decrease in those layers. The Reklaw plot (Figure 9.1.30b) shows that the Carrizo aquifer and upper Wilcox layers are most positively correlated with the Reklaw vertical conductivity. An increase in the Reklaw conductivity allows pressure support from the Queen City aquifer to reach the Carrizo aquifer (and upper Wilcox) so the drawdown in the Carrizo aquifer is reduced. These plots show the difference in response for strongly stressed and relatively unstressed layers.

Figures 9.1.31 and 9.1.32 show the sensitivity of selected hydrographs to varying two important parameters. Figure 9.1.31 shows transient hydrograph sensitivities for the Sparta aquifer when the GHB head is varied. As expected, the hydrographs trend slightly in the direction of head change. Figure 9.1.32 shows transient hydrograph sensitivities for the Queen City aquifer when the vertical conductivity of the Weches is varied. In general, heads increase slightly in the Queen City aquifer when the Weches conductivity is decreased and heads decrease in the Queen City aquifer when the Weches conductivity is increased, consistent with the results shown in Figure 9.1.26.

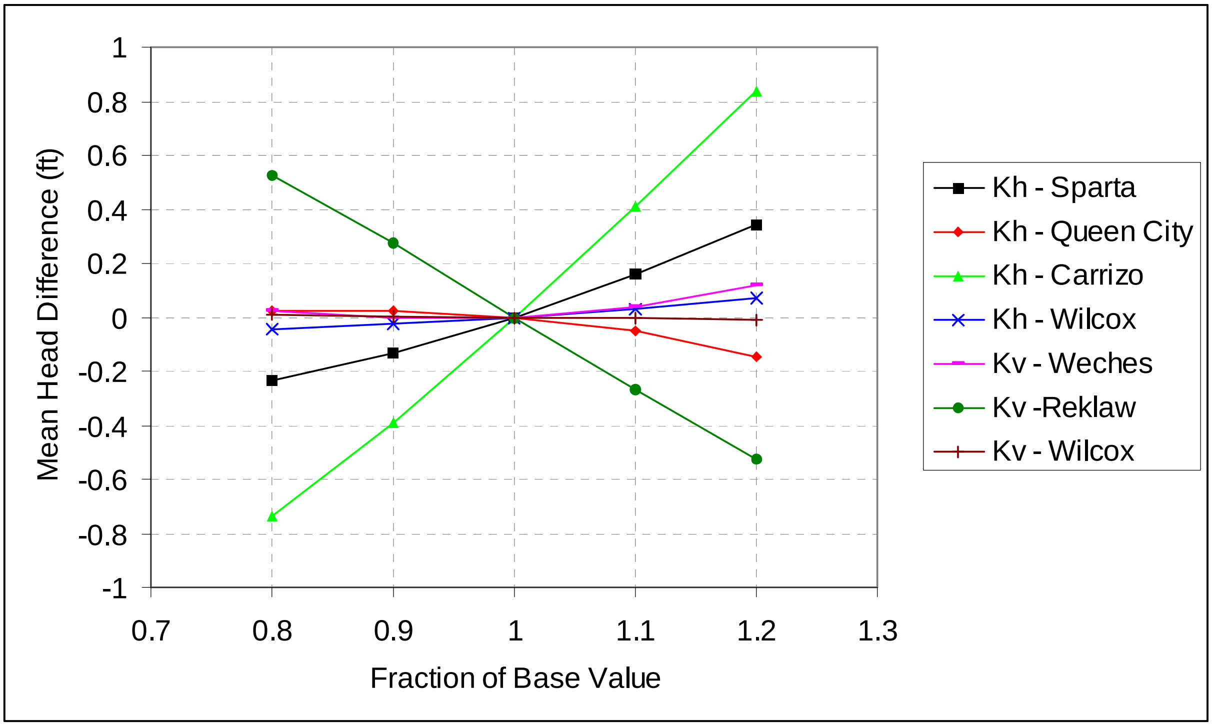


Figure 9.1.25 Transient sensitivity results for the Queen City aquifer (Layer 3) using target locations.

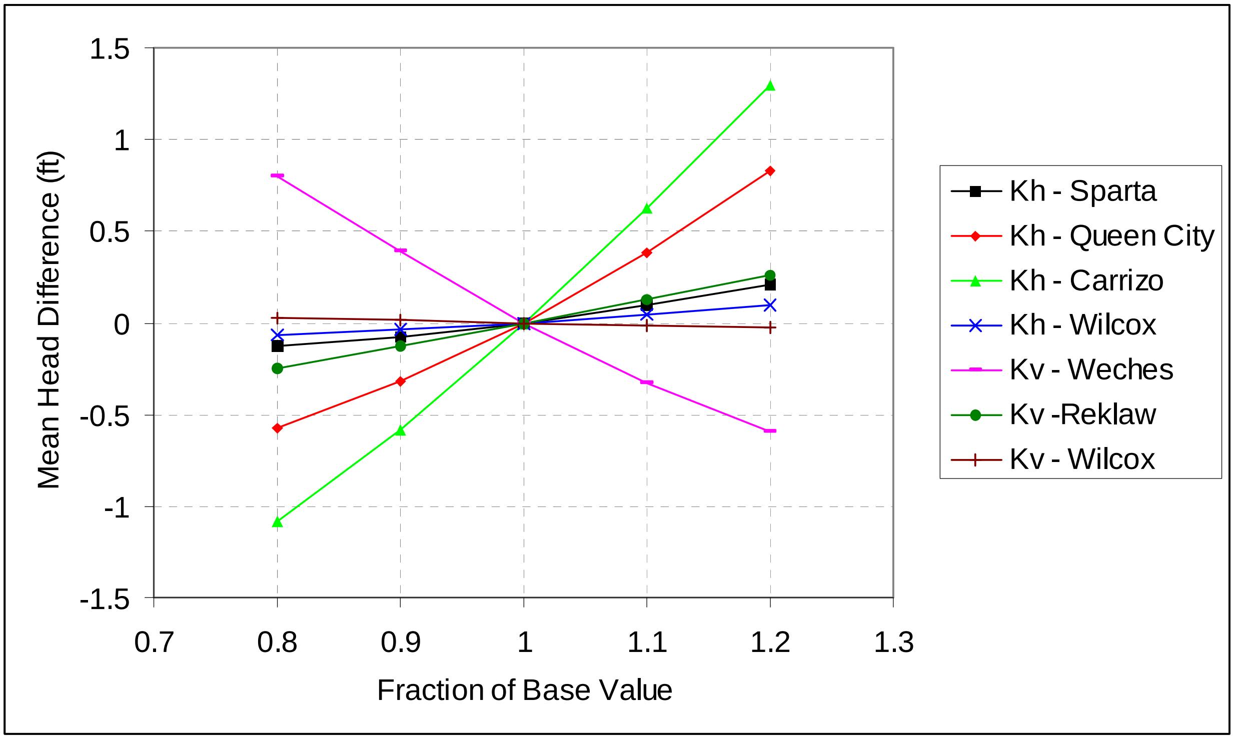
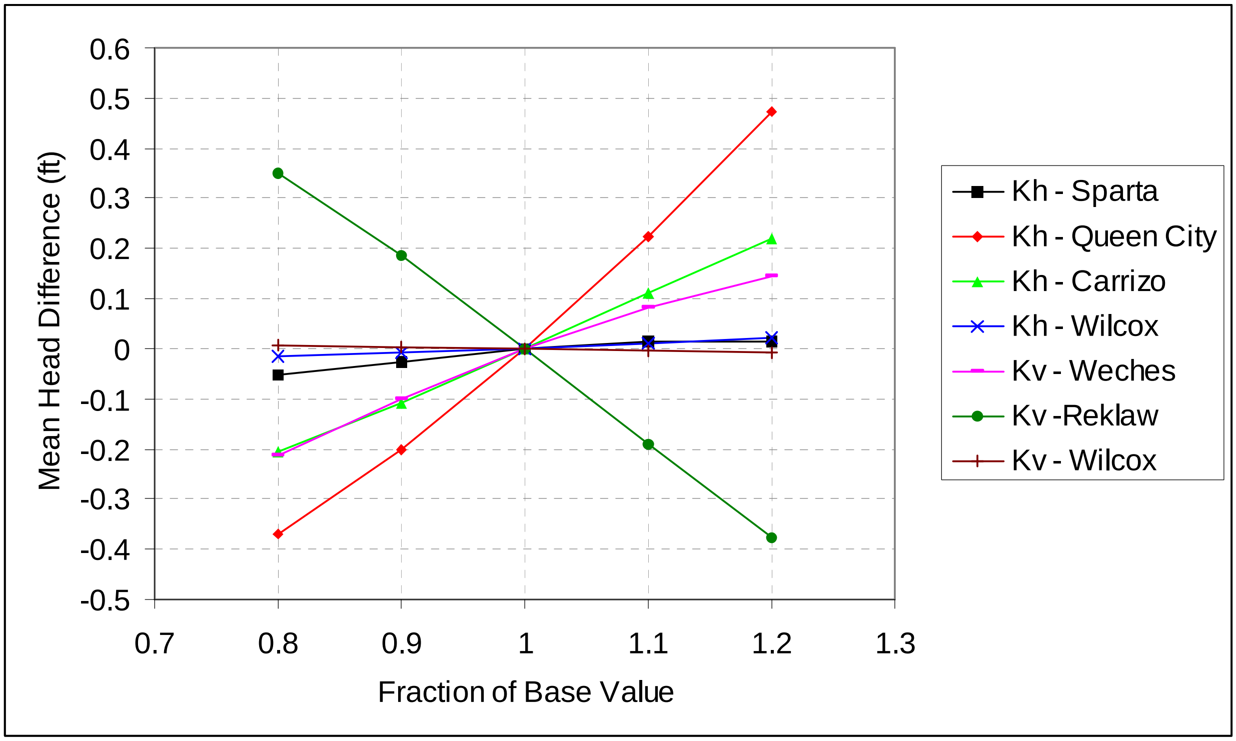


Figure 9.1.26 Transient sensitivity results for the Queen City aquifer (Layer 3) using all active grid blocks.



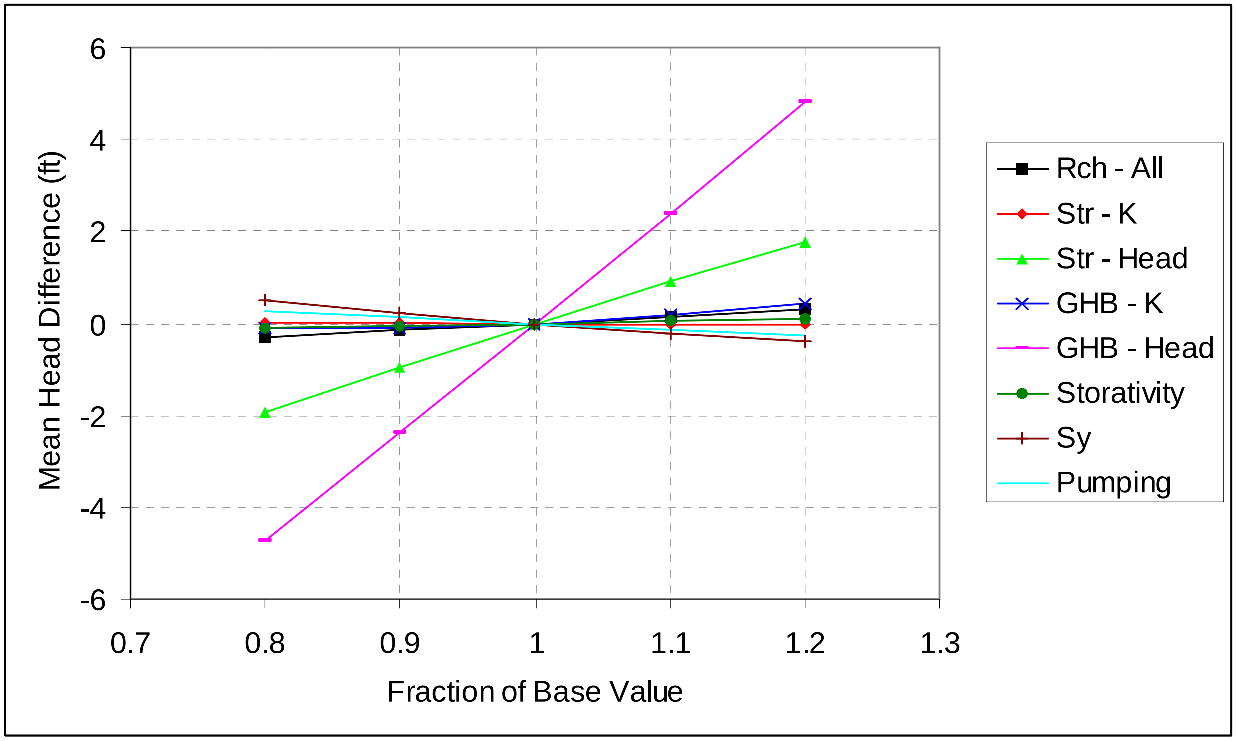
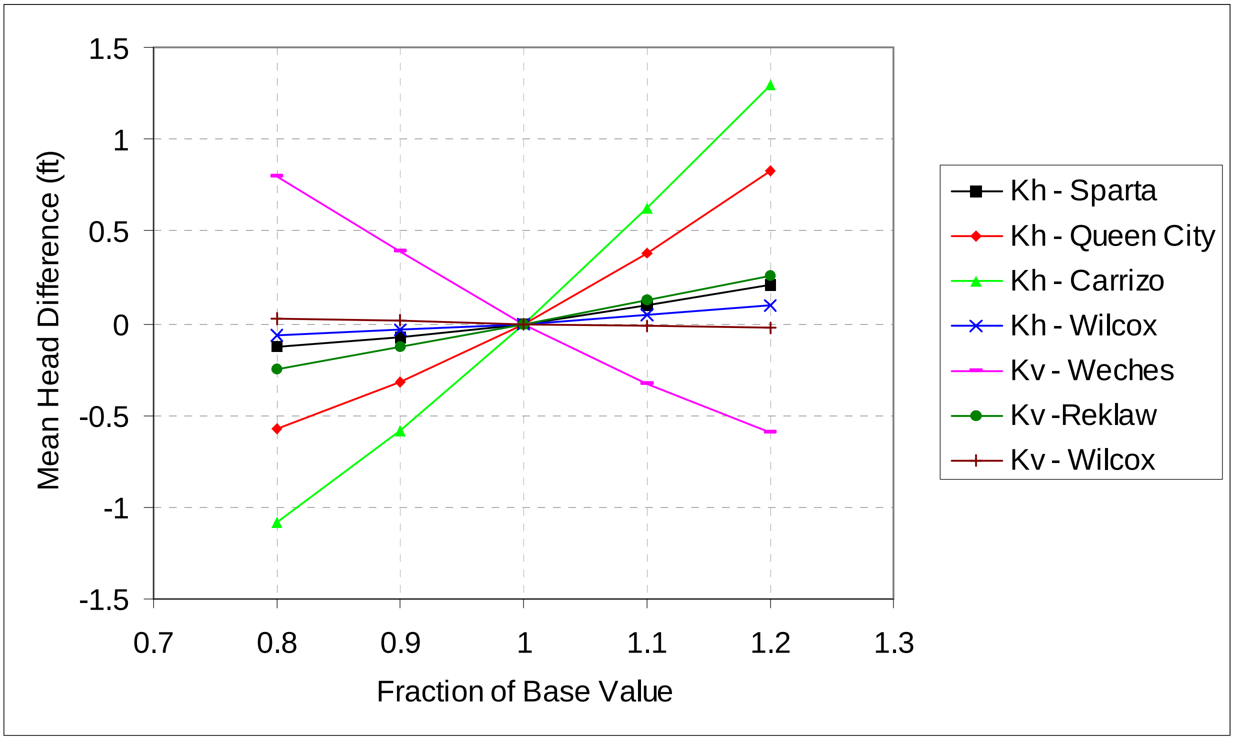


Figure 9.1.27 Transient sensitivity results for the Sparta aquifer (Layer 1) using all active grid blocks.



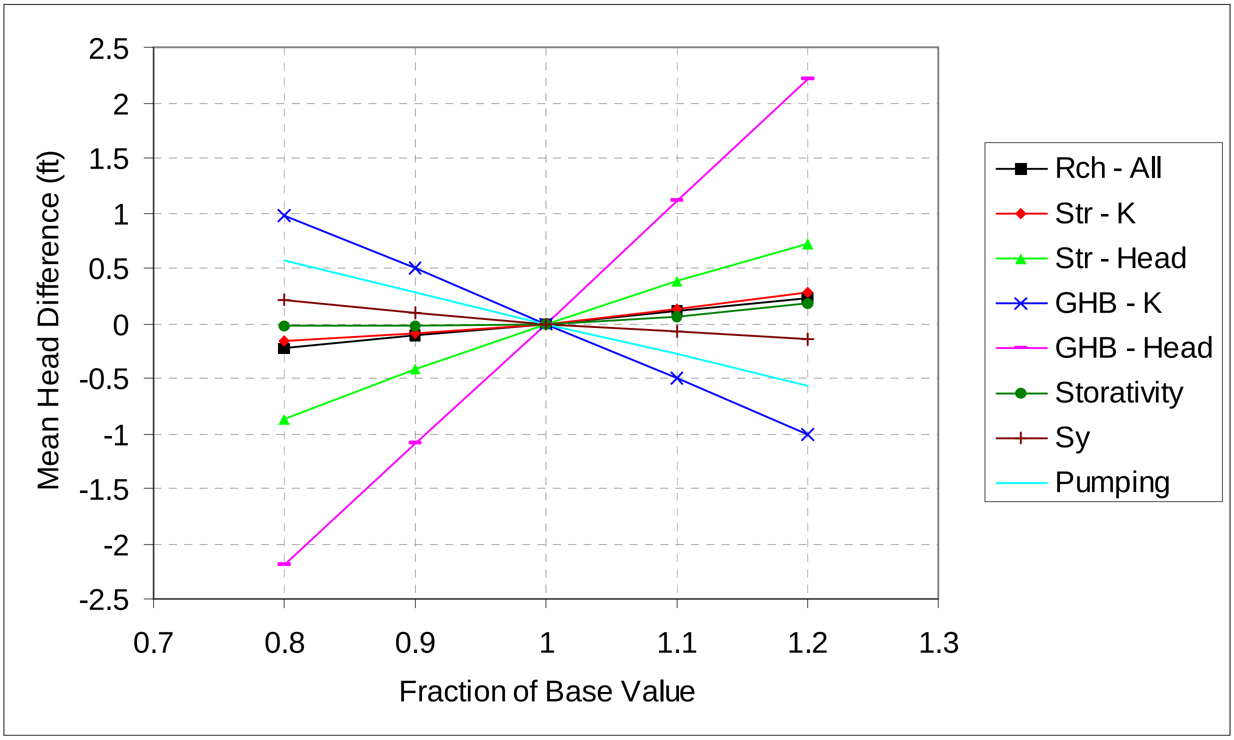
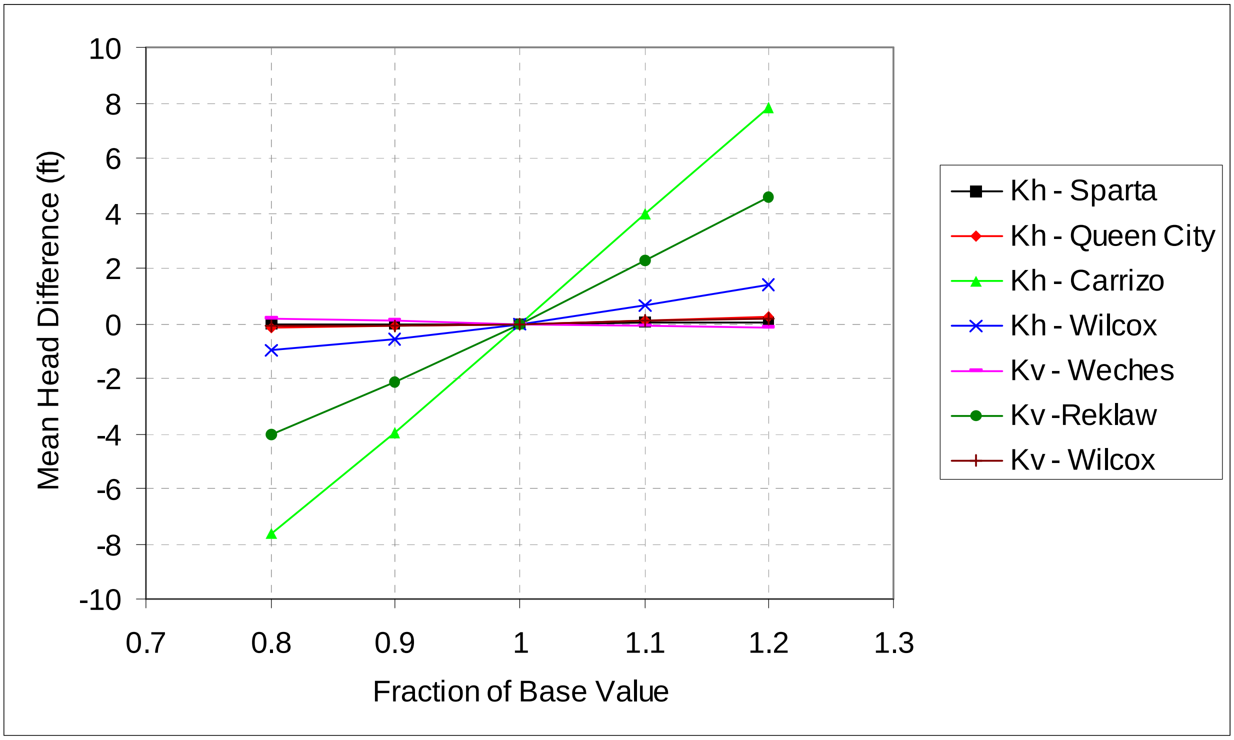


Figure 9.1.28 **Transient sensitivity results for the Queen City aquifer (Layer 3) using all active grid blocks.**



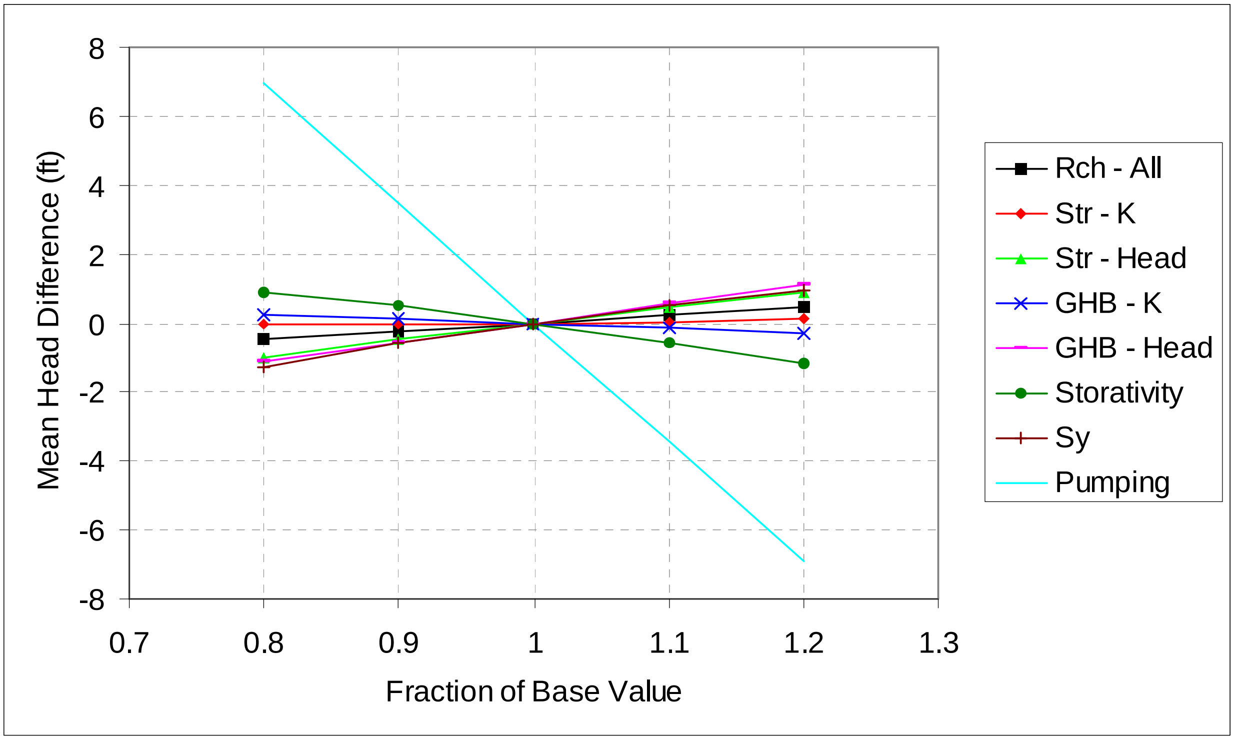
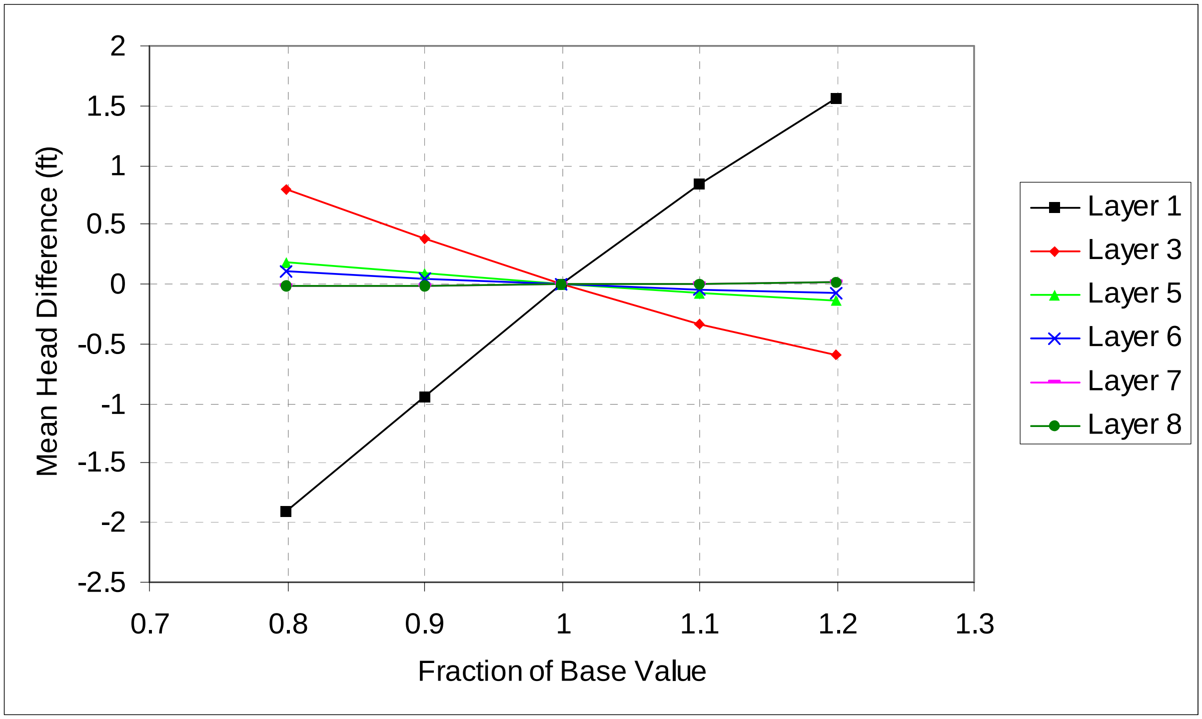
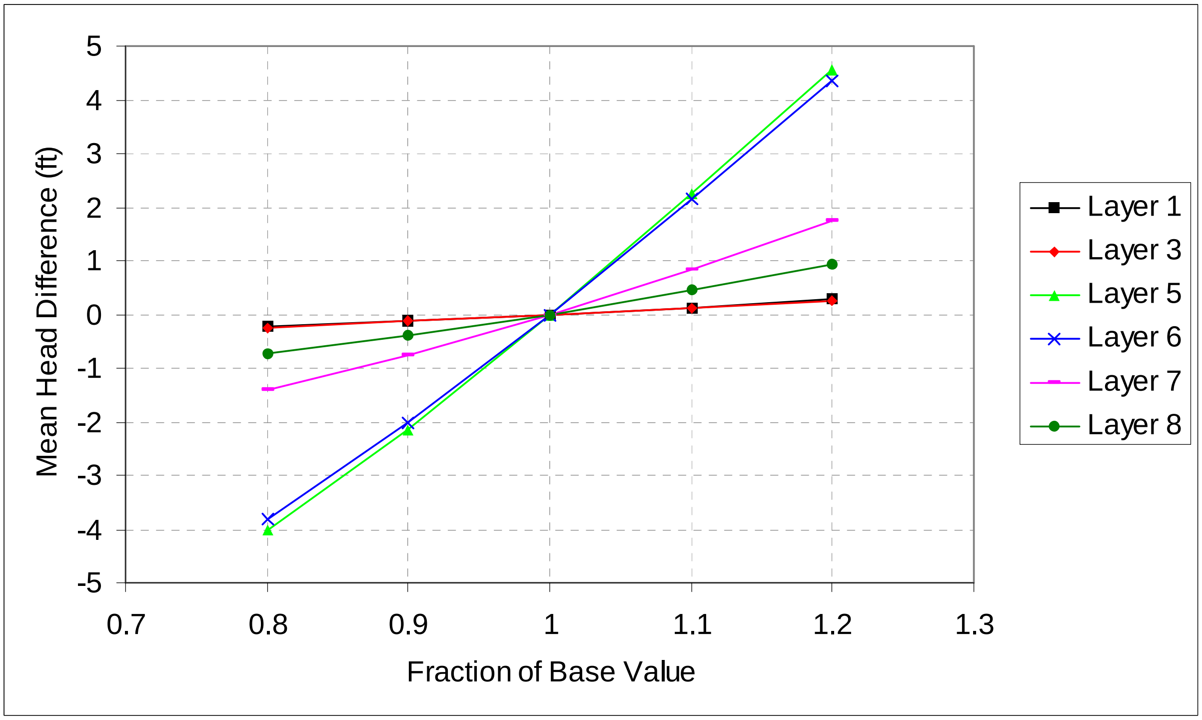


Figure 9.1.29 **Transient sensitivity results for the Carrizo aquifer (Layer 5) using all active grid blocks.**



a.



b.

Figure 9.1.30 Transient sensitivity results for all layers when varying the vertical conductance of the Weches (a) and Reklaw (b) using all active grid blocks.

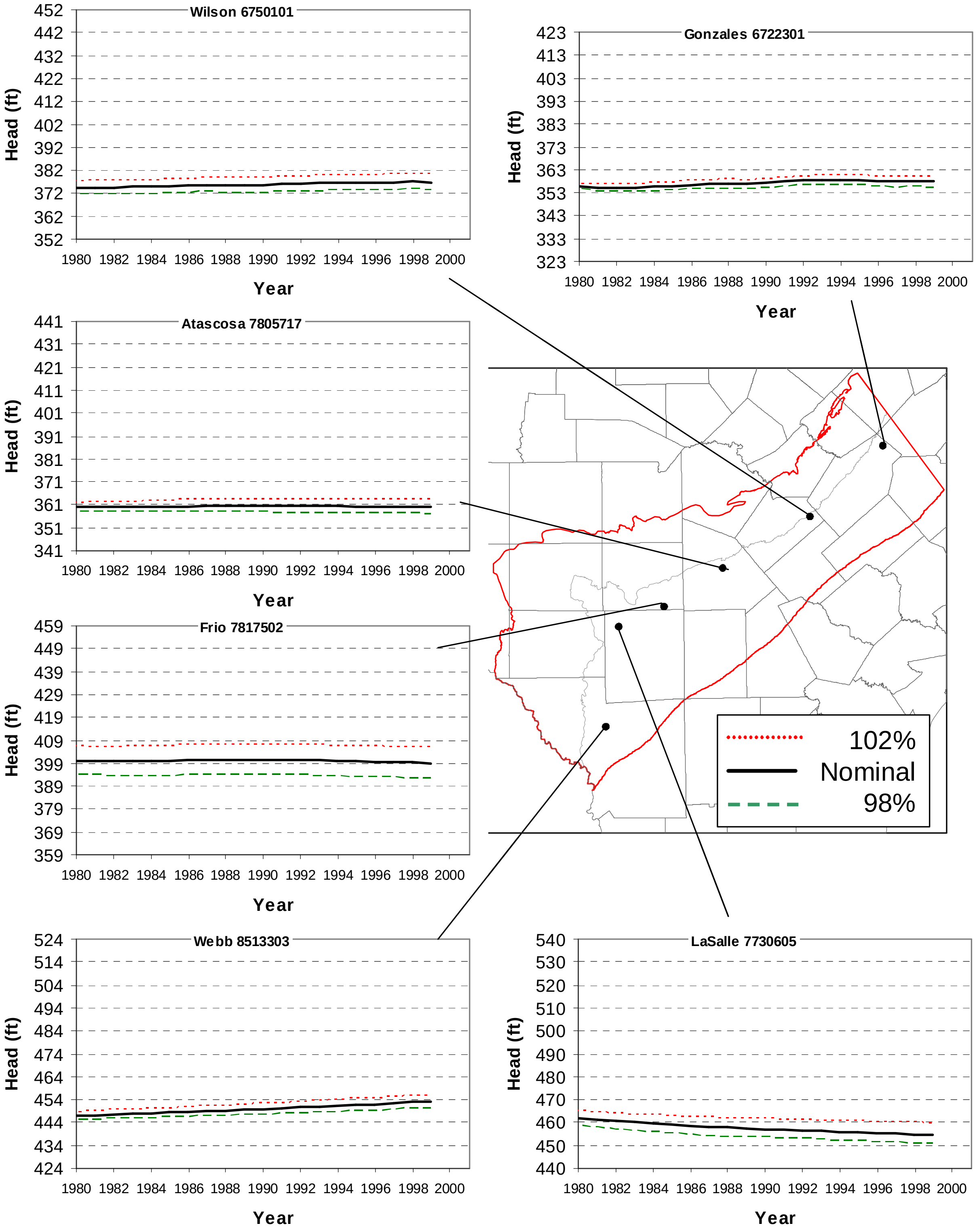


Figure 9.1.31 Transcribent sensitivity hydrographs for the Sparta aquifer when GHB head is varied.

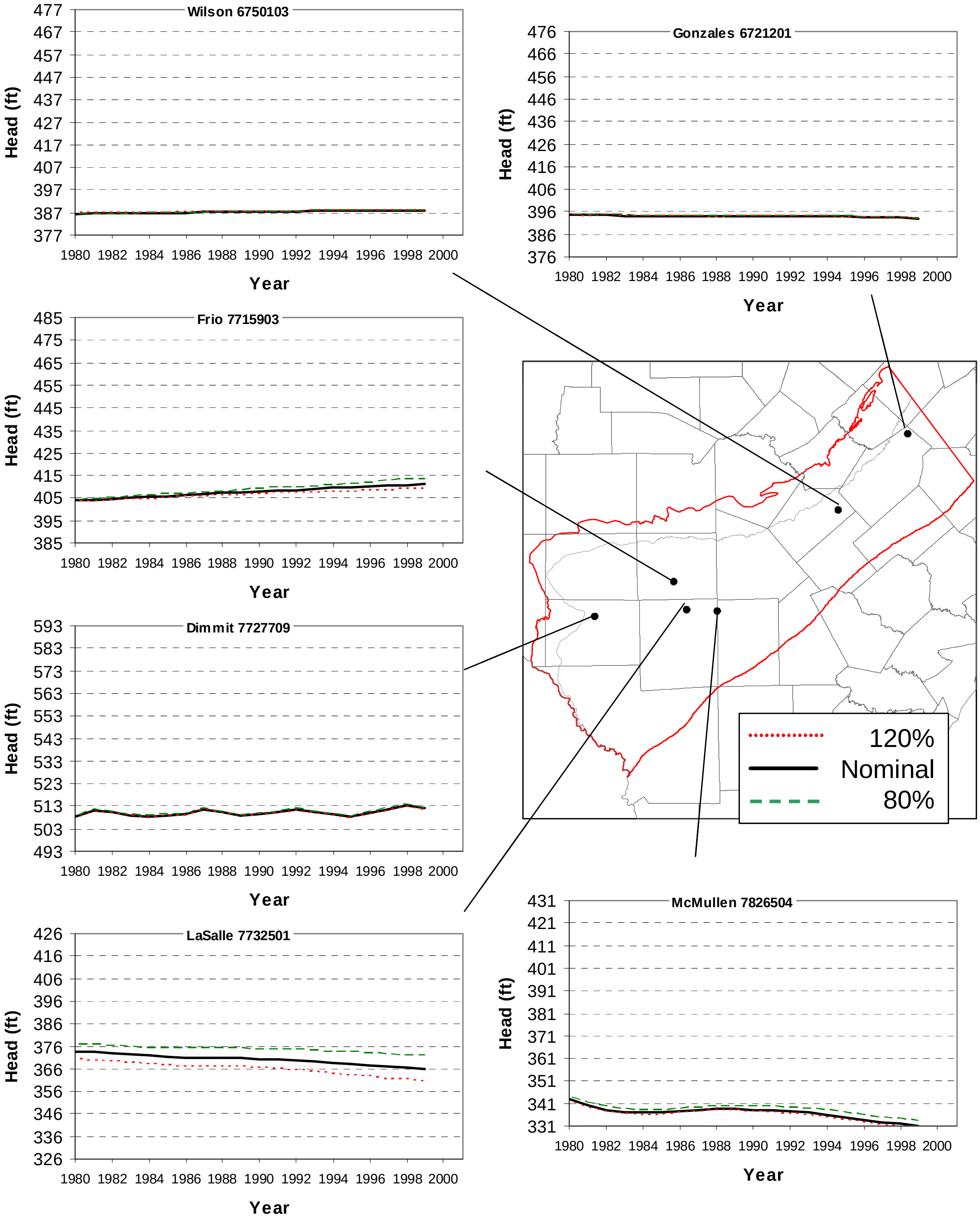


Figure 9.1.32 Transient sensitivity hydrographs for the Queen City aquifer when vertical conductivity of the Weches is varied.

9.2 Central Queen City and Sparta GAM

This section details the calibration and verification of the Central Queen City and Sparta transient model and presents the transient model results. Section 9.2.1 describes the salient features of the calibration approach, and Section 9.2.2 presents the results of the transient calibration and verification together with the examination of residuals, hydrographs, and stream flow. A formal sensitivity analysis with the calibrated transient model can be found in Section 9.2.3.

9.2.1 Calibration

Most properties or parameters common with the steady-state model are identical in the transient model. Storativity and specific yield have been discussed in Section 6.4.2. No final adjustment was made to the initial storativity field, although trial variations of the sand and clay specific storage as well as the depth function parameters were performed. Changes were made to the conductivity fields in the Carrizo aquifer and Reklaw Formation as described in the steady-state section because, in the transient mode, the cross-formational flow through the Reklaw Formation was too high, especially in the northern area of the Central model.

There are a total of 18 reservoirs in the Central model. Some of them become active during the simulated period. Impoundment date and stage information were gathered from various sources. Reservoir bed conductivity was estimated at $1x10^{-4}$ ft/day.

In addition to recharge that was varied though time, another major change was the addition of side GHB’s to all layers. The top GHB was held constant through time while the side boundaries were varied through time and imported from heads in those cells of the Southern and Northern models falling on the Central model boundary, as described in Section 6.3.1. The conductance of the side GHB cells was set to the transmissivity of the cell. With this conductance and the current historical pumping, the impact of the imposed lateral GHB heads extends approximately 15 to 20 miles from the boundary into the model relative to the no-flow case.

A change relative to the Central Carrizo-Wilcox GAM (Dutton et al. 2003) was to restrict hydraulically-active faults to areas where they have a large impact on the model results. They are the Milano Fault Zone and the Elkhart-Mt. Enterprise Fault Zone. All other faults, active in the Central Carrizo-Wilcox GAM (Dutton et al. 2003), were given a very high conductance so that they do not impede water flow. The fault coverages are described in Section 6.3.4.

9.2.2 Results

9.2.2.1 Hydraulic Heads

Results are presented for the end of the calibration (1990) and verification (1999) periods. The summary statistics are displayed in Table 9.2.1. The RMSE for heads in the Sparta aquifer (Figures 9.2.1 through 9.2.4) is small (22.0 feet in 1990 and 23.8 feet in 1999). The mean error is also small (6.3 feet in 1990 and 3.5 feet in 1999). The residuals are not obviously spatially biased (see Figure 9.2.2). Because there is a small amount of pumping in the Sparta aquifer, head maps in 1990 and 1999 look very much alike and are also very similar to the steady-state head map. The comparison between the simulated and estimated heads for the Sparta aquifer are reasonable given the sparse observed data coverage. The RMSE for targets in the Queen City aquifer is also small (26.5 and 33.2 feet for 1990 and 1999, respectively) with very small mean errors (3.3 and -0.1 feet). Similar to the Sparta aquifer, head maps for the Queen City aquifer (Figures 9.2.5 through 9.2.8) look very similar at steady state and at the end of the calibration and verification periods. Again the simulated versus estimated heads in the Queen City aquifer are comparable with much greater detail and topographic effects in the simulated heads. Out of a total of 11,070 outcrop cells, including 1,460 and 3,609 for the Sparta and Queen City aquifers, respectively, about 173 (1.6 percent), including 35 and 28 for the Sparta and Queen City aquifers, respectively, were dry at the end of the verification period. The drying of these thin edge cells is a physically correct condition and does not have an adverse impact on model results.

The RMSE comparing simulated and observed water levels in the Carrizo aquifer for 1990 is 36.3 feet (see Table 9.2.1). This represents 5 percent of the range in observed water levels. The dominant feature in the map of simulated water levels for 1990 is the drawdown related to the withdrawal of groundwater in the Lufkin-Angelina County well field (Figure 9.2.9). The model underestimates drawdown in some pumping cells in this well field (Figure 9.2.10). Section 7.1.1 outlines some of the possible reasons for the difference between simulated and observed heads in this area. Other reasons could include local errors in pumping rates or storativity. The cone of depression of the Tyler-Smith county well field, partially visible at the northern boundary of the Central model (see Figure 9.2.9), rendered a GHB head exchange necessary. The cone of depression due to both pumping from the Carrizo aquifer and to water withdrawal in the underlying Simsboro aquifer in the Bryan College Station area is also noticeable in Brazos County. Those three features are even more noticeable in the 1999 head map (Figure 9.2.11). The drawdown underestimation in the pumping centers is also still present (Figure 9.2.12). However, the RMSE for the end of the verification period is 32.1 feet, 4.3 percent of the observed range.

The Simsboro aquifer statistics are also very similar to those for the Central Carrizo-Wilcox GAM, possibly displaying an improvement in the mean error. This shows that the Simsboro hydrologic behavior has not been significantly altered by the addition of three extra layers and by the changes in the Carrizo aquifer properties.

Overall, the match between simulated and observed hydrographs is good. Hydrographs for 10 wells each in the Sparta, Queen City, and Carrizo aquifers were selected so that they offer both location and behavior variability. The RMSE ranges from 2 to 21 feet for the displayed hydrographs in the Sparta aquifer (Figure 9.2.13). The trend of most hydrographs is clearly flat, both for the observed and simulated data, reflecting the small water withdrawal out of the aquifer. Some slight downward (well 3832802 in Cherokee County) or recovery (well 5941704 in Lee County) trends are captured by the model. The hydrographs for wells completed in the Queen City aquifer (Figure 9.2.14) are also mainly flat. The RMSE range of the displayed hydrographs is bounded by 3 and 14 feet.

The hydrographs for wells completed in the Carrizo aquifer show some significant drawdown (Figure 9.2.15) matched by the model for the most part. The RMSE ranges from 1 ft to 37 feet. Hydrographs for wells in the southern section of the Central model show some small measured drawdown, matched both in magnitude and trend by the simulated values. The hydrographs for wells in the vicinity of the Tyler-area and Lufkin-area well fields show greater drawdown and are reasonably matched by the simulated values.

9.2.2.2 Stream-Aquifer Interaction

Rates of discharge to streams simulated for the transient model period are similar to those for the steady state model. Figures 9.2.16 through 9.2.19 display results for years 1989 and 1996. Simulated rates of base-flow discharge fluctuate with annual rates of recharge. There is also a slight trend of decreasing base-flow rate through time (Figure 9.2.20), often obscured with the yearly recharge variations. This simulated decrease in base flow most likely reflects a simulated decline in water levels in the aquifer outcrop attributed to increased pumpage. Most model stream cells are gaining with little change through time. A slight increase in losing stream cells can be observed in 1989 following the driest year of the modeled period (1988).

9.2.2.3 Water Budget

Water budgets for the transient model change each year with changes in recharge and pumping. Annual recharge rates applied to the model were greater or less than average in proportion to how much precipitation was greater or less than average. In addition, the GHB heads on the side boundaries of the model were varied in accordance to heads supplied by the Southern and Northern models. The components of the water budget for the end of the calibration and verification periods are reported in Tables 9.2.2 through 9.2.5. The water balance error for all stress periods of the transient model, which is the difference between inflow and outflow, is always less than 0.1 percent.

As for the steady-state period, during the transient period, most recharge is simulated as being primarily discharged to rivers and streams and also taken up by ET. Storage undergoes important variations as it acts as a buffer to minimize the impact of varying recharge. Recharge and change in storage are negatively correlated (Figure 9.2.20). The magnitude of the storage term in the transient simulation prevents a simple determination of deep recharge as was done in the steady-state section.

Table 9.2.1 Summary statistics at the end of the calibration and verification periods for the Central model.

Calibration Period						
Layer	**RMSE (ft)**	**Range (ft)**	**%**	**ME (ft)**	**MAE (ft)**	**#points**
Layer 1 (Sparta)	22.0	249.9	8.8	6.3	17.1	36
Layer 3 (Queen City)	26.5	328.3	8.1	3.3	20.8	62
Layer 5 (Carrizo)	36.3	730.1	5.0	6.8	23.0	115
Layer 7 (Simsboro)	30.8	362.7	8.5	11.9	22.3	42
Verification Period						
Layer	**RMSE (ft)**	**Range (ft)**	**%**	**ME (ft)**	**MAE (ft)**	**#points**
Layer 1 (Sparta)	23.8	236.7	10.1	3.5	18.4	30
Layer 3 (Queen City)	33.2	322.4	10.3	-0.1	24.1	40
Layer 5 (Carrizo)	32.1	747.2	4.3	14.9	23.8	80
Layer 7 (Simsboro)	43.3	498.0	8.7	17.3	31.3	32

RMSE=Root Mean Square Error; ME=Mean Error; MAE=Mean Absolute Error

Table 9.2.2 Water budget for the end of the calibration period for the Central model. Rates reported in AFY.

IN	Layer	GHBs	Recharge	Streams	Top	Bottom	Wells	Reservoirs	Storage
	1	35,740	161,758	2,646	0	29,121	0	0	15,773
	2	54	18,270	1,574	37,326	26,482	0	302	1,040
	3	324	175,630	12,488	35,428	16,691	0	1,940	77,119
	4	135	21,027	3,156	25,836	16,660	0	475	8,434
	5	2,153	101,922	5,346	31,527	14,288	0	0	29,273
	6	6,172	91,483	6,897	9,403	14,345	0	4,638	29,195
	7	1,765	62,972	6,671	30,199	12,891	0	4,647	28,546
	8	626	33,392	1,993	4,855	0	0	9,695	14,725
	Sum	46,970	666,455	40,771			0	21,698	204,095

OUT	Layer	GHBs	ET	Streams	Top	Bottom	Wells	Drains	Storage
	1	43,863	17,174	40,988	0	37,326	5,652	1,625	98,387
	2	95	1,971	2,118	29,121	35,428	0	189	16,128
	3	263	52,329	97,687	26,482	25,836	5,721	12,717	98,441
	4	325	1,623	7,960	16,691	31,527	0	368	17,214
	5	3,477	16,600	38,522	16,660	9,403	65,411	1,880	32,550
	6	2,696	17,628	53,528	14,288	30,199	20,739	4,266	18,802
	7	3,947	12,455	41,974	14,345	4,855	58,352	672	11,088
	8	1,374	4,013	19,822	12,891	0	10,920	3,955	12,319
	Sum	56,040	123,792	302,600			166,794	25,671	304,888

Layer	GHBs	Recharge	ET	Streams	Top	Bottom	Wells	Reservoirs	Drains	Storage
1	-8,123	161,758	-17,174	-38,343	0	-8,205	-5,652	0	-1,625	-82,614
2	-41	18,270	-1,971	-544	8,205	-8,946	0	302	-189	-15,088
3	62	175,630	-52,329	-85,199	8,946	-9,145	-5,721	1,908	-12,717	-21,322
4	-190	21,027	-1,623	-4,804	9,145	-14,867	0	475	-368	-8,780
5	-1,325	101,922	-16,600	-33,176	14,867	4,885	-65,411	0	-1,880	-3,277
6	3,476	91,483	-17,628	-46,631	-4,885	-15,854	-20,739	4,637	-4,266	10,393
7	-2,182	62,972	-12,455	-35,303	15,854	8,036	-58,352	4,647	-672	17,458
8	-748	33,392	-4,013	-17,828	-8,036	0	-10,920	9,695	-3,955	2,406
Sum	-9,070	666,455	-123,792	-261,830			-166,794	21,665	-25,671	-100,792

Table 9.2.3 Water budget for the end of the calibration period for the Central model with values expressed as a percentage of inflow or outflow.

IN	Layer	GHBs	Recharge	Streams	Wells	Reservoirs	Storage
	1	3.6	16.5	0.3	0.0	0.0	0.0
	2	0.0	1.9	0.2	0.0	0.0	0.0
	3	0.0	17.9	1.3	0.0	0.2	0.0
	4	0.0	2.1	0.3	0.0	0.0	0.0
	5	0.2	10.4	0.5	0.0	0.0	0.0
	6	0.6	9.3	0.7	0.0	0.5	0.0
	7	0.2	6.4	0.7	0.0	0.5	0.0
	8	0.1	3.4	0.2	0.0	1.0	0.0
	Sum	4.8	68.0	4.2	0.0	2.2	0.0
OUT	**Layer**	**GHBs**	**ET**	**Streams**	**Wells**	**Drains**	**Storage**
	1	4.5	1.8	4.2	0.6	0.0	0.2
	2	0.0	0.2	0.2	0.0	0.0	0.0
	3	0.0	5.3	10.0	0.6	0.0	1.3
	4	0.0	0.2	0.8	0.0	0.0	0.0
	5	0.4	1.7	3.9	6.7	0.0	0.2
	6	0.3	1.8	5.5	2.1	0.0	0.4
	7	0.4	1.3	4.3	6.0	0.0	0.1
	8	0.1	0.4	2.0	1.1	0.0	0.4
	Sum	5.7	12.6	30.9	17.0	0.0	2.6

Table 9.2.4 Water budget for the end of the verification period for the Central model. Rates reported in AFY.

IN	Layer	GHBs	Recharge	Streams	Top	Bottom	Wells	Reservoirs	Storage
	1	34,196	88,484	2,151	0	28,670	0	0	26,719
	2	54	9,544	1,530	39,801	25,452	0	276	2,974
	3	389	112,814	8,993	36,523	14,680	0	2,196	86,813
	4	142	11,323	3,163	26,203	14,209	0	403	11,123
	5	2,067	51,504	5,924	32,289	12,655	0	0	49,338
	6	6,322	53,198	6,693	10,621	13,217	0	4,204	54,197
	7	2,089	33,805	5,137	36,611	15,512	0	2,826	68,368
	8	748	18,535	1,972	4,965	0	0	6,183	26,299
	Sum	46,007	379,205	35,561			0	16,089	325,776

OUT	Layer	GHBs	ET	Streams	Top	Bottom	Wells	Drains	Storage
	1	44,512	15,120	43,349	0	39,801	6,251	1,310	29,856
	2	105	1,668	3,129	28,670	36,523	0	165	9,371
	3	277	47,447	100,929	25,452	26,203	6,198	10,243	45,550
	4	373	1,324	9,103	14,680	32,289	0	391	8,392
	5	4,099	13,387	36,867	14,209	10,621	68,224	1,299	5,066
	6	2,831	13,942	53,357	12,655	36,611	22,588	3,629	2,853
	7	2,764	7,653	38,762	13,217	4,965	94,773	1,176	1,034
	8	1,243	4,182	19,638	15,512	0	11,375	4,545	2,214
	Sum	56,204	104,725	305,134			209,407	22,759	104,331

Layer	GHBs	Recharge	ET	Streams	Top	Bottom	Wells	Reservoirs	Drains	Storage
1	-10,316	88,484	-15,120	-41,198	0	-11,131	-6,251	0	-1,310	-3,137
2	-51	9,544	-1,668	-1,600	11,131	-11,072	0	276	-165	-6,396
3	112	112,814	-47,447	-91,935	11,072	-11,523	-6,198	2,196	-10,243	41,263
4	-231	11,323	-1,324	-5,940	11,523	-18,080	0	403	-391	2,731
5	-2,032	51,504	-13,387	-30,943	18,080	2,033	-68,224	0	-1,299	44,272
6	3,491	53,198	-13,942	-46,664	-2,033	-23,394	-22,588	4,202	-3,629	51,344
7	-675	33,805	-7,653	-33,626	23,394	10,547	-94,773	2,826	-1,176	67,334
8	-494	18,535	-4,182	-17,666	-10,547	0	-11,375	6,183	-4,545	24,085
Sum	-10,197	379,205	-104,725	-269,572			-209,407	16,088	-22,759	221,445

Table 9.2.5 Water budget for the end of the verification period for the Central model with values expressed as a percentage of inflow or outflow.

IN	Layer	GHBs	Recharge	Streams	Wells	Reservoirs	Storage
	1	4.3	11.0	0.3	0.0	0.0	0.0
	2	0.0	1.2	0.2	0.0	0.0	0.0
	3	0.0	14.1	1.1	0.0	0.3	0.0
	4	0.0	1.4	0.4	0.0	0.1	0.0
	5	0.3	6.4	0.7	0.0	0.0	0.0
	6	0.8	6.6	0.8	0.0	0.5	0.0
	7	0.3	4.2	0.6	0.0	0.4	0.0
	8	0.1	2.3	0.2	0.0	0.8	0.0
	Sum	5.7	47.2	4.4	0.0	2.0	0.0
OUT	**Layer**	**GHBs**	**ET**	**Streams**	**Wells**	**Drains**	**Storage**
	1	5.5	1.9	5.4	0.8	0.0	0.2
	2	0.0	0.2	0.4	0.0	0.0	0.0
	3	0.0	5.9	12.6	0.8	0.0	1.3
	4	0.0	0.2	1.1	0.0	0.0	0.0
	5	0.5	1.7	4.6	8.5	0.0	0.2
	6	0.4	1.7	6.6	2.8	0.0	0.5
	7	0.3	1.0	4.8	11.8	0.0	0.1
	8	0.2	0.5	2.4	1.4	0.0	0.6
	Sum	7.0	13.0	38.0	26.1	0.0	2.8

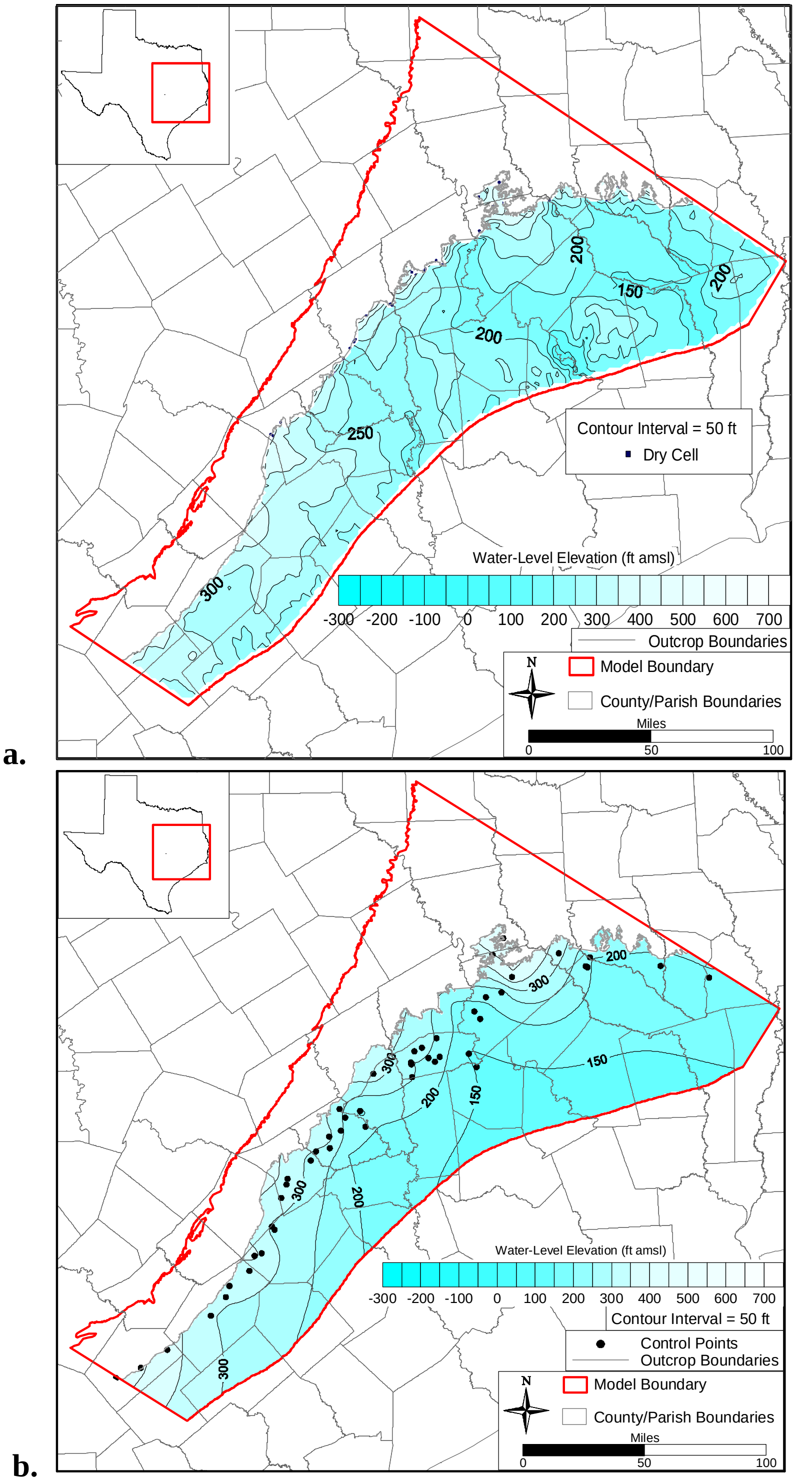
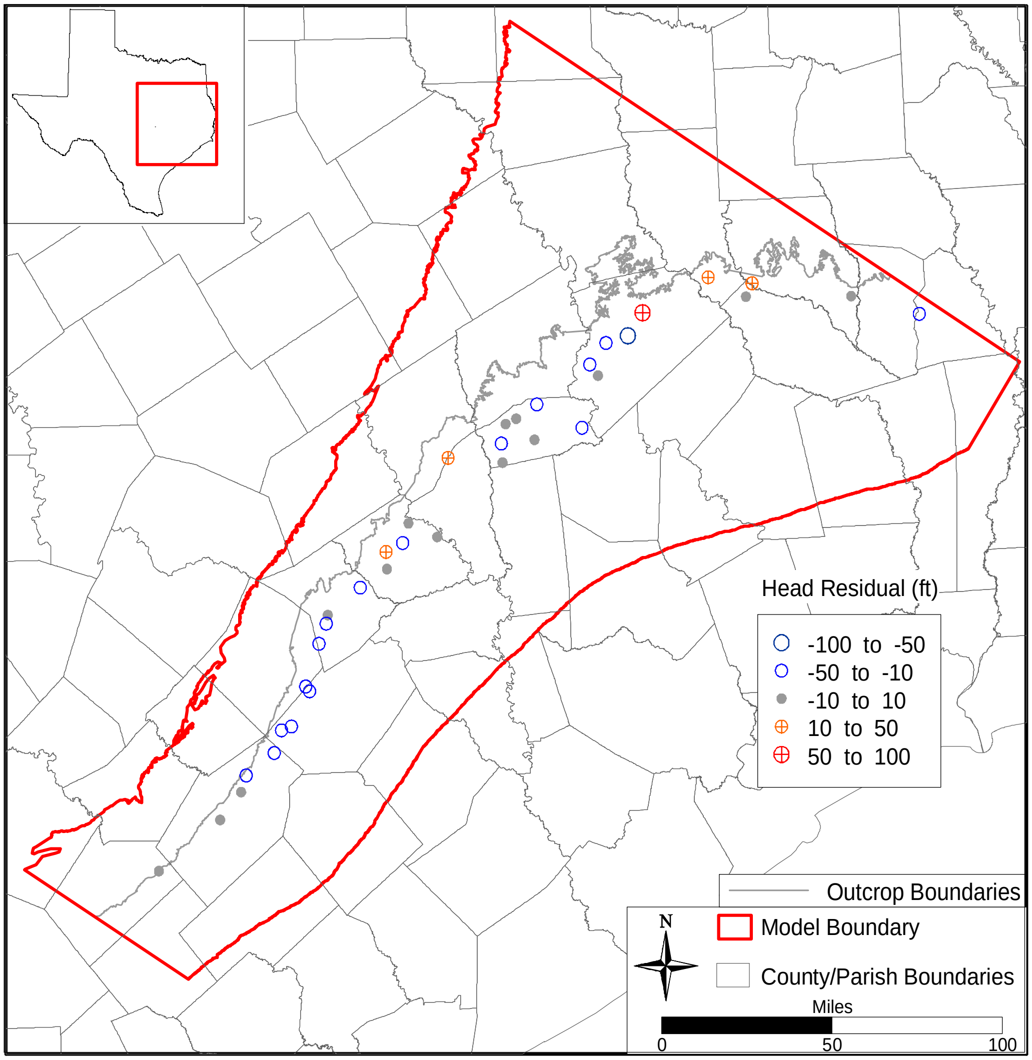


Figure 9.2.1 **Comparison between simulated (a) and estimated (b) Sparta aquifer (Layer 1) heads for 1990 (the end of the calibration period).**

a.



b.

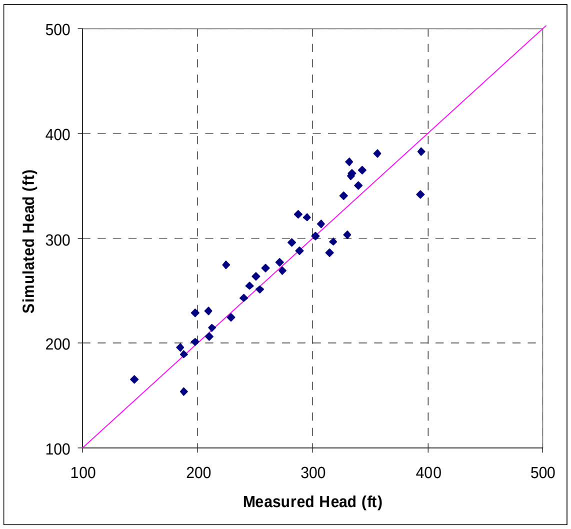


Figure 9.2.2 **Residuals (a) and scatterplot (b) for the Sparta aquifer (Layer 1) in the calibration period.**

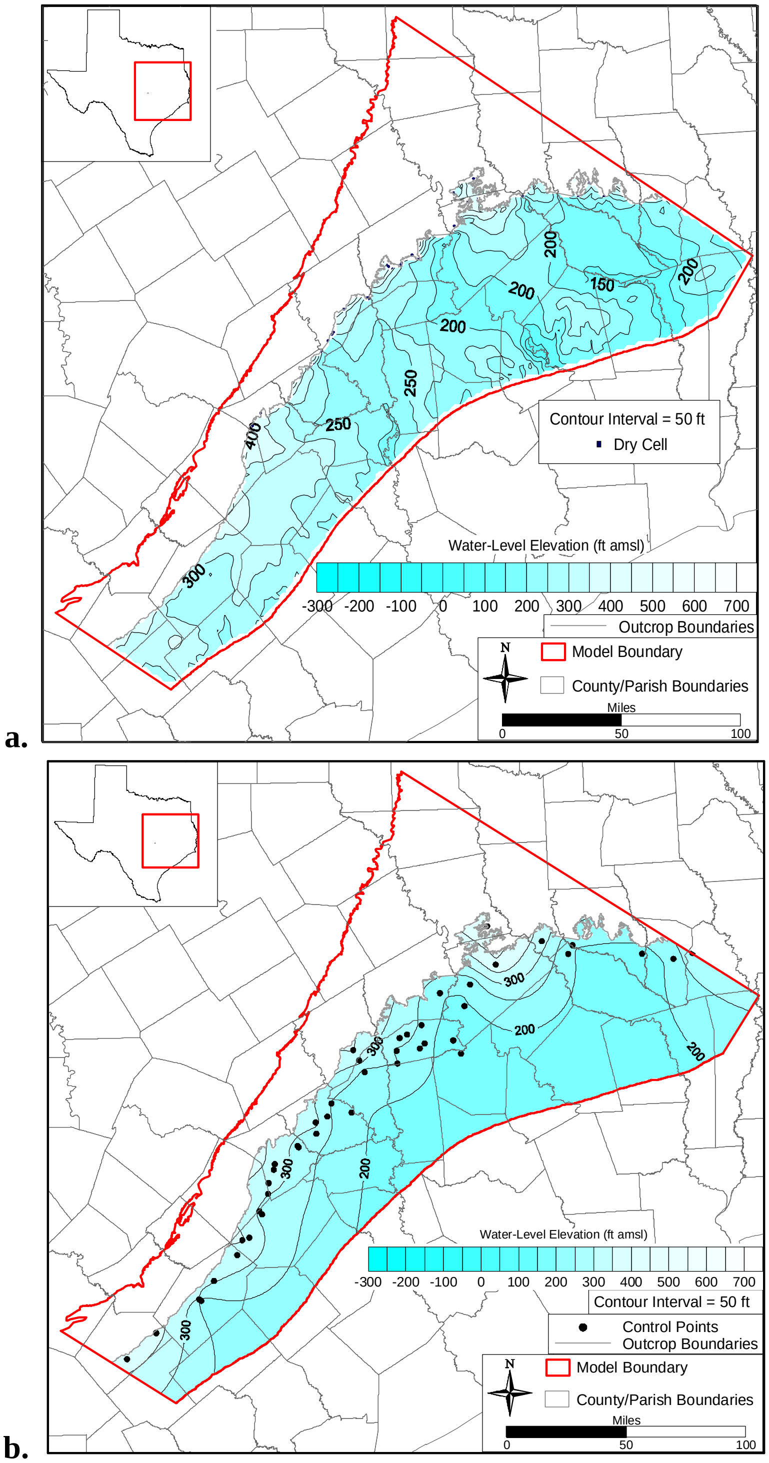
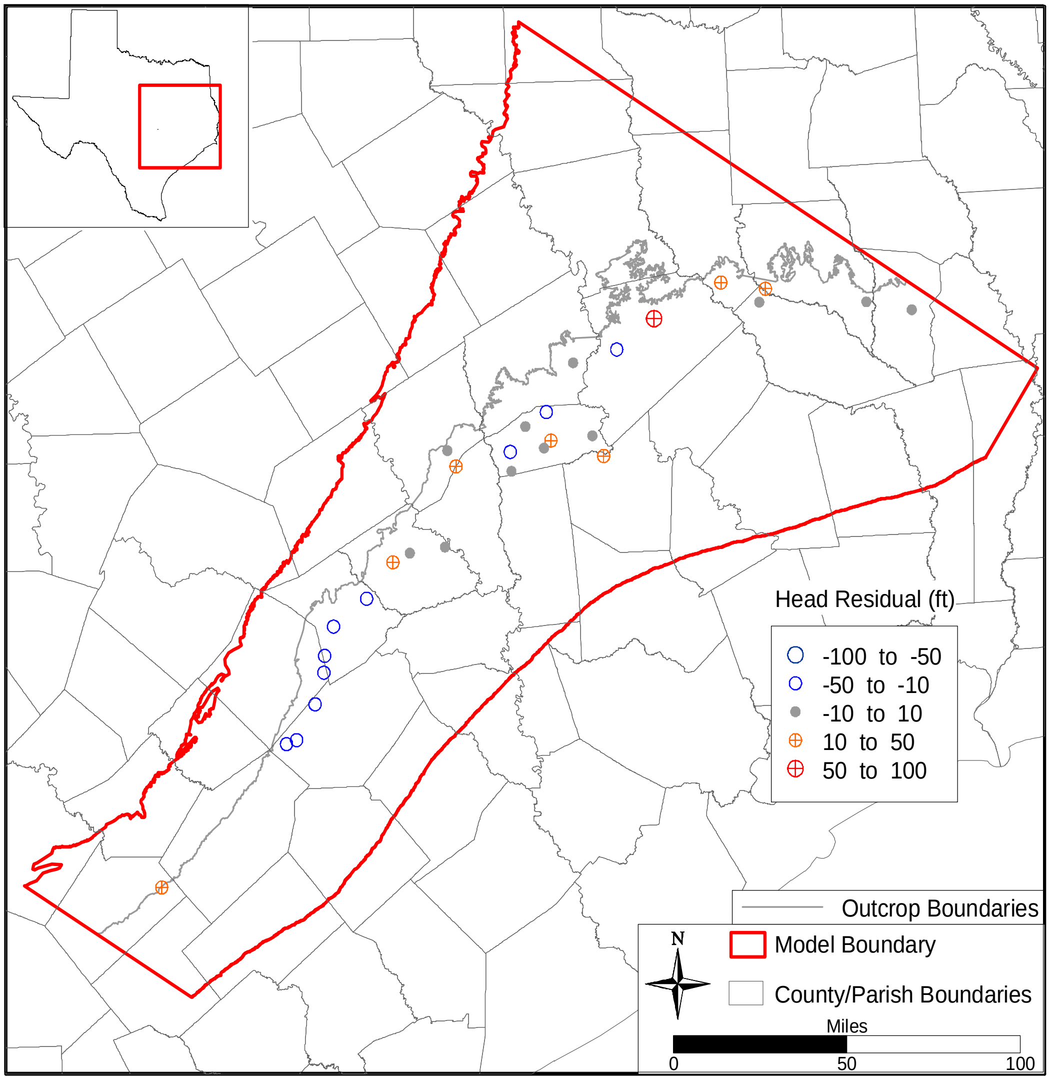


Figure 9.2.3 Comparison between simulated (a) and estimated (b) Sparta aquifer (Layer 1) heads 1999 (the end of the verification period).

a.



b.

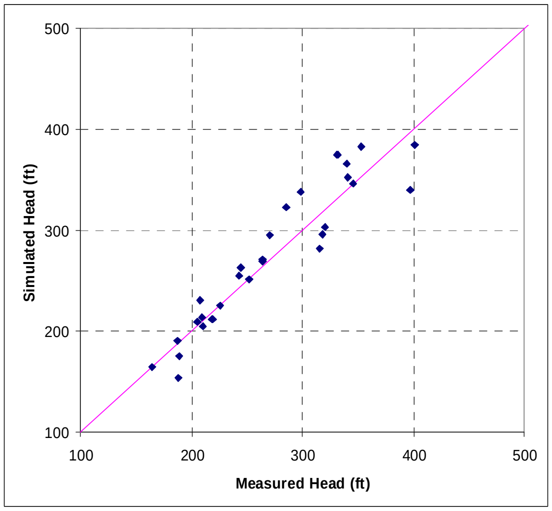


Figure 9.2.4 Residuals (a) and scatterplot (b) for the Sparta aquifer (Layer 1) in the verification period.

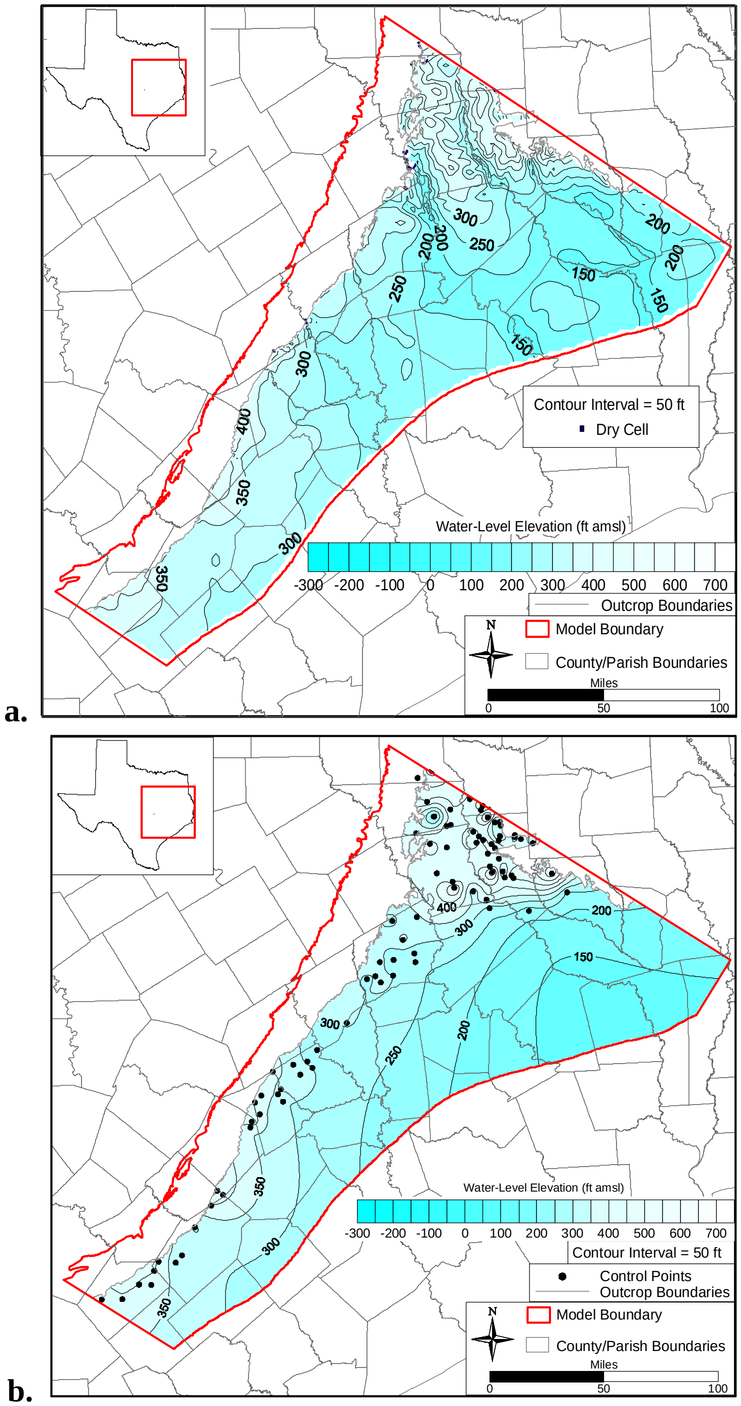


Figure 9.2.5 Comparison between simulated (a) and estimated (b) Queen City aquifer heads for 1990 (the end of the calibration period).

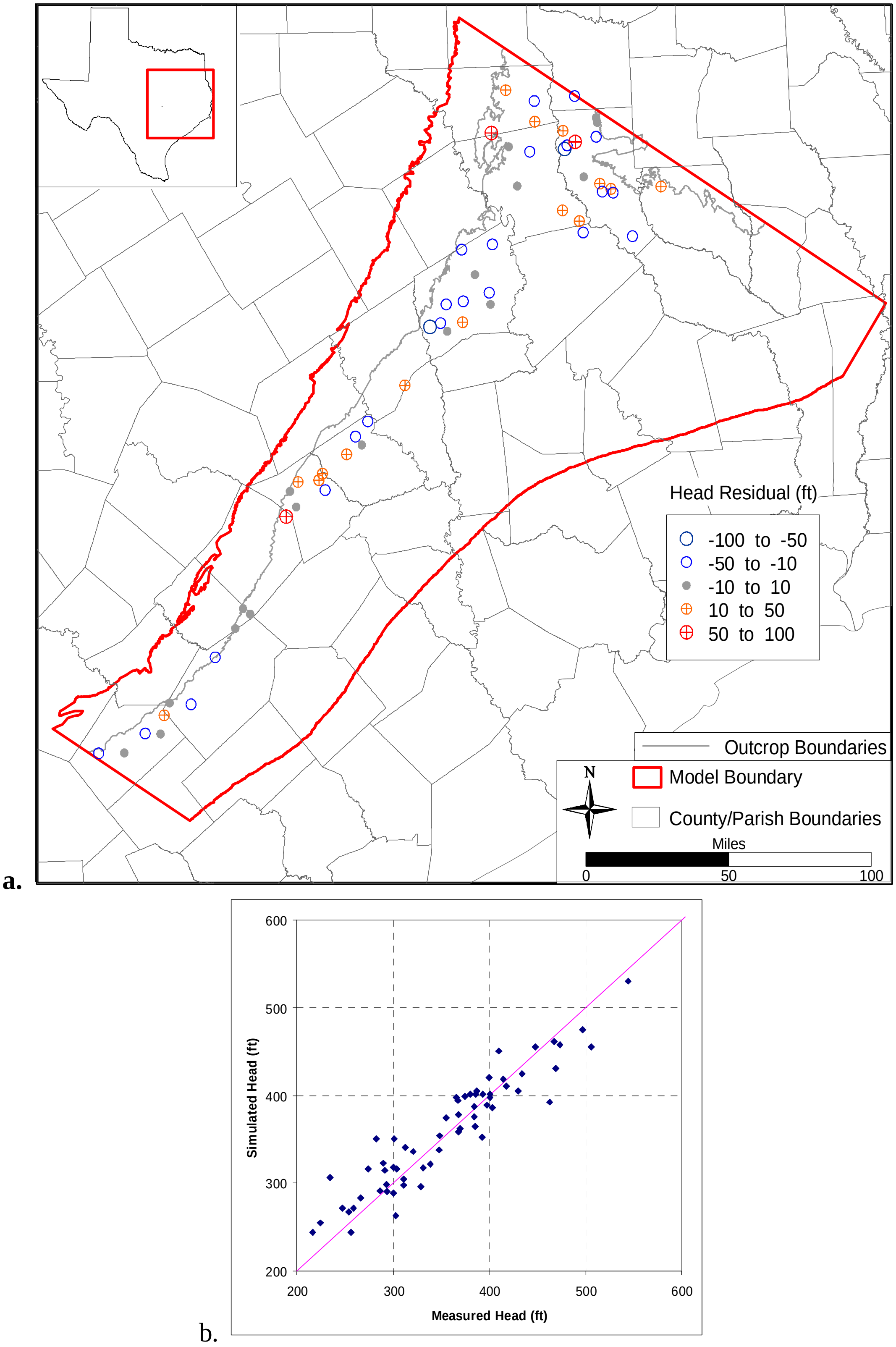


Figure 9.2.6 **Residuals (a) and scatterplot (b) for the Queen City aquifer (Layer 3) in the calibration period.**

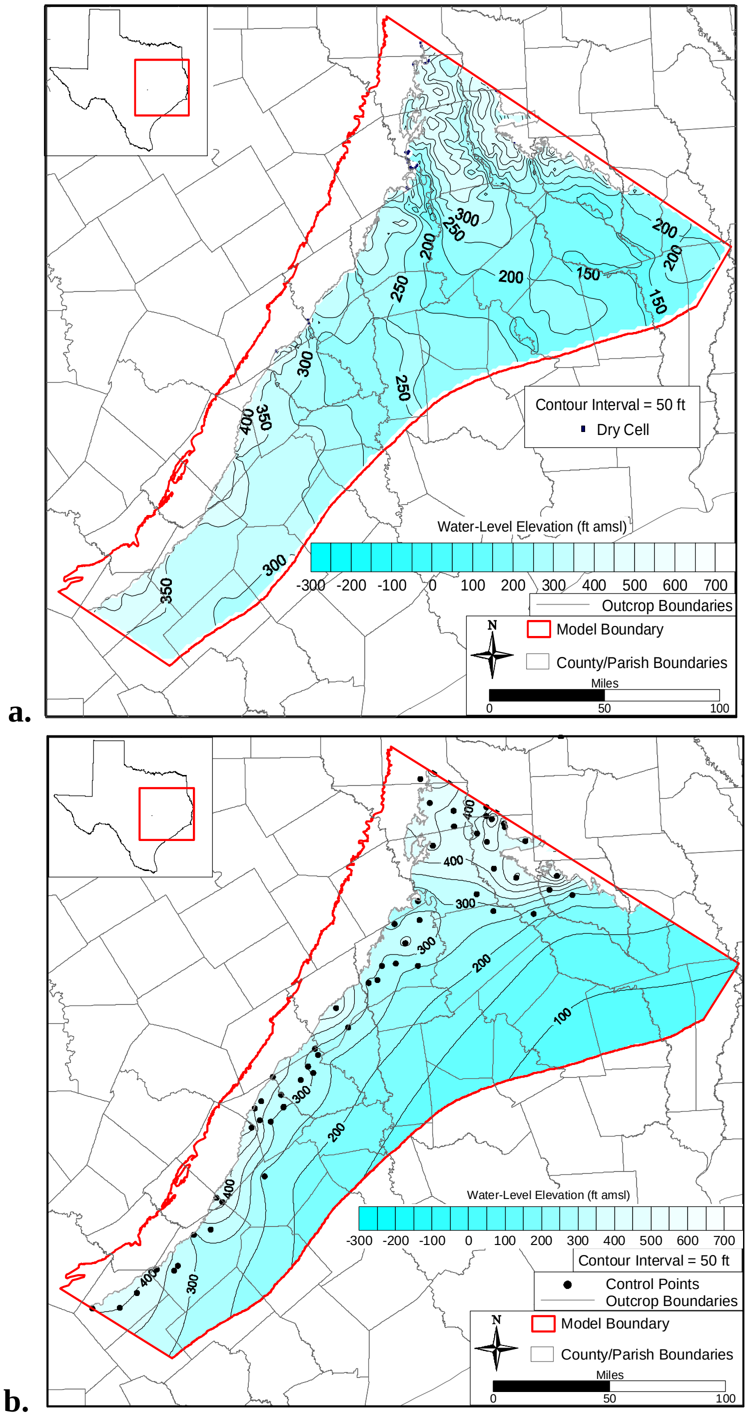


Figure 9.2.7 Comparison between simulated (a) and estimated (b) Queen City aquifer heads for 1999 (the end of the verification period).

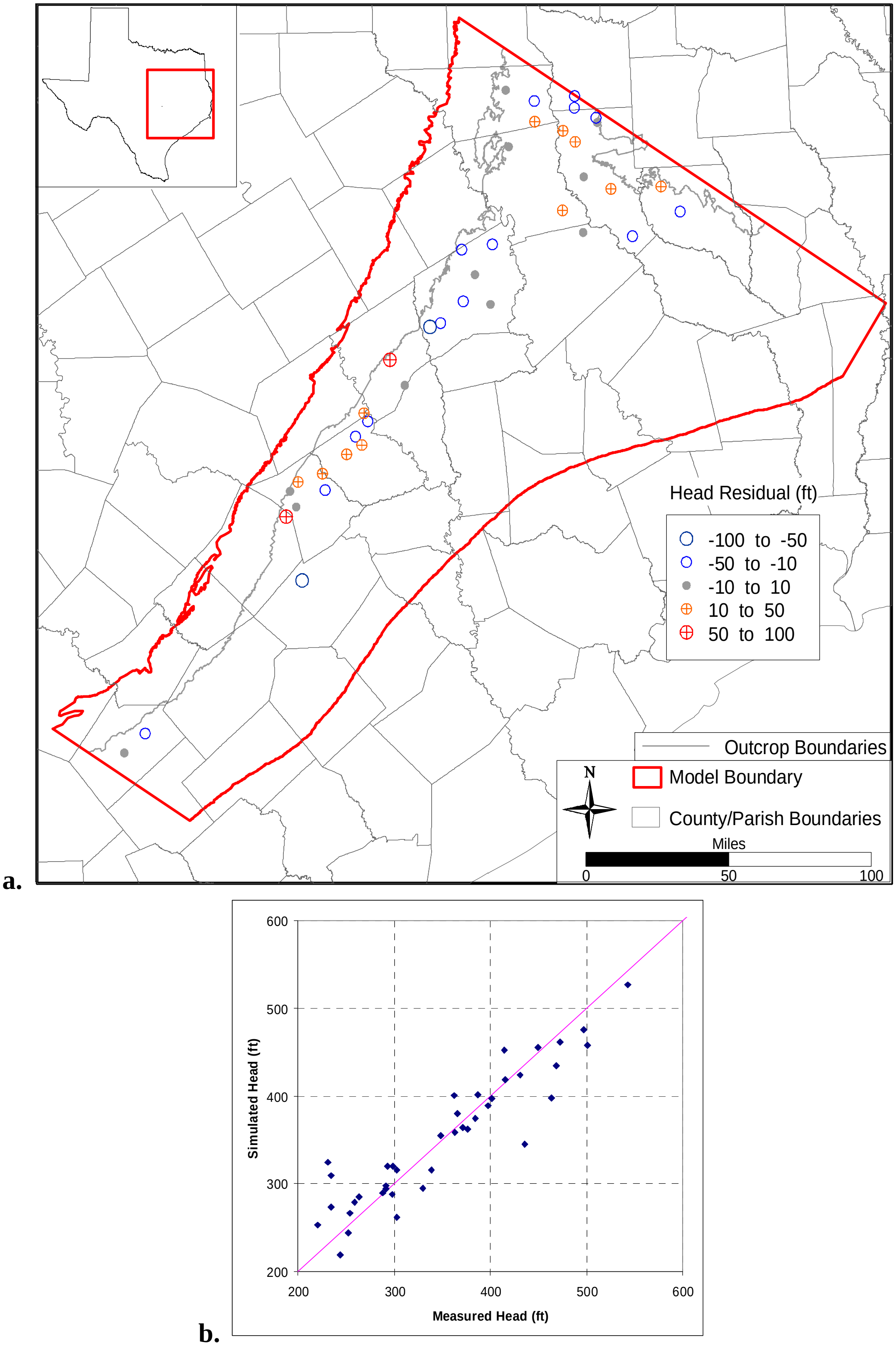


Figure 9.2.8 **Residuals (a) and scatterplot (b) for the Queen City aquifer (Layer 3) in the verification period.**

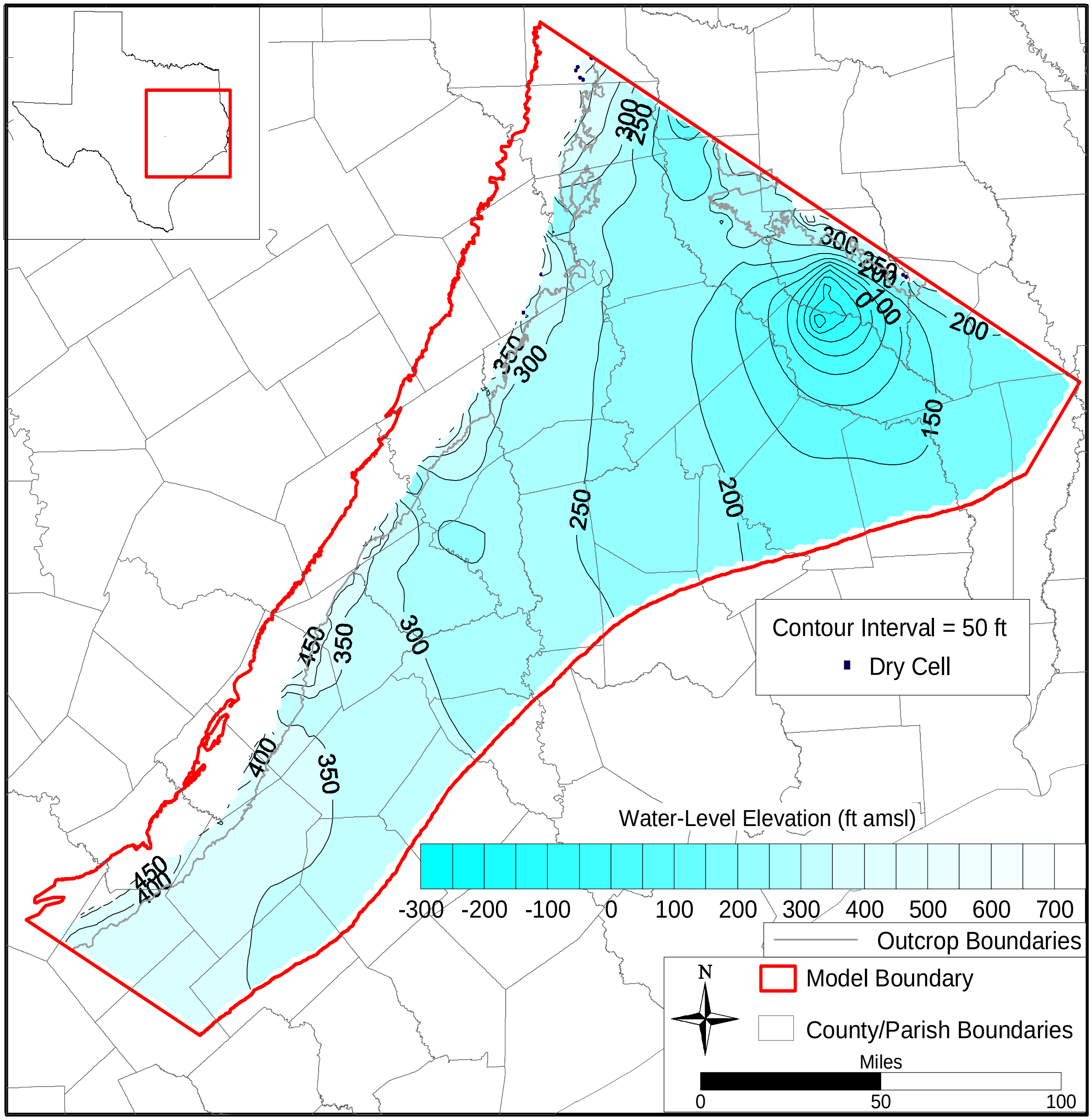


Figure 9.2.9 Simulated hydraulic heads at the end of the calibration period in the Carrizo aquifer.

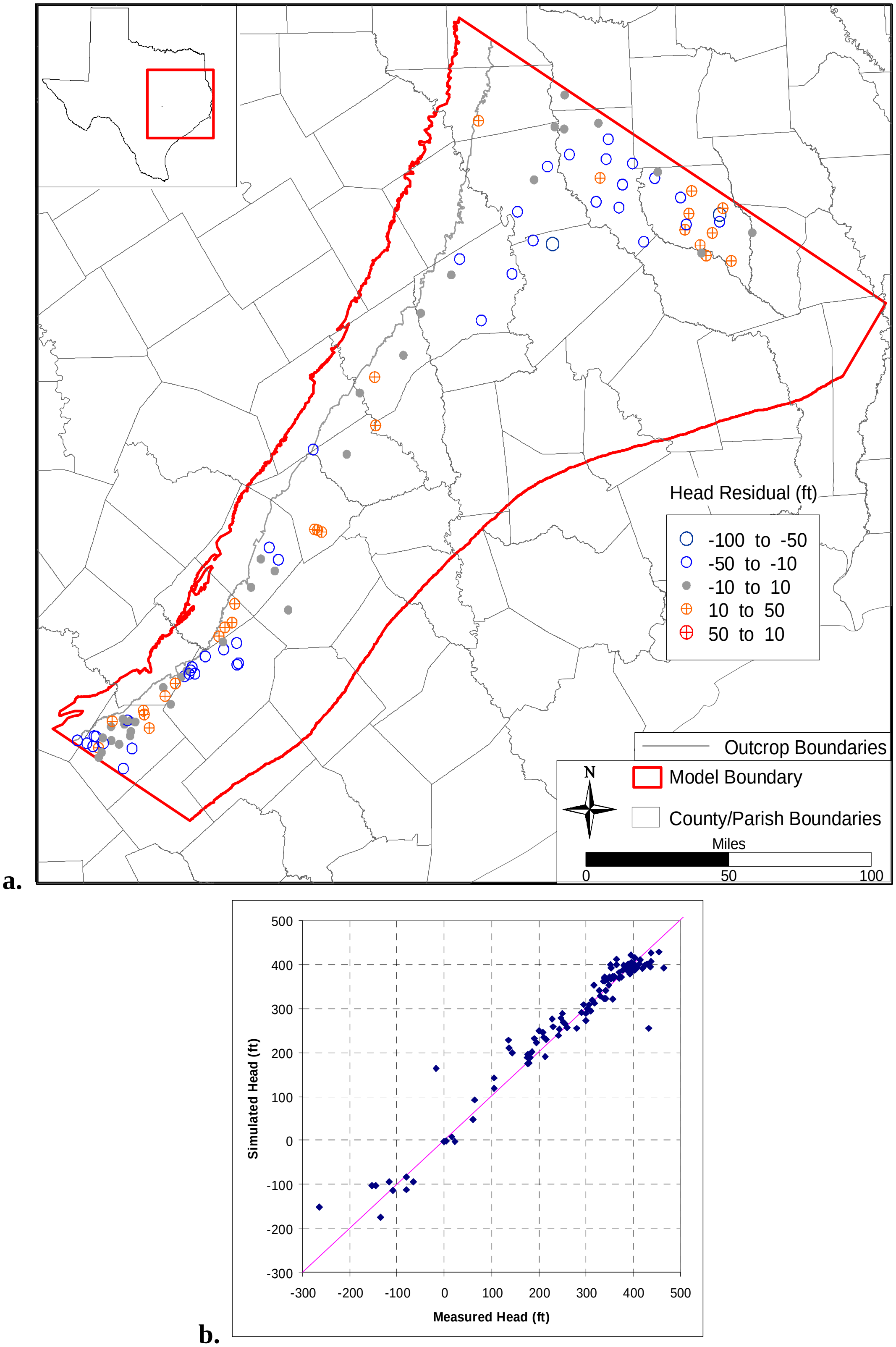


Figure 9.2.10 Residuals (a) and scatterplot (b) for the Carrizo aquifer (Layer 5) in the calibration period.

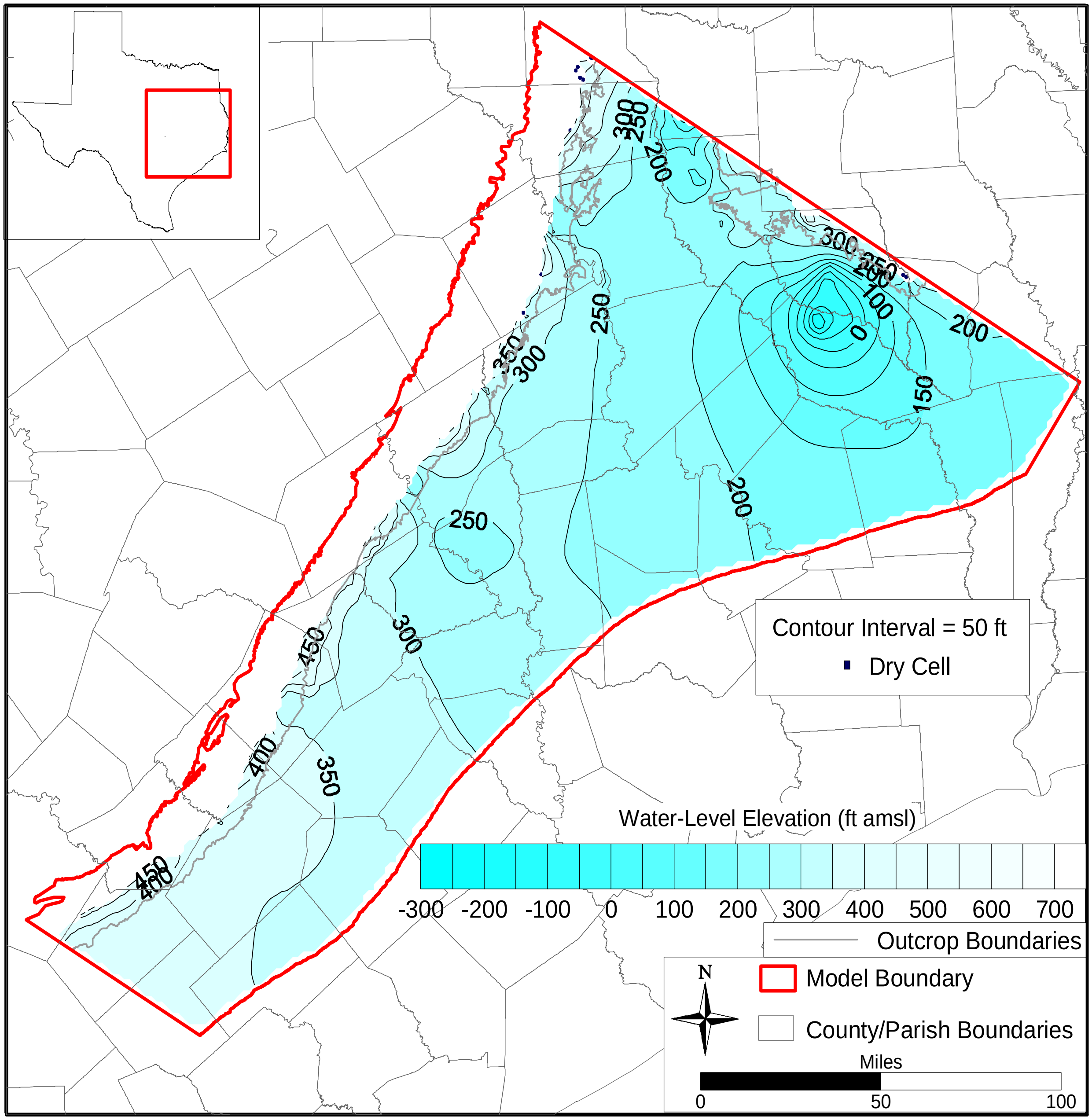


Figure 9.2.11 Simulated hydraulic heads at the end of the verification period in the Carrizo aquifer.

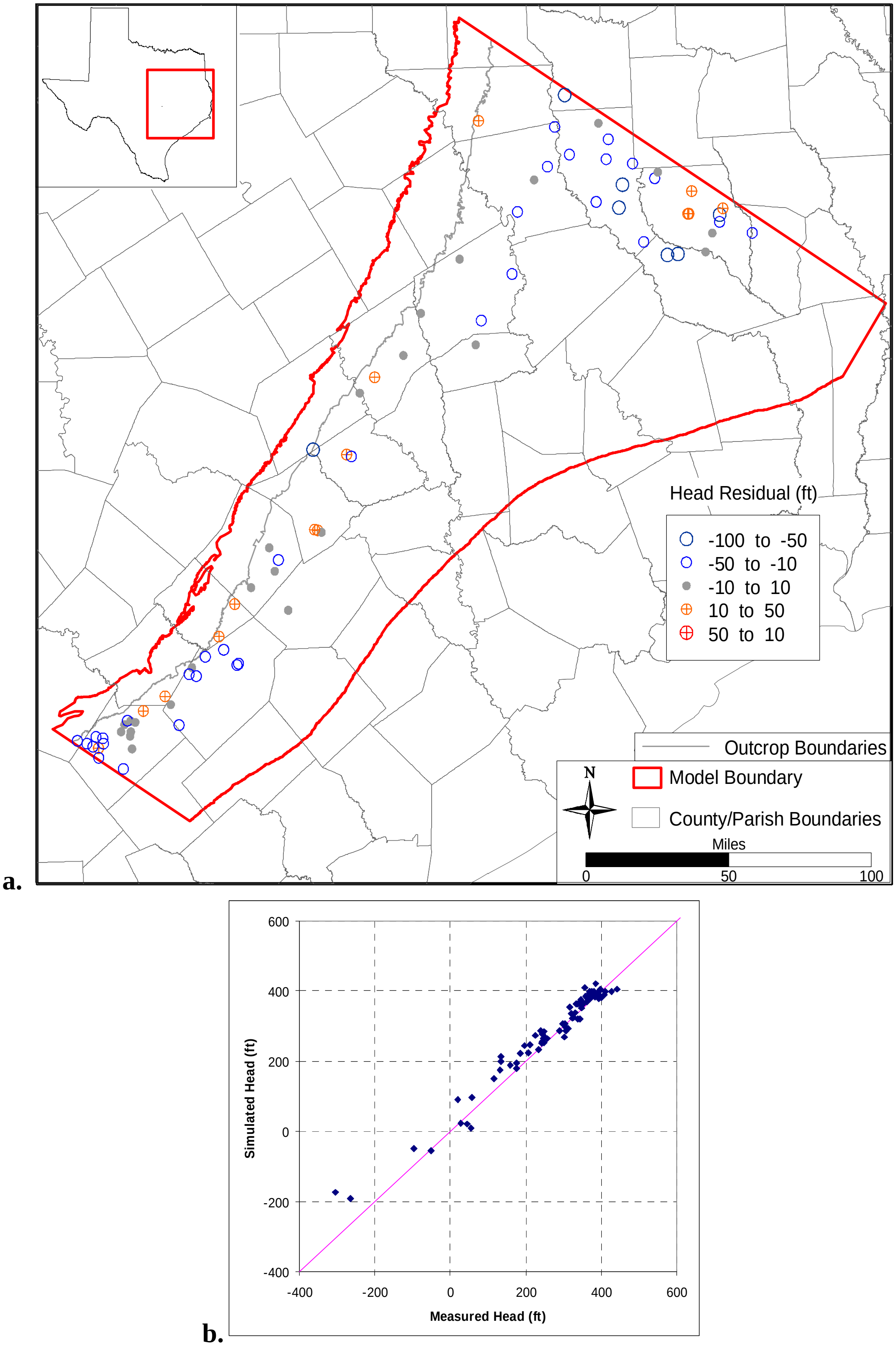


Figure 9.2.12 Residuals (a) and scatterplot (b) for the Carrizo aquifer (Layer 5) in the verification period.

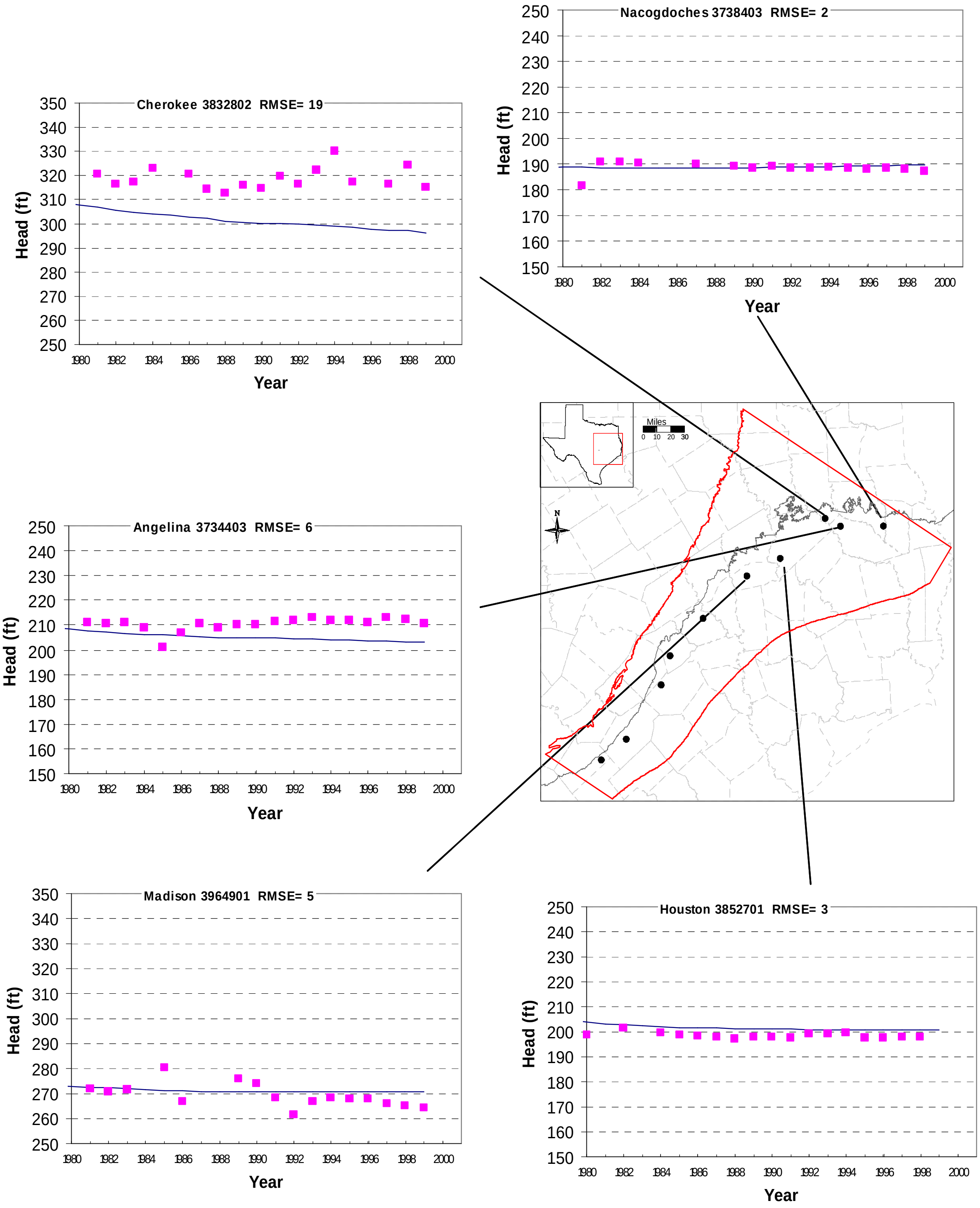


Figure 9.2.13a Transient model hydrographs for the Sparta aquifer (Layer 1) in Angelina, Cherokee, Houston, Nacogdoches, and Madison counties. Simulated and measured data are shown as lines and points, respectively.

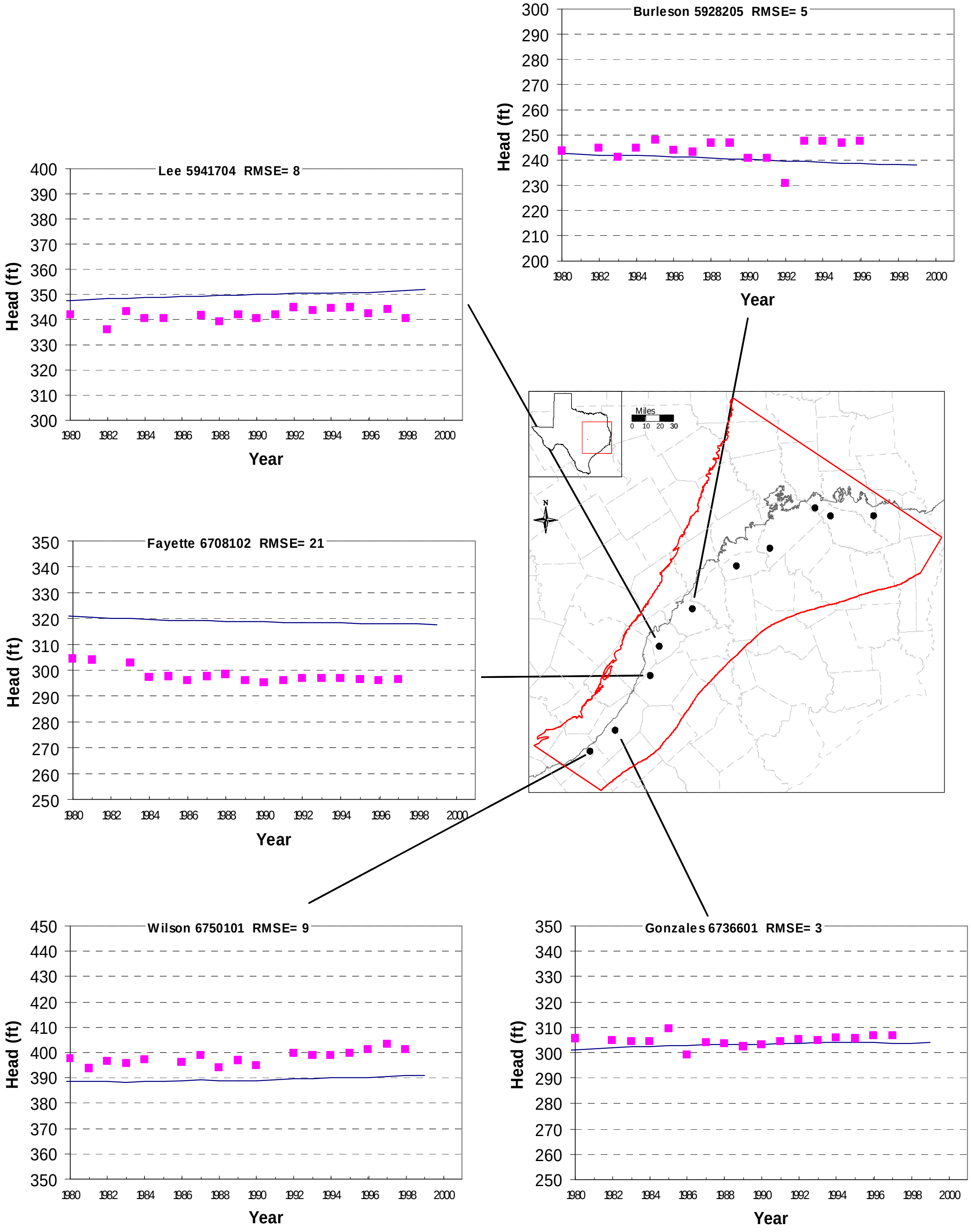


Figure 9.2.13b Transient model hydrographs for the Sparta aquifer (Layer 1) in Burleson, Fayette, Gonzales, Lee, and Wilson counties. Simulated and measured data are shown as lines and points, respectively.

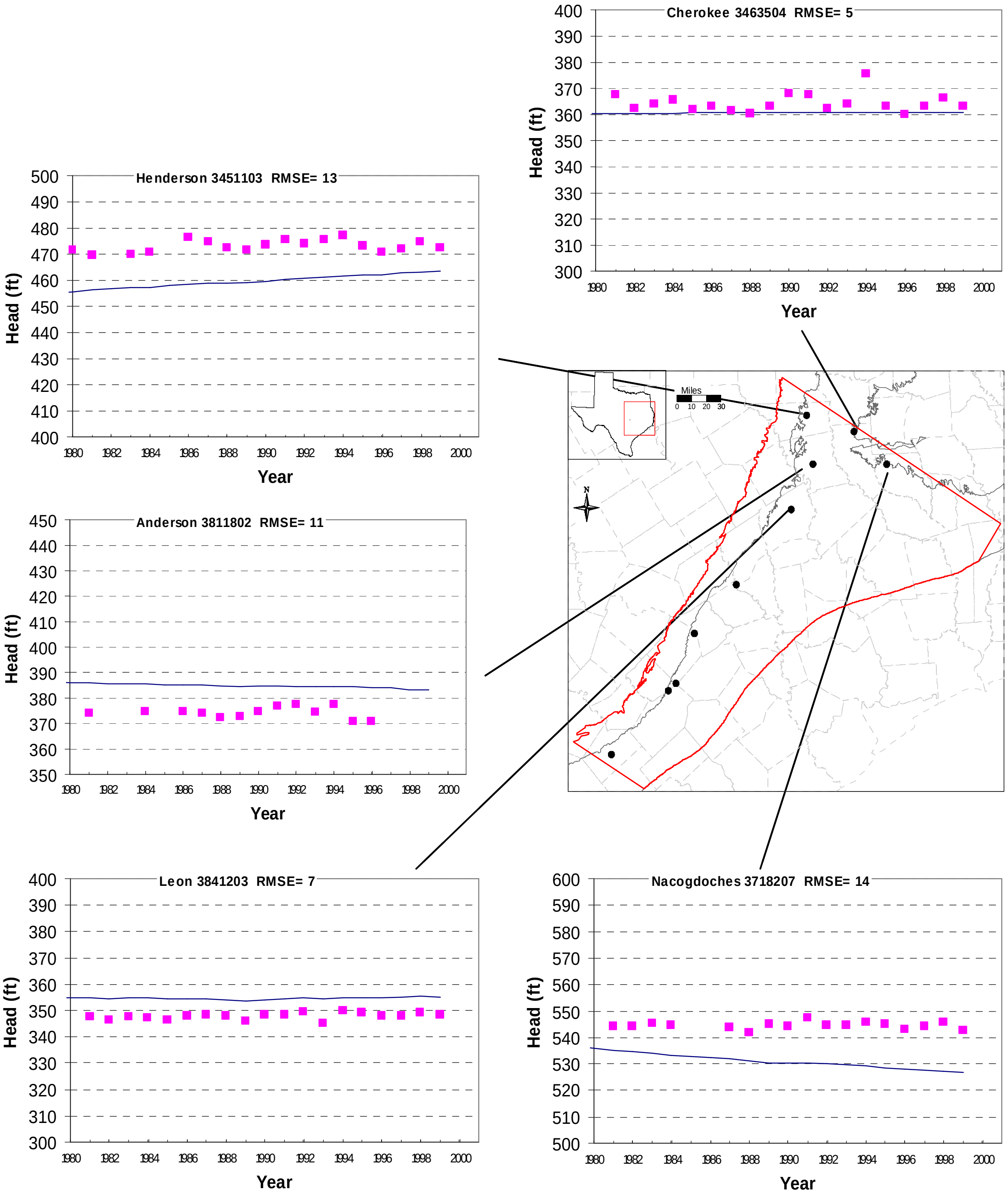


Figure 9.2.14a Transient model hydrographs for the Queen City aquifer (Layer 3) in Anderson, Cherokee, Henderson, Leon, and Nacogdoches counties. Simulated and measured data are shown as lines and points, respectively.

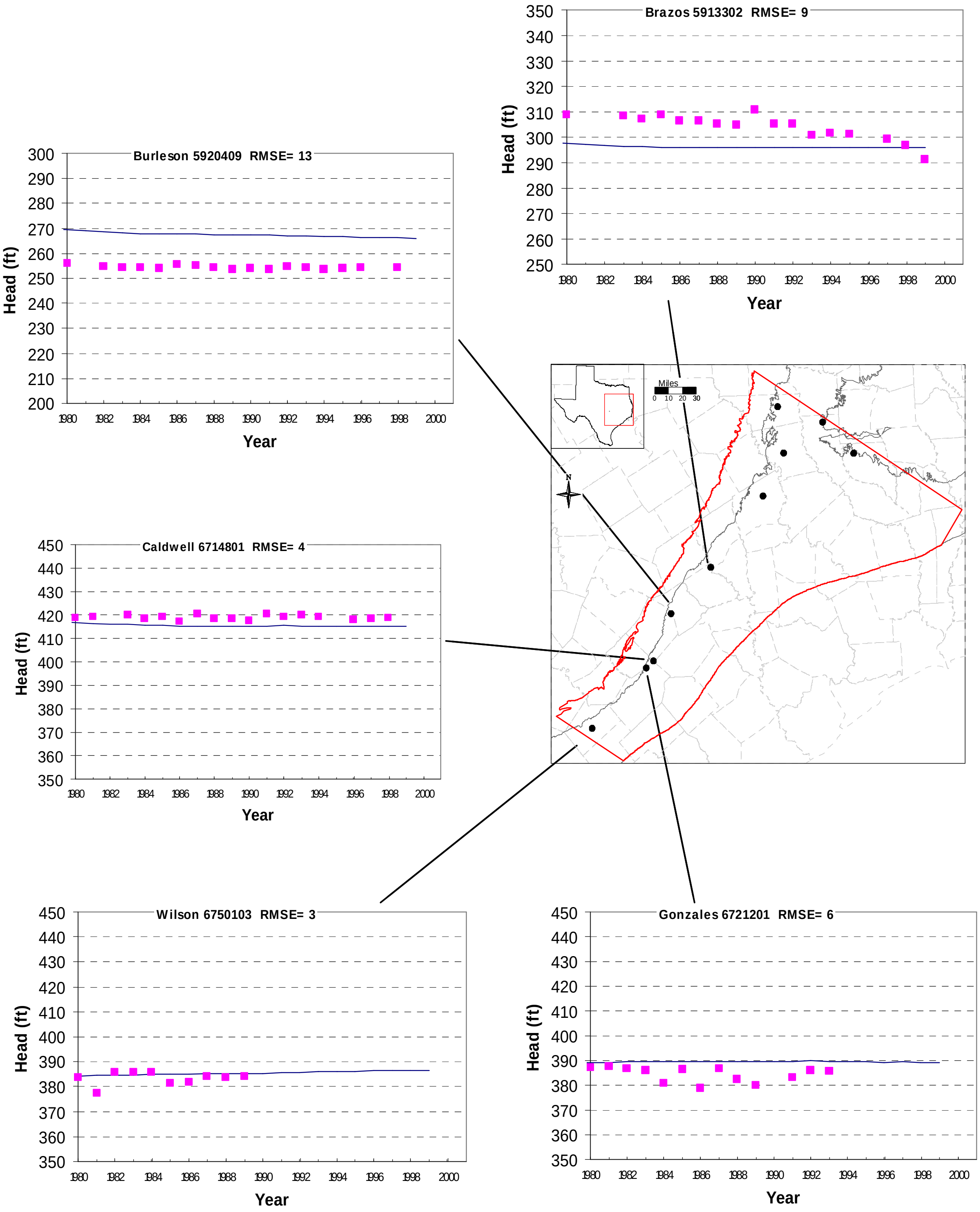


Figure 9.2.14b Transient model hydrographs for the Queen City aquifer (Layer 3) in Brazos, Burleson, Caldwell, Gonzales, and Wilson counties. Simulated and measured data are shown as lines and points, respectively.

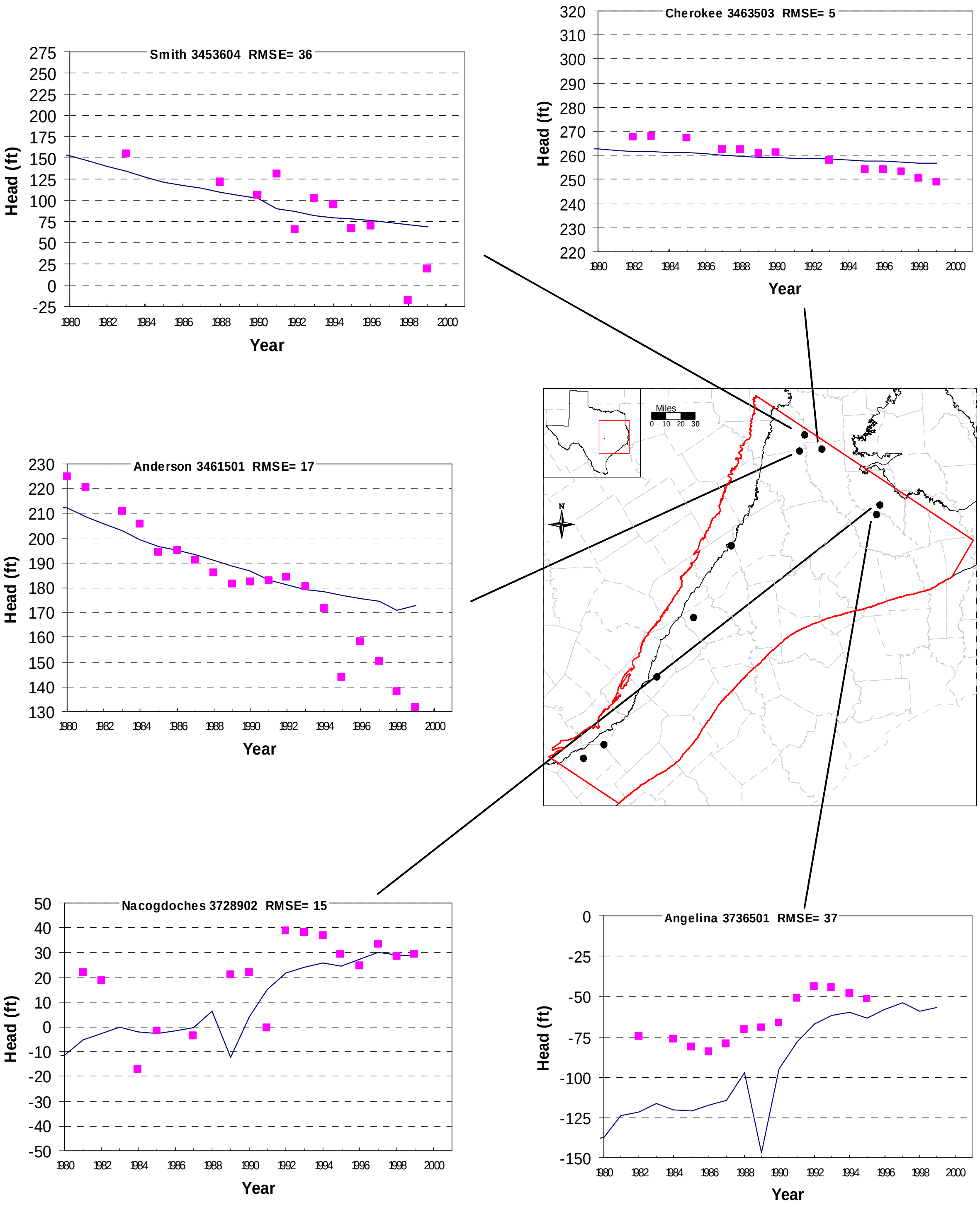


Figure 9.2.15a Transient model hydrographs for the Carrizo aquifer (Layer 5) in Andersen, Angelina, Cherokee, Nacogdoches, and Smith counties. Simulated and measured data are shown as lines and points, respectively.

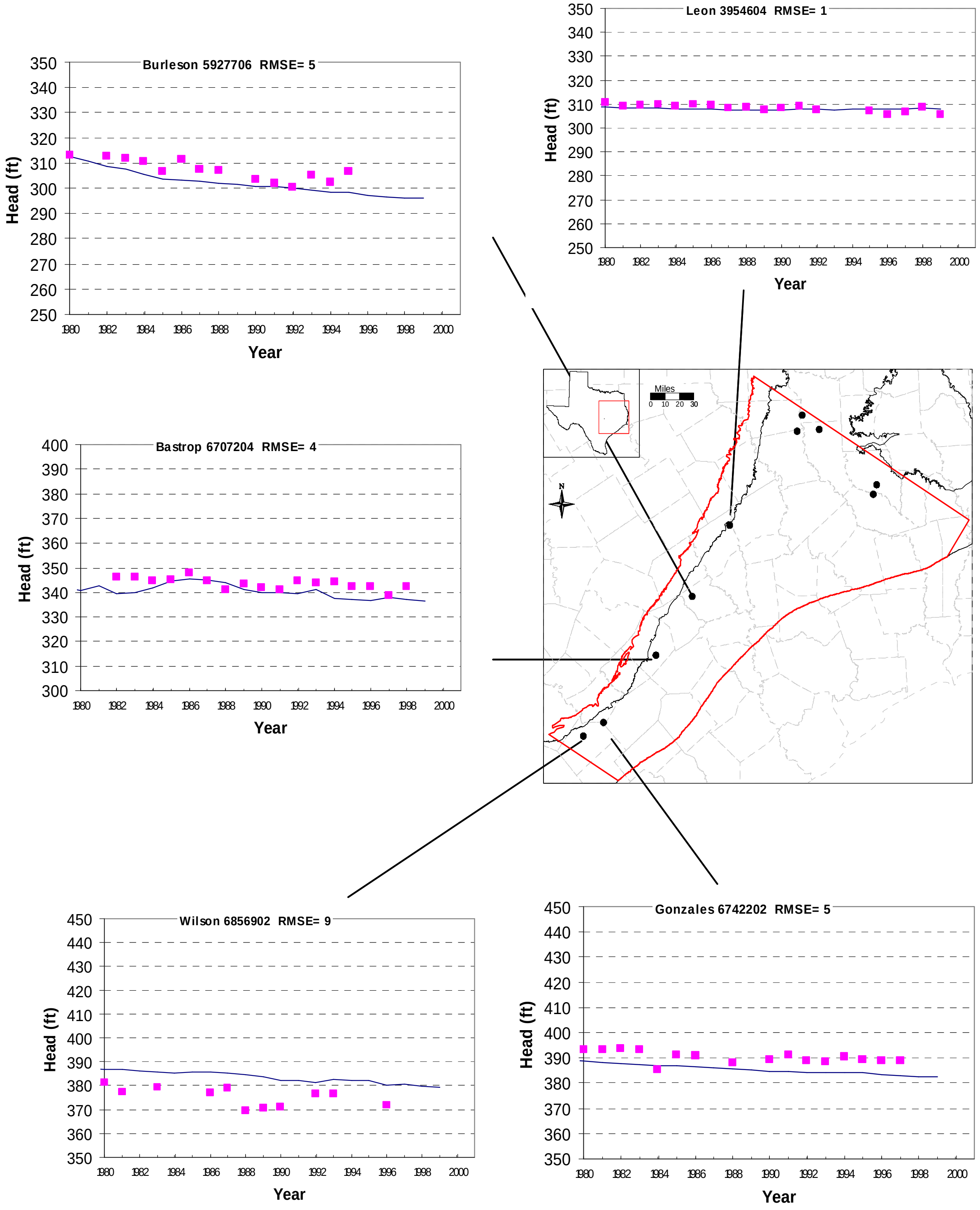


Figure 9.2.15b Transient model hydrographs for the Carrizo aquifer (Layer 5) in Bastrop, Burleson, Gonzales, Leon, and Wilson counties. Simulated and measured data are shown as lines and points, respectively.

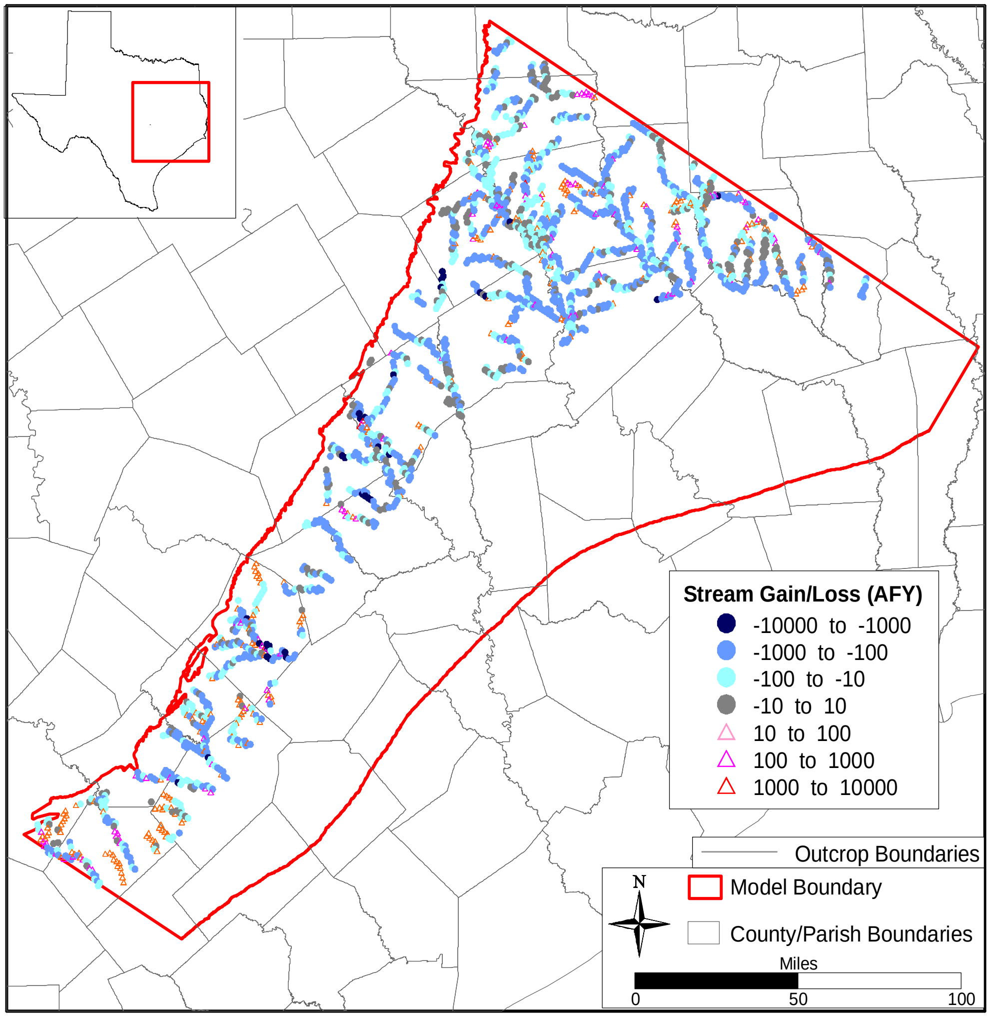


Figure 9.2.16 Transient model stream gain/loss in 1989 (positive value denotes a gaining stream).

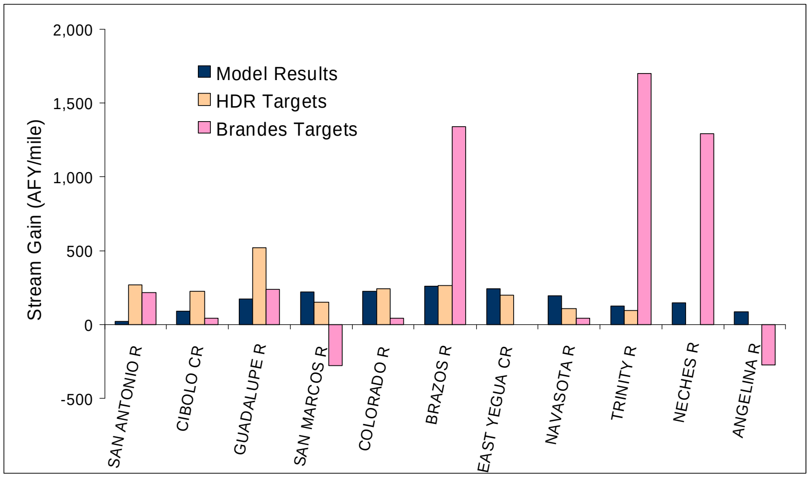


Figure 9.2.17 Comparison of 1989 transient model stream gain/loss to measured gain/loss.

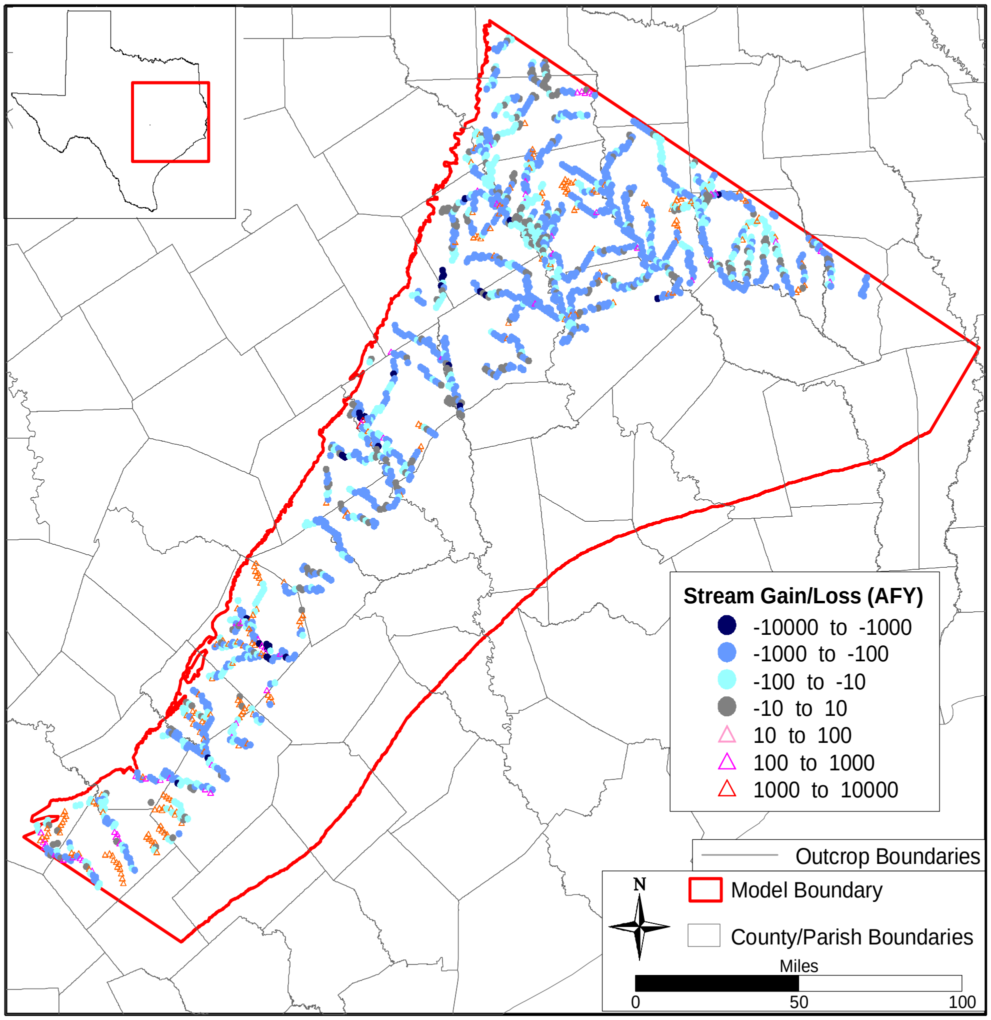


Figure 9.2.18 **Transient model stream gain/loss in 1996 (positive value denotes a gaining stream).**

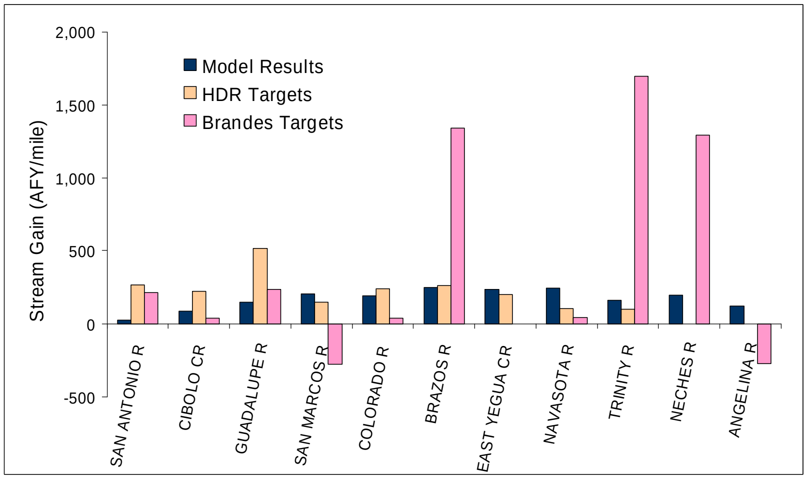


Figure 9.2.19 **Comparison of 1996 transient model stream gain/loss to measured gain/loss.**

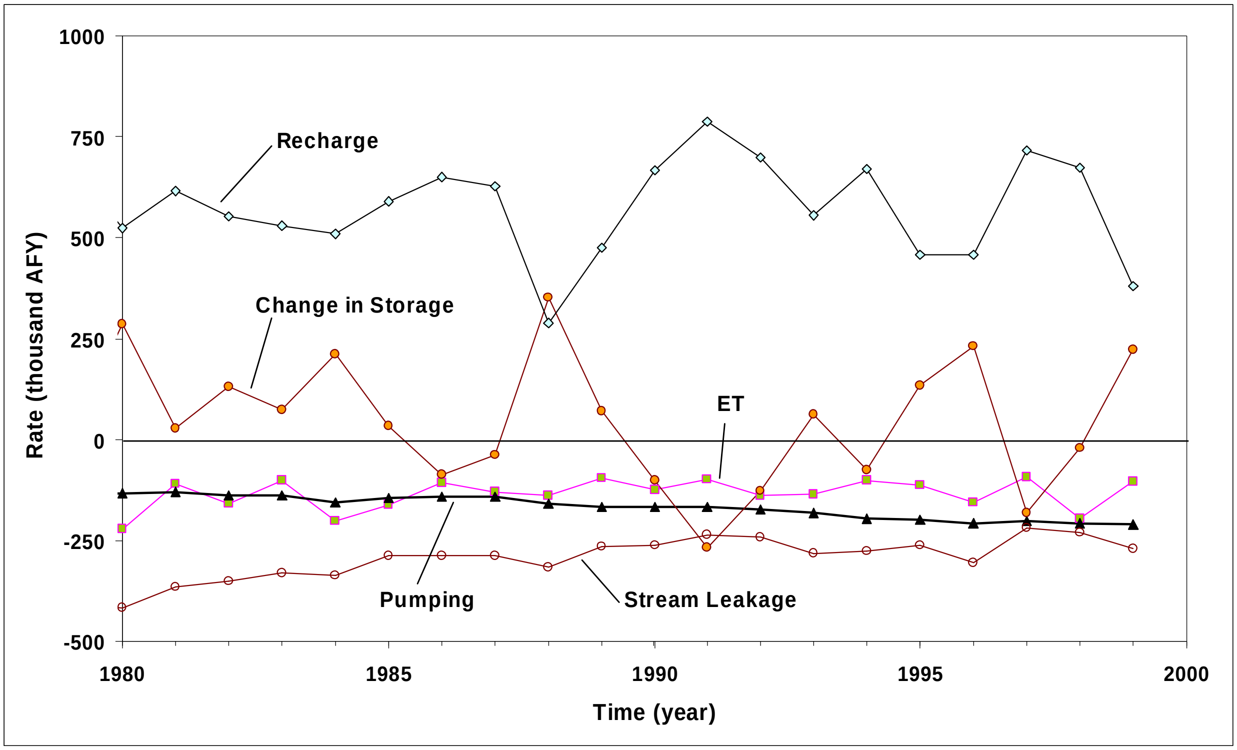


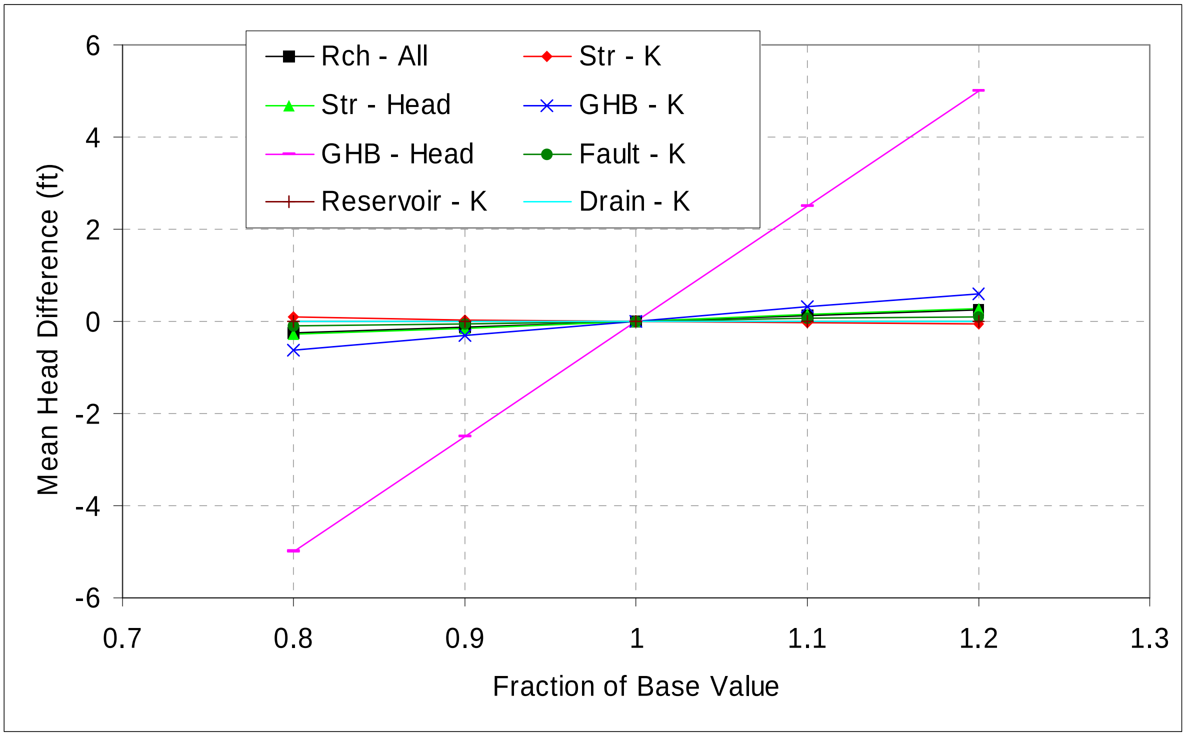
Figure 9.2.20 Change in model-wide rates through time for the transient model.

9.2.3 Sensitivity Analysis

The application of the sensitivity analysis was the same as that of the Southern model, described in Section 9.1.3. Simulated water levels for the Sparta aquifer (Layer 1) and the Queen City aquifer (Layer 3) are most sensitive to GHB heads and storativity (Figures 9.2.21 and 9.2.22). There is a general lack of pumping in the Sparta and Queen City aquifers, but pumping displaces storativity as the most sensitive parameter in the Carrizo aquifer (Layer 5) while changes in storativity generate approximately the same head difference in all three aquifers (Figure 9.2.23). Conductivity variations do not have a major impact on Layers 1 and 3, but do on Layer 5 (Figure 9.2.24) because of pumping.

Layer comparisons of sensitivity to GHB heads, storativity, pumping, and vertical conductivity of the Reklaw Formation are displayed in Figures 9.2.25 through 9.2.28. Review of these figures indicates that the steady-state and transient model sensitivities are similar. GHB heads have a large impact on Layer 1, a smaller impact on Layer 2, and an even smaller impact on the underlying layers. Pumping has the largest effect on the Simsboro aquifer, which is the layer with the most pumping. It also impacts neighboring Layers 6 and 8. The Carrizo aquifer (Layer 5), which has a significant amount of pumping, is also sensitive to pumping variation. Vertical conductivity of the Reklaw Formation has the largest impact on the Carrizo aquifer (Layer 5).

Figures 9.2.29 and 9.2.30 show the sensitivity of selected hydrographs to varying two important parameters. Figure 9.2.29 shows transient hydrograph sensitivities for the Sparta, Queen City, and Carrizo aquifers when the GHB head is varied. As expected, an increase in the GHB head translates into an increase in the Sparta aquifer heads, while the head change in the Queen City and Carrizo aquifers is less noticeable. Figure 9.1.30 shows transient hydrograph sensitivities for selected locations in the Sparta, Queen City, and Carrizo aquifers when the vertical conductivity of the Weches Formation is varied. In general, heads decrease in the Sparta aquifer when the Weches Formation conductivity is decreased and heads decrease in the Queen City and Carrizo aquifers when the Weches Formation conductivity is increased, consistent with the results shown in Figure 9.2.24.



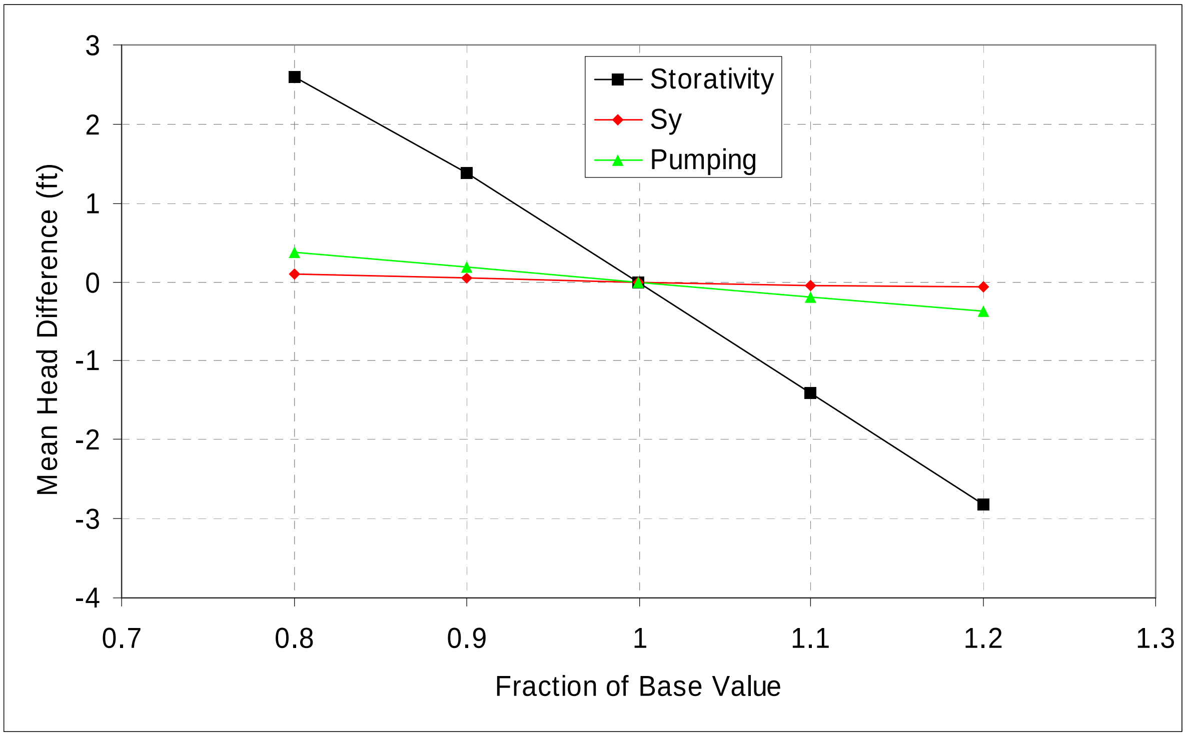


Figure 9.2.21 Transient sensitivity results for the Sparta aquifer (Layer 1) using all active grid blocks.

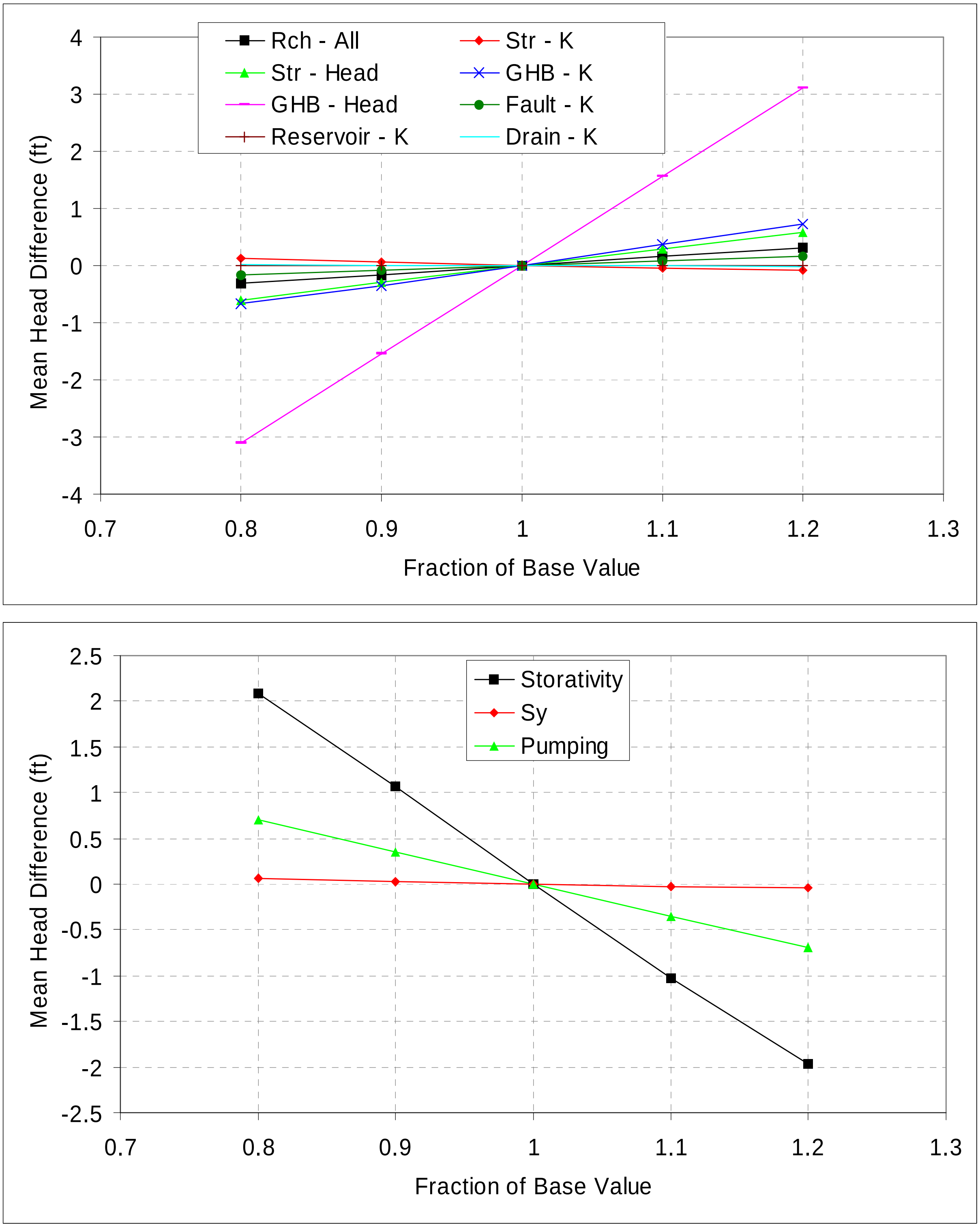
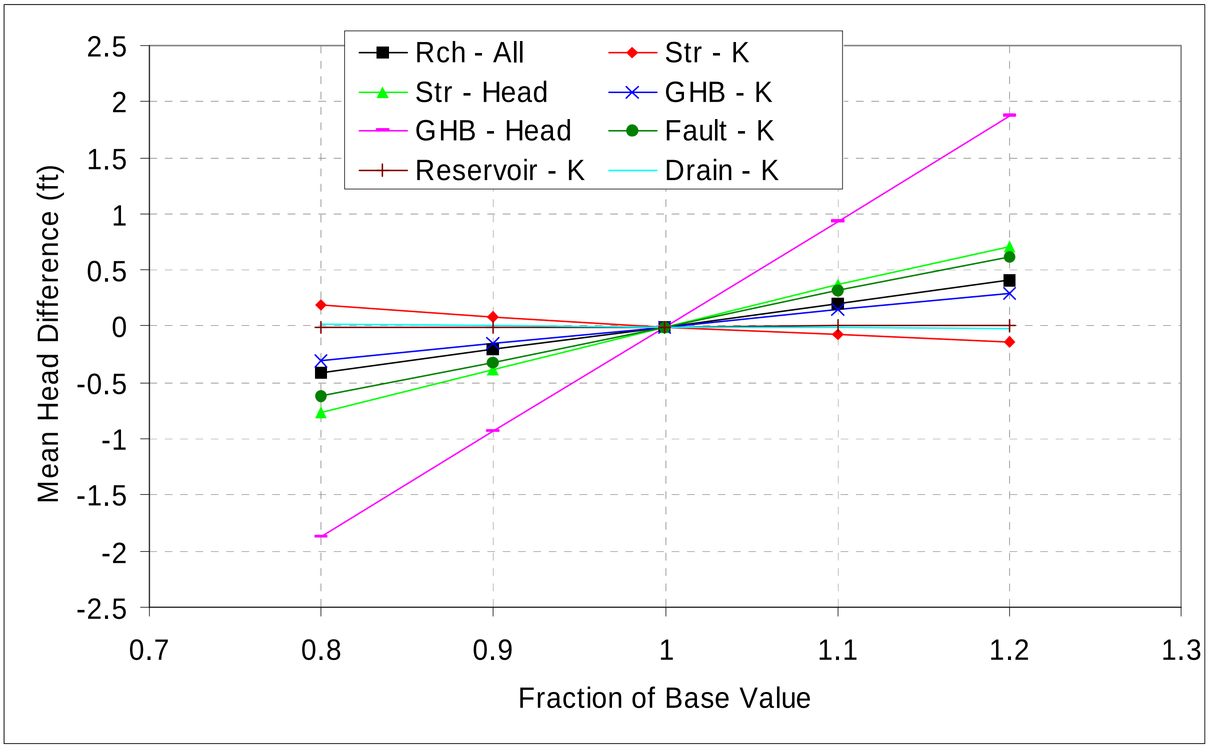


Figure 9.2.22 Transient sensitivity results for the Queen City aquifer (Layer 3) using all active grid blocks.



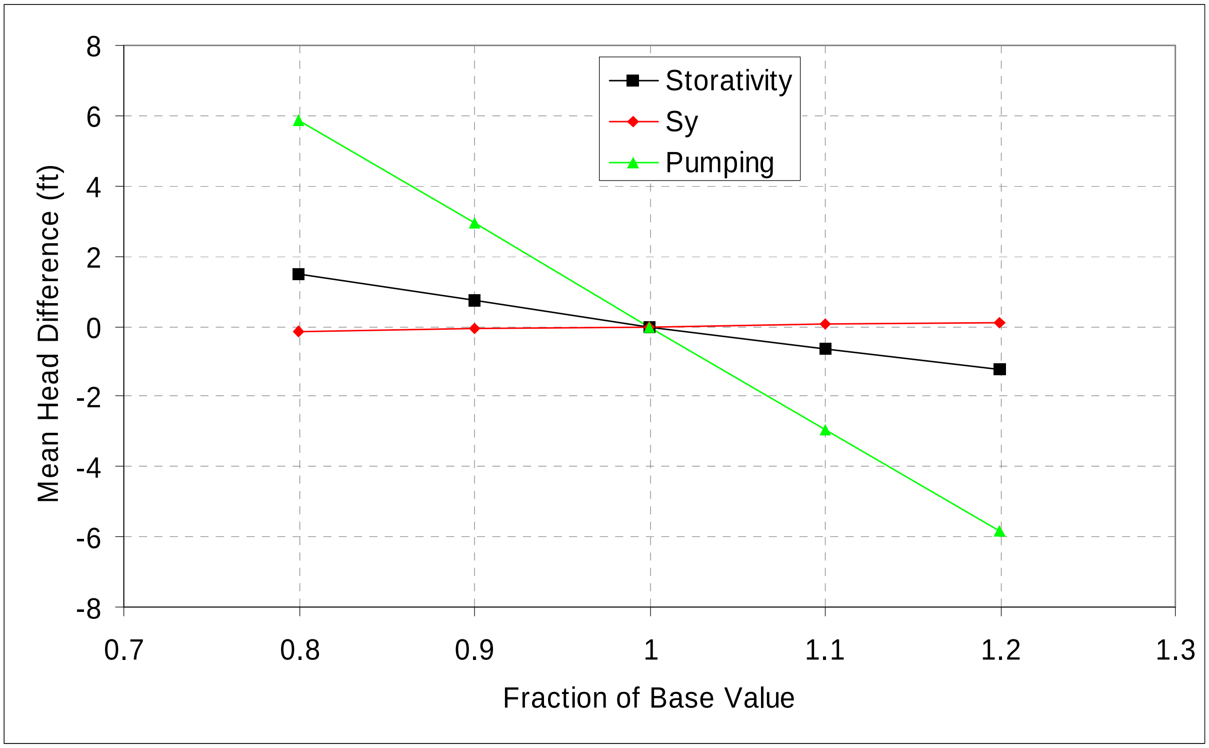


Figure 9.2.23 Transient sensitivity results for the Carrizo aquifer (Layer 5) using all active grid blocks.

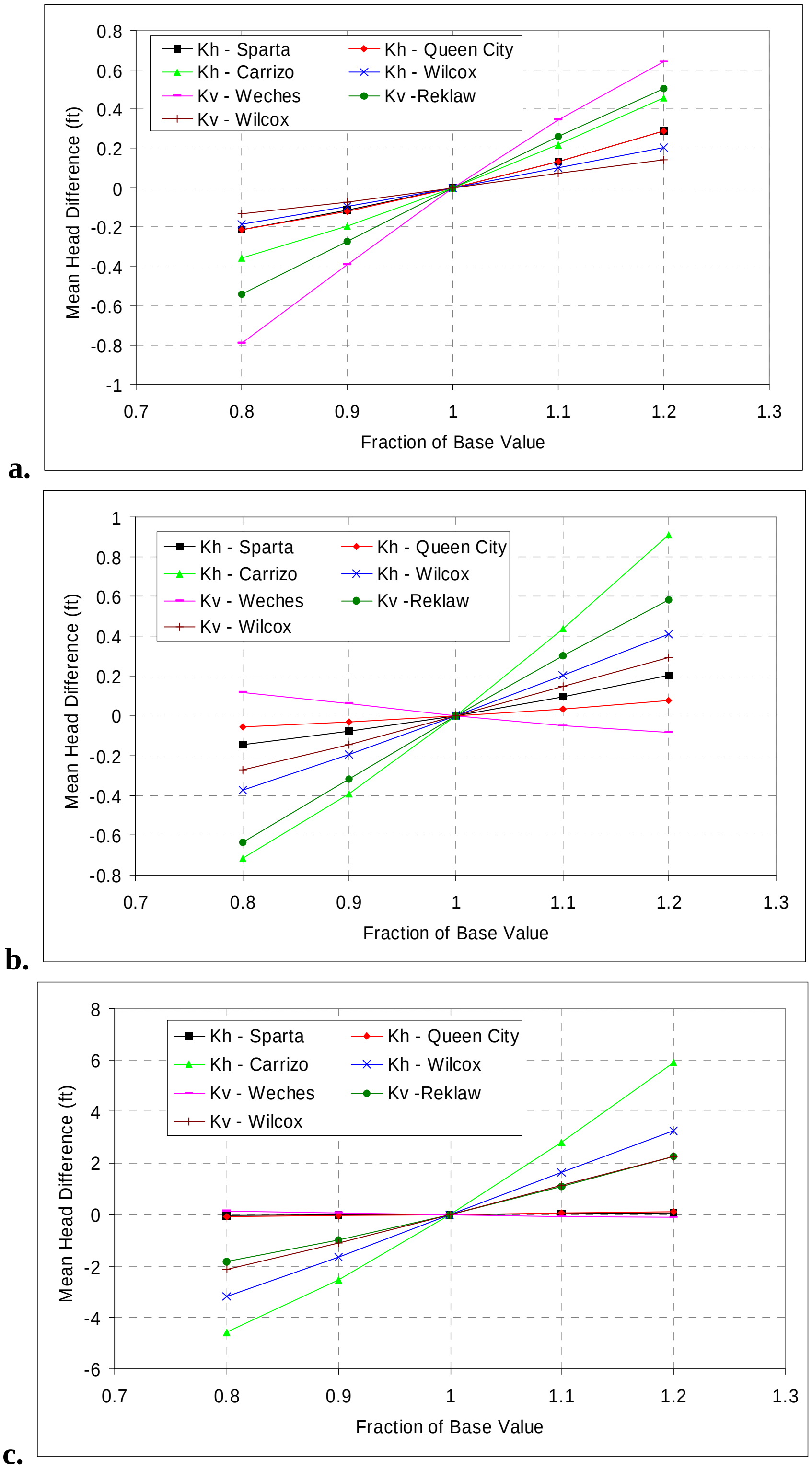


Figure 9.2.24 Transient sensitivity results for horizontal and vertical conductivity in Layer 1 (a), Layer 3 (b), and Layer 5 (c) using all active grid blocks.

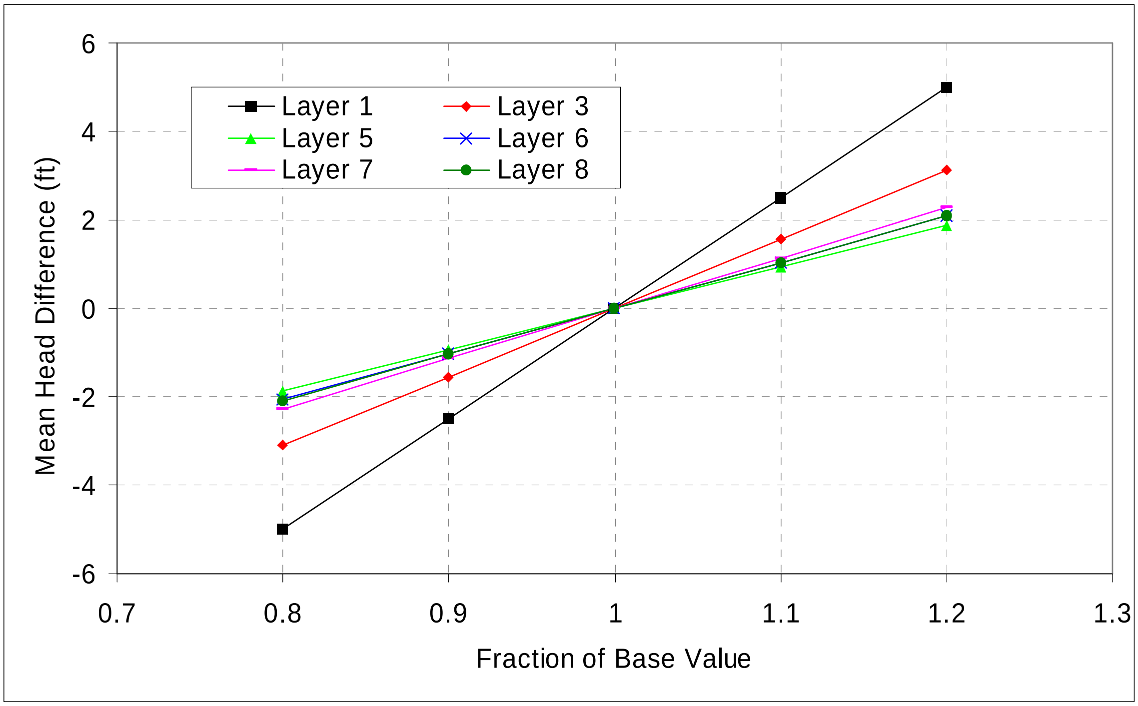


Figure 9.2.25 **Transient sensitivity results using all active grid blocks where GHB heads are varied.**

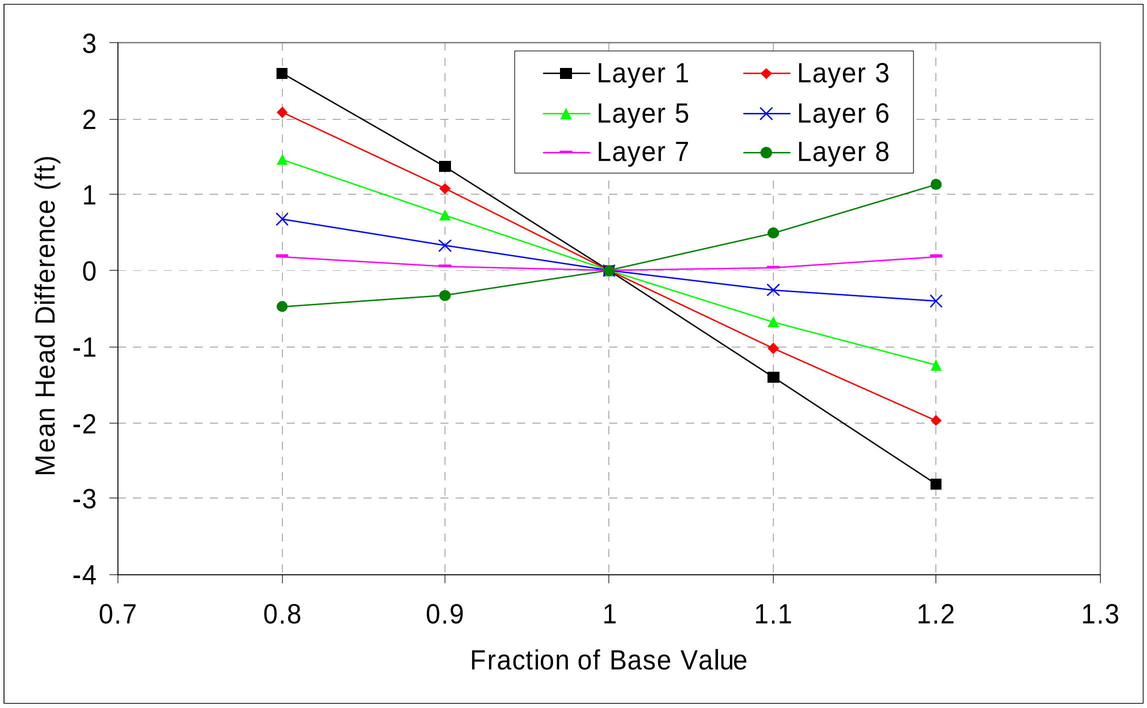


Figure 9.2.26 **Transient sensitivity results using all active grid blocks where storativity is varied.**

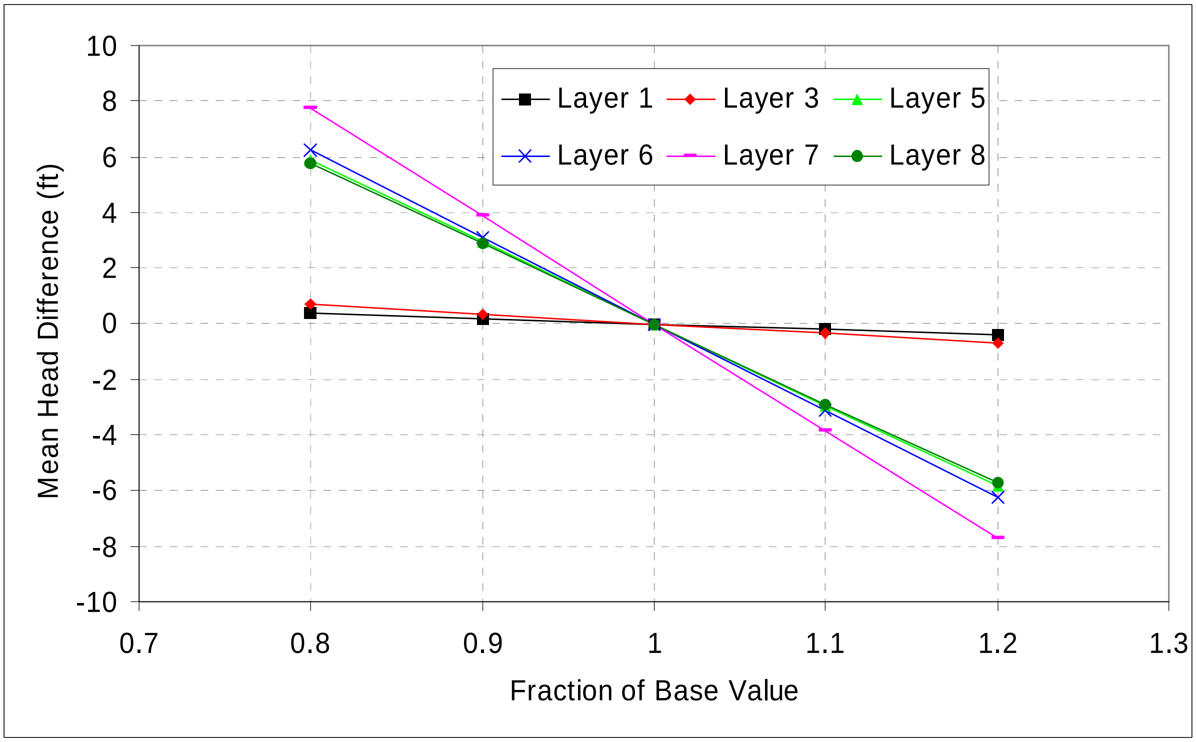


Figure 9.2.27 **Transient sensitivity results using all active grid blocks where pumping is varied.**

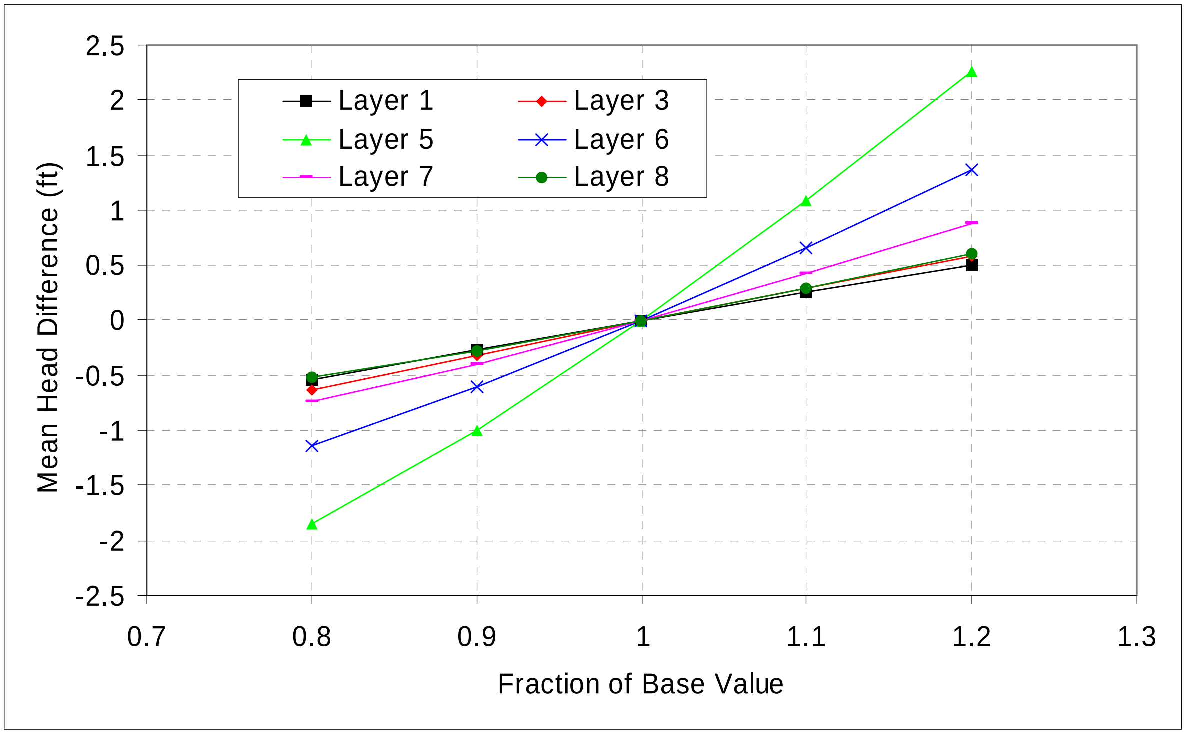


Figure 9.2.28 **Transient sensitivity results using all active grid blocks where Reklaw Formation vertical conductivity is varied.**

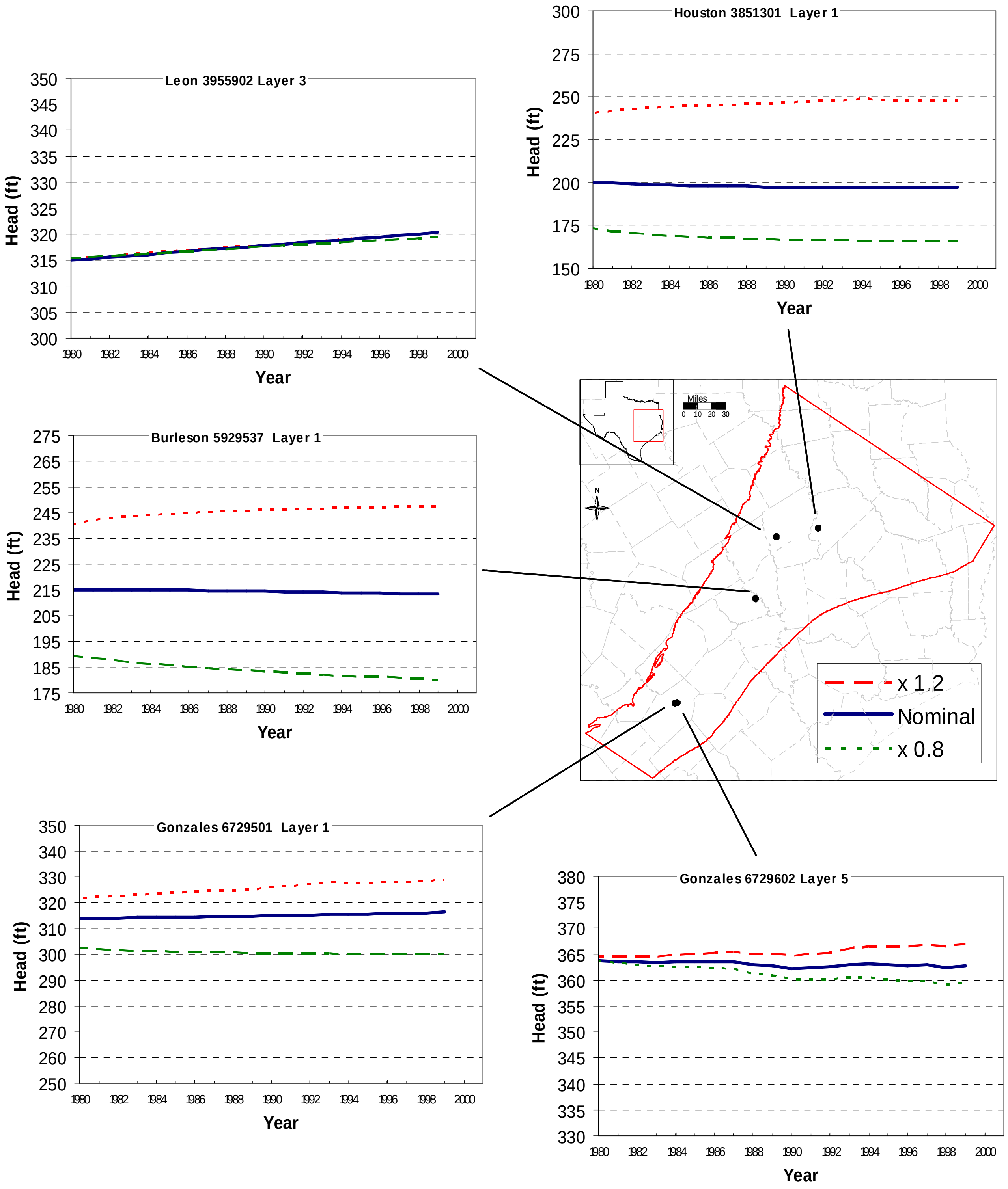


Figure 9.2.29 Transient sensitivity hydrographs for the Sparta (Layer 1), Queen City (Layer 3), and Carrizo (Layer 5) aquifers when GHB heads are varied. Layer number is indicated in the heading of each hydrograph.

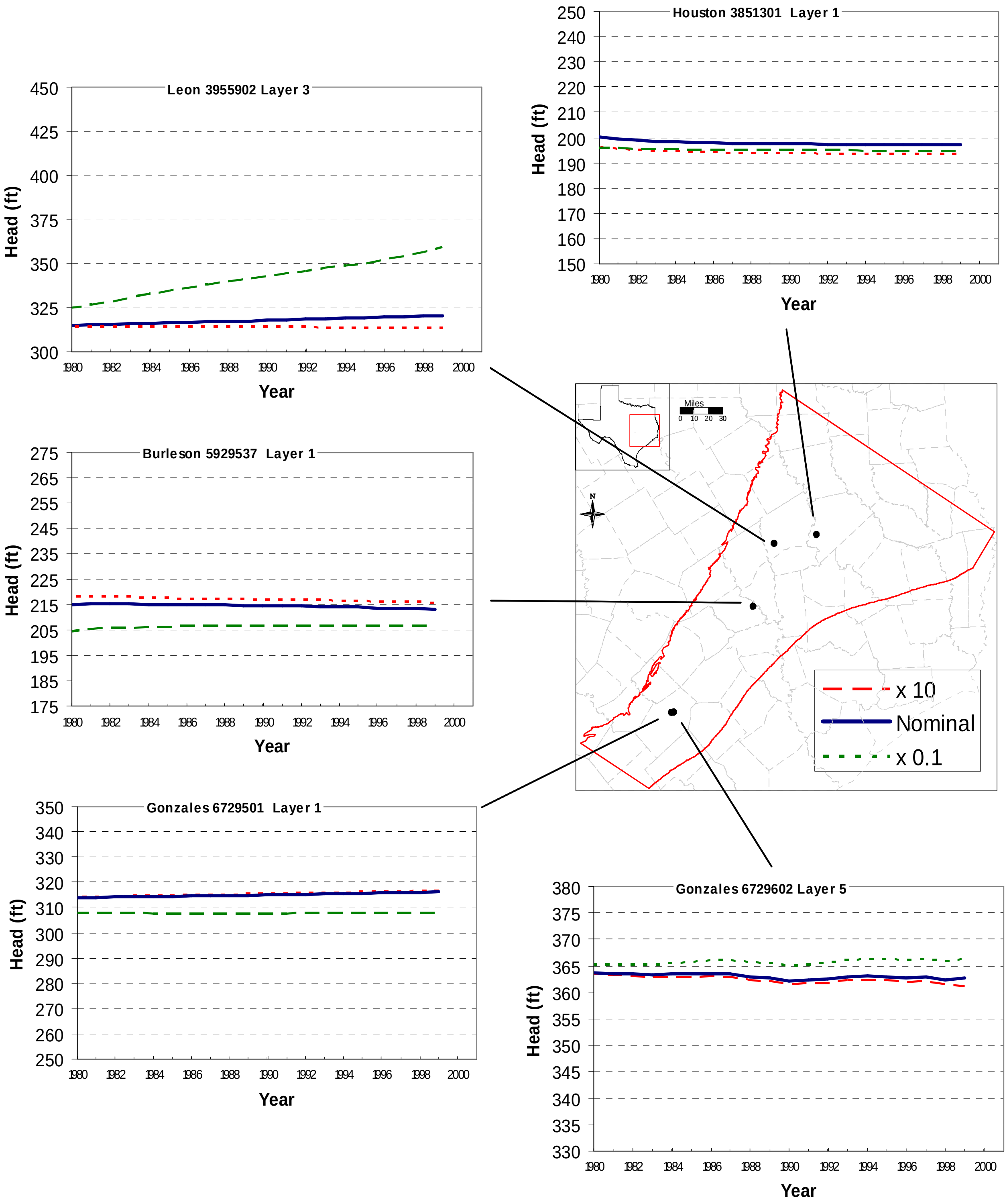


Figure 9.2.30 Transient sensitivity hydrographs for the Sparta (Layer 1), Queen City (Layer 3), and Carrizo (Layer 5) aquifers when the vertical conductivity of the Weches is varied. Layer number is indicated in the heading of each hydrograph.

9.3 Northern Queen City and Sparta GAM

9.3.1 Calibration

Hydraulic properties and model geometry of the transient model are identical to those shared by the steady-state model. Section 8.3 contains the discussion of hydraulic properties in the steady-state model. The transient model also required input of storativity and specific yield. In addition to the stresses applied to the steady-state model, reservoir interaction, lateral GHB boundaries, and pumping were applied to the transient model. A discussion of the calibration changes and new inputs and properties follows. Figure 9.3.1 shows the distribution of calibration targets (head measurements) used for the transient model calibration.

Section 6.4.1 describes the determination of initial horizontal and vertical hydraulic conductivities for the model. During calibration, the vertical hydraulic conductivity of the Reklaw Formation had to be lowered over much of the model area. Also, some modification of the Carrizo Formation horizontal hydraulic conductivity field was required. All other hydraulic conductivity fields were unchanged during calibration.

The initial vertical hydraulic conductivity values for the confining units (the Weches and Reklaw formations) were set at $1\text{x}10^{-4}$ ft/day. However, with this value for the Reklaw vertical hydraulic conductivity, drawdowns could not be maintained at the estimated pumping rates. Water was moving into the Carrizo aquifer through the Reklaw as cross-formational flow resulting from the initialized drawdown cones, especially in Smith and Angelina counties. The initial estimate of $1\text{x}10^{-4}$ ft/day was lowered to $1\text{x}10^{-5}$ ft/day over most of the model domain, with an area of $1\text{x}10^{-6}$ ft/day trending north-south through parts of Upshur, Wood, Smith, Henderson, Cherokee, and Anderson counties. An area in Nacogdoches, southern Rusk, and eastern Cherokee counties was left at $1\text{x}10^{-4}$ ft/day. The calibrated Reklaw vertical hydraulic conductivity field is shown in Figure 8.3.2.

There is no clear geologic or hydrologic information that can be used to support these spatial changes in vertical hydraulic conductivities of the Reklaw Formation. However, the final vertical hydraulic conductivities are within published limits, and similar conductivities were required to calibrate the Northern Carrizo-Wilcox GAM (Fryar et al., 2003).

During calibration, it was determined that the Carrizo Formation hydraulic conductivity values in an area running from Upshur County through Smith County and into northern

Cherokee County needed to be lowered to maintain Carrizo aquifer drawdowns in that area. The hydraulic conductivity in a small area around the city of Lufkin in Angelina County was also reduced slightly to reduce the rebound that occurs in the Carrizo aquifer head surface in the Lufkin area. The calibrated hydraulic conductivity field is shown in Figure 8.3.1.

Primary and secondary storage (also called storativity and specific yield) are properties of a transient model that are not present in a steady-state model. Storativity fields for the Sparta, Weches, Queen City, Reklaw, and Carrizo formations were developed as outlined in Section 6.4.2. Storativity fields for the Wilcox layers were taken from the Northern Carrizo-Wilcox GAM (Fryar et al., 2003). Storativity values were not changed during calibration. For specific yield, a value of 0.10 was used for the Weches and Reklaw formations and a value of 0.15 was used for the Sparta, Queen City, and Carrizo-Wilcox aquifer layers.

Stream leakance factors and elevations (see Section 8.2.1.5) were adjusted from the initial estimate during calibration. The streams exchange significant volumes of water with the aquifer, so they are important in the outcrop area. However, in the transient model, the hydrology of the outcrop has little effect on downdip regions during the simulation period, as hydraulic heads in the deeper confined section were mostly unaffected by streams or by recharge.

There are a total of 41 reservoirs in the Northern model. Some of them become active during the simulated period. Impoundment date and stage information were gathered from various sources. Reservoir bed conductivity was estimated at $1x10^{-4}$ ft/day.

Lateral GHB boundaries were added along the western edge of the model for the transient simulation. These GHBs were added to the confined cells for all layers. The GHBs used to simulate the sediments above the Sparta aquifer were held constant through time while the lateral GHBs were varied through time based on the Central model heads, as described in Section 6.3.1. The conductance for each lateral GHB cell was set to the transmissivity of the cell.

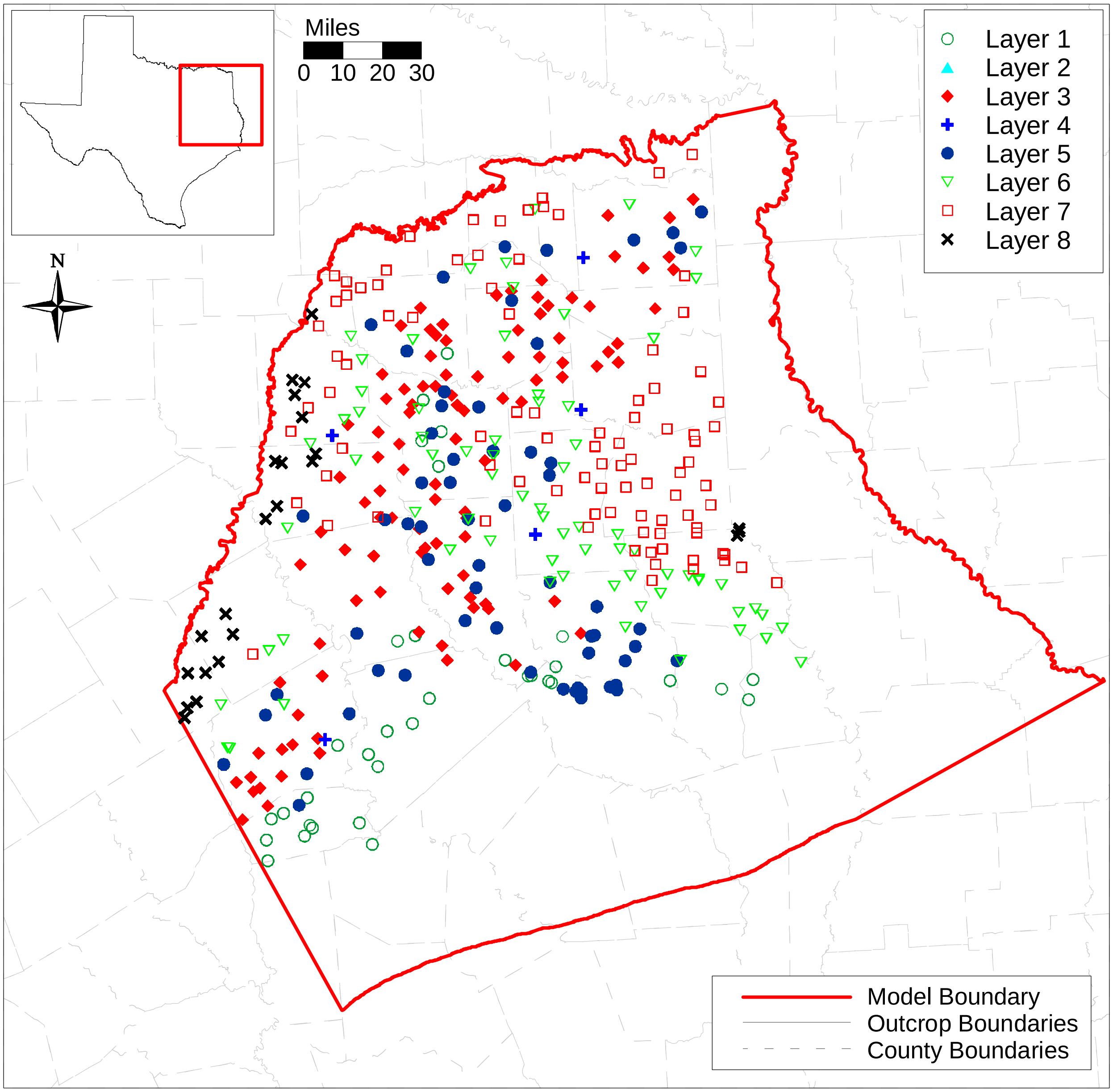


Figure 9.3.1 Target well locations used in the transient calibration.

9.3.2 Results

Results for the transient model are presented in this section. Simulated hydraulic heads are compared to measured values, and stream leakances and water budgets are discussed.

9.3.2.1 Hydraulic Heads

The transient modeling is divided into a calibration period (1980 through 1989) and a verification period (1990 through 1999). Hydraulic head results for the calibration and verification periods are shown in Figures 9.3.2 through 9.3.18. Simulated and measured hydraulic head distributions, head residual maps, head residual scatterplots, and selected hydrographs are presented for the Sparta aquifer (Layer 1), the Queen City aquifer (Layer 3), and the Carrizo Formation (Layer 5). Table 9.3.1 lists the mean error (ME), mean absolute error (MAE), root mean square error (RMSE), range, and RMSE/range for all aquifer layers for the calibration and verification periods. As noted in Section 9.1.2.1, since most of the targets had incomplete records over the simulated time period, calibration statistics have been calculated using all of the available data for the calibration and verification periods. The RMSEs range from about 20 to 35 feet for the calibration period and from about 20 to 40 feet during the verification period. Calibration statistics for the Carrizo-Wilcox layers are comparable to those of the Northern Carrizo-Wilcox GAM (Fryar et al., 2003).

Figure 9.3.2 shows the simulated and measured hydraulic head distribution for the Sparta aquifer at the end of the transient calibration period (1989). Locations where measured water levels were available are posted on the measured head plot. It should be noted that the available head measurements are relatively sparse and primarily limited to the outcrop and shallow confined section. As a result, the contours of measured heads will have much less detail than the simulated head contours and will not correctly define the head surface in the deeper confined portions of the aquifer. In the area where head measurements were available, the simulated heads show good agreement with the contours based on the measured heads. The detail seen in the downdip portion of the simulated head surface is the result of the GHBs assigned to the downdip Sparta cells. The plot of Sparta residuals for the calibration period (Figure 9.3.3a) indicates that there is no spatial bias. The residual scatterplot (Figure 9.3.3b) and low ME also indicate a lack of bias.

Figures 9.3.4 and 9.3.5 show similar plots for the Sparta aquifer for the verification period. The 1999 head surfaces show good agreement and little change from the 1989 heads.

The residual plots indicate that the results are not biased. The RMSE increased only slightly between the calibration and verification periods and was below 10 percent of the range for both periods.

The simulated Queen City aquifer hydraulic heads for 1989 (Figure 9.3.6a) reflect the overall topography in the outcrop area and simulated heads compare reasonably well with the measured head contours (Figure 9.3.6b) in areas where measurements are available. Target locations are well distributed, primarily in and near the outcrop. Residuals (Figure 9.3.7a) show no obvious spatial bias although the ME indicates a slight bias toward overprediction. The residuals show mostly uniform scatter around the unit-slope line on the scatterplot (Figure 9.3.7b), indicating no particular trend in the simulated results.

Figures 9.3.8 and 9.3.9 show similar plots for the Queen City aquifer for the verification period. As with the Sparta aquifer, the 1999 head surfaces show little change from the 1989 heads. The residual plots indicate that the results are not significantly biased. The RMSE increased about 2.5 feet between the calibration and verification periods but was below 10 percent of the range for both periods.

Figure 9.3.10 shows the simulated and measured hydraulic heads for the Carrizo aquifer at the end of the calibration period (1989). Overall, the simulated and measured hydraulic head contours show a good agreement, reproducing the major cones of depression in Nacogdoches and Angelina counties, as well as in Smith County. The residuals shown in Figure 9.3.11 indicate that the data are not spatially biased, with the possible exception of a small area where Anderson, Henderson, Cherokee, and Smith counties meet. Simulated heads are low for all targets in this area. However, during the verification period this is not the case (see Figure 9.3.13a).

Simulated and measured hydraulic heads for the Carrizo aquifer at the end of the verification period are shown in Figure 9.3.12. The model maintained the drawdowns in the Nacogdoches/Angelina and Smith county areas, but could not match the increased drawdown in the Lufkin well field which can be seen in the measured head contours. This can be seen on the residual scatterplot (Figure 9.3.13b) where the points tail off along the -200-foot simulated head line. This is likely due to insufficient pumping for the Lufkin area in the model. As a result of this difference in the Lufkin area, the RMSE error increases by about 7 feet between the calibration and verification periods but is well below 10 percent of the range for both periods.

A few more cells went dry in the transient simulation than in the steady-state simulation. This would be expected in the northern model where water levels would likely be higher under predevelopment conditions. Out of over 20,000 outcrop cells, only 49 were dry at the end of the verification period. All 49 dry cells were in the Carrizo-Wilcox layers. The drying of some cells along the outcrop is expected.

Figures 9.3.14 through 9.3.18 present selected hydrographs of simulated and measured heads, describing the general model response in the different layers. All hydrographs in this section are shown on a 100-foot vertical scale for consistency, unless the data range exceeds 100 feet. Figure 9.3.14 shows hydrographs for wells completed in the Sparta aquifer. The Sparta heads throughout the model area are generally flat over the transient period, with slight downward or upward trends in some wells. In general, the simulated heads tend to follow similar trends, as can be seen in the hydrographs.

Figures 9.3.15 and 9.3.16 show hydrographs for wells completed in the Queen City aquifer. Hydrographs on Figure 9.3.15 are for wells in the southern part of the model; hydrographs on Figure 9.3.16 are for wells in the northern part of the model. Like the Sparta aquifer wells, most of the Queen City aquifer wells in the model area show a relatively flat trend over the transient period. For most Queen City aquifer wells in the model area, the simulated heads tend to parallel the measured heads.

Hydrographs for wells completed in the Carrizo aquifer are shown on Figures 9.3.17 (wells in south part of the model) and 9.3.18 (wells in north part of the model). Several of these hydrographs show the effects of pumping. The western hydrograph in Angelina County shows one of the wells in the Lufkin area. Measured heads for this well show a generally decreasing trend from about 1983 through the end of the transient period. Simulated heads are generally flat until about 1993 when they start to decline, but not at a rate as high as the decline in measured heads. It appears that there is more pumping in this area than is indicated by the available pumping data. Overall, most of the simulated hydrographs for wells completed in the Carrizo aquifer reproduce the general trends in the measured heads.

9.3.2.2 Stream-Aquifer Interaction

Figure 9.3.19 shows gain/loss values for the stream reaches in the transient model during 1989 and 1996. As would be expected, most of the stream segments are gaining. However, many more segments are losing or only slightly gaining during 1989. This is due to low recharge for the previous year (1988 was the lowest throughout the transient period), while 1996 followed seven years of recharge near or above average.

As noted in Section 8.3.2.2, stream leakances were compared to stream gain/loss data from three sources. The stream targets were taken from Slade et al. (2002), Dutton et al. (2003), and a study done for this report by R.J. Brandes Company (Table 4.7.2). The targets from Slade et al. (2002) and Dutton et al. (2003) are shown in Tables 4.7.1 and 4.7.4 of this report, respectively. Two of the ten Slade gain/loss studies that fall within the model outcrop area were not used. Sugar Creek is a minor stream that was not included in the model due to its small size. Lake Fork Creek was not used because the loss estimated for the study reach exceeded the average stream flow for Lake Fork Creek. The remaining Slade gain/loss studies were conducted between 1942 and 1981 and covered reaches of the Sabine River, Little Cypress Bayou, Bowles Creek, Big Elkhart Creek, and Little Elkhart Creek. For the Sabine River and Little Cypress Creek, Slade listed more than one estimate. These multiple estimates were averaged on a per mile basis to develop targets for those streams. Brandes gain/loss estimates for the Navasota River, Trinity River, Neches River, Angelina River, Sabine River, and Big Cypress Bayou intersect the outcrop area of the north model. Of the Dutton et al. (2003) gain/loss studies, only those for the Navasota and Trinity rivers intersect the north model.

Figure 9.3.20 shows a plot of the measured gain/loss values and those derived from the model. The data comparison shows agreement in the direction of flow (gain or loss) between the targets and simulated leakances for most of the streams. The Slade target for Little Elkhart Creek and the Brandes targets for the Angelina and Sulphur rivers indicate losing conditions while the model shows gaining conditions. The differences for Little Elkhart Creek and the Sulphur River are small with both the measured and simulated leakances comparatively low. The large loss estimated by Brandes for the Angelina River is probably not accurate since the gage data used was not ideal for the analysis. Based on the location of the Angelina River and estimated gains in surrounding streams, it is likely that the Angelina River is a gaining stream.

The remaining streams show reasonable agreement between measured and simulated leakances, with the exception of the Brandes estimates for the Trinity and Neches rivers and the Slade estimates for the Sabine River and Little Cypress Bayou. However, other estimates for the

Trinity and Sabine rivers show good agreement with the simulated leakances. These wide variations in estimated gain/loss indicate the large uncertainty in stream targets.

Slade et al. (2002) note that the potential error in stream flow measurements is typically about 5 to 8 percent. Since this error is possible at both ends of a gain/loss subreach, the potential error in gain/loss can equal a significant fraction of the total flow in the subreach. Comparing the gain/loss values discussed in the previous paragraphs to mean stream flows from the EPA RF1 data set shows that almost all of the gain/loss values are less than 5 percent of the mean stream flow. This suggests that the gain/loss values are uncertain and can be used only qualitatively.

9.3.2.3 Water Budget

Table 9.3.2 shows the water budget for the transient model totaled for years 1980, 1988 (drought year for the calibration period), 1989 and 1999. The overall mass balance error for the transient simulation was less than 0.01 percent, well under the GAM requirement of one percent. Figure 9.3.21 shows the change in model-wide rates over the period from 1980 through 1999. In the model, the greatest influx of water consistently occurs from recharge, and the greatest outflow of water is through streams, followed by groundwater ET and pumping. Overall, outflow from pumping increased from 140,000 AFY in 1980 to 168,000 AFY in 1999. Pumping in the Sparta and Queen City aquifers accounts for only about 9 percent of the total pumping over the transient period. On average, stream leakage accounts for about 50 percent of the model discharge, groundwater ET for about 25 percent and pumping for about 20 percent. Although storage decreases in some years, overall, the model shows an increase in storage over the transient period. This may be due to initial heads being set too low, excess recharge, insufficient discharge, or a combination of these factors.

Table 9.3.1 Calibration statistics for the Northern transient model.

Calibration period (1980-1989)						
	Layer 1	**Layer 3**	**Layer 5**	**Layer 6**	**Layer 7**	**Layer 8**
ME	-0.31	-3.56	3.42	-0.29	4.24	-10.06
MAE	15.56	21.48	24.77	20.90	26.24	20.03
RMSE	20.66	28.19	34.24	27.58	33.54	24.18
Range	352	401	742	470	516	298
RMSE/Range	0.059	0.070	0.046	0.059	0.065	0.081
Verification period (1990-1999)						
	Layer 1	**Layer 3**	**Layer 5**	**Layer 6**	**Layer 7**	**Layer 8**
ME	1.31	-4.78	-2.28	-7.05	0.19	-18.59
MAE	15.09	23.62	28.18	24.42	28.59	25.27
RMSE	21.15	30.76	41.21	34.24	36.64	30.59
Range	374	412	820	643	515	289
RMSE/Range	0.057	0.075	0.050	0.053	0.071	0.106

ME = mean error
MAE = mean absolute error
RMSE = root mean square error

Table 9.3.2 Water budget for Northern transient model. All rates reported in acre-ft/yr.

Year	Layer	Reservoirs	ET	Recharge	GHBs	Streams	Drains	Wells	Storage	Top	Bottom
1980	**1**	3,668	-24,719	113,635	7,353	-43,704	-475	-3,995	-4,331	0	-47,438
	2	3,075	-631	9,120	-57	-2,102	-78	0	-6,627	47,438	-50,137
	3	3,939	-100,970	241,649	-1,166	-153,383	-175	-10,202	390	50,137	-30,237
	4	983	-771	26,290	-11	-11,569	-5	0	-377	30,237	-44,773
	5	274	-16,482	104,358	3,100	-38,380	-91	-58,061	-3,273	44,773	-36,224
	6	14,851	-58,454	120,309	1,077	-86,191	-8,825	-33,133	39,073	36,224	-24,941
	7	2,608	-45,007	203,414	595	-153,716	-3,673	-26,727	22,435	24,941	-24,881
	8	1,935	-4,763	15,505	6,128	-7,871	-428	-8,336	-27,053	24,881	0
	Sum	31,331	-251,796	834,280	17,017	-496,915	-13,748	-140,454	20,239		
1988*	**1**	2,659	-23,946	75,692	7,483	-40,795	-927	-4,516	36,253	0	-51,906
	2	2,366	-547	5,904	-57	-2,716	-183	0	-5,884	51,906	-50,787
	3	3,832	-86,700	138,225	-1,239	-137,935	-331	-9,689	74,174	50,787	-31,140
	4	736	-1,230	16,907	-43	-13,001	-10	0	9,481	31,140	-43,978
	5	121	-23,224	70,544	2,838	-36,474	-134	-63,815	40,767	43,978	-34,607
	6	12,643	-48,946	83,966	-90	-72,322	-8,805	-40,465	59,485	34,607	-20,084
	7	3,009	-34,349	148,931	-1,409	-129,910	-3,463	-37,066	53,091	20,084	-18,929
	8	1,998	-3,557	6,643	2,732	-8,021	-405	-8,708	-9,614	18,929	0
	Sum	27,364	-222,499	546,812	10,216	-441,175	-14,259	-164,259	257,753		

Table 9.3.2, continued

Year	Layer	Reservoirs	ET	Recharge	GHBs	Streams	Drains	Wells	Storage	Top	Bottom
1989	**1**	2,548	-12,086	136,942	7,368	-33,744	-980	-4,551	-43,215	0	-52,281
	2	2,286	-290	9,684	-56	-501	-196	0	-12,280	52,281	-50,928
	3	3,793	-41,765	245,489	-1,240	-98,440	-364	-9,430	-117,549	50,928	-31,415
	4	709	-304	31,995	-42	-4,357	-10	0	-14,074	31,415	-45,332
	5	106	-12,524	123,279	2,849	-31,493	-157	-68,391	-24,191	45,332	-34,808
	6	8,719	-14,564	153,728	-61	-47,805	-10,147	-43,137	-62,600	34,808	-18,937
	7	4,287	-20,364	271,417	-1,149	-87,984	-4,468	-31,110	-131,696	18,937	-17,865
	8	6,035	-1,918	15,363	2,523	-1,788	-834	-7,988	-29,258	17,865	0
	Sum	28,483	-103,815	987,897	10,193	-306,112	-17,157	-164,608	-434,863		
1999	**1**	1,851	-20,248	96,622	6,328	-39,281	-1,399	-4,380	15,029	0	-54,522
	2	1,724	-717	7,415	-59	-2,277	-273	0	-8,423	54,522	-51,913
	3	3,359	-63,550	159,370	-1,294	-133,745	-561	-10,054	27,258	51,913	-32,688
	4	503	-1,107	17,905	-50	-12,634	-16	0	7,263	32,688	-44,553
	5	-1	-20,762	66,678	2,728	-38,044	-301	-71,181	47,802	44,553	-31,468
	6	10,017	-27,832	93,725	-2,102	-63,093	-9,224	-35,226	19,761	31,468	-17,492
	7	3,434	-33,527	185,411	-4,239	-114,442	-4,023	-39,123	-534	17,492	-10,774
	8	4,515	-3,216	11,074	-698	-6,961	-1,049	-8,874	-5,562	10,774	0
	Sum	25,401	-170,960	638,200	615	-410,476	-16,846	-168,838	102,594		

*Drought year for calibration period

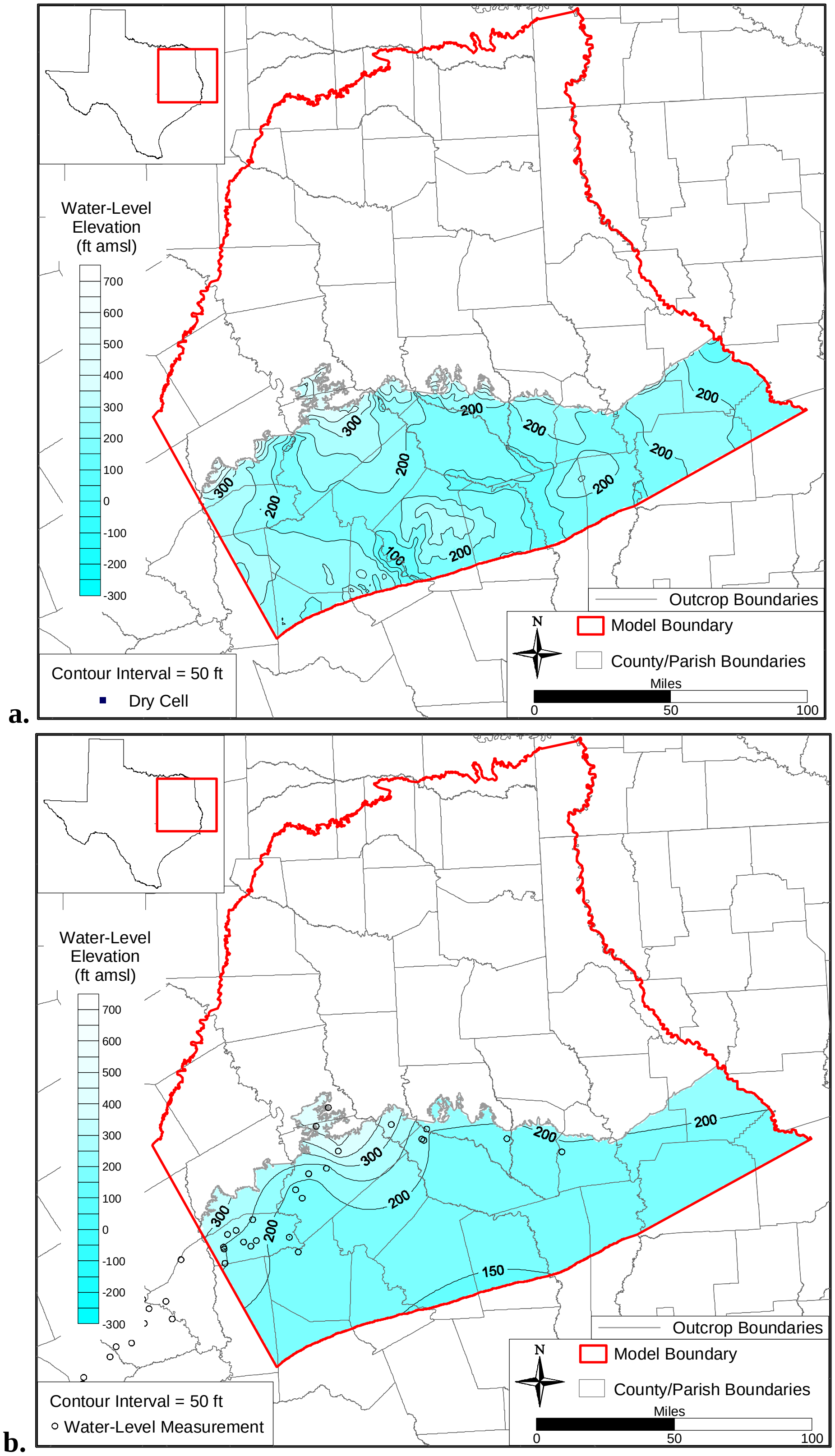
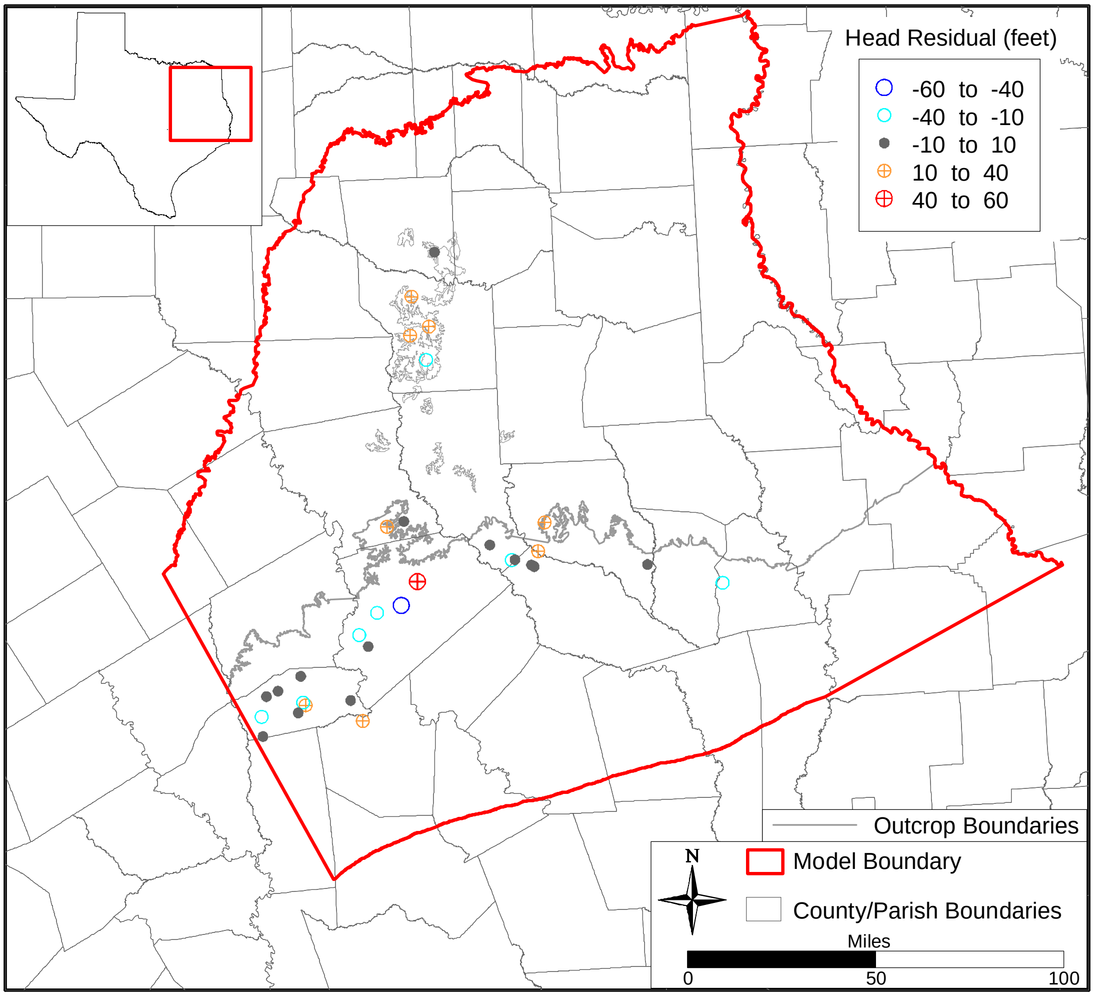


Figure 9.3.2 Simulated (a) and measured (b) head distributions for the Sparta aquifer (Layer 1) at the end of the calibration period (1989).

a.



b.

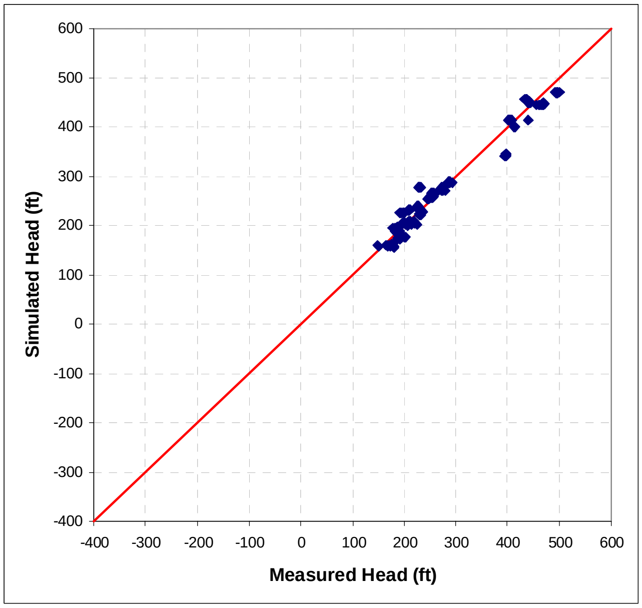


Figure 9.3.3 Calibration period (1980-1989) residuals (a) and scatterplot (b) of simulated and measured heads for the Sparta aquifer (Layer 1).

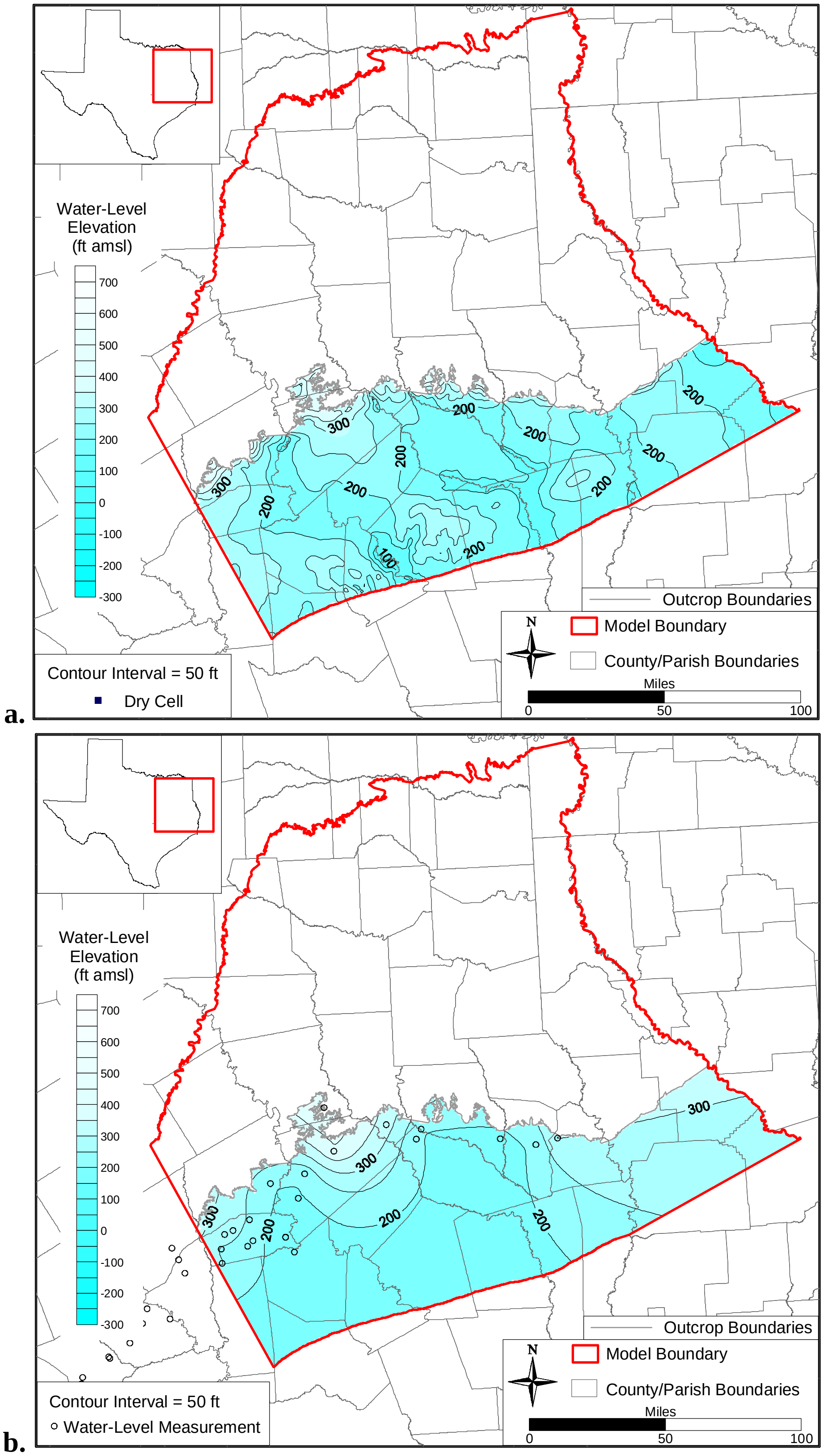
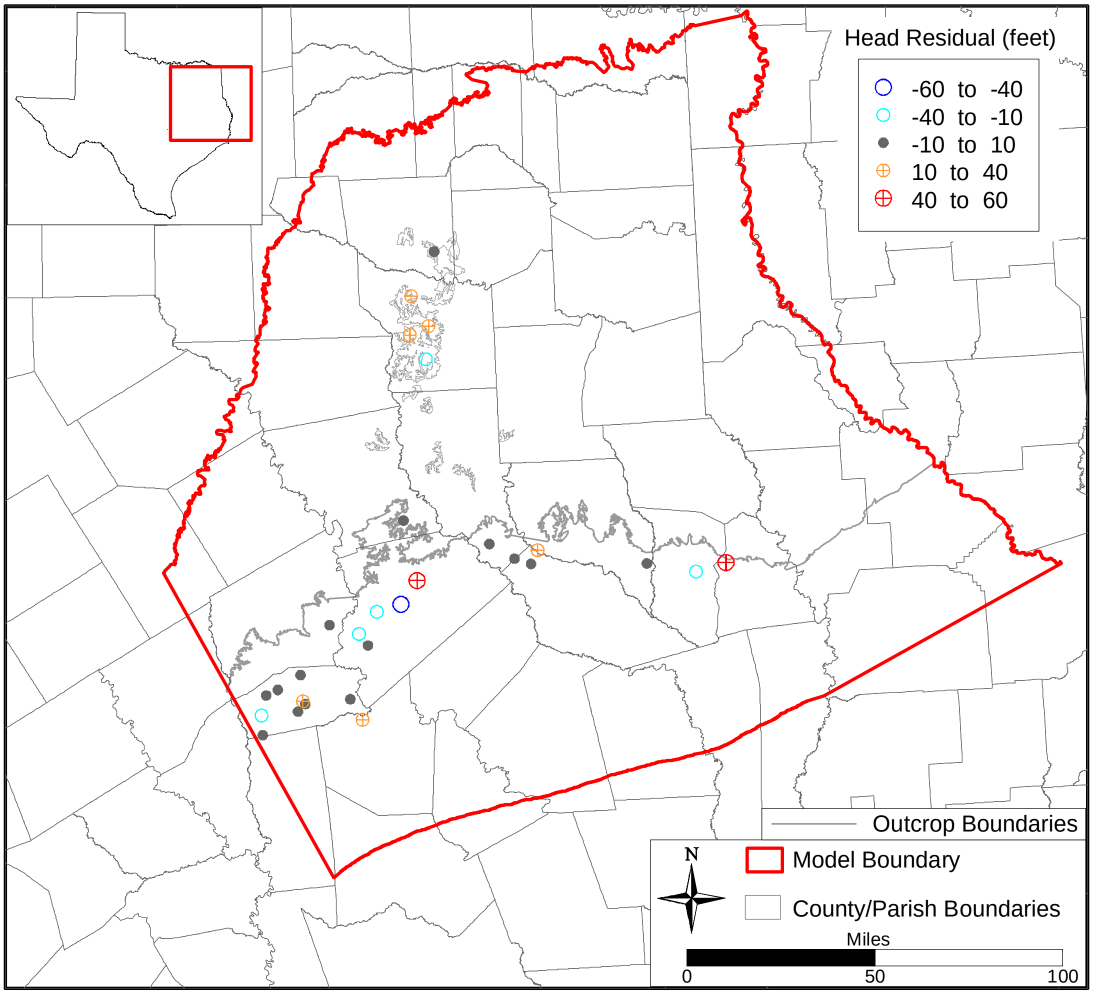
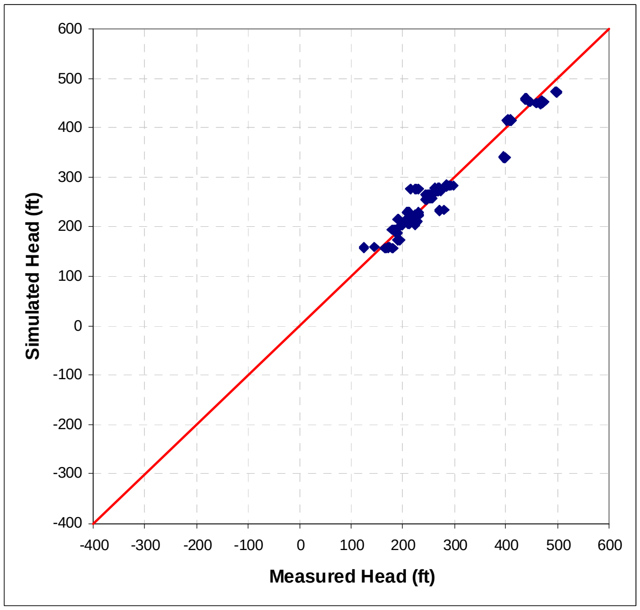


Figure 9.3.4 **Simulated (a) and measured (b) head distributions for the Sparta aquifer (Layer 1) at the end of the verification period (1999).**



a.



b.

Figure 9.3.5 Verification period (1990-1999) residuals (a) and scatterplot (b) of simulated and measured heads for the Sparta aquifer (Layer 1).

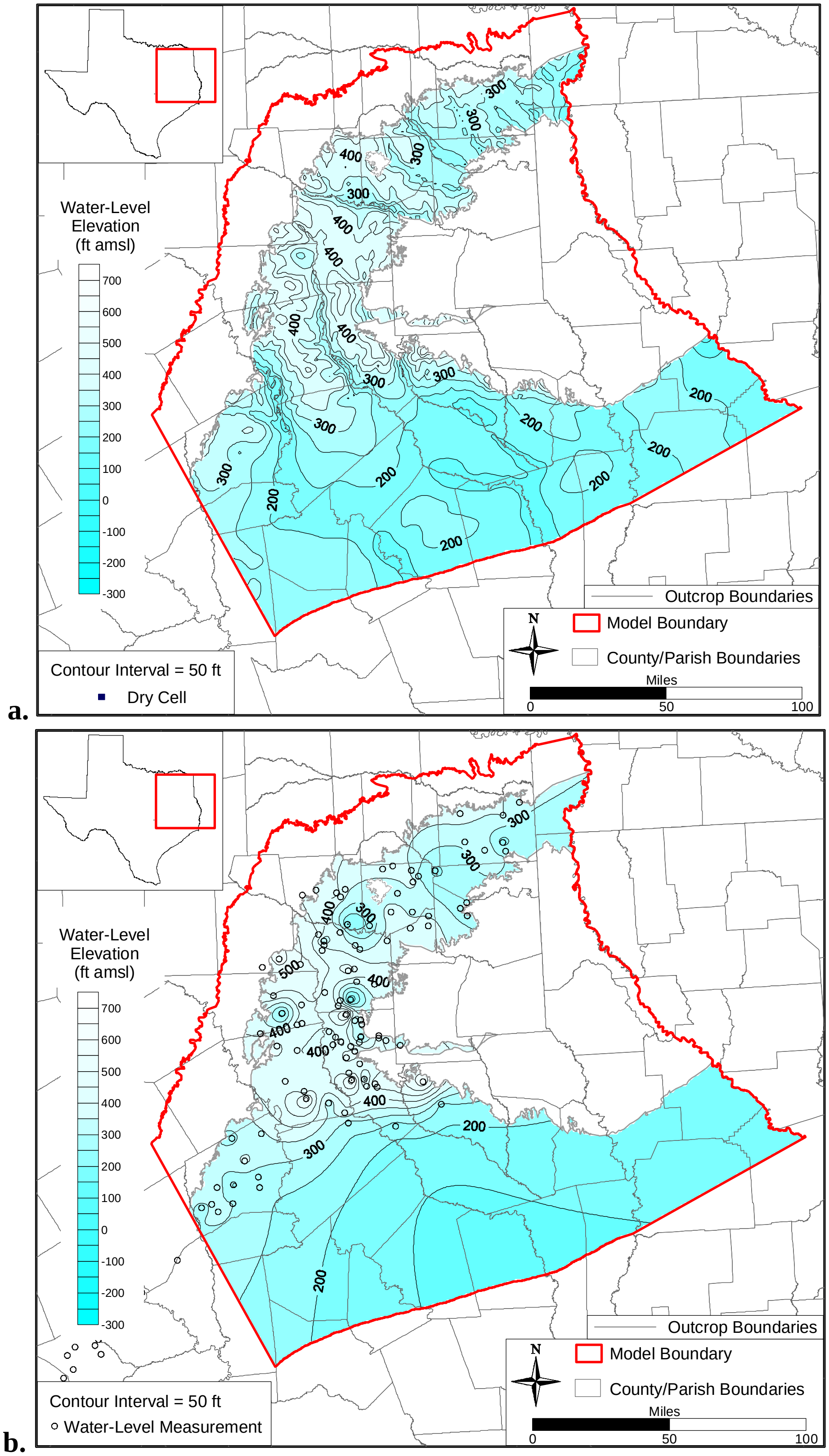


Figure 9.3.6 **Simulated (a) and measured (b) head distributions for the Queen City aquifer (Layer 3) at the end of the calibration period (1989).**

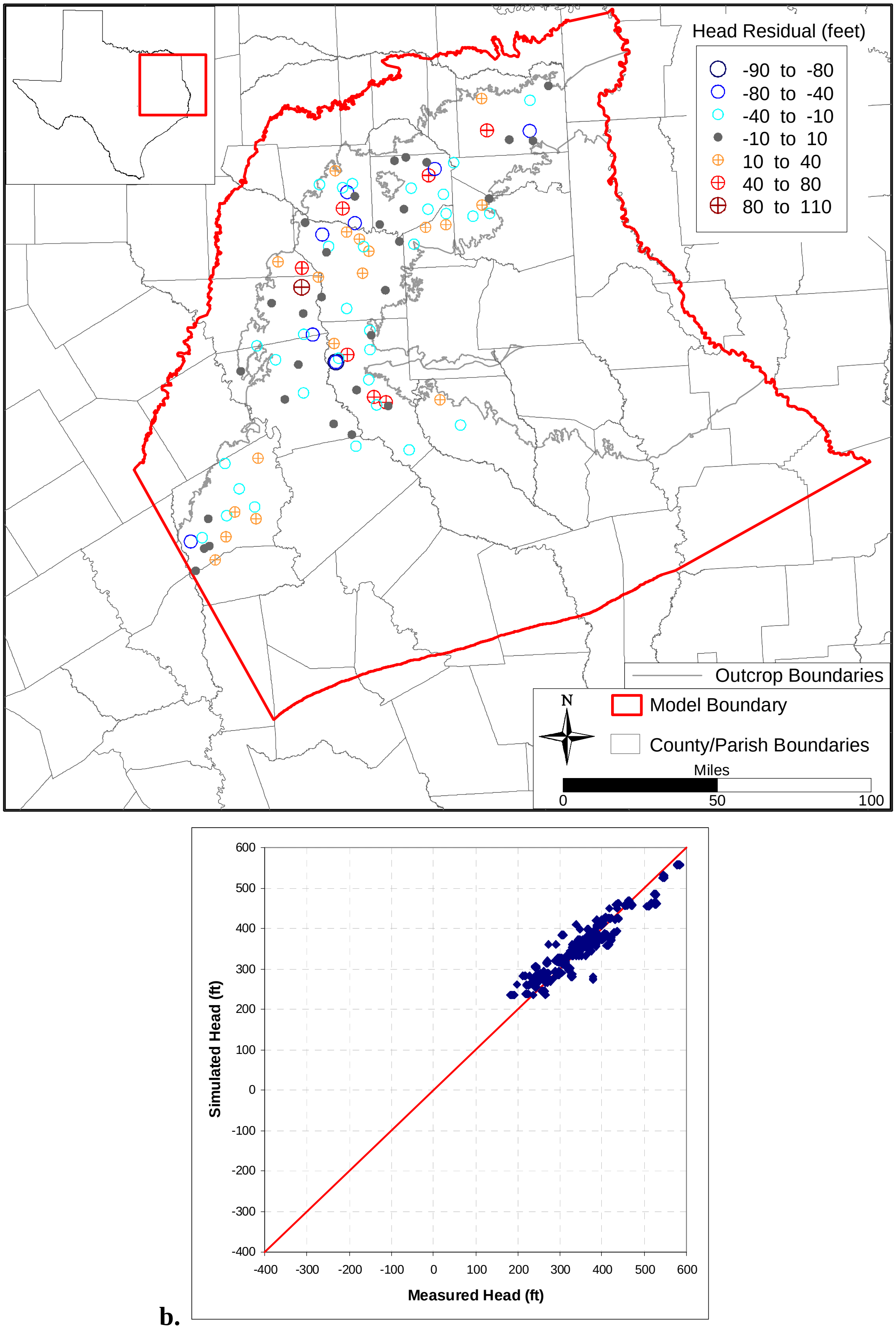


Figure 9.3.7 Calibration period (1980-1989) residuals (a) and scatterplot (b) of simulated and measured heads for the Queen City aquifer (Layer 3).

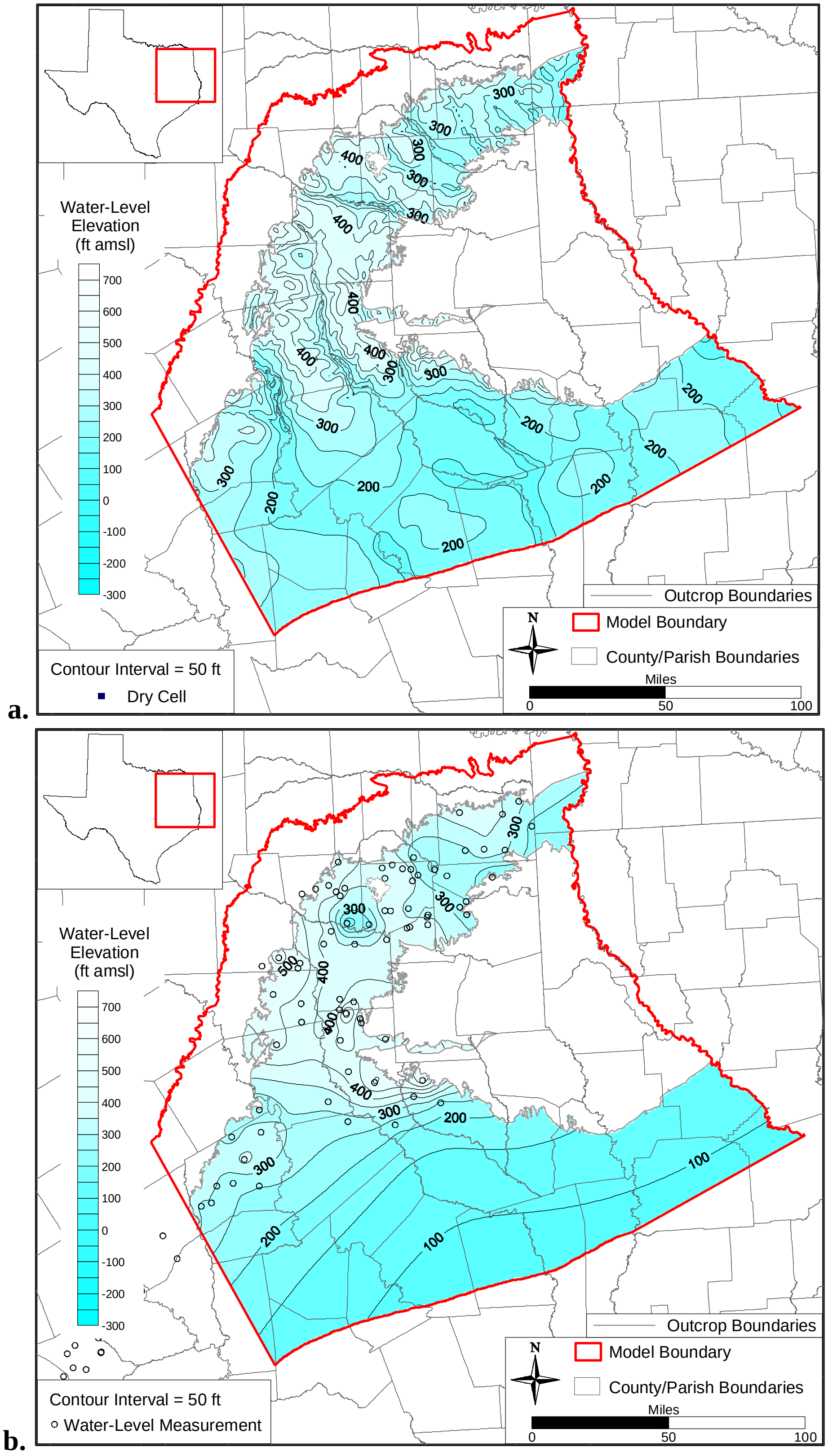
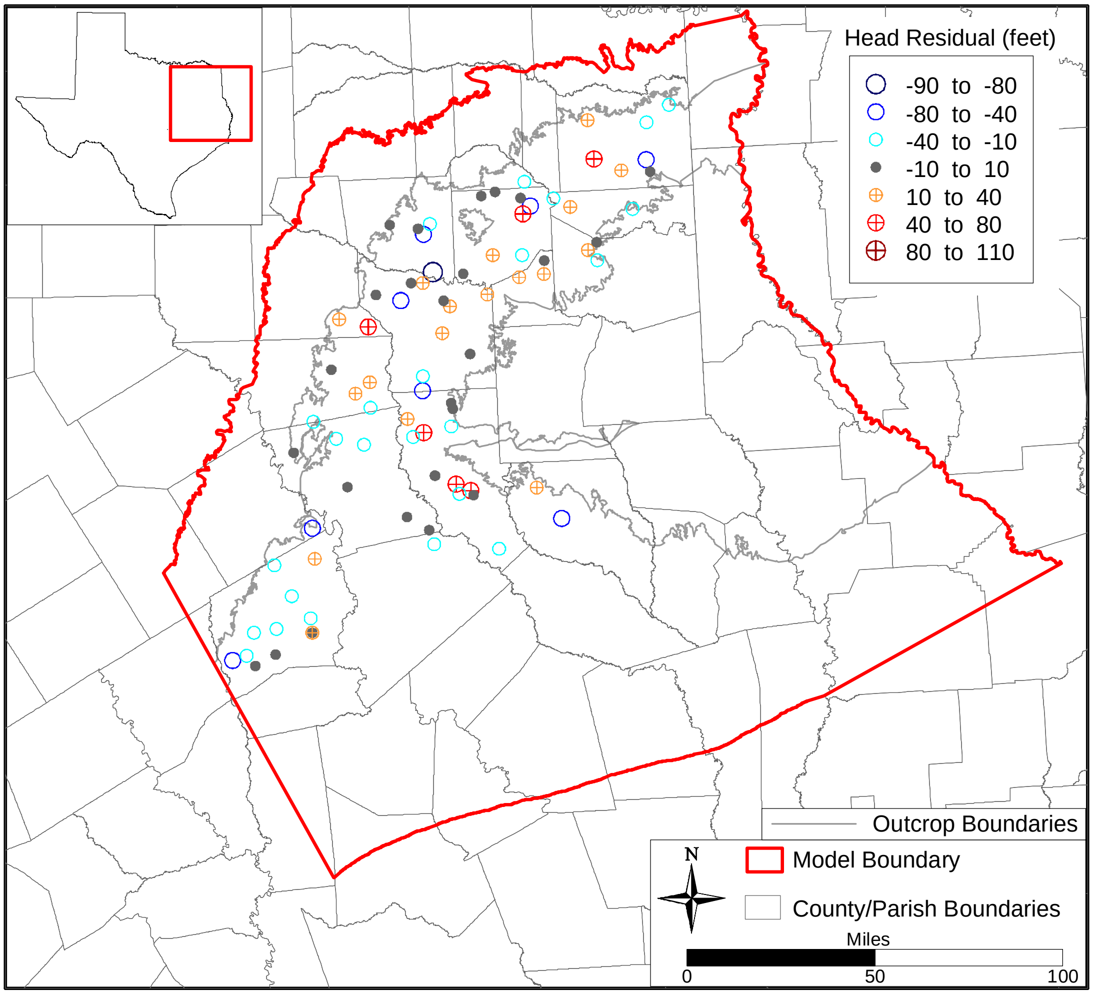


Figure 9.3.8 Simulated (a) and measured (b) head distributions for the Queen City aquifer (Layer 3) at the end of the verification period (1999).

a.



b.

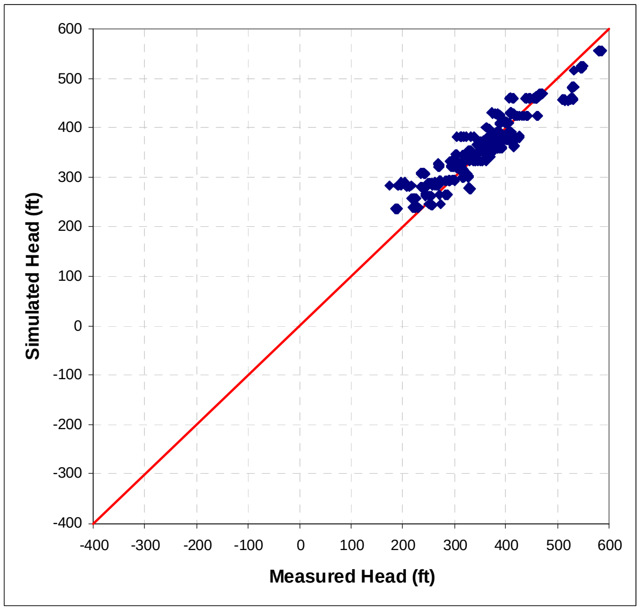


Figure 9.3.9 Verification period (1990-1999) residuals (a) and scatterplot (b) of simulated and measured heads for the Queen City aquifer (Layer 3).

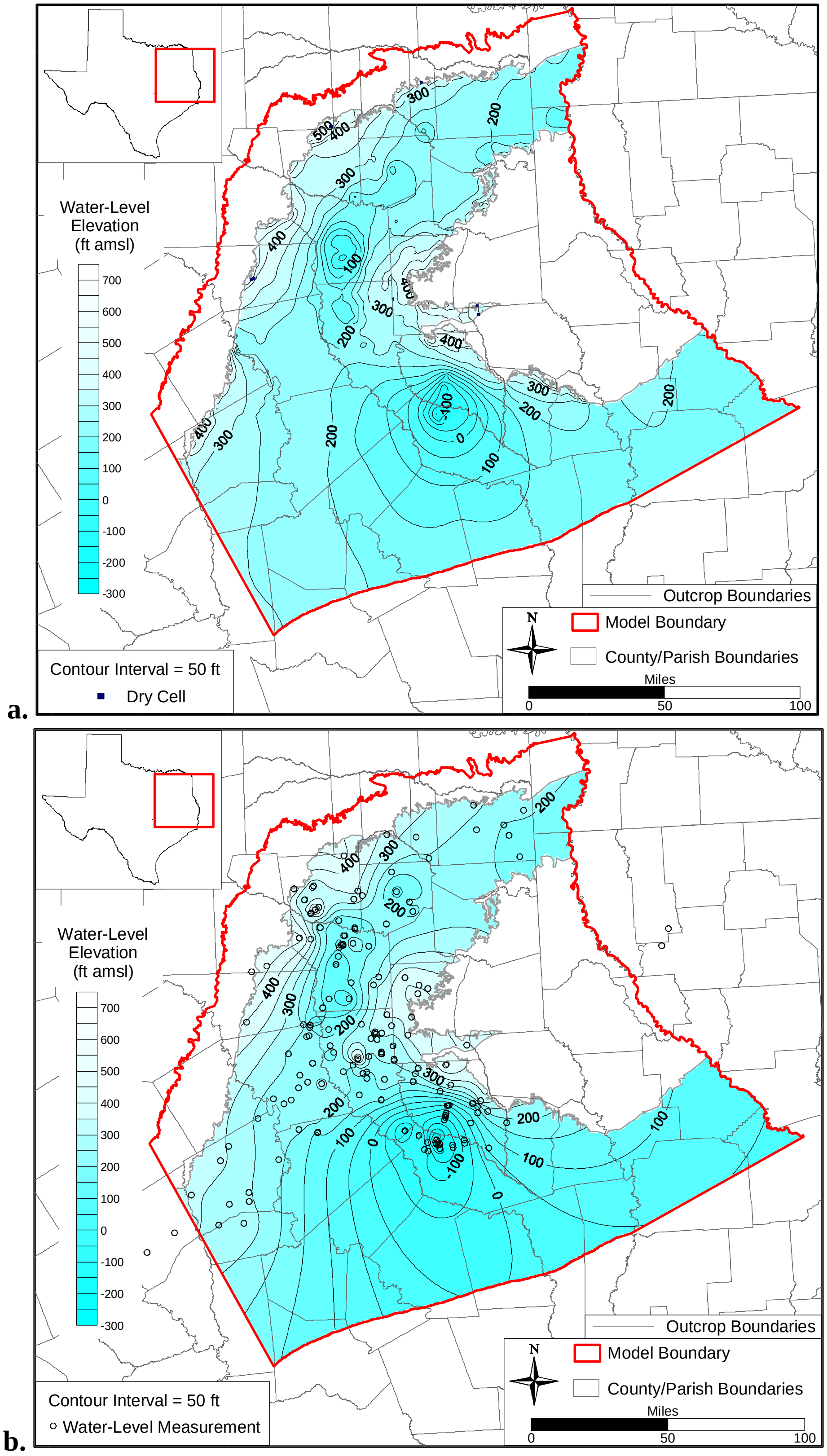
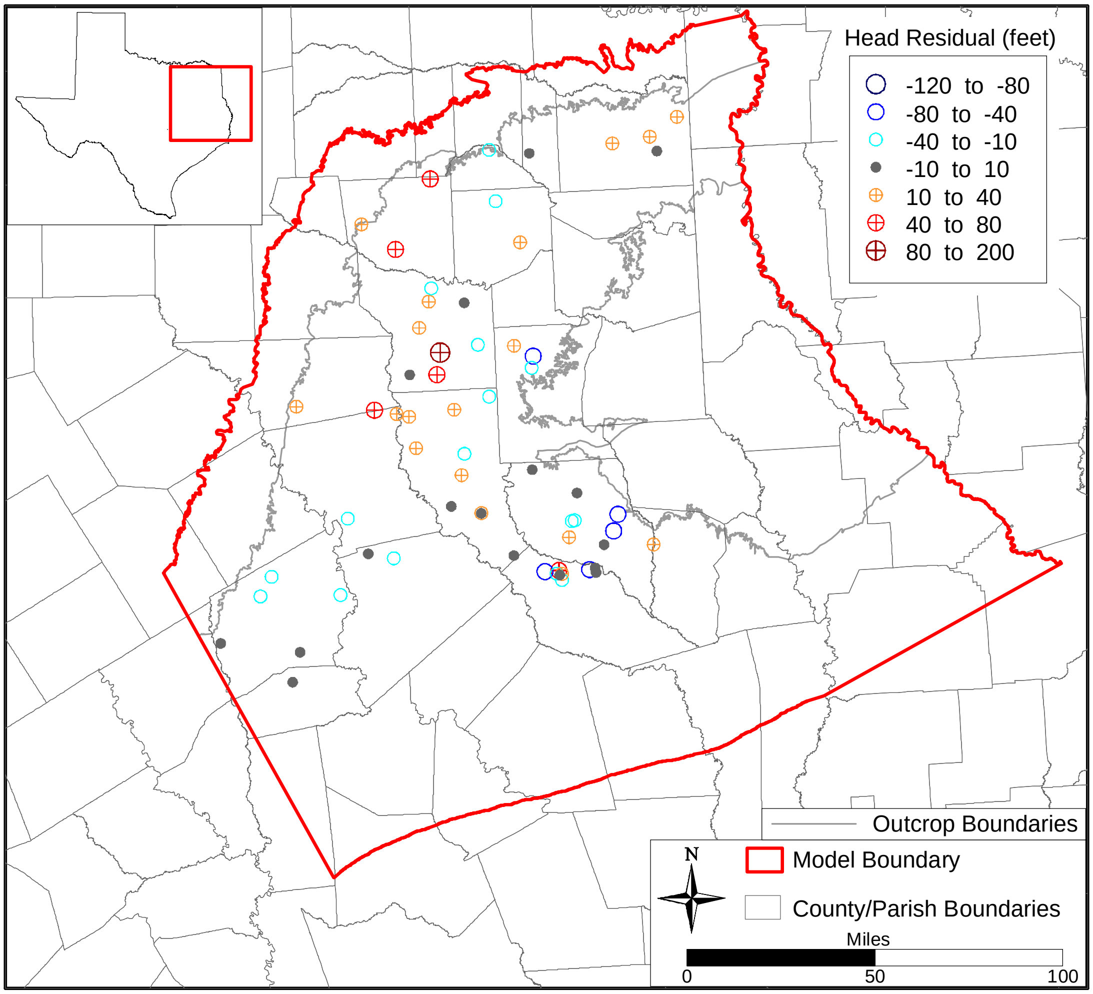


Figure 9.3.10 Simulated (a) and measured (b) head distributions for the Carrizo aquifer (Layer 5) at the end of the calibration period (1989).

a.



b.

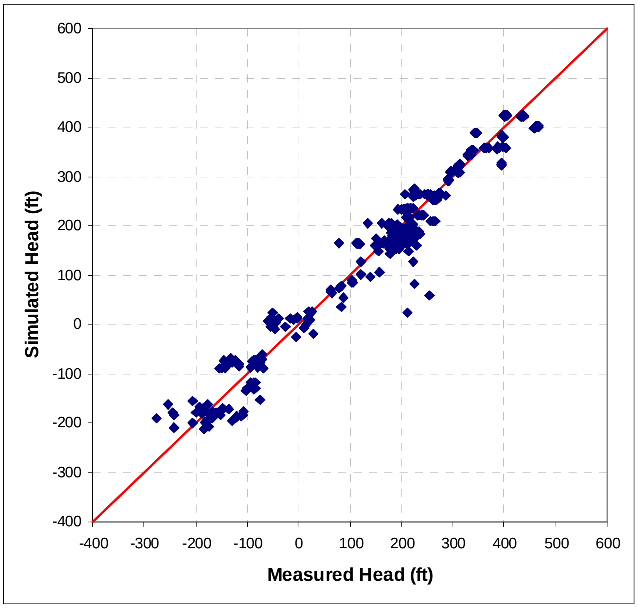


Figure 9.3.11 Calibration period (1980-1989) residuals (a) and scatterplot (b) of simulated and measured heads for the Carrizo aquifer (Layer 5).

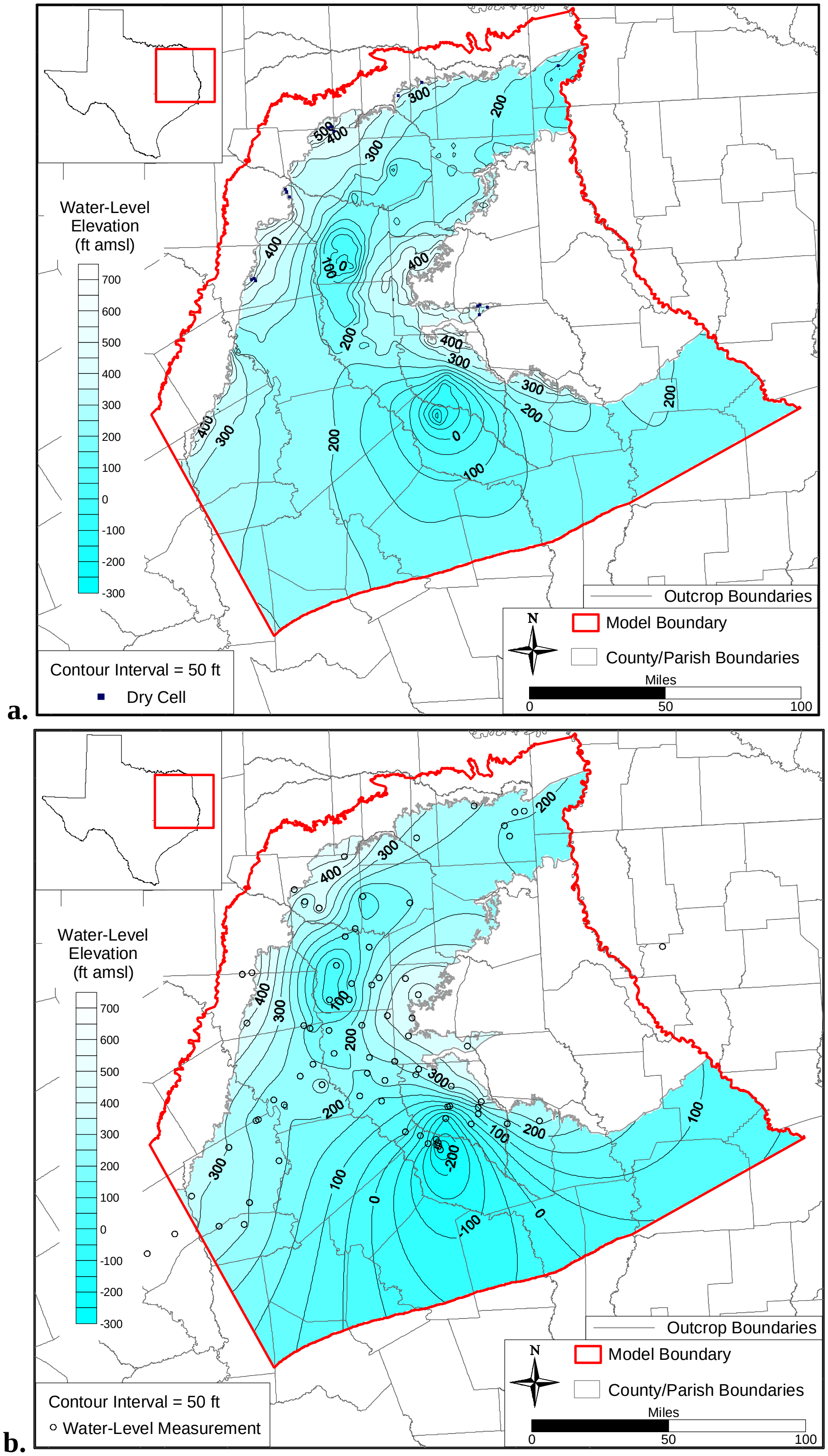
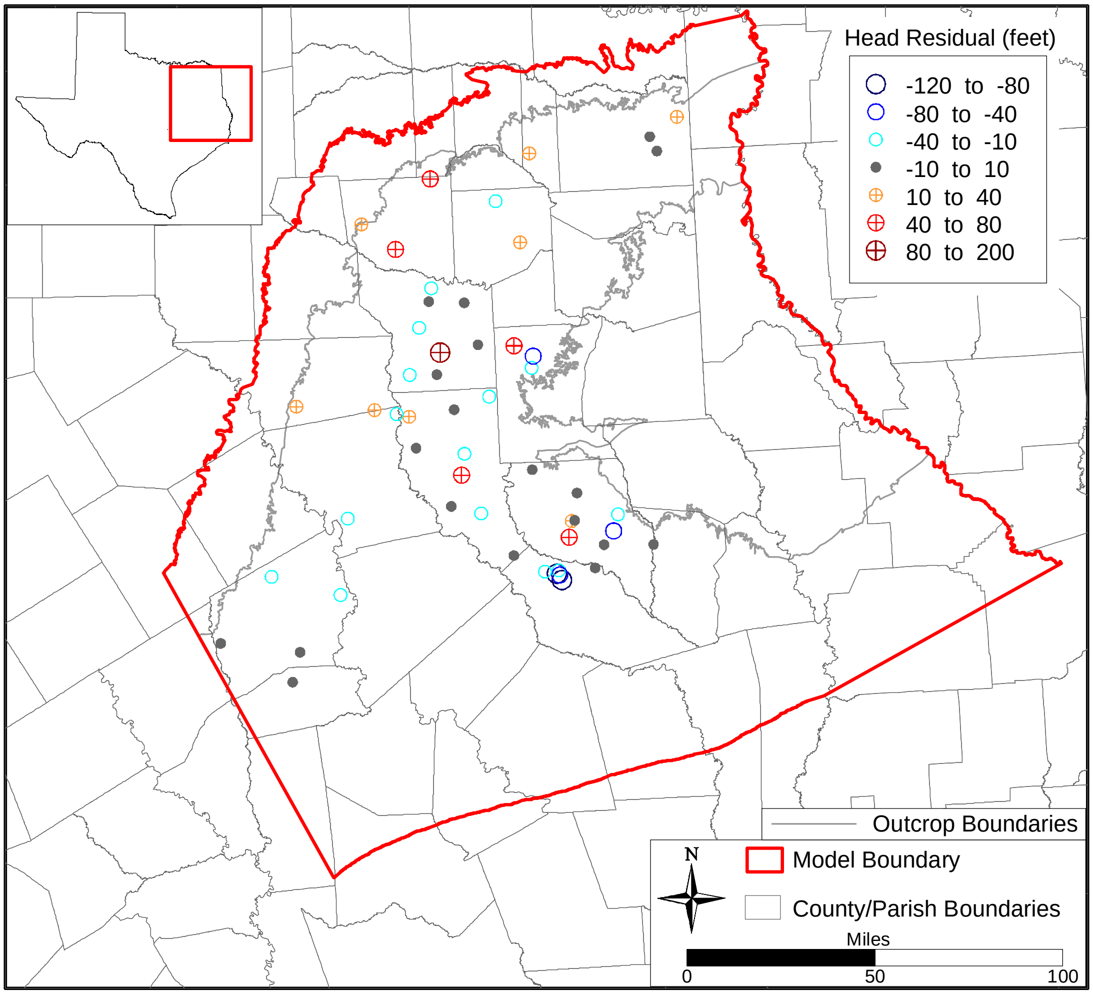


Figure 9.3.12 Simulated (a) and measured (b) head distributions for the Carrizo aquifer (Layer 5) at the end of the verification period (1999).

a.



b.

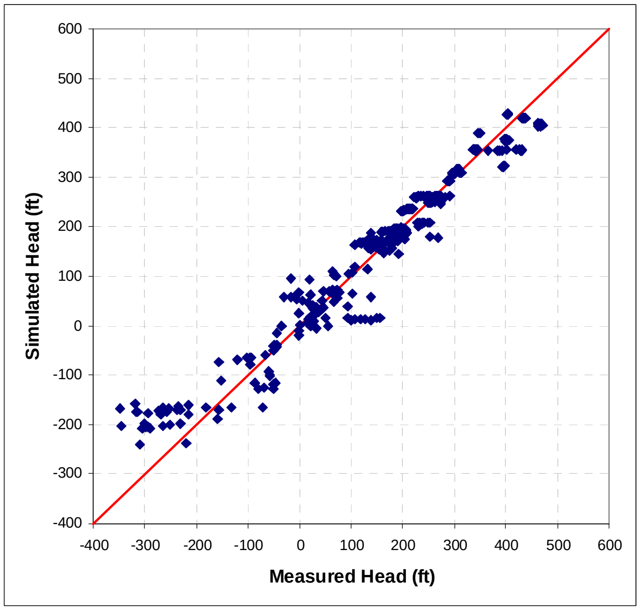


Figure 9.3.13 Verification period (1990-1999) residuals (a) and scatterplot (b) of simulated and measured heads for the Carrizo aquifer (Layer 5).

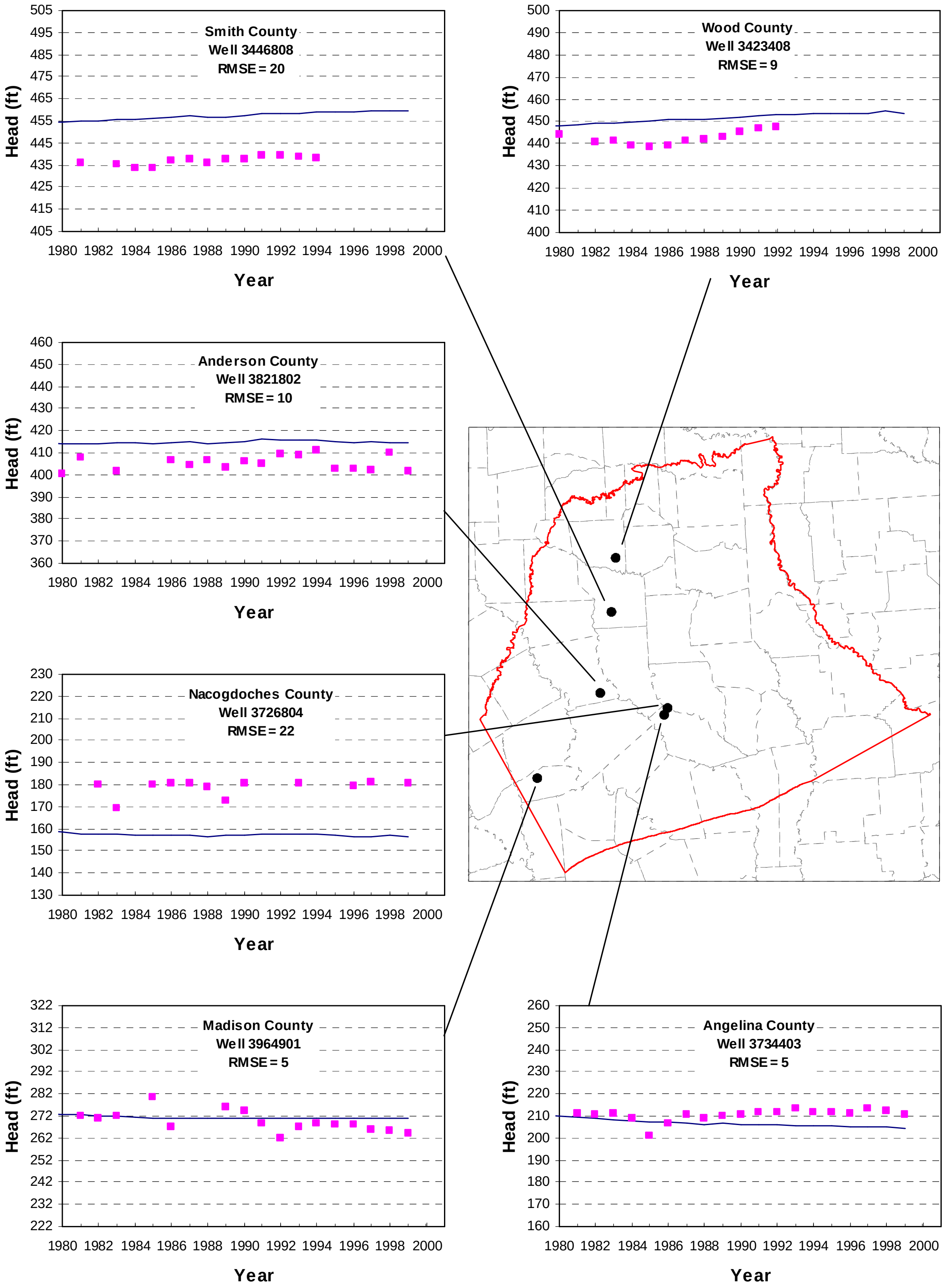


Figure 9.3.14 Selected Sparta aquifer (Layer 1) hydrographs of simulated (lines) and measured (points) hydraulic heads.

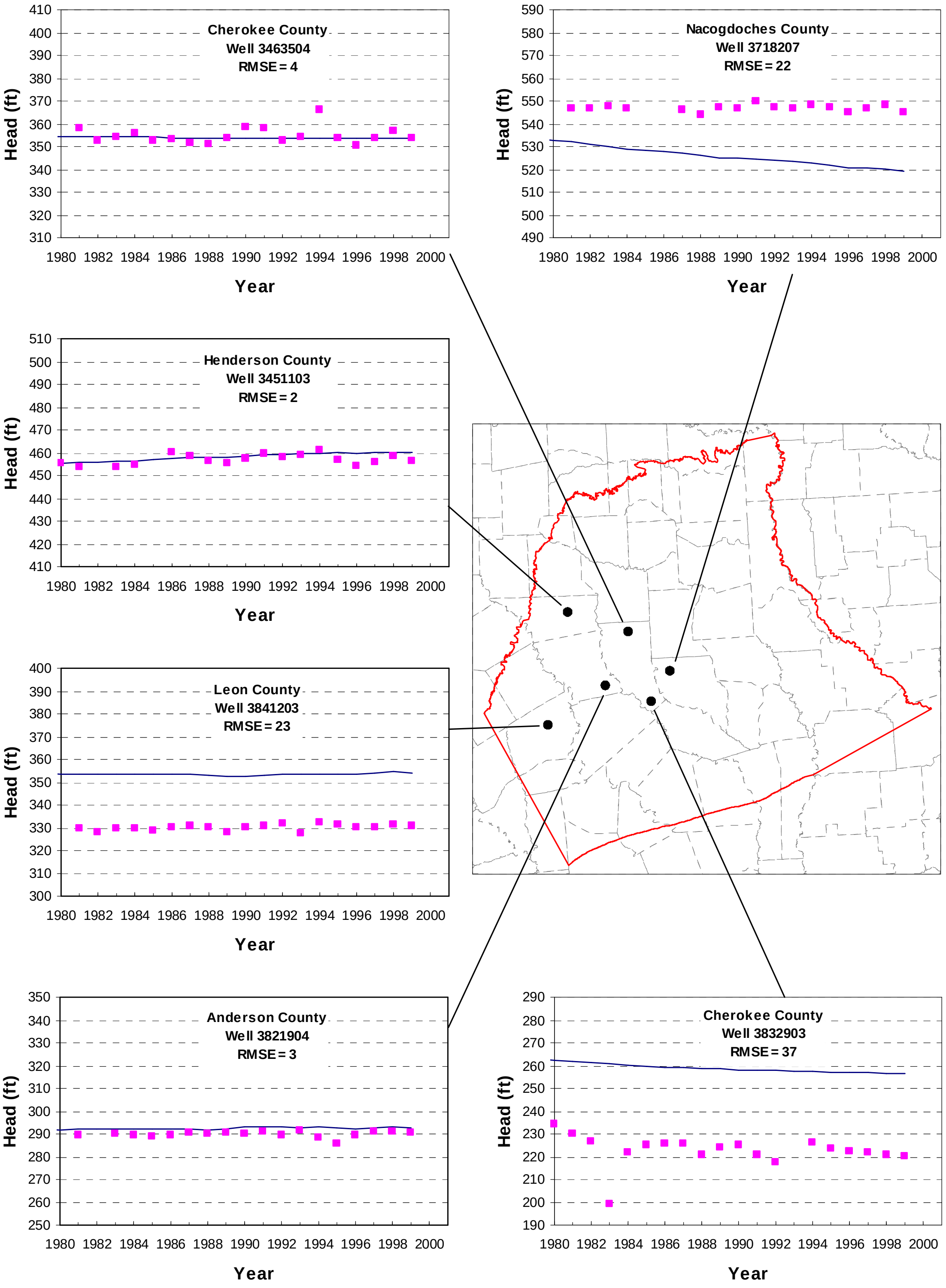


Figure 9.3.15 Selected Queen City aquifer (Layer 3) hydrographs of simulated (lines) and measured (points) hydraulic heads in the southern part of the model.

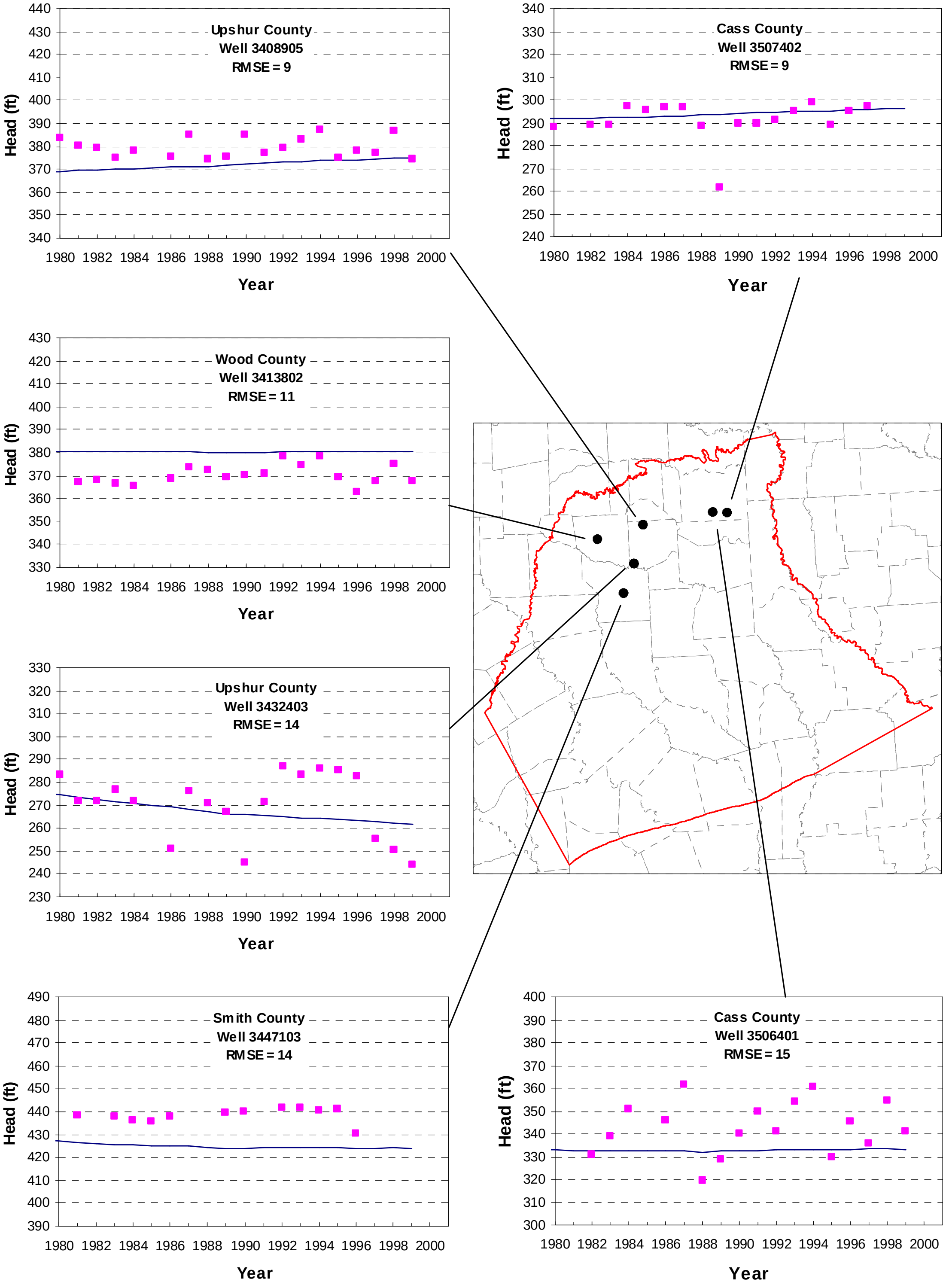


Figure 9.3.16 Selected Queen City aquifer (Layer 3) hydrographs of simulated (lines) and measured (points) hydraulic heads in the northern part of the model.

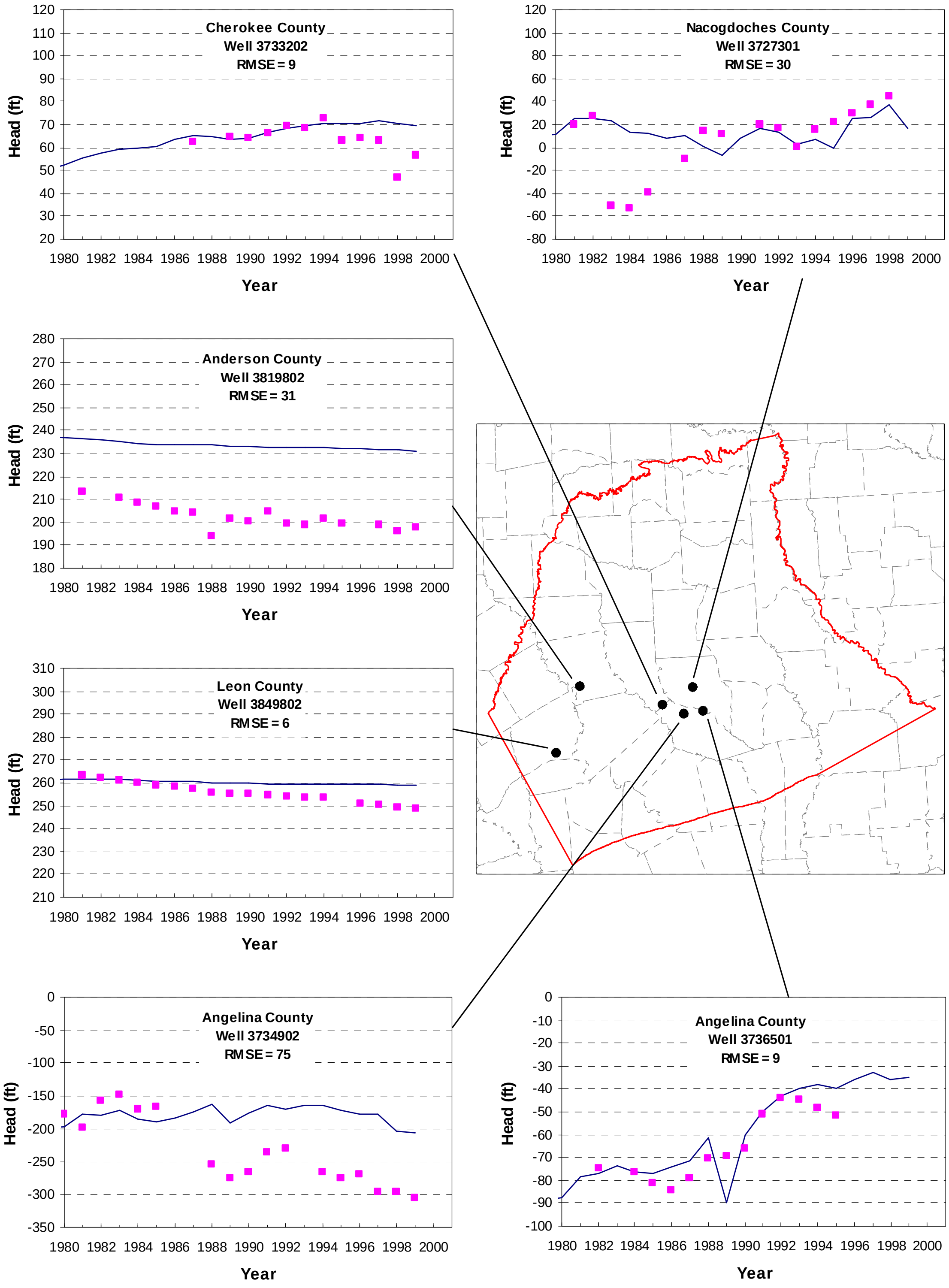


Figure 9.3.17 Selected Carrizo aquifer (Layer 5) hydrographs of simulated (lines) and measured (points) hydraulic heads in the southern part of the model.

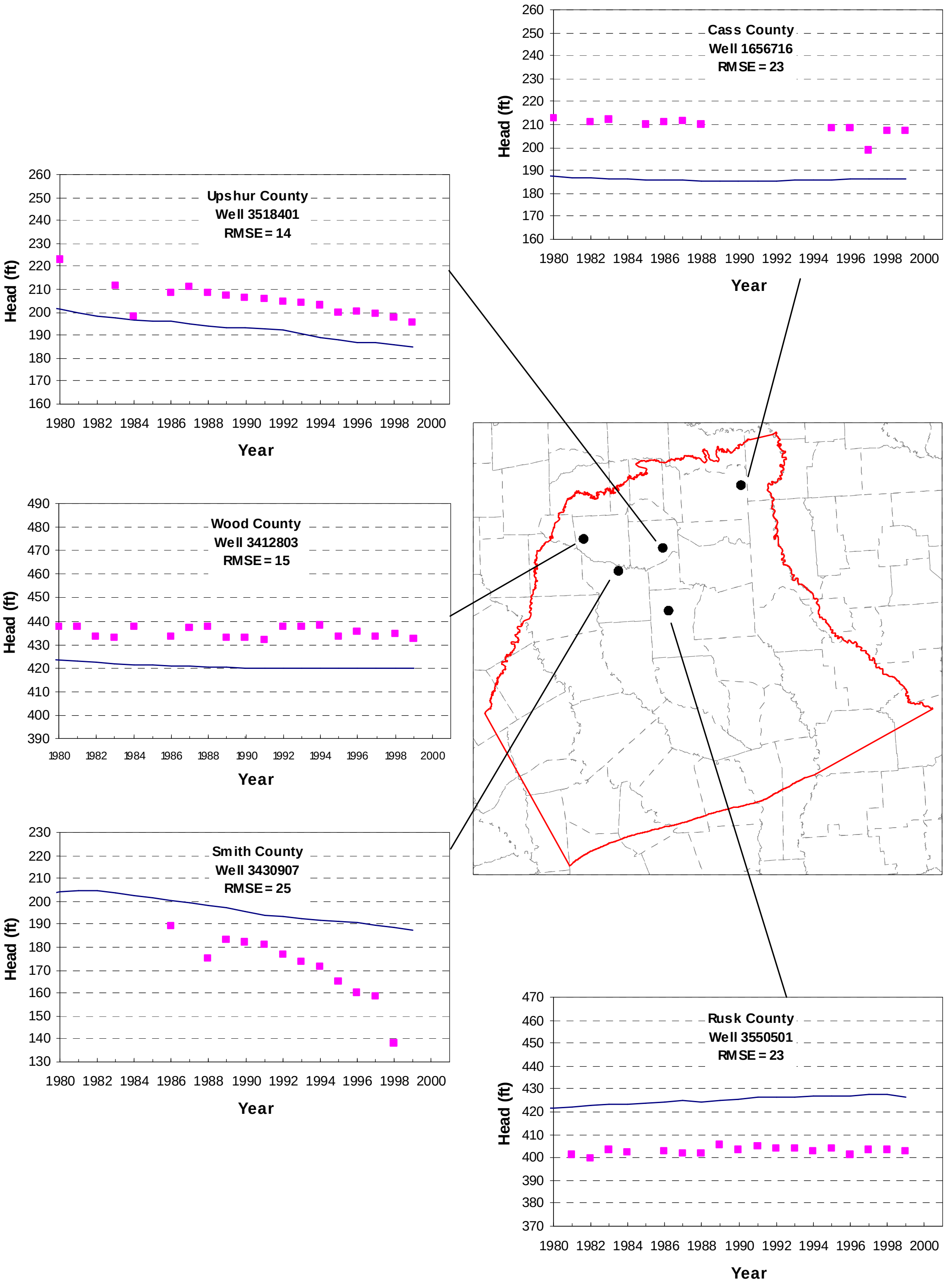


Figure 9.3.18 Selected Carrizo aquifer (Layer 5) hydrographs of simulated (lines) and measured (points) hydraulic heads in the northern part of the model.

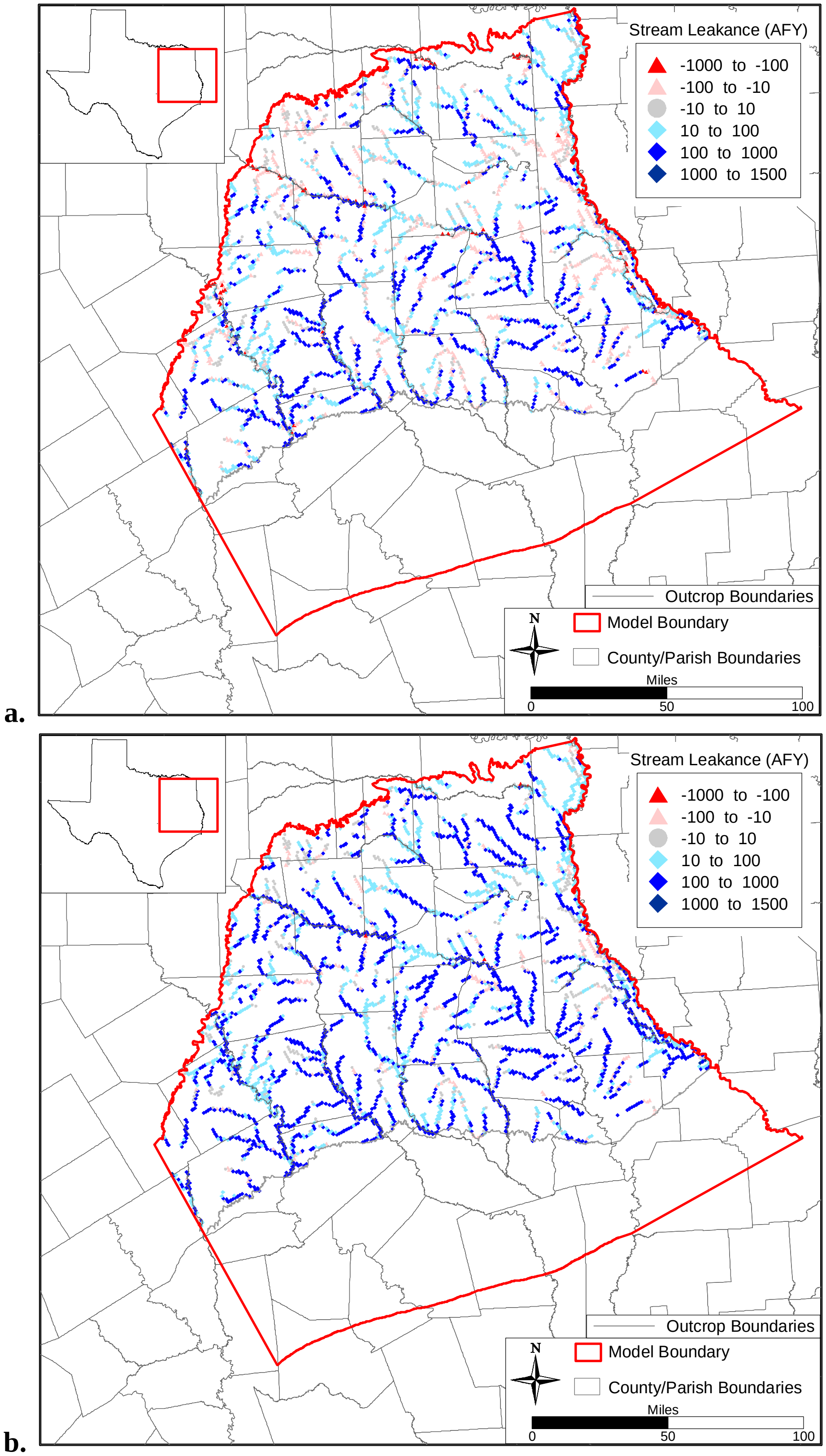


Figure 9.3.19 Simulated stream gain/loss (positive values indicate gaining streams) for 1989 (a) and 1996 (b).

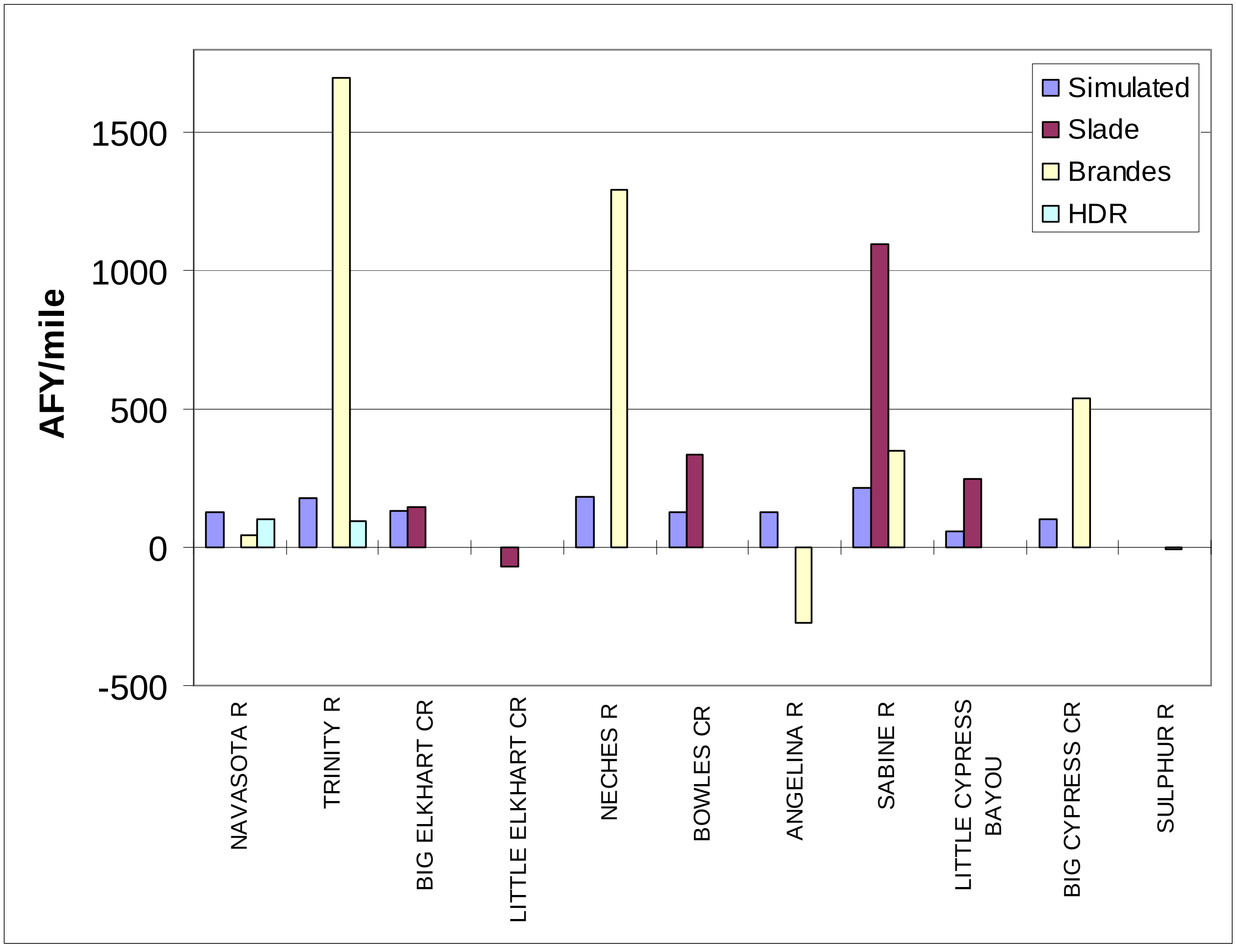


Figure 9.3.20 Simulated stream gain/loss (average of 1980 through 1999) compared to measured values.

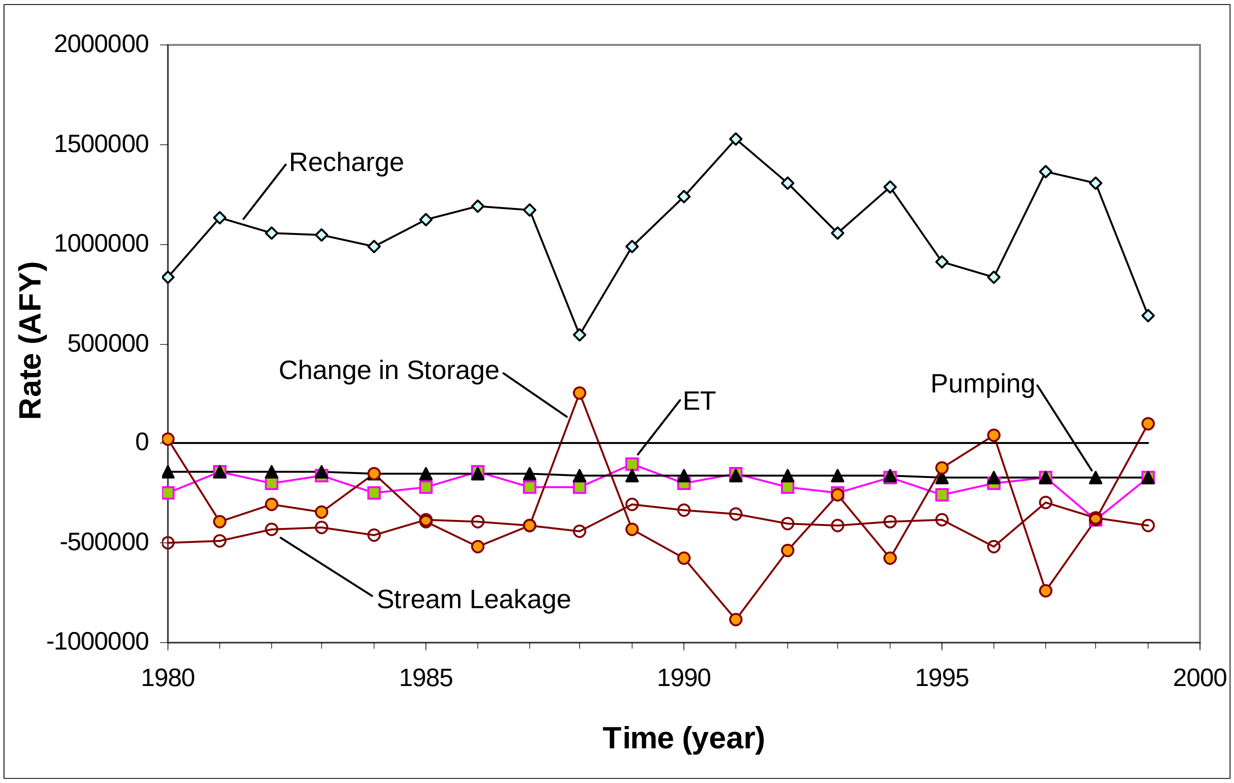


Figure 9.3.21 Change in model-wide rates through time for the transient model.

9.3.3 Sensitivity Analysis

The application of the sensitivity analysis was the same as that of the Southern model, described in Section 9.1.3. Figure 9.3.22 shows the results of the sensitivity analyses for the Queen City aquifer (Layer 3) with *MDs* calculated from only the grid blocks where targets were available. In comparison, Figure 9.3.23 shows the corresponding sensitivity results with *MDs* calculated from all active cells in the layer. Note that the two figures indicate similar trends in sensitivities, with the exception of those affecting storativity and the GHBs. The storativity and GHB sensitivities show a greater effect for the case where all grid blocks were used to calculate the *MDs*. This is to be expected since most of the targets (and groundwater production from the Queen City and Sparta aquifers in east Texas) are in or near the outcrop and, therefore, less affected by the GHBs. The sensitivities that were calculated from all grid blocks are more affected by storativity and the GHBs since a large portion of the grid blocks are in the confined section. In general, most of the other parameters show reasonable agreement, at least in direction if not in magnitude, between sensitivities calculated using only target cells and those calculated using all active cells. Because the sensitivities calculated using all active cells are more representative of the entire model, only those sensitivities using all active cells are shown for the remaining sensitivities.

Figure 9.3.24 indicates that the change in head in the Sparta aquifer for the transient model is most positively correlated with GHB head, followed by GHB conductance. Increases in GHB heads translate directly to increased Sparta heads and increased GHB conductance allows more pressure support from the GHBs. For the Sparta aquifer, the most negatively correlated parameter is storativity. The remaining parameters varied less than one foot from the base case.

As with the Sparta aquifer, the change in head in the Queen City aquifer is most positively correlated with GHB head (see Figure 9.3.23). The vertical hydraulic conductivity of the Weches Formation also shows a positive correlation. The most negatively correlated parameter is storativity which varied less than one foot from the base case. All of the remaining parameters also varied less than one foot from the base case.

For the Carrizo aquifer (Figure 9.3.25), the horizontal hydraulic conductivity of the Carrizo aquifer shows the strongest positive correlation, followed by the vertical hydraulic conductivity of the Reklaw Formation and the horizontal hydraulic conductivity of the Wilcox layers. All three of these parameters allow more pressure support to reach the drawdowns in the confined section of the Carrizo-Wilcox, resulting in increased heads. Significant negative correlation was demonstrated for pumping. The remaining parameters varied less than one foot from the base case.

Sensitivity to recharge, shown in Figure 9.3.26, indicates a similar positive trend for all layers, with the Queen City (Layer 3) and Wilcox (Layers 6 through 8) showing slightly higher *MDs*. Although increasing recharge increases heads, the maximum variation from the base case is less than one half of a foot. Figure 9.3.27 shows the sensitivity to pumping. The greatest impact for the pumping sensitivity is in the Carrizo aquifer (Layer 5) since it has the most pumping, followed by the upper and middle Wilcox layers.

Figures 9.3.28 and 9.3.29 show the sensitivity of selected hydrographs to varying two sensitive parameters. Figure 9.3.28 shows transient hydrograph sensitivities for the Sparta aquifer when the GHB head is varied. GHB head is the most sensitive parameter identified for the Sparta aquifer. As expected, the hydrographs trend slightly in the direction of head change. Figure 9.1.29 shows transient hydrograph sensitivities for the Queen City aquifer when the recharge is varied. In general, heads increase slightly in the Queen City when the recharge is increased and heads decrease in the Queen City when the recharge is decreased.

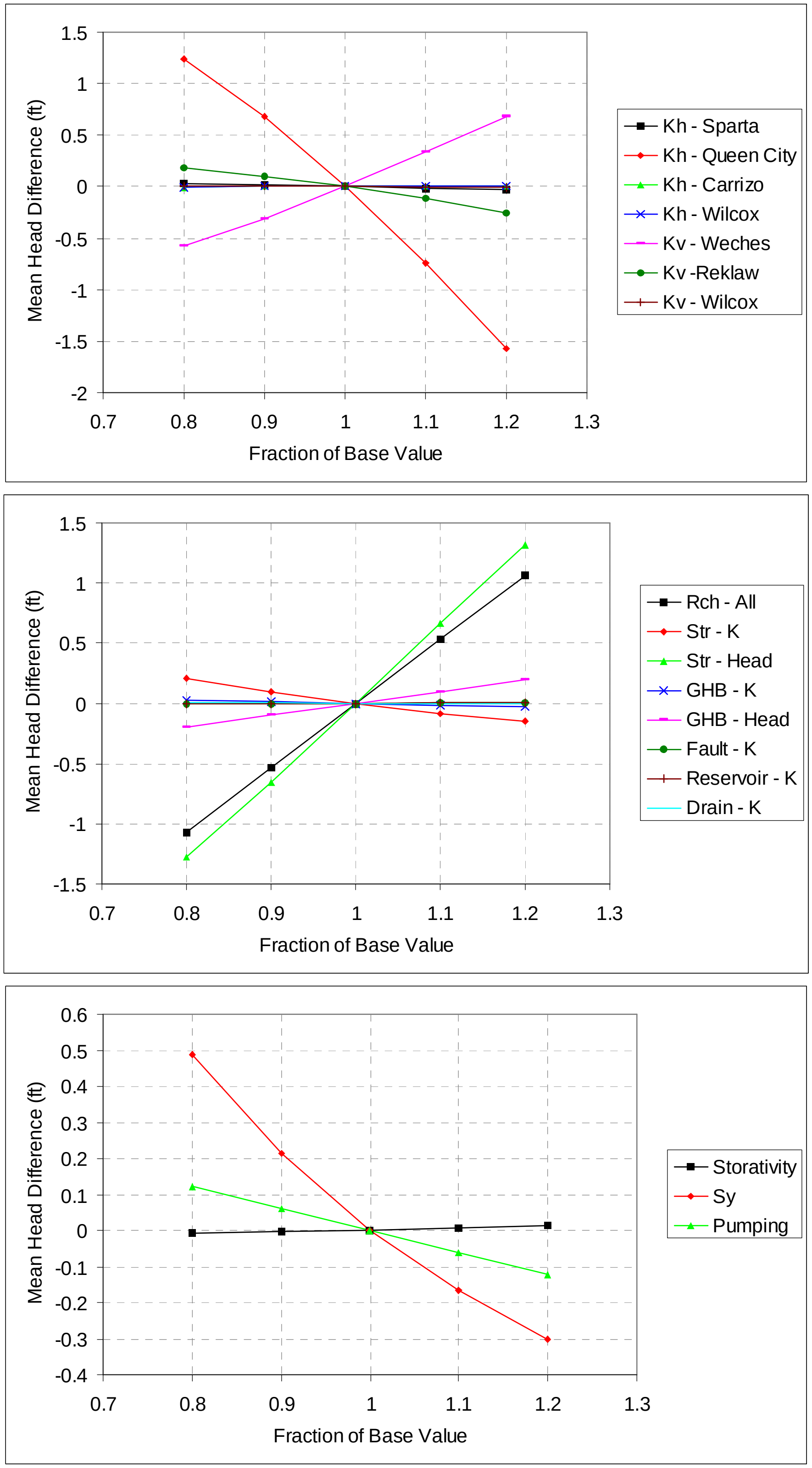


Figure 9.3.22 Transient sensitivity results for the Queen City aquifer (Layer 3) using target locations.

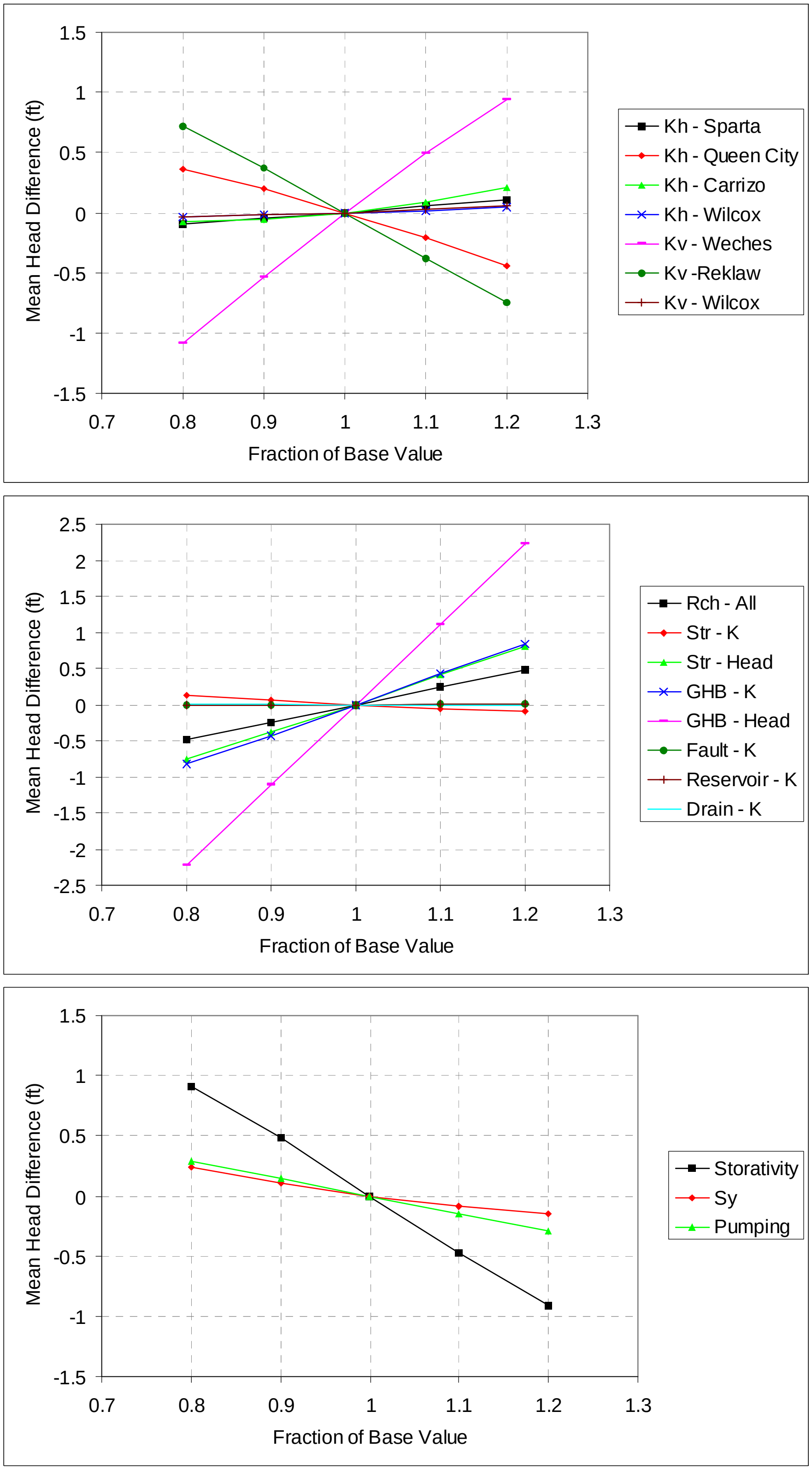


Figure 9.3.23 Transient sensitivity results for the Queen City aquifer (Layer 3) using all active grid blocks.

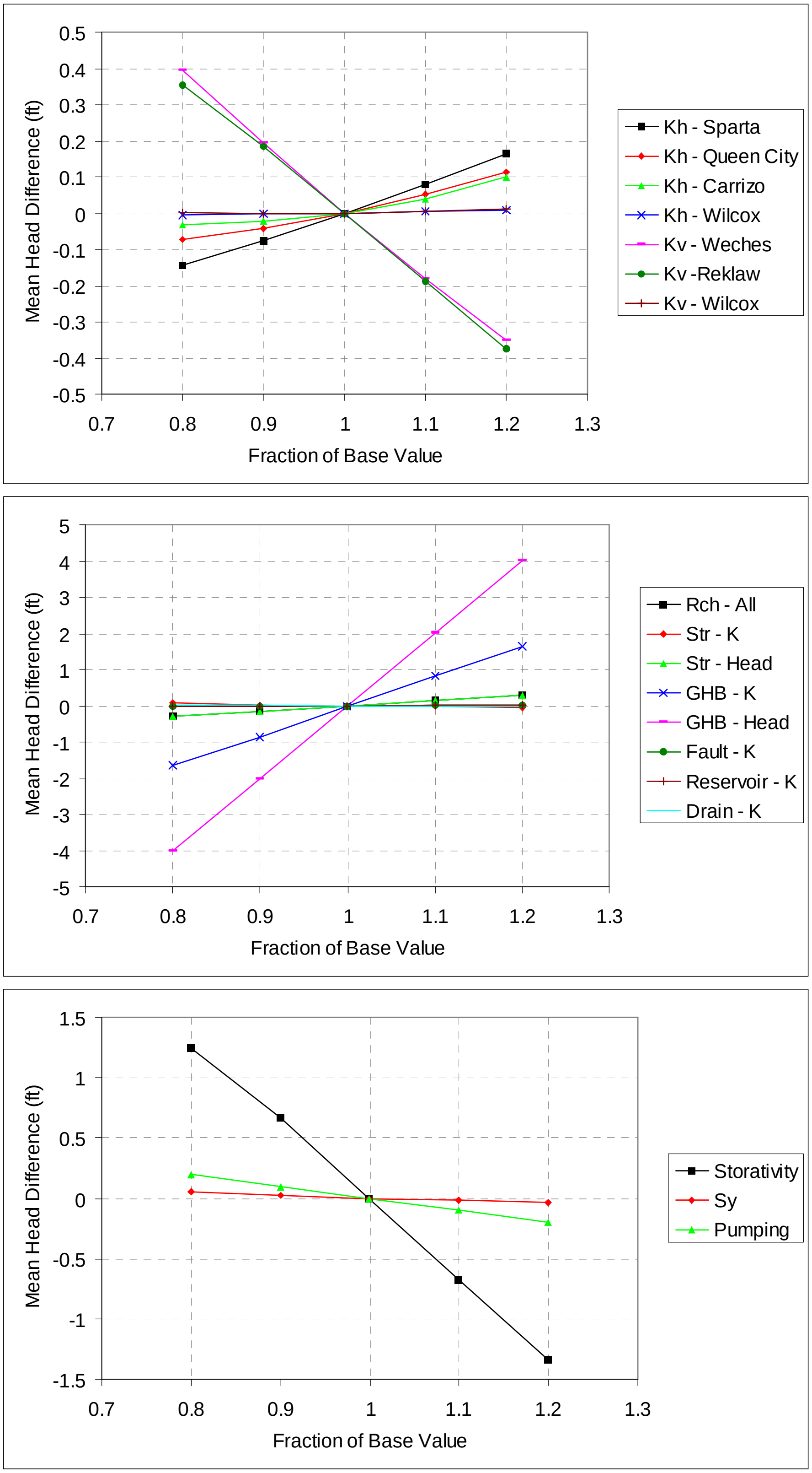


Figure 9.3.24 Transient sensitivity results for the Sparta aquifer (Layer 1) using all active grid blocks.

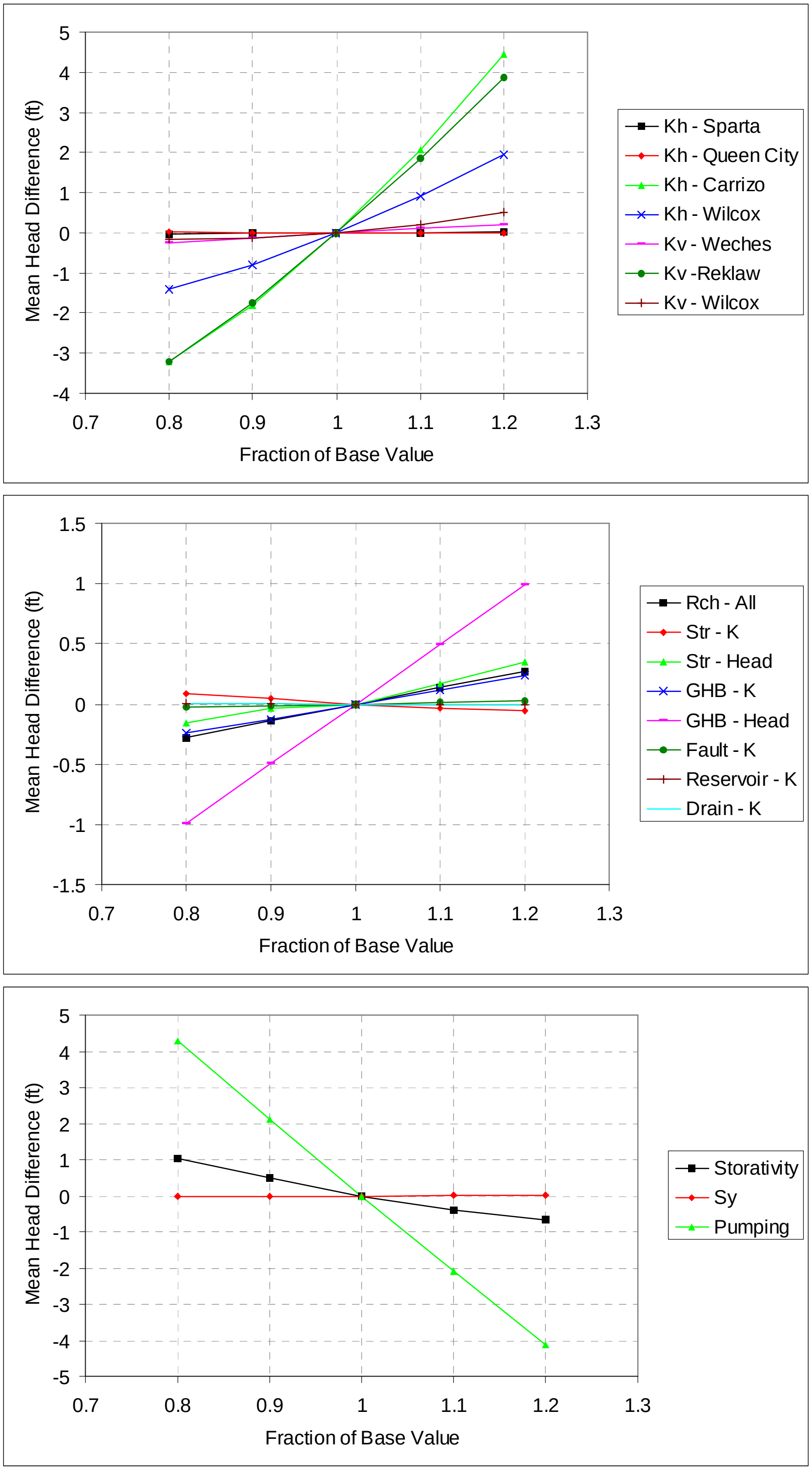


Figure 9.3.25 Transient sensitivity results for the Carrizo aquifer (Layer 5) using all active grid blocks.

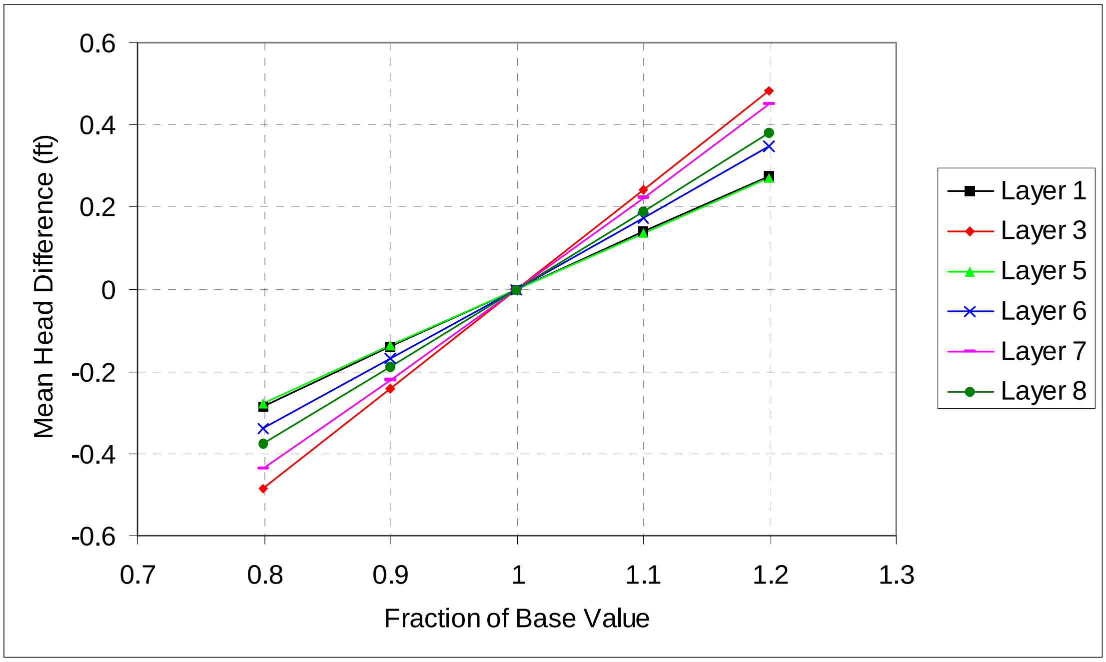


Figure 9.3.26 Transient sensitivity of all layers to recharge using all active grid blocks.

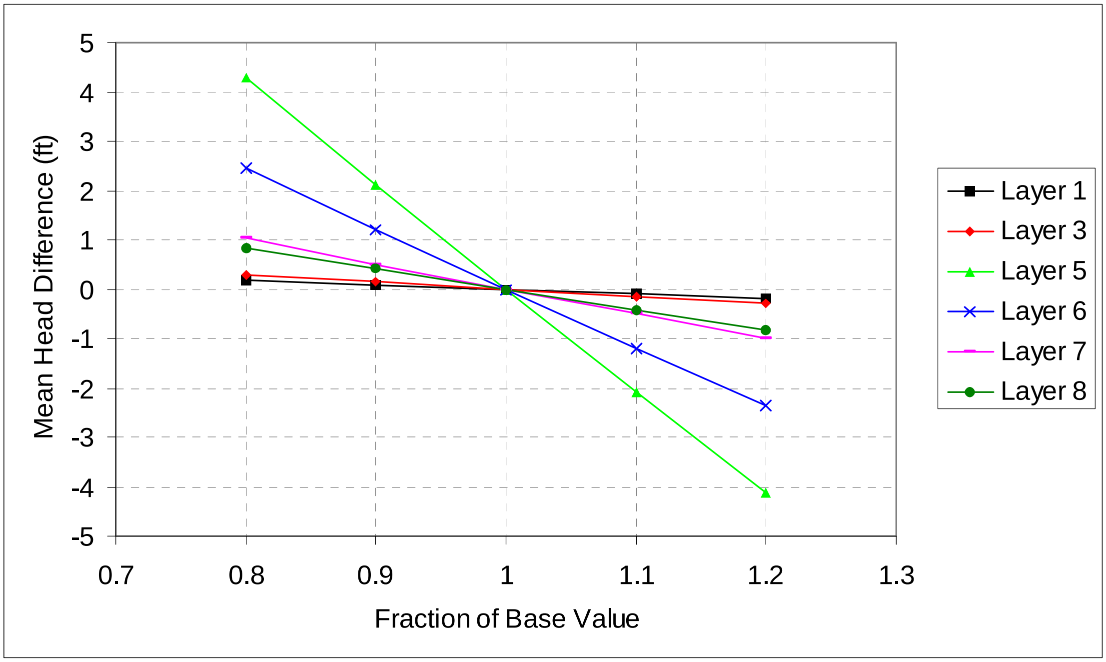


Figure 9.3.27 Transient sensitivity of all layers to pumping using all active grid blocks.

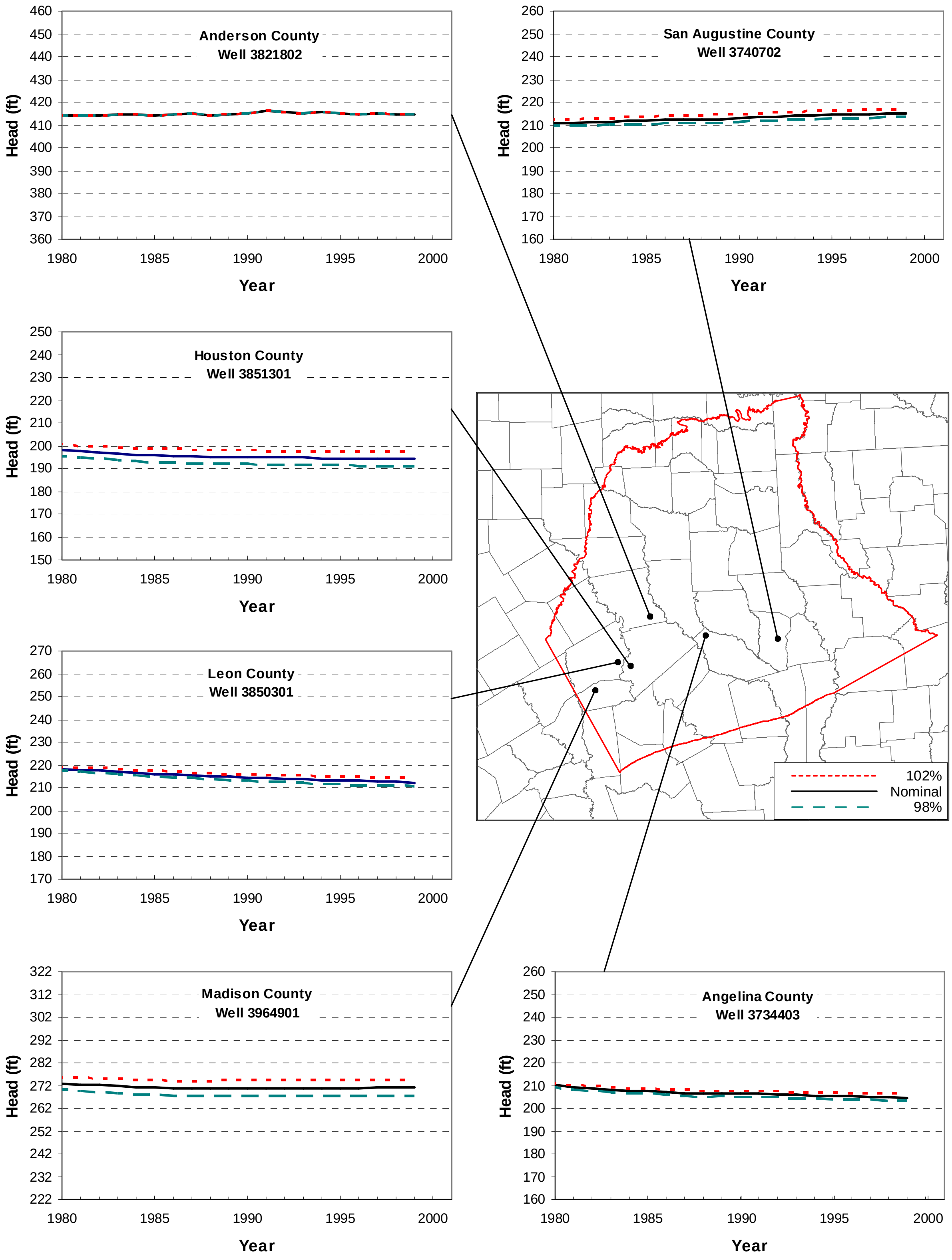


Figure 9.3.28 Transient sensitivity hydrographs for the Sparta aquifer when GHB head is varied.

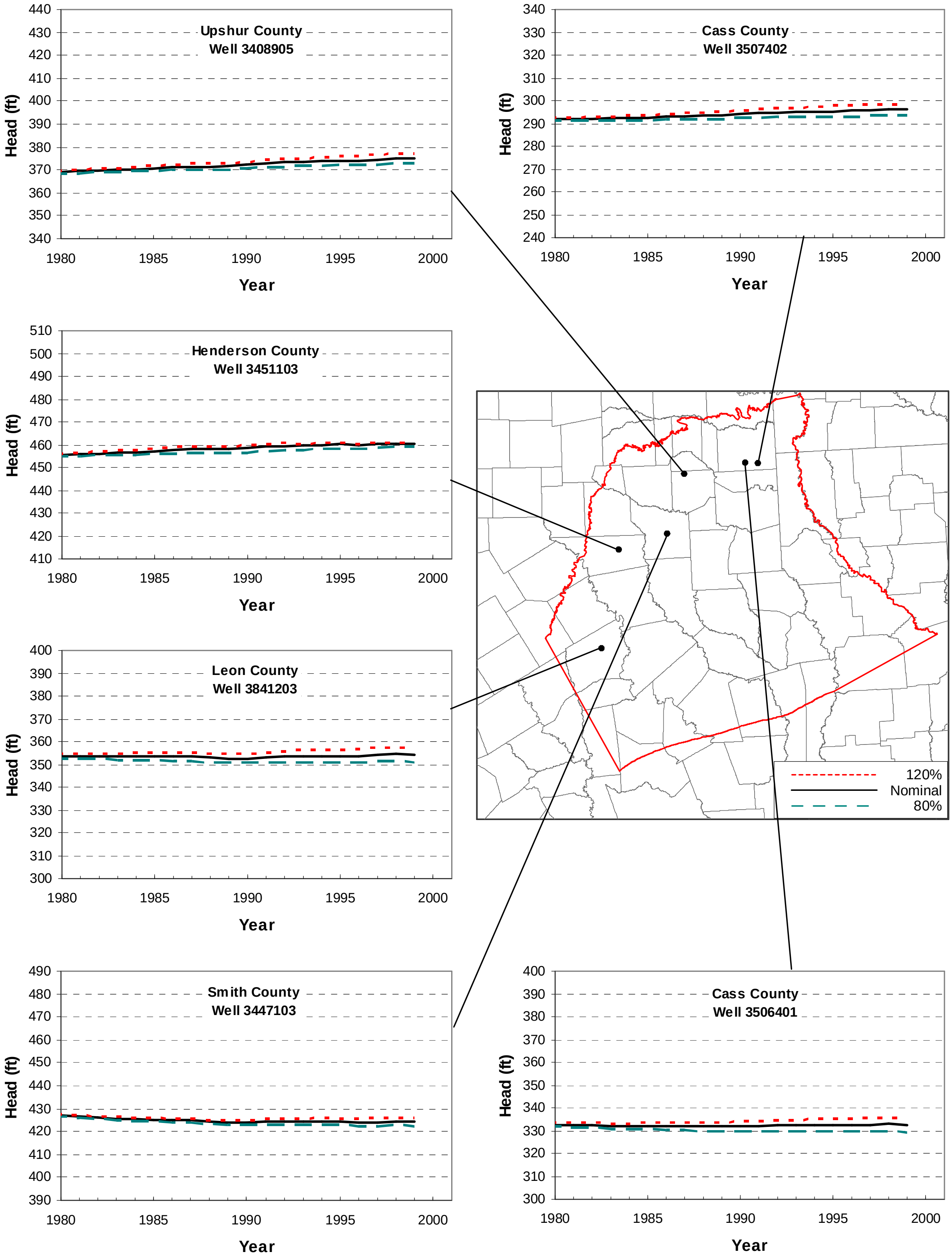


Figure 9.3.29 Transient sensitivity hydrographs for the Queen City aquifer when recharge is varied.

10.0 MODEL PREDICTIVE SIMULATIONS

The purpose of the GAMs is to assess groundwater availability within the modeled regions over a 50-year planning period (2000-2050) using RWPG water-demand projections under drought-of-record (DOR) conditions. The GAM will be used to predict changes in regional groundwater water levels (heads) and fluxes (baseflow to major streams and rivers, springs, and cross-formational flow).

Six basic predictive model runs are presented and documented for each model region: (1) average recharge through 2050, (2) average recharge ending with the DOR in 2010, (3) average recharge ending with the DOR in 2020, (4) average recharge ending with the DOR in 2030, (5) average recharge ending with the DOR in 2040, and (6) average recharge ending with the DOR in 2050.

To complete the predictive simulations, estimates of groundwater evapotranspiration (ET), and streamflow were completed for an average condition. These averages are similar to the steady-state cases. Recharge was estimated for the average condition and the DOR (Section 6.3.5). To estimate recharge for the DOR, the climatic conditions for the DOR years were input to the same algorithm that was used to derive historical recharge. Predictive pumping demands from the RWPGs are used in the predictive simulations assuming that the pumping distribution (as determined in Appendix C) for the year 1999 applies in the future (2000-2050). Appendix D provides more detail for the derivation of predictive pumping.

For the predictive runs, heads for the lateral GHBs were again iteratively determined by sampling heads from the adjoining model that corresponded with the boundary cells.

10.1 Drought of Record

The drought of record for each of the three Queen City and Sparta GAM regions had been determined previously for their respective Carrizo-Wilcox GAMs. Please refer to Deeds et al. (2003), Dutton et al. (2003), and Fryar et al. (2003) for a discussion of the DOR and its derivation for each model. Table 10.1.1 shows the previously derived DOR periods for each Carrizo-Wilcox GAM. Because the current models use only annual stress periods, we chose

1954 to 1956 as the DOR for all of the Queen City and Sparta GAMs. This period was relatively consistent among all three of the Carrizo-Wilcox models.

Table 10.1.1 Drought of record periods for the Carrizo-Wilcox GAMs

Model	Start of DOR	End of DOR
Southern Carrizo-Wilcox	October 1953	February 1957
Central Carrizo-Wilcox	1954	1956
Northern Carrizo-Wilcox	June 1954	March 1957
All Queen City Sparta GAMs	1954	1956

10.2 Southern Queen City and Sparta GAM

In this section, we present the head and drawdown surfaces from the predictive simulation results of the Southern Queen City and Sparta GAM. We also discuss a comparison between the average recharge condition simulation and the simulation with a DOR. Finally, we present the water budget for the predictive simulations.

10.2.1 Predictive Simulation Results

Figure 10.2.1 shows the simulated head surface for the Sparta aquifer in 2000, for comparison to the later predictive runs. Figure 10.2.2 shows the Sparta aquifer simulated head surface in 2010 along with the drawdown from 2000. Drawdown for a particular year is defined as the head in year 2000 minus the head in that year, so drawdown will be positive, and rebound negative. The only significant feature in the drawdown surface is a small depression in southern Atascosa County that represents proposed pumping for a power utility. Figure 10.2.3 shows the Sparta aquifer simulated head surface in 2020 along with the drawdown from 2000. The same feature is evident in Atascosa County, with slightly increased drawdown. Figure 10.2.4 shows the Sparta aquifer simulated head surface in 2030 along with the drawdown from 2000. The drawdown in southern Atascosa County continues to increase, and a small drawdown cone is forming on the eastern border of Atascosa County. Figure 10.2.5 shows the Sparta aquifer simulated head surface in 2040 along with the drawdown from 2000. The drawdown in southern Atascosa County continues to increase to over 150 ft, and the small drawdown cone remains on the eastern border of Atascosa County. Figure 10.2.6 shows the Sparta aquifer simulated head surface in 2050 along with the drawdown from 2000. The drawdown in southern Atascosa

County has reached over 200 ft, and the small drawdown cone remains on the eastern border of Atascosa County. A small amount of drawdown along the eastern model boundary can be seen, which is due to the GHBs at this boundary. The GHB heads reflect the edge of the large drawdown cone in Fayette County in the Central model. Figure 10.2.7 shows the Sparta aquifer simulated head surface in 2050 with average recharge conditions rather than the DOR along with the drawdown from 2000. There is no noticeable difference between these surfaces and the DOR surfaces. In general, there is little drawdown in the Sparta aquifer outside of the two features described above.

Figure 10.2.8 shows the simulated head surface for the Queen City aquifer in 2000, for comparison to the later predictive runs. Figure 10.2.9 shows the Queen City aquifer simulated head surface in 2010 along with the drawdown from 2000. Similar to the Sparta aquifer, the only significant feature in the drawdown surface is a small depression in southern Atascosa County that represents proposed pumping for the same power utility. Figure 10.2.10 shows the Queen City aquifer simulated head surface in 2020 along with the drawdown from 2000. The same feature is evident in Atascosa County, with slightly increased drawdown, now over 50 ft. Figure 10.2.11 shows the Queen City aquifer simulated head surface in 2030 along with the drawdown from 2000. The drawdown in southern Atascosa County continues to increase, now over 100 ft. In a few sections of the outcrop we can see some fluctuation of the water table. Figure 10.2.12 shows the Queen City aquifer simulated head surface in 2040 along with the drawdown from 2000. The drawdown in southern Atascosa County continues to increase to over 150 ft, and we observe what looks like some recovery occurring in Webb County. As with the Sparta, a small amount of drawdown along the eastern model boundary can be seen, which is due to the GHBs at this boundary. The GHB heads reflect the edge of the drawdown cones in Fayette and Lavaca counties in the Central model. Figure 10.2.13 shows the Queen City aquifer simulated head surface in 2050 along with the drawdown from 2000. The drawdown in southern Atascosa County has reached over 200 ft, and about 25-50 ft of recovery has occurred in Webb County. Figure 10.2.14 shows the Queen City aquifer simulated head surface in 2050 with average recharge conditions rather than the DOR along with the drawdown from 2000. There is no noticeable difference between these surfaces and the DOR surfaces. In general, there is little effect in the Queen City aquifer outside of the outcrop, except the two features described above, the drawdown in Atascosa and the slight recovery in Webb County.

Figure 10.2.15 shows the simulated head surface for the Carrizo Formation in 2000, for comparison to the later predictive runs. Figure 10.2.16 shows the Carrizo Formation simulated head surface in 2010 along with the drawdown from 2000. As with the Southern Carrizo-Wilcox GAM, we see two major features. First, there is a large recovery occurring in the Wintergarden area due to a decrease in pumping from historical to predictive of about 90,000 acre-ft. Second, there is drawdown occurring in northern Webb County that is a result of a proposed Region M water development project serving the city of Laredo. Figure 10.2.17 shows the Carrizo Formation simulated head surface in 2020 along with the drawdown from 2000. A new feature that is evident in the drawdown plot is the drawdown in western Gonzales County of between 25 and 50 ft. Figure 10.2.18 shows the Carrizo Formation simulated head surface in 2030 along with the drawdown from 2000. The recovery continues in the Wintergarden area and the drawdown in northern Webb County has reached over 150 ft. The increased pumping in eastern Wilson and western Gonzales counties has expanded the drawdown feature in the eastern portion of the model. Figure 10.2.19 shows the Carrizo Formation simulated head surface in 2040 along with the drawdown from 2000. The same three features are evident, with a slight expansion of their effect. Figure 10.2.20 shows the Carrizo Formation simulated head surface in 2050 along with the drawdown from 2000. By this point, the head surface in the Wintergarden area has moved back towards the steady-state head surface, where gradients are predominantly south-southeast, rather than directed towards the large drawdown cone that previously existed in the area. The recovery in the Wintergarden area exceeds 100 ft, the drawdown in Webb County is greater than 200 ft, and the heads in most of Gonzales and the eastern portion of Wilson County have decreased by more than 25 ft. Figure 10.2.21 shows the Carrizo Formation simulated head surface in 2050 with average recharge conditions rather than the DOR along with the drawdown from 2000. There is no noticeable difference between these surfaces and the DOR surfaces.

Figure 10.2.22 shows selected Sparta aquifer hydrographs from the 2050 simulation. The increased pumping in Wilson and Gonzales counties is evident in the slight drawdown that occurs over the predictive period. Atascosa County shows increased pumping in year 2000 that causes a gradual drawdown over this period. This well for this hydrograph is not very near the pumping center that is more evident in, for example, Figure 10.2.6. Frio County shows a gradual, continuous drawdown throughout the historical and predictive periods. Webb County shows a slight recovery over the course of the predictive period. LaSalle County remains relatively flat in the predictive period.

Figure 10.2.23 shows selected Queen City aquifer hydrographs from the 2050 simulation. As with the Sparta aquifer, the increased pumping in Wilson and Gonzales counties is evident in the slight drawdown that occurs over the predictive period. The Atascosa well shown in the hydrograph again is located away from the proposed pumping center, so it shows a slight recovery in the predictive period. Frio County also shows about 20 ft of recovery over the predictive period. The hydrograph for Dimmit County is relatively flat. LaSalle County shows an obvious decrease in pumping near this well for the predictive period, as the drawdown that occurs in the historical period reverses in the predictive period.

Figure 10.2.24 shows selected Carrizo Formation hydrographs from the 2050 simulation. The increase in pumping Gonzales County is reflected in a significant negative increase in slope in the hydrograph. In Wilson County, pumping appears to remain relatively constant near the well for this hydrograph, with a constant decline from the historical period. The hydrographs for Atascosa and Frio counties reflect the significant decrease in pumping from the historical to predictive periods, with immediate rebound occurring in 2000. The hydrograph for Dimmit County also shows rebound, but further into the predictive period, at approximately 2030. The hydrograph for LaSalle County shows a significant decrease in pumping in 2000.

The number of dry cells increased in the predictive simulation from 103 dry cells in 2000 to 157 dry cells in 2050 (152 without drought conditions). Of the 157 dry cells in 2050, 41 were in the Queen City and Sparta layers. All dry cells occurred in the outcrop. Considering there are 7,944 outcrop cells, the number of dry cells has little impact on the model.

The DOR simulations did not differ significantly from the average recharge simulations. Figure 10.2.25 shows the difference between the head surfaces for the two runs for the Sparta aquifer. All head differences are less than 10 ft. The only noticeable features are small changes in the thinnest part of the outcrop in Gonzales County. Figure 10.2.26 shows the difference between the head surfaces for the two runs for the Queen City aquifer. No differences are noticeable. Figure 10.2.27 shows the difference between the head surfaces for the two runs for the Carrizo. All head differences are less than 10 ft. Small differences are noticeable in the outcrop in the northeastern portion of the model.

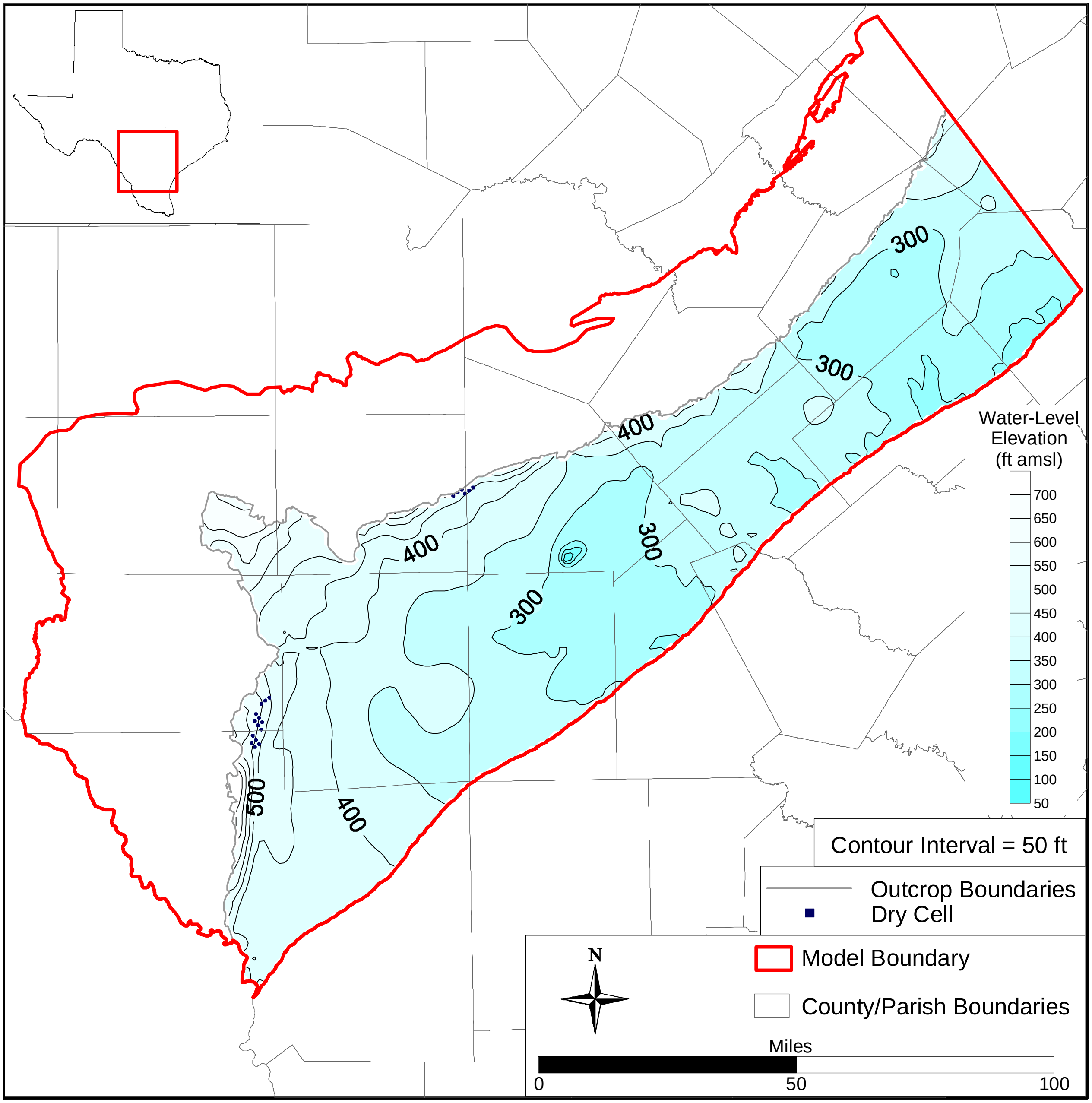


Figure 10.2.1 Simulated 2000 head surface for the Sparta aquifer (Layer 1).

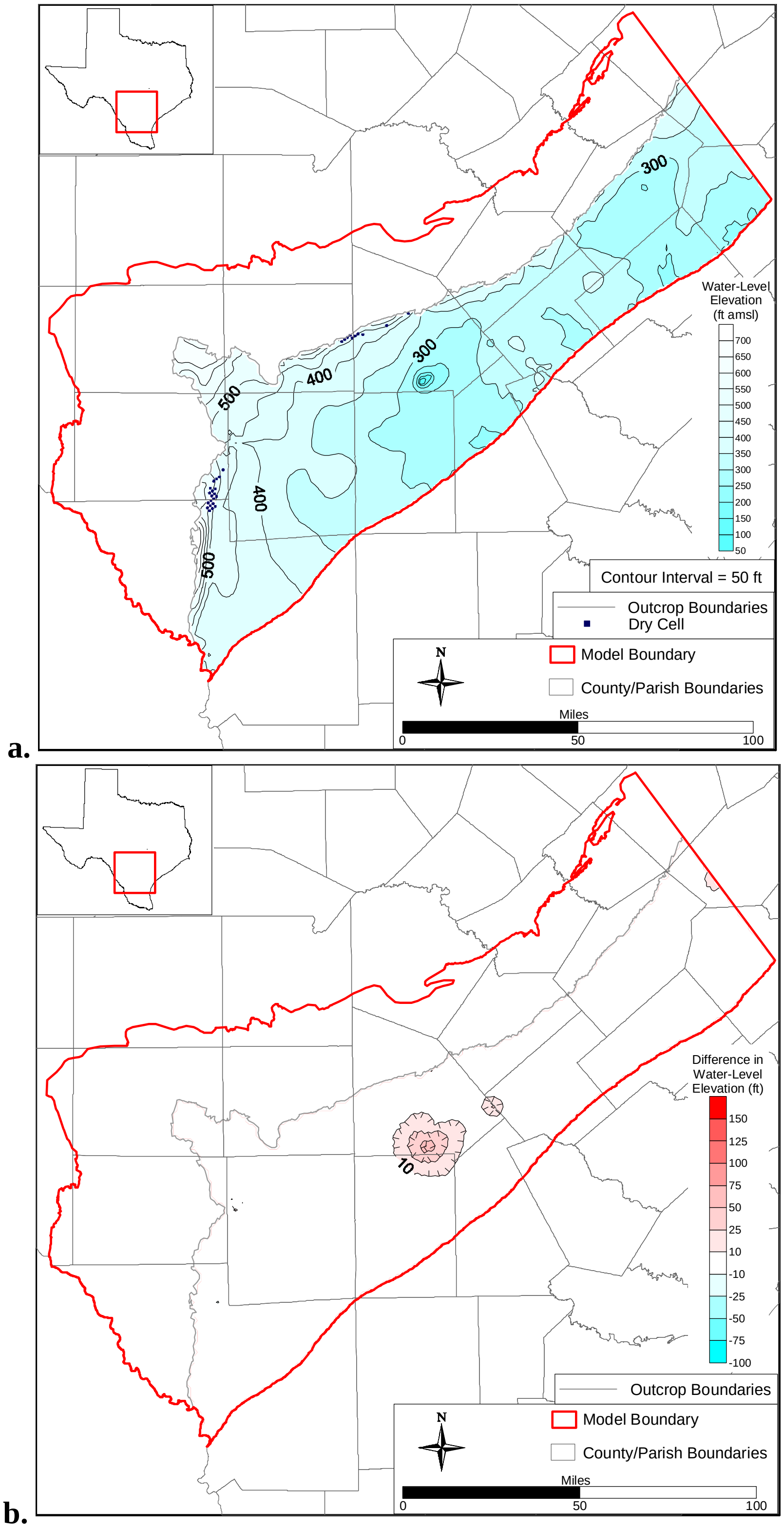


Figure 10.2.2 Simulated 2010 head surface (a) and drawdown from 2000 (b) for the Sparta aquifer (Layer 1).

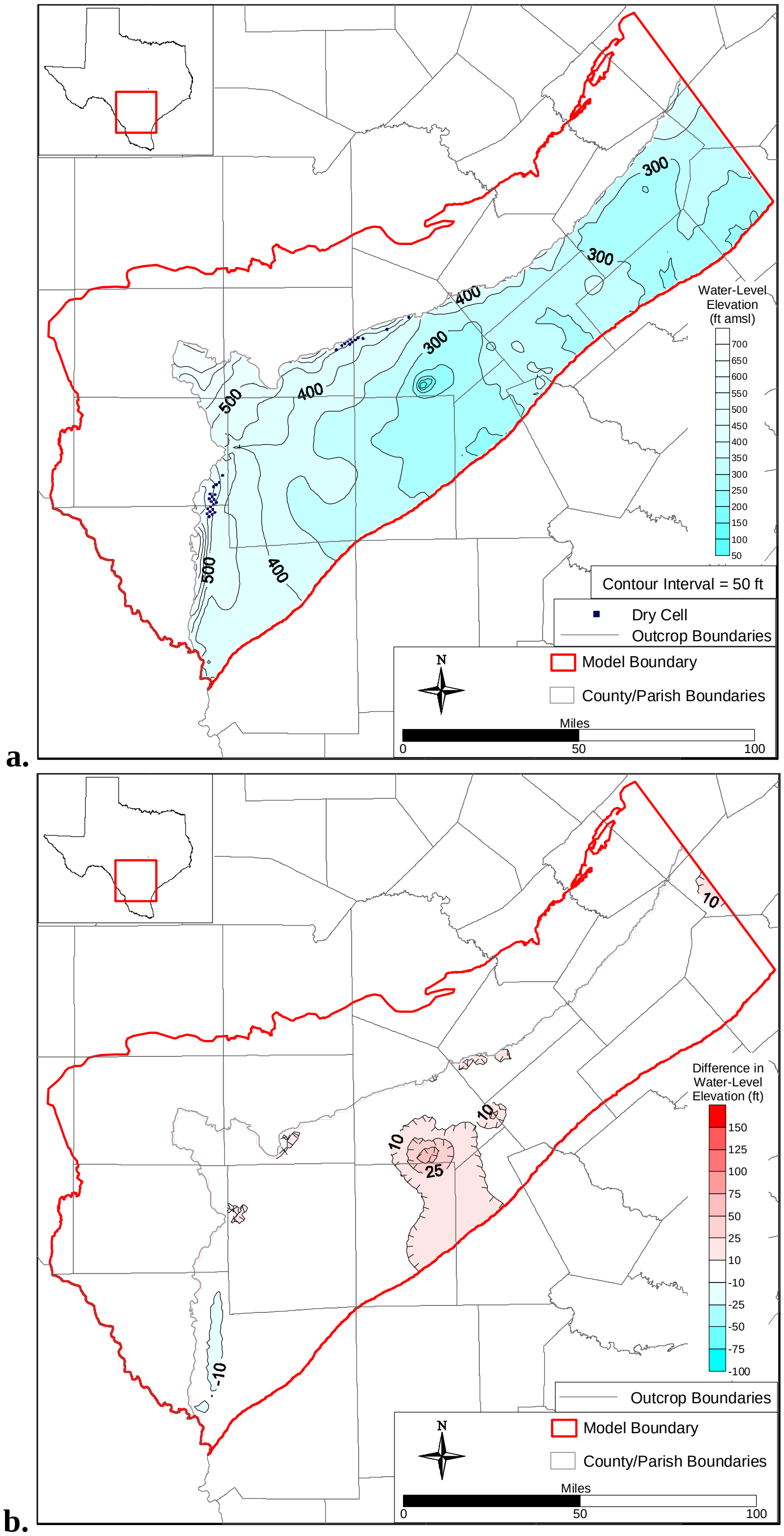


Figure 10.2.3 Simulated 2020 head surface (a) and drawdown from 2000 (b) for the Sparta aquifer (Layer 1).

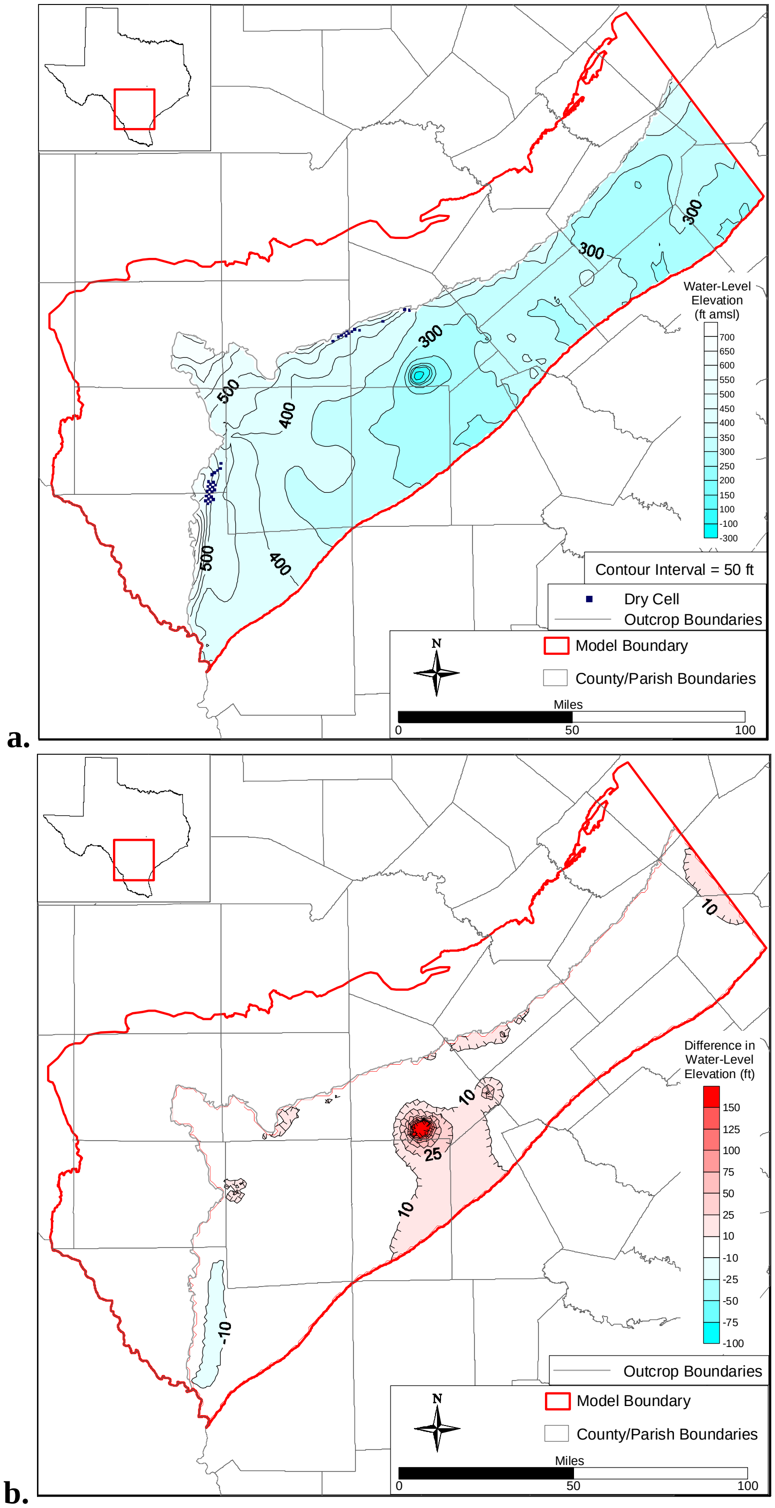


Figure 10.2.4 Simulated 2030 head surface (a) and drawdown from 2000 (b) for the Sparta aquifer (Layer 1).

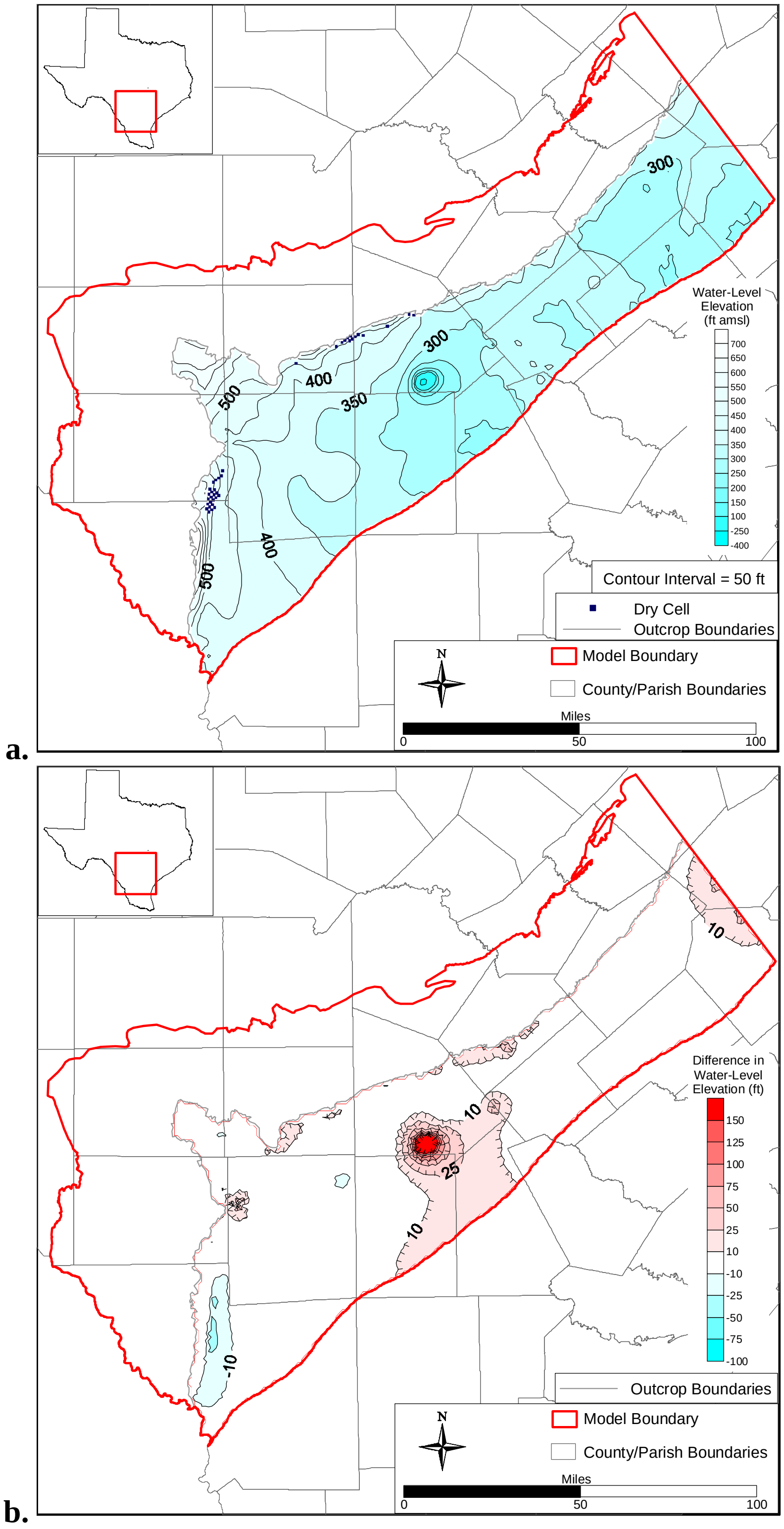


Figure 10.2.5 Simulated 2040 head surface (a) and drawdown from 2000 (b) for the Sparta aquifer (Layer 1).

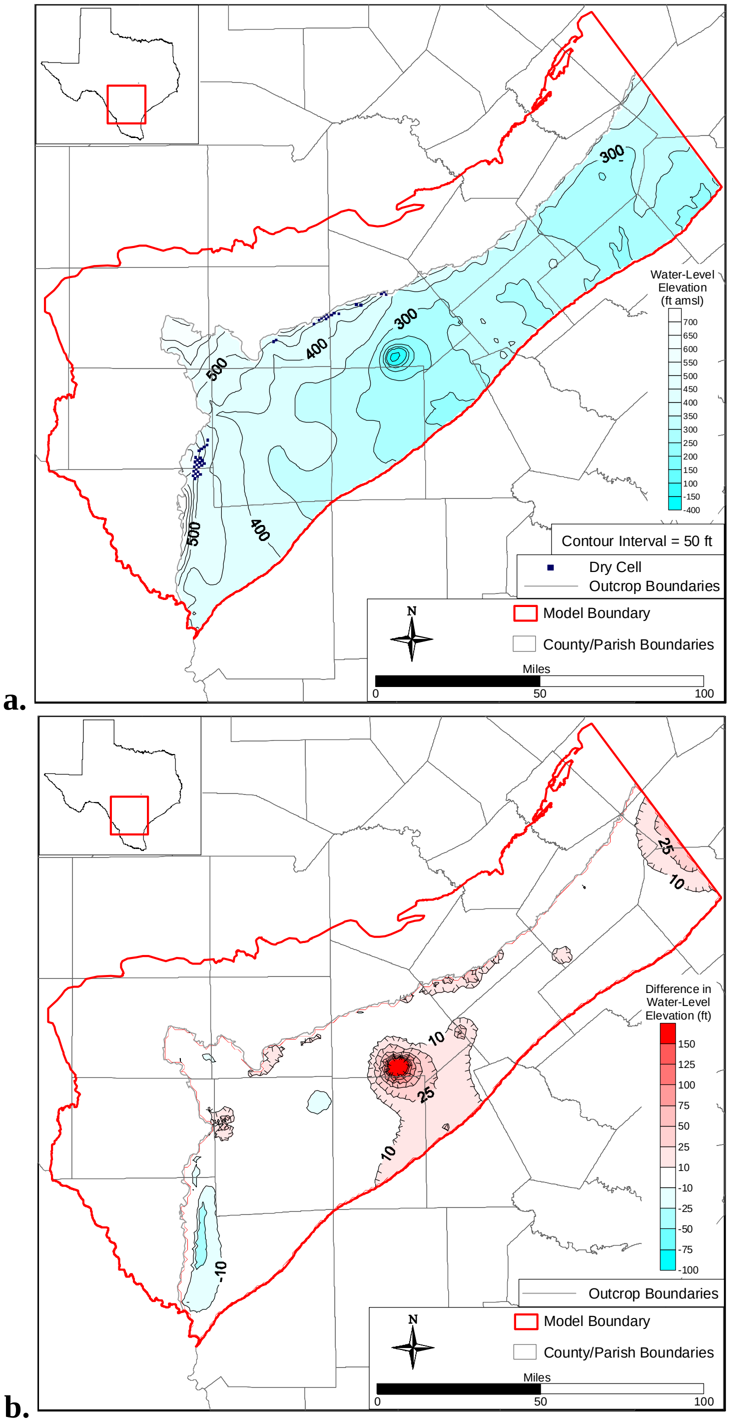


Figure 10.2.6 Simulated 2050 head surface (a) and drawdown from 2000 (b) for the Sparta aquifer (Layer 1).

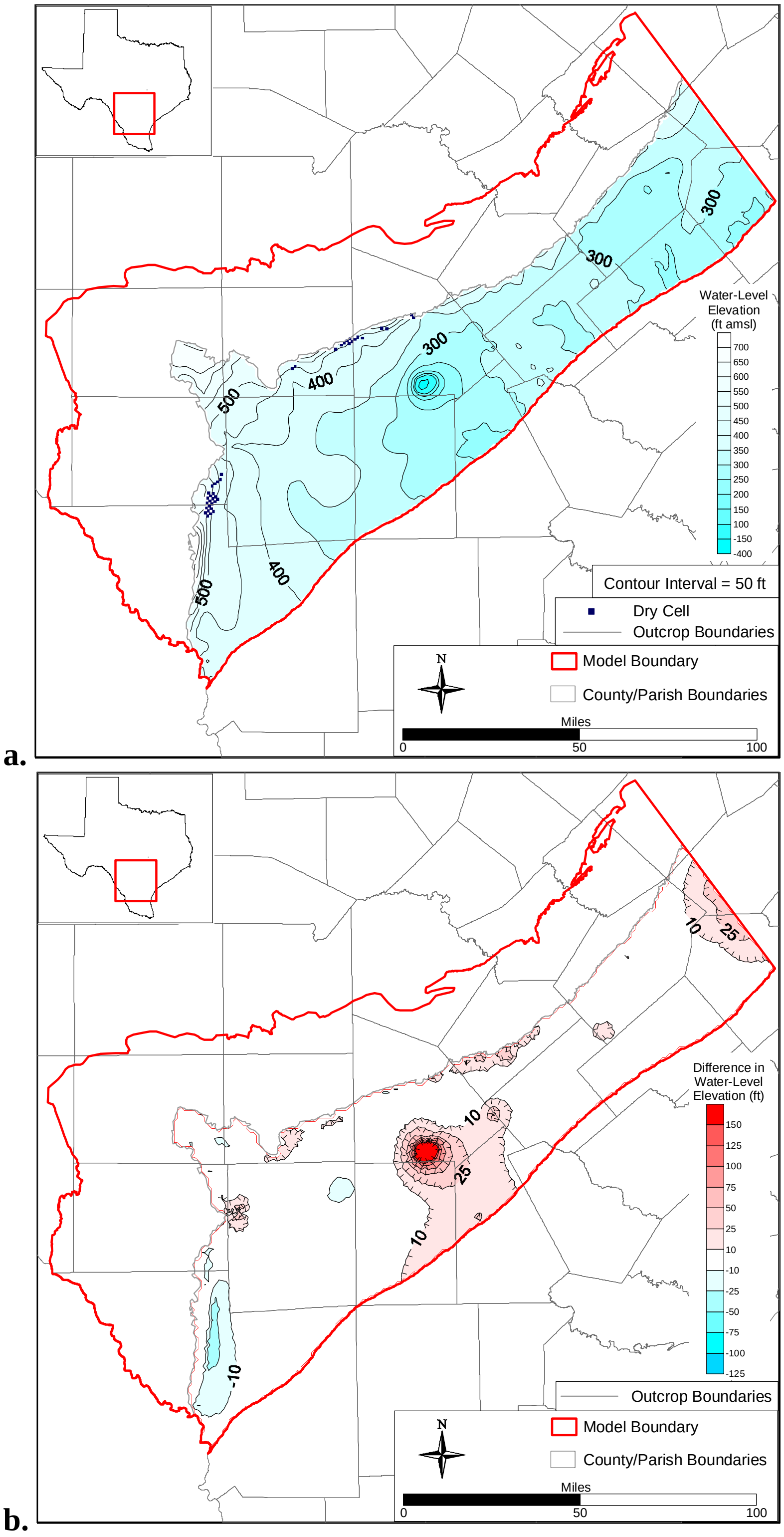


Figure 10.2.7 Simulated 2050 head surface without drought of record (a) and drawdown from 2000 (b) for the Sparta aquifer (Layer 1).

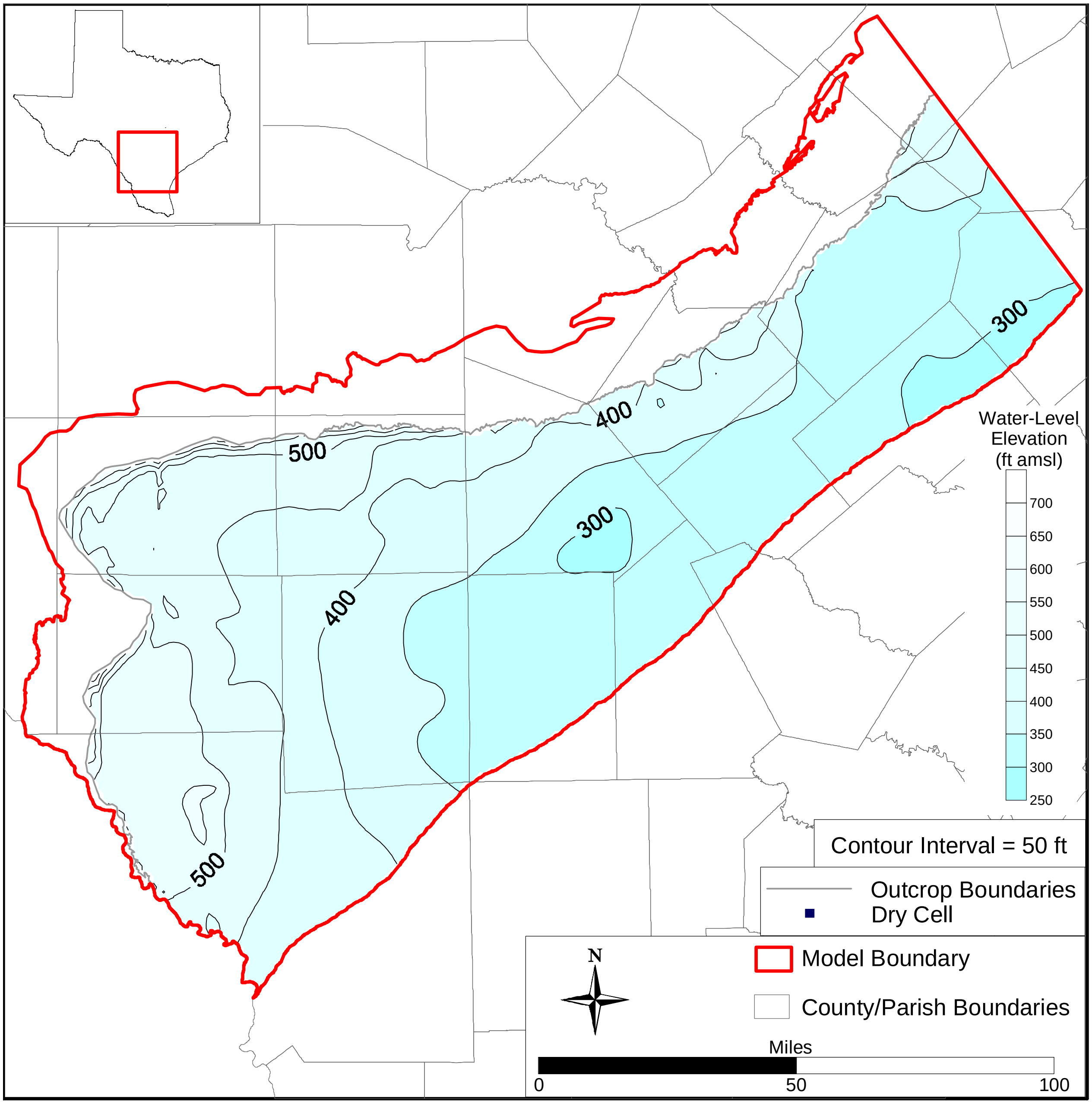


Figure 10.2.8 Simulated 2000 head surface for the Queen City aquifer (Layer 3).

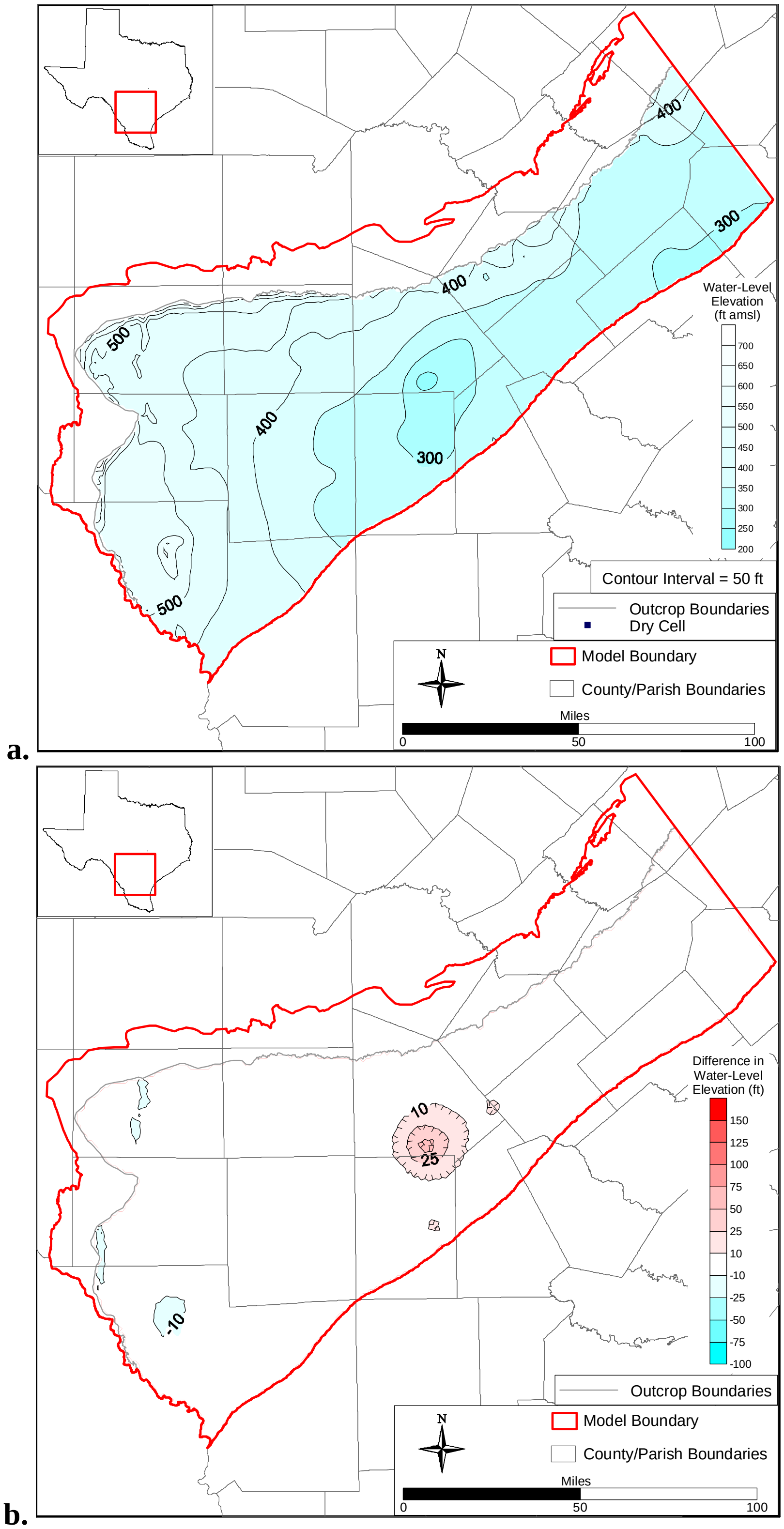


Figure 10.2.9 Simulated 2010 head surface (a) and drawdown from 2000 (b) for the Queen City aquifer (Layer 3).

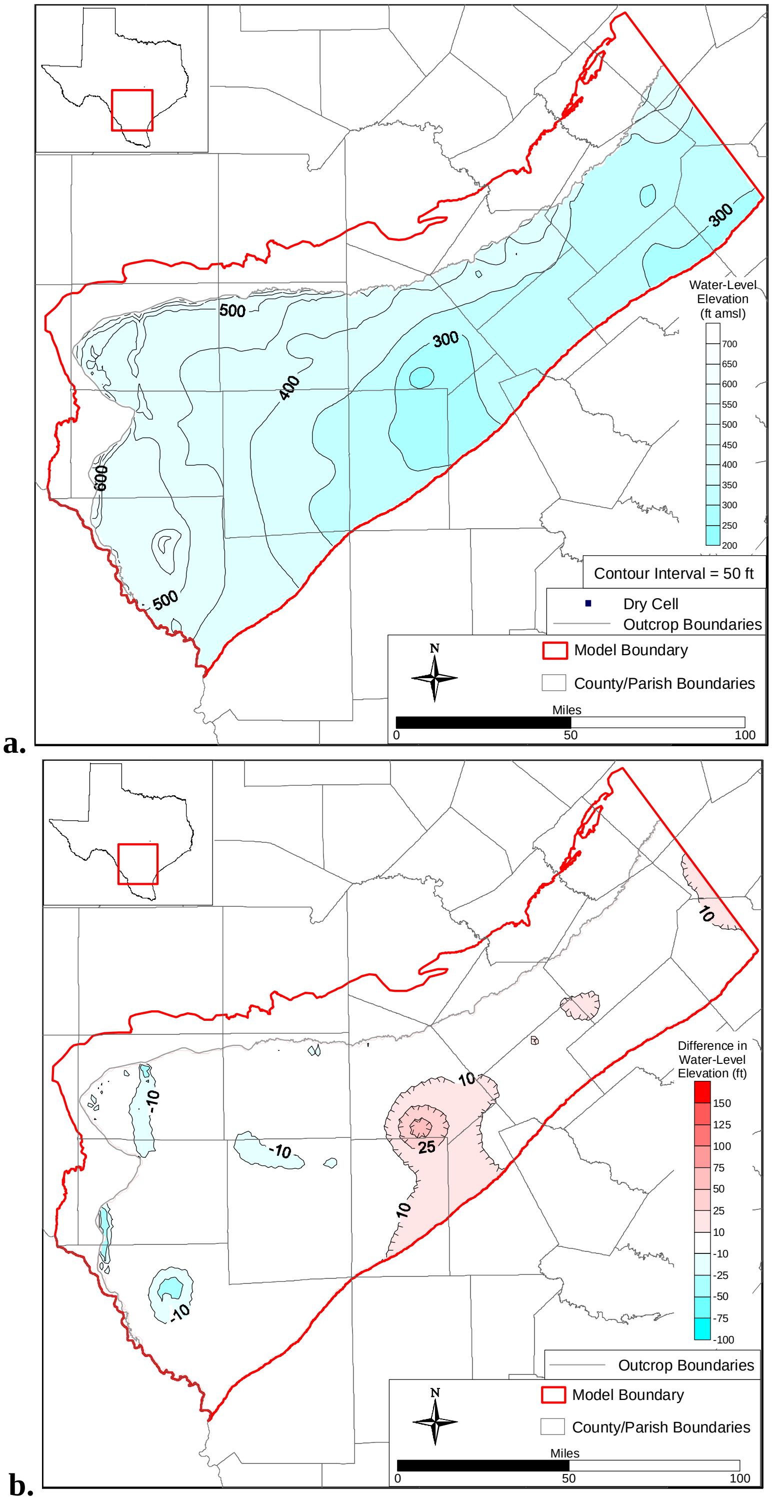


Figure 10.2.10 Simulated 2020 head surface (a) and drawdown from 2000 (b) for the Queen City aquifer (Layer 3).

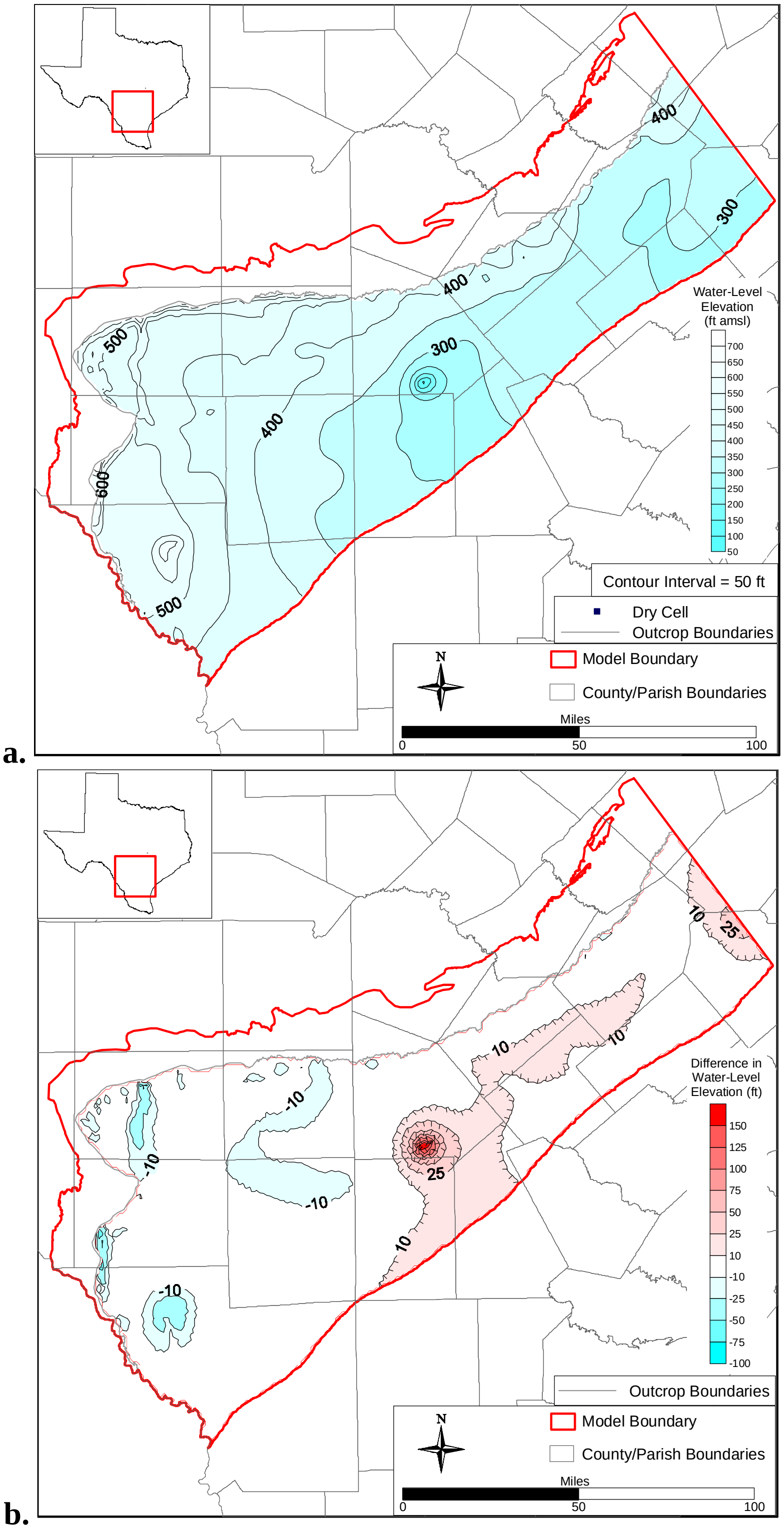


Figure 10.2.11 Simulated 2030 head surface (a) and drawdown from 2000 (b) for the Queen City aquifer (Layer 3).

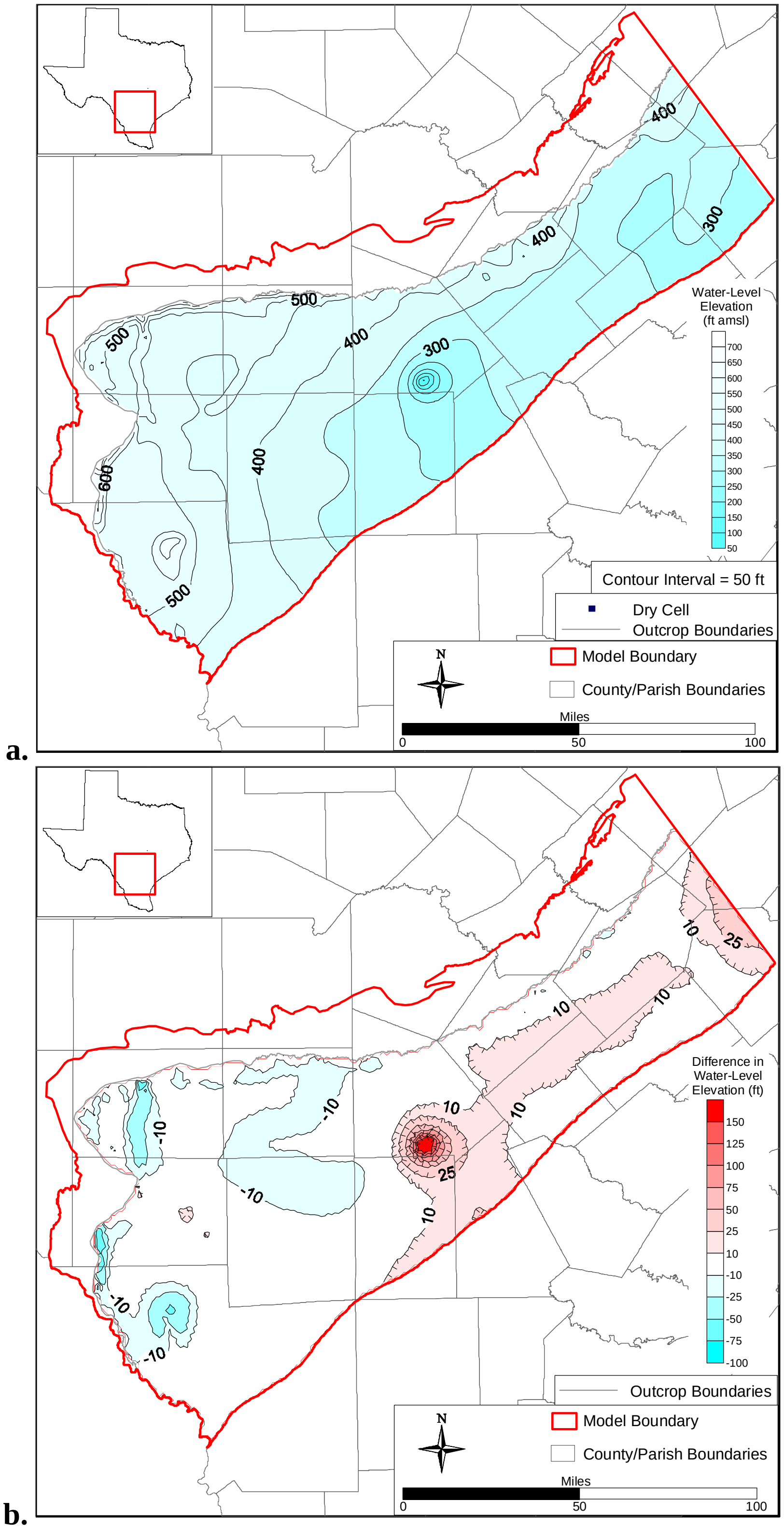


Figure 10.2.12 Simulated 2040 head surface (a) and drawdown from 2000 (b) for the Queen City aquifer (Layer 3).

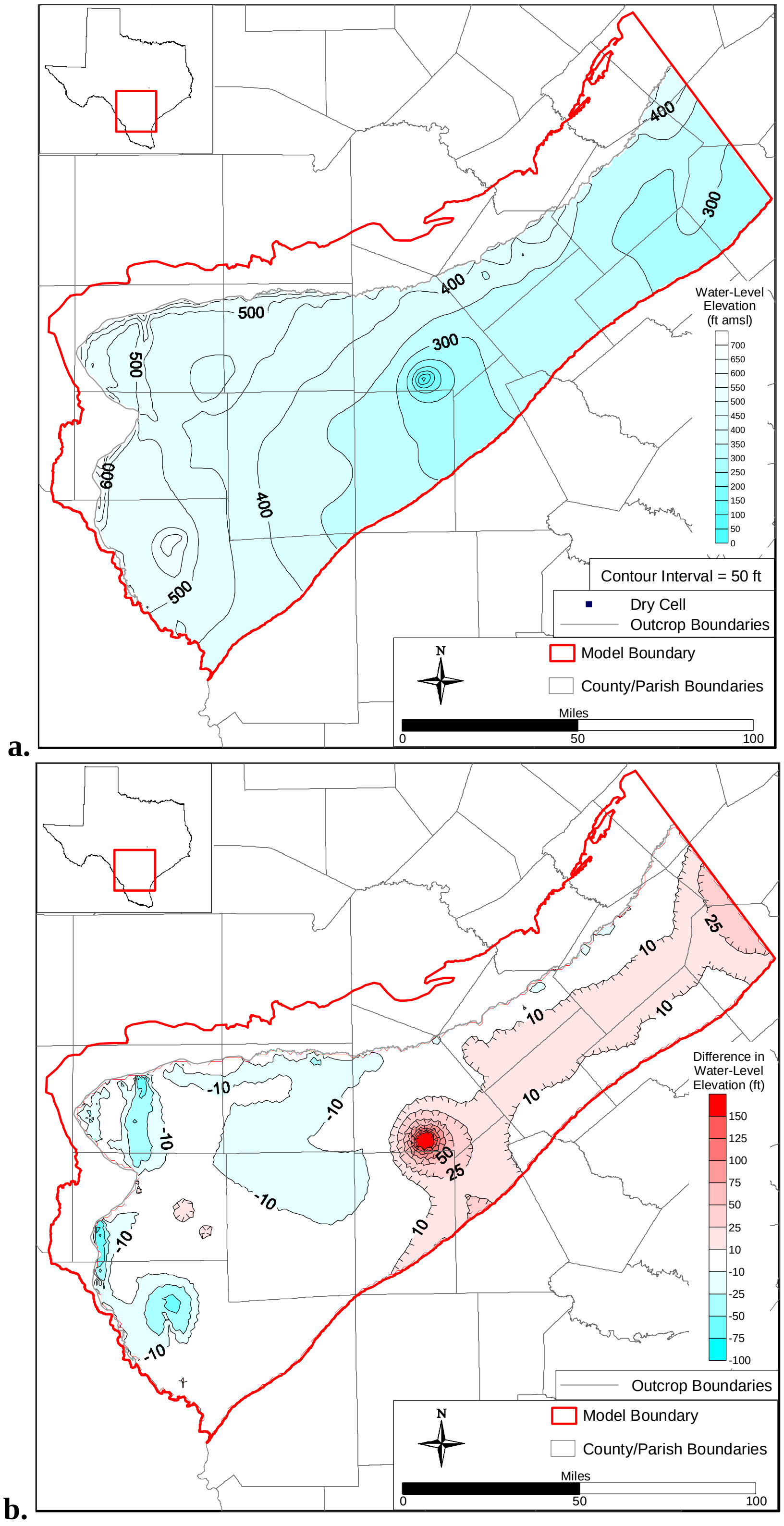


Figure 10.2.13 Simulated 2050 head surface (a) and drawdown from 2000 (b) for the Queen City aquifer (Layer 3).

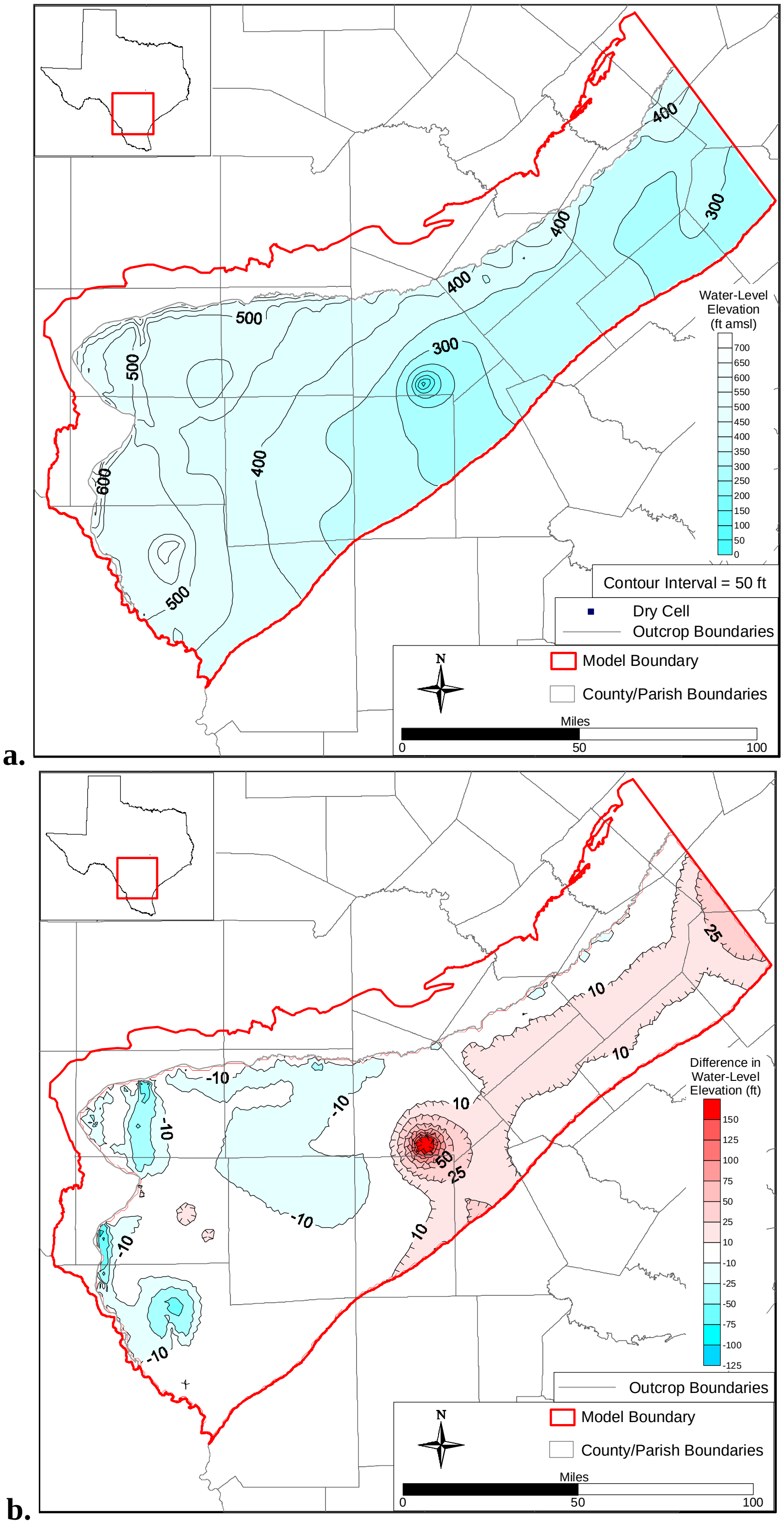


Figure 10.2.14 Simulated 2050 head surface without the drought of record (a) and drawdown from 2000 (b) for the Queen City aquifer (Layer 3).

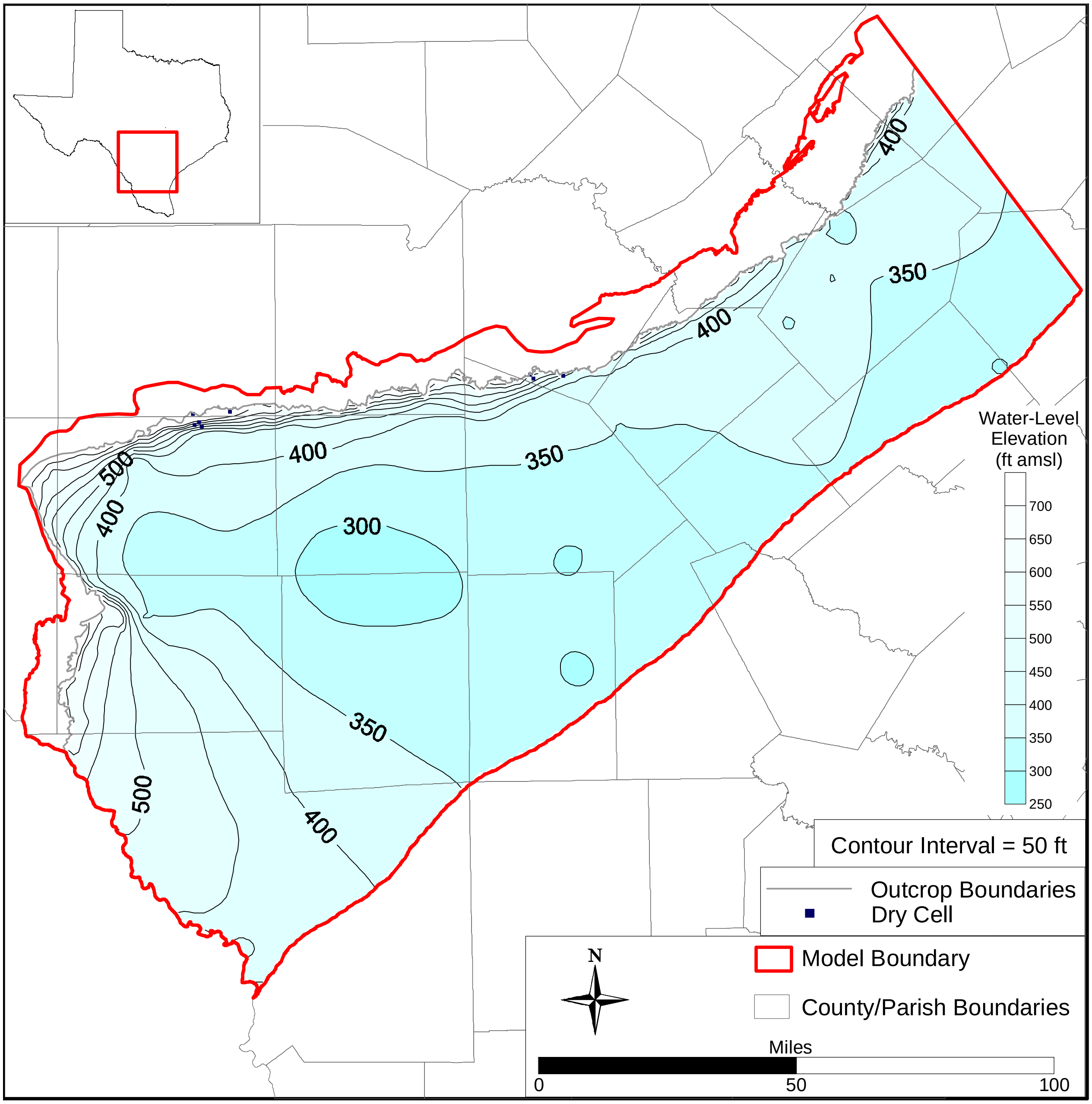


Figure 10.2.15 Simulated 2000 head surface for the Carrizo Formation (Layer 5).

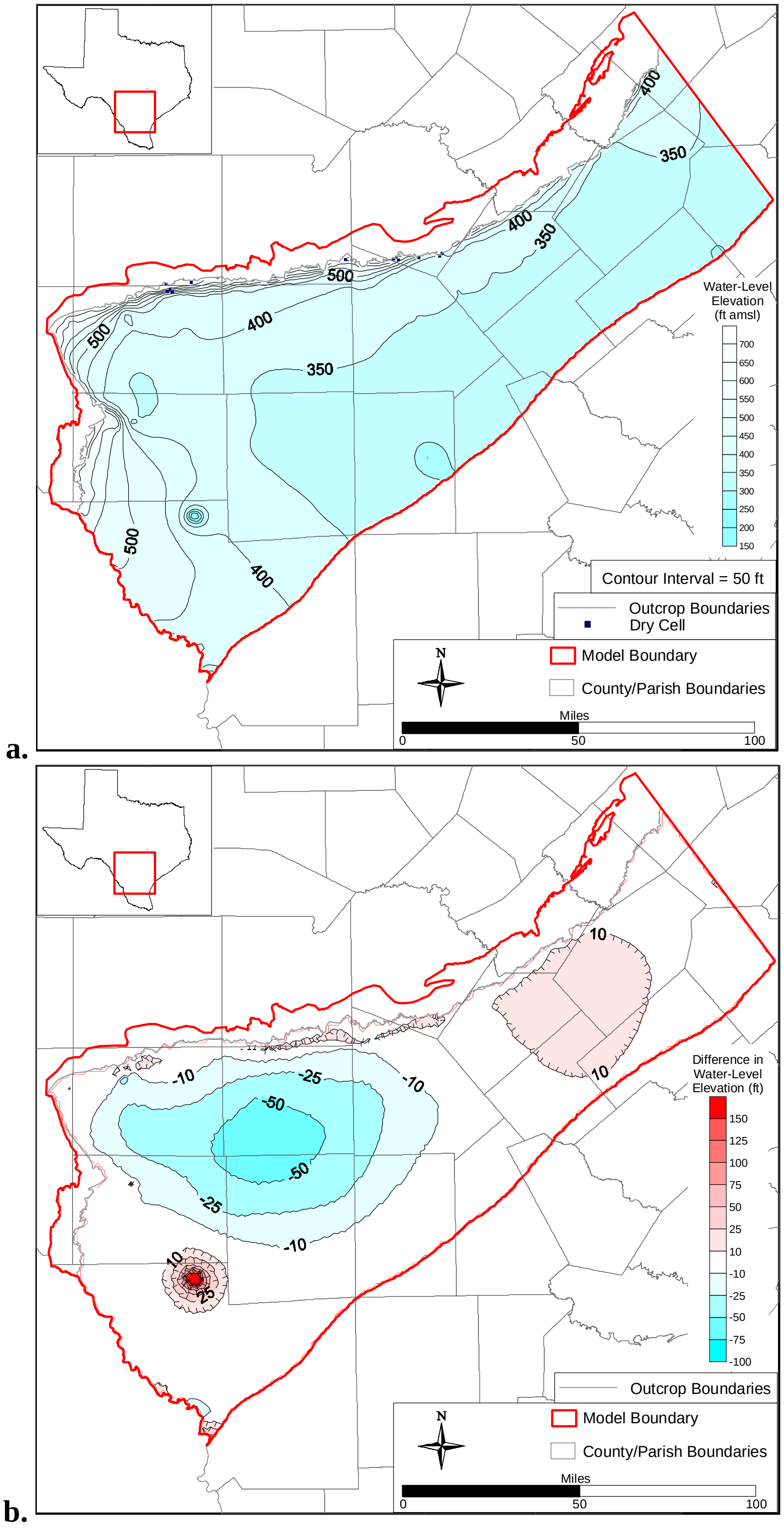


Figure 10.2.16 Simulated 2010 head surface (a) and drawdown from 2000 (b) for the Carrizo Formation (Layer 5).

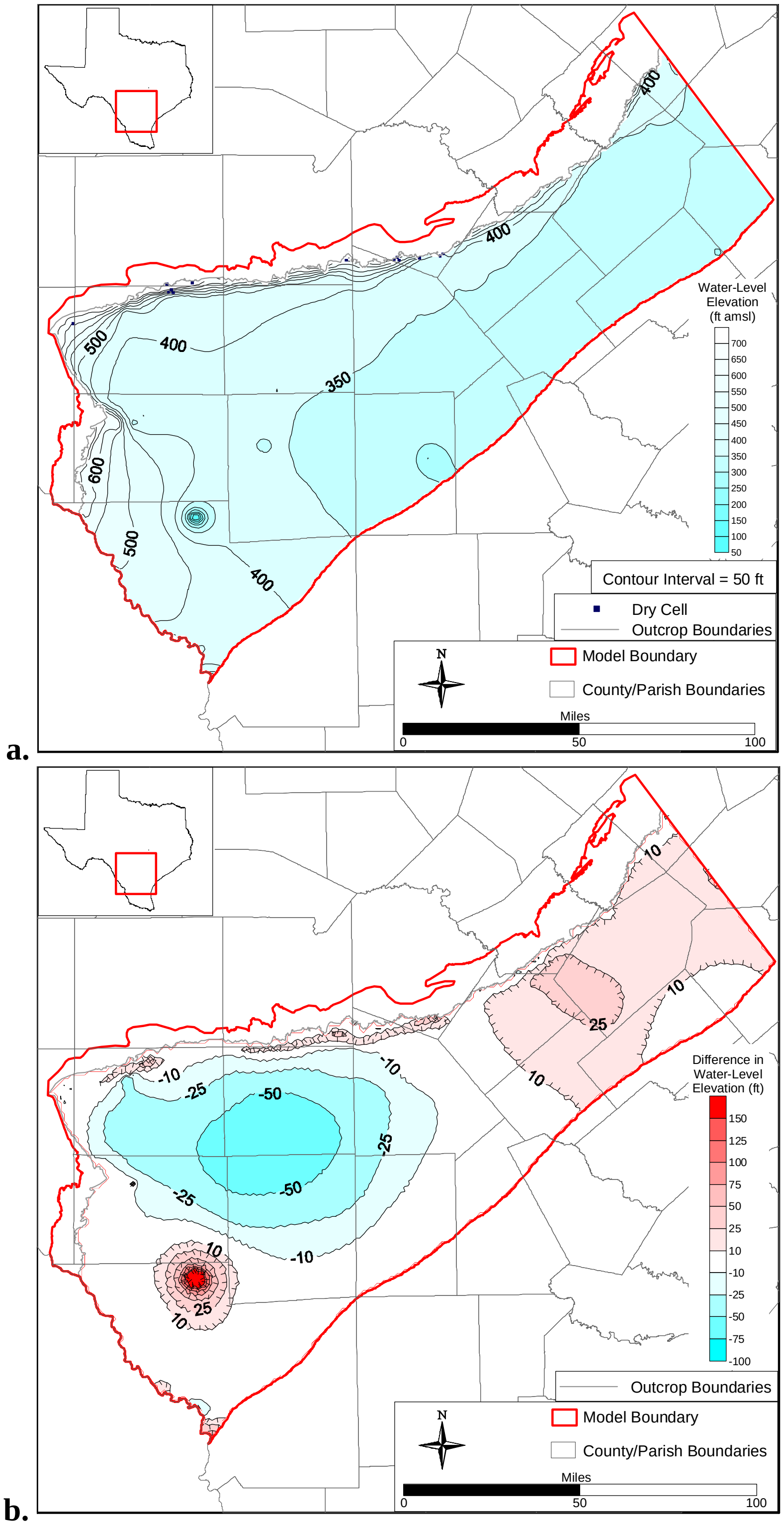


Figure 10.2.17 Simulated 2020 head surface (a) and drawdown from 2000 (b) for the Carrizo Formation (Layer 5).

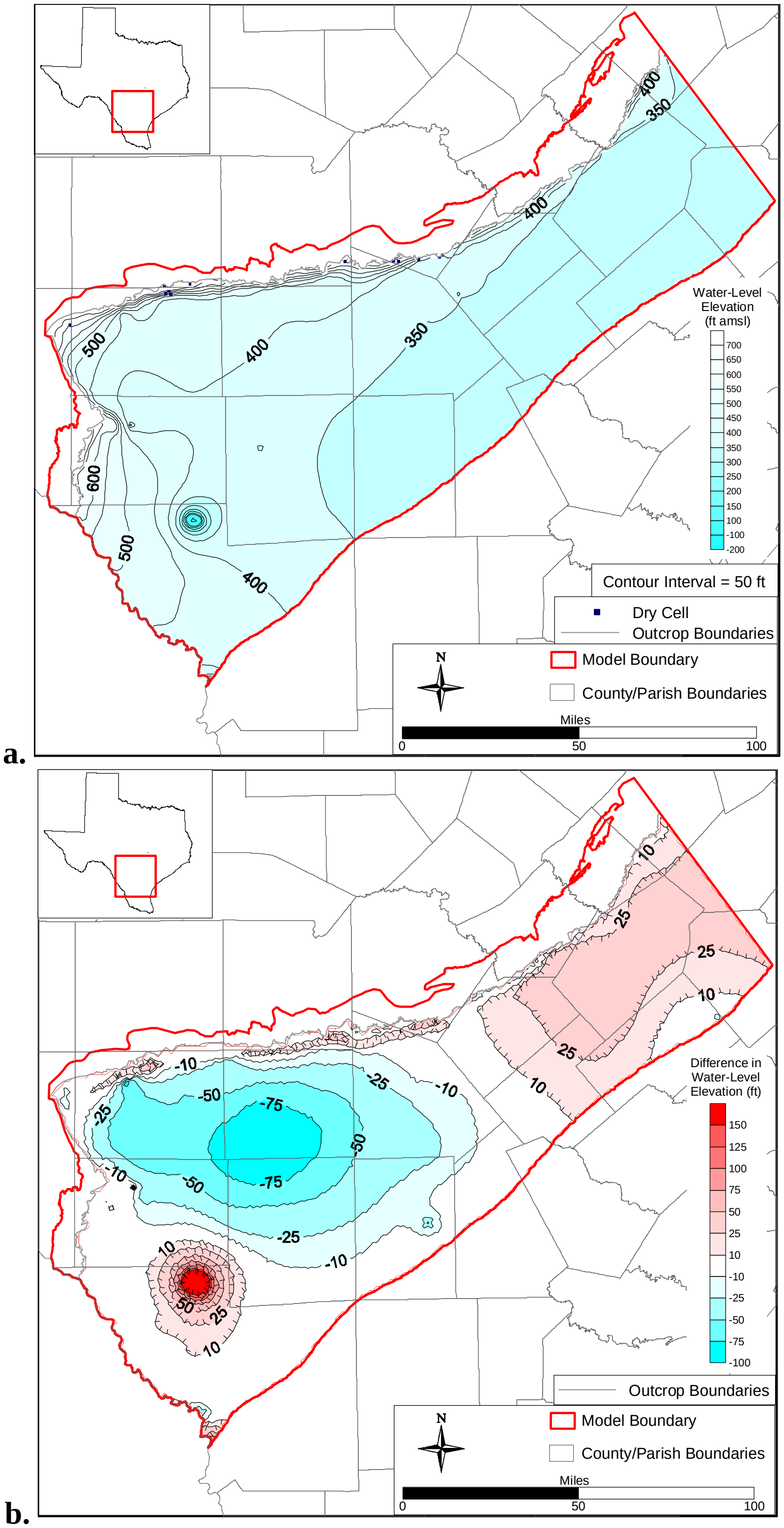


Figure 10.2.18 Simulated 2030 head surface (a) and drawdown from 2000 (b) for the Carrizo Formation (Layer 5).

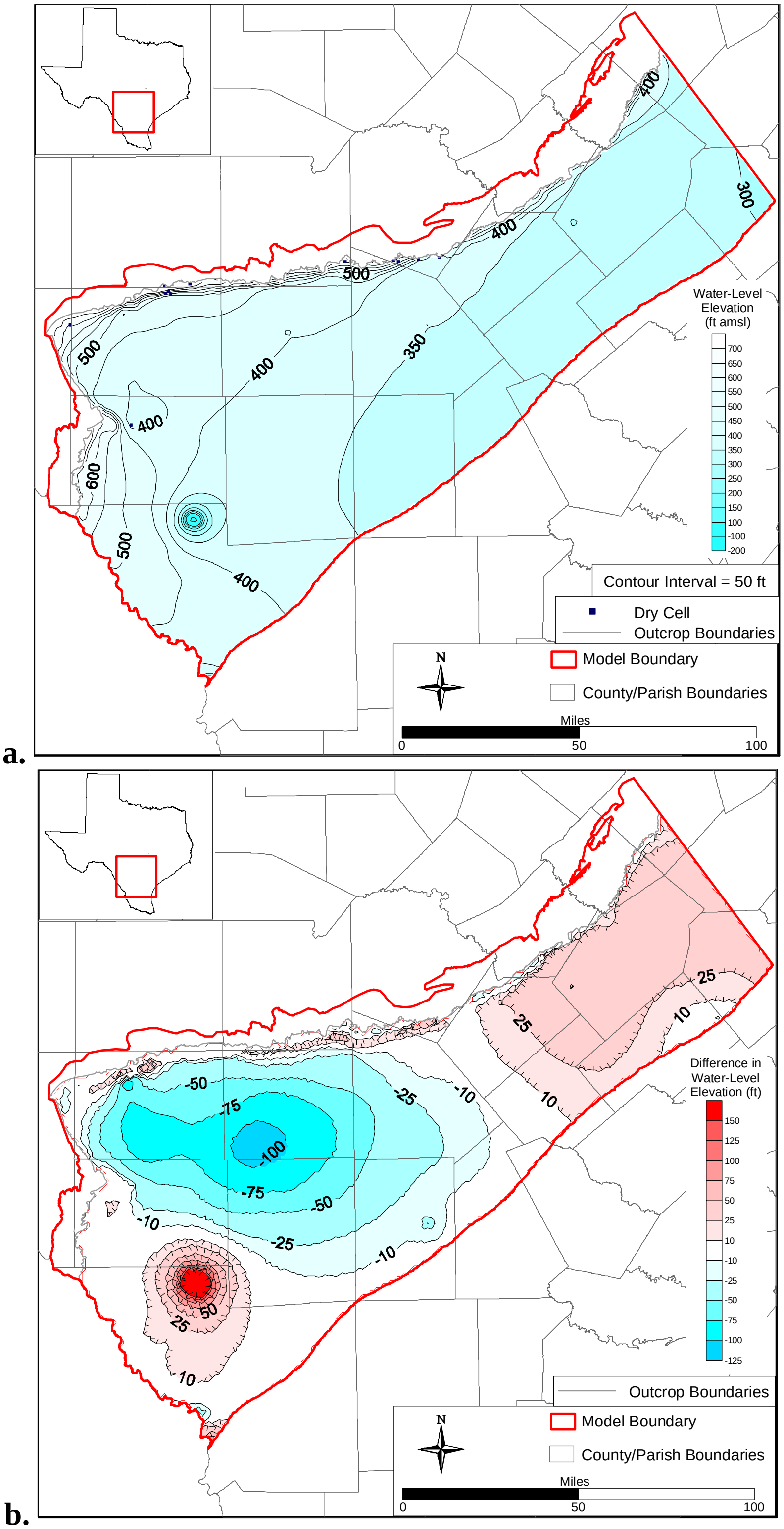


Figure 10.2.19 Simulated 2040 head surface (a) and drawdown from 2000 (b) for the Carrizo Formation (Layer 5).

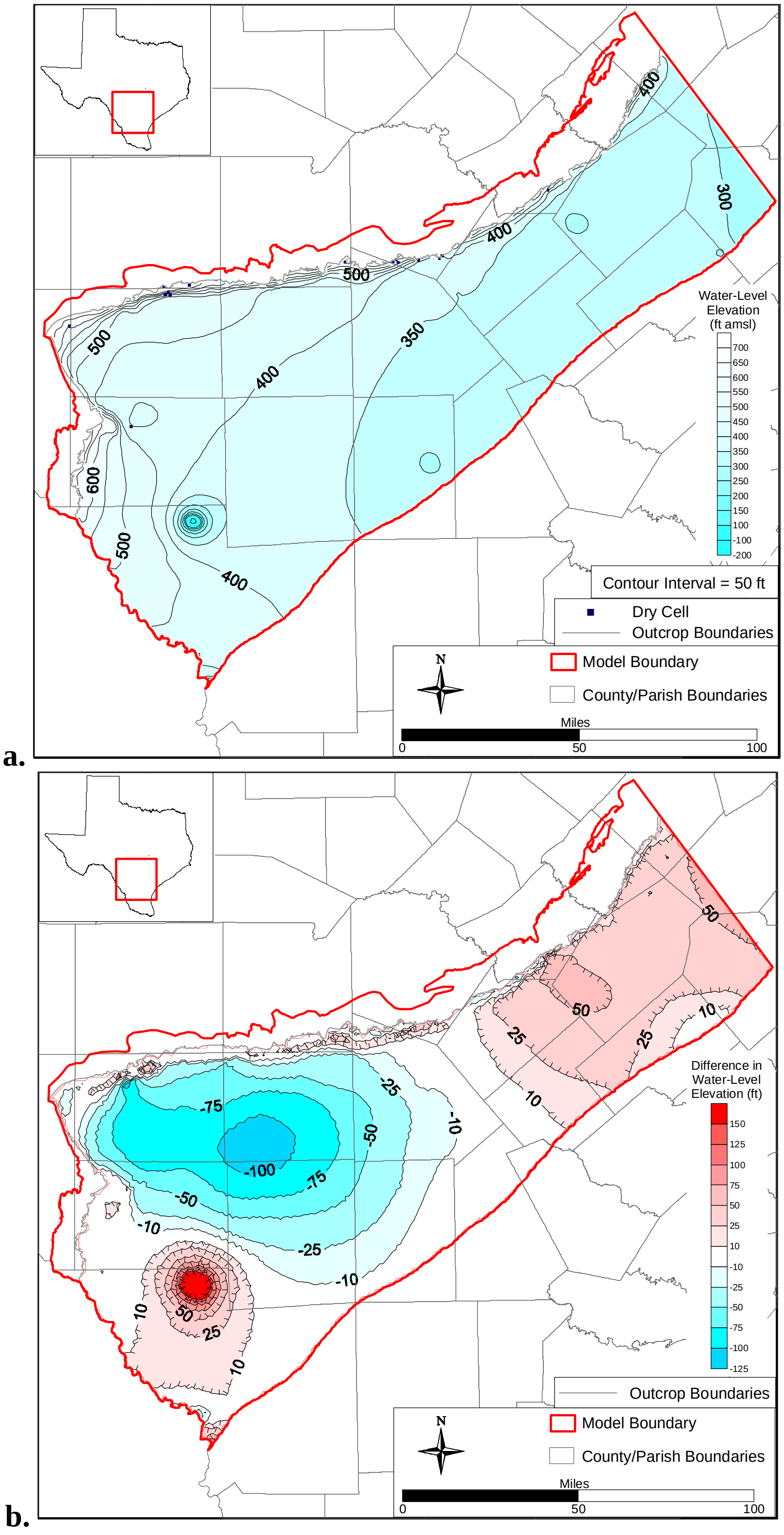


Figure 10.2.20 Simulated 2050 head surface (a) and drawdown from 2000 (b) for the Carrizo Formation (Layer 5).

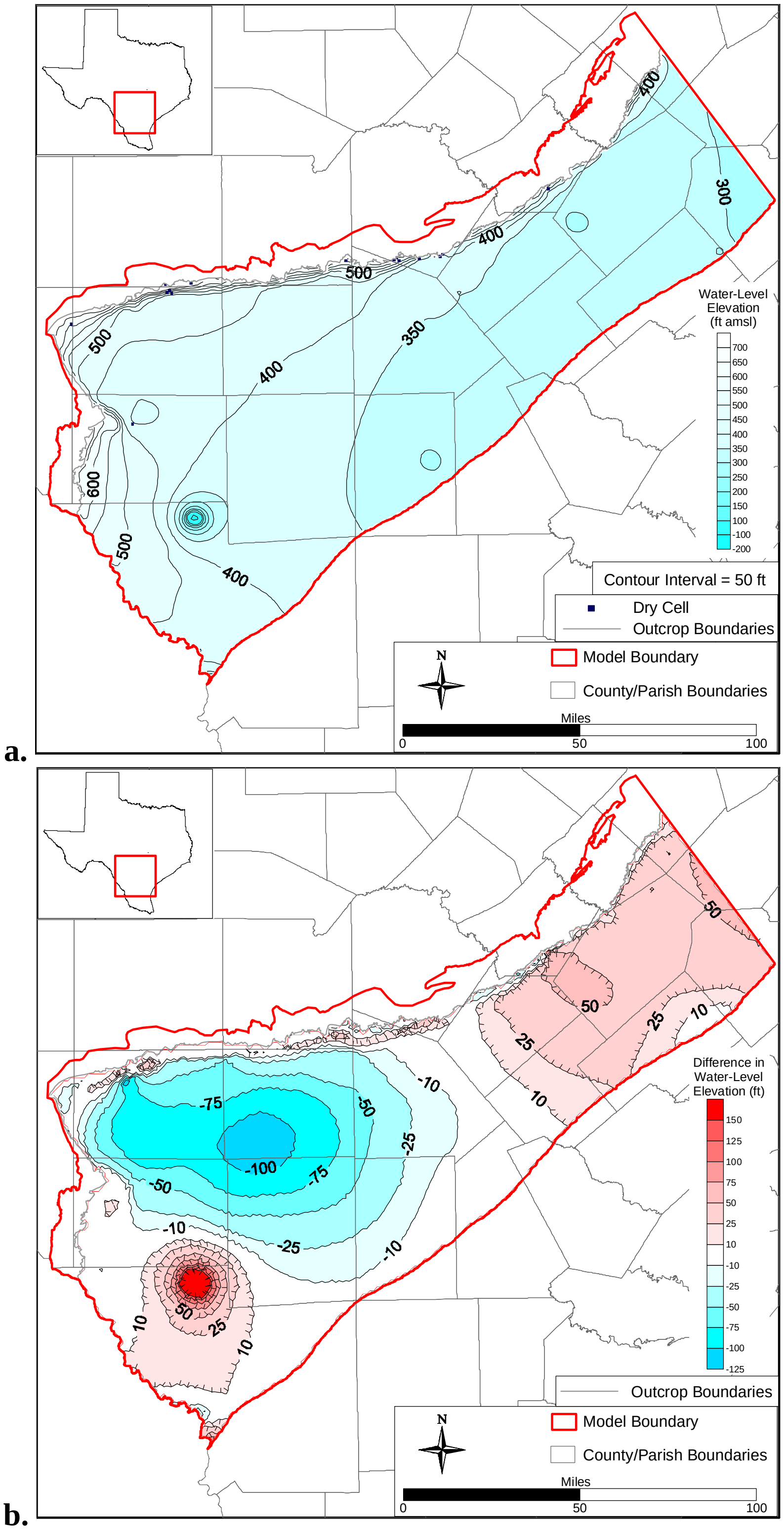


Figure 10.2.21 Simulated 2050 head surface without drought of record (a) and drawdown from 2000 (b) for the Carrizo Formation (Layer 5).

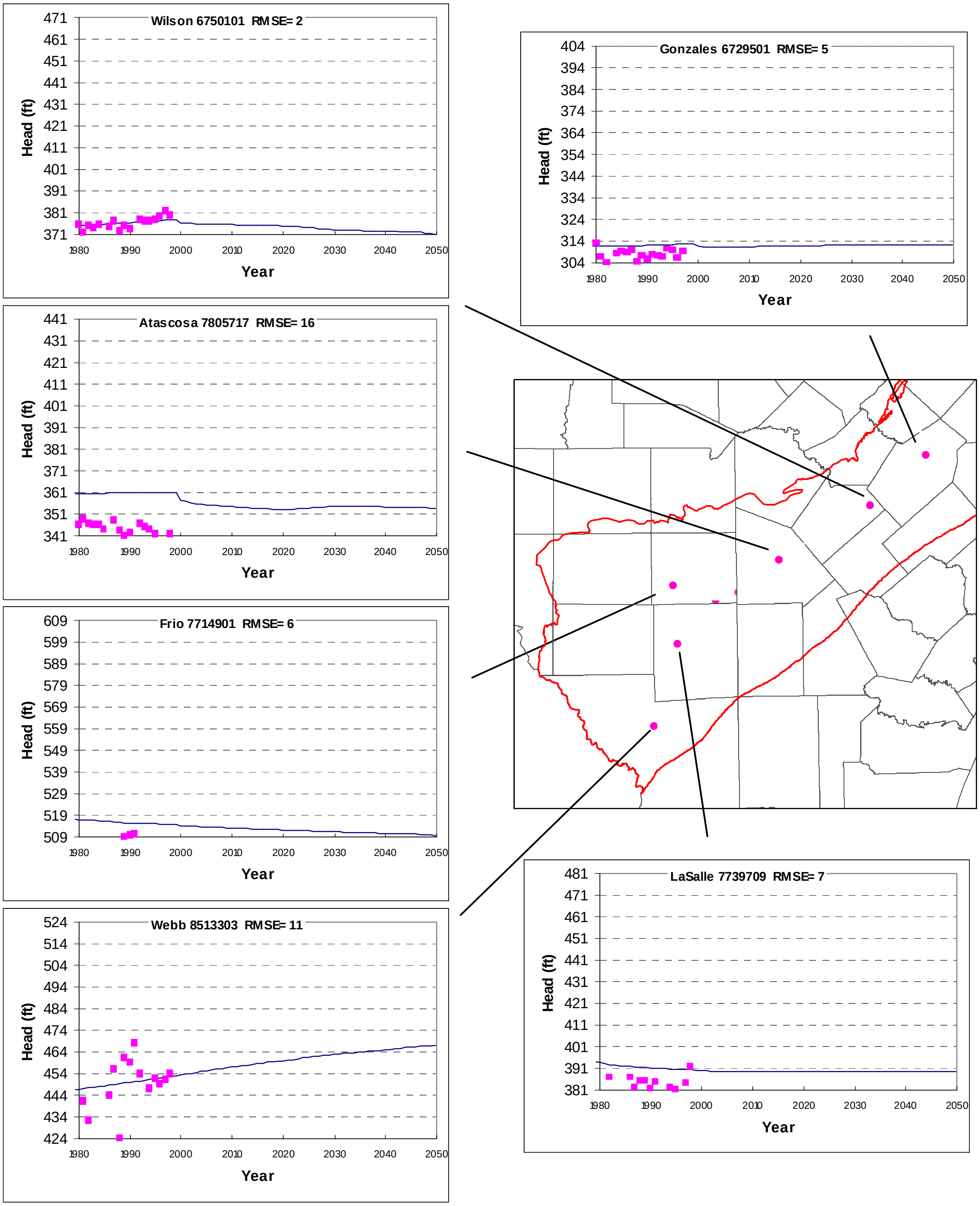


Figure 10.2.22 Selected Sparta aquifer hydrographs from the predictive simulation to 2050 with the DOR.

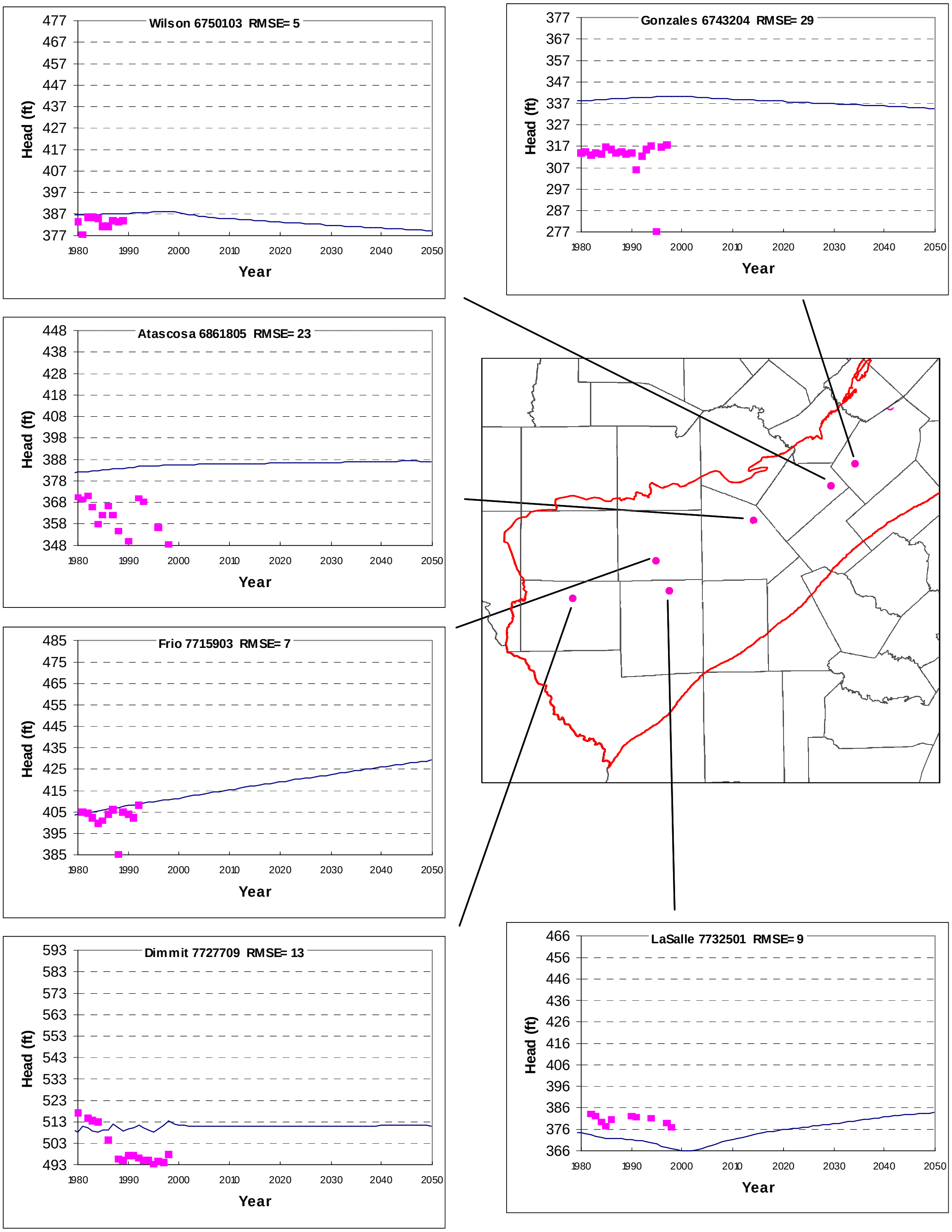


Figure 10.2.23 Selected Queen City aquifer hydrographs from the predictive simulation to 2050 with the DOR.

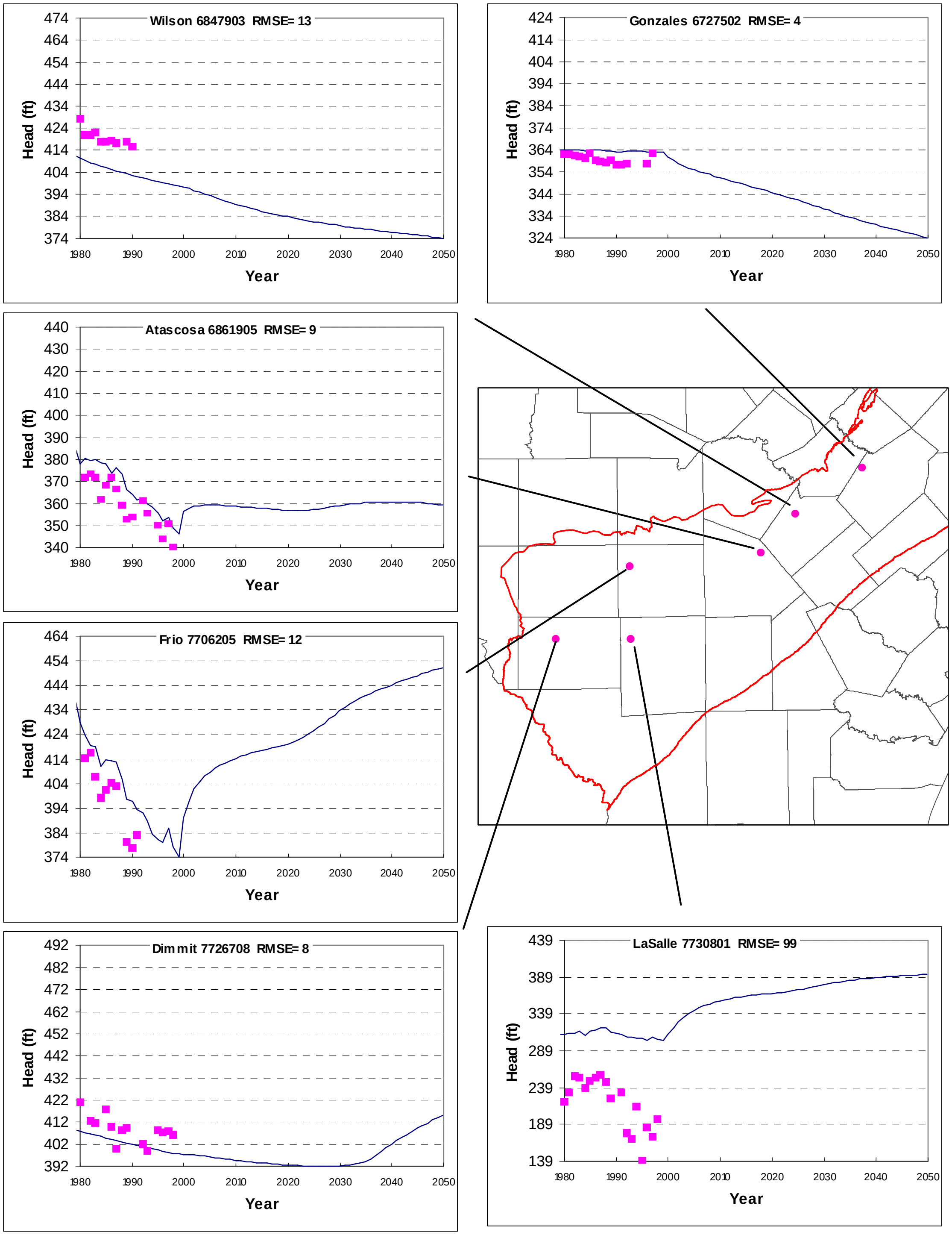


Figure 10.2.24 Selected Carrizo Formation hydrographs from the predictive simulation to 2050 with the DOR.

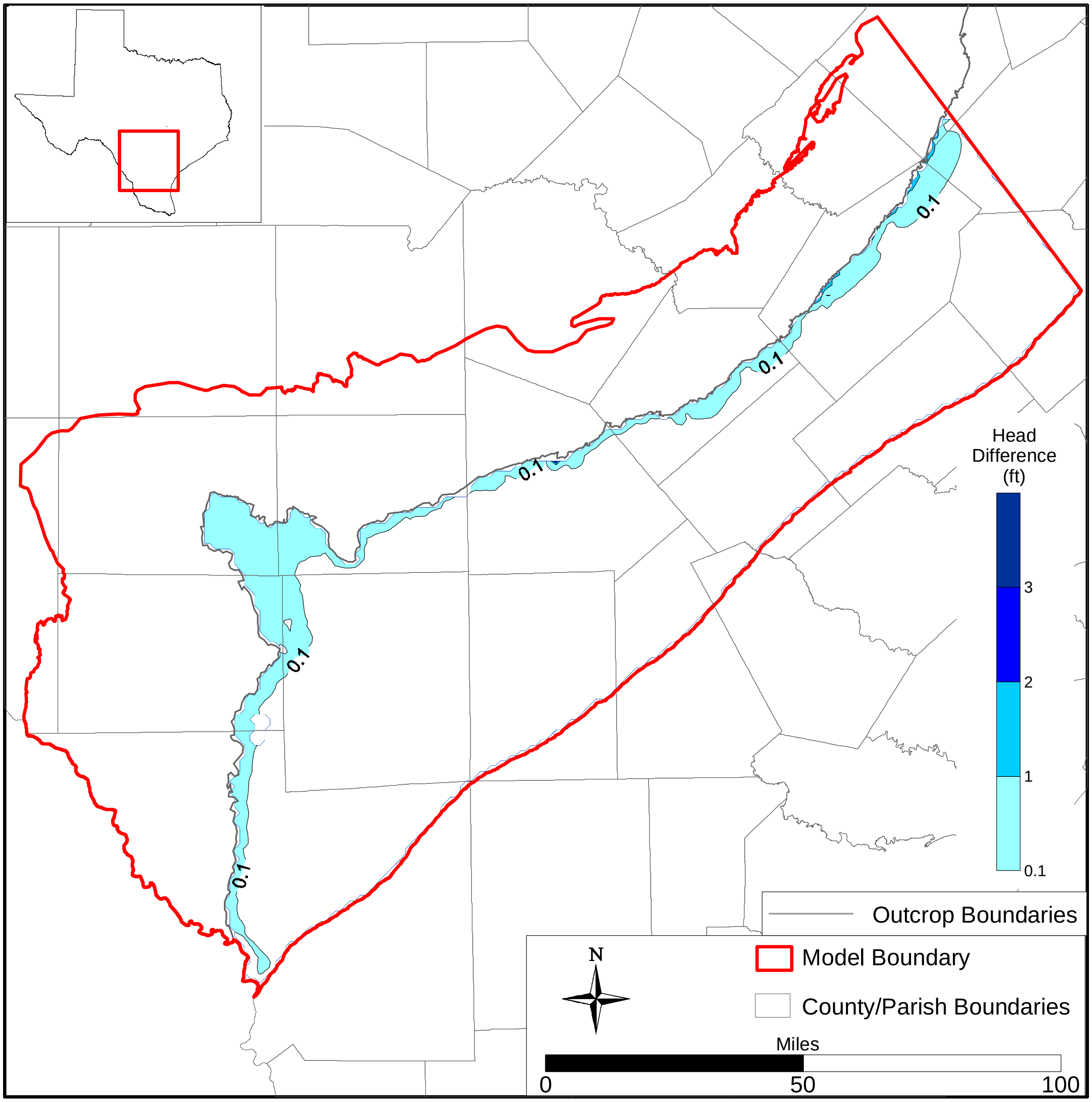


Figure 10.2.25 Simulated difference in head surfaces for the Sparta aquifer between the average condition 2050 simulation and the drought of record 2050 simulation.

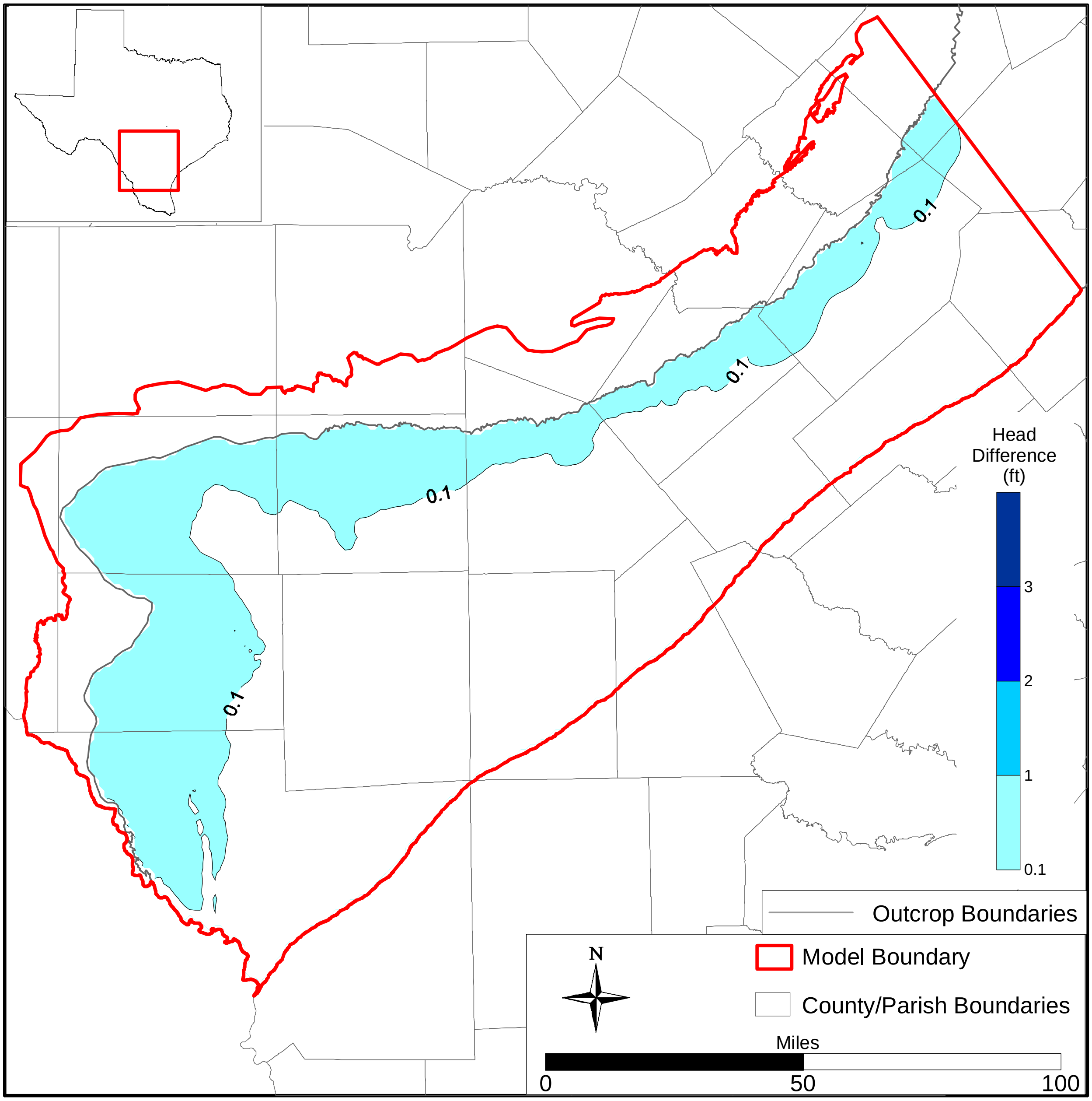


Figure 10.2.26 Simulated difference in head surfaces for the Queen City aquifer between the average condition 2050 simulation and the drought of record 2050 simulation.

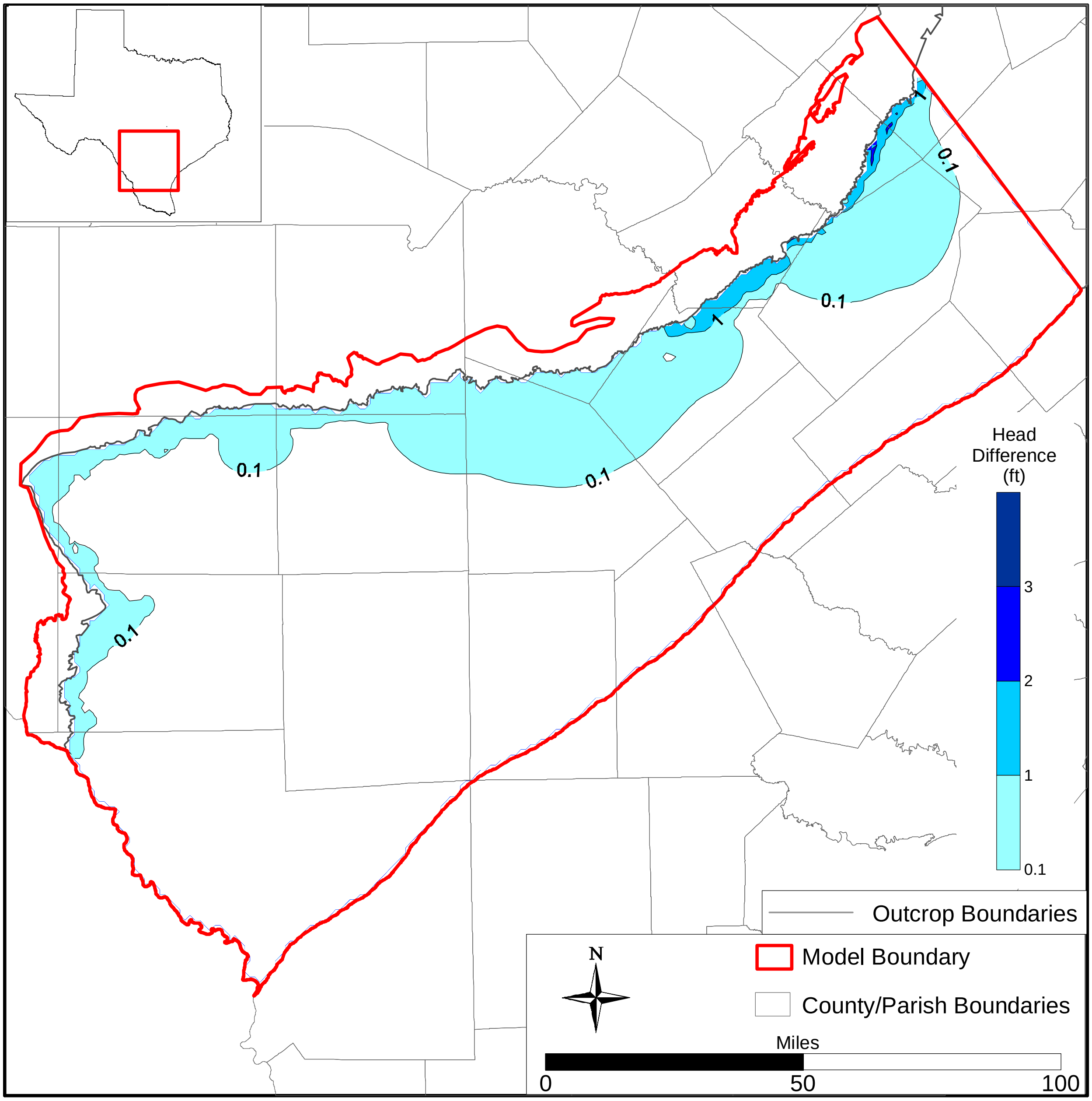


Figure 10.2.27 Simulated difference in head surfaces for the Carrizo Formation between the average condition 2050 simulation and the drought of record 2050 simulation.

10.2.2 Predictive Simulation Water Budget

Table 10.2.1 shows the water budget for the predictive simulations. The table shows the water budget for the final year of each of the predictive simulations. In general, the predictive simulation water budget shows similar trends and variations to that of the calibration/verification simulations, with the exception of pumping. Note that from 1999 to 2000, pumping increases in the Sparta aquifer by about 16,000 acre-ft, increases in the Queen City aquifer by about 6,000 acre-ft, and decreases in the Carrizo Formation by about 112,000 acre-ft. These trends are consistent with what we observed in the predictive drawdown surfaces and hydrographs. Recharge (Table 10.2.1) is essentially equal for the 2010-2050 runs because these runs all end in the same DOR. The difference between recharge in 2050 with average conditions and with DOR is about 140,000 acre-ft. Recall that the drought of record has very little short term effect on heads. However, note that the storage value is negative for the average recharge case, meaning water is going into storage in the model. For the DOR case, the storage value is positive, meaning that water is moving out of storage. This buffering effect of storage in the outcrop allows heads to remain relatively unchanged in the majority of the model despite changing climate conditions.

Table 10.2.1 Water budget for predictive simulations for the Southern model. All rates reported in acre-ft/yr.

Year	Layer	Reserv.	ET	Drains	Rech.	GHBs	Streams	Storage	Wells	Bot. Flow	Top Flow
1999	1	0	-4,018	-845	14,364	-10,181	-71,664	80,185	-3,042	-4,805	0
	2	0	-871	-341	2,121	-41	-16,278	20,695	0	-10,094	4,805
	3	0	-3,897	-62	39,176	-518	-59,051	63,505	-1,676	-47,592	10,094
	4	0	-2,719	-148	4,294	-85	-102,440	110,599	0	-57,097	47,592
	5	0	-29	0	40,061	-4,910	-9,551	144,310	-221,645	-5,339	57,097
	6	0	-4	0	472	303	-824	89	-18,870	13,493	5,339
	7	1,652	-280	-116	14,628	491	-11,656	25,763	-22,594	5,600	-13,493
	8	0	-1,724	-82	13,651	1,091	-1,761	10,661	-16,379	0	-5,600
	Sum	1,652	-13,544	-1,593	128,767	-13,850	-273,224	455,807	-284,206	-105,834	105,834
2000	1	0	-4,132	-818	25,621	-5,007	-9,349	14,381	-18,946	-1,751	0
	2	0	-718	-332	3,765	-33	777	2,348	0	-7,560	1,751
	3	0	-1,883	-55	68,833	-488	37,827	-57,682	-7,512	-46,605	7,560
	4	0	-1,701	-144	6,963	-84	-1,814	-2,585	0	-47,242	46,605
	5	0	-130	0	65,301	-4,852	7,420	14,961	-109,908	-20,035	47,242
	6	0	-69	0	858	234	-112	-9,316	-19,949	8,318	20,035
	7	1,635	-215	-122	23,553	86	-6,172	6,986	-22,348	4,913	-8,318
	8	0	-884	-181	22,780	484	2,451	-4,827	-14,912	0	-4,913
	Sum	1,635	-9,733	-1,652	217,674	-9,658	31,028	-35,734	-193,575	-109,962	109,962
2010	1	0	-3,797	-568	9,946	-199	-2,893	18,805	-18,765	-2,535	0
	2	0	-579	-255	1,260	-21	1,612	3,150	0	-7,705	2,535
	3	0	-1,684	-32	24,543	-470	44,815	-34,079	-7,428	-33,389	7,705
	4	0	-1,702	-103	2,036	-72	5,589	-1,705	0	-37,435	33,389
	5	0	-130	0	22,257	-5,255	11,740	61,176	-115,584	-11,646	37,435
	6	0	-69	0	412	-442	111	1,313	-20,203	7,231	11,646
	7	1,625	-206	-129	7,939	-2,445	-2,774	18,822	-17,548	1,941	-7,231
	8	0	-997	-191	9,779	-1,862	3,317	7,326	-15,437	0	-1,941
	Sum	1,625	-9,164	-1,277	78,172	-10,766	61,517	74,806	-194,966	-83,538	83,538

Table 10.2.1, continued

Year	Layer	Reserv.	ET	Drains	Rech.	GHBs	Streams	Storage	Wells	Bot. Flow	Top Flow
2020	1	0	-3,245	-407	9,946	841	-1,944	16,357	-18,967	-2,582	0
	2	0	-576	-193	1,260	-24	1,600	2,625	0	-7,275	2,582
	3	0	-1,640	-21	24,543	-524	43,464	-32,403	-7,794	-32,904	7,275
	4	0	-1,691	-64	2,036	-100	5,896	148	0	-39,132	32,904
	5	0	-130	0	22,244	-6,552	13,502	60,765	-120,306	-8,657	39,132
	6	0	-69	0	418	-727	37	2,847	-20,464	9,301	8,657
	7	1,614	-202	-131	7,950	-3,156	-2,239	21,273	-18,109	2,301	-9,301
	8	0	-1,028	-191	9,737	-2,653	3,525	8,700	-15,791	0	-2,301
	Sum	1,614	-8,581	-1,007	78,134	-12,896	63,840	80,310	-201,430	-78,948	78,948
2030	1	0	-3,141	-288	9,930	3,066	-1,459	15,371	-21,887	-1,600	0
	2	0	-453	-142	1,276	-31	1,597	2,096	0	-5,948	1,600
	3	0	-1,603	-24	24,543	-587	41,942	-31,645	-8,582	-30,009	5,948
	4	0	-1,680	-34	2,036	-115	6,198	-3,330	0	-33,088	30,009
	5	0	-130	0	22,244	-6,851	15,248	33,012	-87,894	-8,724	33,088
	6	0	-69	0	405	-939	-20	226	-16,481	8,152	8,724
	7	1,599	-197	-136	7,963	-3,845	-1,395	18,507	-15,991	1,640	-8,152
	8	0	-1,108	-185	9,724	-3,766	3,589	6,789	-13,408	0	-1,640
	Sum	1,599	-8,380	-809	78,120	-13,069	65,701	41,026	-164,242	-69,576	69,576
2040	1	0	-3,054	-191	9,930	4,307	-1,209	14,309	-22,926	-1,168	0
	2	0	-423	-110	1,276	-36	1,563	1,713	0	-5,153	1,168
	3	0	-1,621	-23	24,543	-640	40,169	-30,747	-9,010	-27,827	5,153
	4	0	-1,634	-20	2,036	-121	6,425	-2,806	0	-31,712	27,827
	5	0	-126	0	22,244	-6,798	16,537	35,719	-91,292	-7,998	31,712
	6	0	-69	0	405	-1,045	-64	1,248	-17,161	8,688	7,998
	7	1,585	-192	-139	7,963	-4,461	-228	19,696	-17,178	1,640	-8,688
	8	0	-1,102	-181	9,666	-4,251	3,654	7,986	-14,135	0	-1,640
	Sum	1,585	-8,221	-665	78,062	-13,046	66,849	47,118	-171,702	-63,530	63,530

Table 10.2.1, continued

Year	Layer	Reserv.	ET	Drains	Rech.	GHBs	Streams	Storage	Wells	Bot. Flow	Top Flow
2050	1	0	-2,937	-121	9,914	4,936	-985	13,700	-22,911	-1,604	0
	2	0	-415	-83	1,292	-33	1,579	1,457	0	-5,405	1,604
	3	0	-1,626	-25	24,543	-656	38,818	-28,494	-9,071	-28,913	5,405
	4	0	-1,631	-7	2,036	-114	6,622	-2,160	0	-33,661	28,913
	5	0	-124	0	22,229	-6,282	17,660	39,722	-100,285	-6,591	33,661
	6	0	-69	0	405	-1,231	-99	2,837	-17,634	9,199	6,591
	7	1,573	-188	-141	7,957	-5,435	1,027	20,743	-18,128	1,785	-9,199
	8	0	-1,142	-169	9,686	-4,948	3,718	9,296	-14,662	0	-1,785
	Sum	1,573	-8,131	-545	78,062	-13,765	68,341	57,102	-182,691	-65,189	65,189
2050 No DOR	1	0	-2,960	-124	25,527	4,895	-2,073	-307	-22,947	-2,018	0
	2	0	-419	-83	3,858	-34	1,317	-1,125	0	-5,536	2,018
	3	0	-1,674	-27	68,833	-703	36,850	-70,634	-9,071	-29,131	5,536
	4	0	-1,633	-7	6,963	-117	6,054	-6,645	0	-33,749	29,131
	5	0	-124	0	64,879	-6,401	16,222	-728	-100,285	-7,318	33,749
	6	0	-69	0	1,024	-1,232	-161	1,701	-17,634	9,051	7,318
	7	1,549	-194	-154	23,642	-5,447	-703	7,231	-18,160	1,283	-9,051
	8	0	-1,559	-510	22,762	-4,962	2,256	-2,038	-14,672	0	-1,283
	Sum	1,549	-8,633	-906	217,488	-14,000	59,763	-72,547	-182,769	-67,418	67,418

*Does not include DOR.

10.3 Central Queen City and Sparta GAM

In this section, we present the head surfaces from the predictive simulation results and the corresponding drawdown surfaces relative to the modeled 2000 water levels. We also discuss changes in the water budget during the predictive years.

10.3.1 Predictive Simulation Results

There are two primary features that stand out from the head and drawdown predictive maps: the LaGrange well field located in the Sparta and Queen City aquifers in Fayette County and the Lee County well field in the Carrizo-Wilcox aquifer put forward by the Brazos G Regional Water Plan strategy to meet Williamson County water needs. There are secondary features as well, such as the large recovery in the Carrizo-Wilcox aquifer in Angelina/Nacogdoches counties. This is possibly an artifact due to differences in historical and predictive pumping in the TWDB database.

It should be noted that the 2050 DOR simulation for the Central model experienced numerical difficulties using the PGC2 solver. This problem is isolated to the 2050 DOR simulation. The 2050 DOR simulation abnormally terminated a few time steps short of year 2050 in the last stress period using the PGC2 solver. The simulation does converge using the SIP solver, albeit with a much longer run time. Results for the 2050 DOR presented in this section were obtained with the SIP solver. Despite numerous attempts to fix the problem, it was realized that, apparently, nothing short of substituting the average recharge in place of any one or two of the drought years will let the simulation to completion. Another way to improve the simulation, although not to full completion, is to introduce a cut-off value for recharge in individual cells, replacing those low recharge values with the cut-off value. Some combinations of low or no recharge cells are thought to be the source of the problem for the PGC2 solver.

Figure 10.3.1 shows the simulated head surface in the Sparta aquifer in 2000, for comparison to later simulations. Figure 10.3.2 shows a drawdown of 60 ft in Fayette County after a few years of pumping in the LaGrange well field in 2010. In 2020 (Figure 10.3.3), the drawdown has reached a maximum of approximately 90 ft in the well field and a second cone of depression has appeared north of the Fayette/Lee county line. It is due to localized industrial pumping. The two cones of depression have clearly merged in 2030 with a maximum drawdown of about 120 ft (Figure 10.3.4). A localized recovery feature also appears in Bastrop County. The same trend continues (Figures 10.3.5 and 10.3.6) on to 2050 where the maximum drawdown in the LaGrange well field is approximately 170 ft. The maximum recovery in 2050 in Bastrop County is approximately 60 ft. There are only small differences between the DOR and average recharge 2050 result (Figure 10.3.7). As it has been commented on in previous instances, recharge variations have initially little impact on downdip heads and drawdowns.

Figure 10.3.8 shows the simulated head surface for the Queen City aquifer in 2000. The head and drawdown maps in the Queen City aquifer tell a similar story to those in the Sparta aquifer, although there is a more extended cone of depression almost reaching the outcrop area. Figure 10.3.9 shows the beginning of the LaGrange well field drawdown (65 ft maximum in 2010) as well as a regional water level drop in Lee County likely due to cross-formational flow because of the large pumping in the underlying Carrizo-Wilcox aquifer. The same trend continues in 2020 (Figure 10.3.10) and 2030 (Figure 10.3.11) where the maximum drawdown in the LaGrange well field is approximately 95 ft and 120 ft, respectively. In 2040 (Figure 10.3.12), the drawdown, as computed from simulated 2000 water level, has reached 150 ft. Small localized recovery centers are also appearing, particularly in the northern half of the central model with a maximum of 30 ft in Leon County. In 2050 (Figure 10.3.13), the drawdown has reached a maximum of 175 ft in the LaGrange well field, supplemented by other local water withdrawal, and a maximum of approximately 70 ft over the footprint of the Carrizo-Wilcox aquifer Lee County well field. Secondary cones of depression are also starting to be visible in Leon, Anderson, and Cherokee counties. Figure 10.3.14 shows the 2050 simulated heads in the Queen City aquifer for average recharge conditions. There is very little difference between the two cases.

Figure 10.3.15 shows the simulated head surface in the Carrizo Formation in 2000. In 2010, the Lee County well field drawdown is approximately 200 ft (Figure 10.3.16). The spread of the area of drawdown is affected by the Karnes-Milano-Mexia fault zone which limits drawdown in the outcrop area. The western side of the Tyler well field cone of depression in Smith County is also apparent at the northern boundary of the Central model. This feature is entirely driven by the GHB heads imported from the Northern model since pumping in the model is not sufficient to generate such a cone of depression in the Central model at that location. The

Carrizo-Wilcox model (Dutton et al., 2003) also did not capture that feature, since the predictive GHB heads were kept at their 2000 level. The other striking feature is the recovery in the Lufkin well field area (a maximum of 80 ft) and in minor centers in Cherokee County. Figure 10.3.17 shows the year 2020 results for the Carrizo Formation, and contains an accentuation of the same features. In addition, the Schertz-Seguin well field in Gonzales County produces a drawdown of approximately 30 ft. The cone of depression also extends towards Brazos County where the Bryan-College Station well field is located. In 2030 (Figure 10.3.18), the cones of depression have merged. The maximum drawdown is about 300 ft in the Lee County well field, which is similar to Dutton et al. (2003). The Lee County well field has also merged with a secondary pumping center in Madison County. The same trend continues in 2040 (Figure 10.3.19) and 2050 (Figures 10.3.20 and 10.3.21). In 2050, the maximum drawdown is 340 ft in the Lee County well field, 60 ft in the Schertz-Seguin well field, 40 ft in Madison County, and 150 ft in Smith County. Pumping has also resumed in the Angelina/Nacogdoches area, decreasing the amount of recovery. In 2050, the impact of the fault zone is more clearly expressed on the Lee County well field, forcing the cone of depression into an elongated shape parallel to the fault direction (and outcrop).

Selected hydrographs, chosen from among the 10 already presented in the transient model (Section 9.2), exhibit the same features already observed from the head and drawdown maps. Figure 10.3.22 shows hydrographs from the Sparta aquifer. They show water level decline in the vicinity of the LaGrange well field and recovery in the northern part of the model. The same observations hold true for the Queen City aquifer (Figure 10.3.23). Figure 10.3.24 shows the dramatic effect of new pumping in the Carrizo-Wilcox aquifer as well as recovery in Angelina County.

The number of dry cells increased slightly in the predictive simulation from 173 dry cells in 1999 to 177 and 178 dry cells in 2050, in average and drought conditions, respectively. Of those dry cells in 2050, 35 and 34 were in the Queen City and Sparta layers, respectively. Those numbers are to be compared to the 35 and 28 cells for the Sparta and Queen City aquifers, respectively, that were dry at the end of the verification period. Again, all dry cells occurred in the outcrop.

The DOR simulations did not differ significantly from the average recharge simulations. Figure 10.3.25 shows the difference between the head surfaces for the two runs for the Sparta aquifer. All head differences are less than 5 ft. The only noticeable features are small changes in the outcrop areas. Figure 10.3.26 shows the difference between the head surfaces for the two runs for the Queen City aquifer. Most differences are less than 5 ft except in a few locations in Nacogdoches County where the difference can be slightly higher than 10 ft. Figure 10.3.27 shows the difference between the head surfaces for the two runs for the Carrizo. All head differences are less than 5 ft. Small differences are noticeable in the outcrop around the Sabine Uplift.

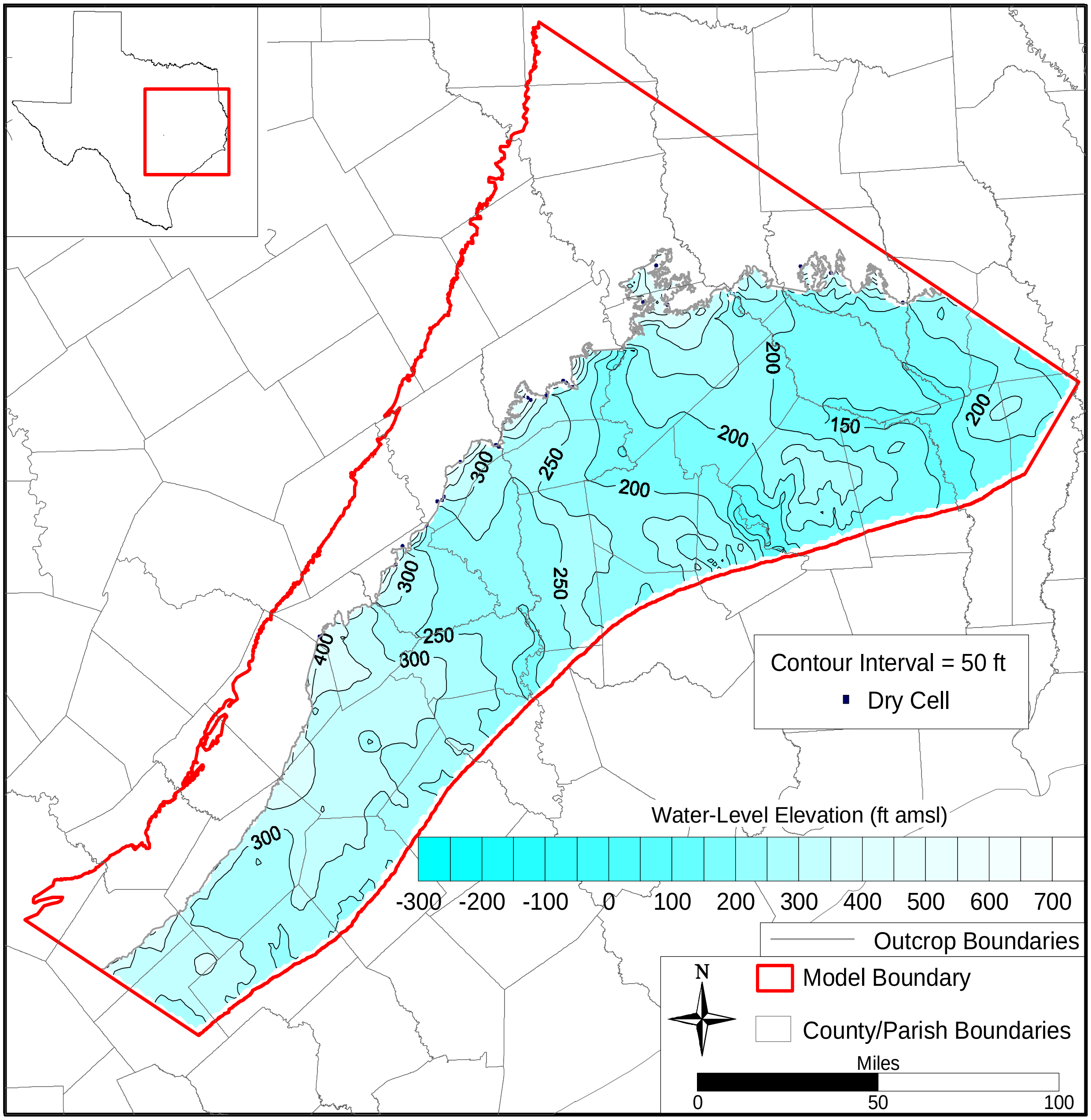


Figure 10.3.1 Predictive heads (ft) in the Sparta aquifer in 2000.

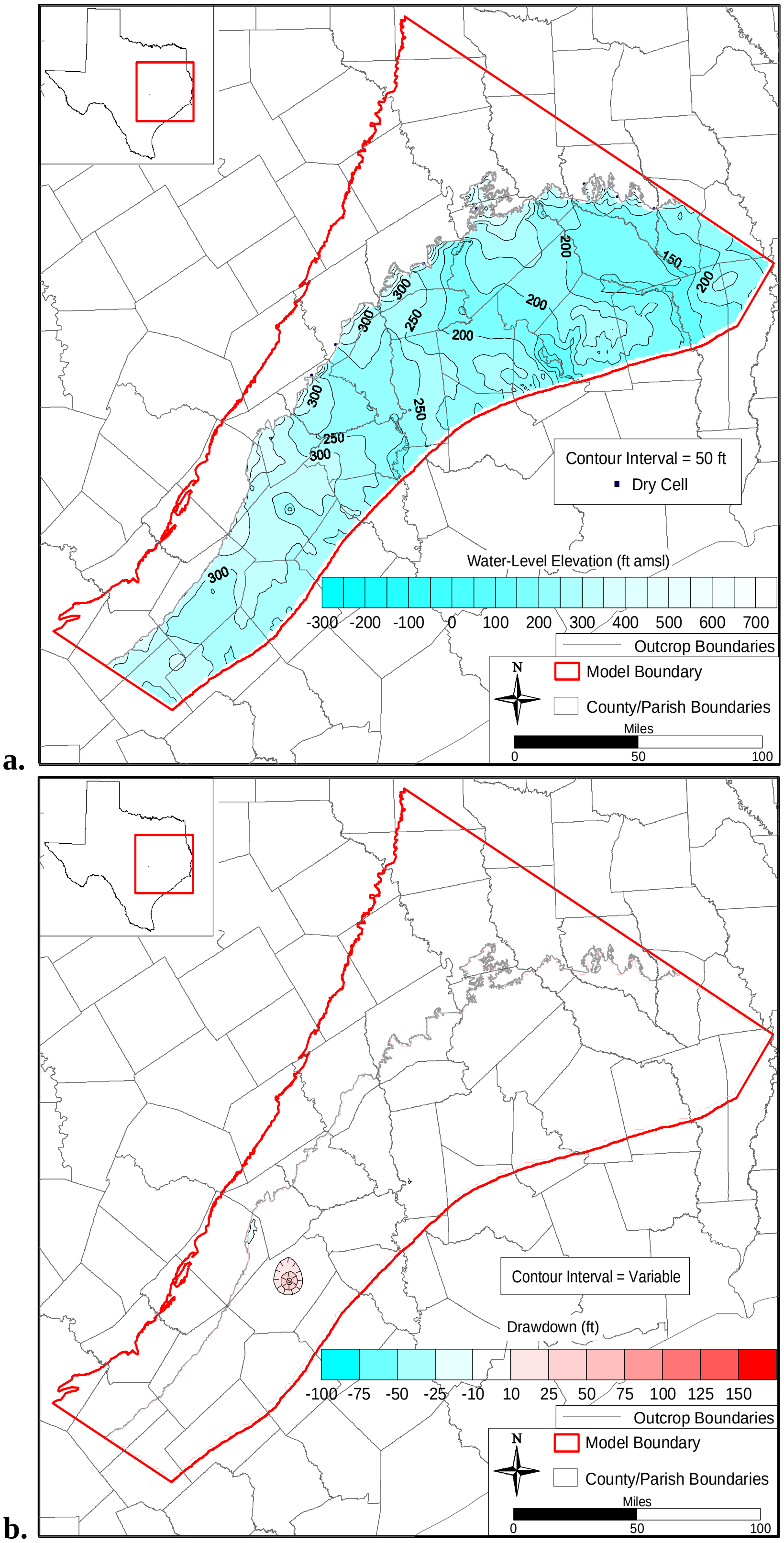


Figure 10.3.2 Predictive heads (ft) (a) and drawdown (b) in Sparta aquifer in 2010.

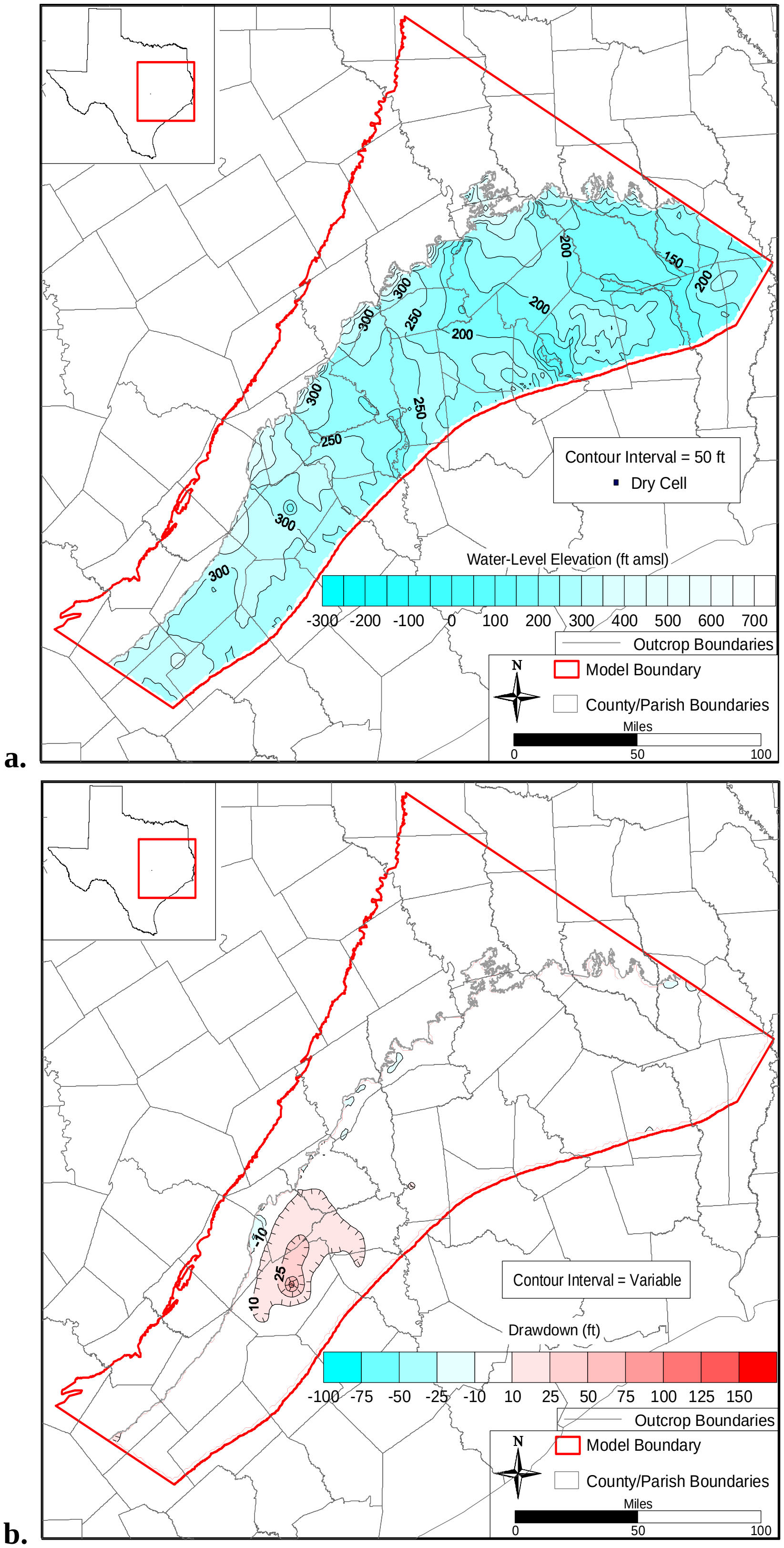


Figure 10.3.3 Predictive heads (ft) (a) and drawdown (b) in Sparta aquifer in 2020.

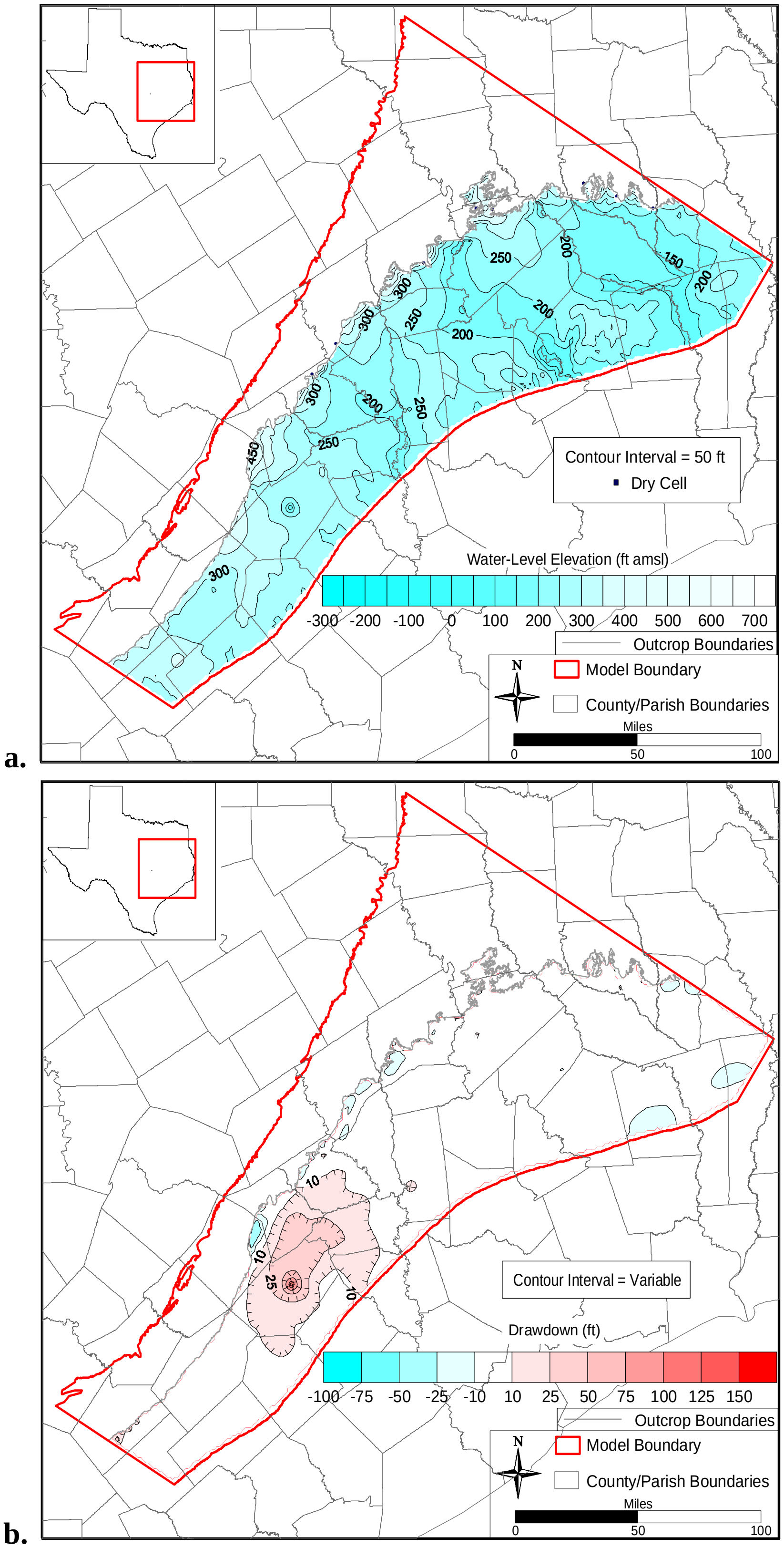


Figure 10.3.4 Predictive heads (ft) (a) and drawdown (b) in Sparta aquifer in 2030.

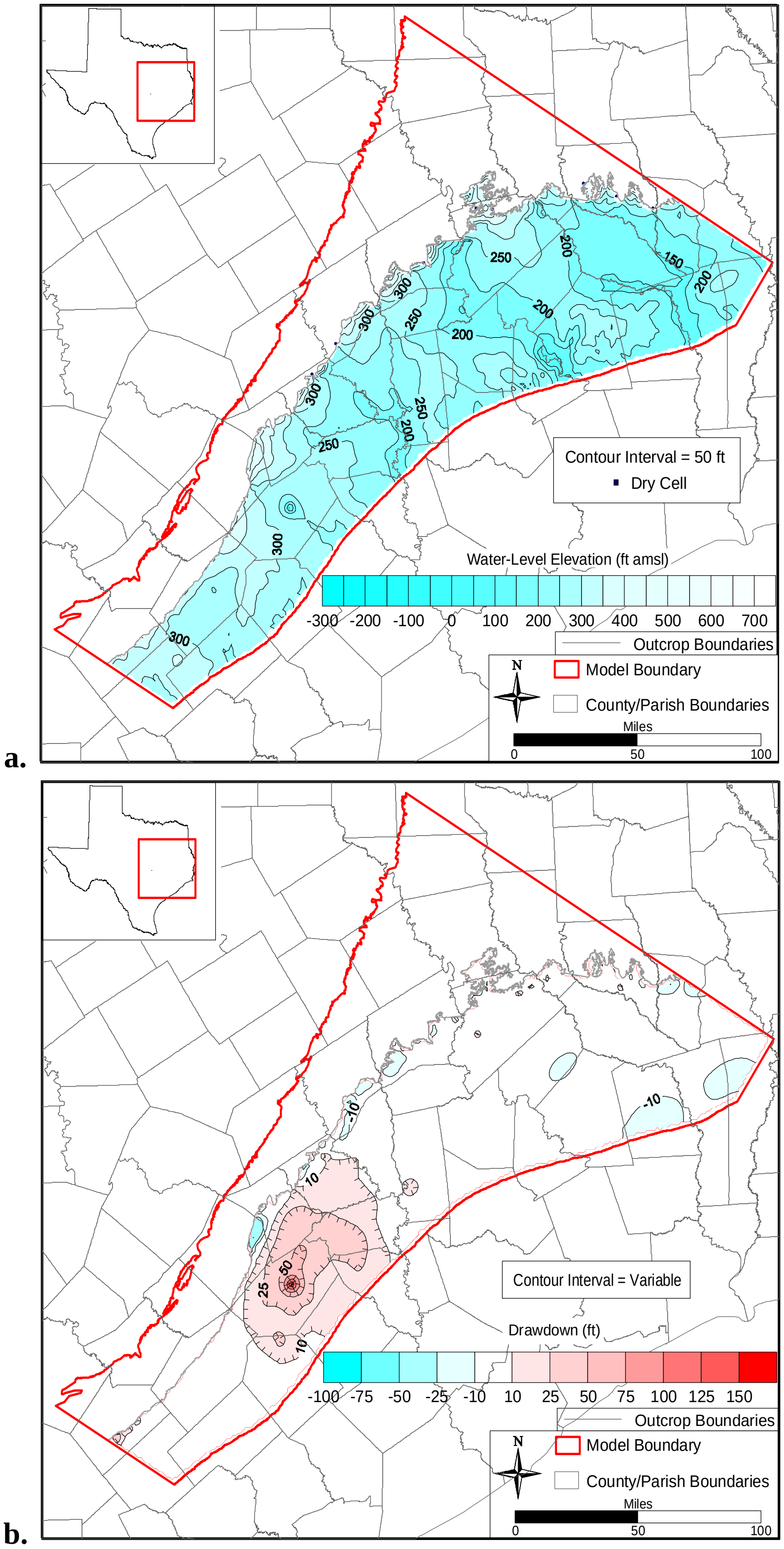


Figure 10.3.5 Predictive heads (ft) (a) and drawdown (b) in Sparta aquifer in 2040.

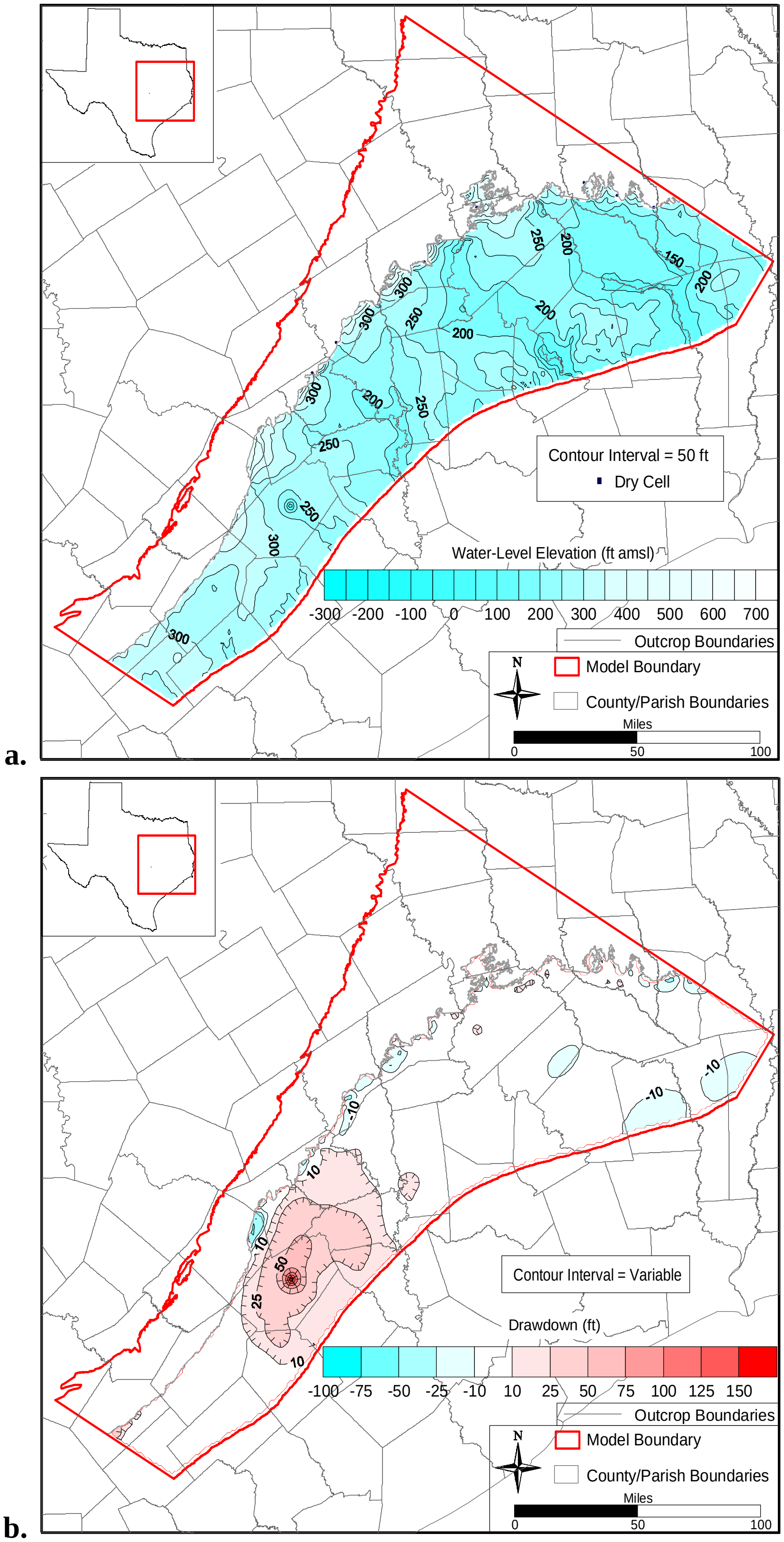


Figure 10.3.6 Predictive heads (ft) (a) and drawdown (b) in Sparta aquifer in 2050 DOR.

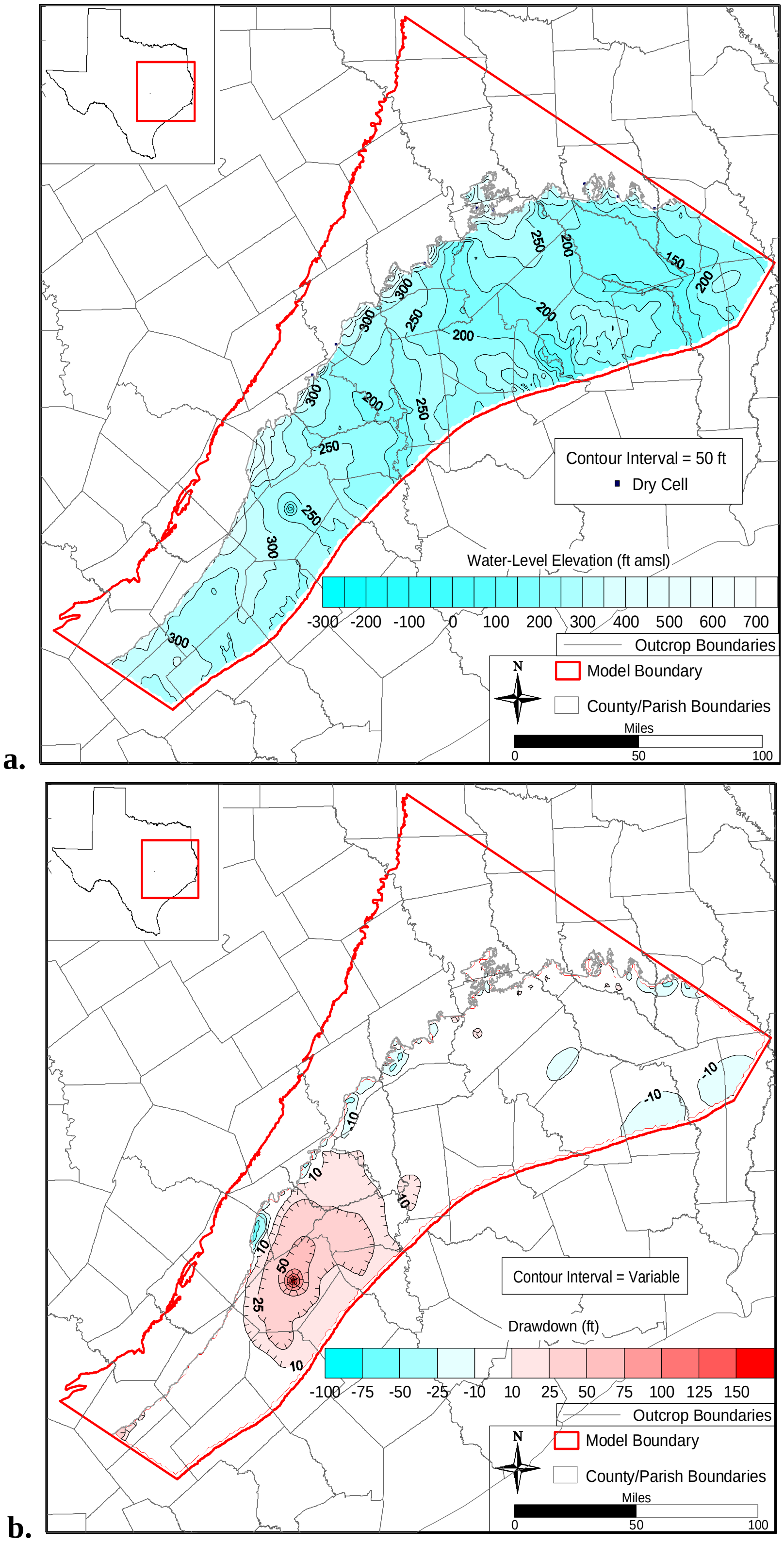


Figure 10.3.7 Predictive heads (ft) (a) and drawdown (b) in Sparta aquifer in 2050 no DOR.

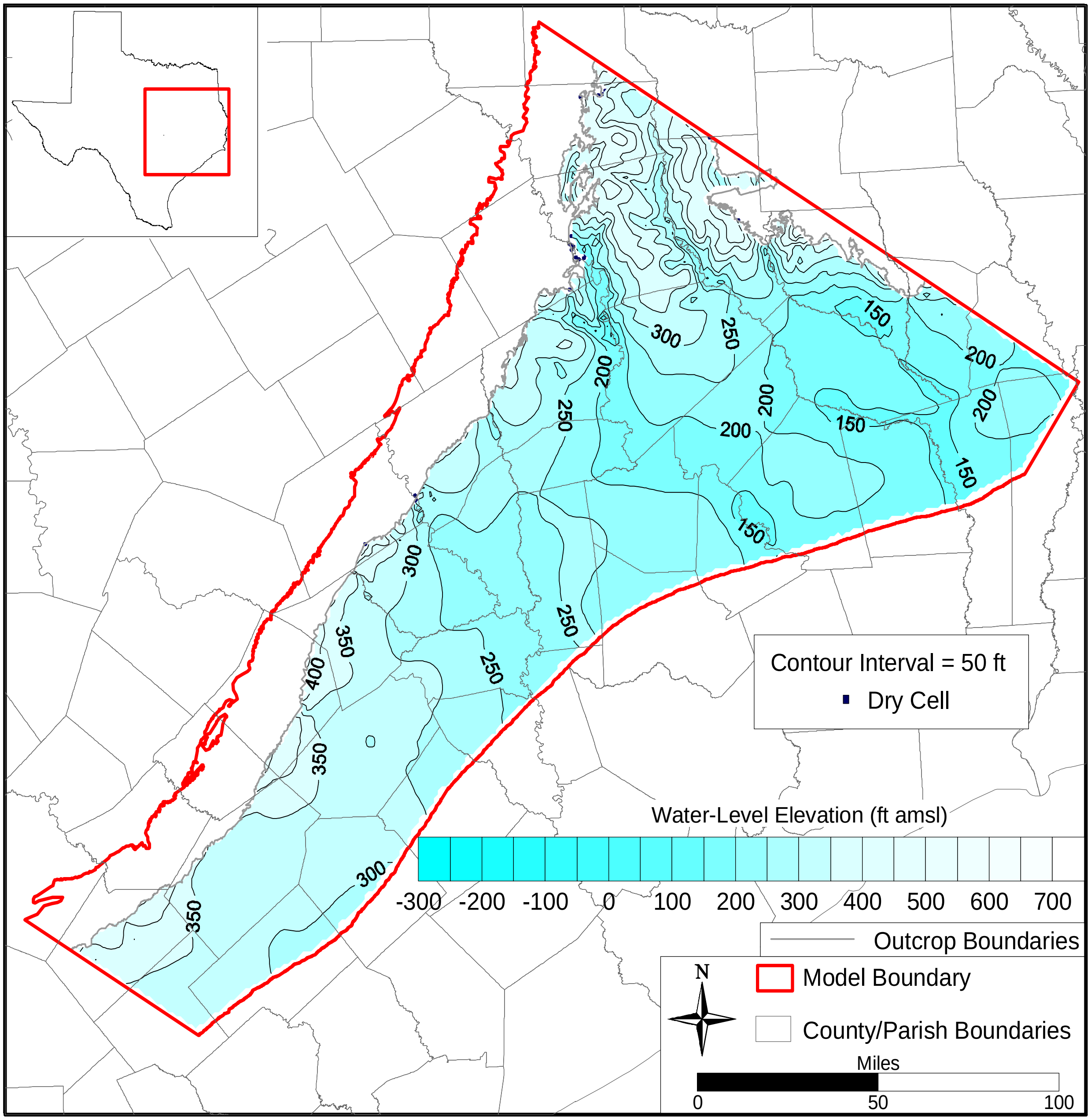


Figure 10.3.8 Predictive heads (ft) in Queen City aquifer in 2000.

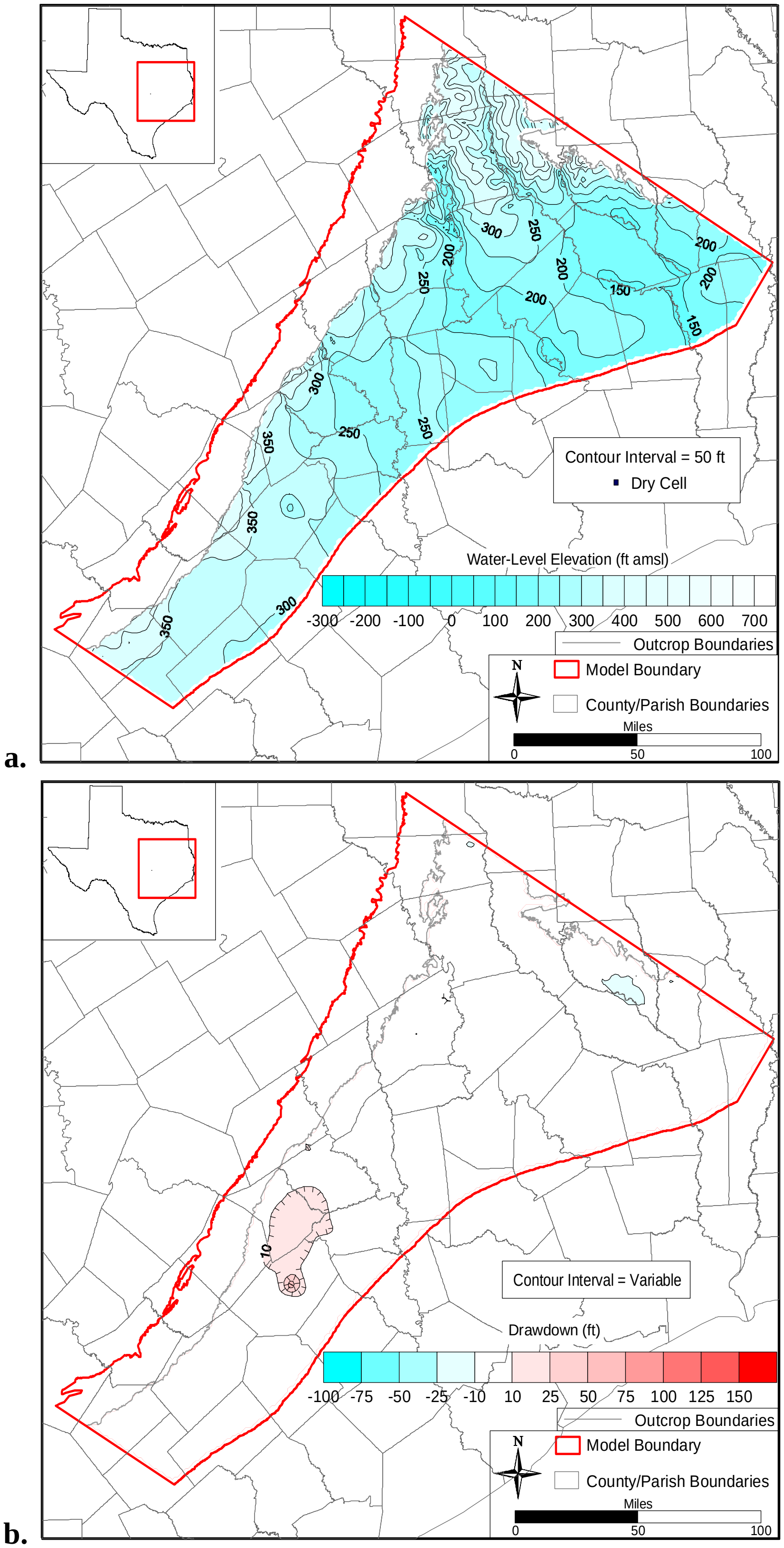


Figure 10.3.9 Predictive heads (ft) (a) and drawdown (b) in Queen City aquifer in 2010.

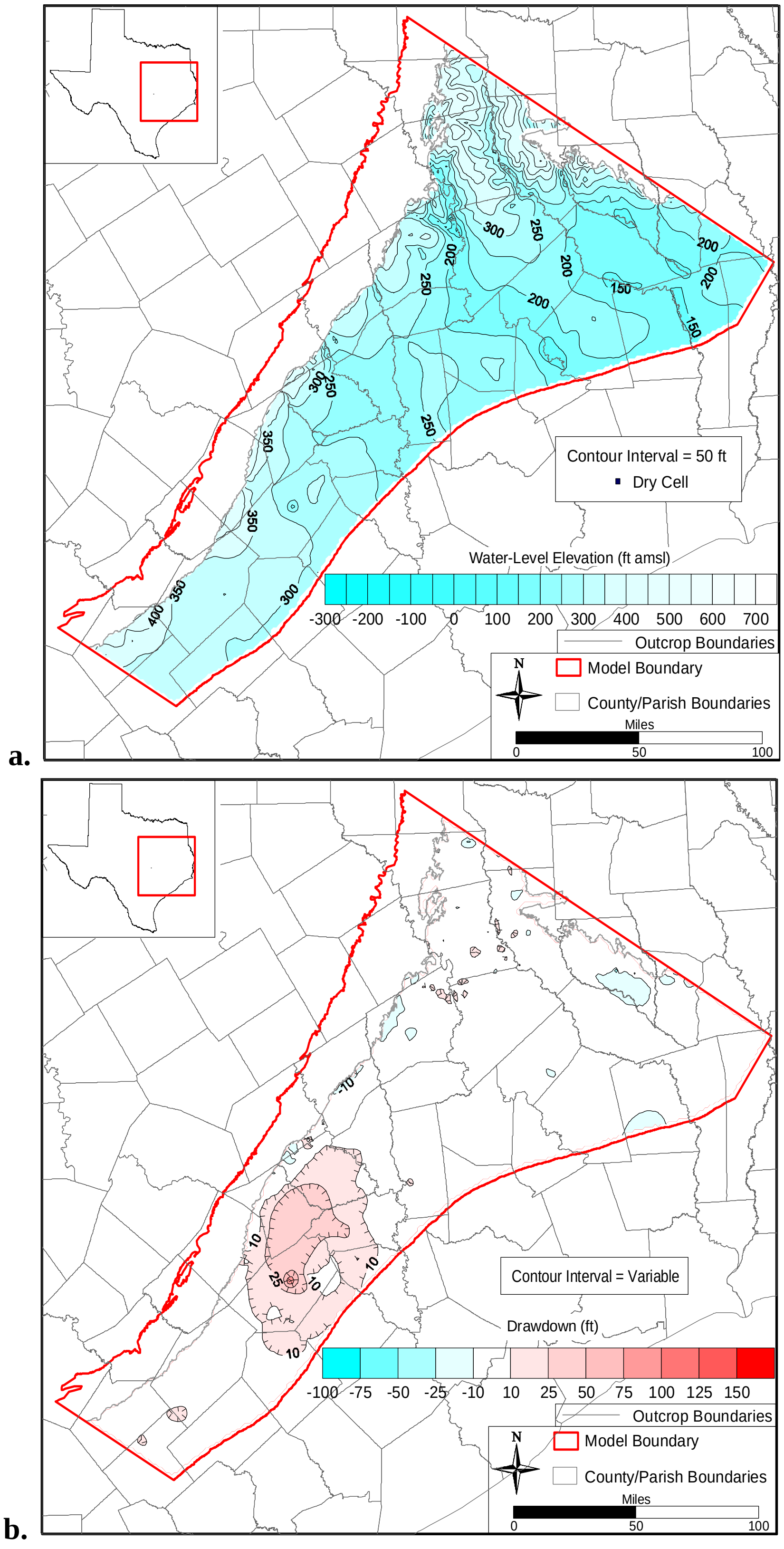


Figure 10.3.10 Predictive heads (ft) (a) and drawdown (b) in Queen City aquifer in 2020.

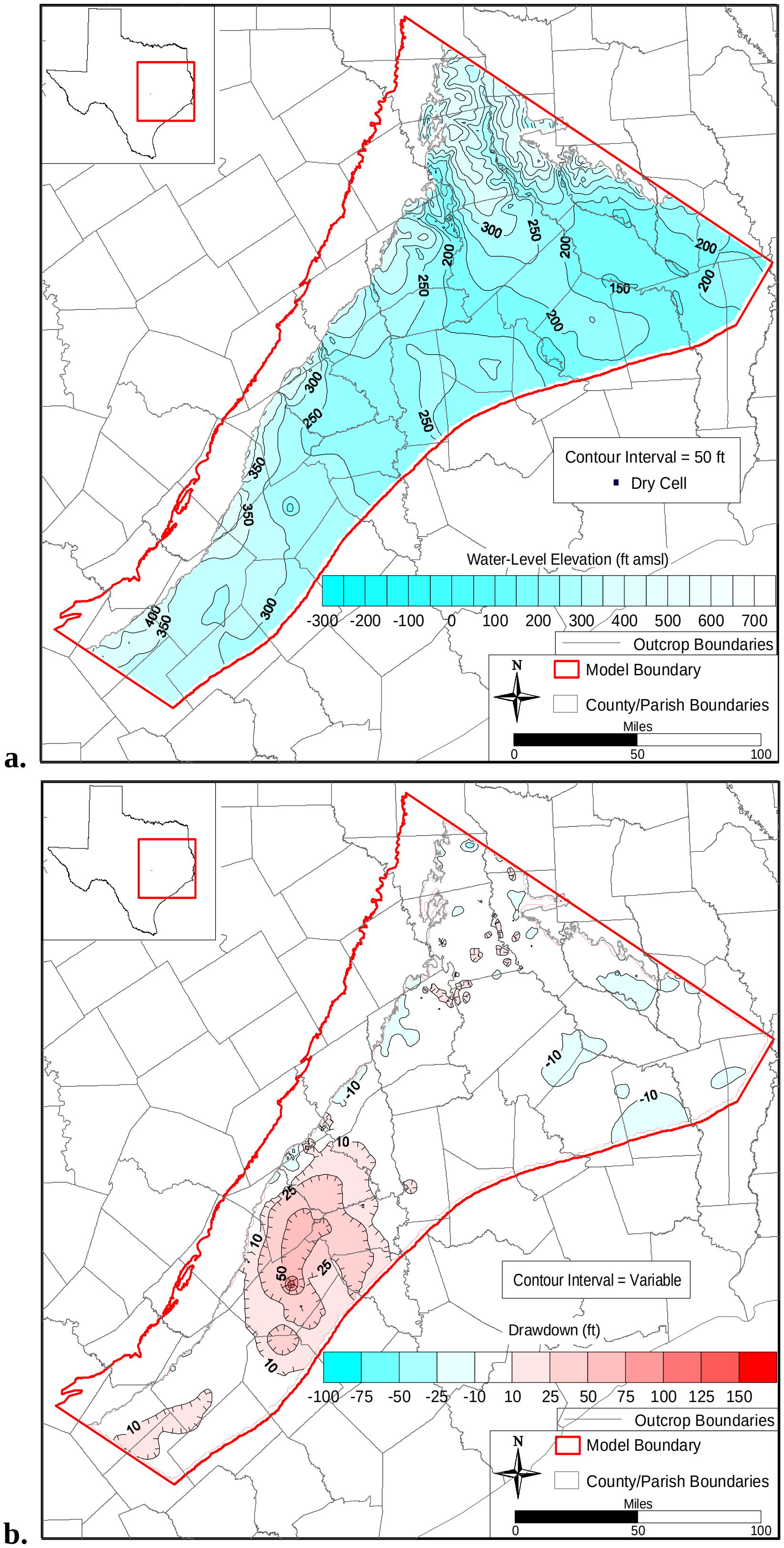


Figure 10.3.11 Predictive heads (ft) (a) and drawdown (b) in Queen City aquifer in 2030.

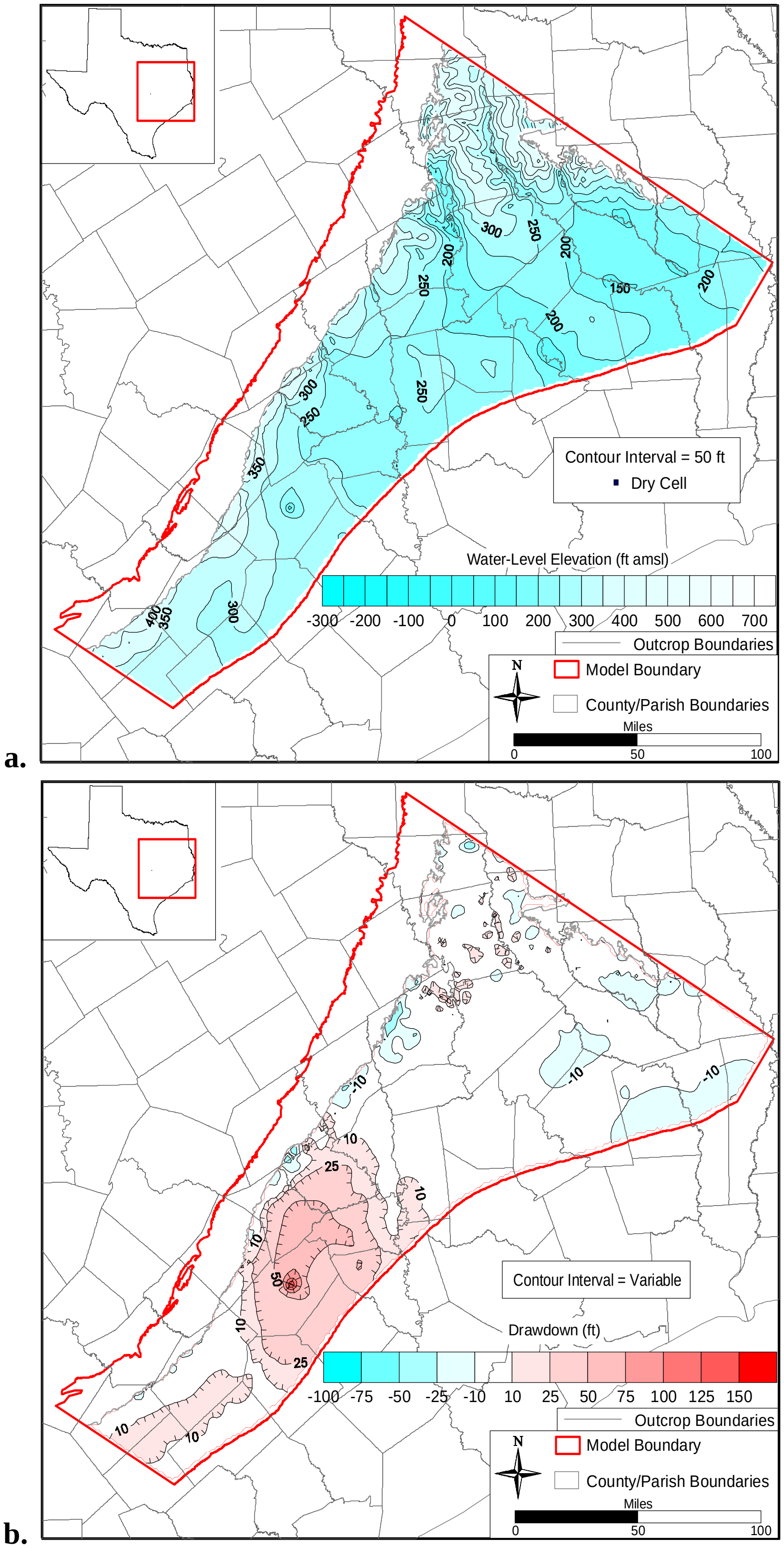
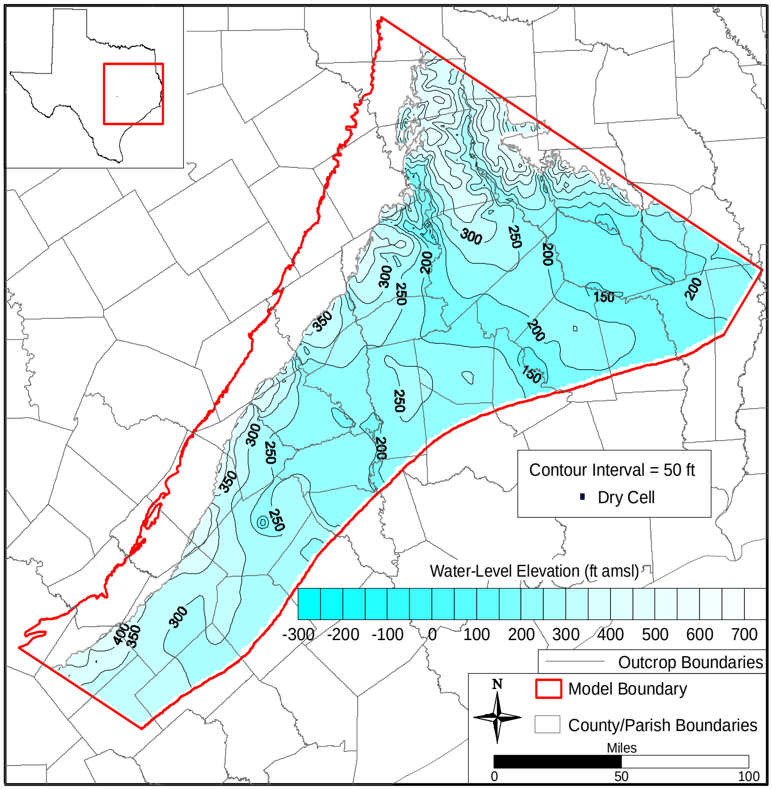


Figure 10.3.12 Predictive heads (ft) (a) and drawdown (b) in Queen City aquifer in 2040.

a.



b.

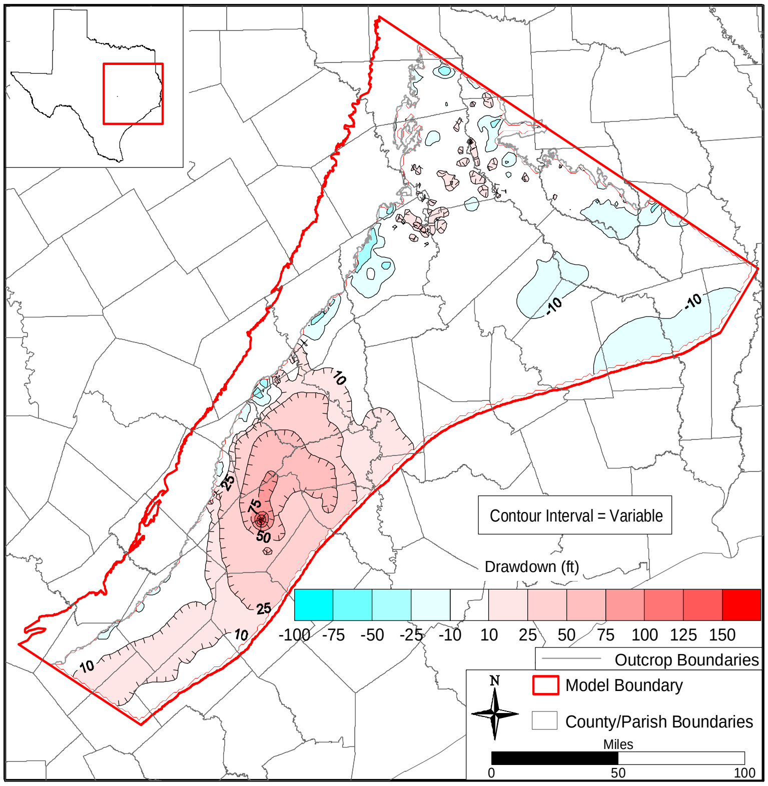


Figure 10.3.13 Predictive heads (ft) (a) and drawdown (b) in Queen City aquifer in 2050 DOR.

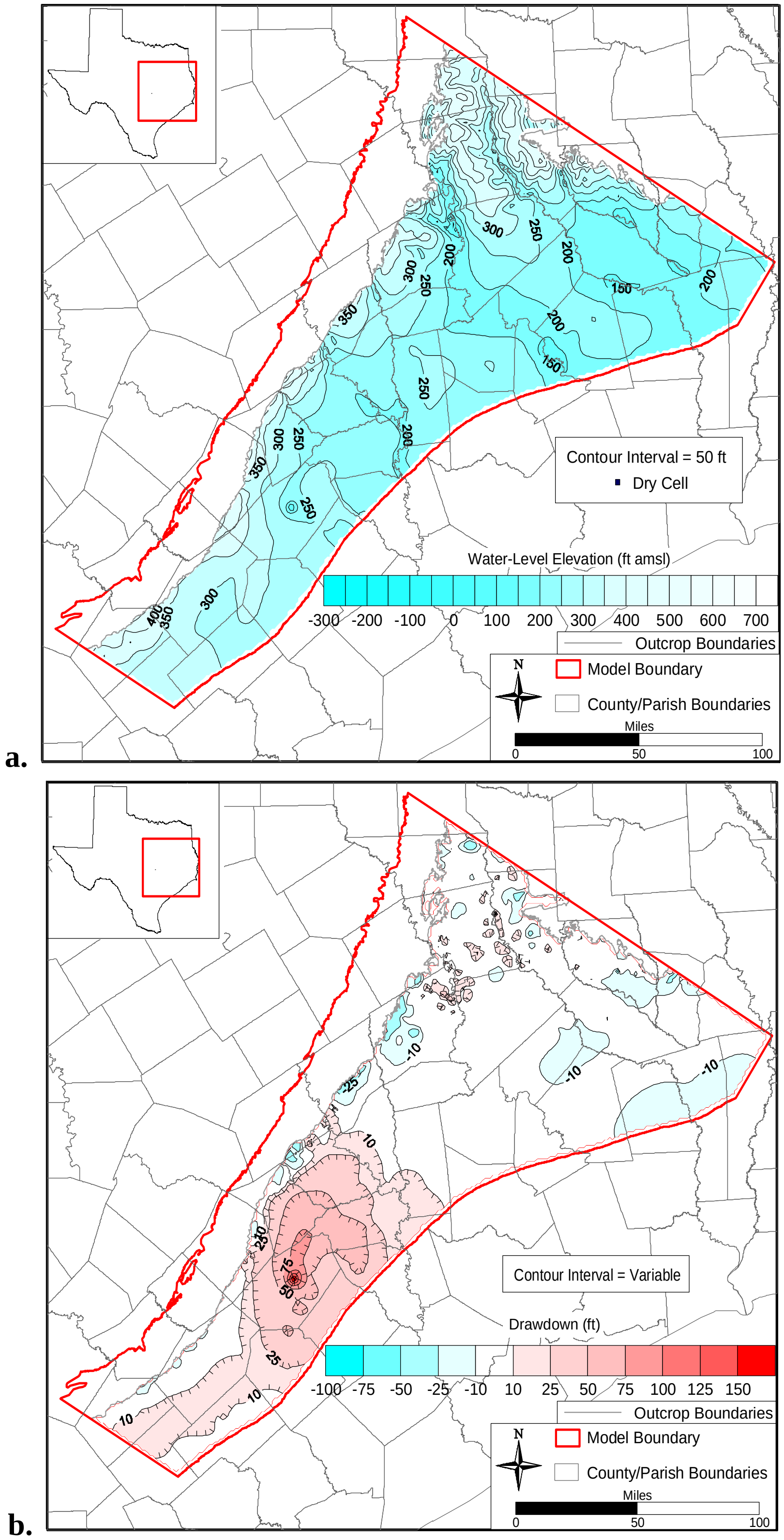


Figure 10.3.14 Predictive heads (ft) (a) and drawdown (b) in Queen City aquifer in 2050 no DOR.

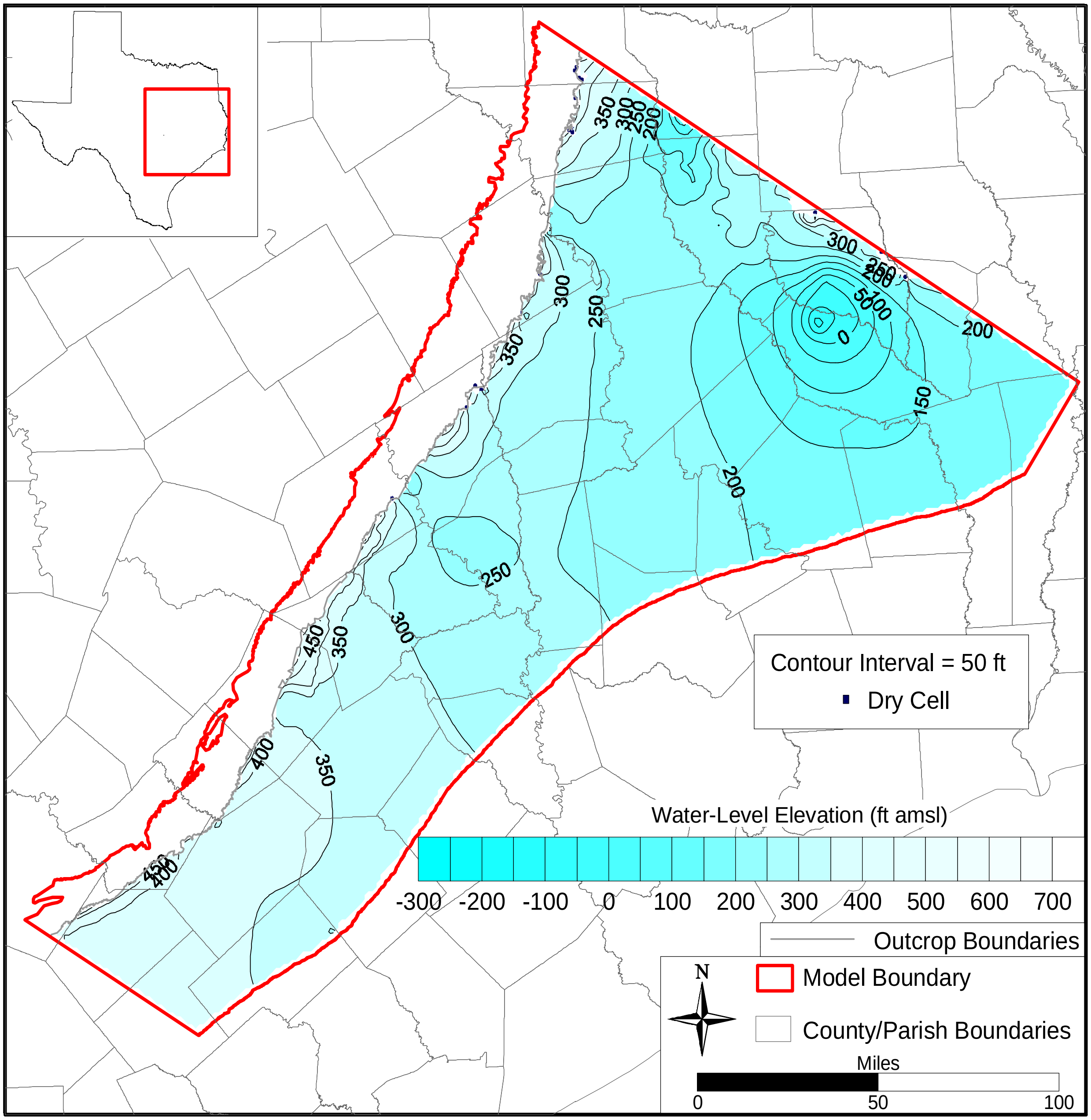


Figure 10.3.15 Predictive heads (ft) in the Carrizo Formation in 2000.

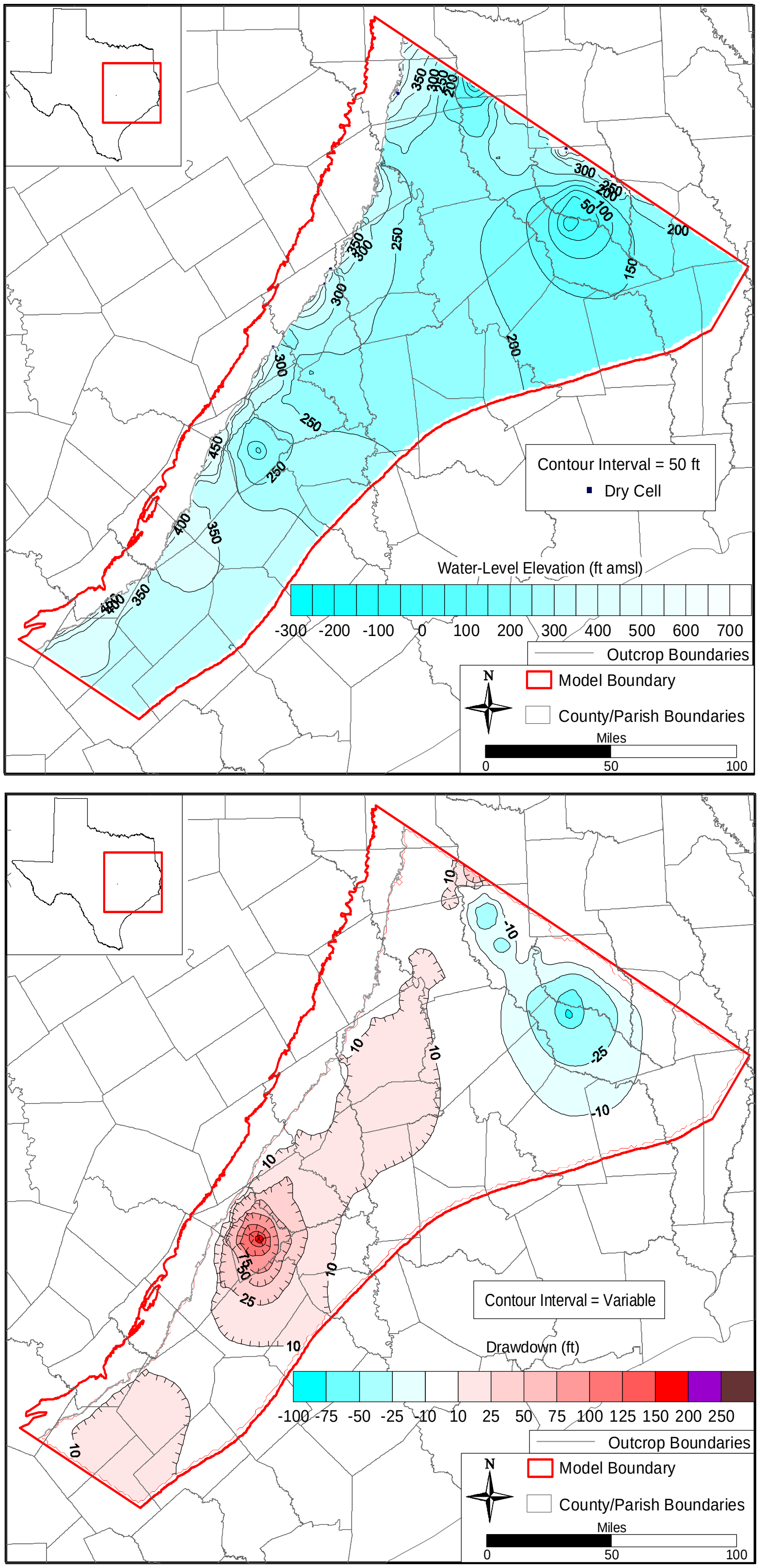


Figure 10.3.16 Predictive heads (ft) (a) and drawdown (b) in Carrizo Formation in 2010.

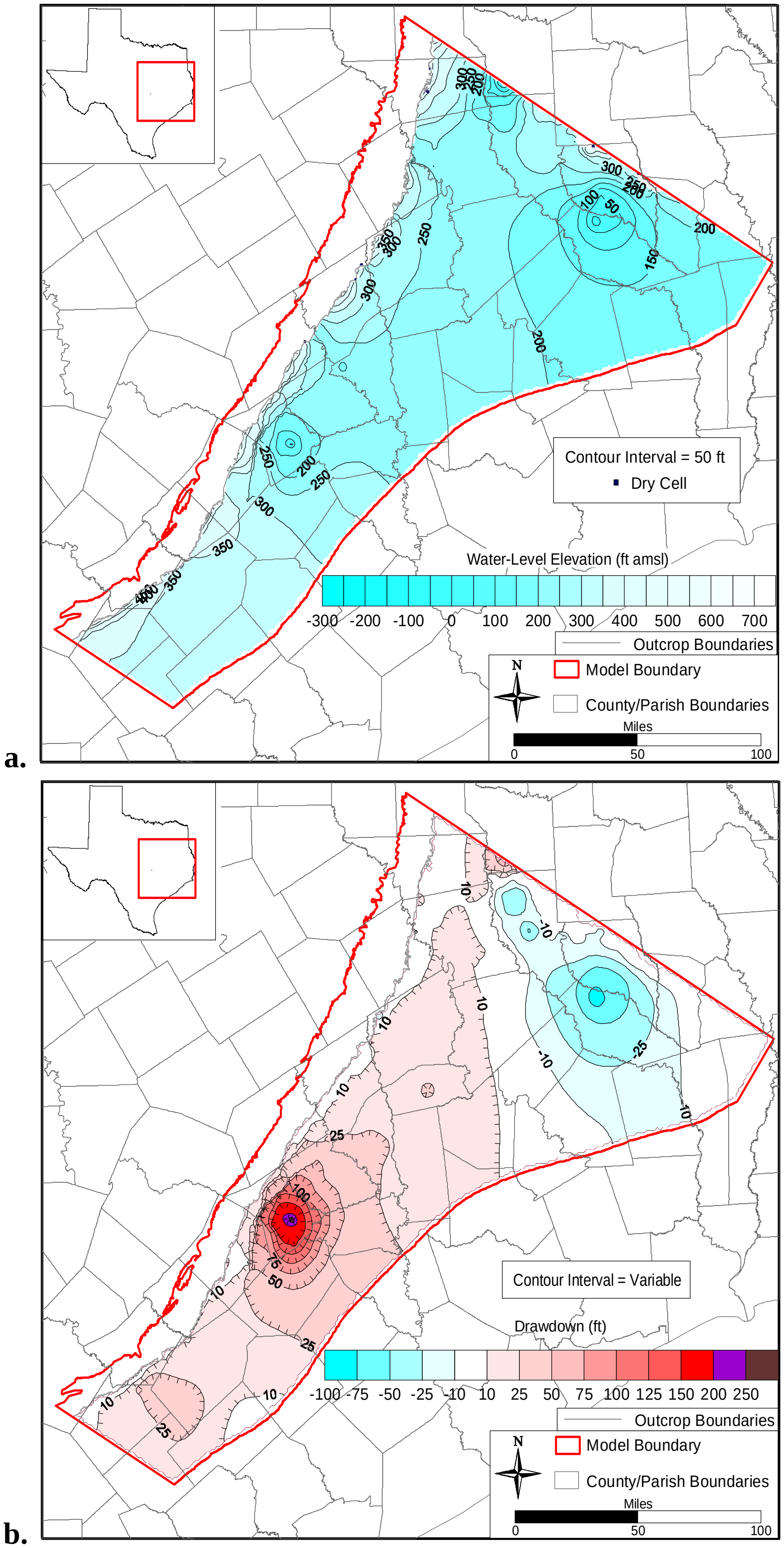


Figure 10.3.17 Predictive heads (ft) (a) and drawdown (b) in Carrizo Formation in 2020.

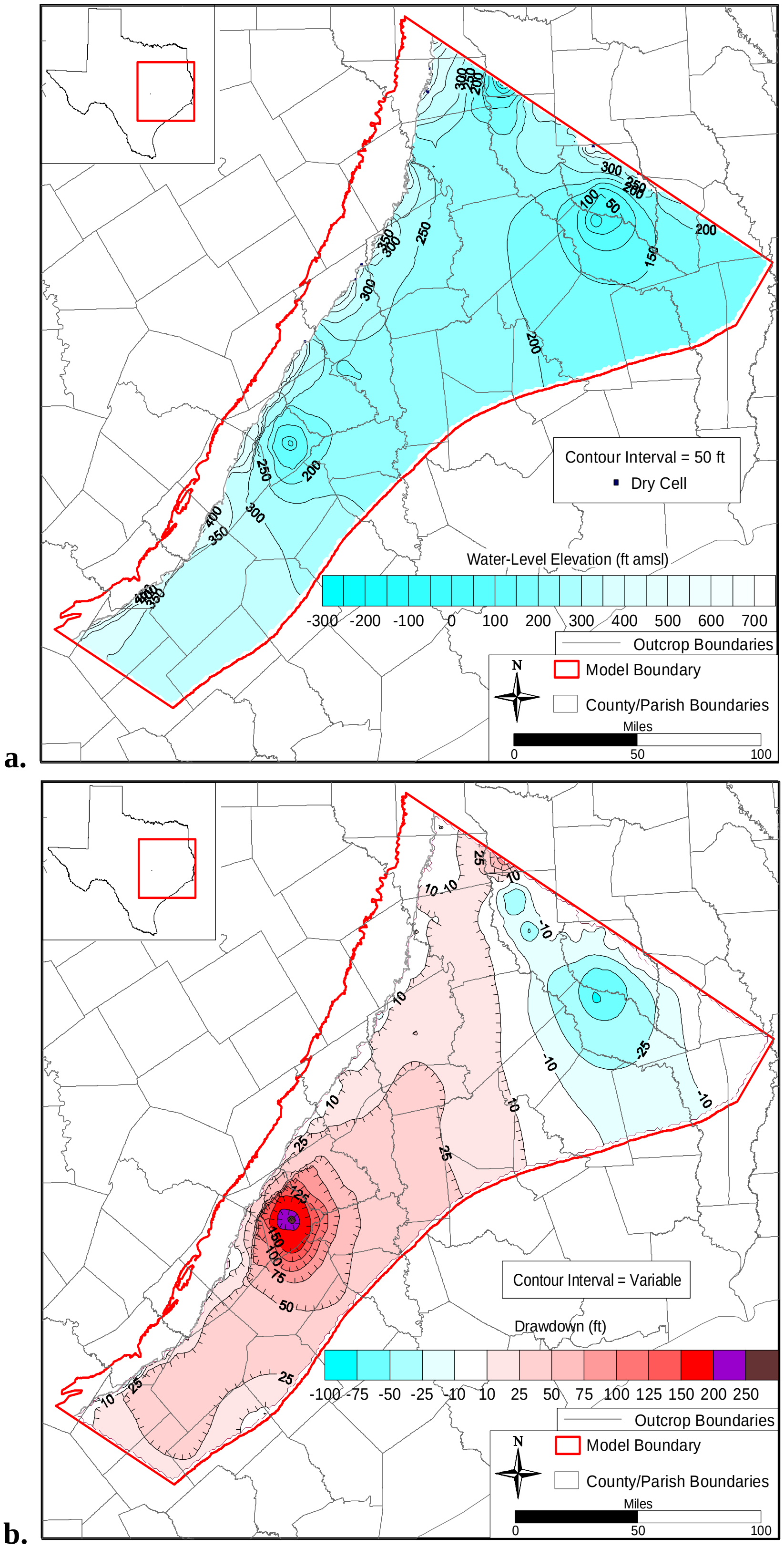
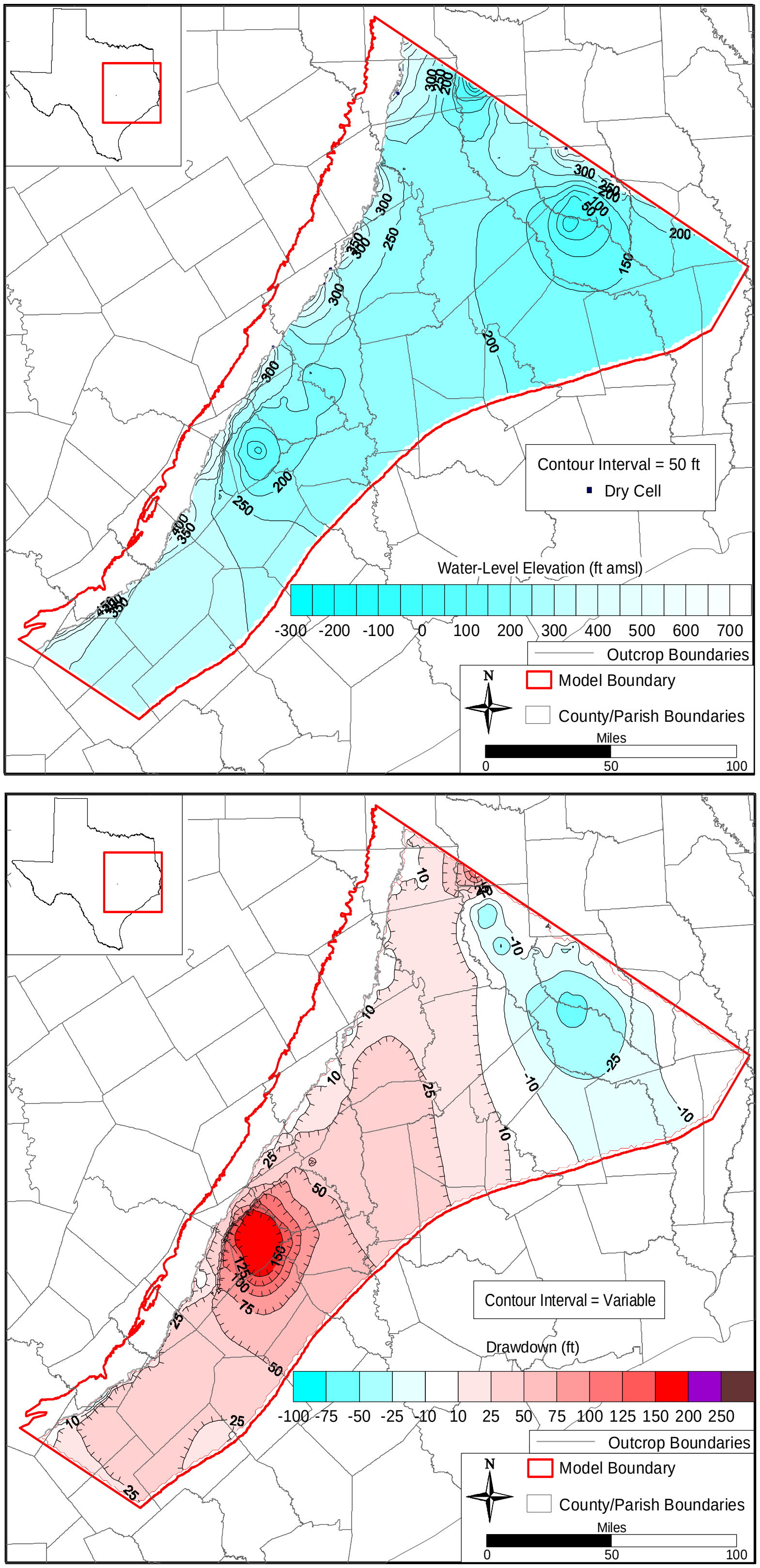


Figure 10.3.18 Predictive heads (ft) (a) and drawdown (b) in Carrizo Formation in 2030.


a.

b.

Figure 10.3.19 Predictive heads (ft) (a) and drawdown (b) in Carrizo Formation in 2040.

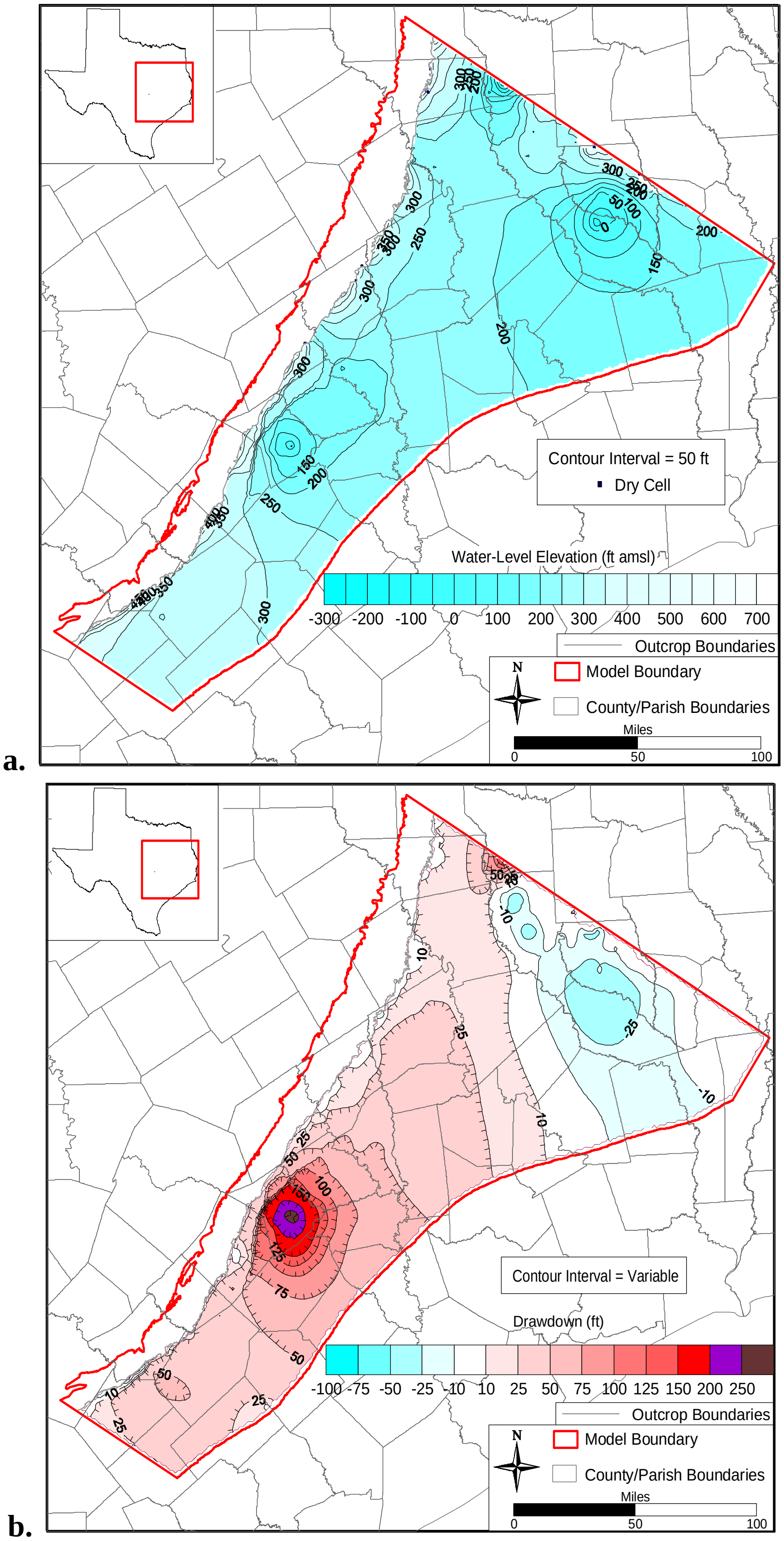


Figure 10.3.20 Predictive heads (ft) (a) and drawdown (b) in Carrizo Formation in 2050 DOR.

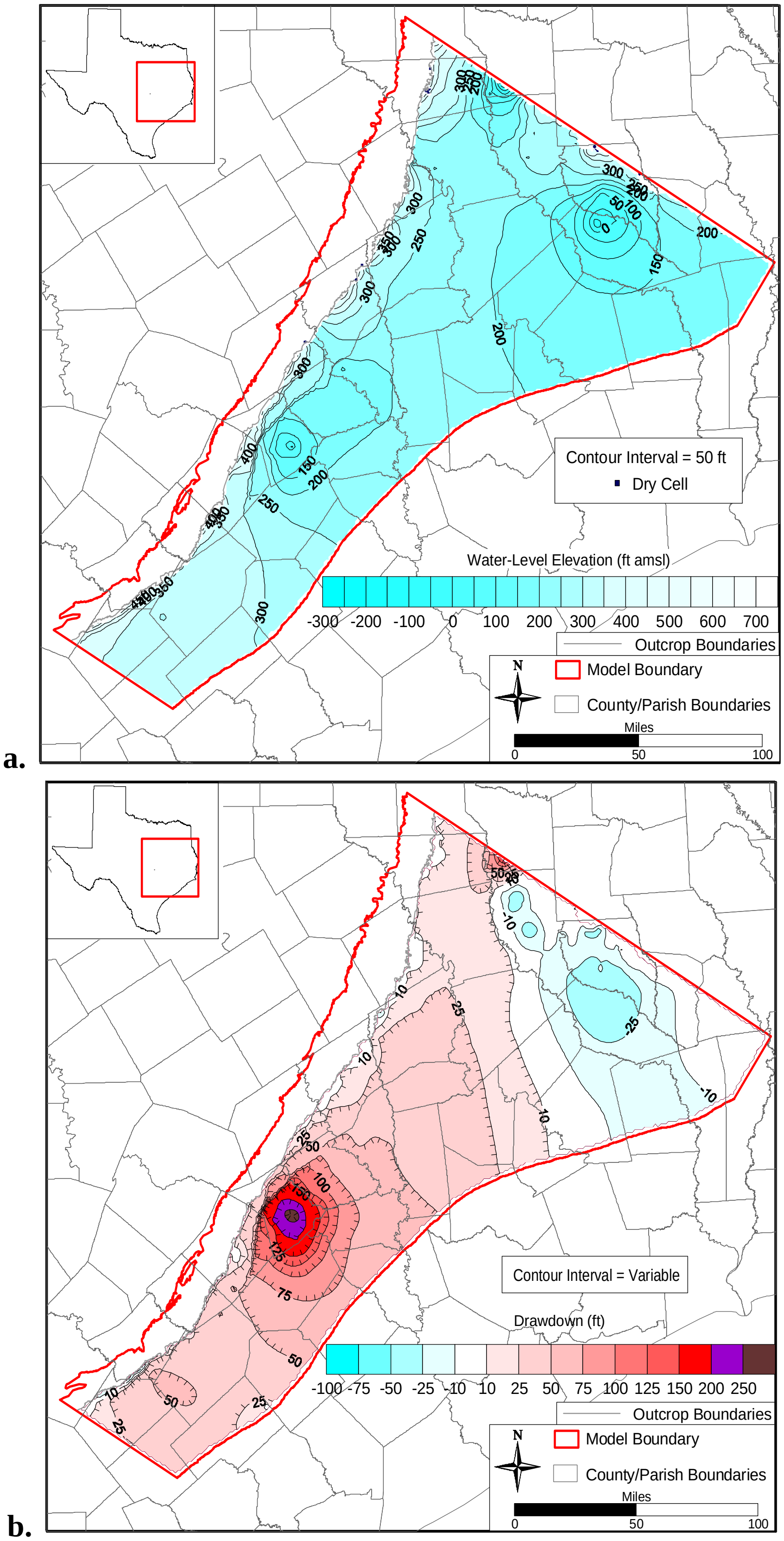


Figure 10.3.21 Predictive heads (ft) (a) and drawdown (b) in Carrizo Formation in 2050 no DOR.

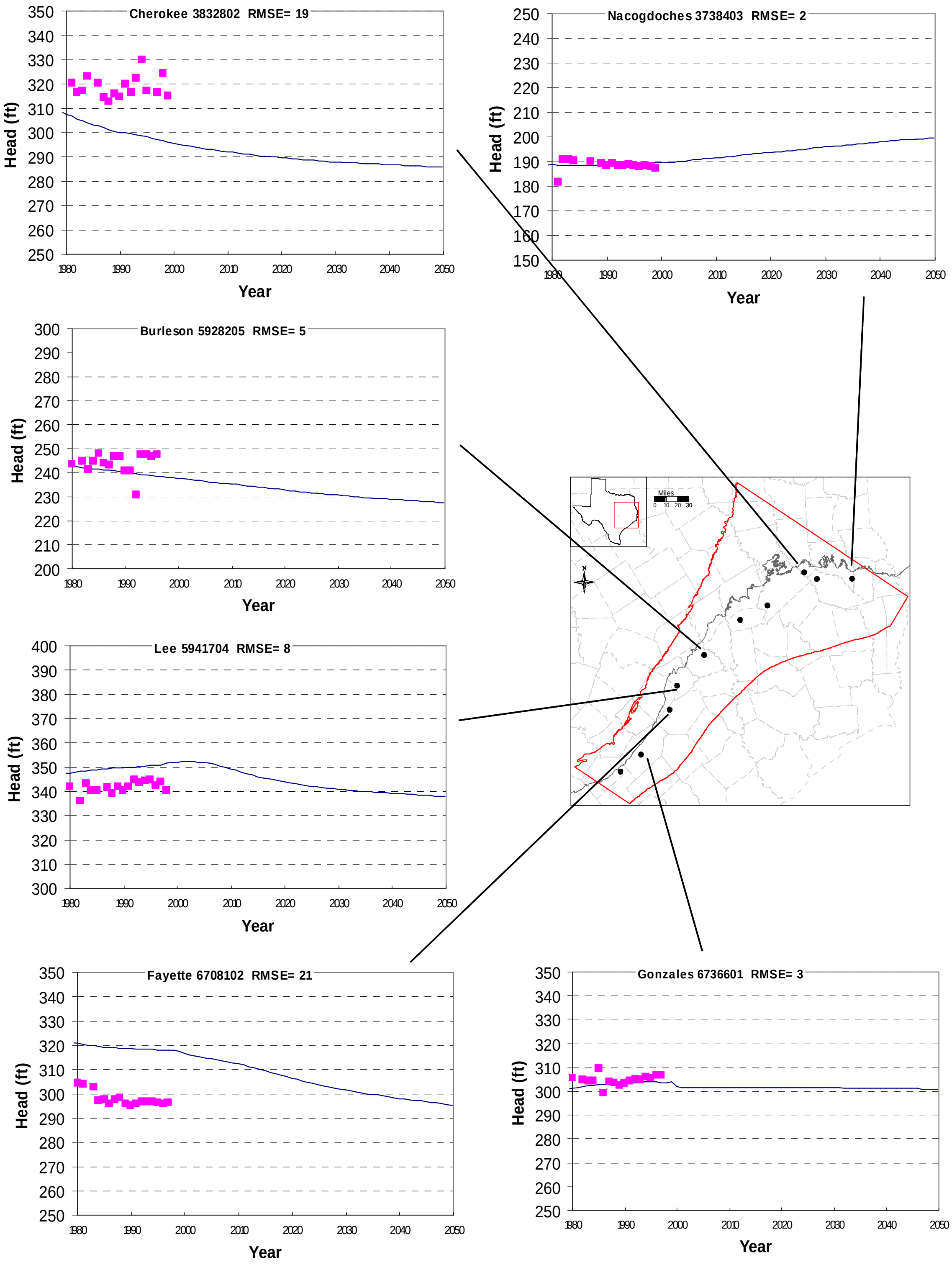


Figure 10.3.22 Selected Sparta hydrographs from the predictive simulation to 2050 with the DOR. Simulated and measured data are shown as lines and points, respectively.

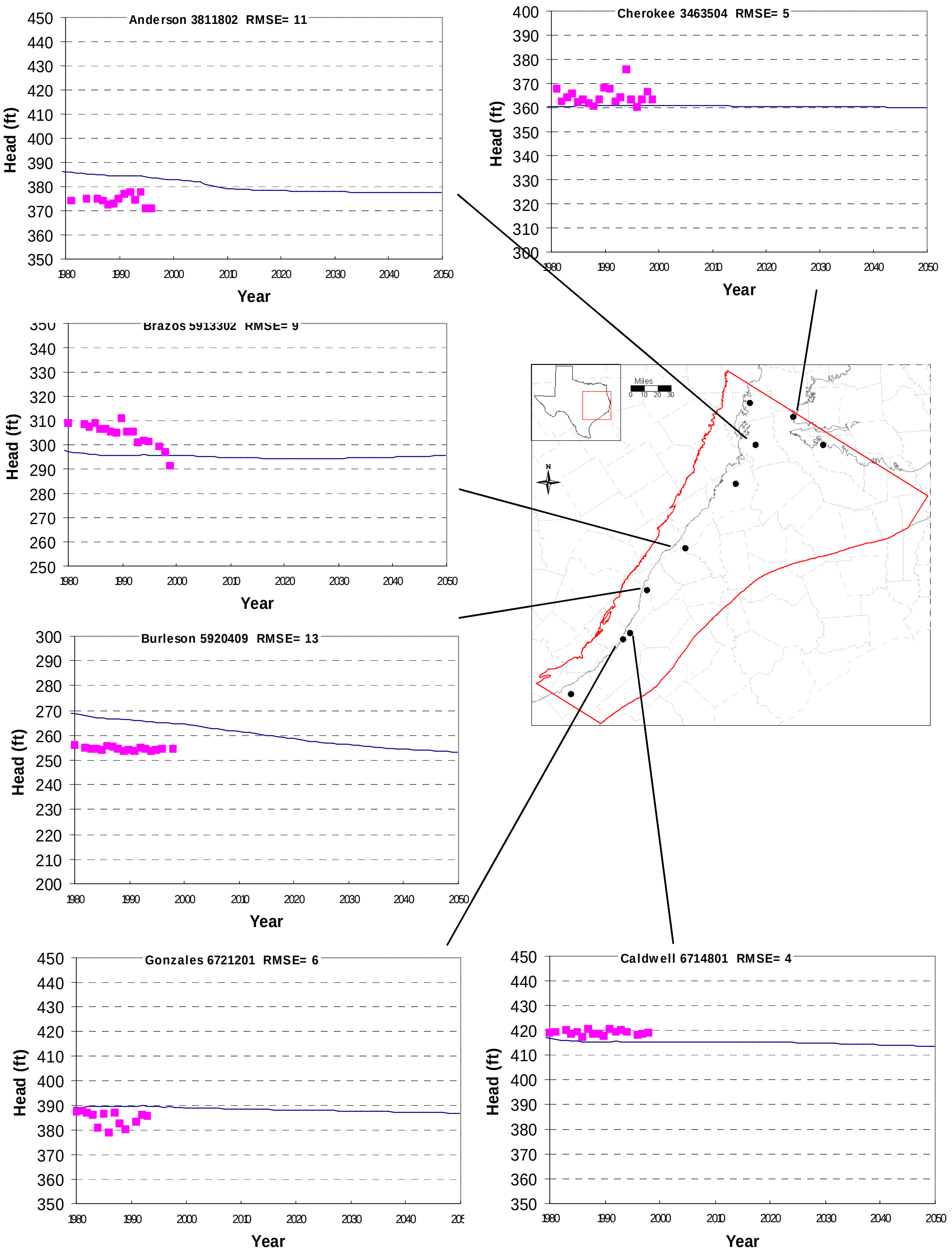


Figure 10.3.23 Selected Queen City aquifer hydrographs from the predictive simulation to 2050 with the DOR. Simulated and measured data are shown as lines and points, respectively.

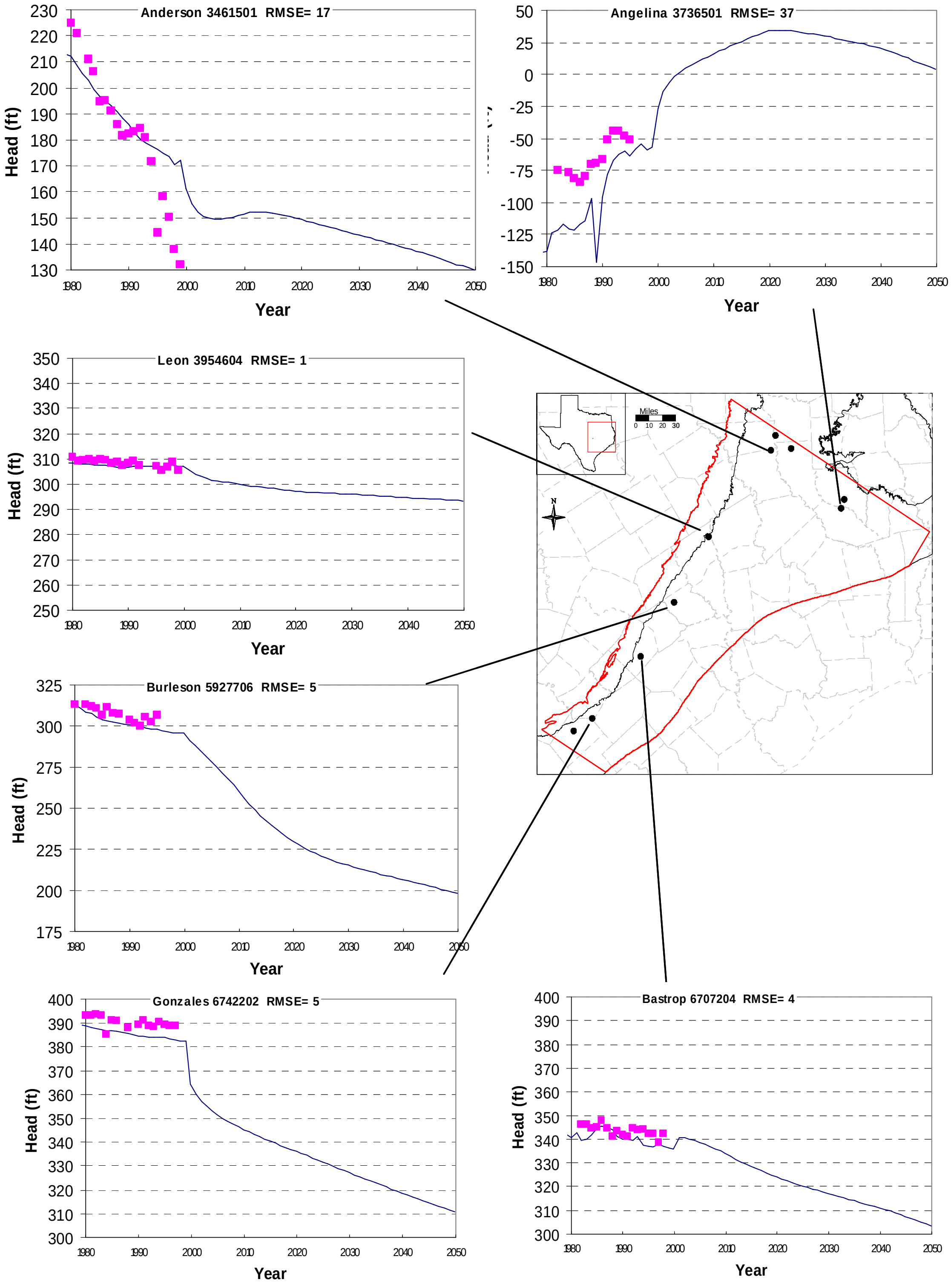


Figure 10.3.24 Selected Carrizo Formation hydrographs from the predictive simulation to 2050 with the DOR. Simulated and measured data are shown as lines and points, respectively.

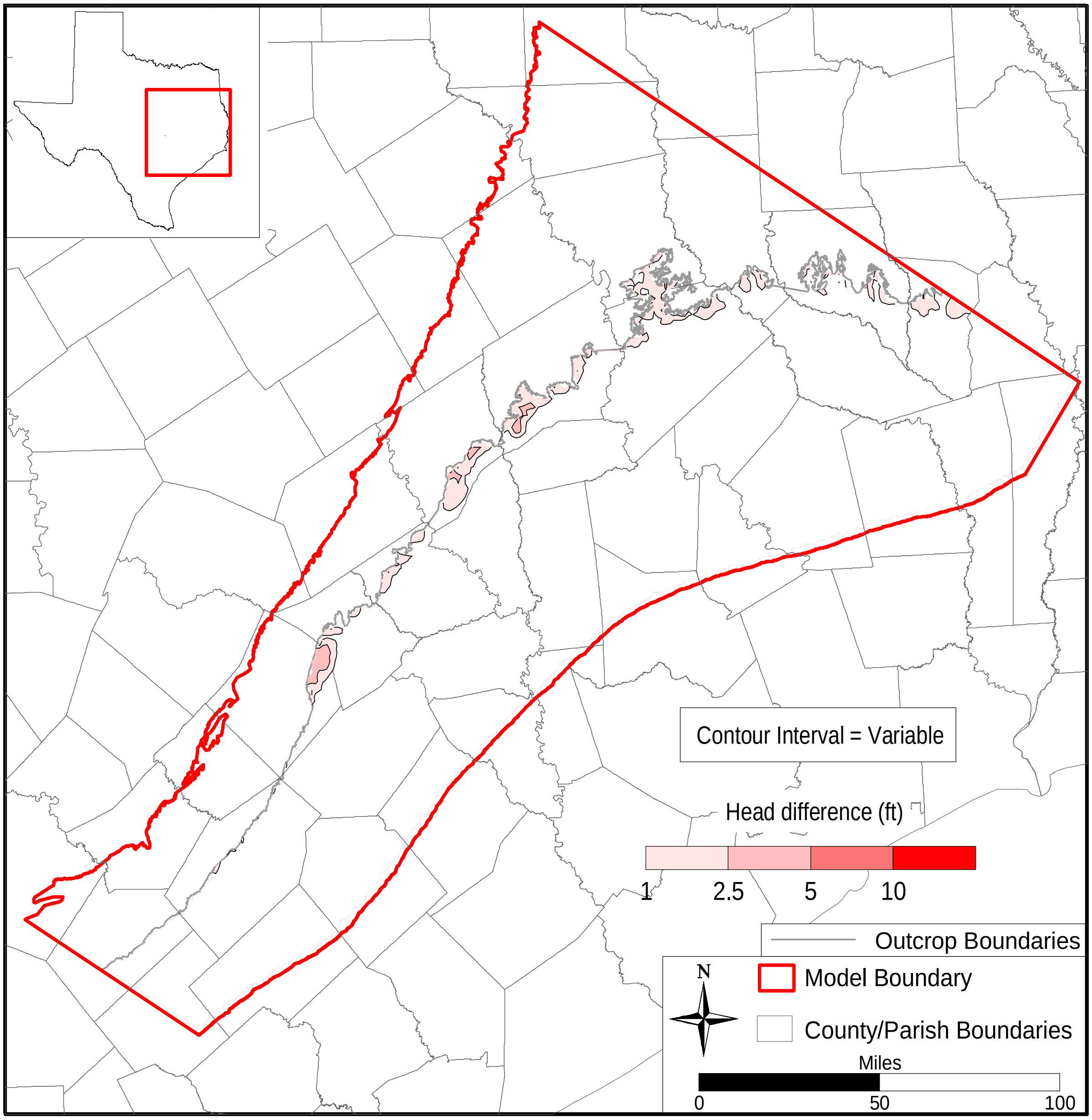


Figure 10.3.25 Simulated difference in head surfaces for the Sparta aquifer between the average condition 2050 simulation and the drought of record 2050 simulation.

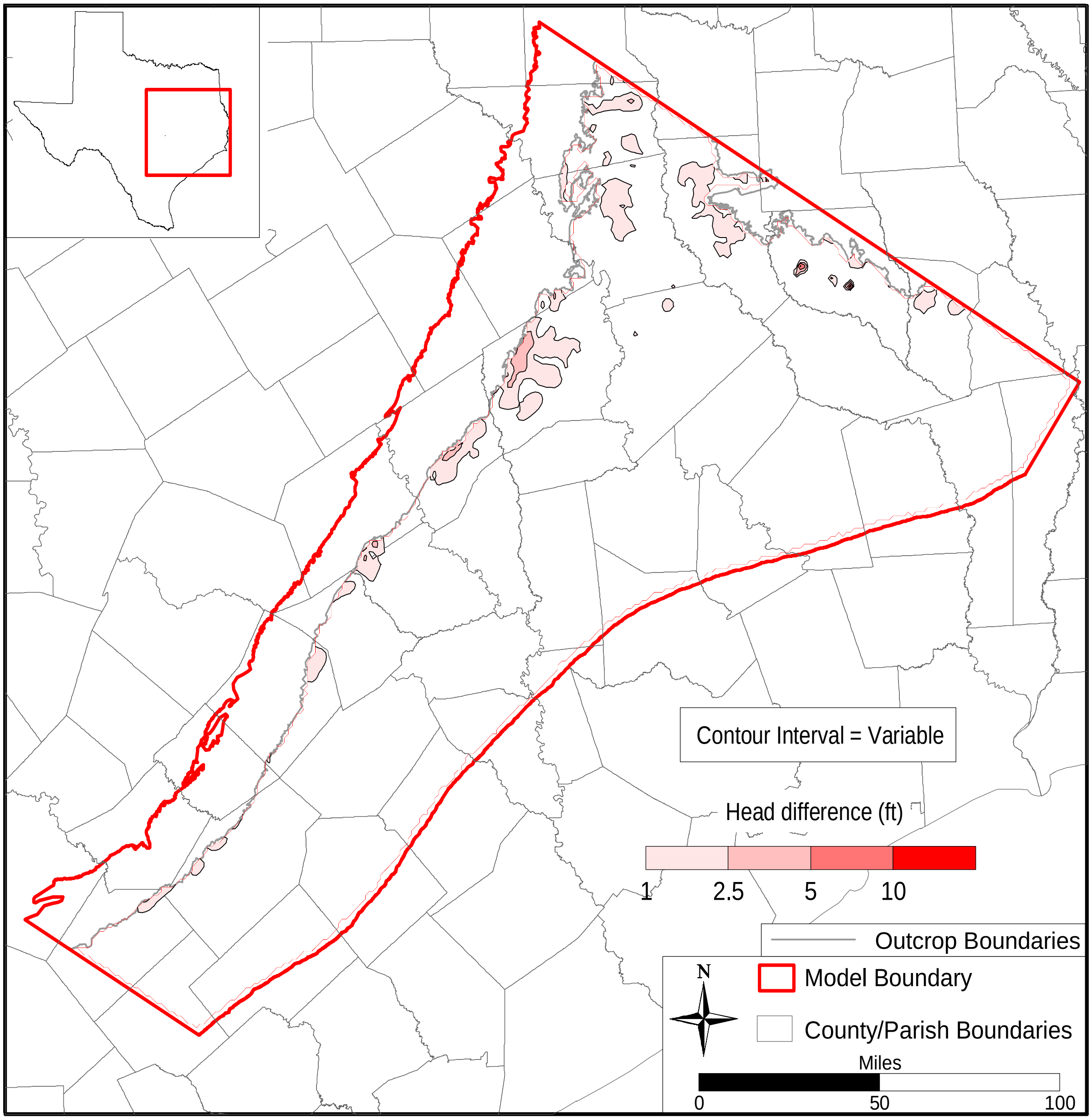


Figure 10.3.26 Simulated difference in head surfaces for the Queen City aquifer between the average condition 2050 simulation and the drought of record 2050 simulation.

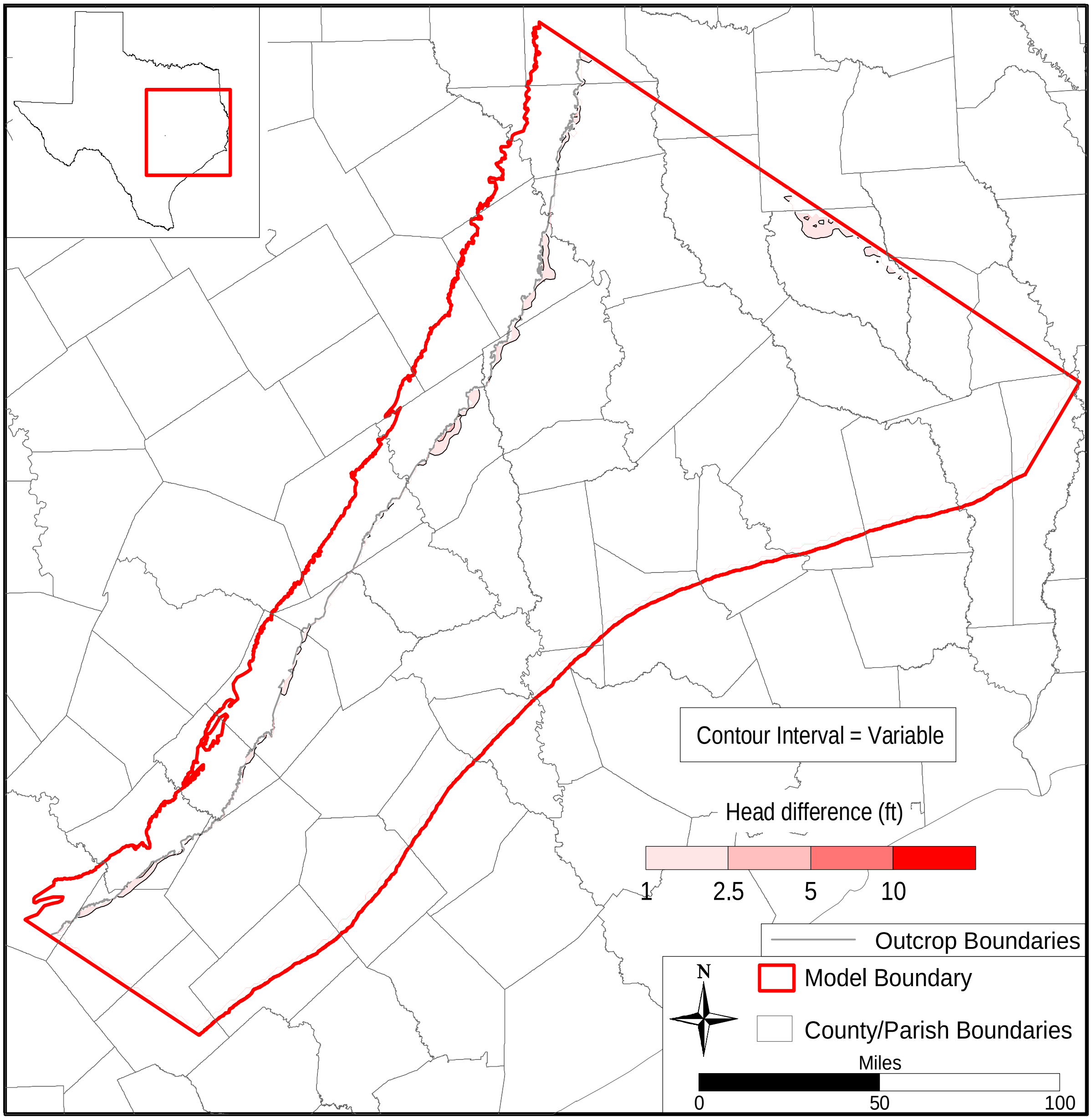


Figure 10.3.27 Simulated difference in head surfaces for the Carrizo Formation between the average condition 2050 simulation and the drought of record 2050 simulation.

10.3.2 Predictive Simulation Water Budget

Table 10.3.1 presents the water budget for the preceding predictive simulations. The table shows the water budget for the final year of each of the predictive simulations. Average recharge was used except for the last 3 years of each simulation, for which a recharge rate predicted from precipitation during the 1954-56 drought of record was used instead. Groundwater withdrawal is predicted to increase from approximately 235,500 acre-ft/yr to 395,000 acre-ft/yr model-wide (17,400 to 25,000 acre-ft/yr for the combined Sparta and Queen City aquifers). This increase results in some changes in the budget but the main characteristics and trends are similar to those of the historical transient budget. ET and base-flow discharge to streams are predicted to decrease as predicted water levels decline in the outcrop. Base-flow, however, is a small fraction of total stream flow. Comparison of the simulated 2050 water levels with average versus drought-of-record shows that recharge, ET, and stream gains are reduced during droughts.

Predicted water budgets also show that inflow from GHB boundary continues to increase. The top boundary (layer 1) goes from a net upward flow to the Gulf Coast area to a net downwards flow, capturing water from the overlying formations as described in Section 5.

Table 10.3.1 Water budget for predictive simulations for the Central model. All rates in 100 acre-ft/yr.

Year	Layer	Reservoir	ET	Recharge	GHBs	Streams	Drains	Storage	Wells	Top	Bottom
2000	**1**	0	-17,855	124,578	-9,195	-40,447	-1,241	-34,399	-10,703	0	-10,736
	2	321	-1,708	13,975	-52	-992	-199	-10,773	0	10,736	-11,314
	3	2,206	-53,087	154,406	114	-90,107	-9,940	3,970	-6,720	11,314	-12,170
	4	387	-1,226	17,251	-205	-5,610	-404	-3,227	0	12,170	-19,152
	5	0	-14,136	83,371	-1,178	-27,156	-1,304	23,907	-83,836	19,152	1,183
	6	4,130	-16,304	83,573	3,508	-45,017	-3,677	21,819	-22,373	-1,183	-24,491
	7	2,914	-8,641	53,466	-835	-31,435	-1,143	49,636	-99,423	24,491	10,972
	8	6,327	-4,143	30,848	-456	-16,441	-4,476	11,613	-12,308	-10,972	0
	Sum	16,286	-117,099	561,466	-8,298	-257,205	-22,383	62,549	-235,361		
2010	**1**	0	-13,201	45,108	-7,080	-36,227	-1,022	39,914	-11,088	0	-16,399
	2	322	-1,833	5,146	-40	-601	-205	-1,084	0	16,399	-18,109
	3	2,316	-41,587	50,908	179	-80,958	-8,004	92,493	-7,121	18,109	-26,335
	4	390	-1,288	5,959	-83	-4,574	-404	9,484	0	26,335	-35,833
	5	0	-9,493	29,410	108	-19,873	-966	82,138	-113,705	35,833	-3,449
	6	4,253	-9,511	29,329	3,249	-35,637	-3,124	73,949	-23,555	3,449	-42,418
	7	2,665	-4,271	20,026	-310	-21,873	-1,140	90,916	-145,529	42,418	17,101
	8	6,174	-3,425	12,098	-266	-13,256	-4,172	35,036	-15,095	-17,101	0
	Sum	16,120	-84,609	197,983	-4,244	-212,998	-19,036	422,849	-316,089		
2020	**1**	0	-15,204	45,108	-2,300	-35,914	-882	46,074	-11,822	0	-25,057
	2	322	-1,856	5,146	-36	-582	-206	6	0	25,057	-27,857
	3	2,358	-39,975	50,908	217	-77,741	-6,551	88,929	-8,422	27,857	-37,581
	4	391	-1,425	5,959	-47	-4,241	-381	10,248	0	37,581	-48,098
	5	0	-8,769	29,410	432	-15,723	-861	76,929	-123,318	48,098	-6,193
	6	4,369	-8,632	29,329	3,236	-31,641	-2,800	73,328	-24,068	6,193	-49,329
	7	2,631	-3,984	20,026	-40	-16,241	-1,130	81,659	-150,719	49,329	18,469
	8	6,085	-3,224	12,075	-90	-11,523	-4,013	34,711	-15,559	-18,469	0
	Sum	16,156	-83,069	197,960	1,373	-193,607	-16,824	411,814	-333,908		

Table 10.3.1, continued

Year	Layer	Reservoir	ET	Recharge	GHBs	Streams	Drains	Storage	Wells	Top	Bottom
2030	**1**	0	-16,773	45,108	2,080	-35,745	-755	50,020	-13,397	0	-30,535
	2	322	-1,877	5,146	-35	-574	-206	1,033	0	30,535	-34,349
	3	2,388	-38,317	50,908	256	-75,370	-5,458	84,265	-9,336	34,349	-43,692
	4	391	-1,511	5,959	-6	-3,899	-368	11,018	0	43,692	-55,290
	5	0	-8,380	29,410	967	-12,524	-794	74,272	-130,887	55,290	-7,349
	6	4,447	-8,353	29,329	3,517	-28,368	-2,537	72,777	-25,296	7,349	-52,882
	7	2,626	-3,874	19,987	338	-12,456	-1,114	74,377	-152,437	52,882	19,673
	8	6,052	-3,052	12,113	-15	-9,932	-3,896	35,560	-17,165	-19,673	0
	Sum	16,226	-82,138	197,960	7,101	-178,869	-15,128	403,278	-348,515		
2040	**1**	0	-17,729	45,098	5,034	-35,584	-672	51,789	-13,712	0	-34,222
	2	322	-1,917	5,155	-31	-569	-206	1,988	0	34,222	-38,968
	3	2,408	-37,730	50,908	316	-73,736	-4,611	81,896	-10,086	38,968	-48,340
	4	392	-1,608	5,959	48	-3,578	-354	11,659	0	48,340	-60,871
	5	0	-8,386	29,410	1,489	-10,000	-742	73,202	-136,372	60,871	-9,468
	6	4,513	-8,120	29,329	3,966	-25,464	-2,326	73,460	-27,031	9,468	-57,812
	7	2,626	-3,782	19,977	891	-9,279	-1,107	74,273	-162,312	57,812	20,902
	8	6,043	-2,865	12,124	187	-8,514	-3,823	36,013	-18,273	-20,902	0
	Sum	16,304	-82,138	197,960	11,901	-166,723	-13,839	404,235	-367,786		

Table 10.3.1, continued

Year	Layer	Reservoir	ET	Recharge	GHBs	Streams	Drains	Storage	Wells	Top	Bottom
2050 DOR	1	0	-18,462	45,139	7,115	-35,528	-626	51,996	-14,210	0	-36,775
	2	321	-1,957	5,155	-19	-563	-206	2,647	0	36,775	-42,225
	3	2,420	-38,065	50,867	379	-72,906	-4,080	80,271	-10,811	42,225	-52,389
	4	392	-1,682	5,959	81	-3,342	-343	12,346	0	52,389	-66,132
	5	0	-8,408	29,337	1,664	-8,150	-708	73,005	-143,573	66,132	-11,538
	6	4,556	-7,992	29,403	4,440	-23,246	-2,170	73,448	-29,140	11,538	-62,820
	7	2,627	-3,697	19,977	1,381	-7,135	-1,102	77,940	-177,844	62,820	22,808
	8	6,044	-2,737	12,115	376	-7,510	-3,744	36,833	-19,697	-22,808	0
	Sum	16,361	-83,000	197,951	15,418	-158,379	-12,978	408,412	-395,271		
2050 Aver.	1	0	-32,563	124,437	7,468	-39,347	-633	-7,328	-14,210	0	-37,806
	2	320	-2,268	14,115	-27	-1,082	-219	-4,433	0	37,806	-44,217
	3	2,421	-47,797	154,406	310	-77,692	-3,960	-7,590	-10,811	44,217	-53,464
	4	390	-2,137	17,251	81	-4,163	-361	2,491	0	53,464	-67,026
	5	0	-13,236	83,371	1,738	-9,678	-727	26,959	-143,649	67,026	-11,789
	6	4,507	-12,975	83,573	4,388	-26,837	-2,271	30,568	-29,140	11,789	-63,614
	7	2,588	-6,835	53,349	1,417	-8,911	-1,116	51,007	-177,869	63,614	22,764
	8	6,012	-3,067	30,790	400	-8,423	-3,797	20,541	-19,697	-22,764	0
	Sum	16,238	-120,876	561,292	15,774	-176,131	-13,085	112,195	-395,372		

10.4 Northern Queen City and Sparta GAM

In this section we present the predictive simulation head and drawdown surfaces for the Northern Queen City and Sparta GAM. Drawdowns and recoveries of less than ten feet are not shown on the figures and are not considered in the discussions. Selected hydrographs are shown for the 2050 no DOR simulation. A comparison between the 2050 average recharge simulation and the 2050 DOR simulation is also included. Finally, we present the water budget for the predictive simulations.

10.4.1 Predictive Simulation Results

Figure 10.4.1 shows the simulated 2000 head surface for the Sparta aquifer. Figure 10.4.2 shows simulated 2010 head surface for the Sparta aquifer and the drawdown from 2000. The blank drawdown plot indicates that there were no changes that exceeded ten feet during that time period. The head and drawdown surfaces for 2020 are shown in Figure 10.4.3. The drawdown plot shows a few small areas of recovery along the outcrop and an area of drawdown along the eastern model boundary. This is may be a boundary effect. The 2030 Sparta aquifer head and drawdown surfaces (Figure 10.4.4) are almost identical to the 2020 surfaces. By 2040 (Figure 10.4.5), the drawdown along the eastern model boundary has increased slightly and some additional small drawdowns have appeared in Leon and Houston counties. By 2050 (Figure 10.4.6), two small areas of recovery have appeared in the downdip section in Trinity and Jasper and Newton counties. The maximum water level change from 2000 to 2050 is less than 50 feet.

The 2000 simulated head surface for the Queen City aquifer is shown in Figure 10.4.7. Queen City aquifer heads and drawdowns for 2010 (Figure 10.4.8) show only slight recovery in isolated areas, with the only area of significant size along the Nacogdoches/Angelina county line. This is probably due to the rebound seen in the Carrizo Formation heads in the Lufkin area. By 2020 (Figure 10.4.9), several small areas of drawdown have developed in Leon, Anderson, Cherokee, Wood, Morris, and Cass counties. Also, as with the Sparta aquifer, an area of drawdown developed along the eastern model boundary. As noted previously, this may be a boundary effect. By 2030 (Figure 10.4.10), the drawdowns have increased slightly and a few new areas have appeared in Marion, Nacogdoches, and Houston counties, as well as in the counties previously mentioned. Significant areas of recovery can be seen in Leon, Nacogdoches, Smith, Wood, and Upshur counties. By 2040 (Figure 10.4.11), it can be seen that most of the significant areas of drawdown are along the major rivers (Trinity, Sabine, and Neches rivers). Many of the areas showing significant recovery are in areas between the major streams. Figure 10.4.12 shows that drawdowns continue to increase in 2050. The maximum water level change from 2000 to 2050 is less than 75 feet.

Figure 10.4.13 shows the simulated Carrizo Formation head surface for the year 2000. In the ten year period from 2000 to 2010, several large areas experience drawdown and recovery (Figure 10.4.14). The most significant drawdown occurs in Smith County (almost 50 ft) and extends slightly into some neighboring counties. Another large area of drawdown developed in Leon, Madison, and Grimes counties. This drawdown along the western model boundary is due to pumping in the Central model area. A large area of recovery, including parts of several counties, developed in an area centered around the city of Lufkin in Angelina County. Rebound in excess of 75 feet has occurred in the center of this area. Additional areas of recovery developed in Cherokee, Upshur, Morris, and Cass counties. By 2020 (Figure 10.4.15), the drawdown centered in Smith County has increased to over 75 feet and the recovery in the Angelina/Nacogdoches area has increased to almost 100 feet. The area of drawdown along the western edge of the model has increased in size, but the magnitude remained below 25 feet. The areas of recovery in Upshur, Morris, and Cass counties have joined into a single area of recovery, but the magnitude of this recovery remained below 25 feet.

By 2030 (Figure 10.4.16), the drawdown in Smith County has increased to over 100 feet. The recovery in the Angelina/Nacogdoches area has decreased slightly to less than 90 feet, indicating that some drawdown has occurred in this area between 2020 and 2030. The area of drawdown along the western edge of the model has increased only slightly in size, but the magnitude has increased to more than 25 feet. By 2040 (Figure 10.4.17), the drawdown in Smith County has increased to over 135 feet and the recovery in the Angelina/Nacogdoches area has decreased almost another ten feet since 2030, indicating a continued reversal of the original recovery in that area. The drawdown along the western edge of the model continued to increase. At the end of the predictive time period in 2050 (Figure 10.4.18), drawdown in Smith County has exceeded 150 feet and drawdown along the western edge of the model is more than 40 feet.

By 2050, heads in the Angelina/Nacogdoches area, which had shown almost 100 feet of recovery by 2020, have dropped over 30 feet from the levels of maximum recovery. Drawdown occurred in this area over the last 30 years of the predictive time period. Recoveries in the area around Upshur, Morris, and Cass counties remained below 25 feet through 2050. Recovery in Cherokee exceeded 50 feet.

The number of dry cells increased in the predictive simulation from 49 dry cells in 2000 to 73 dry cells in 2050. Of the 73 dry cells in 2050, five were in the Queen City and there were none in the Sparta. All dry cells occurred in or very near the outcrop. Since there are over 20,000 outcrop cells, the number of dry cells has little impact on the model.

Selected hydrographs for the transient calibration period and the subsequent 50 year predictive period are shown in Figures 10.4.19 through 10.4.21. The 2050 predictive simulation without the DOR was used to produce the hydrographs. Sparta aquifer hydrographs (Figure 10.4.19) show mostly flat (Madison) to slightly increasing (Wood, Nacogdoches) or decreasing (Cherokee, Houston) trends, with ranges of generally less than 20 feet. Madison County well 6003202 shows a sudden drop in water level at the beginning of the predictive period, followed by a very slightly increasing trend. The sudden drop is probably due to different pumping allocations between the historical and predictive periods.

Queen City aquifer hydrographs (Figure 10.4.20) show similar trends to the Sparta hydrographs, with mostly gently increasing or decreasing trends. However, the head change over the 70-year time period is higher for the Queen City aquifer than for the Sparta aquifer. Overall, the Carrizo Formation hydrographs (Figure 10.4.21) show much steeper increases and decreases than those for the Sparta and Queen City aquifers. This is to be expected since there is much more pumping in the Carrizo-Wilcox aquifer. The hydrographs from Smith and Madison counties show significant drawdown, while the hydrographs from Angelina and Nacogdoches counties show a large recovery followed by slight drawdowns. The hydrographs from Anderson and Cass counties show flatter trends.

Figure 10.4.22 shows the differences between the simulated head surfaces for 2050 with average recharge and the simulated head surfaces for 2050 with the DOR for the Sparta aquifer, the Queen City aquifer, and the Carrizo Formation. In all of these layers there is a maximum head difference of less than five feet. All of the simulated head differences are in or near the outcrop, where recharge will have the most impact. These figures emphasize an important point about the hydrology of this aquifer system. Recharge does not have a significant impact on downdip heads over the timescale of these simulations. One aspect of these simulations that is misleading is that pumping does not increase during the DOR. The DOR only impacts climate data and subsequently, recharge. Therefore, the effect of a DOR will be seen predominantly in the updip and outcrop areas.

10.4.2 Predictive Simulation Water Budget

Table 10.4.1 shows the water budget for the predictive simulations. The table shows the water budget for 1990, 2000, and the final year of each of the predictive simulations. In general, the predictive simulation water budget shows similar trends and variations to that of the calibration/verification simulations. There is a decrease in overall pumping as the model passes from the historical period into the predictive period. Total model area pumping in 1999 was about 168,000 acre-ft/yr. Predictive pumping for 2000 was about 148,500, a decrease of almost 12% from 1999 levels. However, pumping in the Sparta aquifer remained about the same between 1999 and 2000, and Queen City aquifer pumping increased almost 20%.

Table 10.4.1 shows that predicted pumping increases over the predictive period (2000-2050) by about 23,000 acre-ft/yr, an increase of about 16% over 2000 predicted levels. However, the model shows an overall trend of water-level increase in the confined section. For the Sparta aquifer, predictive pumping increases about 60% between 2000 and 2050. Queen City aquifer predictive pumping drops from about 12,500 acre-ft/yr in 2000 to about 8,700 acre-ft/yr in 2050.

As with the calibration/verification simulations, the amount of leakance from the streams and reservoirs can vary significantly through time. In all years shown in the table, the streams are showing a net gain of between 300,000 and 400,000 acre-ft/yr, with the highest stream gain in 2050 under average conditions (non-drought). Reservoirs show a net loss of about 25,000 acre-ft/yr throughout the time period. Drains remove about 20,000 acre-ft/yr throughout the time period. Water is being removed from storage during the drought years. Comparing the 2050 results with average recharge conditions to the 2050 DOR results shows that the difference between average and drought condition recharge is just over 600,000 acre-ft/yr, over half of the average recharge.

Table 10.4.1 Water budget for Northern model predictive simulations. All rates reported in acre-ft/yr.

Year	Layer	Reservoir	ET	Recharge	GHBs	Streams	Drains	Storage	Wells	Top	Bottom
1990	**1**	2,461	-30,115	177,106	7,258	-33,186	-1,031	-64,746	-4,566	0	-53,180
	2	2,216	-609	13,916	-57	-967	-206	-16,403	0	53,180	-51,070
	3	4,142	-72,492	302,795	-1,240	-106,454	-411	-136,076	-9,629	51,070	-31,696
	4	684	-1,245	38,452	-43	-7,100	-11	-17,580	0	31,696	-44,854
	5	93	-23,802	163,293	2,817	-35,353	-177	-52,323	-64,551	44,854	-34,848
	6	9,786	-28,866	197,180	-198	-49,585	-10,367	-97,200	-37,368	34,848	-18,228
	7	3,258	-33,529	330,952	-1,511	-95,781	-4,183	-164,249	-35,611	18,228	-17,571
	8	5,813	-4,097	17,182	2,309	-3,470	-840	-25,832	-8,634	17,571	0
	Sum	28,454	-194,755	1,240,875	9,336	-331,895	-17,226	-574,409	-160,360		
2000	**1**	1,790	-26,052	140,050	6,105	-37,199	-1,432	-25,010	-3,376	0	-54,881
	2	1,678	-695	10,798	-61	-1,800	-279	-12,112	0	54,881	-52,410
	3	3,342	-81,477	275,641	-1,300	-113,875	-568	-88,919	-12,501	52,410	-32,769
	4	486	-1,320	33,225	-51	-8,520	-17	-13,693	0	32,769	-42,876
	5	-10	-34,080	131,863	2,742	-37,045	-314	-14,787	-56,864	42,876	-34,386
	6	10,903	-40,022	166,280	-2,037	-53,725	-9,233	-54,264	-34,299	34,386	-17,999
	7	3,521	-38,121	278,448	-4,111	-104,066	-4,128	-107,135	-35,108	17,999	-7,307
	8	4,797	-3,633	18,680	-800	-4,038	-1,056	-14,812	-6,446	7,307	0
	Sum	26,506	-225,399	1,054,986	488	-360,269	-17,027	-330,732	-148,594		
2010	**1**	1,384	-17,900	52,766	5,307	-32,907	-1,672	47,314	-3,729	0	-50,562
	2	1,305	-711	4,381	-67	-1,638	-328	-1,725	0	50,562	-51,778
	3	3,257	-69,367	118,209	-1,357	-109,887	-648	48,141	-7,767	51,778	-32,354
	4	344	-1,444	15,642	-53	-8,257	-22	1,813	0	32,354	-40,377
	5	-72	-23,705	61,080	2,981	-32,131	-413	44,522	-57,485	40,377	-35,151
	6	11,374	-32,395	75,491	-4,921	-49,968	-8,797	27,423	-34,957	35,151	-18,399
	7	4,242	-33,682	119,660	-10,396	-95,081	-3,876	47,145	-42,887	18,399	-3,522
	8	4,589	-3,699	7,191	-5,210	-5,020	-1,075	4,781	-5,077	3,522	0
	Sum	26,423	-182,903	454,420	-13,715	-334,890	-16,830	219,414	-151,903		

Table 10.4.1, continued

Year	Layer	Reservoir	ET	Recharge	GHBs	Streams	Drains	Storage	Wells	Top	Bottom
2020	**1**	1,142	-19,023	52,766	4,775	-33,250	-1,879	48,749	-4,083	0	-49,200
	2	1,059	-793	4,381	-71	-1,770	-358	69	0	49,200	-51,716
	3	3,189	-72,786	118,209	-1,394	-109,591	-747	52,120	-8,454	51,716	-32,277
	4	246	-1,635	15,642	-61	-8,164	-27	2,207	0	32,277	-40,482
	5	-110	-24,730	61,074	2,626	-32,199	-565	46,696	-58,386	40,482	-34,891
	6	11,416	-33,168	75,498	-6,038	-49,638	-8,771	30,238	-35,476	34,891	-18,961
	7	4,208	-37,876	119,660	-10,841	-96,178	-3,971	51,333	-43,047	18,961	-2,260
	8	4,457	-4,231	7,191	-6,403	-5,157	-1,085	6,924	-3,959	2,260	0
	Sum	25,606	-194,242	454,420	-17,408	-335,947	-17,403	238,336	-153,406		
2030	**1**	994	-20,034	52,766	4,390	-33,646	-2,042	50,072	-4,515	0	-47,985
	2	896	-852	4,381	-74	-1,879	-376	1,275	0	47,985	-51,357
	3	3,128	-77,383	118,209	-1,413	-110,068	-859	58,687	-9,138	51,357	-32,515
	4	179	-1,847	15,642	-72	-8,089	-32	3,216	0	32,515	-41,512
	5	-135	-25,327	61,034	2,365	-32,271	-705	48,574	-61,291	41,512	-33,753
	6	11,419	-34,111	75,538	-5,755	-49,903	-8,788	33,686	-36,741	33,753	-19,094
	7	4,163	-42,765	119,660	-11,038	-98,209	-4,120	59,153	-43,995	19,094	-1,940
	8	4,378	-4,673	7,191	-5,772	-5,303	-1,090	7,487	-4,157	1,940	0
	Sum	25,020	-206,991	454,420	-17,369	-339,368	-18,013	262,151	-159,837		
2040	**1**	903	-21,018	52,766	4,125	-34,022	-2,173	51,556	-4,911	0	-47,228
	2	788	-970	4,381	-76	-1,955	-387	2,229	0	47,228	-51,238
	3	3,080	-82,531	118,175	-1,421	-111,045	-983	64,713	-8,336	51,238	-32,906
	4	132	-2,054	15,676	-79	-8,033	-38	4,138	0	32,906	-42,645
	5	-152	-25,695	61,034	2,216	-32,296	-827	49,946	-63,847	42,645	-33,028
	6	11,405	-35,147	75,538	-6,688	-50,467	-8,816	39,064	-38,760	33,028	-19,168
	7	4,108	-47,869	119,660	-12,043	-100,512	-4,216	68,745	-45,370	19,168	-1,683
	8	4,318	-4,967	7,191	-6,932	-5,447	-1,093	9,678	-4,433	1,683	0
	Sum	24,582	-220,251	454,420	-20,899	-343,776	-18,534	290,070	-165,657		

Table 10.4.1, continued

Year	Layer	Reservoir	ET	Recharge	GHBs	Streams	Drains	Storage	Wells	Top	Bottom
2050	**1**	846	-21,855	52,766	3,988	-34,330	-2,284	52,848	-5,410	0	-46,568
	2	715	-1,049	4,381	-77	-2,022	-394	3,013	0	46,568	-51,136
	3	3,042	-87,233	118,175	-1,424	-112,172	-1,119	71,697	-8,667	51,136	-33,428
	4	99	-2,246	15,676	-76	-7,990	-45	5,239	0	33,428	-44,086
	5	-164	-25,946	61,034	2,182	-32,282	-931	51,154	-67,218	44,086	-31,912
	6	11,380	-36,139	75,538	-6,874	-51,099	-8,853	42,664	-39,422	31,912	-19,105
	7	4,013	-53,215	119,660	-12,570	-102,845	-4,304	78,048	-46,313	19,105	-1,576
	8	4,221	-5,239	7,191	-7,156	-5,585	-1,095	10,715	-4,628	1,576	0
	Sum	24,153	-232,921	454,420	-22,006	-348,326	-19,025	315,378	-171,656		
2050*	**1**	843	-35,957	140,050	3,949	-39,563	-2,324	-13,130	-5,410	0	-48,459
	2	715	-1,398	10,798	-77	-2,427	-395	-3,344	0	48,459	-52,331
	3	3,036	-108,765	275,451	-1,427	-118,975	-1,153	-58,105	-8,667	52,331	-33,720
	4	99	-2,949	33,415	-77	-9,294	-46	-10,449	0	33,720	-44,421
	5	-165	-43,356	131,773	2,065	-37,752	-977	3,777	-67,218	44,421	-32,565
	6	10,986	-45,977	166,370	-6,876	-56,264	-9,246	-32,655	-39,422	32,565	-19,478
	7	3,715	-68,124	278,448	-12,616	-113,664	-5,501	-53,576	-46,313	19,478	-1,845
	8	4,167	-6,319	18,680	-7,180	-6,040	-1,100	576	-4,628	1,845	0
	Sum	23,396	-312,845	1,054,986	-22,238	-383,980	-20,742	-166,906	-171,656		

*Does not include drought of record

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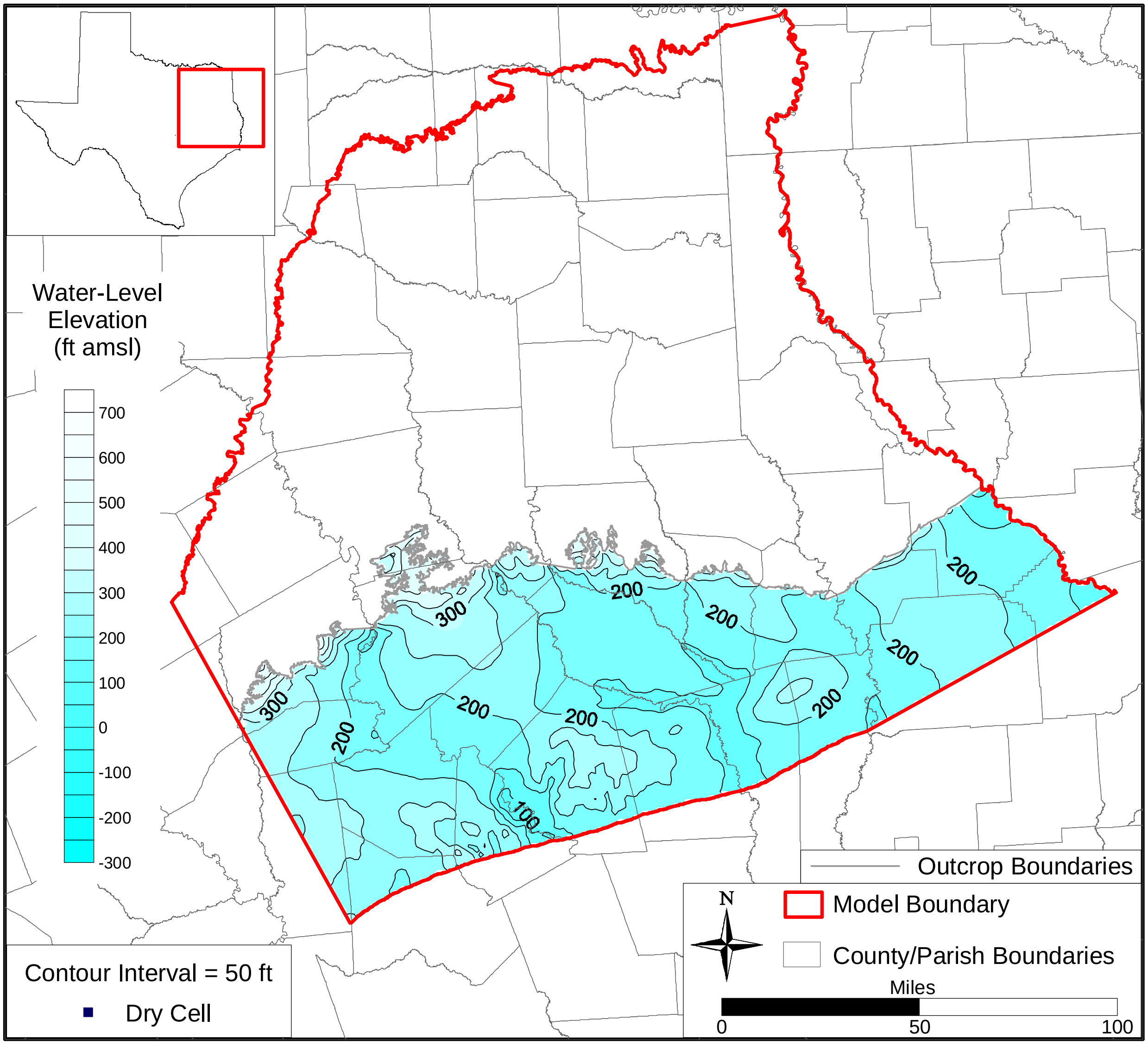

Figure 10.4.1 Simulated 2000 head surface for the Sparta aquifer (Layer 1).

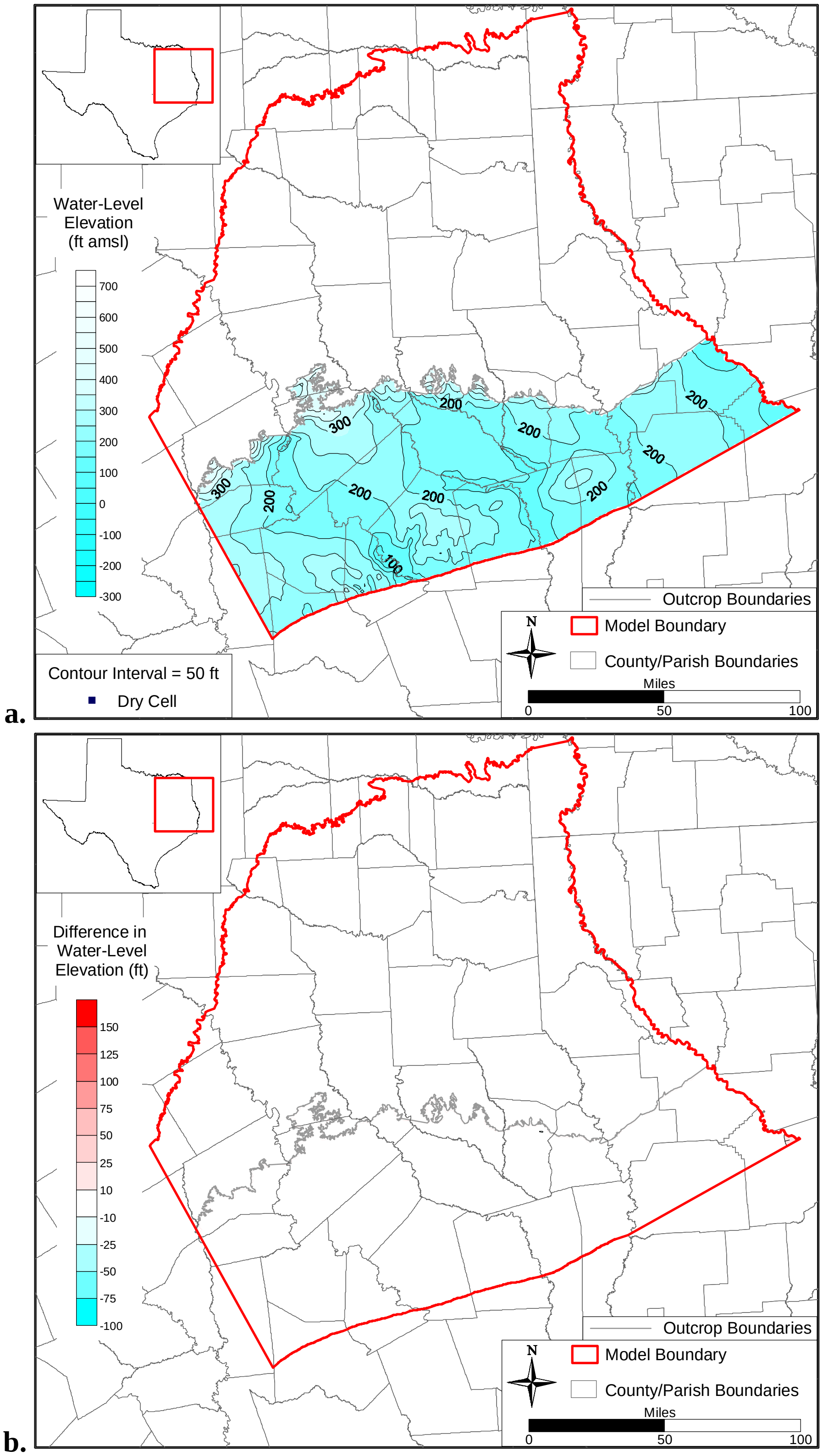

Figure 10.4.2 Simulated 2010 head surface (a) and drawdown from 2000 (b), Sparta aquifer (Layer 1).

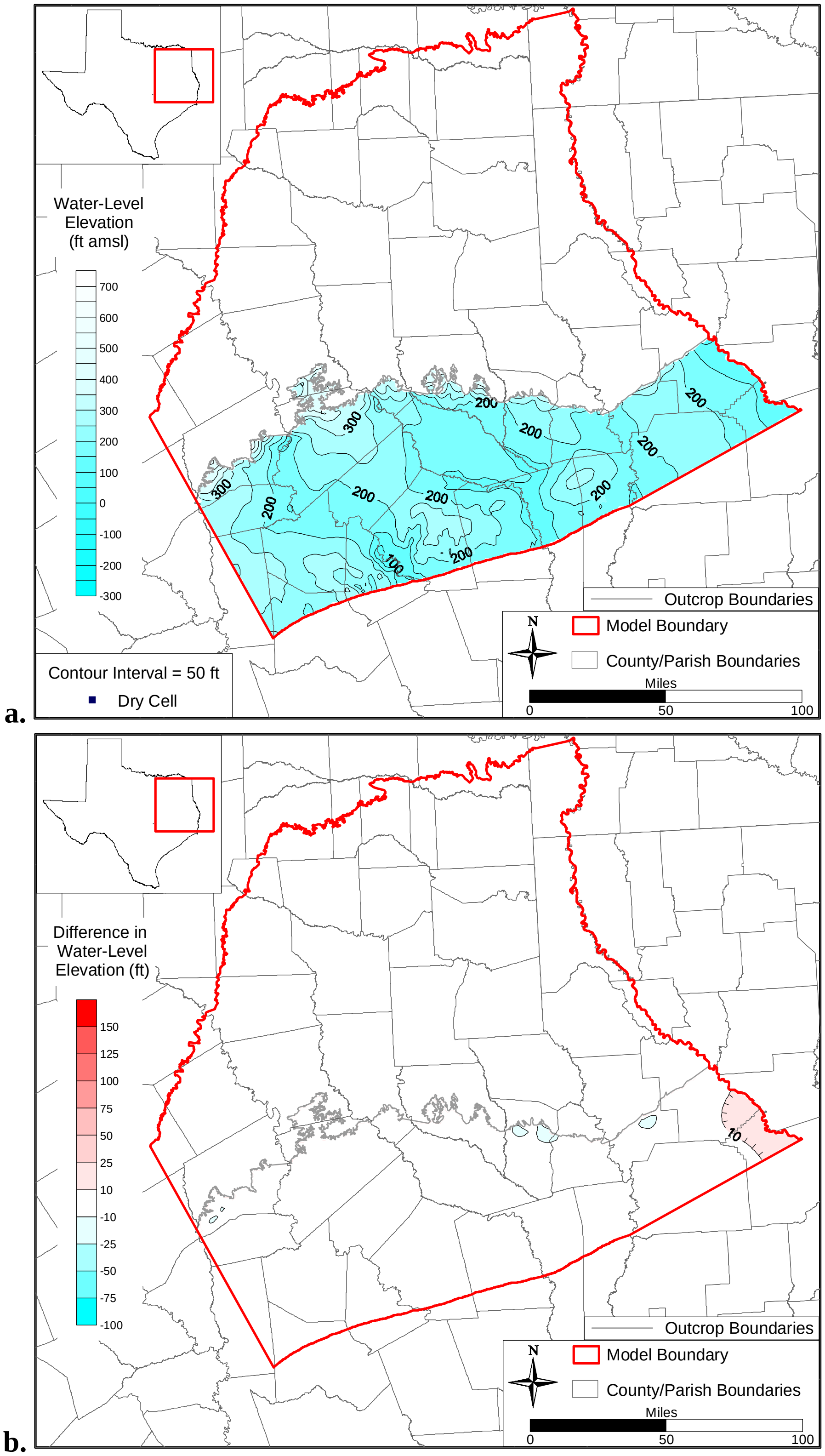

Figure 10.4.3 Simulated 2020 head surface (a) and drawdown from 2000 (b), Sparta aquifer (Layer 1).

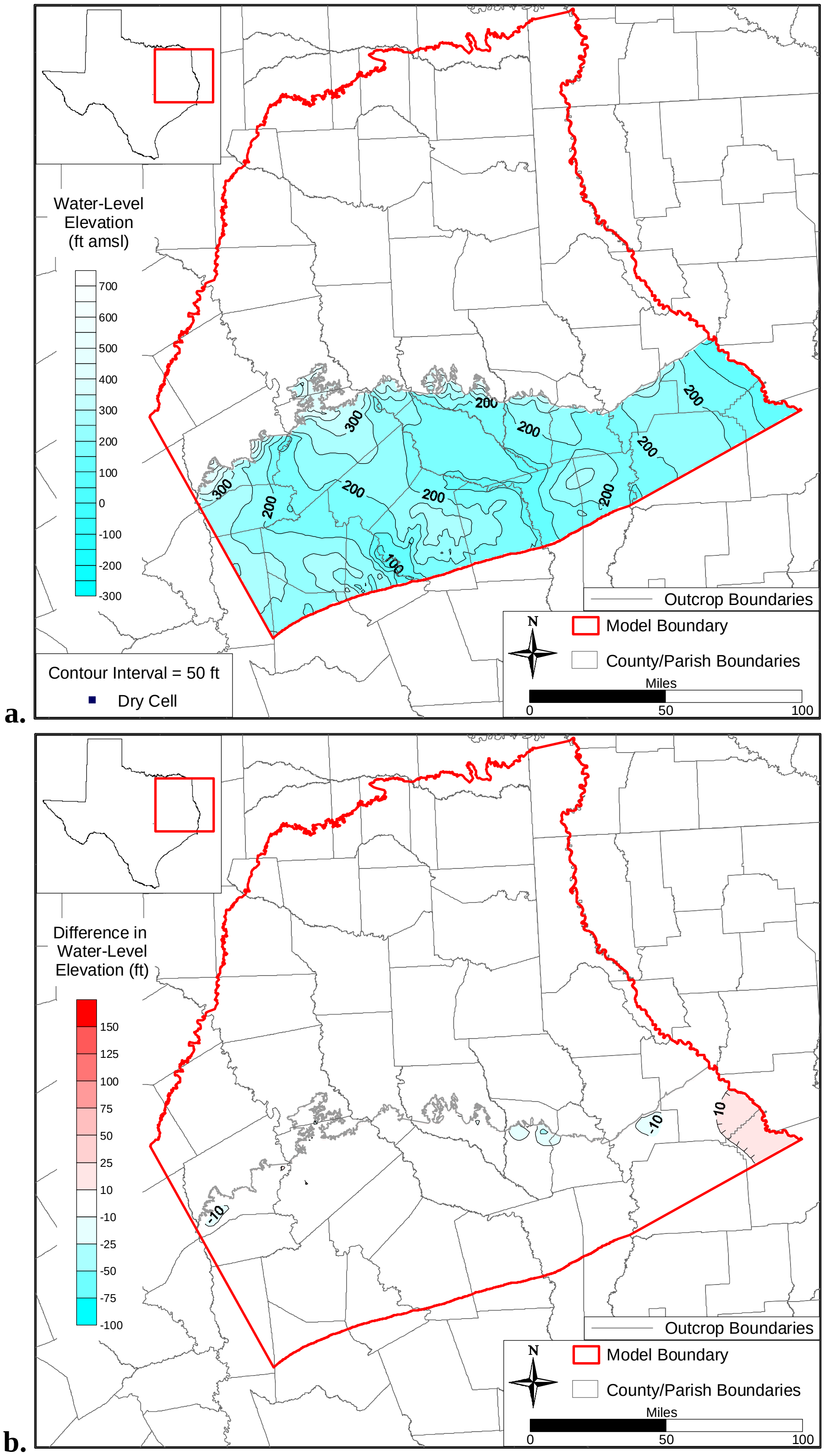

Figure 10.4.4 Simulated 2030 head surface (a) and drawdown from 2000 (b), Sparta aquifer (Layer 1).

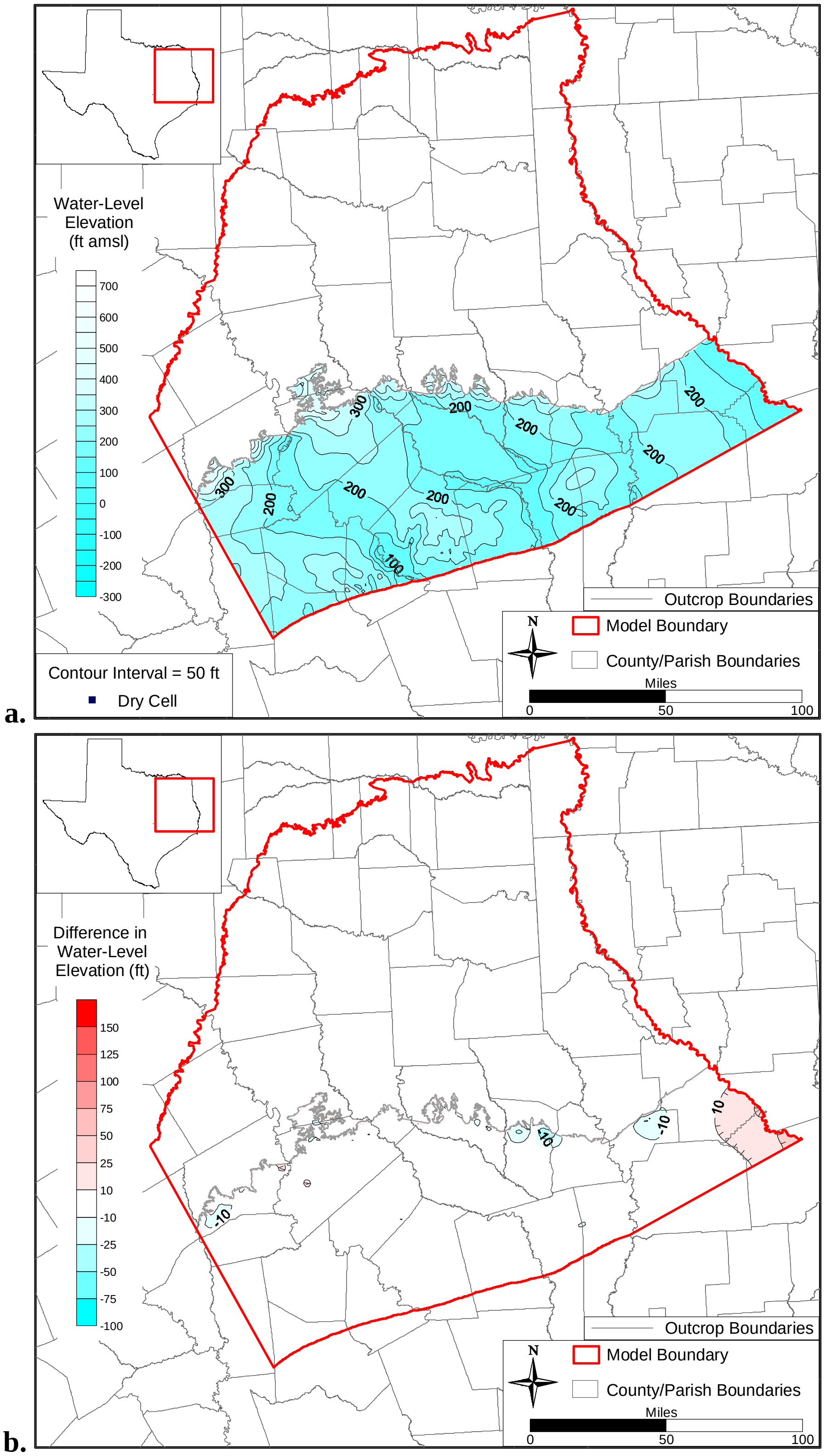

Figure 10.4.5 Simulated 2040 head surface (a) and drawdown from 2000 (b), Sparta aquifer (Layer 1).

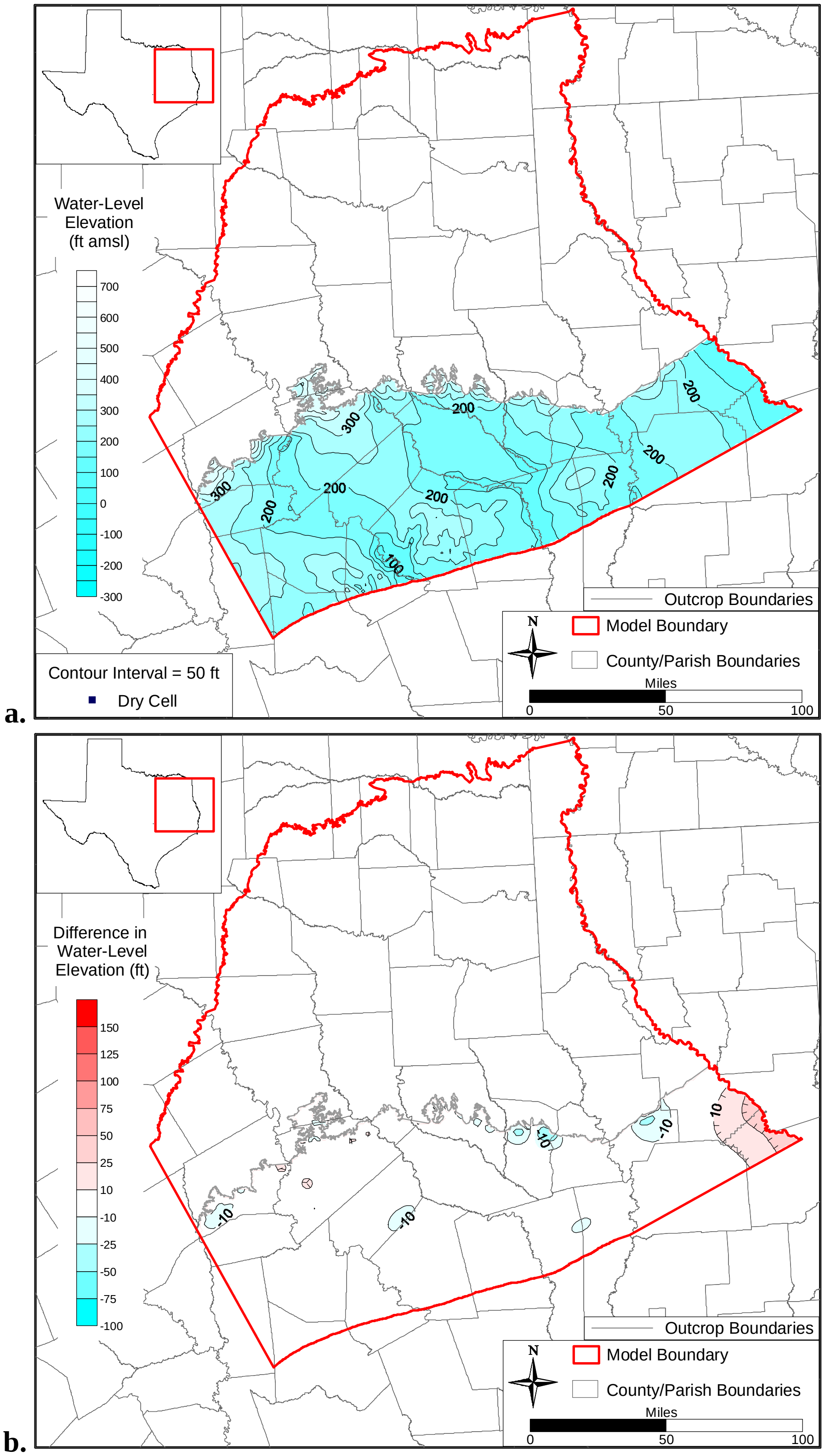

Figure 10.4.6 Simulated 2050 head surface (a) and drawdown from 2000 (b), Sparta aquifer (Layer 1).

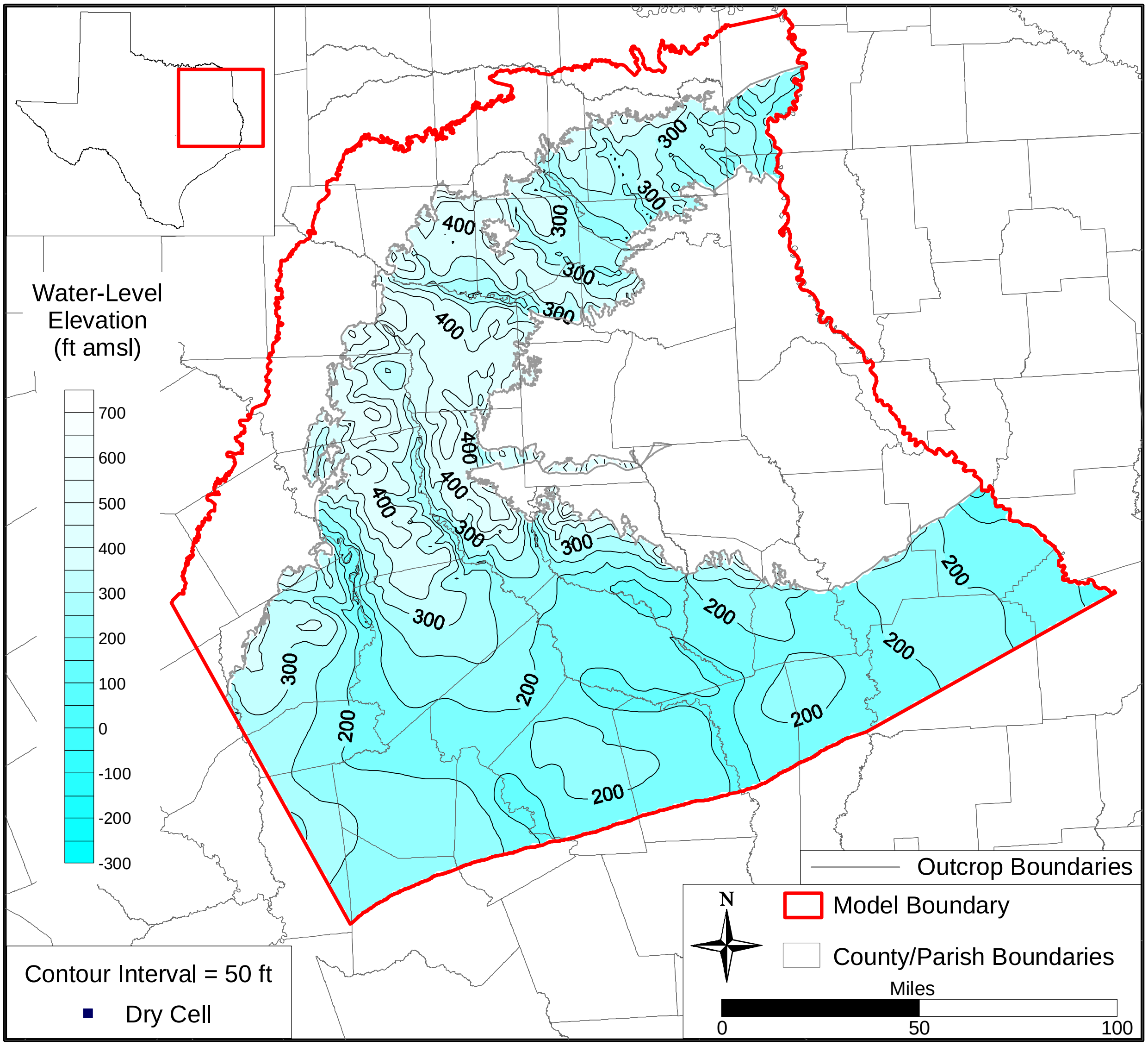

Figure 10.4.7 Simulated 2000 head surface for the Queen City aquifer (Layer 3).

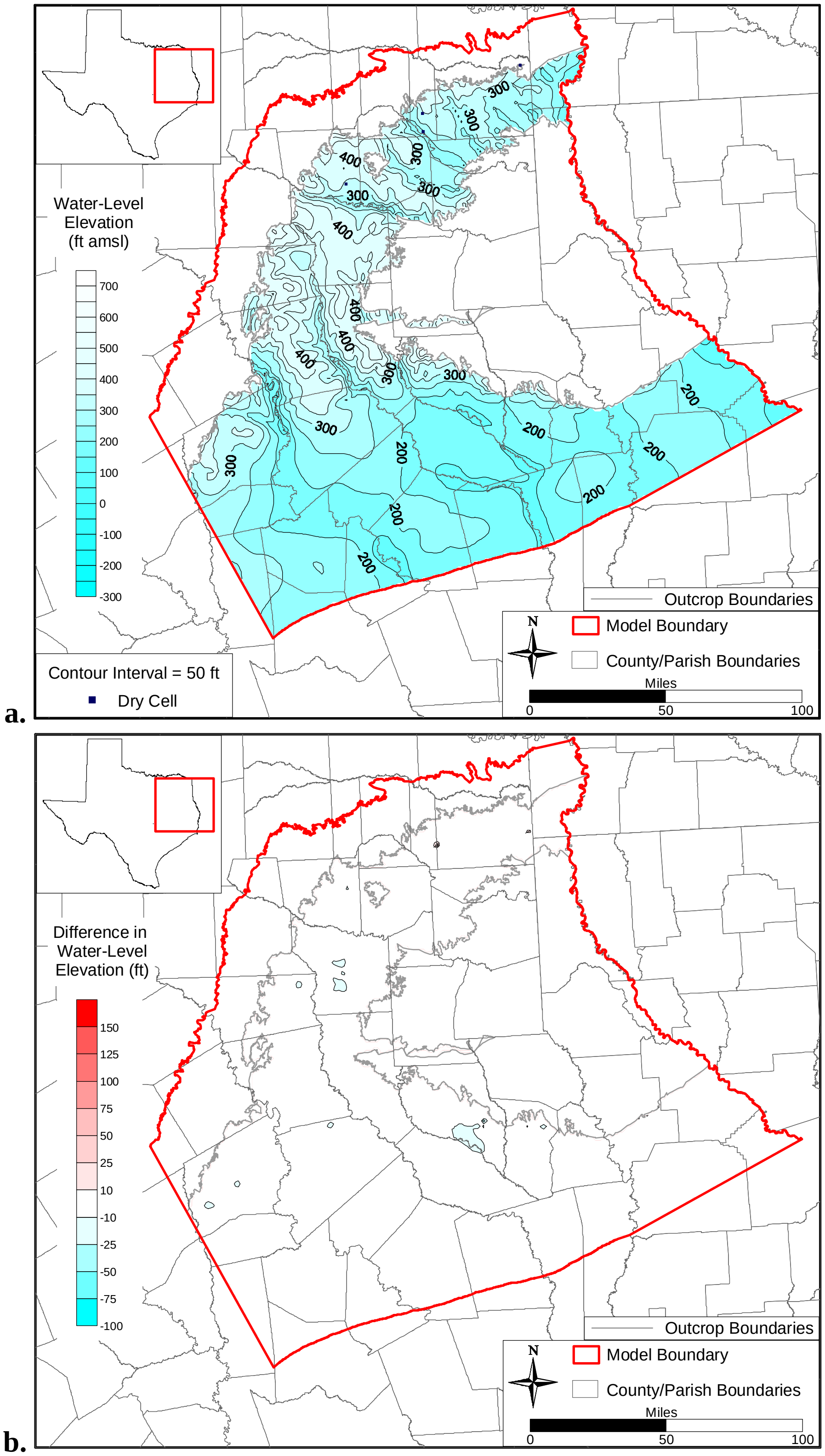

Figure 10.4.8 Simulated 2010 head surface (a) and drawdown from 2000 (b), Queen City aquifer (Layer 3).

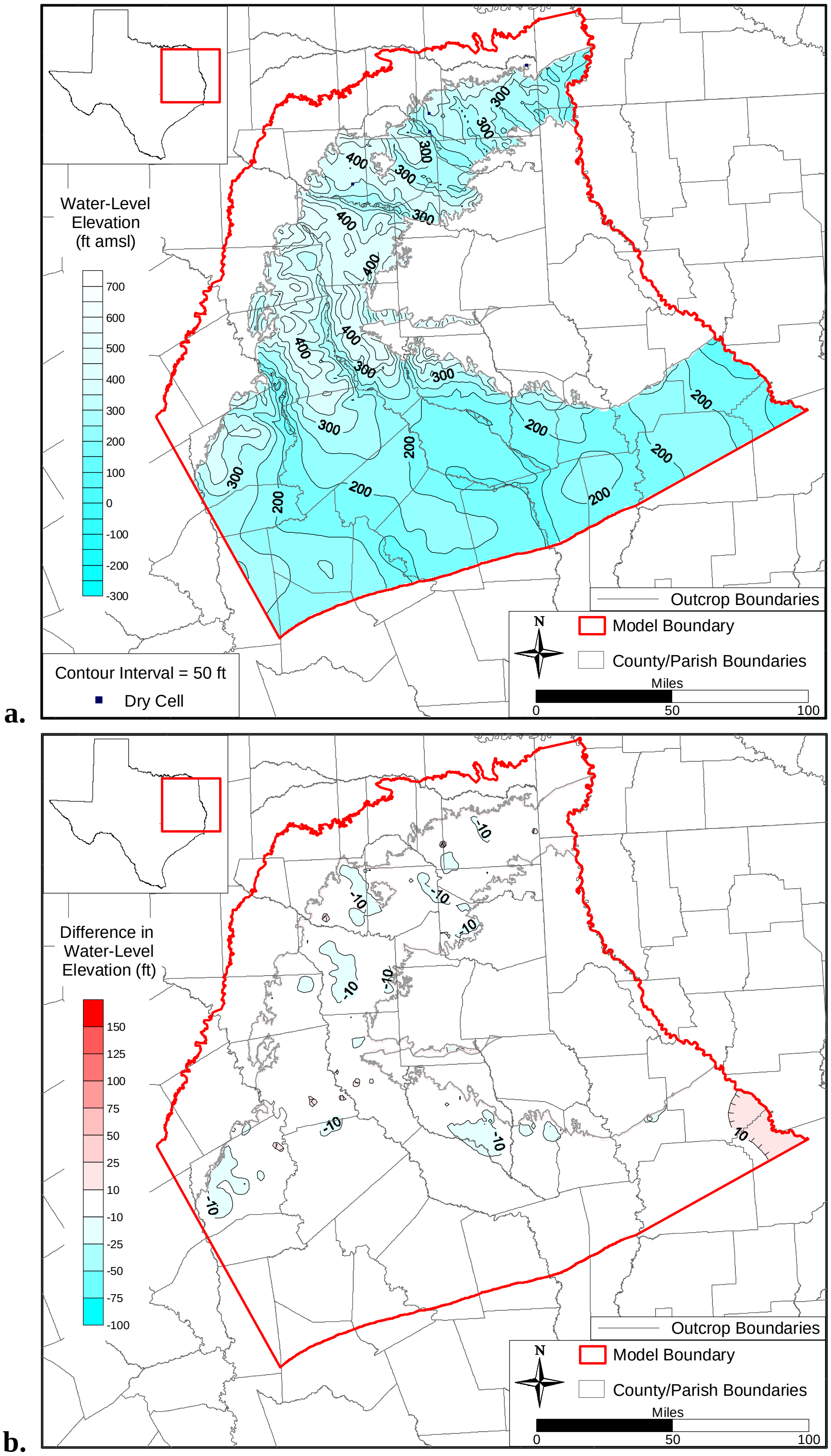

Figure 10.4.9 Simulated 2020 head surface (a) and drawdown from 2000 (b), Queen City aquifer (Layer 3).

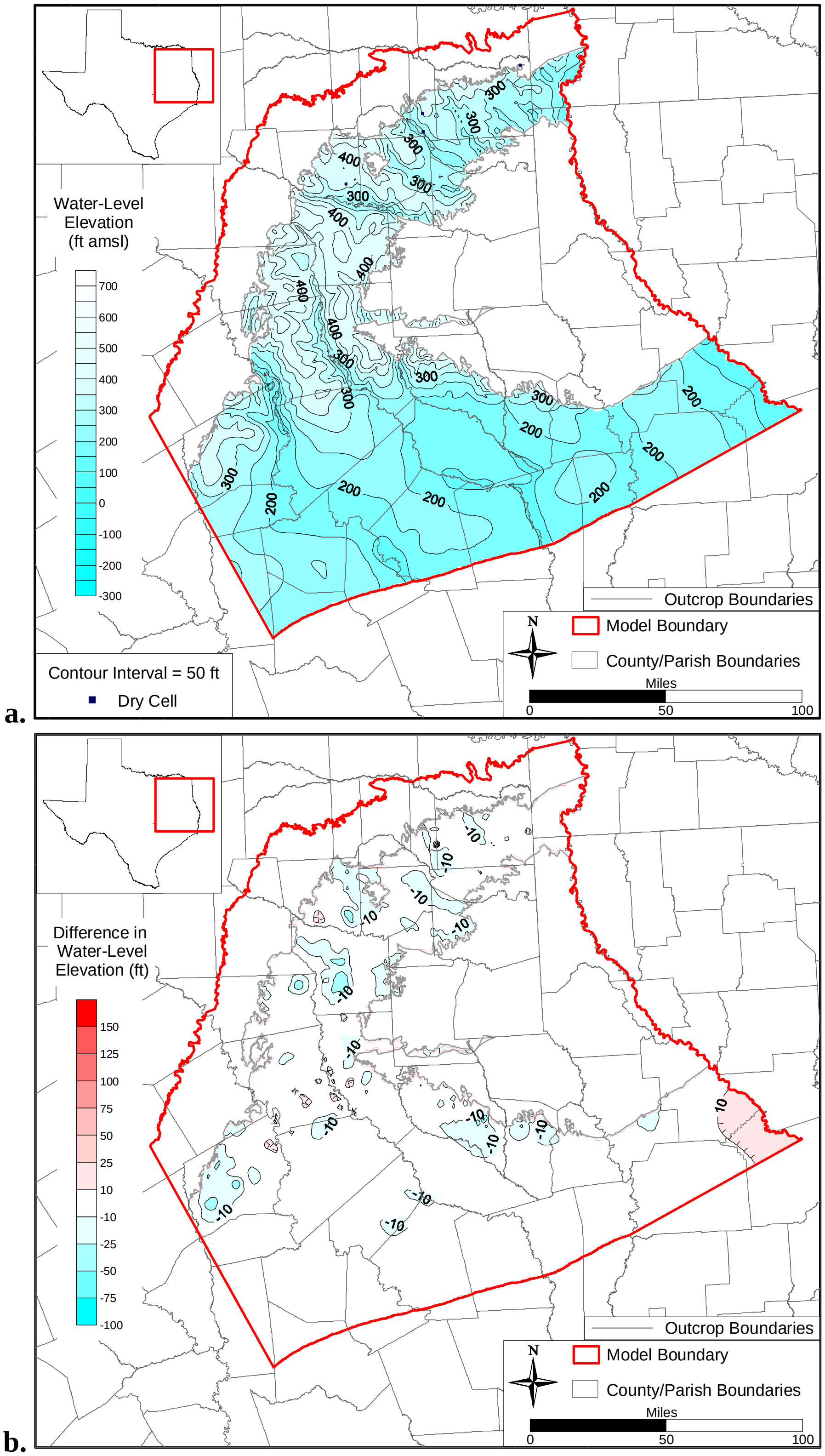

Figure 10.4.10 Simulated 2030 head surface (a) and drawdown from 2000 (b), Queen City aquifer (Layer 3).

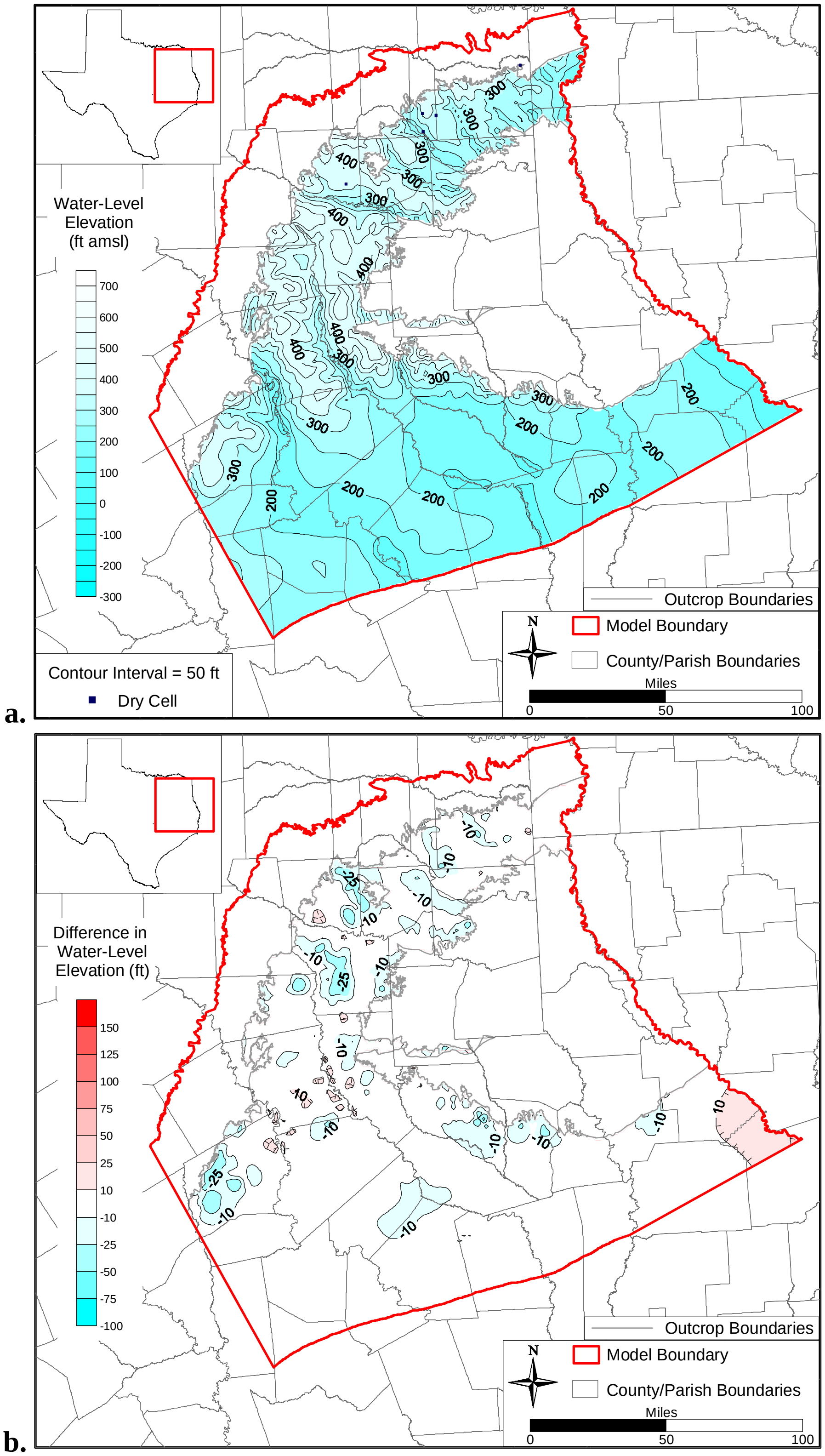

Figure 10.4.11 Simulated 2040 head surface (a) and drawdown from 2000 (b), Queen City aquifer (Layer 3).

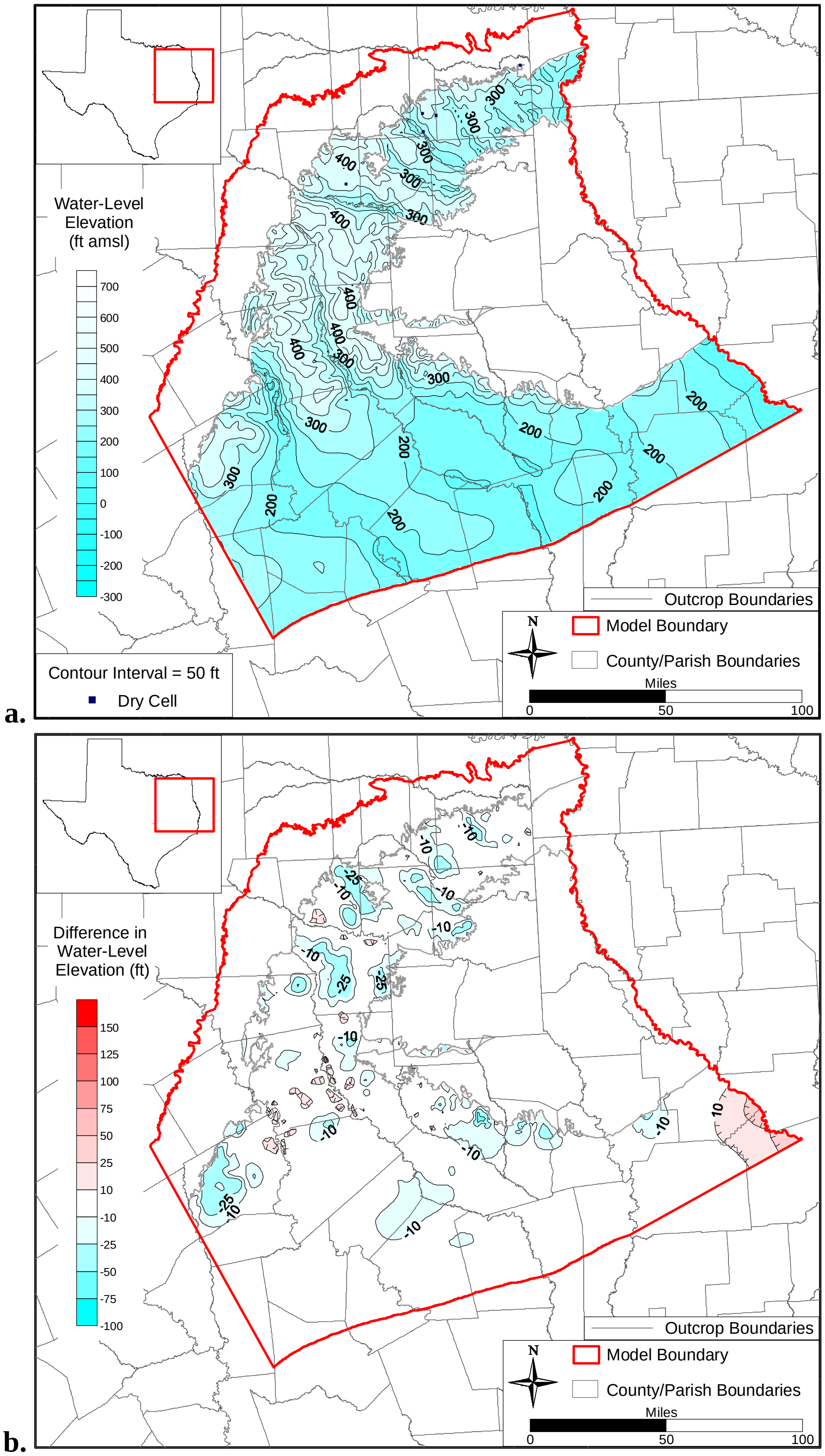

Figure 10.4.12 Simulated 2050 head surface (a) and drawdown from 2000 (b), Queen City aquifer (Layer 3).

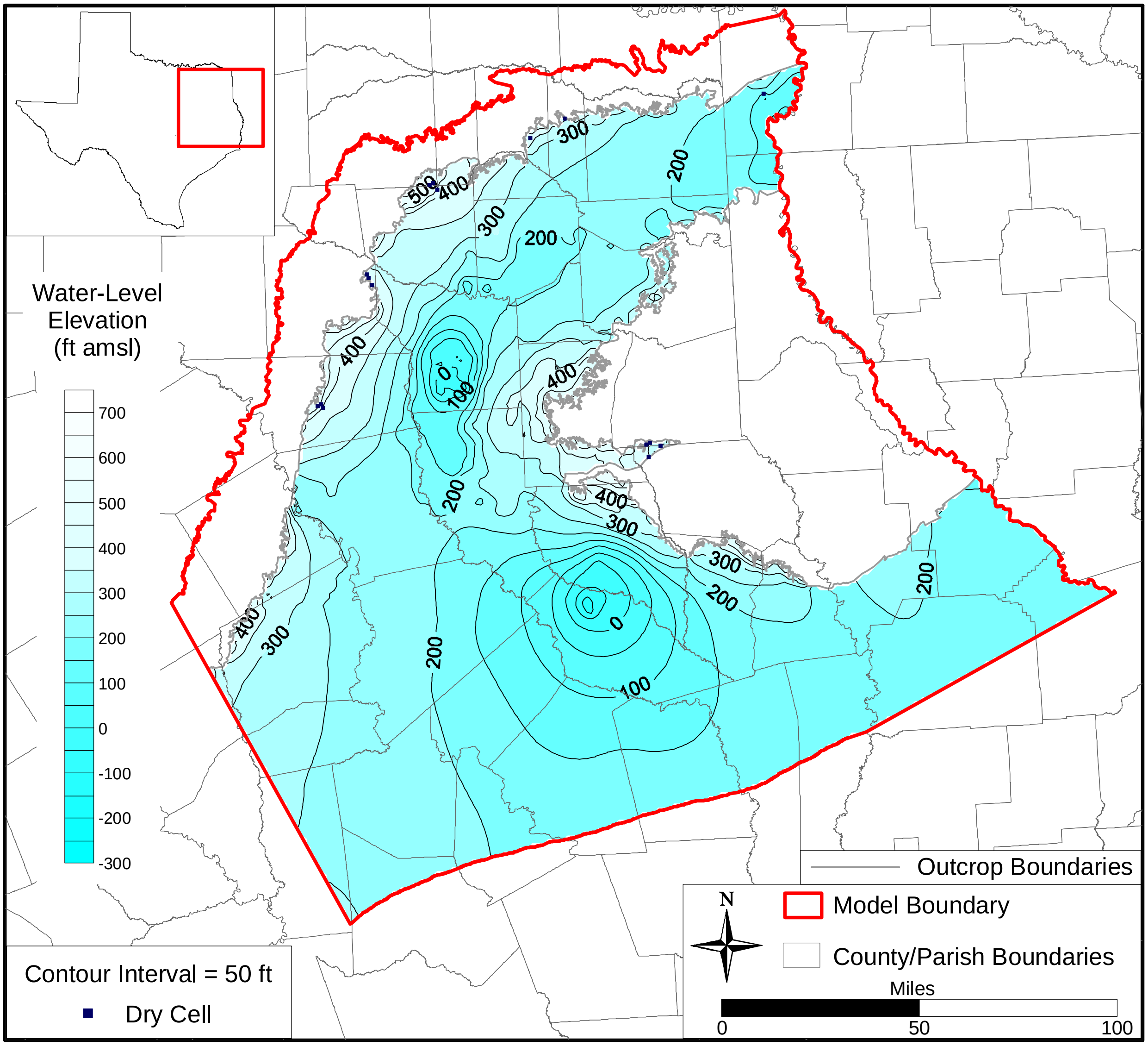

Figure 10.4.13 Simulated 2000 head surface for the Carrizo Formation (Layer 5).

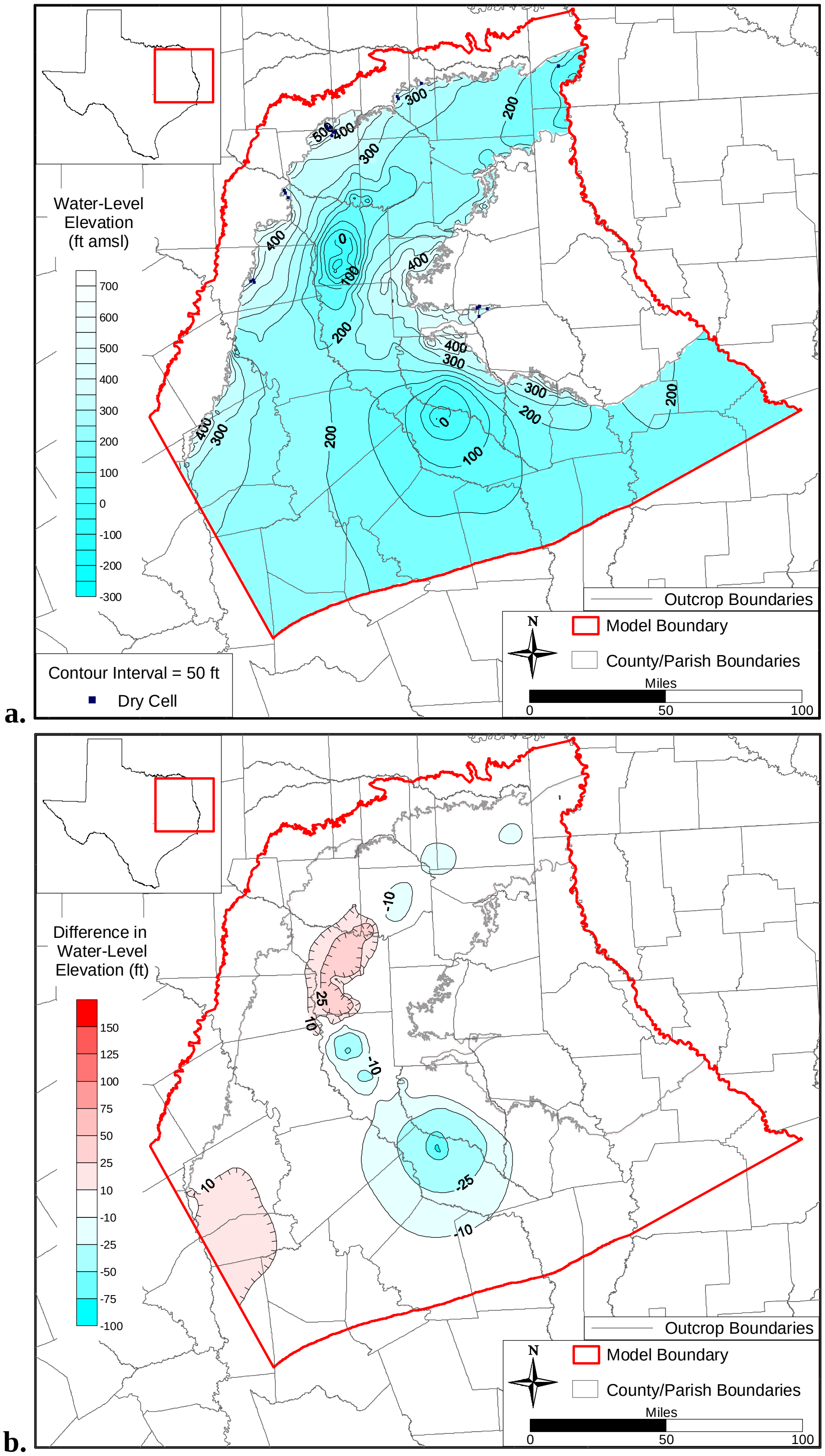

Figure 10.4.14 Simulated 2010 head surface (a) and drawdown from 2000 (b), Carrizo Formation (Layer 5).

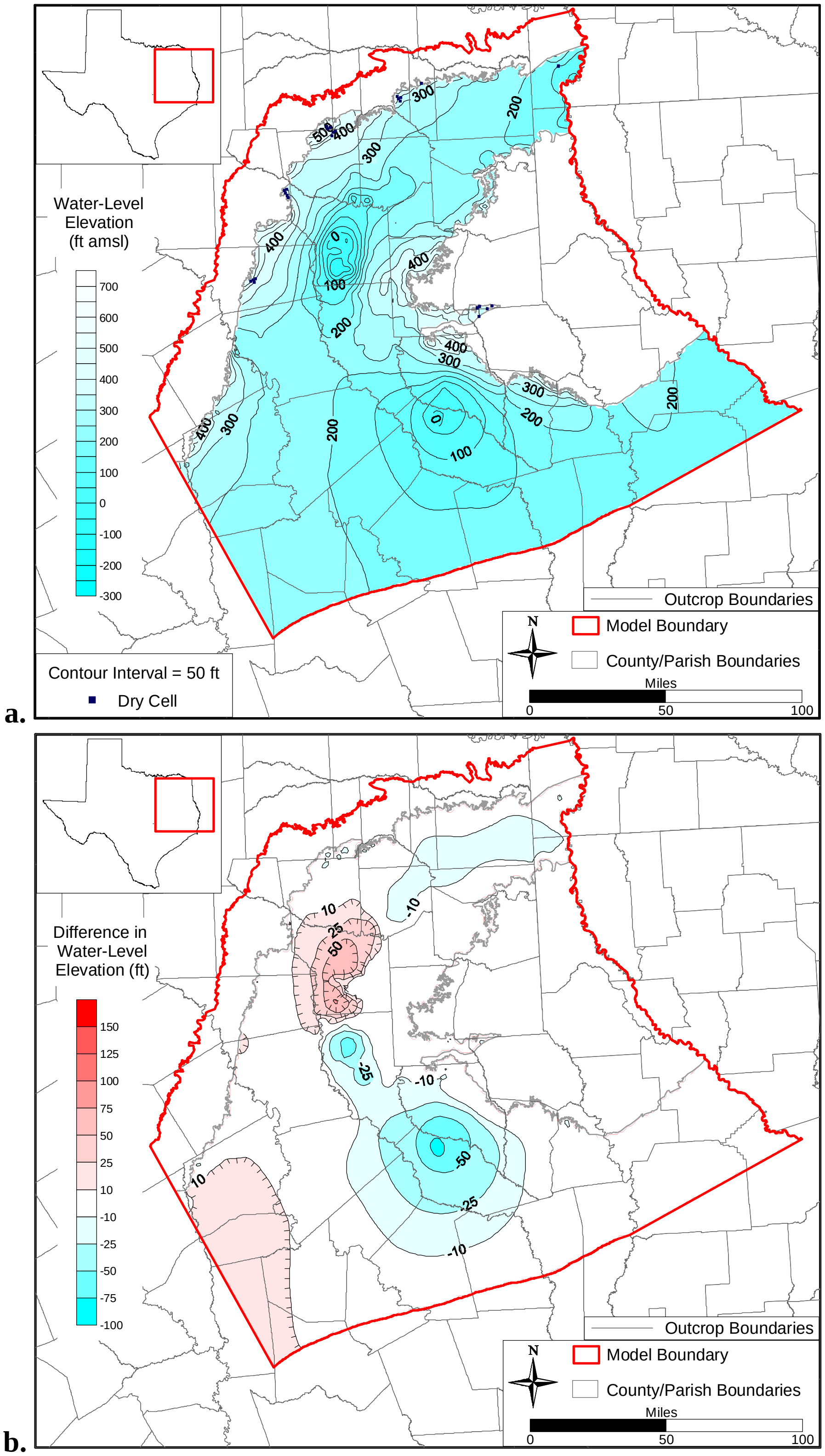

Figure 10.4.15 Simulated 2020 head surface (a) and drawdown from 2000 (b), Carrizo Formation (Layer 5).

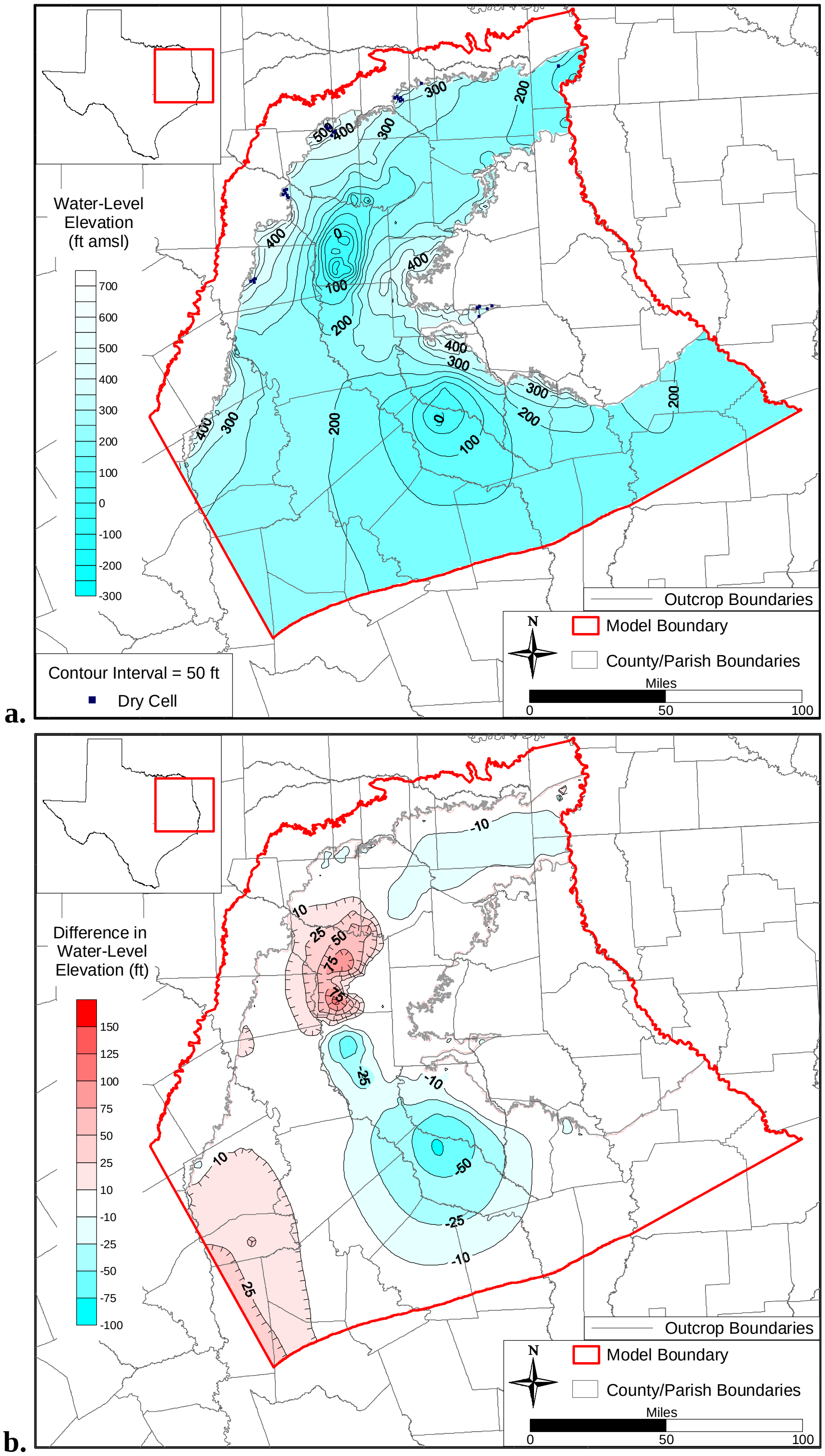

Figure 10.4.16 Simulated 2030 head surface (a) and drawdown from 2000 (b), Carrizo Formation (Layer 5).

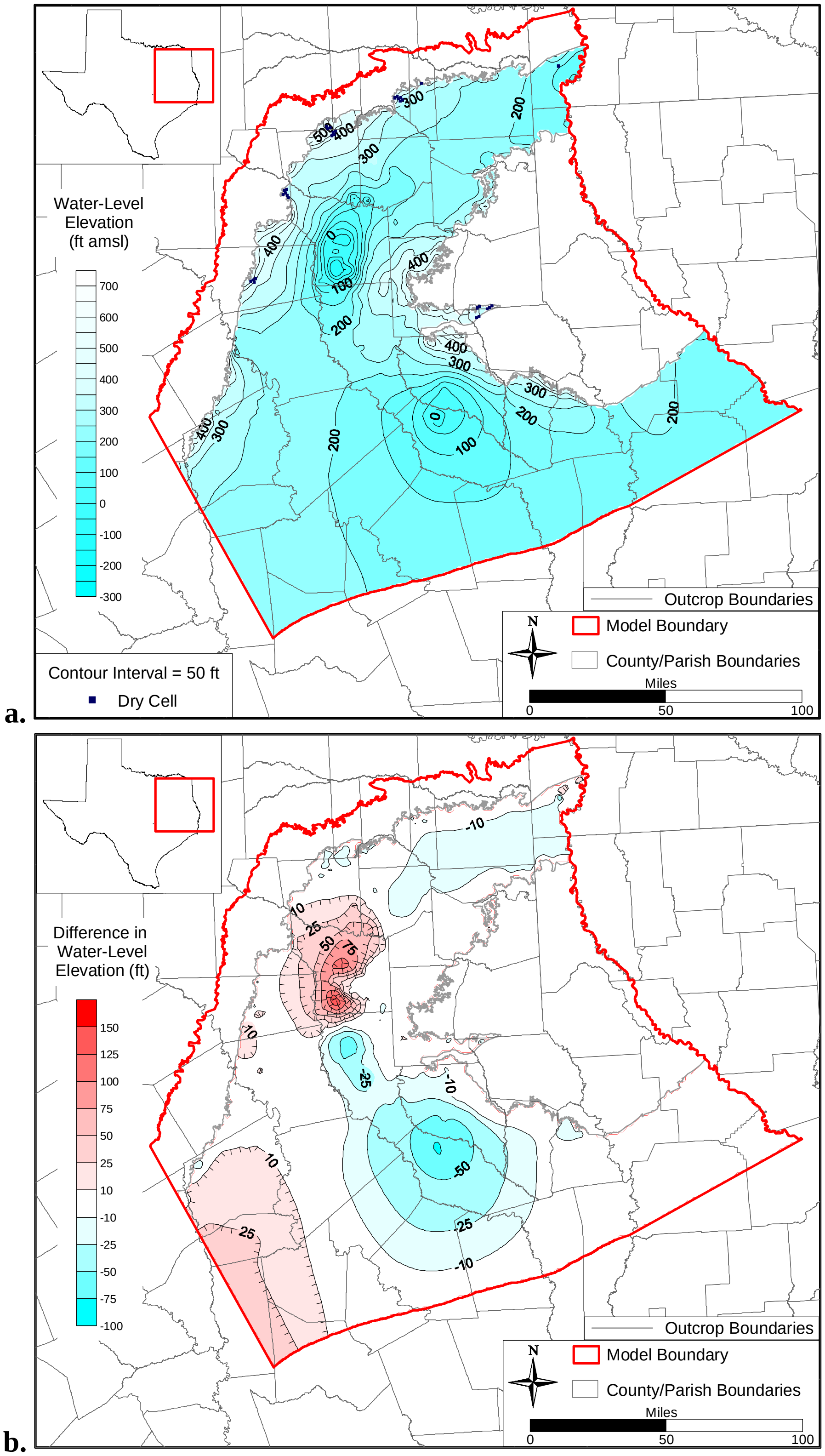

Figure 10.4.17 Simulated 2040 head surface (a) and drawdown from 2000 (b), Carrizo Formation (Layer 5).

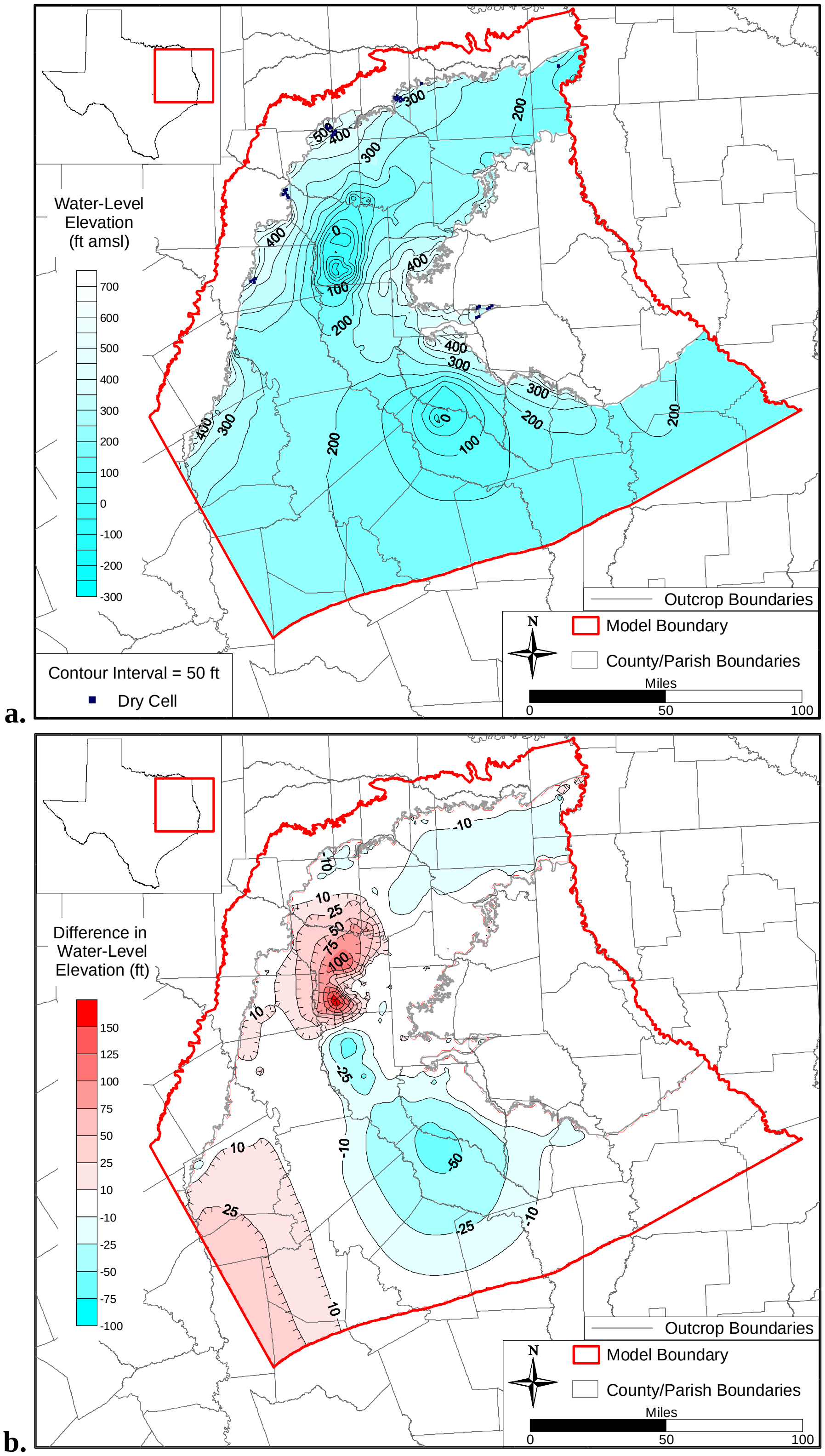

Figure 10.4.18 Simulated 2050 head surface (a) and drawdown from 2000 (b), Carrizo Formation (Layer 5).

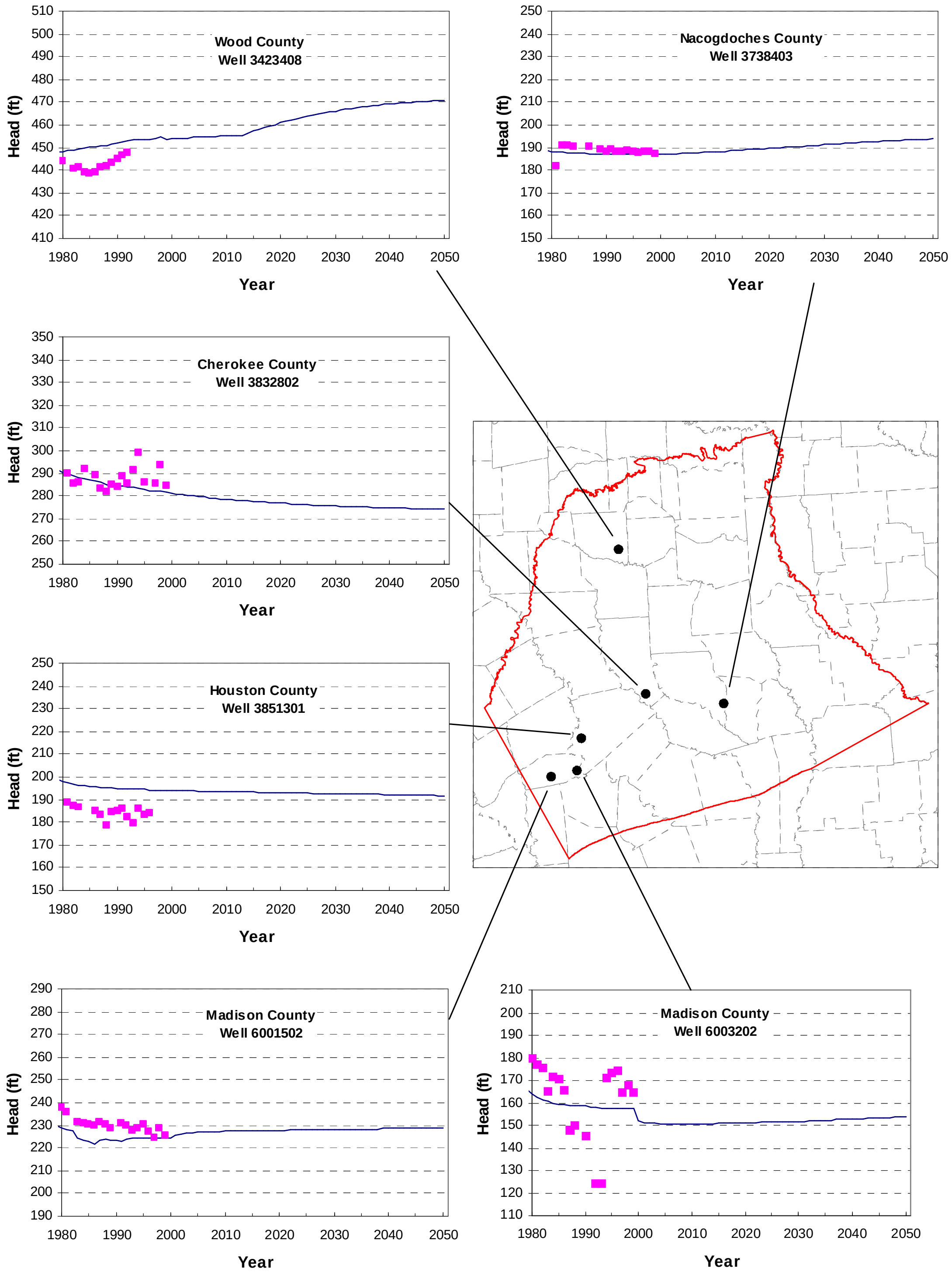

Figure 10.4.19 Selected Sparta aquifer (Layer 1) hydrographs from the 2050 no DOR predictive simulation (solid lines). Observed heads through 1999 are also posted (points).

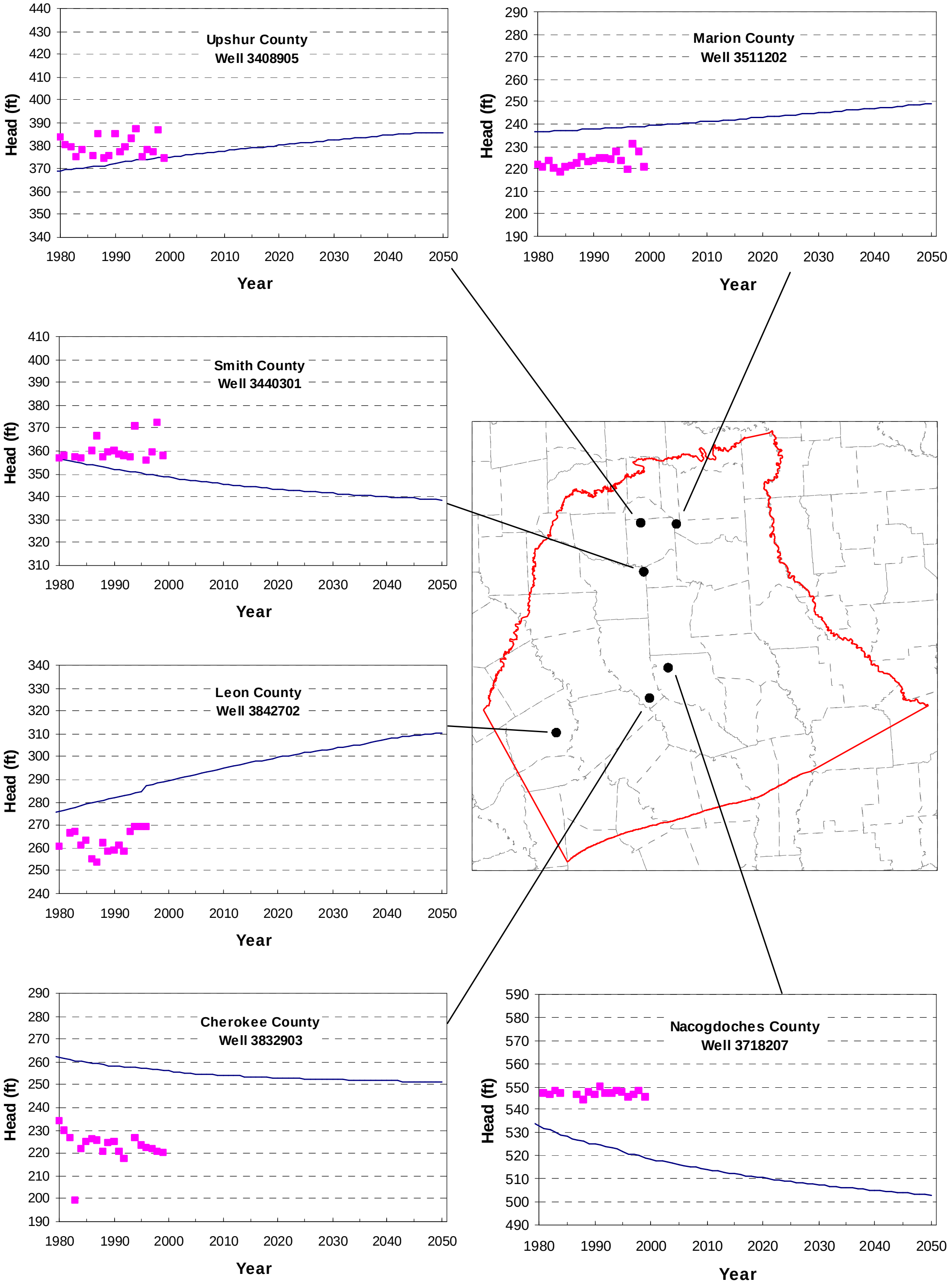

Figure 10.4.20 Selected Queen City aquifer (Layer 3) hydrographs from the 2050 no DOR predictive simulation (solid lines). Observed heads through 1999 are also posted (points).

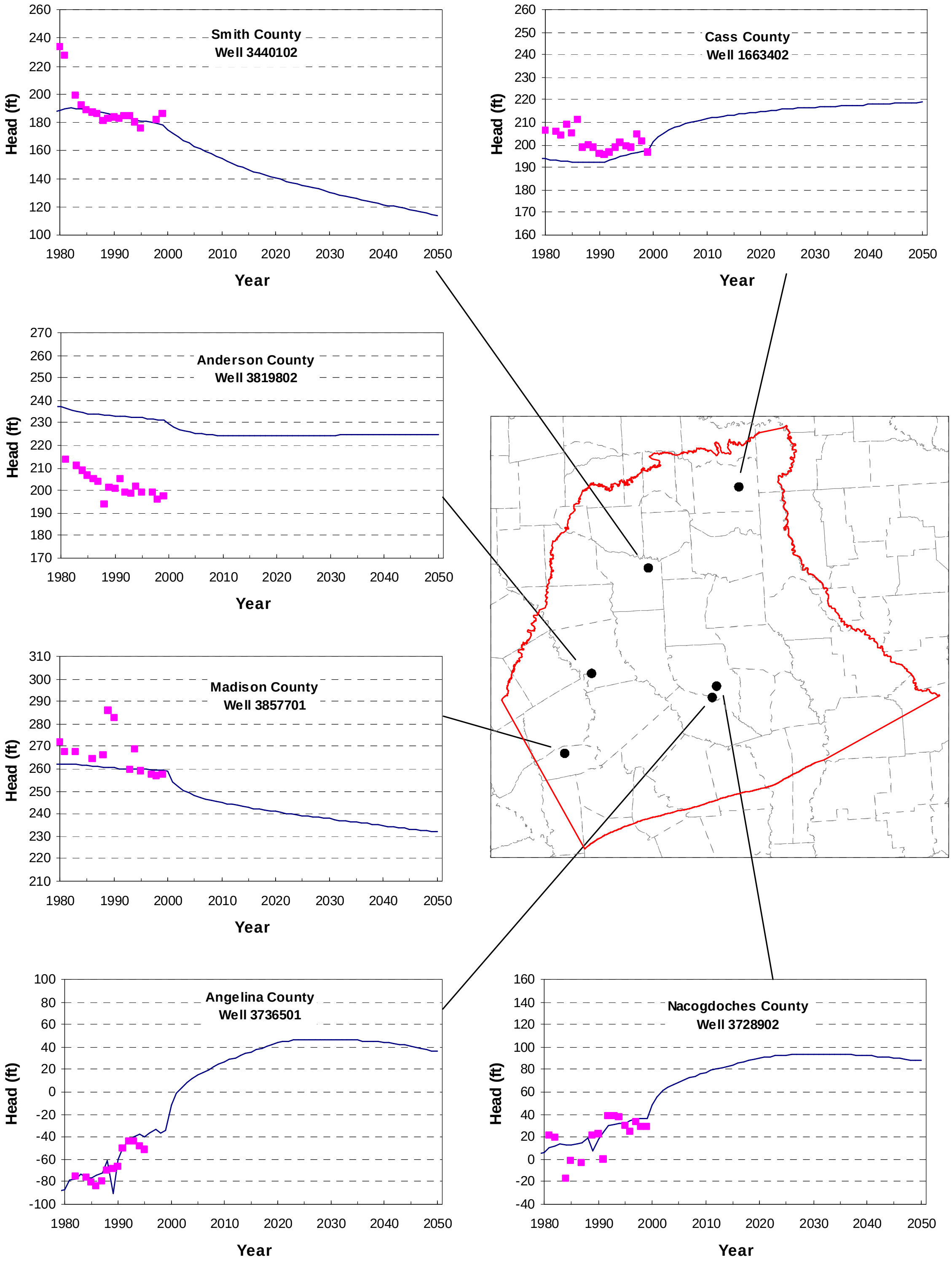

Figure 10.4.21 Selected Carrizo Formation (Layer 5) hydrographs from the 2050 no DOR predictive simulation (solid lines). Observed heads through 1999 are also posted (points).

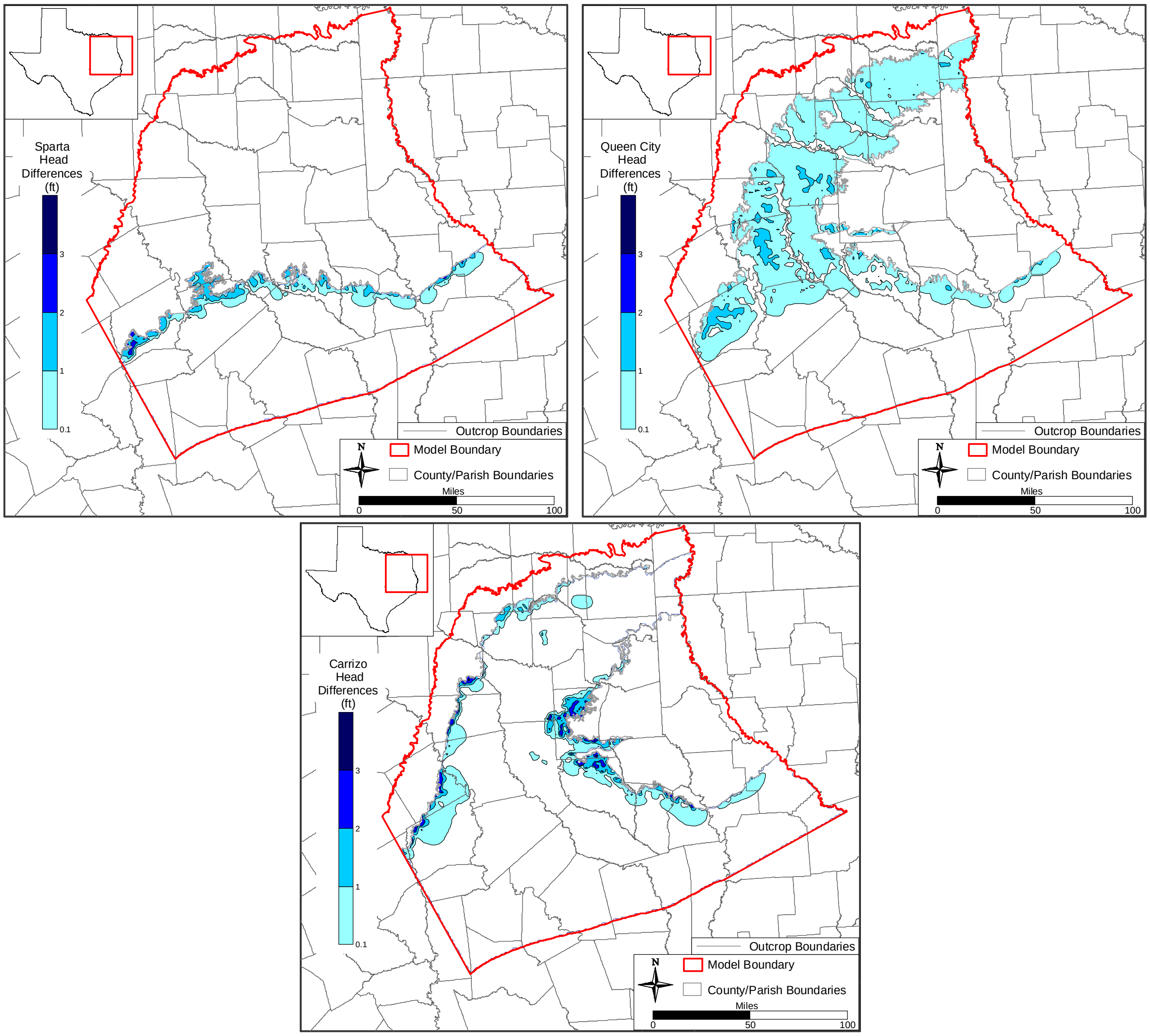

Figure 10.4.22 Differences in simulated head surfaces between the average condition 2050 simulation and the DOR 2050 simulation.

11.0 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 that 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 below.

11.1 Limitations of Supporting Data

Developing the supporting database for a regional model at this scale and with this large number of grid cells is a challenge. The Central and Northern Queen City and Sparta GAMs contain more than 170,000 active model cells each. Several types of data must be defined for the development of these GAMs. First, hydraulic properties of the aquifers must be estimated, including structure, hydraulic conductivities, and storativities. Second, a critical stress for the GAMs is pumping which requires allocation both vertically and spatially. Finally, the models are calibrated using observations (generally called calibration targets) which, in these models, include hydraulic heads and stream gain-loss estimates. Each of these data types will be described below with an assessment of their potential limitations with respect to the Queen City and Sparta GAMs.

The model database for structure for these GAMs was developed from a total of approximately 250 well logs (Figure 4.2.2). The selected wells largely correspond to those used by Ricoy (1976), Garcia (1972), and Guevara (1972) to prepare their cross sections. Some additional wells were correlated to the cross sections and added from areas between those that were represented by the published cross sections. The structural surfaces for the Queen City and Sparta aquifers have been developed based upon a sparse data set as compared to the density of the model grid nodes. Because these models have been developed on a super-regional scale, structural data will not have every bend and discontinuity found at a local scale. However, we believe that the structural data is adequate for the scale and purpose of the models. Refinements to structure may become necessary as these models are refined to specific counties or subregions.

We have implemented all mapped faults in the models for future users to explore their significance on local groundwater flow. The faults are not necessarily active in the current models, but await compelling evidence as to their sealing nature.

There are many parameters which control groundwater flow within the aquifers and model behavior. For the steady-state models, the primary parameters controlling model behavior are recharge and vertical conductivity. Generally, for the transient models, the primary parameters controlling model behavior are pumping and horizontal hydraulic conductivity. However, in transient models where little pumping stress is applied to the aquifer, vertical conductivity may be more important that horizontal conductivity.

Information regarding hydraulic conductivity is limited within the study region. We developed a database of aquifer hydraulic conductivity from a compilation of specific capacity data from the well records at the TCEQ, from TWDB and USGS reports, and from Mace and Smyth (2003). The database includes 1029 estimates of hydraulic conductivity for the Queen City aquifer and 38 estimates of hydraulic conductivity for the Sparta aquifer. The Queen City database provides an adequate number of estimates for the aquifer at the scale of interest. However, the number of Sparta estimates of hydraulic conductivity is very limited and model reliability could be improved with additional measurements.

Vertical estimates of hydraulic conductivity of the aquifers and aquitards are best derived from the application of models such as these GAMs. In the steady-state models, the vertical conductivity of the aquifer system is reasonably sensitive and is often correlated to recharge. In the transient models, the sensitivity to vertical hydraulic conductivity decreases except in areas of the northern GAM. We have noted that in the area of the East Texas Embayment, the vertical conductivity of the Reklaw must be very low to match the significant drawdown observed in the region (see Fryar et al., 2003). We view this parameterization with suspicion, believing that part of the problem may be caused by insufficient pumping in the model, a result of unreported pumping in the area (see discussion on pumping below). In general, for the three GAMs we believe that the parameter values for the hydraulic conductivity for the aquifer systems are reasonable and in line with values from the literature and previous models. It is important to note that, in areas with little drawdown, the vertical conductivity is likely estimated with less certainty.

The data set for storativity is very limited for the Queen City and Sparta aquifers. We used the available estimates along with aquifer lithology to scale up storativity to the model scale. The approach is physically based. We developed a method for estimation of storage that is applicable to the scale of the models and that provides a lower limit for storativity to prevent non-physical parameterization. However, there is uncertainty in the storativity distributions, especially with respect to how storativity decreases with depth. These issues will become more critical as development moves from the potable to the brackish water resources. The models are less sensitive to storage than aquifer transmissivity because drawdown is much more a function of transmissivity than storage. However, storage is a critical parameter for availability models. Aquifer storage is a crucial parameter in determining when, or if, a developed aquifer will transition from providing water from storage to providing water from discharge capture. These GAMs incorporate a reasonable estimate of storage for the Queen City and Sparta aquifers, but these estimates could be improved with more measurements.

Recharge is an important parameter requiring specification and estimation in groundwater availability models. There are no satisfactory methods for measuring recharge at the scale of interest for these models. We developed a methodology based upon an understanding of the factors controlling recharge, including precipitation, topography, and underlying geology. Our estimates of recharge are reasonable based upon the work of Scanlon et al. (2002) and use the work of Scanlon et al. (2003) as a basis. The estimates also compare well with availability and recharge estimates developed by Muller and Price (1979). Table 11.1 compares the steady-state estimates of recharge to the estimates found in Muller and Price (1979). In general the GAM recharge estimates are comparable. We believe that the GAM estimates to have a better basis that the estimates of Muller and Price (1979). We recognize that the regional estimates of recharge included in these models should be considered to be very uncertain.

Table 11.1 Comparison of steady-state GAM recharge estimates to Muller and Price (1979).

Aquifer	Southern GAM	Muller & Price (1979)	Central GAM	Muller & Price (1979)	Northern GAM	Muller & Price (1979)
Sparta	24,486	60,000	126,400	136,400	140,025	96,800
Queen City	69,019	23,800	154,300	294,300	275,580	655,600
Carrizo-Wilcox	113,602	186,340	220,300	479,700	590,276(1)	327,460
Total	207,107	270,140	501,000	910,400	1,005,881	1,079,860

(1) Contains a significant amount of recharge in LA which is not considered by Muller and Price (1979).

Pumping is another parameter that must be considered to be uncertain. There are many limitations to the pumping data. First, a significant portion of the Queen City and Sparta pumping is non-point pumping, which must be allocated both between aquifers (in the historical period) and spatially. There is significant uncertainty in this process. As a result, the ability of the model to match drawdowns with uncertain spatial pumping distributions and/or volumetric rates is poor and could result in scaling hydraulic parameters from their "true" values during model calibration. Refinements of the pumping data in Texas with regards to location and volume would greatly improve GAM reliability.

The primary type of calibration target for the GAM is hydraulic head. There is a general lack of hydraulic heads representative of the predevelopment for all model layers. However, we believe the steady-state model is important to the constraint of the model calibration and accept the uncertainty in predevelopment conditions. Head calibration targets for the transient (historical) model are also lacking in the Wilcox in the Southern GAM region and in the downdip portions of both the Queen City and Sparta aquifers in all three GAM regions. The model calibration could be improved by an increased density of head targets in these areas. Many of the groundwater conservation districts have implemented, or are in the process of implementing, monitoring programs. These efforts should be continued and supported.

The other type of calibration target used was stream gain/loss estimates. Our experience with the stream gain/loss estimates in the model regions indicates that they can be inconsistent between studies, but generally indicate gaining conditions east of the Frio River or San Antonio River. Targets for specific reaches can vary greatly between studies. Many of these differences could result from the historical period analyzed, the method of analysis, or the specific climate at the time of analysis. It would be useful to the GAM program for an analysis of stream targets to be performed for the major and minor aquifers from the available body of literature.

11.2 Limiting Assumptions

There are several assumptions that are key to the model regarding construction, calibration, and prediction. These are briefly discussed below with a discussion of the potential limitations of the assumption.

We modeled the lower boundary of the GAM models as a no-flow boundary at the base of the Wilcox Group. This assumption is consistent with other regional models in the area and is probably a reasonable assumption for the model in the overall sense. However, in the Wilcox outcrop, the no-flow nature of the base of the lower Wilcox creates some problems with recharge rates where the lower Wilcox is thin. This is not considered a significant limitation to the model since it causes only limited-area edge effects.

There are many assumptions inherent in our development of recharge rates for the GAMs. In general, we believe that our approach is reasonable and that the underlying assumptions defining recharge are not limiting. We use SWAT to estimate groundwater ET rates and groundwater ET extinction depths (rooting depth). It is possible that assumptions regarding estimation of these parameters in SWAT are not well suited to the regional model application with deep water tables (vadose zones). Groundwater ET is an important part of the GAM water balance and critical review of these parameters is warranted for application to GAMs in Texas.

The estimation of storage is based upon modeling the aquifer as a whole, which is correct for this scale of model. This implies that we estimate specific storage from storativity estimates and then upscale them with aquifer thickness. This process can result in large storativity numbers for thick aquifer sections. However, when modeling the entire aquifer as one layer, the estimation of a large storativity is correct. If one applies a storativity estimated from a relatively short-screened aquifer test to the aquifers as a whole, one is systematically underestimating storage for the aquifer system as a whole and also implying that the compressibility of the aquifer matrix becomes less that that of water (an unlikely event). It is important to note that if one is evaluating the drawdown associated with a relatively thin screen relative to our model layers, the GAM will provide misleading results (i.e., will underestimate drawdown) and would require standard correction methods for partial penetration to improve predictive capability.

11.3 Limits for Model Applicability

The Carrizo-Wilcox GAMs, like the Queen City and Sparta GAM, include significant regions of overlap. These large overlap regions were conceptualized and parameterized differently in the Carrizo-Wilcox GAMs (Deeds, et al., 2003, Dutton et al., 2003, and Fryar et al., 2003). Many of these differences were legitimate based upon uncertainty in conceptualization. Whatever the case, these differences created difficulty for stakeholders using the GAMs in or near the overlap areas. In an effort to address this issue, we have made parameterization of the Sparta, Weches, Queen City, Reklaw, and Carrizo formations the same in these three GAMs. However, there are still questions as to which GAM is best suited for use in the overlap regions.

If the Simsboro aquifer is to be included in a model, then the Central GAM should be used (either Dutton et al., 2003 or the one documented within this report). Figure 11.1 shows the model region with the GAM model grids overlain. We have included our recommendations regarding which GAM should apply in the various planning regions in Texas. This should not preclude an individual GCD from developing a sub-regional model which may use pieces from two GAMs. One obvious example of where this may be needed is Gonzales County. Because the Carrizo aquifer dominates water use in Gonzales County, a model could relatively easily be constructed from the Central and Southern GAMs developed herein.

Although we have made all possible attempts to make the GAMs consistent from the Sparta through the Carrizo in the overlap zones, there are inevitable differences which will be observable between the models. For properties, this is the result of having to resample parameters to different grids. Interpolation algorithms will develop slightly different nodal values for two GAM cells that intersect. These differences are small and not important. All parameters including recharge will be potentially impacted by the grid orientation issue. The models will also predict different heads at the same hydrograph as a result of: (1) different elevations within the outcrop, (2) different properties within the cell of observation, (3) differences in grid cell allocation of non-point pumping (as a result of grid orientation and weighting functions) and (4) interaction with the Wilcox. In general, these differences are not great and are at the magnitude of target uncertainty.

The models are developed at a grid scale of one square mile. At this scale, the models are not capable of predicting aquifer responses at specific points such as a particular well. The GAMs are accurate at the scale of tens of miles, which is adequate for understanding groundwater availability at the regional scale. Drawdowns that are observable at the regional scale should be reproducible with GAMs. The Queen City and Sparta GAMs produce water levels representative of large volumes of aquifer (e.g., 5,280 ft X 5,280 ft X aquifer thickness in feet). The 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. The concept of a grid-block effective radius is a good way to illustrate the idea of scale and how drawdown at a particular well would relate to drawdown as predicted by a GAM. In order to understand the scale issues related to the GAM size grids and how they relate to an individual well, 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 $\triangle x$ equal to $\triangle y$ (as in our case), the effective grid block radius (Re) is equal to:

$$Re = 0.198 \ \triangle x \tag{11-1}$$

In the case of the GAMs, the effective grid block radius is equal to approximately 1,045 feet. A typical high production well might have a screen or casing with a 6 inch effective radius. Table 11.2 summarizes the steady-state drawdown predicted for a 12 inch well versus a GAM grid block with an effective radius of 1,045 feet for a production rate of 1,000 gpm (1.44 MGD) and 500 gpm (0.7 MGD). This example assumes a hydraulic conductivity of 15 ft/day, a specific storage of $3x10^{-6}$ 1/ft and a fully penetrated aquifer 600 feet thick. For the case of a 1000 gpm production rate, the well would observe a drawdown of 44 feet versus the GAM grid observed drawdown of 18 feet. Likewise, for the case of a 500 gpm production rate, the well would observe a drawdown of 22 feet and the model would predict 9 feet, with identical hydraulic properties.

Table 11.2 Comparison of steady-state drawdown for a 12 inch production well and a GAM grid block.

Effective Radius of Observation	1,000 gpm (1.44 MGD)	500 gpm (0.7 MGD)
Well (6 inch or 0.5 ft)	43.9	22.0
Effective GAM Grid Block Radius (1,045 feet)	17.9	9.0

The GAM models are ideal for refinement for more local scale issues related to specific water resource questions. Questions regarding local drawdown to a well should be based upon analytical solutions to the diffusion equation or a refined numerical model.

The GAMs are routinely used to develop estimates of recharge to aid in groundwater availability planning. The validity of this concept is questionable in the aquifers that are the subject of this report (see Bredehoeft, 2002 for a complete review of these concepts). However, if one has developed a definition of availability which is equal to recharge, the following concept is worth consideration. Table 11.3 summarizes the steady-state recharge in AFY and aquifer discharge resulting from groundwater ET in AFY and as a percent of recharge for the three Queen City and Sparta GAMs. From Table 11.3, one can note that groundwater ET is a significant, although uncertain, component of the water balance as a natural discharge mechanism for recharge. In the Southern GAM groundwater ET consumes approximately 8 percent of the recharge whereas groundwater ET consumes up to 48 percent of the recharge in the Northern GAM. The point is that groundwater ET is a significant discharge mechanism in these aquifers and can consume a large percentage of the recharge. This implies that it is not a good use of GAMs to just apply the recharge package as an estimate of available groundwater. By pumping groundwater equal to the recharge volume over a long period of time (i.e., to steady-state) implies that the natural aquifer discharge components of groundwater ET, spring and stream discharge, and cross formational flow will be captured (potentially reduced to zero).

Table 11.3 Comparison of steady-state recharge and groundwater evapotranspiration for the three Queen City and Sparta GAMs.

GAM	Recharge (AFY)	Groundwater ET (%)	Groundwater ET (AFY)
Southern	218,510	8%	20,398
Central	561,600	34%	191,400
Northern	1,049,957	48%	521,182

GAMs are routinely used to estimate groundwater in place or “in storage”. There are two limitations that apply to these types of calculations for the unconfined portions of the aquifer. The first, is in regards to the model estimated head surfaces. The average error in the estimated model heads in a given aquifer is provided by the root-mean square error (RMSE). The RMSE for the modeled aquifers ranges from 25 to 35 feet, which implies that the model, on average, is accurate in simulating heads within 25 to 35 feet. Therefore, model estimates of groundwater “in-storage” have errors on the order of the RMSE for that model layer (aquifer). The model error associated with the calibration and verification periods does not fully address the potential error in future predicted head surfaces.

A second potential limitation for using the GAMs to estimate the volume of groundwater in place in the unconfined portions of an aquifer is dry cells. If an aquifer has a high percentage of dry cells it may provide an inaccurate estimate of groundwater volumes. This is not an issue with the Queen City and Sparta GAMs. For both the Queen City and Sparta aquifers, in each of the GAMs, the number of dry cells remains a very low percentage of the number of outcrop cells. For all models across all simulation periods, the percentage of dry cells never exceeded two percent of the outcrop cells. In all cases, the dry cells are proximal to, or are within the aquifer outcrop where dry conditions are physically plausible. In all of the head contours provided for the model simulated heads, dry cells have been posted so that the model user can consider the ramifications of their presence.

The GAMs provide a first-order approach to coupling surface water to groundwater, which is adequate for the GAM model purposes and for the scale of application. However, these models do not provide a rigorous solution to surface water modeling in the region and should not be used as a surface water modeling tool in isolation.

The GAMs were not developed to simulate the transport of solute (water quality). As a result, they should not be used in their current form to explicitly address water-quality issues. The focus of this study was not to delineate specific regions within the Queen City and Sparta aquifers having poorer water quality and thus potentially not being suitable as a groundwater resource. The study only documents a limited assessment of water quality in the study area.

The GAMs were developed on a regional scale and are applicable for assessing regional aquifer conditions resulting from groundwater development over a fifty-year time period.

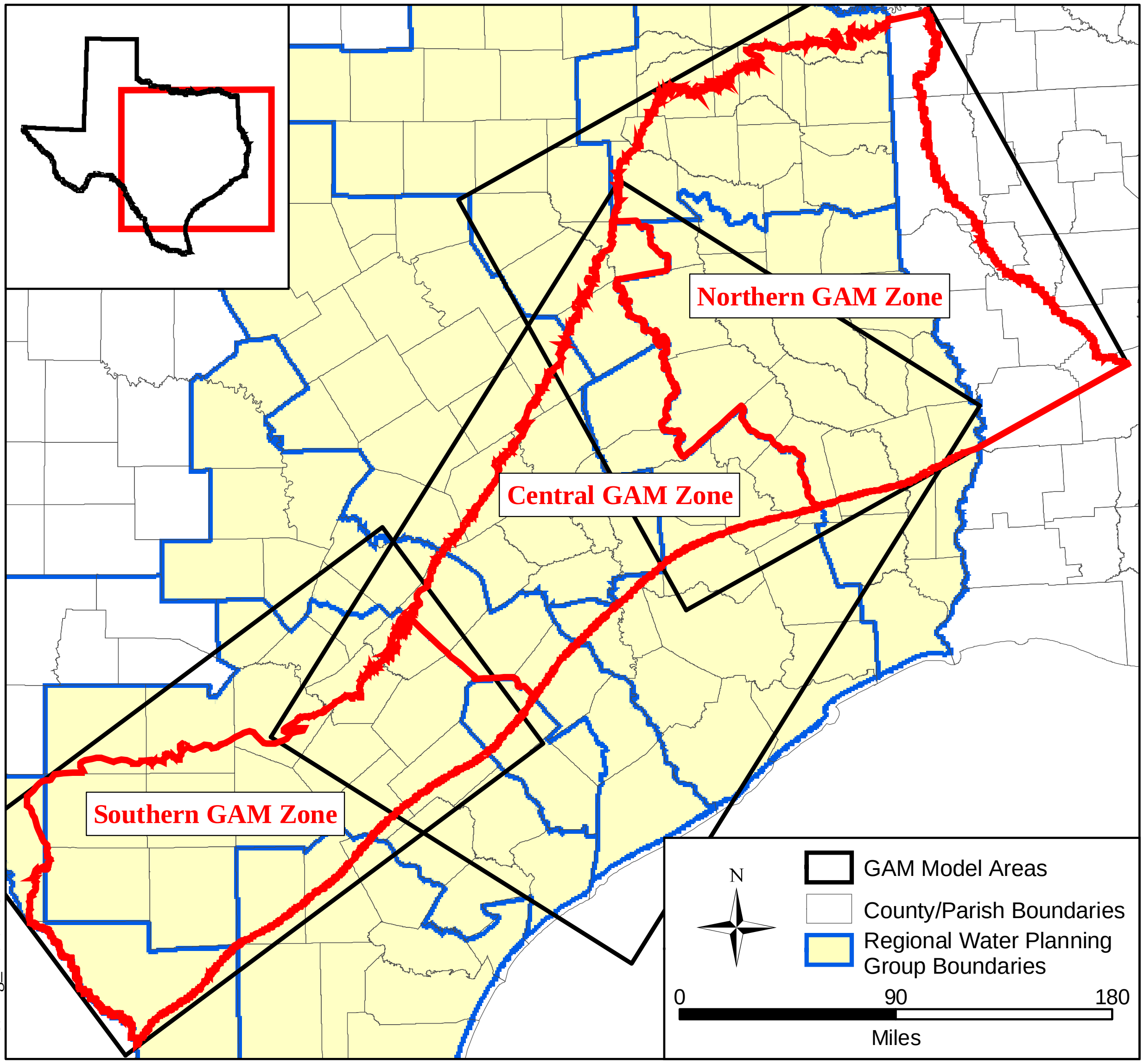

Figure 11.1 Recommended areas of applicability for each GAM.

12.0 FUTURE IMPROVEMENTS

To use models to predict future conditions requires a commitment to improve the model as new data becomes available or when modeling assumptions or implementation issues change. Through the modeling process, one generally learns what can be done to improve the model's performance, what data would help better constrain the model calibration, or what issues related to the model need further study. Future improvements to the model will be discussed below.

12.1 Supporting Data

Several types of data could be collected to better support the GAM model development process. These include recharge studies, groundwater ET studies, surface water-groundwater studies and additional water level monitoring and aquifer property measurements in the confined portions of the Queen City and Sparta aquifers.

Estimates of recharge are important to the GAM modeling process because they provide a means of constraining the vertical hydraulic conductivity of the aquifer system when calibrating to steady-state and transient conditions. Likewise, under predevelopment conditions recharge provides a means of characterizing aquifer discharge volumes under natural conditions. Scanlon et al (2002) and Scanlon et al. (2003) provide a good basis for initial parameterization of recharge in Texas. Studies should be continued including studies focused on groundwater ET.

Groundwater availability and sustainability are largely a function of groundwater capture which includes proper characterization of natural discharge mechanisms such as groundwater ET and stream baseflow. The Northern Queen City and Sparta GAM estimates that in predevelopment conditions groundwater ET consumes 50 percent of the recharge and stream discharge consumes 48 percent of the recharge. Proper characterization of these flow balance components through data collection and analysis is recommended to provide a better means of constraining the GAMs. This is especially true in portions of the study area where it is projected that significant resource development will occur.

Additional water-level monitoring in the downdip portions of the Queen City and Sparta aquifers would be helpful for future model development. Nearly all available Sparta, and the majority of the Queen City water-level measurements in Central and Southern Texas in the study area are located in outcrop regions of the aquifer. Although these aquifers may not contain potable groundwater, it is still advantageous to monitor these regions to improve aquifer understanding and to implement those improvements into the models. It is also important to increase water-level monitoring in areas that are potential areas of future development but which are currently not greatly developed. If monitoring begins prior to increased development, the GAMs can be calibrated against the aquifer response to improve model predictive capability in those regions.

Currently, horizontal hydraulic conductivity data are lacking for the Sparta aquifer. There are large regions of the Sparta where we had no hydraulic conductivity measurements (see Figure 4.3.4). Hydraulic conductivity is the key aquifer property controlling drawdown for a given development rate. Likewise, the storativity database is sparse for both the Queen City and the Sparta. Additional hydraulic conductivity estimates and storativity estimates from pump tests will help further constrain the models and will increase model reliability in the future.

Finally, groundwater age dating and simple experimental model development would be beneficial to the study of these aquifers systems. This data provides a good means for developing simple experimental models of the aquifer systems to investigate various conceptual models for hydraulic parameters and recharge. Castro and Goblet (2002) provide an excellent study of the Carrizo-Reklaw aquifer-aquitard system in Atascosa County. They combined a simple cross-sectional model with groundwater age dating to improve an understanding of recharge rates and Reklaw vertical hydraulic conductivity. Experimental models, though rare in Texas, have proven to be excellent information sources for future investigators such as the Oakwood Dome model in East Texas (Fogg et al., 1983).

12.2 Future Model Improvements

A key improvement for these GAMs would be to develop a common grid for the three models. This would get rid of the grid sampling issues in the overlap zones discussed in Section 11.3. With the model parameters re-sampled to a common grid (the hard part), it would be possible to make a single GAM from the three GAMs. With the development of local-grid refinement methods in MODFLOW (Mehl and Hill, 2002), future users could then develop refined models which would run iteratively with the regional GAM.

Pumping estimates in Leon County for the Queen City seem to be low relative to the hydraulic responses seen in hydrographs in the area. Likewise, the Carrizo model still behaves as if it is missing pumping in the Wintergarden area and in the Lufkin area. At this time, we do not know if these conditions are the result of under-estimated historical pumping or errors in hydraulic parameterization. Pumping estimates in these regions should be reviewed in terms of whether they could be higher.

The predictive pumping data set for the Carrizo-Wilcox in the southern GAM contains total values that are far less than the total values in the historical period. This loss of pumping of nearly 90,000 AFY results in a significant rebound in Carrizo heads in the predictive period. Much of this rebound would not occur if pumping were held constant at 1999 rates. With the rebound, vertical gradients between the Carrizo and the Queen City are significantly affected which has implications for Queen City heads.

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13.0 CONCLUSIONS

This report documents the development of groundwater availability models of the Queen City and Sparta aquifers. These models were developed to the GAM standards defined by the TWDB. They were developed as an addition to the existing Carrizo-Wilcox GAMs documented in Deeds et al. (2003), Dutton et al. (2003) and Fryar et al. (2003) and therefore share a common x-y grid with those GAMs.

The Queen City and Sparta GAMs are regional-scale models developed using MODFLOW with the stream-routing package to simulate stream-aquifer interaction and the reservoir package to model groundwater interaction with lakes and reservoirs. Each of the Queen City and Sparta GAMs are eight-layer models. They divide the Carrizo-Wilcox aquifer into four layers: the Carrizo, and the upper, middle, and lower Wilcox. The Reklaw and its equivalents are modeled as an individual model layer. The Queen City aquifer, the Weches Formation, and the Sparta aquifer are each modeled as an individual layer.

The existing Carrizo-Wilcox GAMs have significant overlap between their model boundaries which has been inherited by the Queen City and Sparta GAMs. The Carrizo model layer for all three Queen City and Sparta GAMs has been recalibrated with the same hydraulic parameters and stresses for each GAM in the overlap regions. The Queen City and Sparta aquifer properties and stresses have been developed consistently between all GAMs including in the overlap regions.

The purpose of these GAMs is to provide a tool to be used to make predictions of groundwater availability through the year 2050 based on projections of groundwater demands during drought-of-record conditions. The three Queen City and Sparta GAMs provide an integrated tool for the assessment of water management strategies to directly benefit state planners, Regional Water Planning Groups (RWPGs), and Groundwater Conservation Districts (GCDs).

The GAMs have been 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) model verification, (5) sensitivity analysis, (6) model prediction, and (7) reporting.

The three Queen City and Sparta GAMs have been calibrated to predevelopment conditions (prior to significant resource use) which are considered to be at steady state. All three GAMs reproduce the predevelopment aquifer heads within the uncertainty in the head estimates. Table 13.1 presents a simplified water balance of the three steady-state GAMs where aquifer discharge is expressed as a percent of recharge.

Table 13.1 Steady-State Water Balance for Queen City and Sparta GAMs.

GAM	Recharge (AFY)	Groundwater ET (%)	Streams & Drains (%)	Cross-Formational Flow to Younger (%)
Southern	218,510	8%	69%	23%
Central	561,600	31%	58%	11%
Northern	1,049,957	48%	49%	2%

The area weighted average recharge rate for the Sparta aquifer varied from 0.6 inches per year in the southern GAM to a high of 1.7 inches per year in the northern GAM. The area weighted average recharge rate for the Queen City aquifer varied from 0.4 inches per year in the southern GAM to a high of 0.8 inches per year in both the central and northern GAMs. Consistent with our conceptual model, Table 13.1 shows that groundwater ET becomes a significant groundwater discharge process as one moves from the southeast to the northeast. Likewise, the percent of recharge which flows to the confined section is greatest in the southern GAM.

The models were also satisfactorily calibrated to transient aquifer conditions from 1980 through December 1989. The model did a good job of reproducing aquifer heads and available estimates of aquifer-stream interaction. The transient-calibrated models were verified by simulating to aquifer conditions from 1990 through December 1999. Again, the models satisfactorily simulated observed conditions. In general, there is very little regional drawdown occurring in the Queen City and Sparta GAMs from 1980 through 1999.

Model predictions were performed to estimate aquifer conditions for the next 50 years based upon projected pumping demands under DOR conditions as developed by the Regional Water Planning Groups. The pumping demand estimates developed from the regional water plans predicted a significant increase in pumping for both the Sparta aquifer and the Queen City aquifers. The Sparta aquifer pumping demand is projected to increase from an estimated 7,073

AFY in 1999 to 25,798 AFY by 2010. Likewise, the Queen City aquifer pumping demand is projected to increase from an estimated 14,458 AFY in 1999 to 36,423 by 2010. Predictions of drawdown in the Sparta aquifer by 2050 are generally from 0 to 50 feet with the exception of a deep drawdown cone predicted in Southern Atascosa County and a broad drawdown cone greater than 50 feet in Fayette County. The same drawdown features are predicted in the Queen City by year 2050 with other regional drawdowns less than 50 feet.

These models, like all models, have limitations and can be improved. However, these models are calibrated, documented, publicly-available tools which are well suited for the assessment of groundwater dynamics in the Queen City and Sparta and the Carrizo-Wilcox aquifers in Texas. These GAMs are able to reproduce the natural (predevelopment) and historical conditions of the aquifers as measured by multiple calibration measures. These models provide the means to develop understandings of groundwater basin dynamics and groundwater sustainability based upon issues of natural discharge capture.

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14.0 ACKNOWLEDGEMENTS

The Queen City and Sparta GAMs were developed with the participation of a committed group of stakeholders representing varied interests within the model region. Interaction with these stakeholders was performed through a series of Stakeholder Advisory Forums (SAF) held across the model region. In these meetings, stakeholders were solicited for data and were provided updates on a regular basis. The model described in this report has benefited from the stakeholders involvement and interest. Of particular note is the contributions of Barry Miller of the Gonzales Underground Water Conservation District who has provided us with a great deal of beneficial data to help parameterize the southern GAM and to calibrate against. In addition, we would like to specifically thank those members of the SAF who have hosted meetings across the model region, including: Steve Raabe and Ronnie Hernandez at the San Antonio River Authority, David Smith with the City of Nacogdoches and the Piney Woods Groundwater Conservation District, Ric Jensen with the Texas Water Resources Institute at Texas A&M University, and the Bureau of Economic Geology.

We would also like to thank the TWDB GAM staff led by Cindy Ridgeway for their support during this modeling exercise. We would like to thank Shirley Wade who has managed our contract with professionalism and support. We would also like to thank Larry French of URS Corporation and Gary Guy of the San Antonio Water Supply for providing aquifer characterization data.

We would like to thank our senior technical reviewers for this project; Dr. Steve Gorelick (Stanford University) and Dr. Graham Fogg (University of California, Davis). Our understanding of the aquifers and of the modeling process has been greatly improved by their oversight and time. We would like to thank Chris Urbina of INTERA for his efforts in compiling and organizing the tremendous amount of data collected for this study and his GIS support. We would also like to thank Katie Kier, Thandar Phyu, and Thet Naing at the BEG for their assistance with the gathering and compilation of hydraulic data. Finally, we would like to thank Judy Ratto of INTERA for her efforts above and beyond the call of duty in developing this report.

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APPENDIX A

Brief Summary of the Historical Development of the Queen City and Sparta Aquifers on a County by County Basis

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Understanding historical development in the Queen City and Sparta aquifers guided in estimating predevelopment conditions for those aquifers. This appendix provides a brief summary of historical development of these two aquifers on a county by county basis. Dates at which wells were first drilled and the dates of earliest water-level measurements, as given on the TWDB website, for each county are also summarized. Also provided is a discussion of the water-level data used to construct water-level elevation contours estimated to be representative of predevelopment conditions. These contours will be used as qualitative data for calibrating the steady-state models. Measurement points used in the construction of these contours will be used as calibration targets for the steady-state models.

The Queen City Sand is a minor aquifer in Texas extending from the Sabine Uplift and East Texas Embayment area in the northeast portion of the state southwestward to the Rio Grande Embayment in south-central Texas (see Figure 2.5 in the main body of this report). The majority of wells completed to the Queen City aquifer supply groundwater for rural domestic and livestock use. In a few counties, the Queen City also provides groundwater to small towns for public supply purposes. The following discussion is based on data found on the TWDB website. Development of the Queen City aquifer first occurred in counties located in the northern model area. Over a dozen wells were dug in this area between 1830 and 1900. The earliest completion data for a Queen City well located in the central model area is 1880 and in the southern model is 1906. Determination of water levels representative of predevelopment conditions in the Queen City aquifer considered water levels taken at early time periods, and average water levels for wells with stable hydrographs over long periods of time.

The Sparta Sand is a minor aquifer in Texas extending from the Sabine Arch area in the eastern-central portion of the state southwestward to the Rio Grande Embayment in south-central Texas (see Figure 2.5 in the main body of this report). The majority of wells completed to the Sparta aquifer supply groundwater for rural domestic and livestock use. In a few counties, the Sparta also provides groundwater for public water supply purposes. The most significant of these are the cities of Bryan and College Station, and Texas A&M University, located in Brazos County. The following discussion is based on data found on the TWDB website. The earliest wells to the Sparta aquifer were dug in Nacogdoches County in 1871 and in Nacogdoches and Cherokee counties in 1896. Further development in the northern model area did not occur until 1925. The earliest completion data for a Sparta well located in the central model area is 1900.

Several wells were completed to the Sparta in this area between 1900 and 1910. Only one well was completed to the Sparta in the southern model area prior to 1910. That well is located in Wilson County and was dug in 1901. Determination of water levels representative of predevelopment conditions in the Sparta aquifer considered water-level data from early time periods, the number of wells completed to the aquifer prior to the first water-level measurements, the transient nature of water levels in individual wells, and maximum water levels measured.

Anderson County

Little information related to the historical development of the Queen City and Sparta sands in Anderson County was found during the literature review. Unless stated otherwise, the following discussion comes from William F. Guyton & Associates (1972). There are four principal aquifers in Anderson County. In order of importance, they are the Carrizo aquifer, the Wilcox aquifer, the Queen City aquifer, and the Sparta aquifer. The Queen City is an important aquifer in this county not because it supplies large quantities of water but rather because it is widespread and shallow. Water from the Queen City is used predominately for rural domestic and livestock purposes. The Sparta aquifer is not an important source of water in Anderson County because of its limited extent and its location at the top of hills.

In the three counties of Anderson, Cherokee, and Henderson, about 322 wells were completed to the Queen City aquifer in 1969. Of those, 11 wells supplied water for municipal purposes, and one each supplied water for industrial and irrigation purposes. The remaining wells were used for rural domestic and livestock purposes. In these same three counties, approximately 76 wells were completed to the Sparta aquifer in 1969. Of those, one each supplied water for industrial and irrigation purposes and the remaining wells supplied water for rural domestic and livestock purposes. Approximately 12.7 million gallons per day of groundwater was pumped in Anderson, Cherokee, and Henderson counties in 1969. The source of this groundwater was about 43 percent from the Carrizo aquifer, about 43 percent from the Wilcox aquifer, about 8 percent from the Queen City aquifer, a very small percentage from the Sparta aquifer, and the remaining from other formations.

The first well completed to the Queen City aquifer in Anderson County was dug in 1880 (TWDB, website). Approximately 10 wells were completed to the Queen City prior to the first water-level measurement taken in 1944 (TWDB, website). This earliest water-level measurement is considered to be representative of predevelopment conditions in the Queen City aquifer.

No water levels for wells identified as being completed to the Sparta aquifer and located within the outline of the Sparta aquifer as defined by the TWDB were found in Anderson County (TWDB, website).

Angelina County

Little information related to the historical development of the Queen City and Sparta sands in Angelina County was found during the literature review. Unless stated otherwise, the following discussion comes from William F. Guyton & Associates (1970). In order of importance, the major water-bearing units in Angelina County are the Carrizo Sand, the Wilcox Group, the Yegua Formation, and the Sparta Sand. Of these, the Carrizo Sand is by far the most productive. Groundwater from the Sparta aquifer is obtained from numerous small capacity wells, most of which are located in the outcrop. The Queen City Sand is present in Angelina County but is not considered a principal water-bearing unit in the county. In 1968, 67 wells completed to the Sparta aquifer were present in northern Angelina County and southern Nacogdoches County. These wells predominately supplied water for domestic and livestock purposes. One well supplied water to a municipality and several wells were originally drilled as test wells. Only a few domestic and livestock wells tapping the Queen City aquifer were present in 1968. About 22 million gallons per day of groundwater was pumped in Angelina County in 1968. Of that, 19 million gallons per day was supplied by the Carrizo aquifer, 3 million gallons per day was supplied by the Yegua Formation, and 0.1 million gallons per day was supplied by the Sparta aquifer.

No water levels for wells identified as being completed to the Queen City aquifer and located within Angelina County were found on the TWDB website.

The first well completed to the Sparta aquifer in Angelina County was drilled in 1940 and the first water-level measurement was taken in 1941 (TWDB, website). This earliest water level is not considered representative of predevelopment conditions in the Sparta aquifer.

Atascosa County

The information regarding the history of development of the Queen City and Sparta Sands in Atascosa County comes from Alexander and White (1966). The following discussion is taken from that report. The principal aquifer in Atascosa County is the Carrizo Sand. Aquifers of minor importance are the Queen City Sand, the Edwards and associated limestones, the Wilcox, and the Sparta Sand. The Queen City aquifer can supply moderate to large quantities of fresh water in the central portion of this county. Small to moderate quantities of water are available from the Sparta Sand in the outcrop and a few miles downdip of the outcrop. The breakdown of total pumpage in the county by aquifer for 1964 yields 93 percent from the Carrizo Sand, 3 percent from the Queen City Sand, 2 percent from the Edwards and associated limestones, 1.7 percent from the Wilcox, and 0.3 percent from the Sparta Sand. Of the water used from the Queen City Sand, 56 percent was used for public supply and 44 percent was used for irrigation. The use of water from the Sparta Sand was 38 percent for industrial purposes and 62 percent for irrigation purposes.

Four wells completed to the Queen City aquifer supply water for the city of Pleasanton in Atascosa County. These wells were drilled between 1954 and 1962. The city of Christine and the community of Coughran are each supplied by one well completed in the Queen City aquifer in 1954 and 1915, respectively. Nine irrigation wells were drilled to the Queen City between 1929 and 1930 in the Pleasanton area. A total of 13 irrigation wells in the Queen City were present in this area by 1945.

The first well tapping the Queen City aquifer was completed in 1906 (TWDB, website). By the time of the earliest water-level measurement taken in 1928, about 6 wells tapped the Queen City (TWDB, website). This earliest measurement plus one taken in 1935 and in 1944 were considered to be representative of predevelopment conditions in the Queen City aquifer.

The first well tapping the Sparta aquifer in Atascosa County was completed in 1911 (TWDB, website). About five wells tapped the Sparta at the time of the first water-level measurement taken in 1928 (TWDB, website). This earliest measurement is also the maximum water-level elevation recorded for the county. That measurement plus three others that represent maximum conditions were considered to be representative of predevelopment conditions in the Sparta aquifer.

Bastrop County

Little information related to the historical development of the Queen City and Sparta sands in Bastrop County was found during the literature review. Unless stated otherwise, the following discussion comes from Follett (1970). The principal water-bearing units in Bastrop County, in order of importance, are the Wilcox Group, the Carrizo Sand, the Queen City Sand, and the Sparta Sand. Small to moderate amounts of fresh to slightly saline water are available in the Queen City and Sparta sands in and near the outcrop areas. In 1966, one irrigation well tapped the Sparta aquifer and no water for irrigation purposes was produced from the Queen City aquifer. A limited number of shallow and small capacity wells completed to the Queen City and Sparta sands provide groundwater for livestock use.

The first well completed to the Queen City aquifer in Bastrop County was dug in 1910 (TWDB, website). Two wells tapped the Queen City at the time of the first water-level measurement taken in 1915 (TWDB, website). This measurement plus a measurement taken in 1938 were considered to be representative of predevelopment conditions in the Queen City aquifer.

The first well completed to the Sparta aquifer in Bastrop County was dug in 1906 (TWDB, website). About six wells tapped the Sparta at the time of the first water-level measurement taken in 1947 (TWDB, website). This earliest measurement is considered to be representative of predevelopment conditions in the Sparta aquifer.

Brazos County

Little information related to the historical development of the Queen City and Sparta sands in Brazos County was found during the literature review. Unless stated otherwise, the following discussion comes from Follett (1974). Large quantities of groundwater are available from the Wilcox Group, Carrizo Sand, Queen City Sand, Sparta Sand, terrace deposits, and flood-plain alluvium in this county. Neither the Queen City or Sparta sands outcrop in Brazos County but they are located beneath all of the county except the southeastern tip. Small to large quantities of fresh to slightly saline water are available from both the Queen City and Sparta sands beneath this county.

Pumpage of groundwater for use by the city of Bryan began in 1915 with a well completed to the Queen City Sand and the Carrizo-Wilcox sands. An additional city well was drilled in 1933 to the Sparta Sand. These original wells were replaced in 1940 by a new well field tapping the Sparta Sand. Additional wells completed to the Wilcox Group and the Sparta Sand were installed as needed beginning in 1954. The city of Bryan is the largest user of groundwater in Brazos County. Groundwater withdrawals for the city of Bryan increased steadily from 1940 to 1970. In 1960, a total of 6,300 acre-feet of groundwater was pumped by the city of Bryan. Of this, 83 percent was supplied by the Sparta Sand and 13 percent was supplied by the Carrizo-Wilcox aquifer. Beginning in 1951, water needs for Texas A&M University and the city of College Station have been supplied by wells tapping the Sparta Sand and the Wilcox Group.

Pumpage of water from the Sparta Sand by the city of Bryan and by Texas A&M University has reduced the water level in this aquifer over a relatively large area. Water level declines as much as 35 feet were measured from 12 to 15 miles east of the well fields. Water levels within the Sparta outcrop near these well fields have also been lowered. In addition, water-level decreases in the overlying alluvium deposits have been attributed to lowering of head levels within the hydraulically connected Sparta Sand. In areas within Brazos County not directly impacted by the city of Bryan and Texas A&M well fields, significant water-level declines have not been measured.

The first well completed to just the Queen City aquifer in Brazos County was drilled in 1955 (TWDB, website). The first water-level measurement was taken in this same year (TWDB, website). Because a well tapping both the Queen City and Carrizo aquifers had been withdrawing water for use by the city of Bryan since 1915, this earliest water-level measurement and all subsequently measured water levels are not considered representative of predevelopment conditions in the Queen City aquifer.

The first well completed to the Sparta aquifer in Brazos County was dug in 1915 (TWDB, website). Two wells tapped the Sparta at the time of the first water-level measurement taken in 1938 (TWDB, website). This earliest water level appeared to be affected by pumpage. Three water levels representing maximum values measured in different areas of the aquifer in this county were determined to be most representative of predevelopment conditions.

Burleson County

Little information related to the historical development of the Queen City and Sparta sands in Burleson County was found during the literature review. Unless stated otherwise, the following discussion comes from Follett (1974). Large quantities of groundwater are available from the Wilcox Group, Carrizo Sand, Queen City Sand, Sparta Sand, terrace deposits, and flood-plain alluvium in this county. Both the Queen City and Sparta sands outcrop in Burleson

County and extend beneath the county. Small to large quantities of fresh to slightly saline water are available from both the Queen City and Sparta sands beneath this county. The Queen City aquifer provides small to large quantities of fresh to slightly saline water to numerous shallow rural domestic and livestock wells in and near the outcrop in this county.

The first well completed to the Queen City aquifer in Burleson County was dug in 1910 (TWDB, website). The first water-level measurements were taken in 1936 in all 16 wells tapping the Queen City at that time (TWDB, website). Four of these first water levels were considered to be representative of predevelopment conditions.

The first well completed to the Sparta aquifer in Burleson County was dug in 1900 (TWDB, website). At the time of the first water-level measurement in 1927, approximately four wells tapped the Sparta (TWDB, website). This early water level was considered to be representative of predevelopment conditions in the Sparta aquifer along with a water level measured in 1936 and six other measurements representing maximum water-level conditions is various portions of the county.

Caldwell County

The Sparta aquifer as defined by the TWDB is not present in Caldwell County. Little information related to the historical development of the Queen City Sand in this county was found during the literature review. Unless stated otherwise, the following discussion comes from Follett (1966). The Queen City Sand is considered one of the principal water-bearing units in Caldwell County but, unlike the Carrizo Sand and Wilcox Group, most likely will not be a source for large-scale groundwater development. Small quantities of fresh to slightly saline water are produced from the Queen City Sand in the outcrop area.

The first well tapping the Queen City aquifer was dug in 1900 (TWDB, website). At the time of the first three water-level measurements taken in 1946, about four wells tapped the aquifer (TWDB, website). Two of these earliest water levels are considered to be representative of predevelopment conditions.

No wells completed to the Sparta aquifer in Caldwell County were found on the TWDB website.

Camp County

The Sparta aquifer as defined by the TWDB is not present in Camp County. Little information related to the historical development of the Queen City Sand in this county was found during the literature review. Unless stated otherwise, the following discussion comes from Broom et al. (1965). The principle water bearing units in Camp County are the Wilcox Group and the Carrizo Sand, the Reklaw Formation, and the Queen City Sand. These four units are considered to have similar hydrologic properties, to be hydraulically connected, and to act as a single aquifer, referred to the “Cypress aquifer”, in this county. The outcrop of the Queen City is present throughout the southern portion of Camp County.

A total of 4,300 acre-feet of groundwater usage from the Cypress aquifer was utilized in 1963 in Camp, Franklin, Morris, and Titus counties for public water supply (1,100 acre-feet), industrial (1,200 acre-feet), domestic (1,700 acre-feet) and livestock (290 acre-feet) purposes. The percentage of that groundwater removed from the Queen City portion of the Cypress aquifer was not determined. The majority of the 4,000 wells within the Cypress aquifer are shallow wells, 50 to 70 feet deep, with small to moderate capacities. The low transmissibility of the Cypress aquifer has limited and will continue to limit the development of the Cypress aquifer as a groundwater resource. Also, the corrosive nature of the shallow groundwater and the high iron content at lower depths deters the use of the groundwater.

Data on the TWDB website indicates only one well completed to the Queen City aquifer in Camp County. That well was drilled in 1983 and the first water-level measurement in that well was taken in 1995. This water level is not considered to be representative of predevelopment conditions in the Queen City aquifer.

Cass County

The Sparta aquifer as defined by the TWDB is not present in Cass County. Little information related to the historical development of the Queen City aquifer in this county was found during the literature review. Unless stated otherwise, the following discussion comes from Broom (1971). The principle water bearing units in Cass County are the Wilcox Group, Carrizo Sand, Reklaw Formation and the Queen City Sand. These four units are considered to have similar hydrologic properties, to be hydraulically connected, and to act as a single aquifer, referred to as the “Cypress aquifer”, in this county. The outcrop of the Queen City is present throughout all of Cass County except along the northern edge of the county. The Queen City aquifer provides small quantities of groundwater from shallow wells for rural domestic and livestock usage. Although not considered an aquifer in this county, isolated sections of the Sparta Sand are found along the tops of ridges and high hills and, to a less extent than the Queen City aquifer, provide small quantities of groundwater from shallow wells for rural domestic and livestock usage.

In 1967, approximately 4,000 acre-feet of groundwater from the Cypress aquifer was utilized in Cass and Marion Counties for public water supply (1,200 acre-feet), industrial (2,200 acre-feet), and rural domestic and livestock (560 acre-feet) purposes. Approximately 85% of the groundwater withdrawals were in Cass County. The percentage of the groundwater that was withdrawn from the Queen City portion of the Cypress aquifer was not determined.

Water levels within the Cypress aquifer have not varied significantly with time except in three areas: centered on the city of Bryans Mill, north of the city of Atlanta, and in parts of the Rodessa oil field. Declines in water levels of as much as 86 feet have been observed near Bryans Mill between 1961 and 1967. From 1936 to 1967, the declines in water levels north of Atlanta have been as much as 100 ft. Near the Rodessa oil field, declines of as much as 109 feet were observed between 1964 and 1967.

The first well completed to the Queen City aquifer in Cass County was dug in 1919 (TWDB, website). At the time of the first water-level measurements taken in 1941, about five wells tapped the Queen City. These earliest measurements are considered to be representative of predevelopment conditions in the aquifer.

Cherokee County

Little information related to the historical development of the Queen City and Sparta sands in Cherokee County was found during the literature review. Unless stated otherwise, the following discussion comes from William F. Guyton & Associates (1972). There are four principal aquifers in Anderson County. In order of importance, they are the Carrizo aquifer, the Wilcox aquifer, the Queen City aquifer, and the Sparta aquifer. The Queen City is an important aquifer not because it supplies large quantities of water but rather because it is widespread and shallow over most of the county. Water from the Queen City is used predominately for rural domestic and livestock purposes. In general, the Sparta aquifer is not an important source of water in Cherokee County because of its limited extent and its location at the top of hills. However, water from the Sparta aquifer is more important in the southern portion of the county were it outcrops in a wide belt.

In the three counties of Anderson, Cherokee, and Henderson, about 322 wells were completed to the Queen City aquifer in 1969. Of those, 11 wells supplied water for municipal purposes, and one each supplied water for industrial and irrigation purposes. The remaining wells were used for rural domestic and livestock purposes. In these same three counties, approximately 76 wells were completed to the Sparta aquifer in 1969. Of those, one each supplied water for industrial and irrigation purposes and the remaining wells supplied water for rural domestic and livestock purposes. Approximately 12.7 million gallons per day of groundwater was pumped in Anderson, Cherokee, and Henderson counties in 1969. The source of this groundwater was about 43 percent from the Carrizo aquifer, about 43 percent from the Wilcox aquifer, about 8 percent from the Queen City aquifer, a very small percentage from the Sparta aquifer, and the remaining from other formations.

The first eight wells tapping the Queen City aquifer in Cherokee County were drilled from 1850 to 1890 (TWDB, website). At the time of the first water-level measurements in 1936, about 63 wells tapped the Queen City (TWDB, website). All of the 1936 measurements are considered to be representative of predevelopment conditions.

The first well completed to the Sparta aquifer in Cherokee County was dug in 1896 (TWDB, website). At the time of the first water-level measurements in 1936, about 25 wells were completed to the Sparta (TWDB, website). One of these earliest measurements is considered to be representative of predevelopment conditions in the Sparta aquifer.

Fayette County

Little information related to the historical development of the Queen City and Sparta sands in Fayette County was found during the literature review. Unless stated otherwise, the following discussion comes from Rogers (1967). The principal sources of fresh to slightly saline groundwater in this county are the Sparta Sand, the Yegua Formation, sands in the upper portion of the Jackson Group, the Catahoula Tuff, the Oakville Sandstone, and the Lagarto Clay. Similar quality of water is also available in the western and northwestern portions of the county from the Carrizo Sand, Queen City Sand, and sands of the Wilcox Group. These later formations are rarely utilized as sources for groundwater though because good quality water can be found at shallower depths. A search of the water-level data on the TWDB website yielded two wells completed to the Queen City Sand in Fayette County. Small to moderate quantities of water are yielded by the Sparta aquifer in the western and northwestern portions of the county. This water is fresh to moderately saline. Water from the Sparta is used for irrigation, municipal, domestic, and livestock purposes.

Overall groundwater withdrawals for use in public water supplies increased from approximately 824 acre-feet in 1957 to 1,300 acre-feet in 1963. In 1964, a total of 1,106 acre-feet of groundwater was withdrawn for public water supply with only 3.6 acre-feet, or less than one percent, withdrawn from the Sparta Sand. Quantities of groundwater withdrawn from the Sparta Sand for industry, irrigation, rural domestic and livestock were not provided but are assumed to be small given the limited areal extent of the aquifer.

Two wells completed to the Queen City aquifer in Fayette County were found on the TWDB website. One of those wells was drilled in 1979 and the drilling date for the other well was not reported. The first water-level measurement was taken in 1940 (TWDB, website). This earliest water level is considered to be representative of predevelopment conditions in the Queen City aquifer.

The first well completed to the Sparta aquifer in Fayette County was dug in 1900 (TWDB, website). The first water level for this county was taken in this well also in 1900 (TWDB, website). This earliest water level, a water level from 1914, and two maximum water levels in selected portions of the county were considered to be representative of predevelopment conditions in the Sparta aquifer.

Franklin County

The Sparta aquifer as defined by the TWDB is not present in Franklin County. Little information related to the historical development of the Queen City aquifer in this county was found during the literature review. Unless stated otherwise, the following discussion comes from

Broom et al. (1965). The principle water bearing units in Franklin County are the Wilcox Group and the Carrizo Sand, the Reklaw Formation, and the Queen City Sand. These four units are considered to have similar hydrologic properties, to be hydraulically connected, and to act as a single aquifer, referred to the "Cypress aquifer", in this county. The outcrop of the Queen City is present in the southwestern corner of Franklin County.

A total of 4,300 acre-feet of groundwater usage from the Cypress aquifer was utilized in 1963 in Camp, Franklin, Morris, and Titus counties for public water supply (1,100 acre-feet), industrial (1,200 acre-feet), domestic (1,700 acre-feet) and livestock (290 acre-feet) purposes. The percentage of that groundwater removed from the Queen City portion of the Cypress aquifer was not determined. The majority of the 4,000 wells within the Cypress aquifer are shallow wells, 50 to 70 feet deep, with small to moderate capacities. The low transmissibility of the Cypress aquifer has limited and will continue to limit the development of the Cypress aquifer as a groundwater resource. Also, the corrosive nature of the shallow groundwater and the high iron content at lower depths deters the use of the groundwater.

No wells completed to the Queen City Sand alone were found on the TWDB website.

Frio County

The information regarding the history of development of the Queen City and Sparta Sands in Frio County comes from Alexander and White (1966). The following discussion is taken from that report. The principal aquifer in Frio County is the Carrizo Sand. Aquifers of minor importance are the Queen City Sand, the Edwards and associated limestones, the Wilcox, and the Sparta Sand. The Queen City aquifer can supply small to moderate quantities of fresh water in shallow wells in the central portion of this county. Small to moderate quantities of water are also available from the Sparta Sand in the outcrop and a few miles downdip of the outcrop. The breakdown of total pumpage in the county by aquifer for 1964 yields 99 percent from the Carrizo Sand, 1 percent from the Queen City Sand, and 0.1 percent from the Sparta Sand. All of the water pumped from the Queen City and Sparta sands was used for irrigation.

The public water supply for the city of Dilley in Frio County is supplied by several wells completed to the Carrizo Sand and one well completed to the Sparta Sand. The Sparta well was drilled in 1952 and is used only occasionally. The first irrigation well completed to the Sparta

Sand was drilled in 1927 in the vicinity of Dilley. About 40 irrigation wells tapping the Sparta were present in this area by 1930. The first irrigation well completed to the Queen City Sand was drilled in 1902 north of the city of Pearsall.

The earliest well in the TWDB well database to tap the Queen City aquifer in Frio County was completed in 1912 (TWDB, website). About six wells were completed to the Queen City at the time the first water-level measurements were taken in 1929 (TWDB, website). One of these earliest water levels is considered to be representative of predevelopment conditions.

The earliest well in the TWDB well database to tap the Sparta aquifer in Frio County was completed in 1965 (TWDB, website). About four wells were completed to the Sparta at the time of the first water-level measurements taken in 1969. These earliest measurements are not considered to be representative of predevelopment conditions. Rather, the maximum water level found within the outline of the Sparta aquifer as defined by the TWDB was selected as being representative of predevelopment conditions.

Gonzales County

Little information related to the historical development of the Queen City and Sparta sands in Gonzales County was found during the literature review. Unless stated otherwise, the following discussion comes from Shafer (1965). The Carrizo Sand is the most important aquifer within Gonzales County, with the Queen City Sand and the Sparta Sand aquifers utilized but of lesser importance. The Queen City Sand crops out in a band oriented southwest-northeast through the western and northern portions of Gonzales County. The Sparta Sand crops out in a narrow band oriented parallel to the Queen City Sand also through the western and northern portions of Gonzales County. Both sands dip to the southeast with water of fresh to slightly saline quality located in and near the outcrop locations. A few to several miles downdip, the waters become too saline and mineralized for most usages.

Ground water withdrawals for both domestic and livestock needs are obtained from both the Queen City and Sparta sands. The Sparta Sand is the source of the public water supplies for the towns of Waelder and Cost within Gonzales County. A total of approximately 9,900 acre-feet of ground water were withdrawn in Gonzales County in 1962, with ten percent from the Queen City and Sparta aquifers combined. Of this ten percent, 90 acre-feet were withdrawn for public water supply, 336 acre-feet for domestic usage, 168 acre-feet for livestock needs, and 336 acre-feet for miscellaneous needs. Insufficient data records are available for determining the changes in groundwater withdrawals and any subsequent water level changes over time in the Queen City and Sparta sands.

The first well completed to the Queen City aquifer in Gonzales County was dug in 1880 (TWDB, website). At the time the first water-level measurements were taken in 1938, about seven wells tapped the Queen City. Two of these earliest measurements are considered to be representative of predevelopment conditions in the Queen City aquifer.

The first well completed to the Sparta aquifer in Gonzales County was dug in 1903 (TWDB, website). About ten wells tapped the Sparta at the time of the first water-level measurements in 1938 (TWDB, website). For several wells, the 1938 water level is significantly lower than later water levels. Therefore, none of the earliest water levels are considered to be representative of predevelopment conditions. Rather, maximum water levels measured at selected locations within the county are considered to be representative of predevelopment conditions.

Gregg County

The Sparta aquifer as defined by the TWDB is not present in Gregg County. Little information related to the historical development of the Queen City aquifer in this county was found during the literature review. Unless stated otherwise, the following discussion comes from Broom (1969). The principle aquifers within Gregg County are the Carrizo-Wilcox and the Queen City aquifers. The Queen City outcrops across 90 percent of the county. Wells within the Queen City primarily yield small to moderate quantities of water. The overlying Weches Greensand and Sparta Sand are limited in extent with the outcrops present in the western portion of the county. The Sparta Sand yields only small quantities of water. The water in the Queen City aquifer is considered fresh with elevated iron content and localized elevated sulfate and total dissolved solids.

Prior to 1910, most water used in Gregg County come from shallow dug wells located in the Queen City. The City of Longview maintained three dug wells tapping the Queen City for water supply prior to 1910. Increased water needs for the city prompted the drilling of two wells into the Carrizo-Wilcox aquifer in 1910. Those wells were abandoned in 1914 due to poor water quality. Development of groundwater then stopped in Gregg County for about 20 years. With the start of oil business development in the county in the 1930s, increased demand for water was met by tapping the resources of the Carrizo-Wilcox aquifer. In 1966, a total of 1,883 acre-feet per year of groundwater was used in Gregg County, all from the Carrizo-Wilcox aquifer and none from the Queen City aquifer. Available water level records show no overall decline in aquifer water levels within the Queen City. However, some older and shallower dug wells had to be replaced with deeper wells due to limited well capacities, along with increased demand and lift capabilities.

The earliest well in the TWDB well database completed in the Queen City aquifer in Gregg County was drilled in 1941 (TWDB, website). About four wells tapped the Queen City at the time of the first water-level measurements in 1966 (TWDB, website). These earliest water levels are not considered to be representative of predevelopment conditions.

Grimes County

Little information related to the historical development of the Queen City and Sparta sands in Grimes County was found during the literature review. Unless stated otherwise, the following discussion comes from Baker et al. (1974). Both the Queen City and Sparta are located at depth in Grimes County. No wells are known to be completed in either formation. It is estimated that both the Queen City and Sparta can yield large quantities of fresh to slightly saline water in the northern third and northwestern portions of the county, respectively.

No wells completed to just the Queen City aquifer or just the Sparta aquifer in Grimes County were found on the TWDB website.

Harrison County

The Sparta aquifer as defined by the TWDB is not present in Harrison County. Little information related to the historical development of the Queen City aquifer in this county was found during the literature review. Unless stated otherwise, the following discussion comes from Broom and Myers (1966). The principle water bearing units within Harrison County are the Wilcox Group, Carrizo Sand, Reklaw Formation and the Queen City Sand. These four units are considered to have similar hydrologic properties, to be hydraulically connected, and to act as a single aquifer, referred to as the “Cypress aquifer”, in this county. The outcrop of the Queen City is present throughout the northwestern corner of Harrison County. Isolated sections of the Sparta Sand are found along ridges in the northwestern corner of the county.

Prior to 1949, the city of Marshall removed approximately 1 million gallons per day from the Cypress aquifer. In 1949, Marshall abandoned its well field and switched to surface water for its municipal water supply. In 1964, a total of 2,700 acre-feet of groundwater usage from the Cypress aquifer was utilized in Harrison County for public water supply (269 acre-feet), industrial (964 acre-feet), domestic (1,087 acre-feet) and livestock (381 acre-feet) purposes. The percentage of the groundwater that was withdrawn from the Queen City section of the Cypress aquifer was not determined. A comparison of water levels from the early 1940s to 1964 indicates no general decline in shallow wells under water-table conditions.

The first wells tapping the Queen City aquifer in Harrison County were completed in 1910 (TWDB, website). About five wells tapped the Queen City at the time of the first water-level measurements taken in 1942 (TWDB, website). These earliest water levels are considered to be representative of predevelopment conditions.

Henderson County

The Sparta aquifer as defined by the TWDB is not present in Henderson County. Little information related to the historical development of the Queen City aquifer in this county was found during the literature review. Unless stated otherwise, the following discussion comes from William F. Guyton & Associates (1972). There are four principal aquifers in Henderson County. In order of importance, they are the Carrizo aquifer, the Wilcox aquifer, the Queen City aquifer, and the Sparta aquifer. The Queen City is an important aquifer not because it supplies large quantities of water but rather because it is widespread and shallow in the eastern half of the county. Water from the Queen City is used predominately for rural domestic and livestock purposes. The Sparta aquifer is not an important source of water in Henderson County because of its limited extent and its location at the top of hills.

In the three counties of Anderson, Cherokee, and Henderson, about 322 wells were completed to the Queen City aquifer in 1969. Of those, 11 wells supplied water for municipal purposes, and one each supplied water for industrial and irrigation purposes. The remaining wells were used for rural domestic and livestock purposes. In these same three counties, approximately 76 wells were completed to the Sparta aquifer in 1969. Of those, one each supplied water for industrial and irrigation purposes and the remaining wells supplied water for rural domestic and livestock purposes. Approximately 12.7 million gallons per day of groundwater was pumped in Anderson, Cherokee, and Henderson counties in 1969. The source of this groundwater was about 43 percent from the Carrizo aquifer, about 43 percent from the Wilcox aquifer, about 8 percent from the Queen City aquifer, a very small percentage from the Sparta aquifer, and the remaining from other formations.

The first well completed to the Queen City aquifer in Henderson County was dug in 1830 (TWDB, website). Over 60 wells tapped the Queen City at the time of the first water-level measurements taken in 1936 (TWDB, website). These earliest measurements are considered to be representative of predevelopment conditions.

Houston County

Little information related to the historical development of the Queen City and Sparta sands in Houston County was found during the literature review. Unless stated otherwise, the following discussion comes from Tarver (1966). The Sparta Sand crops out across most of northern Houston County and underlies nearly all of the county. The Queen City Sand is present at the surface in the northeastern and northwestern corners of the county and underlies most of the county. Groundwater used in Houston County is provided predominately by the Carrizo Sand, the Queen City Sand, and the Sparta Sand. The principal source of groundwater in this county is the Sparta Sand which yields small to large quantities of water. Many of the wells tapping the Sparta Sand provide water for domestic purposes. The towns of Crockett and Kennard obtain their water from the Sparta Sand as does the Eastham State Prison Farm. The Queen City Sand yields small to moderate quantities of water in the northwestern half of the county. In the remainder of the county, water from the Queen City is highly mineralized and not used. The majority of the 3,300 acre-feet of groundwater used in Houston County in 1963 was most likely obtained from the Sparta aquifer. Limited data are available to determine the change in water levels over time but it is assumed that, given the relatively low groundwater withdrawals, the water levels have not changed substantially with time.

The first well completed to the Queen City aquifer in Houston County was drilled in 1948 (TWDB, website). Two wells tapped the Queen City at the time of the first water-level measurement in 1957 (TWDB, website). This earliest water-level measurement is not considered to be representative of predevelopment conditions.

La Salle County

Little information related to the historical development of the Queen City and Sparta sands in La Salle County was found during the literature review. Unless stated otherwise, the following discussion comes from Harris (1965). The Carrizo Sand is the principal aquifer within La Salle County, with the Queen City Sand and the Sparta Sand aquifers utilized but of lesser importance. The Sparta Sand crops out in the northwestern corner of La Salle County and dips to the southeast under the northern and central portions of the county. The Queen City Sand is located at depth and underlies approximately the same portion of the county as the Sparta Sand. The Queen City Sand yields large quantities of fresh to moderately saline water and in most areas, wells flow under artesian pressures. Small to moderate quantities of fresh to slightly saline water are available from the Sparta Sand only in the western portion of La Salle County.

Approximately 750 acre-feet of groundwater was withdrawn in La Salle County in 1962 for public supply purposes. Of this total, 22 acre-feet was removed from the Queen City Sand to supply the city of Fowlerton and 56 acre-feet were removed from the Sparta Sand to supply the city of Encinal. Of the estimated 4,000 acre-feet of groundwater withdrawn for irrigation purposes in 1962, about 500 acre-feet was obtained from the Sparta Sand. During the drought years of 1947 to 1956, the volume of ground water withdrawn for both public water supply and irrigation needs increased and were most likely greater than those of 1962. However, records are not available which quantify the ground water volumes utilized during these drought years. In addition, data records are not available for determining the changes in water levels over time in the Queen City and Sparta sands.

One well is identified in the data on the TWDB website as being completed to the Queen City aquifer in La Salle County. That well was drilled in 1943. The first water-level measurement for that well was taken in 1962 (TWDB, website). That first water level is not considered to be representative of predevelopment conditions in the Queen City aquifer. One of the hydrographs of transient water-level data for a Queen City well in this county shows stable water levels over an extended time period. The average water level in that well is considered to be representative of predevelopment conditions. A water level measured in 1942 in the Bigford Formation was used to develop the water-level elevations contours representative of predevelopment conditions in the Queen City aquifer as shown in Figure 4.4.7 in the main body of this report.

The first well to tap the Sparta aquifer in La Salle County was completed in 1912 (TWDB, website). About nine wells tapped the Sparta at the time of the first water-level measurements in 1959 (TWDB, website). One of the 1959 water levels plus two other water levels representing maximum value in the county are considered to be representative of predevelopment conditions in the Sparta aquifer.

Lee County

Little information related to the historical development of the Queen City and Sparta sands in Lee County was found during the literature review. Unless stated otherwise, the following discussion comes from Thompson (1966). The principal aquifers in Lee County are the Simsboro member of the Wilcox Group, the Carrizo Sand, the Queen City Sand, and the Sparta Sand. The Sparta Sand crops out in a narrow band oriented southwest-northeast across the central portion of Lee County. The Queen City Sand crops out to the north and west of the Sparta Sand and is oriented in the same general direction. However, faulting is present in the north-central portion of the county resulting in a widening of the Queen City Sand outcrop towards the northern corner of Lee County. Both units dip to the southeast and are present at depth below the central and southern portions of Lee County. The Queen City Sand and the Sparta Sand yield small to moderate quantities of fresh to moderately saline ground water for municipal, domestic, and livestock purposes.

The use of groundwater for public water supply in Lee County has increased over time, with 200 acre-feet withdrawn in 1943 and 420 acre-feet withdrawn in 1963. A peak of 520 acre-feet was withdrawn in 1959. Of the 420 acre-feet of groundwater withdrawn in 1963 for public supply purposes, 300 acre-feet were used by the city of Giddings. Six wells supplied groundwater for this city between 1930 and 1964. Two of the wells were abandoned, three of the wells obtain water from the Queen City Sand, and one well is completed across both the Queen City and Sparta sands. About 34 acre-feet of the groundwater withdrawn in 1963 for public supply purposes were used by the city of Dime Box. This city has been supplied by a series of wells completed to the Sparta Sand since 1914. Currently, one well supplies water needs for Dime Box.

In 1963, 27 acre-feet of groundwater were used for irrigation purposes by two wells in Lee County. One of the wells taps the Simsboro Member of the Wilcox Group and the other well taps the Queen City Sand. The amount of groundwater used for livestock and domestic purposes in 1963 was 660 and 560 acre-feet, respectively. These numbers represent total groundwater withdrawals and were not broken-out by specific aquifer. A significant amount, over 365 acre-feet, of groundwater was lost during 1963 to uncontrolled flowing wells. The units which these flowing wells tap are unknown.

The earliest well in the TWDB well database completed to the Queen City aquifer in Lee County was drilled in 1958 (TWDB, website). The first water-level measurement was taken in that well also in 1958 (TWDB, website). This earliest water level is not considered to be representative of predevelopment conditions. One of the Queen City wells in this county has stable transient water-level data over a long time period. The average water level for that well is considered to be representative of predevelopment conditions in the Queen City aquifer.

The earliest well in the TWDB well database tapping the Sparta aquifer in Lee County was completed in 1930 (TWDB, website). That was the only well completed to the Sparta at the time of the first water-level measurement in 1938 (TWDB, website). This earliest water level, the maximum water level measured in the county, and the maximum water level from a well with stable water-level elevations over a long period of time are considered to be representative of predevelopment conditions in the Sparta aquifer.

Leon County

Little information related to the historical development of the Queen City and Sparta sands in Leon County was found during the literature review. Unless stated otherwise, the following discussion comes from Peckham (1965). The major aquifers within Leon County are the Carrizo-Wilcox, Queen City, and Sparta aquifers. Of these, the Carrizo-Wilcox aquifer is the principal source of groundwater in the county. The Queen City Sand crops out along the northern half of Leon County and is present throughout most of Leon County with the exception of the northwest corner of the county. The Sparta sand crops out within the central part of the county and is present throughout central and southern Leon County.

The majority of groundwater withdrawals from both the Queen City and Sparta aquifers are from shallow wells utilized for domestic and livestock purposes. Groundwater withdrawal from the Queen City aquifer also occurs through flowing wells. Two municipal wells completed to the Queen City supply water for the town of Centerville. In 1960, this town withdrew 107 acre-feet of groundwater. No other municipal, industrial or irrigation wells are located within either the Queen City or Sparta.

The earliest wells reported for the Queen City and Sparta aquifers in Leon County date to the mid 1920s and early 1930s, respectively. Limited information is available for determining historical changes in water levels, but given the domestic and livestock use of most wells within the Queen City and Sparta aquifers, it is assumed that the water levels have not changed substantially over time.

The first water-level measurements in wells completed to the Queen City aquifer in Leon County were taken in 1936 (TWDB, website). Dates at which wells were completed to the Queen City prior to this time are unknown. The earliest water levels from 1936 are considered to be representative of predevelopment conditions.

The earliest well in the TWDB well database completed to the Sparta aquifer in Leon County was drilled in 1951 (TWDB, website). The first water-level measurement was taken in this well in 1959 (TWDB, website). The maximum water level measured in this well in this county is considered to be representative of predevelopment conditions in the Sparta aquifer.

Marion County

The Sparta aquifer as defined by the TWDB is not present in Marion County. Little information related to the historical development of the Queen City Sand in Marion County was found during the literature review. Unless stated otherwise, the following discussion comes from Broom (1971). The principle water bearing units in Marion County are the Wilcox Group, Carrizo Sand, Reklaw Formation and the Queen City Sand. These four units are considered to have similar hydrologic properties, to be hydraulically connected, and to act as a single aquifer, referred to as the “Cypress aquifer”, in this county. The outcrop of the Queen City is present in Marion County except in the southeastern portion of the county. Isolated sections of the Sparta Sand are found along the tops of ridges and high hills in this county. The Queen City Sand, and to a lesser extent the Sparta Sand, provides small quantities of groundwater from shallow wells for rural domestic and livestock usage.

In 1967, approximately 4,000 acre-feet of groundwater from the Cypress aquifer was utilized in Cass and Marion Counties for public water supply (1,200 acre-feet), industrial (2,200 acre-feet), and rural domestic and livestock (560 acre-feet) purposes. Approximately 85% of the groundwater withdrawals were in Cass County. The percentage of the groundwater that was withdrawn from the Queen City portion of the Cypress aquifer was not determined. Water levels within the Cypress aquifer have not varied significantly with time in Marion County.

The first water-level measurement in a well completed to the Queen City aquifer in Marion County was taken in 1942 (TWDB, website). Dates at which wells were completed to the Queen City prior to this time are unknown. This earliest water level is considered to be representative of predevelopment conditions.

McMullen County

Little information related to the historical development of the Queen City and Sparta sands in McMullen County was found during the literature review. Unless stated otherwise, the following discussion comes from Harris (1965). The Sparta Sand dips to the southeast under the northern and central portions of McMullen County. The Queen City Sand is located at depth and underlies approximately the same portion of the county as the Sparta Sand. The Carrizo Sand is the principal aquifer within McMullen County, with the Queen City Sand utilized but of lesser importance. Water in the Sparta Sand underlying this county is too highly saline for public supply, irrigation, or industrial usage. The Queen City Sand yields large quantities of fresh to moderately saline water and in most areas, wells flow under artesian pressures. In 1962, no groundwater from the Queen City Sand was used for public supply, industrial, or irrigation purposes in McMullen County. Insufficient data records are available for determining the changes in water levels over time in the Queen City Sand in this county.

The first well tapping the Queen City aquifer in McMullen County was completed in 1914. About four wells tapped the Queen City at the time of the first water-level measurements in 1959. These earliest water levels are considered to be representative of predevelopment conditions.

No water levels for wells identified as being completed in the Sparta aquifer in McMullen County were found in the data on the TWDB website.

Morris County

The Sparta aquifer as defined by the TWDB is not present in Morris County. Little information related to the historical development of the Queen City Sand in this county was found during the literature review. Unless stated otherwise, the following discussion comes from Broom et al. (1965). The principle water bearing units in Morris County are the Wilcox Group and the Carrizo Sand, the Reklaw Formation, and the Queen City Sand. These four units are considered to have similar hydrologic properties, to be hydraulically connected, and to act as a single aquifer, referred to the "Cypress aquifer", in this county. The outcrop of the Queen City is present throughout the southern portion of Morris County.

A total of 4,300 acre-feet of groundwater usage from the Cypress aquifer was utilized in 1963 in Camp, Franklin, Morris, and Titus counties for public water supply (1,100 acre-feet), industrial (1,200 acre-feet), domestic (1,700 acre-feet) and livestock (290 acre-feet) purposes. The percentage of that groundwater removed from the Queen City portion of the Cypress aquifer was not determined. The majority of the 4,000 wells within the Cypress aquifer are shallow wells, 50 to 70 feet deep, with small to moderate capacities. The low transmissibility of the Cypress aquifer has limited and will continue to limit the development of the Cypress aquifer as a groundwater resource. Also, the corrosive nature of the shallow groundwater and the high iron content at lower depths deters the use of the groundwater.

No water levels for wells identified as being completed to the Queen City aquifer in Morris County were found in the data on the TWDB website.

Nacogdoches County

Little information related to the historical development of the Queen City and Sparta sands in Nacogdoches County was found during the literature review. Unless stated otherwise, the following discussion comes from William F. Guyton & Associates (1970). In order of importance, the major water-bearing units in Nacogdoches County are the Carrizo Sand, the Wilcox Group, the Yegua Formation, and the Sparta Sand. Of these, the Carrizo Sand is by far the most productive. Groundwater from the Sparta aquifer is obtained from numerous small capacity wells, most of which are located in the outcrop. A few Sparta wells were drilled by the Southland Paper Mill Company in 1942 and 1943. Those wells yielded moderate quantities of water but were not used by the paper mill as a source of water, rather they were used only as observation wells. The Queen City Sand is present in Nacogdoches County but is not considered a principal water-bearing unit in the county. The majority of Queen City wells are of small capacity and are located in the outcrop area. In 1968, 67 wells completed to the Sparta aquifer were present in northern Angelina County and southern Nacogdoches County. These wells predominately supplied water for domestic and livestock purposes. One well supplied water to a municipality and several wells were originally drilled as test wells. Thirty-nine wells tapping the Queen City aquifer were present in 1968 in Nacogdoches and Angelina counties. The majority of these wells were used for domestic and livestock purposes and were located in north, northwest, and west of the city of Nacogdoches. About 9 million gallons per day of groundwater was pumped in Nacogdoches County in 1968. Of that, 8 million gallons per day was supplied by the Carrizo aquifer, 0.5 million gallons per day was supplied by the Wilcox aquifer, and 0.5 million gallons per day was supplied by the remaining water-bearing units.

The first well completed to the Queen City aquifer in Nacogdoches County was dug in 1835 (TWDB, website). At the time of the first water-level measurements in 1936, over 30 wells tapped the Queen City (TWDB, website). These earliest water levels from 1936 are considered to be representative of predevelopment conditions in the Queen City aquifer.

The first well completed to the Sparta aquifer in Nacogdoches County was dug in 1871. Over 25 wells tapped the Sparta at the time of the first water-level measurements taken in 1936. Several of the water levels measured in 1936, one water level measured in 1938, and the average water level for a well with stable water-level elevations over a long period of time are considered to be representative of predevelopment conditions in the Queen City aquifer.

Rusk County

The Sparta aquifer as defined by the TWDB is not present in Rusk County. Little information related to the historical development of the Queen City Sand in this county was found during the literature review. Unless stated otherwise, the following discussion comes from Sandeen (1987). The Queen City Sand outcrops in the very northwestern corner of Rusk County and is found in the downdropped blocks associated with the Mount Enterprise Fault System in the southern portion of the county. The Queen City Sand provides small quantities of water to only a few wells in the county and feeds numerous small springs. The Sparta Sand is found in Rusk County only in the area of the Mount Enterprise Fault System and may supply small quantities of water to dug wells and feeds numerous small springs.

The first well completed to the Queen City aquifer in Rusk County was dug in 1900. About 10 wells tapped the Queen City at the time of the first water-level measurements taken in 1936. These 1936 values are considered to be representative of predevelopment conditions.

Sabine County

The Queen City aquifer as defined by the TWDB is not present in Sabine County. Little information related to the historical development of the Sparta aquifer in this county was found during the literature review. Unless stated otherwise, the following discussion comes from Anders (1967). In Sabine County, the unit between the underlying Carrizo Sand and overlying Sparta Sand is the Cane River Formation. This formation is in the same stratigraphic position as the Queen City Formation, Reklaw Formation, and Weches Greensand in central and south Texas. The Cane River is not considered an important aquifer in this county but does supply small quantities of water to shallow wells.

The principal water-bearing units in Sabine County are, in order of importance, the Carrizo Sand and Wilcox Group, the Sparta Sand, and the Yegua Formation. As of 1967, the Sparta aquifer yielded small quantities of water to many wells in the county and is considered to be capable of yielded large quantities of water to wells screen across most of its sands.

In 1964, groundwater use in Sabine and San Augustine counties for public supply was about 389 acre-feet, for rural domestic and livestock was about 508 acre-feet, and for industrial purposes and irrigation was insignificant. About 560 acre-feet of groundwater was lost through flowing wells in these two counties in 1964. The aquifer sources for the groundwater use in 1964 were not reported.

The first well to tap the Sparta aquifer in Sabine County was completed in 1925 (TWDB, website). That was the only well tapping in aquifer at the time of the first water-level measurement taken in 1942 (TWDB, website). The maximum water level recorded for this well is considered to be representative of predevelopment conditions in the Sparta aquifer.

San Augustine County

The Queen City aquifer as defined by the TWDB is not present in San Augustine County. Little information related to the historical development of the Sparta aquifer in this county was found during the literature review. Unless stated otherwise, the following discussion comes from Anders (1967). In San Augustine County, the unit between the underlying Carrizo Sand and overlying Sparta Sand is the Cane River Formation. This formation is in the same stratigraphic position as the Queen City Formation, Reklaw Formation, and Weches Greensand in central and south Texas. The Cane River is not considered an important aquifer in this county but does supply small quantities of water to shallow wells.

The principal water-bearing units in San Augustine County are, in order of importance, the Carrizo Sand and Wilcox Group, the Sparta Sand, and the Yegua Formation. As of 1967, the Sparta aquifer yielded small quantities of water to many wells in the county and is considered to be capable of yielded large quantities of water to wells screen across most of its sands.

In 1964, groundwater use in Sabine and San Augustine counties for public supply was about 389 acre-feet, for rural domestic and livestock was about 508 acre-feet, and for industrial purposes and irrigation was insignificant. About 560 acre-feet of groundwater was lost through flowing wells in these two counties in 1964. The aquifer sources for the groundwater usages in 1964 were not reported.

The first well completed to the Sparta aquifer in San Augustine County was drilled in 1953 (TWDB, website). The first water-level measurement in the county was taken in this well also in 1953 (TWDB, website). This earliest water level is not considered to be representative of predevelopment conditions. Rather, the maximum water level measured in the county regardless of time was selected as being representative of predevelopment conditions in the Sparta aquifer.

Smith County

The Sparta aquifer as defined by the TWDB is not present in Smith County. Little information related to the historical development of the Queen City Sand in this county was found during the literature review. Unless stated otherwise, the following discussion comes from Dillard (1963). Three aquifers are found in Smith County. The principal aquifer, the Carrizo-Wilcox, is comprised of the Carrizo Sand and the Wilcox Group. Both the Queen City and Sparta sands are also aquifers. Deposition of the Queen City and Sparta formations was controlled by the Tyler Basin within the East Texas Embayment area. Within Smith County, the Queen City and Sparta Formations are oriented relatively horizontal and do not dip significantly towards the southeastern direction as observed in other east Texas counties. The outcrop of the Queen City Formation covers approximately 75 percent of Smith County. The Sparta Formation outcrop covers approximately 20 percent of Smith County and is oriented north-south within the central region of the county. The Sparta Formation is underlain and almost completely surrounded laterally by older formations as a result of infilling of the Tyler Basin. This results in a relatively non-dipping shallow deposit. The areal width of the Sparta Formation narrows to the south and extends into Cherokee County. The Queen City and the Sparta are separated by the Weches Formation.

In 1961, the Queen City aquifer provided 77 acre-feet of groundwater for municipal purposes, 1120 acre-feet for industrial purposes, and about 306 acre-feet for domestic and irrigation purposes. It is estimated that natural discharge from the Queen City aquifer by springs and seeps is greater per year than artificial discharge by pumping. Groundwater withdrawal from the Sparta Sand in 1962 was 40 acre-feet by the city of Bullard for its public supply, 153 acre-feet for industrial purposes, and 307 acre-feet for domestic use. Many springs in the Sparta Sand discharge an unknown quantity of water to streams annually.

No information related to the change in pumping overtime was available. No long-term records related to water levels within the Queen City or Sparta aquifers were available.

However, as of 1962, the Queen City water levels had increased since the “1950’s drought.” The water levels in both aquifers respond quickly to fluctuations in precipitation.

Domestic use of untreated Queen City aquifer water is limited given its odor, taste, corrosive and staining characteristics. The water is acidic in nature with dissolved gases (carbon dioxide and methane) and high iron concentrations. The water from the Sparta aquifer is of higher quality except for higher iron concentrations and low pH at depths near the lower contact with the Weches formation.

The first well completed to the Queen City aquifer in Smith County was dug in 1880 (TWDB, website). About 27 wells tapped this aquifer at the time of the first water-level measurements taken in 1953. These earliest water levels are not considered to be representative of predevelopment conditions in the Queen City aquifer.

Titus County

The Sparta aquifer as defined by the TWDB is not present in Titus County. Little information related to the historical development of the Queen City Sand in this county was found during the literature review. Unless stated otherwise, the following discussion comes from Broom et al. (1965). The principle water bearing units in Titus County are the Wilcox Group and the Carrizo Sand, the Reklaw Formation, and the Queen City Sand. These four units are considered to have similar hydrologic properties, to be hydraulically connected, and to act as a single aquifer, referred to the “Cypress aquifer”, in this county. The outcrop of the Queen City is present in the southeastern corner of the county.

A total of 4,300 acre-feet of groundwater usage from the Cypress aquifer was utilized in 1963 in Camp, Franklin, Morris, and Titus counties for public water supply (1,100 acre-feet), industrial (1,200 acre-feet), domestic (1,700 acre-feet) and livestock (290 acre-feet) purposes. The percentage of that groundwater removed from the Queen City portion of the Cypress aquifer was not determined. The majority of the 4,000 wells within the Cypress aquifer are shallow wells, 50 to 70 feet deep, with small to moderate capacities. The low transmissibility of the Cypress aquifer has limited and will continue to limit the development of the Cypress aquifer as a groundwater resource. Also, the corrosive nature of the shallow groundwater and the high iron content at lower depths deters the use of the groundwater.

No water levels for wells identified as being completed to the Queen City aquifer in Titus County were found in the data on the TWDB website.

Upshur County

The Sparta aquifer as defined by the TWDB is not present in Upshur County. Little information related to the historical development of the Queen City aquifer in this county was found during the literature review. Unless stated otherwise, the following discussion comes from Broom (1969). The principle aquifers in Upshur County are the Carrizo-Wilcox and the Queen City aquifers. The Queen City outcrops across 90 percent of the county. Wells within the Queen City primarily yield small to moderate quantities of water. The overlying Weches Greensand and Sparta Sand are limited in extent with the outcrops present in the western portion of the county. The Sparta Sand yields only small quantities of water. The water in the Queen City aquifer is considered fresh with elevated iron content and localized elevated sulfate and total dissolved solids.

Prior to 1910, most water used in Upshur County come from shallow dug wells located in the Queen City. With the start of oil business development in the county in the 1930s, increase demand for water was met by tapping the resources of the Carrizo-Wilcox aquifer. In 1966, a total of 1,502 acre-feet per year of groundwater was used in Upshur County. Of this, 87 percent was supplied by the Carrizo-Wilcox aquifer and 13 percent was supplied by the Queen City aquifer. Available water level records show no overall decline in aquifer water levels within the Queen City. However, some older and shallower dug wells were required to be replaced with deeper wells due to limited well capacities, along with increased demand and lift capabilities.

The first well completed to the Queen City aquifer in Upshur County was dug in 1900. About five wells tapped this aquifer at the time of the first water-level measurements taken in 1942. These earliest water levels are considered to be representative of predevelopment conditions in the Queen City aquifer.

Van Zandt County

The Sparta aquifer as defined by the TWDB is not present in Van Zandt County. Little information related to the historical development of the Queen City aquifer in this county was found during the literature review. Unless stated otherwise, the following discussion comes from White (1973). The Queen City Sand crops out across the southeastern corner of Van Zandt. The Sparta Sand is present along the tops of hills in southeastern Van Zandt County but does not yield water to wells. As of 1972, the Queen City aquifer supplied small quantities of groundwater for rural domestic and livestock purposes only. Several wells within the Queen City were reported to go dry during extended periods of limited rainfall but would quickly recover after heavy rainfalls.

The first well completed to the Queen City aquifer in Van Zandt County was dug in 1900 (TWDB, website). At the time of the first water-level measurements taken in 1961, about seven wells tapped this aquifer. These earliest water levels are not considered to be representative of predevelopment conditions in the Queen City aquifer.

Walker County

Little information related to the historical development of the Queen City and Sparta sands in Walker County was found during the literature review. Unless stated otherwise, the following discussion comes from Winslow (1950). The Queen City and Sparta sands are located at depth underneath the northern most part of this county. The Sparta extends into the county further than the Queen City. As of 2002, no wells were known to be completed in the Queen City Sand and only one well completed to the Sparta Sand was found in the data on the TWDB website. The Sparta Sand is expected to be able to yield moderate quantities of fresh water based on the results of electrical logs conducted in oil wells in the county.

No water levels for wells identified as being completed to the Queen City aquifer and located in Walker County were found on the TWDB website.

The only well identified as being completed to the Sparta aquifer in this county was drilled in 1973. The first water-level measurement for this well was taken in 1973 also. This earliest water level is considered to be representative of predevelopment conditions.

Washington County

Little information related to the historical development of the Queen City and Sparta sands in Washington County was found during the literature review. Unless stated otherwise, the following discussion comes from Sandeen (1972). The Queen City and Sparta Sands are located at depth beneath the northern edge of Washington County. Given the depth and the limited areal extent, groundwater is currently (2002) not being withdrawn from either the Queen City or Sparta sands based on the data found on the TWDB website. It is estimated that both formations may be capable of yielding small to moderate amounts of slightly saline water.

No water levels for wells identified as being completed to either the Queen City or Sparta aquifers in Washington County were found on the TWDB website.

Wilson County

Little information related to the historical development of the Queen City and Sparta sands in Wilson County was found during the literature review. Unless stated otherwise, the following discussion comes from Anders (1957). In order of importance, the water-bearing units in Wilson County are the Carrizo Sand, the Queen City Sand, the Wilcox Group, the Sparta Sand, the Yegua Formation, and the Jackson Group. The Queen City Sand is present as outcrop in a band oriented southwest-northeast across the central portion of Wilson County, and dips to the southeast under most of the southeastern portion of the county. The Sparta Sand crops out in thinner band also oriented southwest-northeast across the central portion of Wilson County.

All municipal groundwater withdrawals, except for the city of Stockdale, are taken from the Carrizo Sand. A thick section of the Queen City Sand near Stockdale supplies sufficient groundwater to supply this city. Other than this, the Queen City Sand is tapped by numerous shallow and small capacity wells for rural domestic and livestock usage. Because of the limited areal extent of the Sparta Sand, only a limited number of shallow and small capacity wells for rural domestic and livestock usage are located in the Sparta Sand. Good quality fresh water is obtained from the higher transmissive zones of both the Queen City and Sparta Sands within Wilson County. Water within the lower transmissive zones tends to be of lower quality with higher mineral content.

The first well to tap the Queen City aquifer in Wilson County was dug in 1911 (TWDB, website). This was the only well tapping this aquifer at the time of the first water-level measurement taken in 1936 (TWDB, website). This earliest water level plus the average water level for a well with stable transient water-level data over a long period of time are considered to be representative of predevelopment conditions.

Wood County

The Sparta aquifer as defined by the TWDB is not present in Wood County. Little information related to the historical development of the Queen City aquifer in this county was found during the literature review. Unless stated otherwise, the following discussion comes from Broom (1968). The principle aquifers within Wood County are the Carrizo-Wilcox and the Sparta-Queen City aquifers. As of 1965, the majority of water used in the Wood County came from groundwater sources but, even so, groundwater resources of Wood County are considered to be "practically untapped." The Weches Greensand, which separates the Sparta Sand and the Queen City Sand, is considered an ineffective aquiclude in Wood County. As a result, the Sparta and Queen City are hydraulically connected and act as a single aquifer. Water in the Sparta-Queen City aquifer is considered fresh with localized areas of elevation iron concentrations.

At total of 2300 and 1200 acre-feet of water was withdrawn from the Carrizo-Wilcox and Sparta-Queen City aquifers, respectively, in 1965. Of that removed from the Sparta-Queen City aquifer, 314 acre-feet was used for municipal purposes, 225 acre-feet was used for industrial purposes, 448 acre-feet was used for domestic purposes, and 184 acre-feet was used for livestock purposes.

The earliest wells within the Sparta-Queen City date from 1890 to 1900, with at least seven dug wells in operation by 1900 for domestic and livestock use. Comparison of water levels measured in 1942 and 1965 show no overall decline in aquifer water levels. However, some older and shallower dug wells were required to be replaced with deeper wells due to lowered water levels. Groundwater pumping for irrigation occurs only during "unusually dry periods."

The first well to tap the Queen City aquifer in Wood County was dug in 1890 (TWDB, website). About fourteen wells were completed to the Queen City at the time of the first water-level measurements taken in 1942 (TWDB, website). These earliest water levels are considered to be representative of predevelopment conditions in the Queen City aquifer.

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APPENDIX B

Application of Water Availability Models (WAM) for the Development of Stream Gain-Loss Estimates

GROUNDWATER – SURFACE WATER INTERACTION
QUEEN CITY – SPARTA AQUIFER GROUNDWATER AVAILABILITY STUDY

prepared for

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Austin, Texas

October 2004

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GROUNDWATER – SURFACE WATER INTERACTION
QUEEN CITY – SPARTA AQUIFERS

1.0 INTRODUCTION

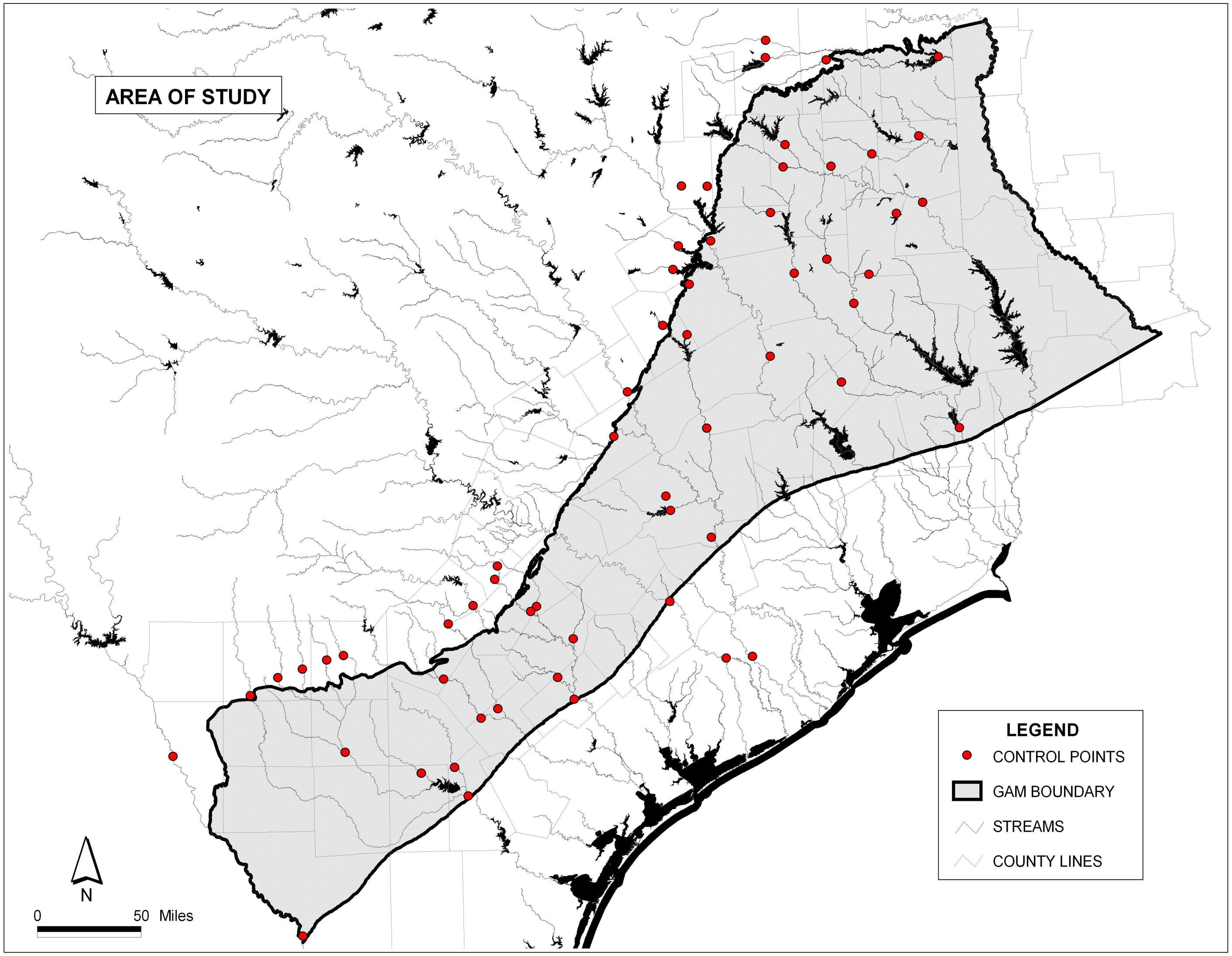
The purpose of this study is to determine the interaction between surface water and groundwater in the Queen City and Sparta aquifers. A greater understanding of the interaction allows for a more precise calculation of the quantity of water available for use in the aquifer. The interaction is quantified in terms of gains to the surface water body or losses from the surface water body. Quantifying the amount of gain or loss cannot be measured directly, so a method using naturalized flow data from the Water Availability Models (WAMs) developed by the Texas Commission on Environmental Quality (TCEQ) was used to quantify the gains or losses in the majority of reaches crossing the aquifer. For the Colorado River and Rio Grande, a method using low flows was used to determine a percent loss for the specified reach. The results of the study are incorporated in the Queen City Sparta Groundwater Availability Model (GAM).

2.0 AREA OF STUDY

The model boundary for the GAM extends from the Rio Grande in Webb County, Texas to Northwestern Louisiana running approximately parallel to the Gulf Coast. A map of the area with control points used in this analysis is located in Figure 1. The model boundary consists of the surface area of the outcrop and down dip portions of the aquifers. The model boundary crosses most of the major river basins in Texas, which typically run from the northwest to the southeast. The following is a list of the rivers and creeks intersecting the model boundary which were selected for the study:

Angelina River
Atascosa River
Big Cypress Creek
Black Cypress Bayou
Brazos River
Cibolo Creek
Colorado River
Frio River
Guadalupe River
Leona River
Navasota River
Neches River
Nueces River
Rio Grande
Sabine River
San Antonio River
San Marcos River
Sulphur River
Trinity River

FIGURE 2-1
AREA OF STUDY



3.0 GROUNDWATER – SURFACE WATER INTERACTION

The interaction of groundwater and surface water occurs over the outcrop of an aquifer. The downdip portion of the Queen City and Sparta aquifers is confined and therefore no interaction with surface water is present. The interaction of surface water with groundwater over the outcrop may be quantified using indirect analysis. Based on the results of the analysis the reach of a river or creek over the outcrop is then defined as either losing or gaining.

For terms of this study a losing reach is a reduction in stream flow due to seepage into the aquifer from the streambed elevation being above the water table of the aquifer. Other factors affect the overall losses of a reach such as evaporation, evapotranspiration, unaccounted-for diversions, domestic and livestock use. These losses from streams, however, are not delivered to the aquifer and may overstate the amount of loss from the stream to the aquifer.

For terms of this study a gaining stream is an increase of flow due to seepage of groundwater into the reach due to the streambed being below the water table of the aquifer. The same factors listed above also affect the overall gains by understating the amount of water being delivered to the stream from the aquifer.

The methods listed below represent an effort to minimize the error introduced by evapotranspiration and unaccounted-for diversions or return flows with respect to the contributions from tributaries. However, the losses from these factors on the main stem of the stream being analyzed could not be accurately accounted for. The naturalized flow method accounts for all authorized TCEQ diversions or return flows so it is expected that errors resulting from unauthorized diversions and return flows would be small. The naturalized flow method considers a minimum twenty year historical record representing a wide range of observed flows. It is expected that errors resulting from evapotranspiration losses will be most significant under low flow conditions. Therefore, it is expected that losses from evapotranspiration will be minimal.

4.0 DETERMINATION OF GAINS AND LOSSES

Two different methods were used to estimate stream gains and losses, the naturalized flow method and the low flow method. The choice of the method for analysis of each river basin was based on the availability of data. The naturalized flow method requires primary control points to be present in the mainstem and tributary areas of interest, an overlapping period of at least 20 years for the flow data, and primary control points that were not affected by significant springs or recharge areas. If all of the criteria were not met the low flow method was used to determine the losses in the area. Each method is a valid method to quantify losses or gains in a river reach.

The naturalized flow method was used for the majority of the basins in the study. From the analysis, the MEDIAN monthly gain/loss was calculated in cfs/day/mile to determine the overall gain/loss. For the Colorado River and Rio Grande, a low-flow method was used to determine the overall gain/loss. The low-flow method was used for the Colorado River because of the presence of springs and major recharge features upstream of the study area, and the lack of tributary stream gages within the study area. The low-flow method was used for the Rio Grande basin because the

TCEQ has recently developed the WAM and in the process has conducted a comprehensive study to determine the losses in the basin. The Leona River and Black Cypress Creek were not studied due to an absence of suitable gages in the area of interest.

4.1 Naturalized Flow Method

The general procedure used in this study to determine gains or losses is a method developed using naturalized flows from the basin-specific WAMs. The naturalized flow method required the identification of two mainstem, long-term gages used as primary control points in the WAM that are within the basin of interest and as close as possible to the upstream and downstream edges of the outcrop. If a suitable upstream control point did not exist then the headwaters were used. At the headwaters, zero flow and zero drainage area were assumed. Tributary gages in the area of interest that were primary control points in the WAM and had periods of record overlapping the mainstem gages' records were also identified.

A list of control points used with their periods of record is located in Attachment A. If tributary control points did not exist or lacked a sufficient overlapping period of record, tributaries from an adjoining river basin that were as close as possible to the basin being evaluated were selected. The minimum overlapping period used in the study was 20 years. A list of rivers with their corresponding period of analysis is listed in Table 3-1.

TABLE 3-1
PERIOD OF ANALYSIS

River	Period of Analysis
Angelina River	1962-1981
Atascosa River	1964-1996
Black Cypress Bayou	1968-1998
Brazos River	1965-1994
Cibolo Creek	1946-1989
Frio River	1964-1996
Guadalupe River	1964-1989
Navasota River	1978-1997
Neches River	1963-1986
Nueces River	1964-1996
Sabine River	1974-1996
San Antonio River	1962-1986
San Marcos River	1957-1989
Sulphur River	1953-1996
Trinity River	1967-1987

Once control points were selected, monthly naturalized flows were extracted from the WAMs and analyzed. Naturalized flows were used to eliminate the effects of various man-related influences from historical streamflow records. These influences include the diversion of water for various uses; return flows from municipal, industrial, or agricultural sources; and the effects of reservoirs. Individual maps of each basin with the location of control points used are shown in Attachment B.

After the naturalized flows were extracted from the WAM, the gains or losses were calculated by the following six (6) steps.

1) Using the identified mainstem gages, incremental flows were calculated on a monthly basis by using the equation:

INCREMENTAL FLOW = DOWNSTREAM NAT FLOW – UPSTREAM NAT FLOW

2) The tributary gages were used to calculate an average unit naturalized runoff rate on a monthly basis for the incremental watershed being analyzed. The unit runoff rate is equal to the volume of runoff per unit area watershed. The equation to calculate the unit runoff rate is:

$$\text{UNIT RUNOFF RATE} = \sum_{j=1}^{n} \mathrm{NF}(j) \Big/ \sum_{j=1}^{n} \mathrm{DA}(j)$$

where the NF(j) is the Naturalized flow rate of tributary (j) and DA(j) is the drainage area of tributary (j).

3) The unit runoff rate was used to calculate the total estimated runoff for the incremental watershed by the equation:

ESTIMATED RUNOFF = UNIT RUNOFF RATE * INCREMENTAL DRAINAGE AREA

4) The monthly loss or gain for the reach in question was then be calculated by the equation:

INCREMENTAL FLOW – ESTIMATED RUNOFF = GAINS (if positive)

LOSSES (if negative)

5) In some months, significant artificial gains or losses are likely to result from the gain/loss calculations. This is primarily because of travel time for floods occurring at the end of a month, and because of small, localized runoff events unrepresentative of the entire incremental drainage area. To reduce the possibility of introducing the artificial gains/losses into the analyses all monthly calculations two standard deviations from the mean monthly gain/loss were eliminated from the data set. Monthly gain/loss charts for each river basin denoting the mean monthly values and outliers that were eliminated are located in Attachment C. With the outliers removed, the MEDIAN monthly gain/loss was calculated in units of cfs/day.

6) The MEDIAN monthly gain/loss per mile was then calculated by dividing by the main stem incremental distance from the upstream gage to the downstream gage in river miles as shown by the following equation and determined to be the overall gain/loss to be incorporated in the GAM. The results are located in Attachment D.

GAIN PER MILE = GAIN/INCREMENTAL DISTANCE

LOSS PER MILE = LOSS/INCREMENTAL DISTANCE

A summary of the results is presented in Table 5-1.

4.2 Low-Flow Method

The low-flow method was used in the Colorado and Rio Grande Basins. The method also requires the identification of two mainstem gages that are in the basin of interest and located as close as possible to the upstream and downstream edges of the outcrop. The general procedure employed in this analysis involved the application of the following equation using available historical data for specific time periods for specific stream reaches.

FLOW OUT – FLOW IN	=	GAINS	(if positive)
		LOSSES	(if negative)

The FLOW OUT term in the above equation represents the total quantity of water that is known to flow out of a particular reach over a particular period of time. Typically, it includes the measured streamflow that passes out the lower end of the reach and the measured diversions of water that are made by water users along the length of the reach. Similarly, the FLOW IN term represents the total quantity of water that is known to flow into the same reach of the river over the same period of time. The FLOW IN term includes the measured river flow at the upstream end of the reach, all quantifiable tributary inflows that enter the river along the reach, quantifiable springflows that may be discharged into the reach, and known return flows.

To facilitate the use of this loss information in estimating the actual natural channel losses/gains the PERCENTAGE LOSS/GAIN RATE for a particular reach has been determined using the following equation.

PERCENTAGE GAIN RATE = (GAINS/UPSTREAM FLOW IN) X 100%

PERCENTAGE LOSS RATE = (LOSSES/UPSTREAM FLOW IN) X 100%

In the gain/loss analysis, streamflows for only those periods during which minimal rainfall was known to have occurred (based on nearby rain gage data) have been used in order to minimize potential errors associated with not knowing the magnitude of inflows from ungaged tributaries. During wet periods, the ungaged tributary inflows can be significant, and unless they are properly accounted for and quantified, significant artificial gains are likely to result from the gain/loss calculations. The PERCENTAGE GAIN RATE for the Colorado River from Columbus to Wharton is 17.8% or 0.26% per mile. The PERCENTAGE LOSS RATE for the Rio Grande from Piedras Negras to Laredo is 14% or 0.10% per mile. These estimates would include potential contributions from springs which may be encountered in the analyzed stream reach. A summary of the results is presented in Table 5-1.

5.0 SUMMARY

Gains and losses were calculated for the selected rivers over the Queen City and Sparta Aquifers using naturalized flow and low-flow methods. The methods were used to reduce the effects of man-related influences such as diversions, return flows, and effects of reservoirs. Both methods also minimize errors due to wet-weather conditions that generate artificial spikes in gains and losses.

The study determined that the gains and losses vary across the study area. In general, rivers in the northern and eastern portions of the study area experienced gains while the rivers in the southern and western portions experienced either small gains or losses. The gains and losses calculated ranged from a 202,366 cfs/day/mile gain on the Trinity River to a 33,111 cfs/day/mile loss on the San Marcos River.

TABLE 5-1
SUMMARY OF RESULTS

River	Incremental Distance (miles)	Mainstem Incremental Drainage Area (square miles)	# of Tributary Gages	Tributary Drainage Area (square miles)	Tributary DA/ Mainstem DA (%)	Gain/Loss (ft^3/day/mile)
ANGELINA R	43	1,278	2	534	41.8%	-32,639
ATASCOSA R	65.8	1,171	1	783	66.9%	18,064
BIG CYPRESS CREEK	-----	-----	-----	-----	-----	-----
BLACK CYPRESS BAYOU	48.5	365	1	383	104.9%	64,198
BRAZOS R	152.8	13,444	4	9,723	72.3%	159,763
CIBOLO CR	69.2	553	1	549	99.3%	4,895
COLORADO R	68.5	363	NA	NA	NA	4,846
FRIO R	79.4	2,798	4	1,341	47.9%	12,926
GUADALUPE R	180.5	2,874	3	1,435	49.9%	28,038
LEONA R	-----	-----	-----	-----	-----	-----
NAVASOTA R	93	1,214	1	97	8.0%	5,223
NECHES R	249	7,342	2	268	3.7%	153,851
NUECES R	263.4	13,566	3	5,383	39.7%	-18,924
RIO GRANDE	139.3	5,266	NA	NA	NA	-8,344
SABINE R	134.1	2,232	4	964	43.2%	41,845
SAN ANTONIO R	57.5	370	1	827	223.5%	25,690
SAN MARCOS R	37.9	426	1	309	72.5%	-33,111
SULPHUR R	114.7	2,916	2	770	26.4%	-557
TRINITY R	125.8	5,373	5	2,261	42.1%	202,366

ATTACHMENT A

LIST OF CONTROL POINTS USED IN STUDY

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Gage #	River/Gage	Nat./Gaged	Period of Record
7342500	South Sulphur River near Cooper	Nat.	1949-2000
7343000	North Sulphur River near Cooper	Nat.	1949-2000
7343500	White Oak Creek near Talco	Nat.	1949-2000
7344200	Wright Patman Lake near Texarkana	Nat.	1949-2000
7346045	Black Cypress Bayou at Jefferson	Nat.	1968-2000
7346050	Little Cypress near Ore City	Nat.	1963-2000
8018500	Sabine River near Mineola	Nat.	1939-2000
8019000	Lake Fort Creek near Quitman	Nat.	1924-2000
8022040	Sabine River near Beckville	Nat.	1938-2000
8022070	Martin Creek near Tatum	Nat.	1974-1996
8031200	Kickapoo Creek near Brownsboro	Nat.	1962-1989
8033300	Piney Creek near Groveton	Gaged	1961-1989
8033900	East Fork Angelina River near Cushing	Nat.	1964-1989
8034500	Mud Creek near Jacksonville	Nat.	1939-1979
8036500	Angelina River near Alto	Nat.	1940-2000
8040600	Neches River near Town Bluff	Nat.	1951-2000
8062700	Trinity River at Trinidad	Nat.	1965-2000
8062800	Cedar Creek near Kemp	Nat.	1963-1987
8062900	Kings Creek near Kaufman	Nat.	1963-1987
8063500	Richland Creek near Richland	Nat.	1939-1989
8064500	Chambers Creek near Corsicana	Nat.	1939-1984
8065350	Trinity River near Crockett	Nat.	1963-2000
8098290	Brazos River near Highbank	Nat.	1965-2000
8106500	Little River at Cameron	Nat.	1916-2000
8110000	Yegua Creek near Summerville	Nat.	1924-1991
8110100	Davidson Creek near Lyons	Nat.	1962-2000
8110325	Navasota River above Groesback	Nat.	1978-2000
8110430	Big Creek near Freestone	Nat.	1978-2000
8111000	Navasota River near Bryan	Nat.	1951-1997
8111500	Brazos River near Hempstead	Nat.	1938-2000
8161000	Colorado River at Columbus	Nat.	1916-2000
8162000	Colorado River at Wharton	Nat.	1938-2000
8168500	Guadalupe River, above Comal River at New Braunfels	Nat.	1927-2000
8169000	Comal River, New Braunfels	Nat.	1927-2000
8170000	San Marcos Springs, San Marcos	Gaged	1956-2000
8171300	Blanco River at Kyle	Nat.	1956-2000
8172000	San Marcos River, Luling	Nat.	1939-2000
8173000	Plum Creek at Luling	Nat.	1930-1993
8174600	Peach Creek, Dilworth	Nat.	1959-1979
8175000	Sandies Creek, Westhoff	Nat.	1930-2000
8175800	Guadalupe River, Cuero	Nat.	1964-2000
8181800	San Antonio River at Elmendorf	Nat.	1962-2000
8183500	San Antonio River at Falls City	Nat.	1925-2000
8185000	Cibolo Creek at Selma	Nat.	1946-2000
8186000	Cibolo Creek near Falls City	Nat.	1930-2000
8192000	Nueces River below Uvalde	Nat.	1939-2000
8197500	Frio River at Uvalde	Nat.	1939-2000
8198500	Sabinal River at Sabinal	Nat.	1952-2000
8200700	Hondo Creek at King Waterhole near Hondo	Nat.	1960-2000
8202700	Seco Creek at D'Hanis	Nat.	1960-2000
8205500	Frio River at Derby	Nat.	1915-2000
8206700	San Miguel Creek near Tilden	Nat.	1964-2000
8208000	Atascosa River at Whitsett	Nat.	1932-2000
8210000	Nueces River near Three Rivers	Nat.	1915-2000
8458000	Rio Grande at Piedras Negras	Nat.	1968-2000
8459000	Rio Grande at Laredo	Nat.	1975-1989

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ATTACHMENT B

INDIVIDUAL RIVER BASIN MAPS

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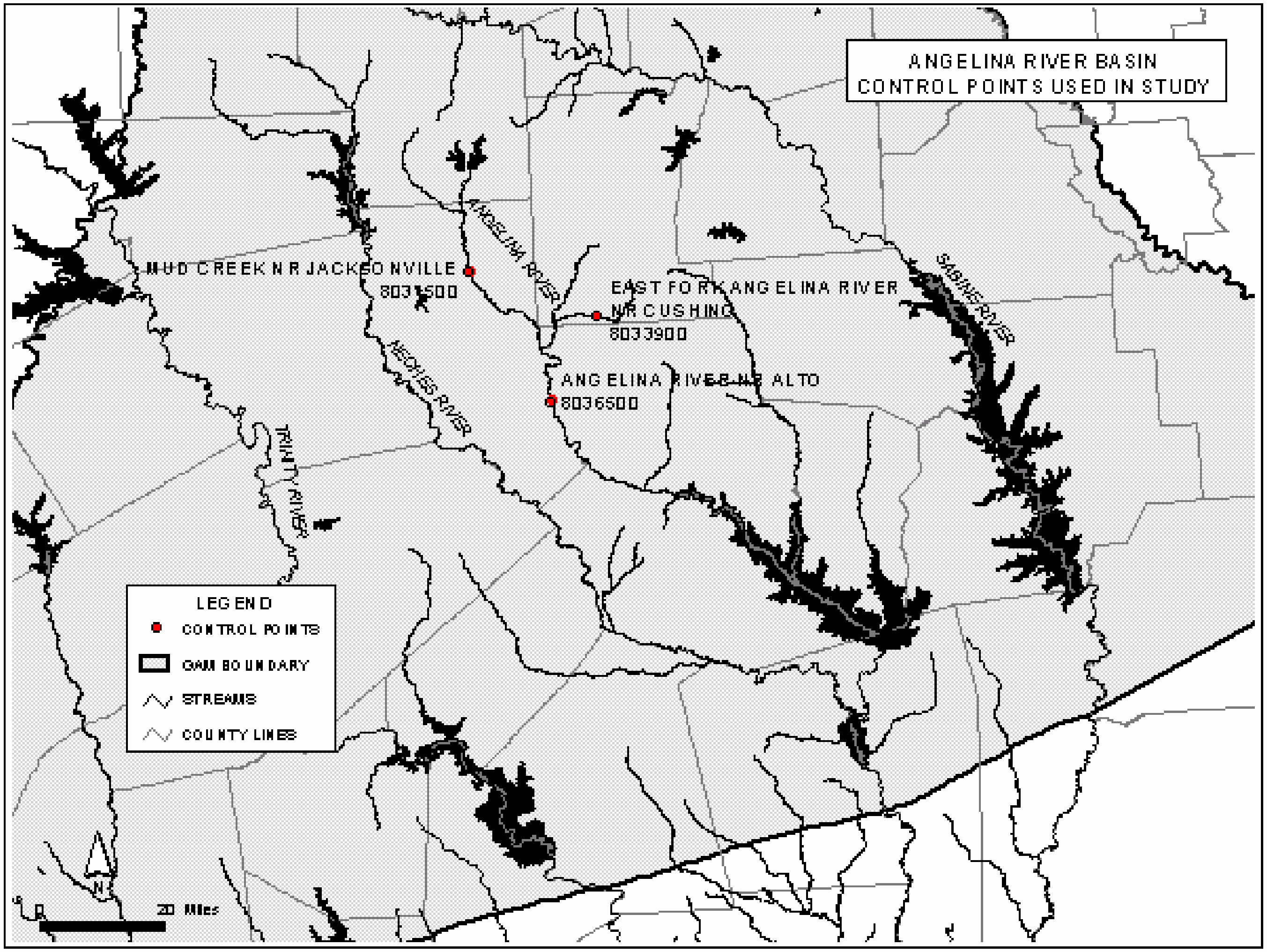
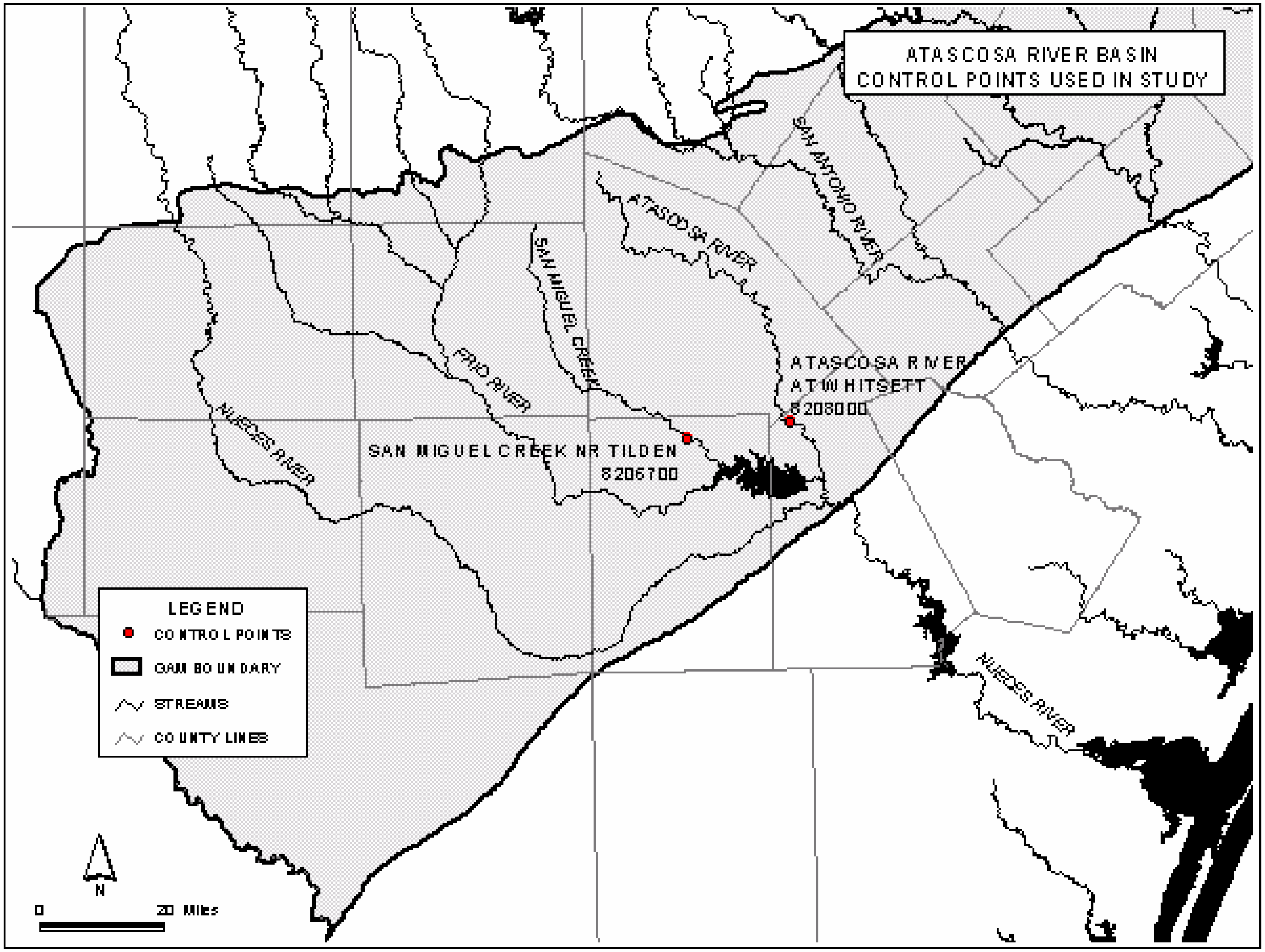
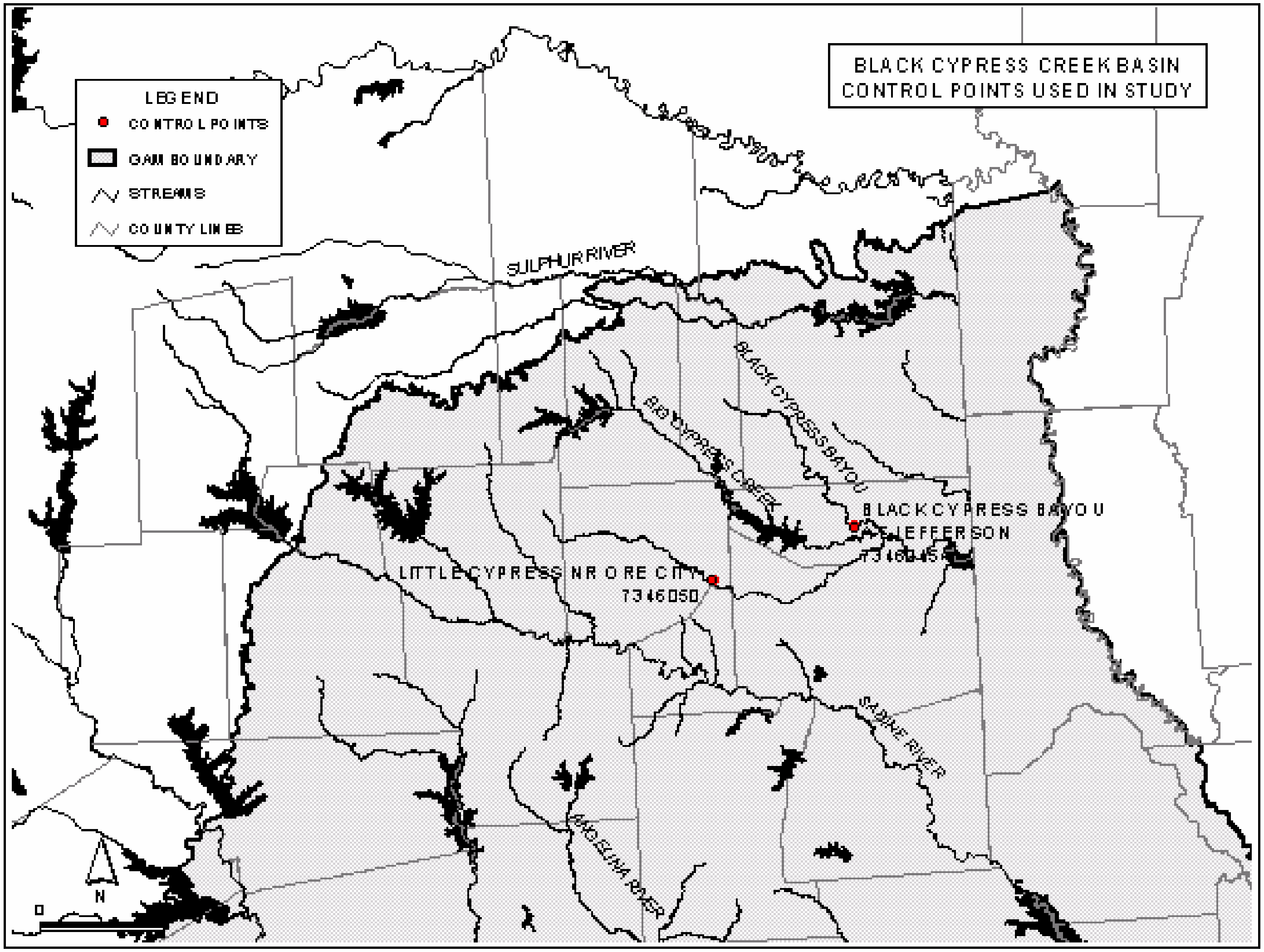

ANGELINA RIVER BASIN
CONTROL POINTS USED IN STUDY
MUD CREEK NR JACKSONVILLE
8031500
EAST FORK ANGELINA RIVER
NR CUSHING
8033900
ANGELINA RIVER NR ALTO
8036500
ANGELINA RIVER
NECHES RIVER
TRINITY RIVER
SABINE RIVER
LEGEND
CONTROL POINTS
GAM BOUNDARY
STREAMS
COUNTY LINES
N
0
20 Miles

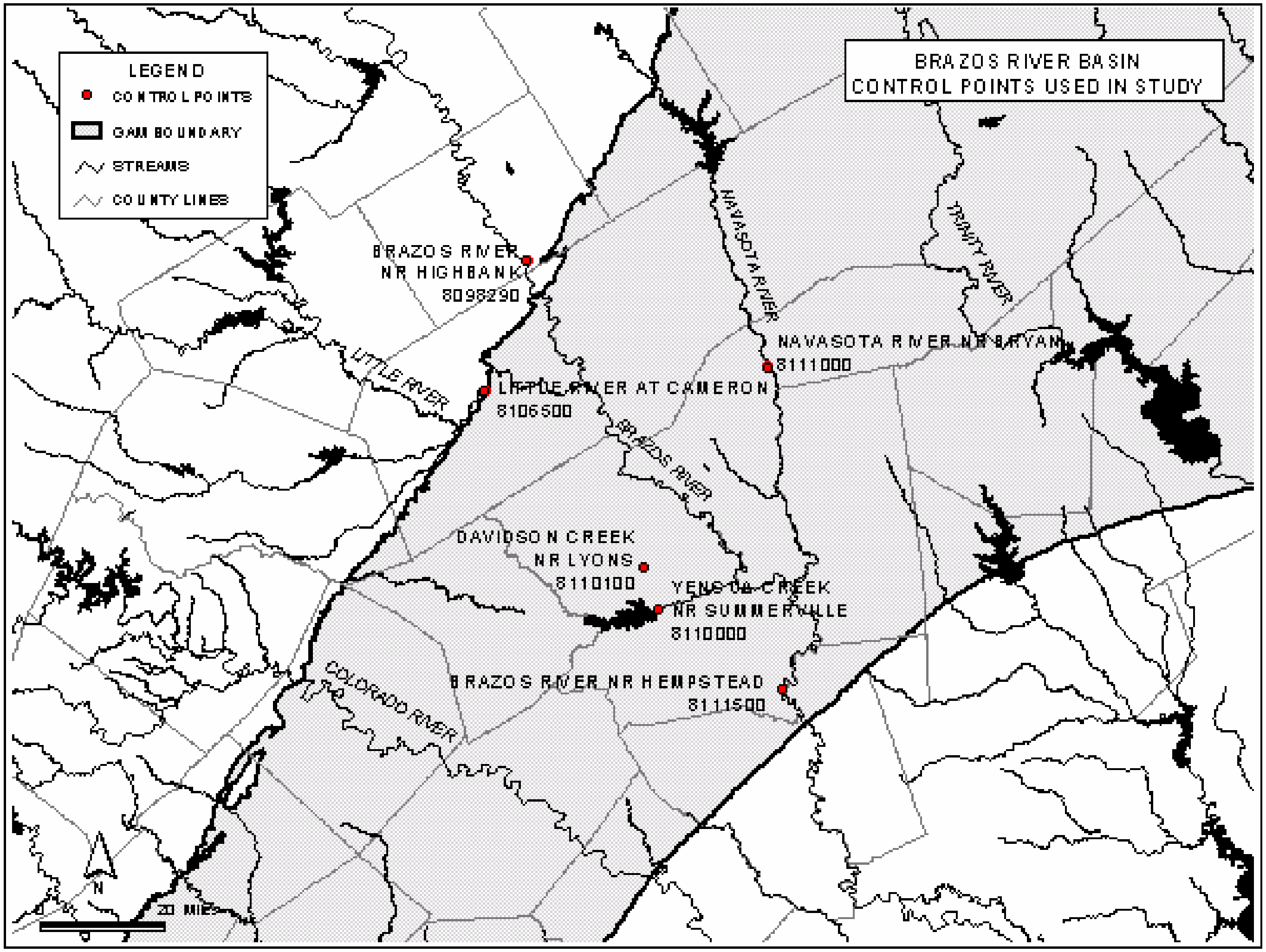
GROUNDWATER – SURFACE WATER INTERACTION
QUEEN CITY – SPARTA AQUIFER GAM



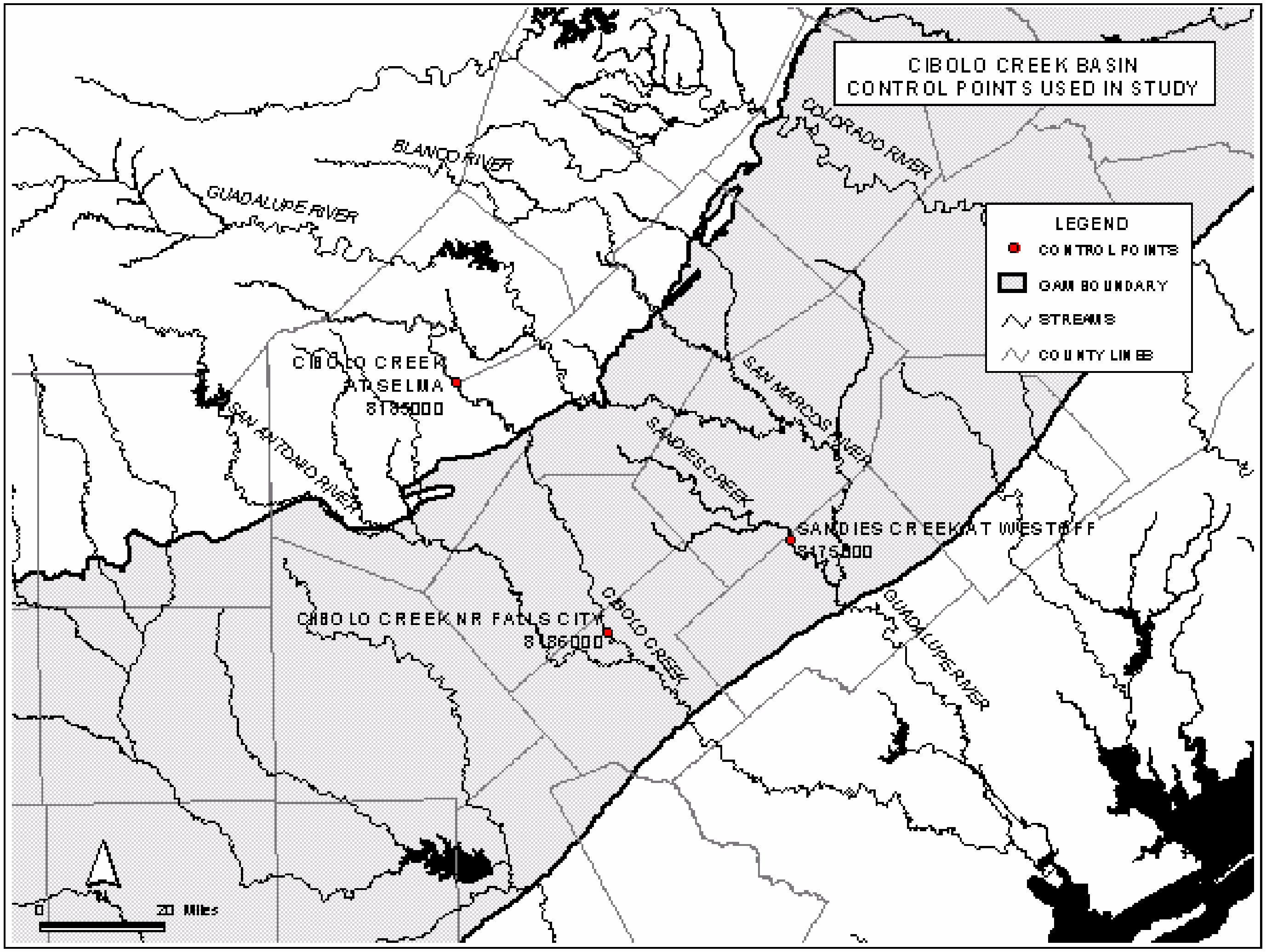
GROUNDWATER – SURFACE WATER INTERACTION
QUEEN CITY – SPARTA AQUIFER GAM



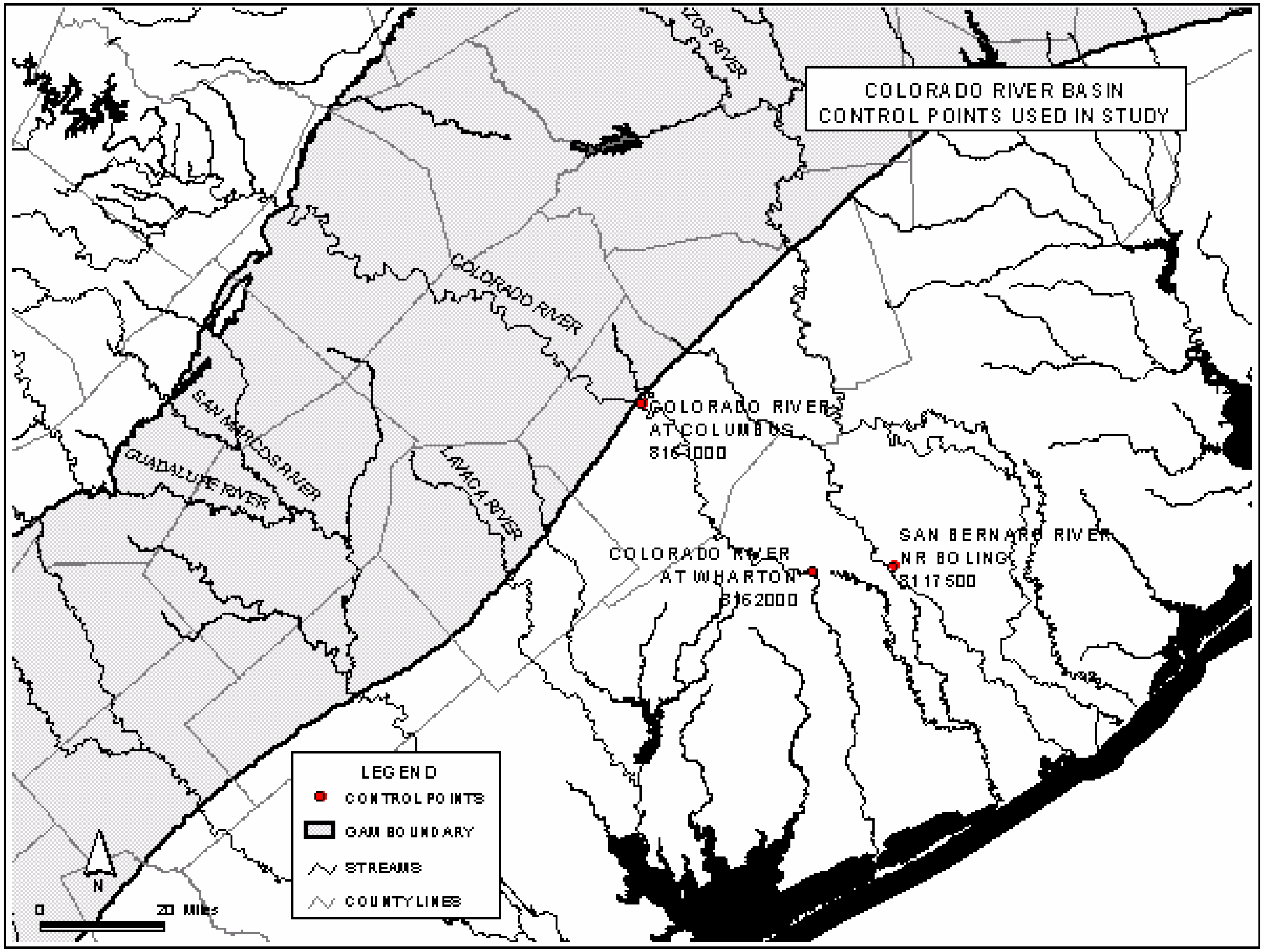
GROUNDWATER – SURFACE WATER INTERACTION
QUEEN CITY – SPARTA AQUIFER GAM

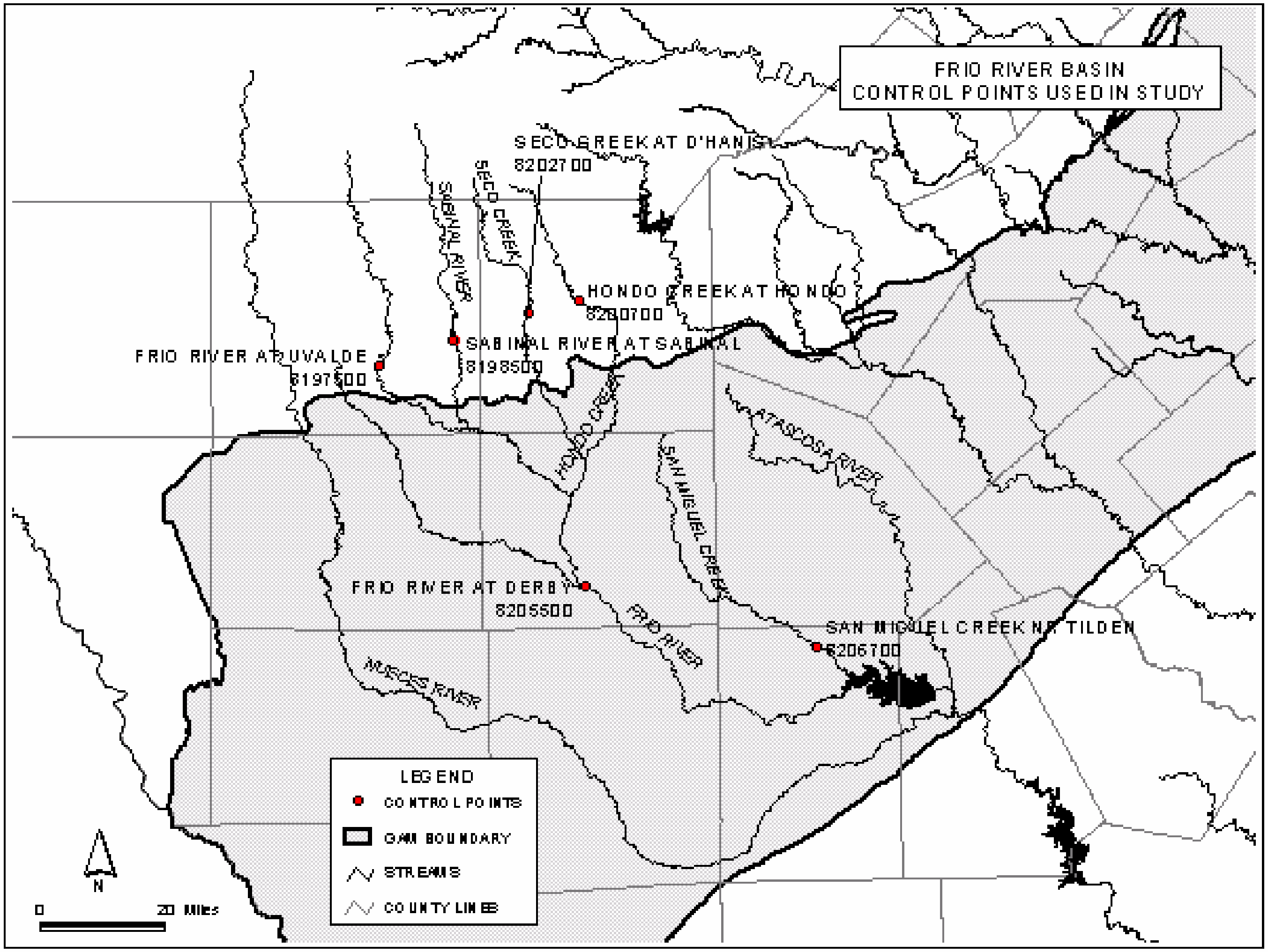


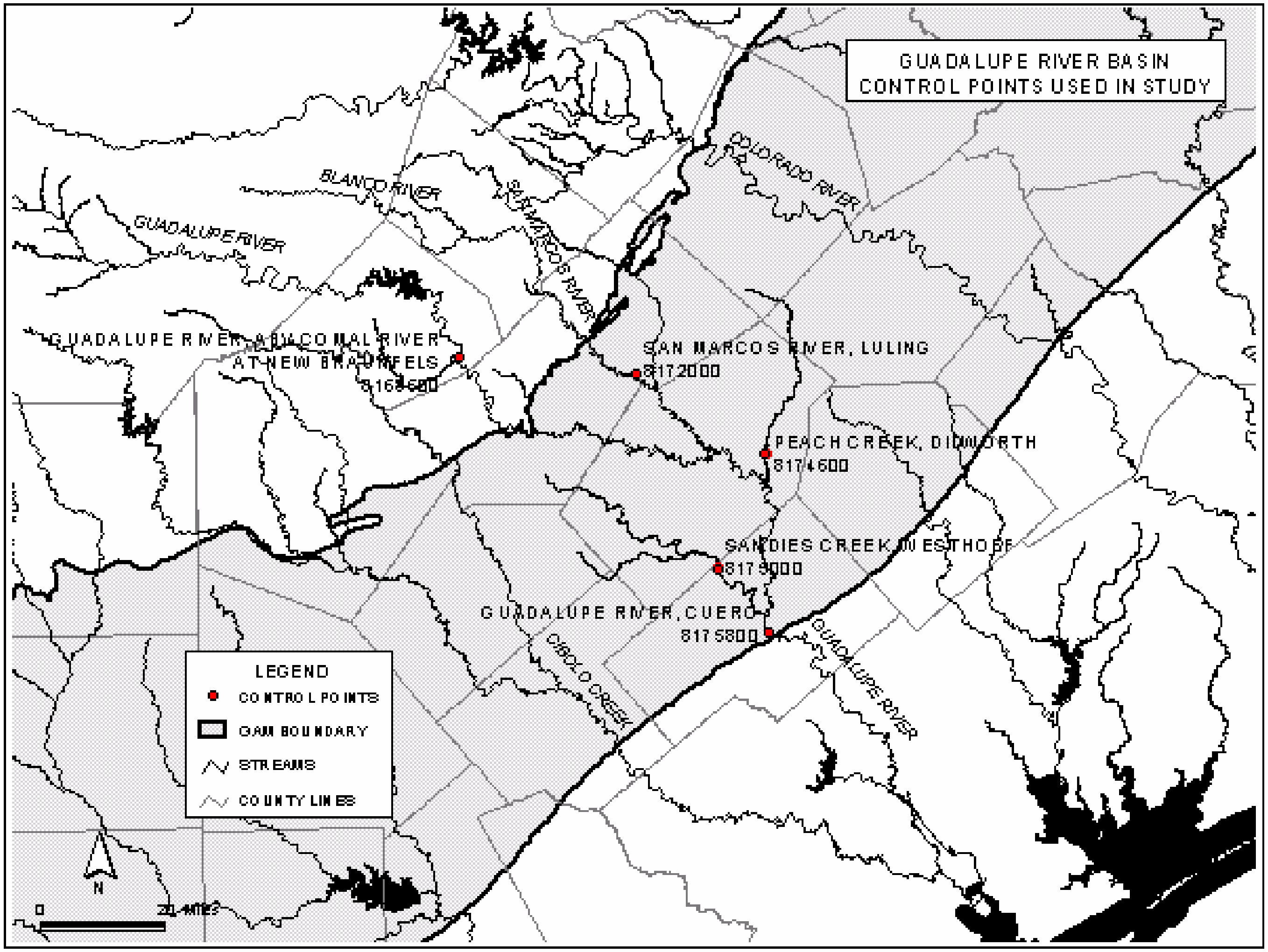
GROUNDWATER – SURFACE WATER INTERACTION
QUEEN CITY – SPARTA AQUIFER GAM

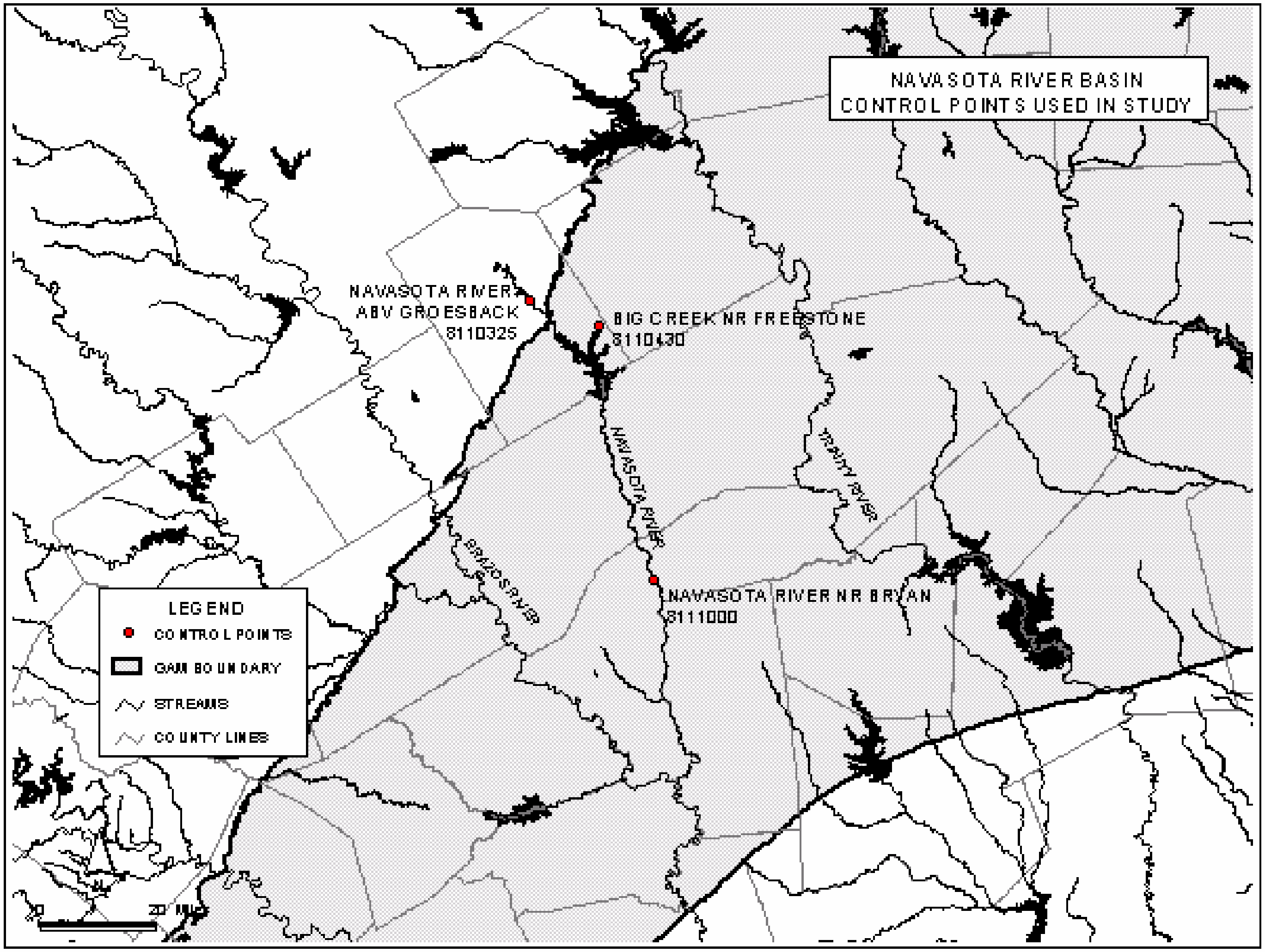


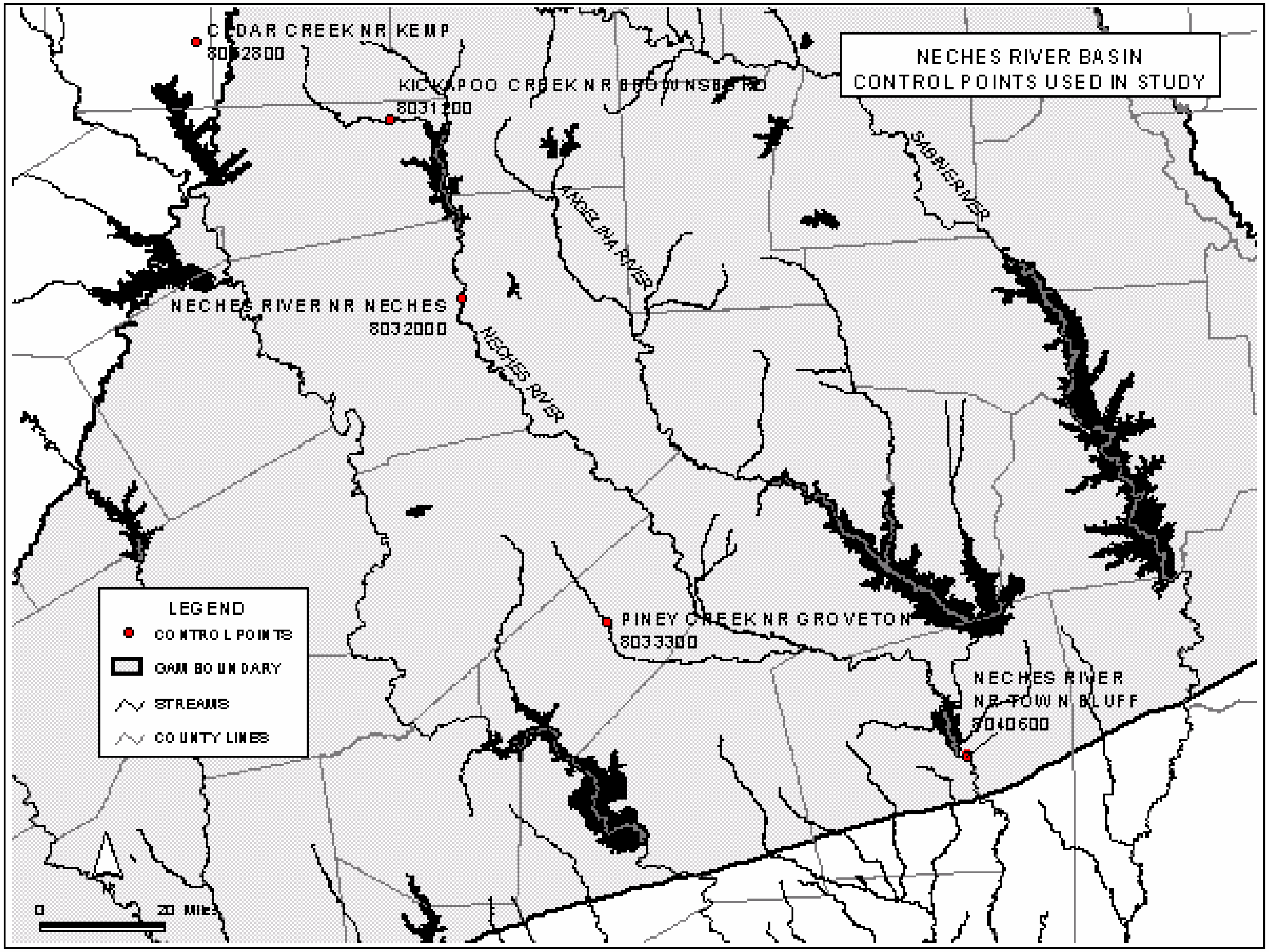
GROUNDWATER – SURFACE WATER INTERACTION
QUEEN CITY – SPARTA AQUIFER GAM

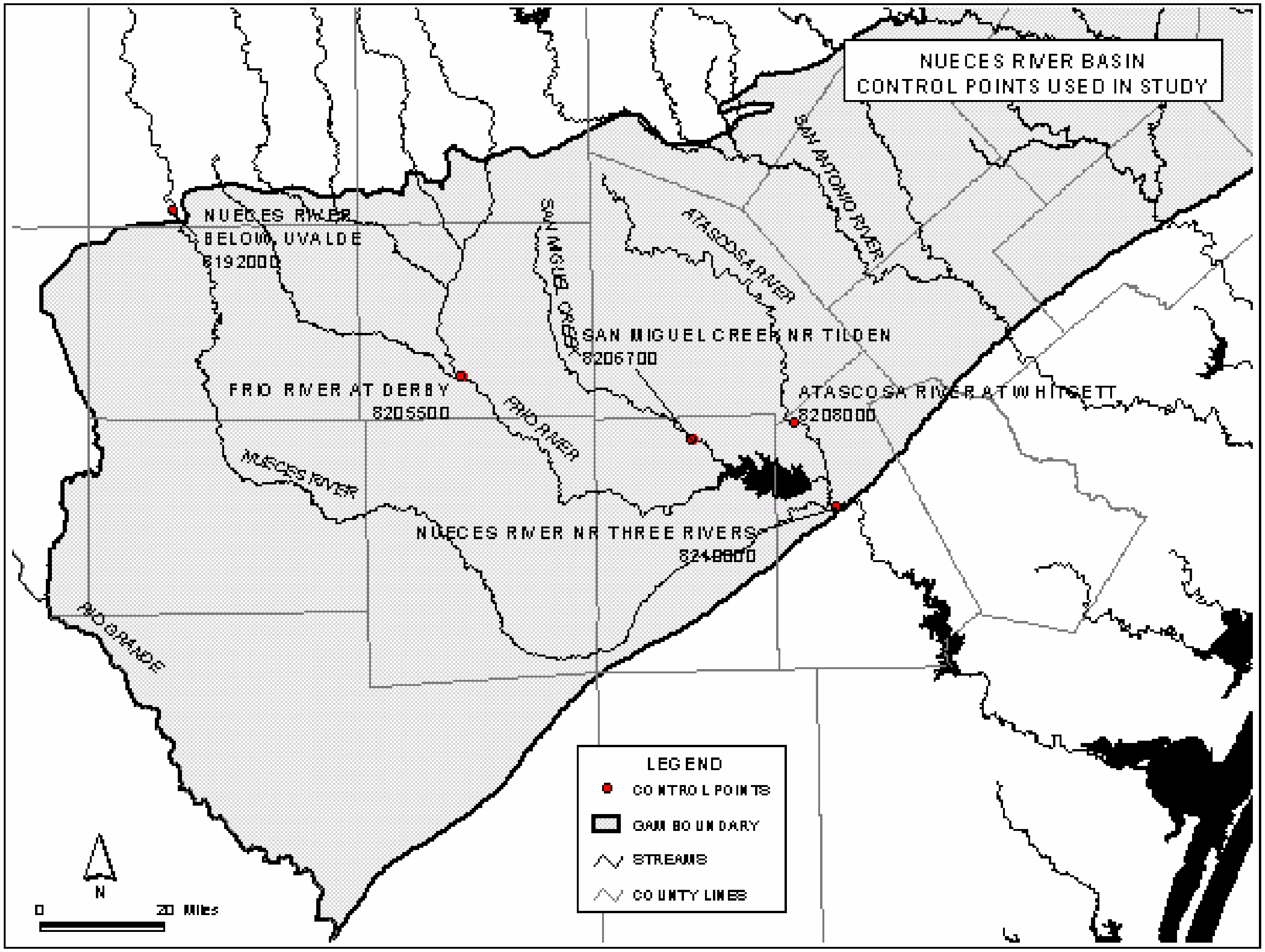



FRIO RIVER BASIN
CONTROL POINTS USED IN STUDY
SECO CREEK AT D'HANIS
8202700
HONDO CREEK AT HONDO
8200700
SABINAL RIVER AT SABINAL
8198500
FRIO RIVER AT UVALDE
8197500
SABINAL RIVER
SECO CREEK
HONDO CREEK
SAN MIGUEL CREEK
ATASCOSA RIVER
FRIO RIVER AT DERBY
8205500
FRIO RIVER
SAN MIGUEL CREEK NR TILDEN
8206700
NUECES RIVER
LEGEND
CONTROL POINTS
GAM BOUNDARY
STREAMS
COUNTY LINES
N
0
20 Miles

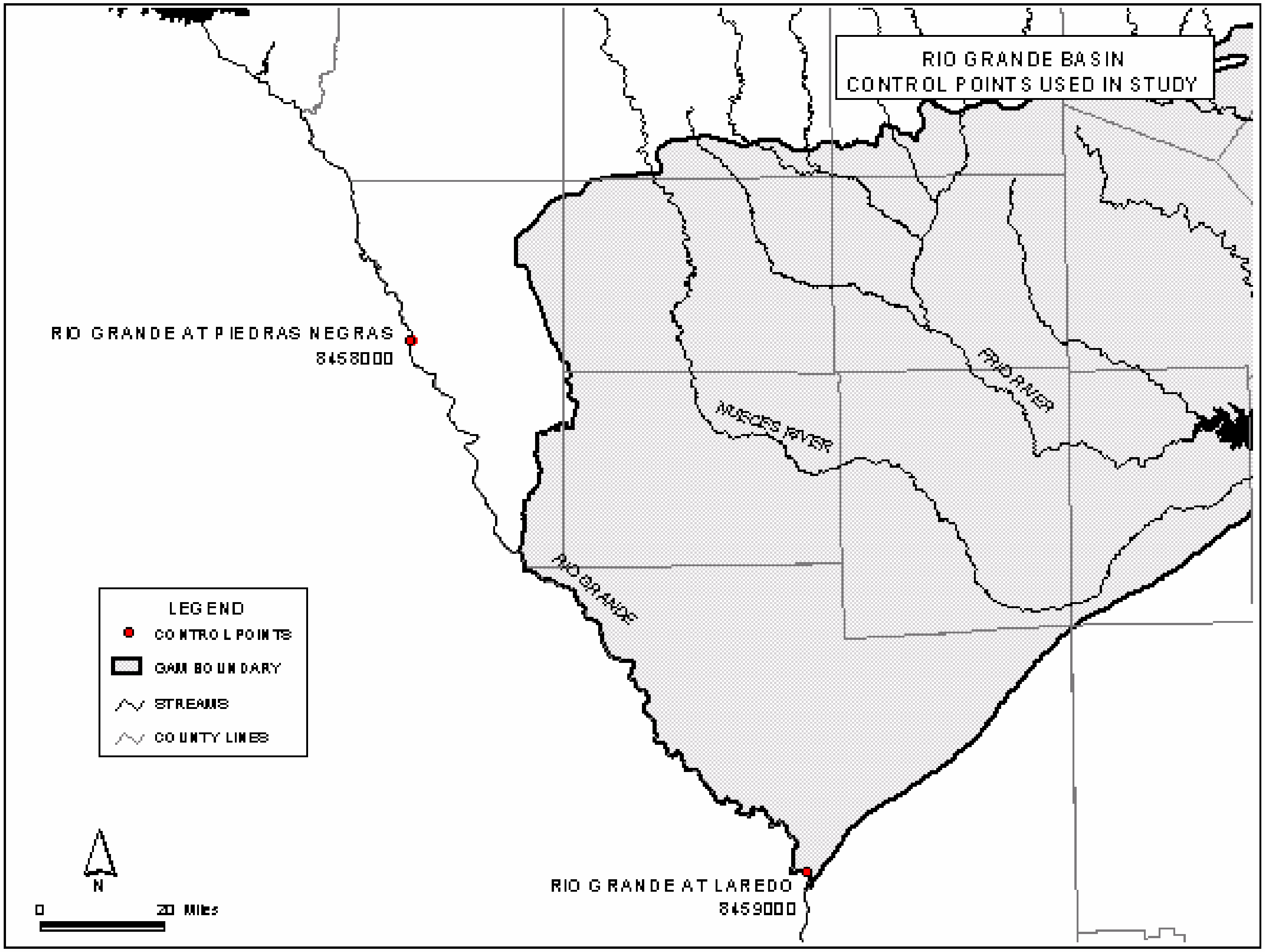

GUADALUPE RIVER BASIN
CONTROL POINTS USED IN STUDY
BLANCO RIVER
GUADALUPE RIVER
SAN MARCOS RIVER
COLORADO RIVER
GUADALUPE RIVER ABV COMAL RIVER
AT NEW BRAUNFELS
8168500
SAN MARCOS RIVER, LULING
8172000
PEACH CREEK, DILWORTH
8174600
SANDIES CREEK, WESTHOFF
8175000
GUADALUPE RIVER, CUERO
8175800
CIBOLO CREEK
GUADALUPE RIVER
LEGEND
CONTROL POINTS
GAM BOUNDARY
STREAMS
COUNTY LINES
N
0
20 MILES

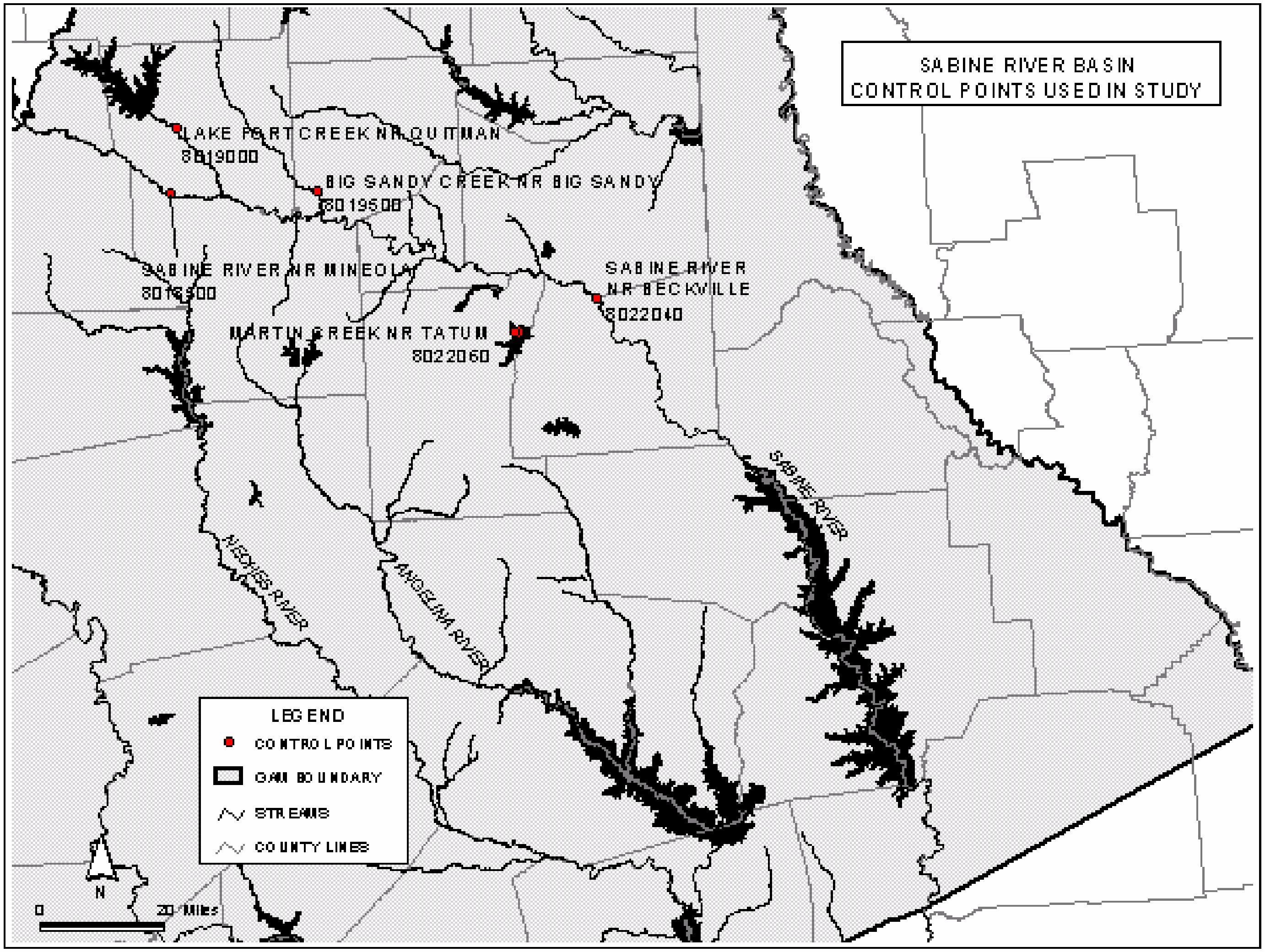

NAVASOTA RIVER BASIN
CONTROL POINTS USED IN STUDY
NAVASOTA RIVER
ABV GROESBACK
8110325
BIG CREEK NR FREESTONE
8110430
NAVASOTA RIVER
TRINITY RIVER
BRAZOS RIVER
NAVASOTA RIVER NR BRYAN
8111000
LEGEND
CONTROL POINTS
GAM BOUNDARY
STREAMS
COUNTY LINES
0
20 MI


NECHES RIVER BASIN
CONTROL POINTS USED IN STUDY
CEDAR CREEK NR KEMP
80 2800
KICKAPOO CREEK NR BROWNSBORO
8031200
NECHES RIVER NR NECHES
8032000
NECHES RIVER
ANGELINA RIVER
SABINE RIVER
PINEY CREEK NR GROVETON
8033300
NECHES RIVER
NR TOWN BLUFF
8040600
LEGEND
● CONTROL POINTS
▭ GAM BOUNDARY
STREAMS
COUNTY LINES
0
20 Miles

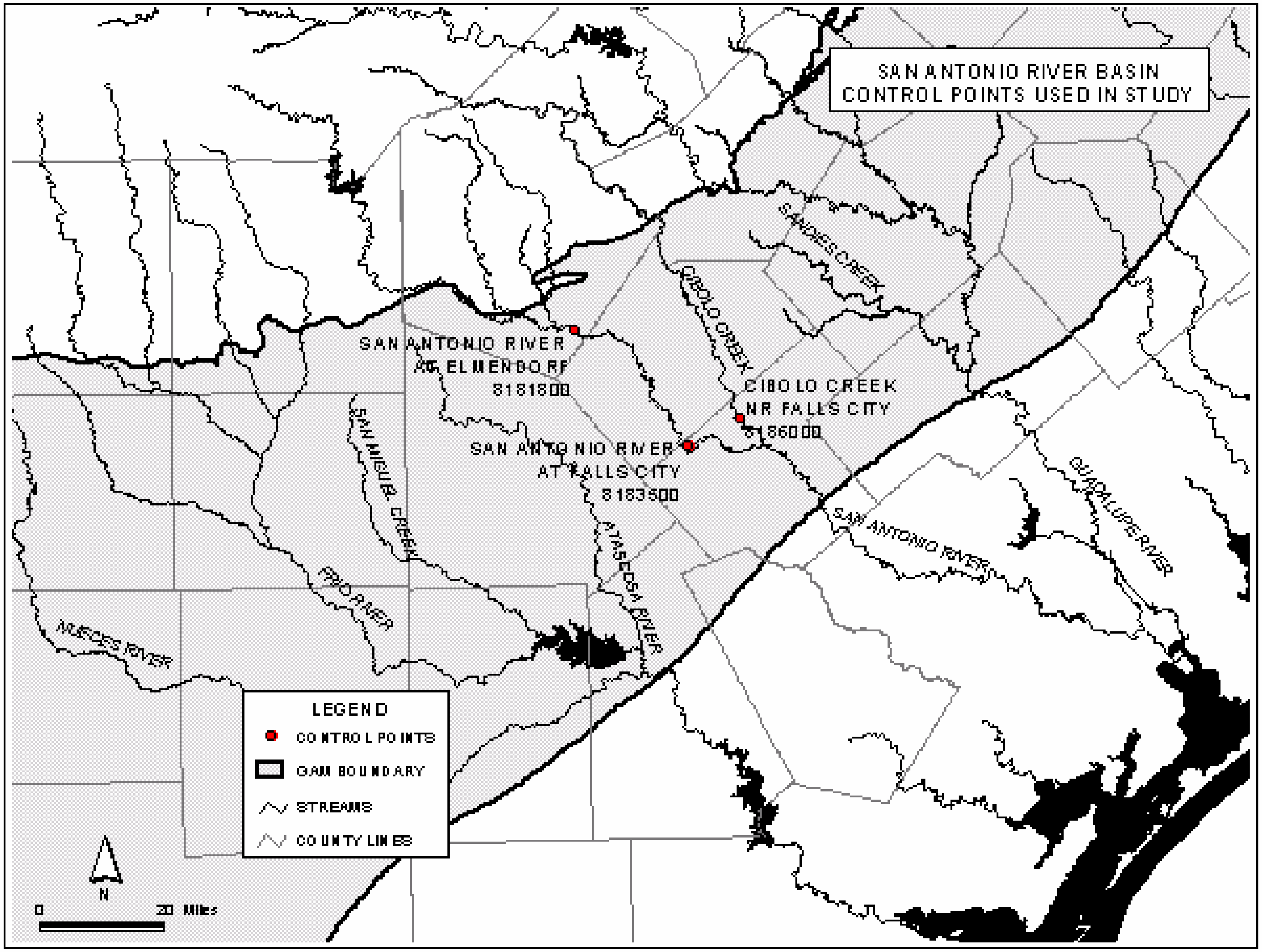

NUECES RIVER BASIN
CONTROL POINTS USED IN STUDY
NUECES RIVER BELOW UVALDE 8192000
FRIO RIVER AT DERBY 8205500
SAN MIGUEL CREEK NR TILDEN 8206700
ATASCOSA RIVER AT WHITSETT 8208000
NUECES RIVER NR THREE RIVERS 8210000
SAN MIGUEL CREEK
ATASCOSA RIVER
SAN ANTONIO RIVER
FRIO RIVER
NUECES RIVER
RIO GRANDE
LEGEND
CONTROL POINTS
GAM BOUNDARY
STREAMS
COUNTY LINES
N
0
20 Miles

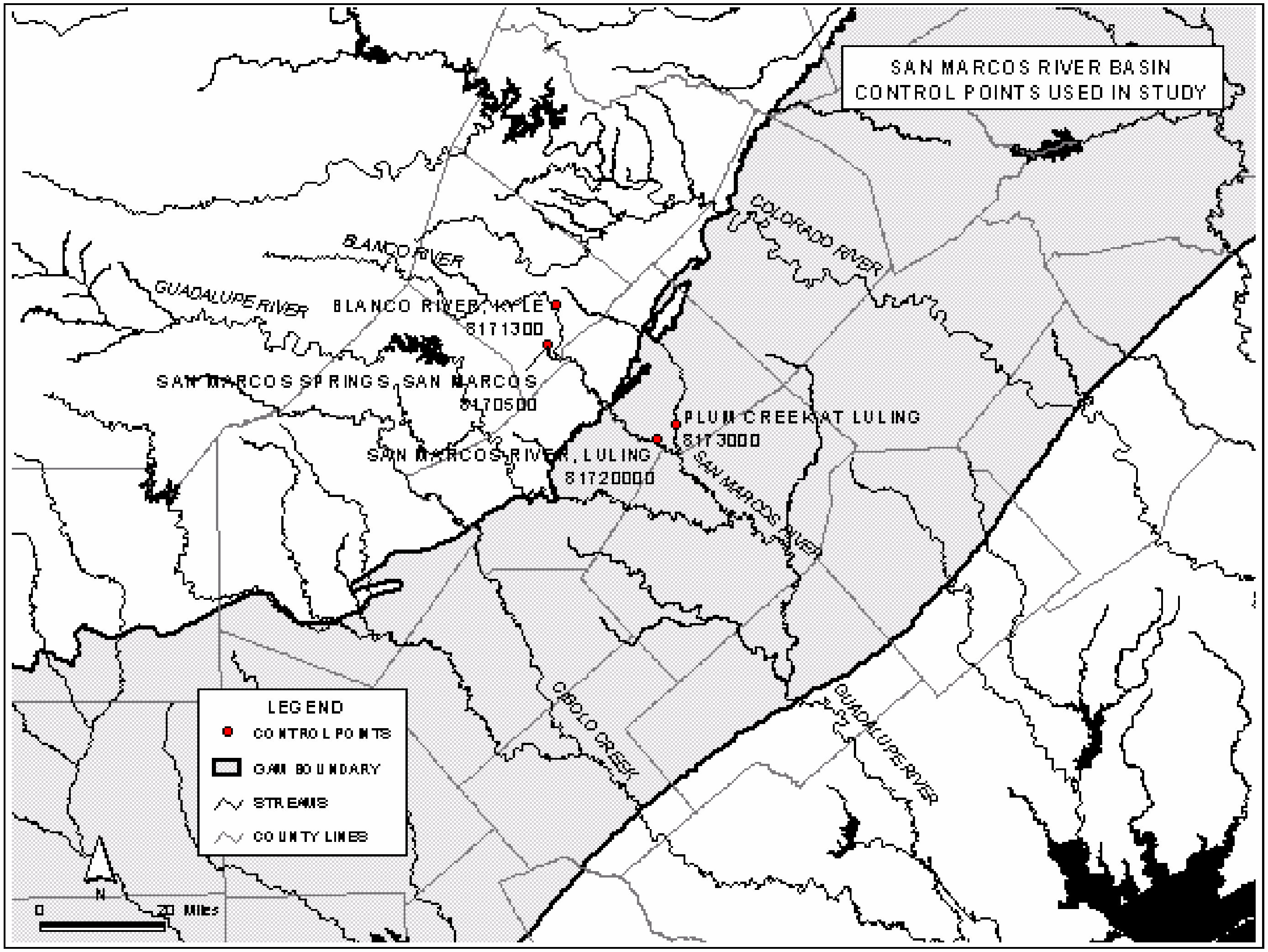
GROUNDWATER – SURFACE WATER INTERACTION
QUEEN CITY – SPARTA AQUIFER GAM

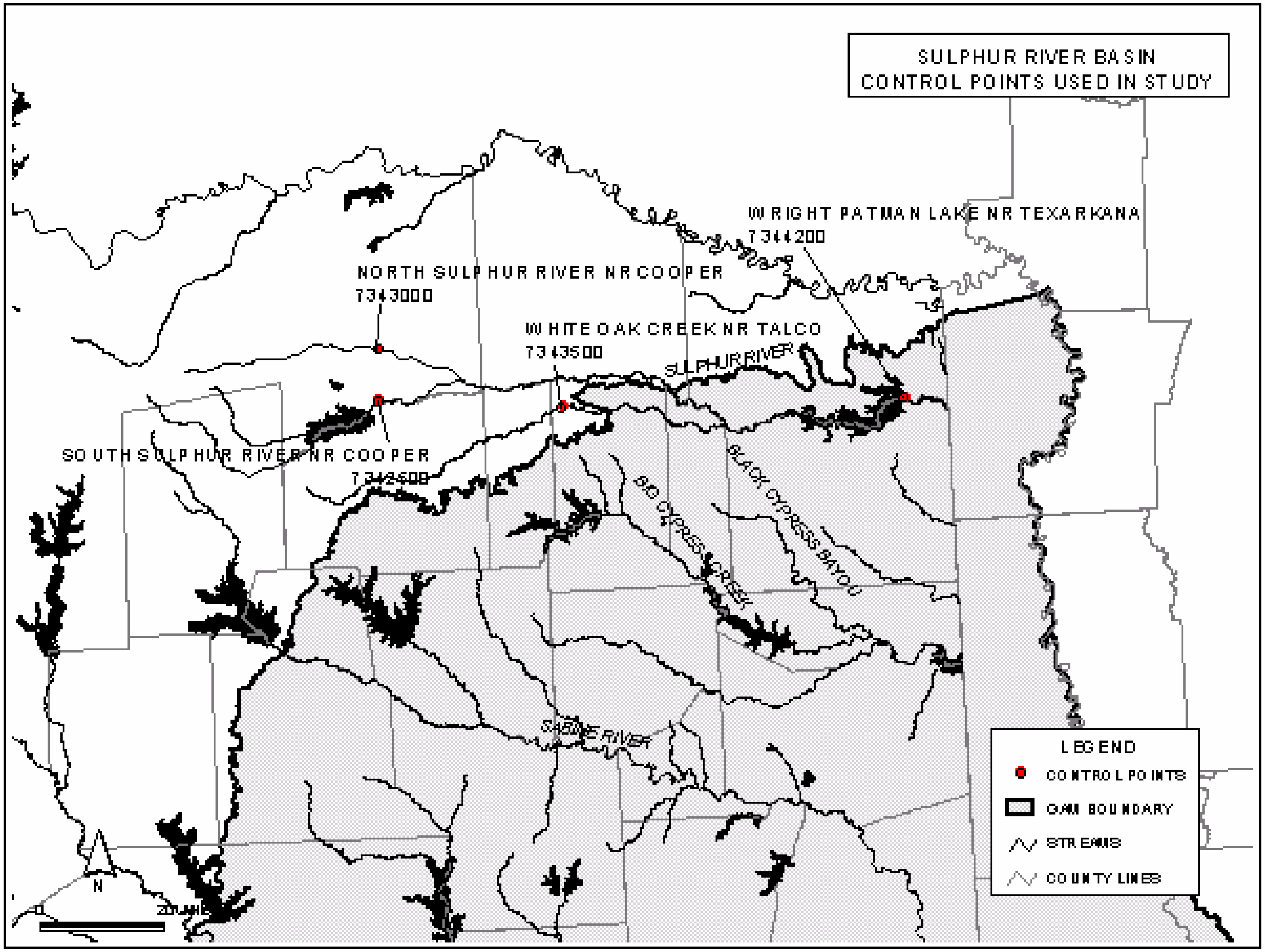


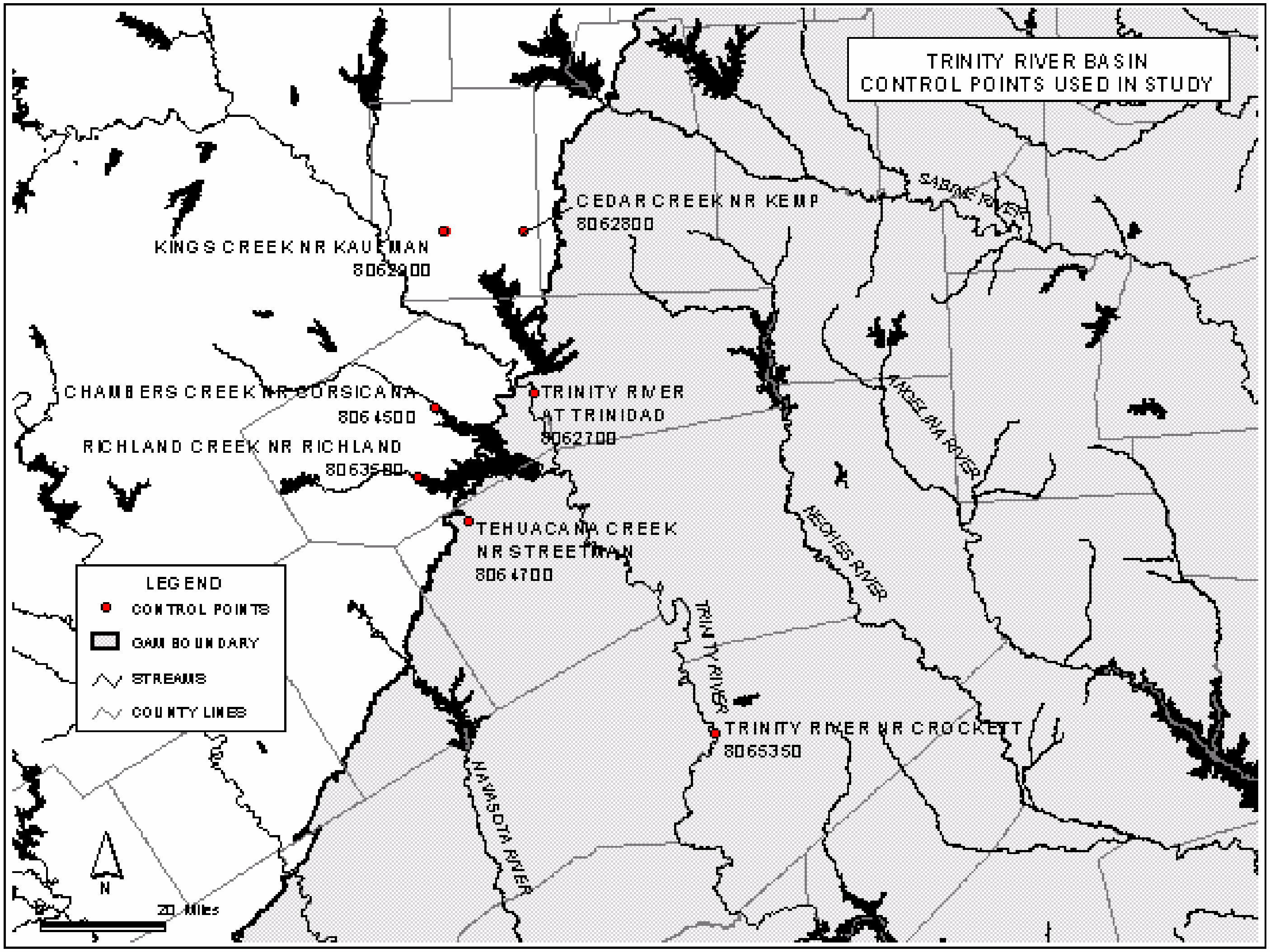

SABINE RIVER BASIN
CONTROL POINTS USED IN STUDY
LAKE FORK CREEK NR QUITMAN
8019000
BIG SANDY CREEK NR BIG SANDY
8019500
SABINE RIVER NR MINEOLA
8018500
SABINE RIVER
NR BECKVILLE
8022040
MARTIN CREEK NR TATUM
8022060
SABINE RIVER
NECHES RIVER
ANGELINA RIVER
LEGEND
● CONTROL POINTS
GAM BOUNDARY
STREAMS
COUNTY LINES
N
0
20 Miles

GROUNDWATER – SURFACE WATER INTERACTION
QUEEN CITY – SPARTA AQUIFER GAM




SAN MARCOS RIVER BASIN
CONTROL POINTS USED IN STUDY
BLANCO RIVER
GUADALUPE RIVER
BLANCO RIVER, KYLE
8171300
SAN MARCOS SPRINGS, SAN MARCOS
8170500
SAN MARCOS RIVER, LULING
8172000
PLUM CREEK AT LULING
8173000
COLORADO RIVER
SAN MARCOS RIVER
CIBOLO CREEK
GUADALUPE RIVER
LEGEND
CONTROL POINTS
GAM BOUNDARY
STREAMS
COUNTY LINES
N
0
20 Miles


SULPHUR RIVER BASIN
CONTROL POINTS USED IN STUDY
WRIGHT PATMAN LAKE NR TEXARKANA
7344200
NORTH SULPHUR RIVER NR COOPER
7343000
WHITE OAK CREEK NR TALCO
7343500
SULPHUR RIVER
SOUTH SULPHUR RIVER NR COOPER
7342500
BIG CYPRESS CREEK
BLACK CYPRESS BAYOU
SABINE RIVER
LEGEND
CONTROL POINTS
GAM BOUNDARY
STREAMS
COUNTY LINES
N
0
20 MILES


TRINITY RIVER BASIN
CONTROL POINTS USED IN STUDY
CEDAR CREEK NR KEMP
8062800
KINGS CREEK NR KAUFMAN
8062900
CHAMBERS CREEK NR CORSICANA
8064500
RICHLAND CREEK NR RICHLAND
8063500
TRINITY RIVER
AT TRINIDAD
8062700
TEHUACANA CREEK
NR STREETMAN
8064700
TRINITY RIVER NR CROCKETT
8065350
SABINE RIVER
ANGELINA RIVER
NECHES RIVER
TRINITY RIVER
NAVASOTA RIVER
LEGEND
CONTROL POINTS
GAM BOUNDARY
STREAMS
COUNTY LINES
N
20 Miles

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ATTACHMENT C

MONTHLY GAIN/LOSS CHARTS

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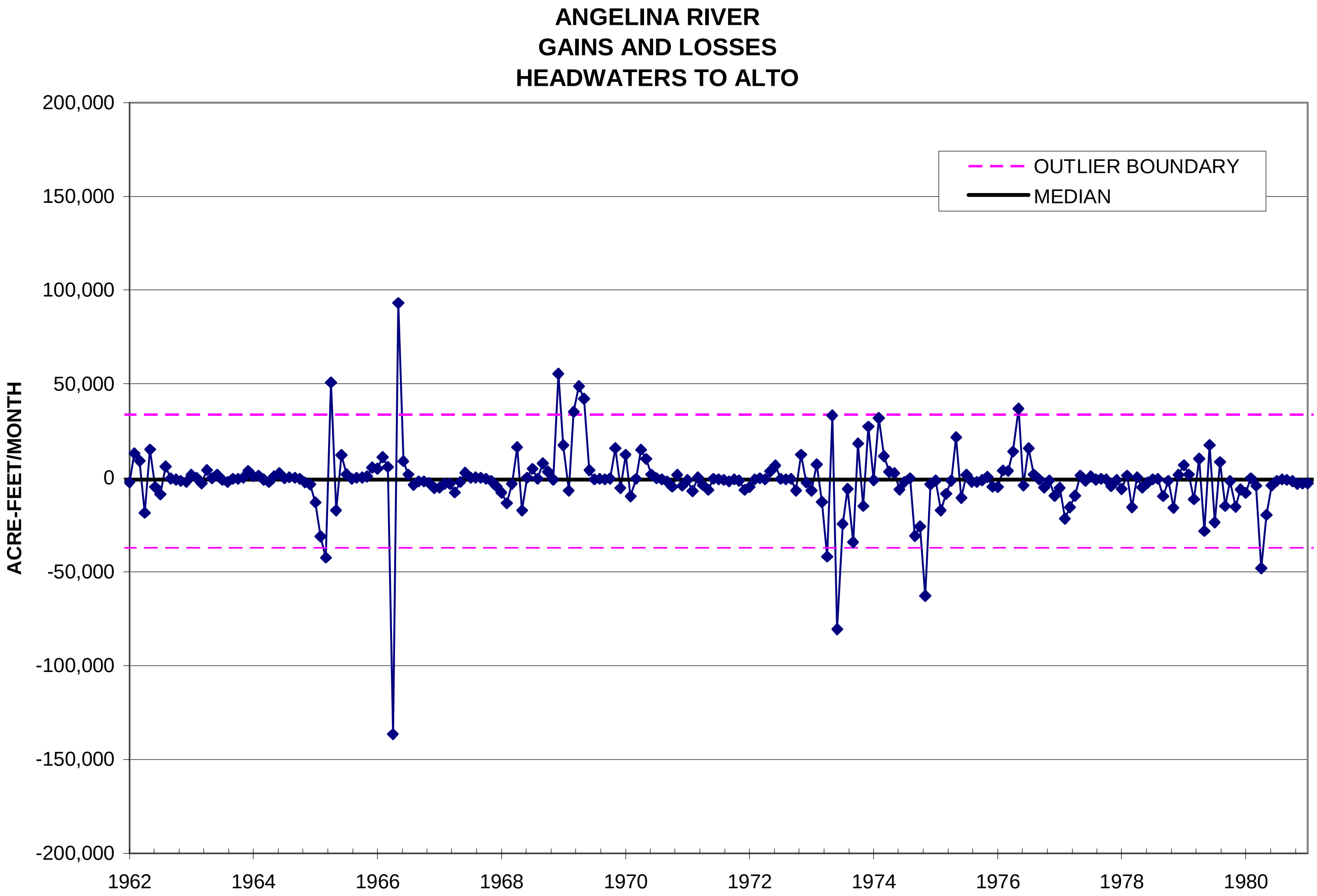
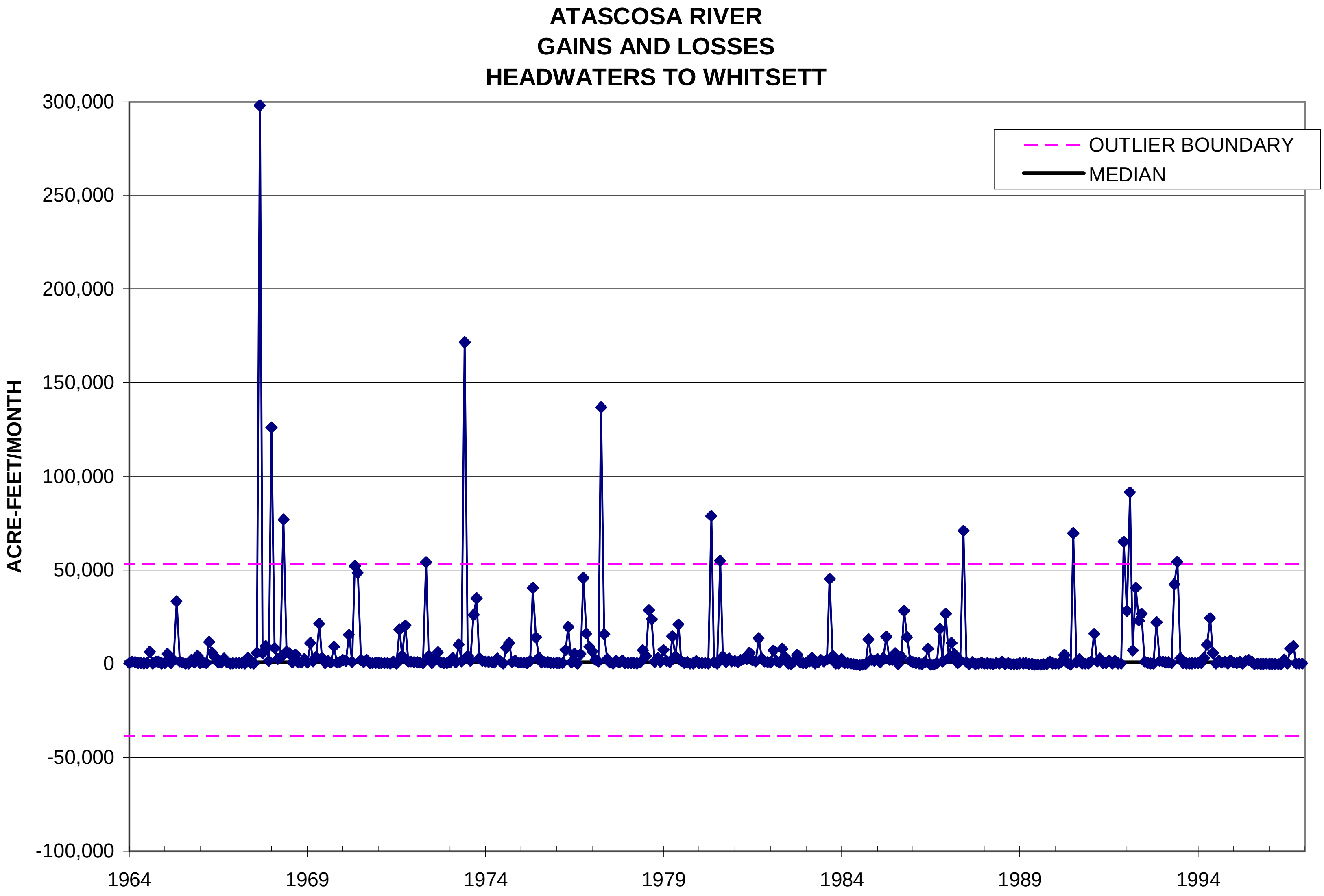
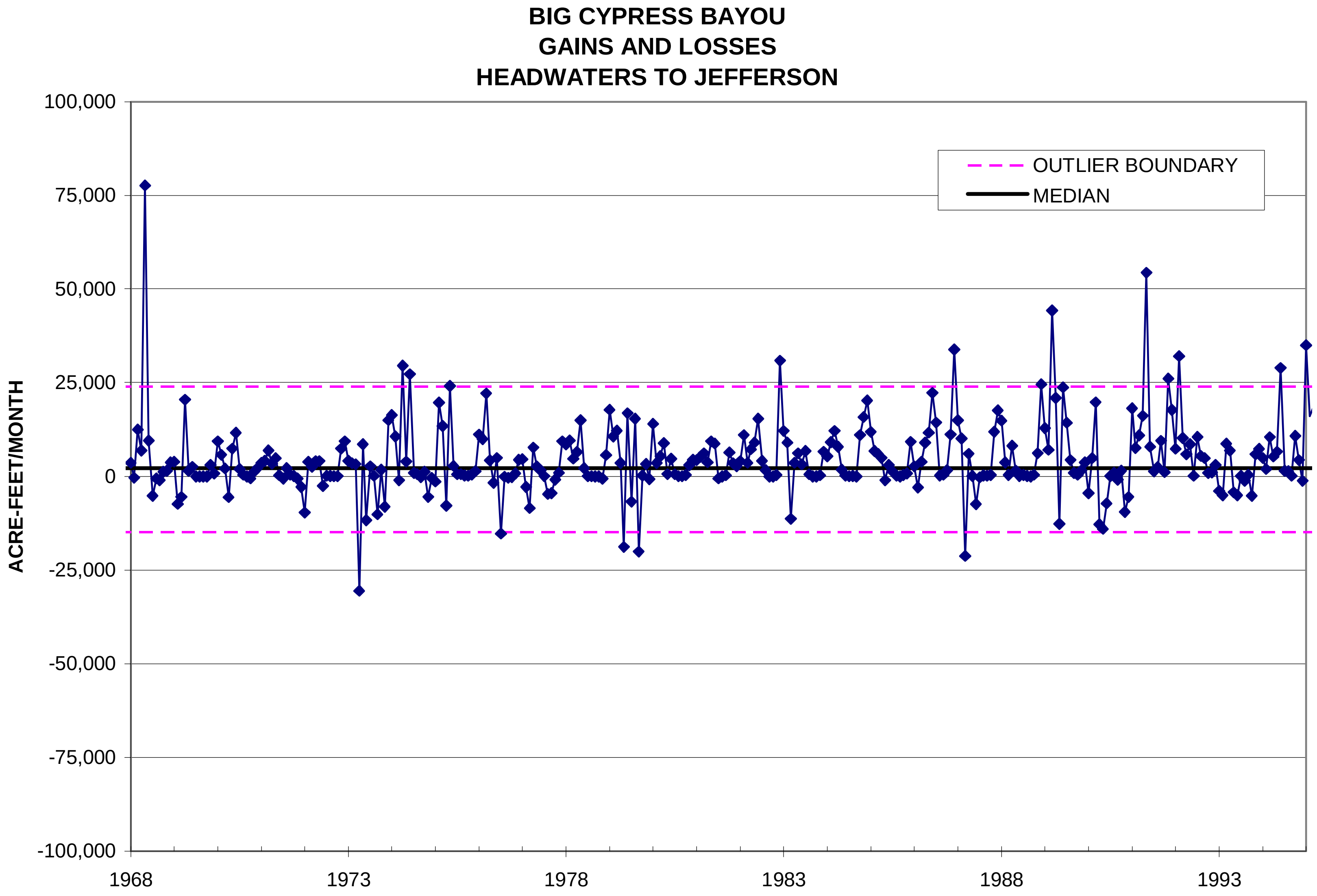
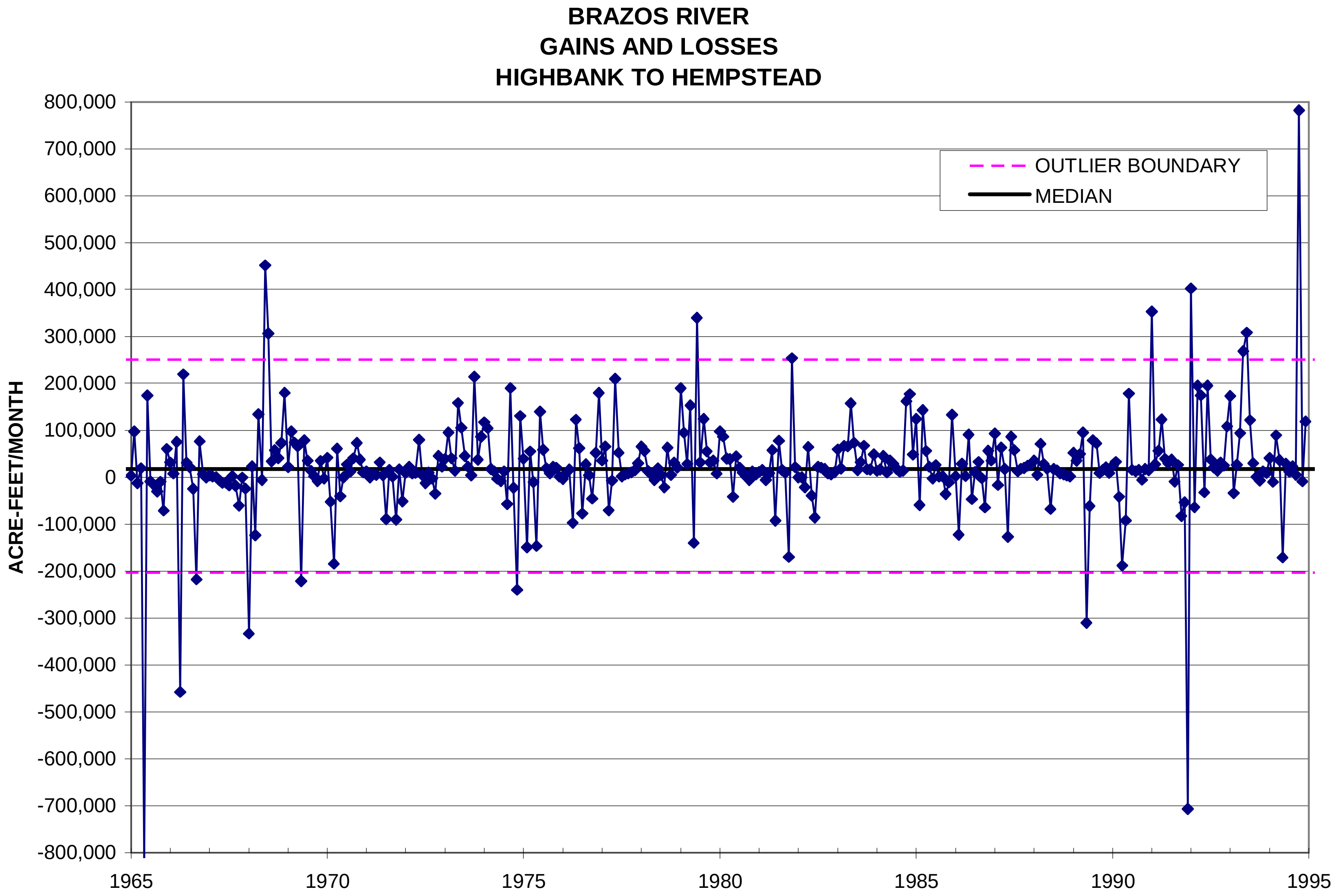
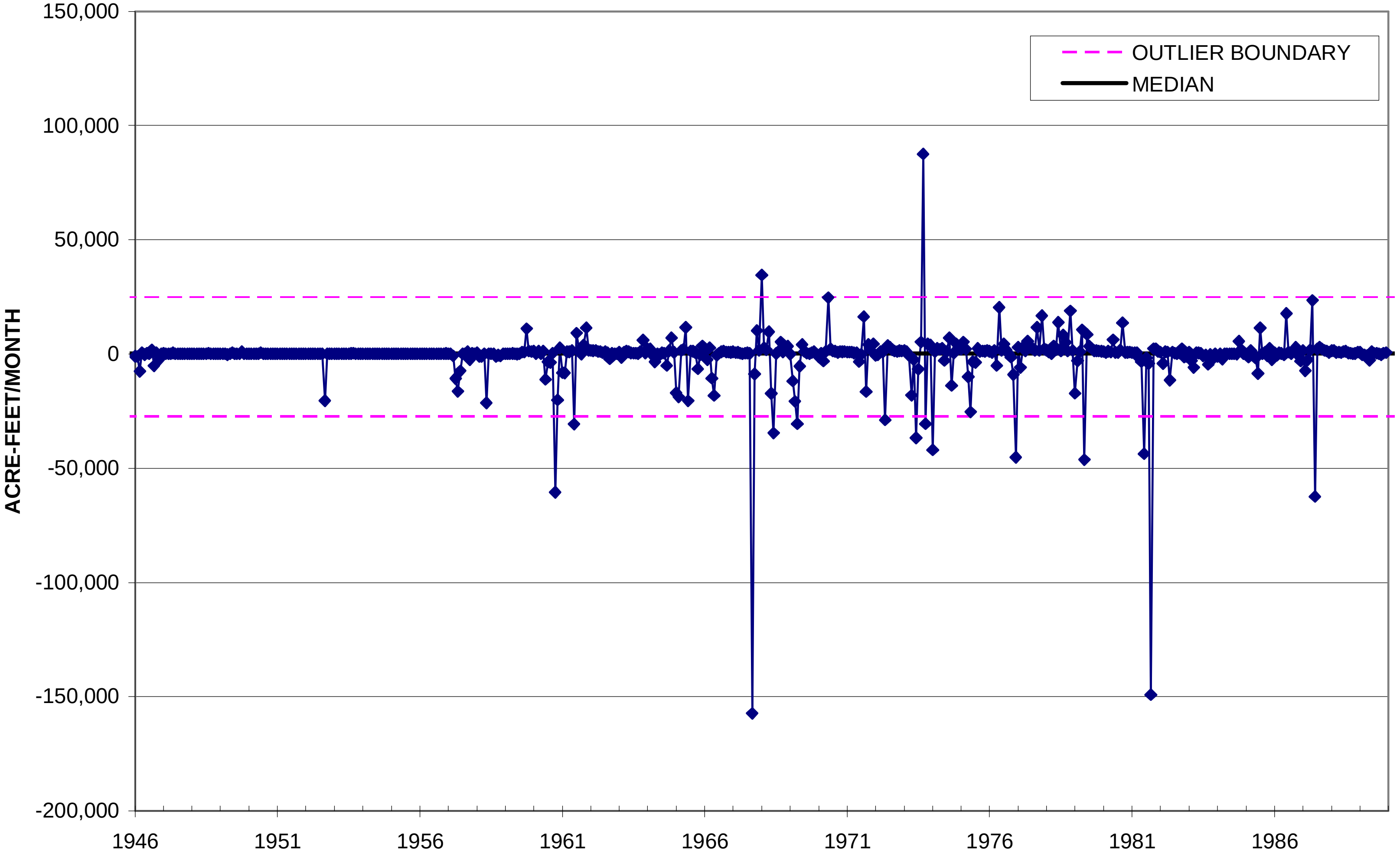

ANGELINA RIVER
GAINS AND LOSSES
HEADWATERS TO ALTO
200,000
150,000
100,000
50,000
0
-50,000
-100,000
-150,000
-200,000
ACRE-FEET/MONTH
1962
1964
1966
1968
1970
1972
1974
1976
1978
1980
OUTLIER BOUNDARY
MEDIAN

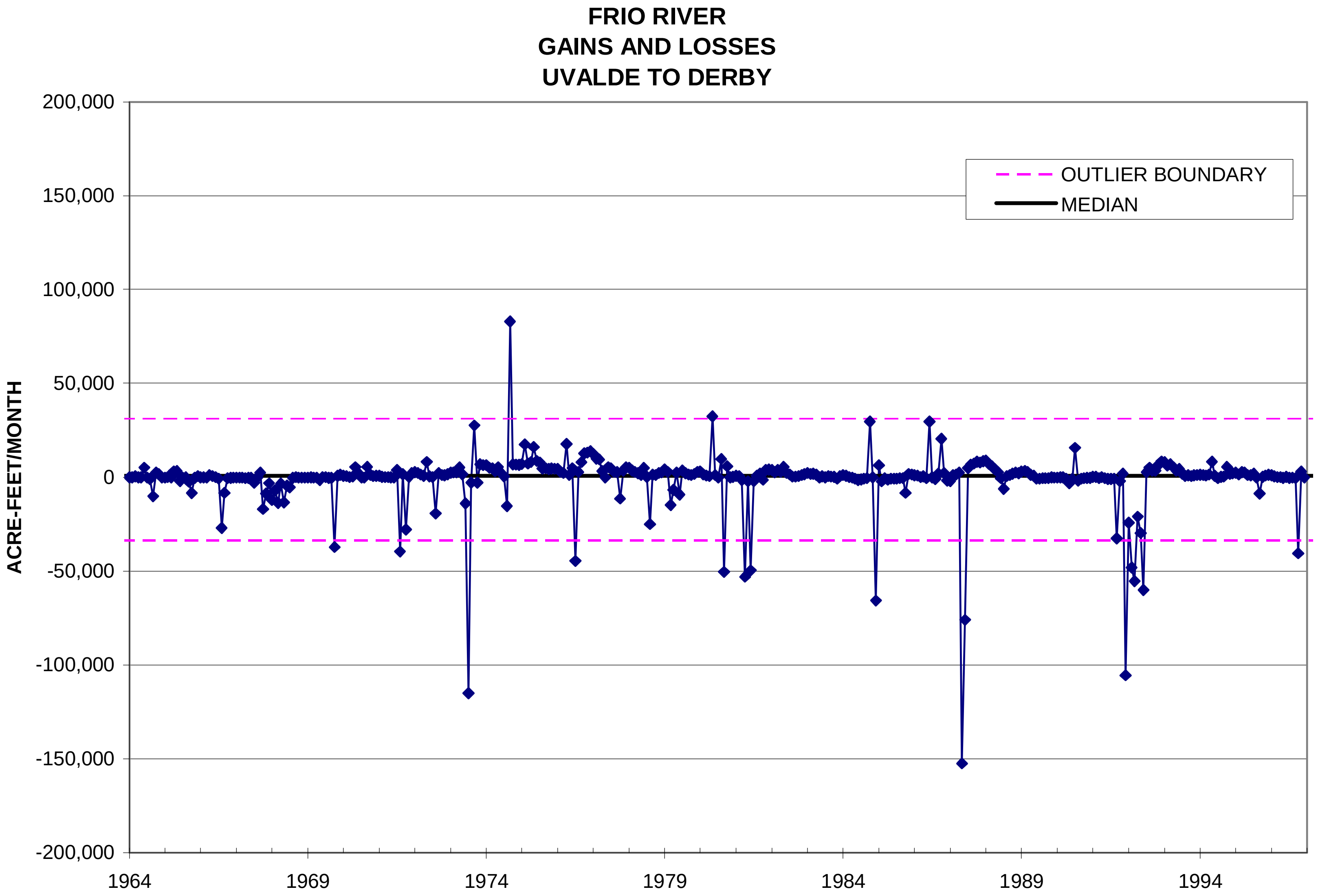

ATASCOSA RIVER
GAINS AND LOSSES
HEADWATERS TO WHITSETT
ACRE-FEET/MONTH
300,000
250,000
200,000
150,000
100,000
50,000
0
-50,000
-100,000
1964
1969
1974
1979
1984
1989
1994
OUTLIER BOUNDARY
MEDIAN

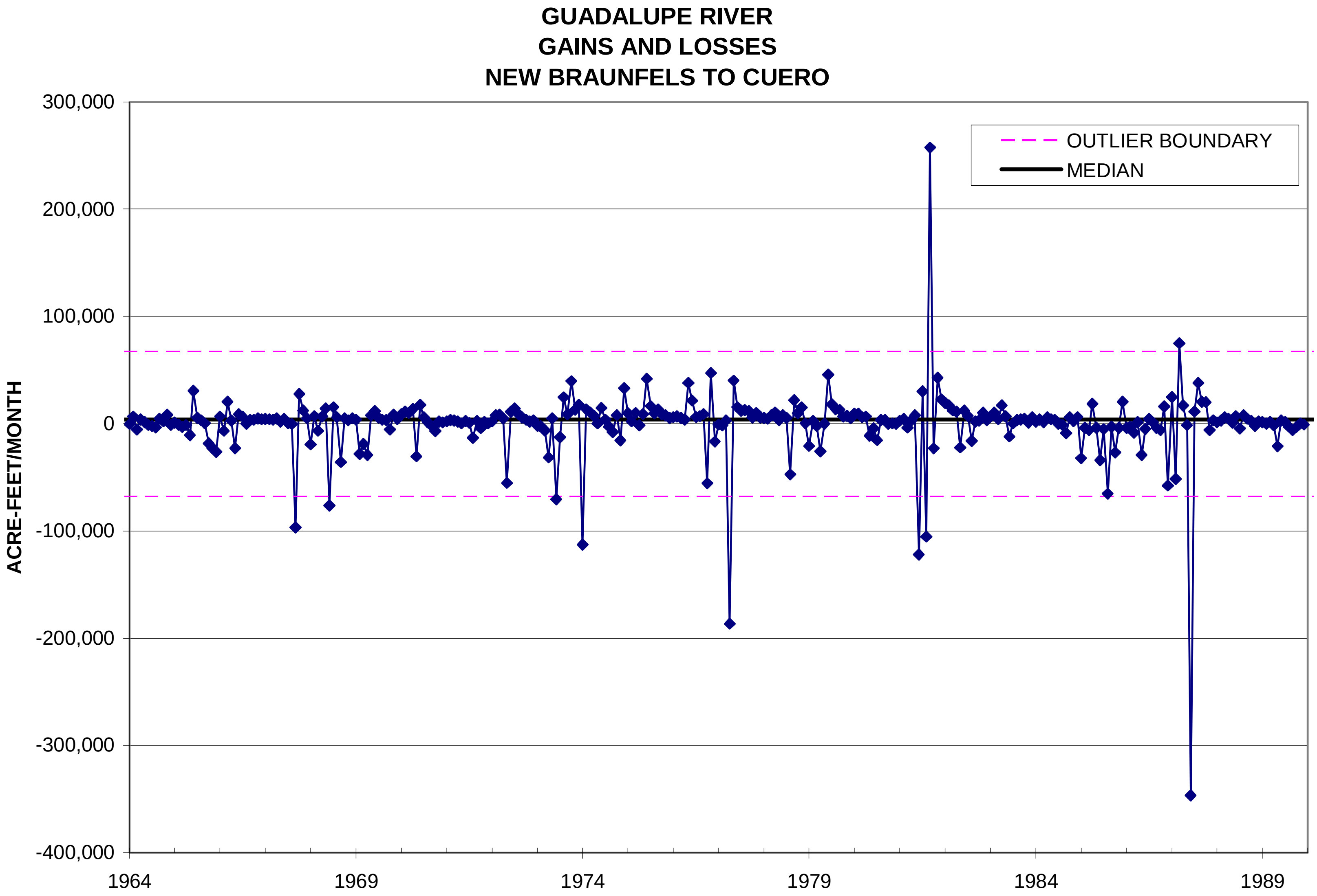

BIG CYPRESS BAYOU
GAINS AND LOSSES
HEADWATERS TO JEFFERSON
ACRE-FEET/MONTH
100,000
75,000
50,000
25,000
0
-25,000
-50,000
-75,000
-100,000
1968
1973
1978
1983
1988
1993
OUTLIER BOUNDARY
MEDIAN

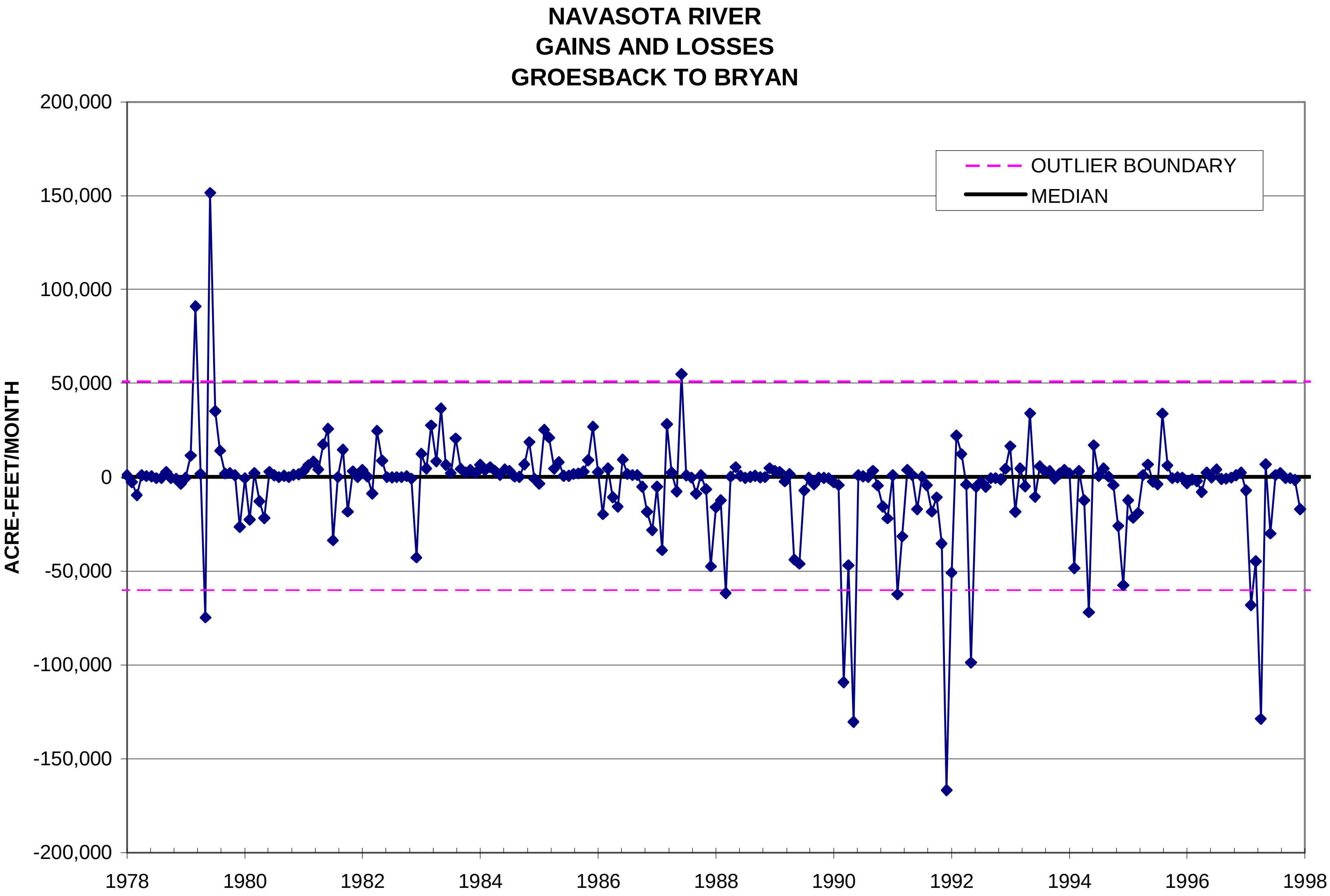

BRAZOS RIVER
GAINS AND LOSSES
HIGHBANK TO HEMPSTEAD
OUTLIER BOUNDARY
MEDIAN
ACRE-FEET/MONTH
800,000
700,000
600,000
500,000
400,000
300,000
200,000
100,000
0
-100,000
-200,000
-300,000
-400,000
-500,000
-600,000
-700,000
-800,000
1965
1970
1975
1980
1985
1990
1995

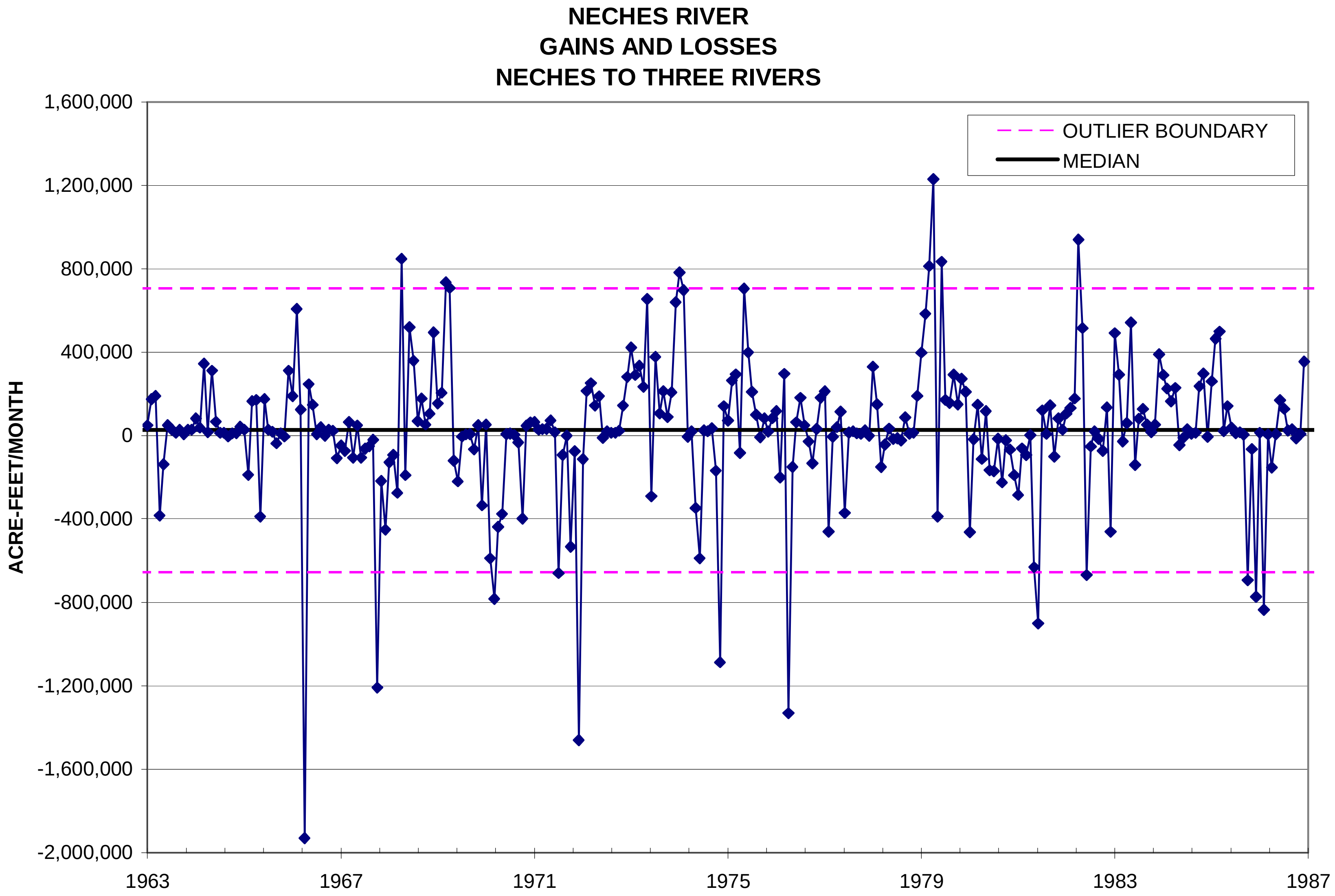
CIBOLO CREEK
GAINS AND LOSSES
SELMA TO FALLS CITY

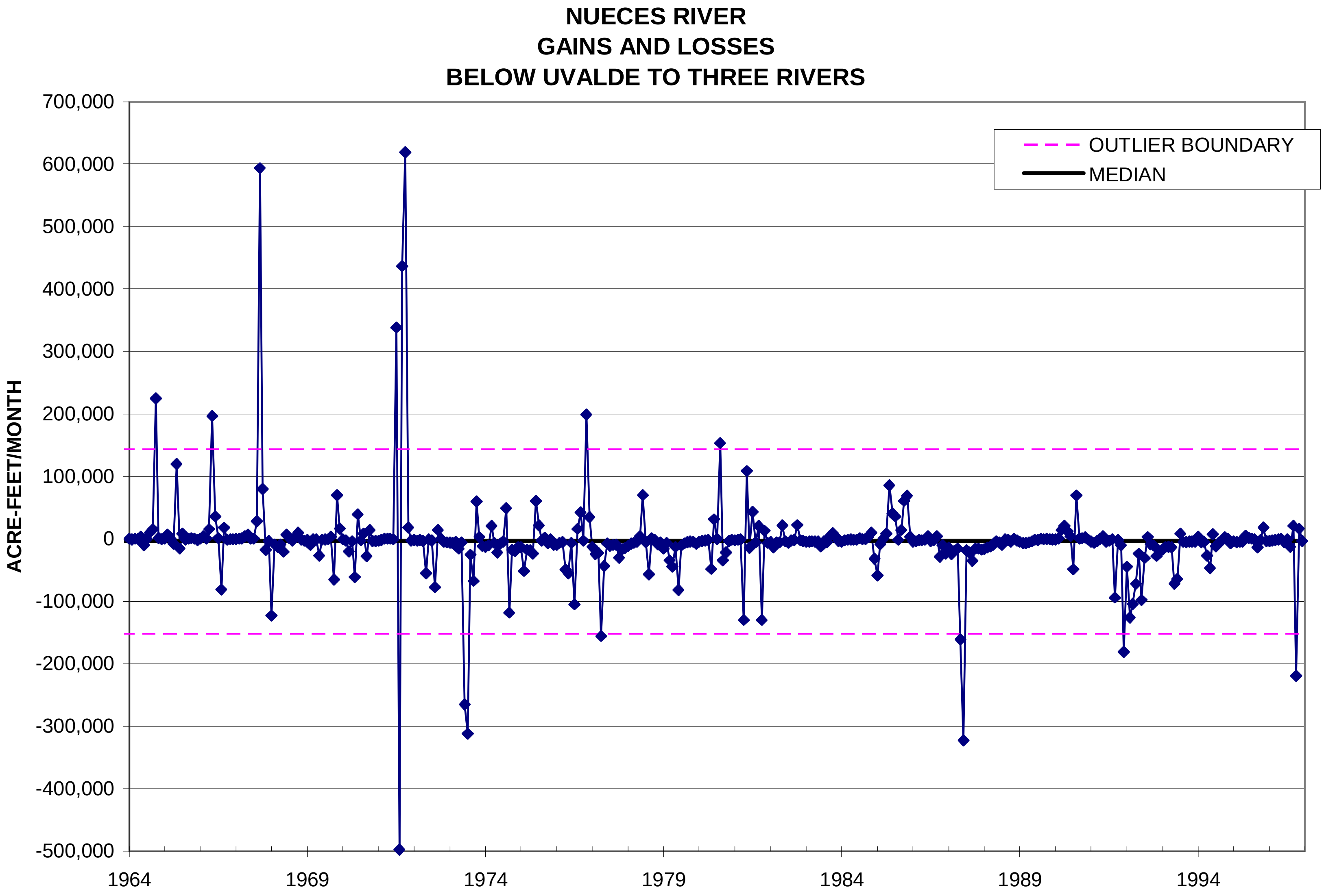


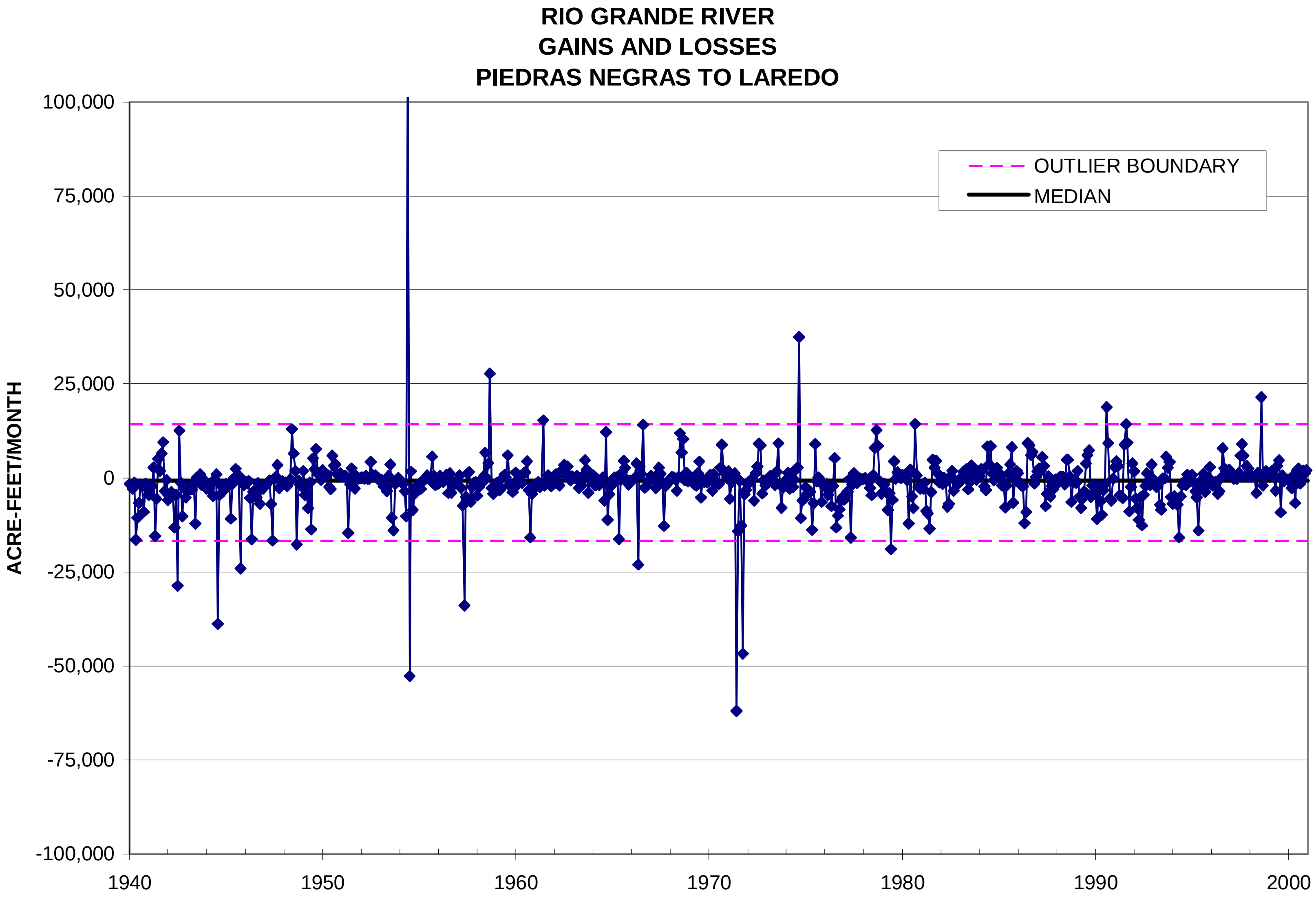

FRIO RIVER
GAINS AND LOSSES
UVALDE TO DERBY
ACRE-FEET/MONTH
200,000
150,000
100,000
50,000
0
-50,000
-100,000
-150,000
-200,000
1964
1969
1974
1979
1984
1989
1994
OUTLIER BOUNDARY
MEDIAN


GUADALUPE RIVER
GAINS AND LOSSES
NEW BRAUNFELS TO CUERO
OUTLIER BOUNDARY
MEDIAN
ACRE-FEET/MONTH
300,000
200,000
100,000
0
-100,000
-200,000
-300,000
-400,000
1964
1969
1974
1979
1984
1989

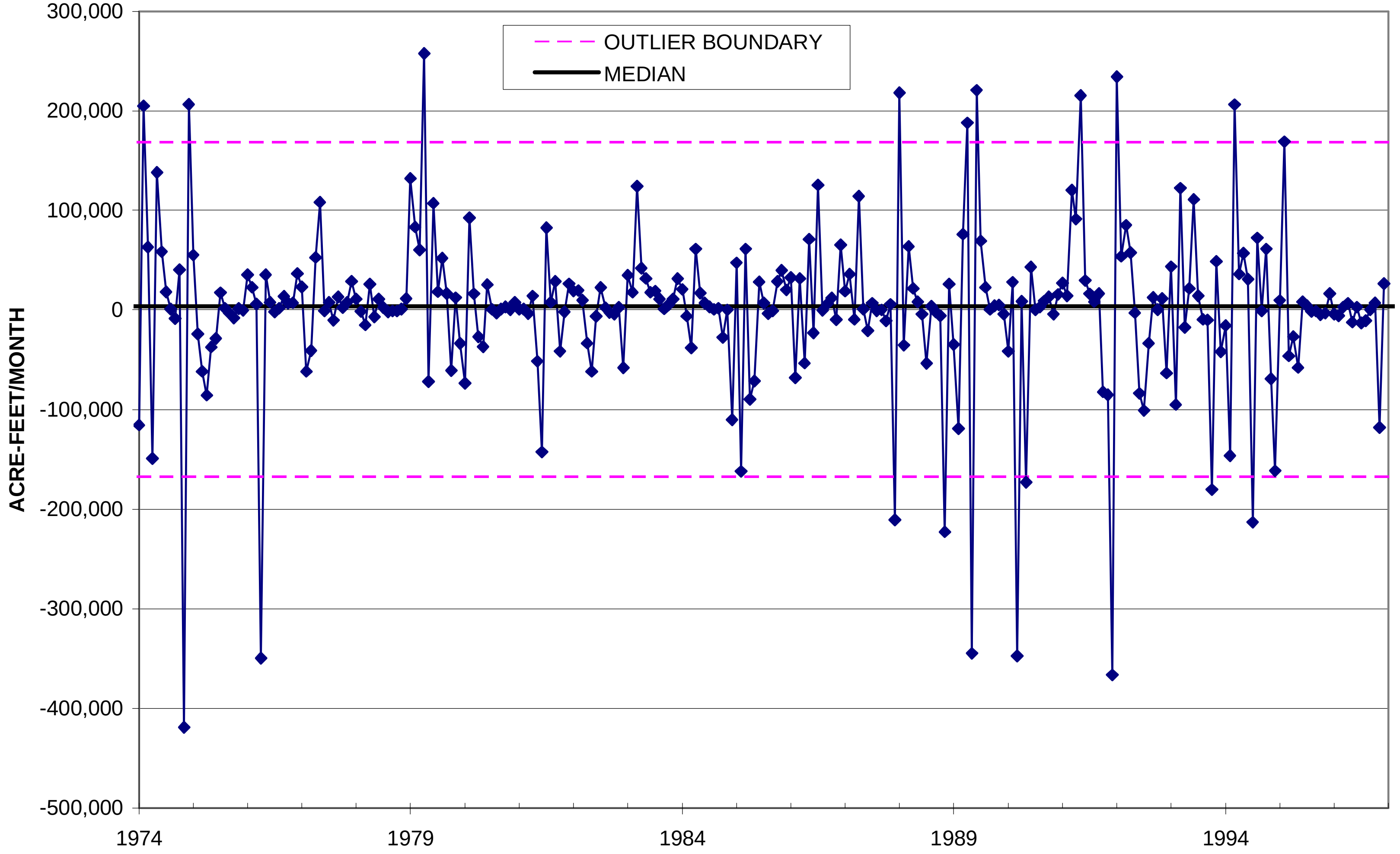

NAVASOTA RIVER
GAINS AND LOSSES
GROESBACK TO BRYAN
OUTLIER BOUNDARY
MEDIAN
ACRE-FEET/MONTH
200,000
150,000
100,000
50,000
0
-50,000
-100,000
-150,000
-200,000
1978
1980
1982
1984
1986
1988
1990
1992
1994
1996
1998

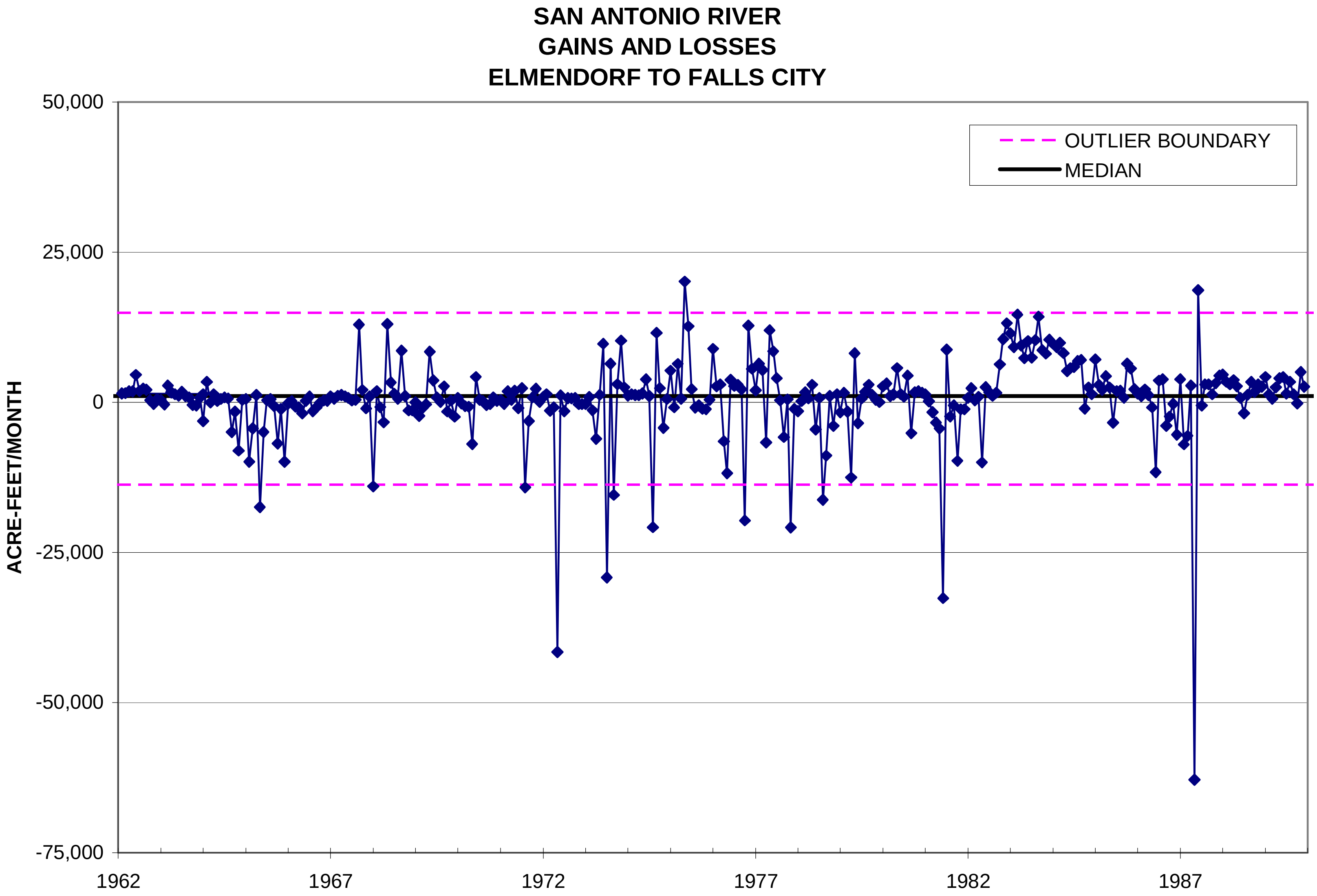

NECHES RIVER
GAINS AND LOSSES
NECHES TO THREE RIVERS
OUTLIER BOUNDARY
MEDIAN
ACRE-FEET/MONTH
1,600,000
1,200,000
800,000
400,000
0
-400,000
-800,000
-1,200,000
-1,600,000
-2,000,000
1963
1967
1971
1975
1979
1983
1987


NUECES RIVER
GAINS AND LOSSES
BELOW UVALDE TO THREE RIVERS
OUTLIER BOUNDARY
MEDIAN
ACRE-FEET/MONTH
700,000
600,000
500,000
400,000
300,000
200,000
100,000
0
-100,000
-200,000
-300,000
-400,000
-500,000
1964
1969
1974
1979
1984
1989
1994

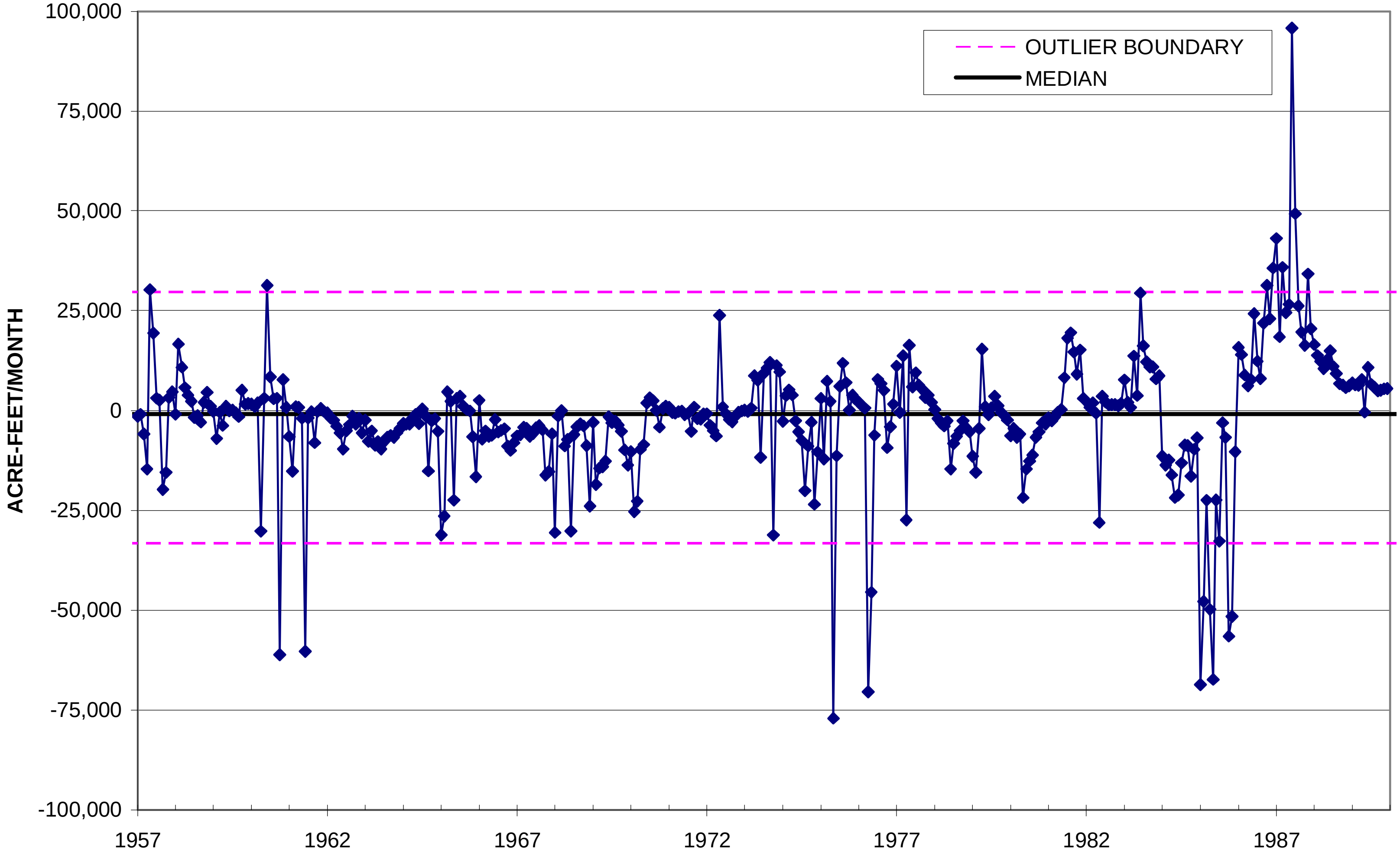

RIO GRANDE RIVER
GAINS AND LOSSES
PIEDRAS NEGRAS TO LAREDO
OUTLIER BOUNDARY
MEDIAN
ACRE-FEET/MONTH
100,000
75,000
50,000
25,000
0
-25,000
-50,000
-75,000
-100,000
1940
1950
1960
1970
1980
1990
2000

SABINE RIVER
GAINS AND LOSSES
MINEOLA TO BECKVILLE

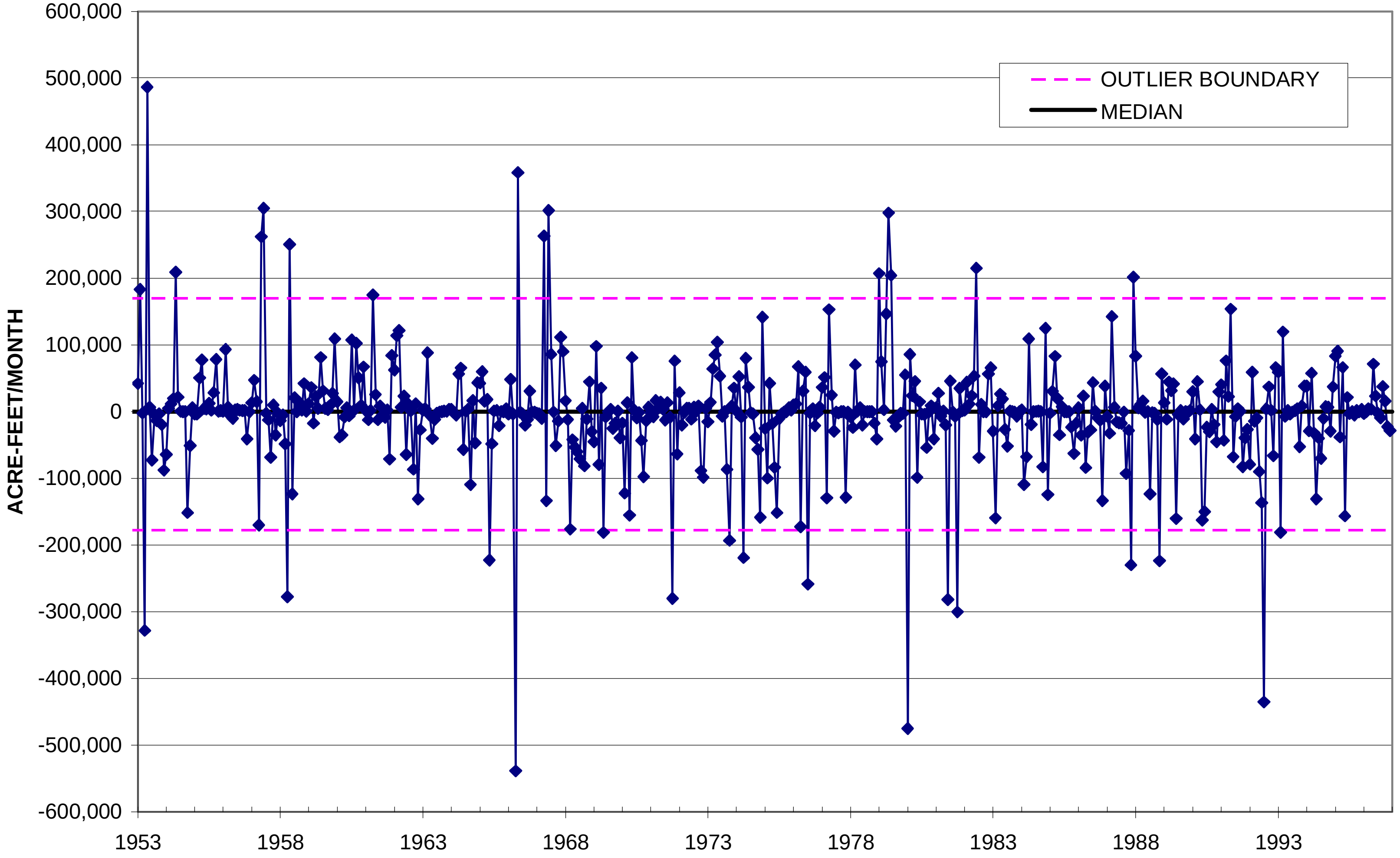


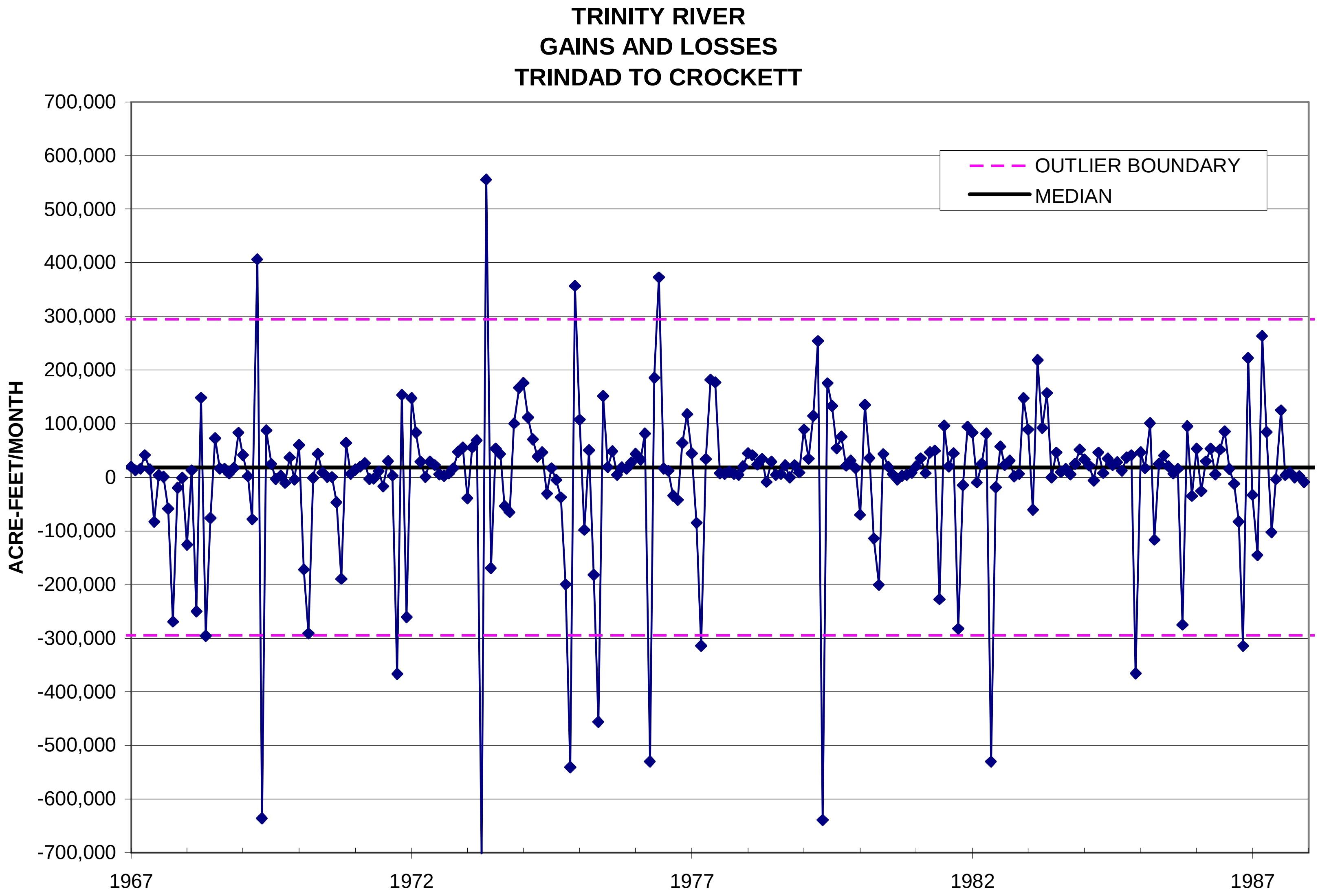

SAN ANTONIO RIVER
GAINS AND LOSSES
ELMENDORF TO FALLS CITY
OUTLIER BOUNDARY
MEDIAN
ACRE-FEET/MONTH
50,000
25,000
0
-25,000
-50,000
-75,000
1962
1967
1972
1977
1982
1987

SAN MARCOS RIVER
GAINS AND LOSSES
HEADWATERS TO LULING



SULPHUR RIVER
GAINS AND LOSSES
COOPER TO WRIGHT PATTMAN




TRINITY RIVER
GAINS AND LOSSES
TRINDAD TO CROCKETT
ACRE-FEET/MONTH
700,000
600,000
500,000
400,000
300,000
200,000
100,000
0
-100,000
-200,000
-300,000
-400,000
-500,000
-600,000
-700,000
1967
1972
1977
1982
1987
OUTLIER BOUNDARY
MEDIAN

ATTACHMENT D

MONTHLY GAIN/LOSS TABLES

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CALCULATED GAINS AND LOSSES

ANGELINA RIVER BASIN
HEADWATERS TO ANGELINA RIVER NEAR ALTO
1962-1981

TOTAL GAIN/LOSS
-32,639 FT^3/DAY/MILE

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	TOTAL	AVE
1940														
1941														
1942														
1943														
1944														
1945														
1946														
1947														
1948														
1949														
1950														
1951														
1952														
1953														
1954														
1955														
1956														
1957														
1958														
1959														
1960														
1961														
1962	-2,367	13,069	9,055	-18,623	15,111	-4,886	-8,863	5,979	-307	-993	-1,668	-2,105	3,402	284
1963	1,609	128	-2,883	4,221	-200	1,747	-1,145	-2,237	-467	-532	123	3,707	4,070	339
1964	897	1,163	-965	-2,274	785	2,433	-227	316	21	-444	-2,429	-3,533	-4,257	-355
1965	-13,089	-31,194	-42,409	50,865	-17,296	12,173	1,817	-417	84	158	745	5,453	-33,110	-2,759
1966	4,886	11,006	5,850	-136,559	93,139	8,917	1,696	-3,685	-1,805	-1,816	-2,740	-5,316	-26,428	-2,202
1967	-5,161	-3,196	-3,195	-7,810	-2,268	2,681	59	237	65	-417	-1,622	-4,371	-24,997	-2,083
1968	-7,911	-13,600	-3,314	16,375	-17,401	44	4,789	-491	7,704	3,271	-979	55,506	43,992	3,666
1969	17,461	-6,924	35,138	48,701	42,054	4,008	-789	-606	-723	-258	15,807	-5,510	148,359	12,363
1970	12,313	-9,782	-470	14,960	10,037	1,673	-168	-679	-1,888	-4,661	1,615	-4,227	18,722	1,560
1971	-1,034	-7,013	217	-3,885	-6,299	-399	-709	-1,046	-1,859	-803	-1,445	-6,337	-30,613	-2,551
1972	-4,894	-778	-216	-692	3,570	6,644	-572	-738	-622	-6,772	12,253	-2,531	4,651	388
1973	-6,691	7,095	-12,956	-41,966	33,265	-80,614	-24,498	-5,950	-34,265	18,351	-14,927	27,257	-135,901	-11,325
1974	-1,164	31,765	11,629	3,216	2,509	-6,289	-2,146	-188	-30,939	-25,865	-62,852	-3,409	-83,731	-6,978
1975	-1,458	-17,250	-8,500	-1,509	21,683	-10,577	1,557	-2,016	-2,158	-1,252	401	-4,685	-25,763	-2,147
1976	-4,987	3,896	3,672	13,939	36,773	-4,045	15,690	1,682	-736	-5,115	-1,381	-9,539	49,850	4,154
1977	-5,348	-21,831	-15,590	-9,632	1,165	-1,636	743	-1,006	-391	-889	-4,442	-1,077	-59,935	-4,995
1978	-6,010	1,199	-15,564	323	-5,094	-2,601	-695	-567	-9,738	-1,565	-15,996	1,592	-54,714	-4,560
1979	6,725	1,773	-11,408	10,186	-28,388	17,523	-23,697	8,366	-14,930	-1,704	-15,508	-6,265	-57,325	-4,777
1980	-8,050	-144	-4,174	-48,075	-19,696	-4,008	-1,567	-829	-1,111	-1,789	-3,133	-3,001	-95,577	-7,965
1981	-2,949	-1,008	-4,272	-843	4,710	7,132	688	-716	-8,576	-22,504	-9,250	-3,246	-40,833	-3,403
1982														
1983														
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1996														
AVG	-1,361	-2,081	-3,018	-5,454	8,408	-2,504	-1,902	-230	-5,132	-2,780	-5,371	1,418	-20,007	-1,221
MAX	17,461	31,765	35,138	50,865	93,139	17,523	15,690	8,366	7,704	18,351	15,807	55,506	148,359	12,363
MIN	-13,089	-31,194	-42,409	-136,559	-28,388	-80,614	-24,498	-5,950	-34,265	-25,865	-62,852	-9,539	-135,901	-11,325

🟦	LOSS OUTLIERS
🟨	GAIN OUTLIERS

	Complete Data Set *(acre-ft/mo.)*	Outliers Removed *(acre-ft/mo.)*	Complete Data Set *(ft^3/day/mile)*	Outliers Removed *(ft^3/day/mile)*
Mean	-1,667	-1,541	-55,558	-51,356
Median	-972	-979	-32,406	-32,639
Std Dev	17,770			

CALCULATED GAINS AND LOSSES

ATASCOSA RIVER BASIN
HEADWATERS TO ATASCOSA RIVER AT WHITSETT
1964-1996

TOTAL GAIN
18,064 FT^3/DAY/MILE

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	TOTAL	AVE
1934														
1935														
1936														
1937														
1938														
1939														
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1964	401	1,242	815	492	542	237	477	6,294	185	1,272	1,028	250	13,234	1,103
1965	424	5,289	373	1,914	33,357	1,156	623	135	228	2,043	600	4,094	50,232	4,186
1966	483	600	371	11,653	5,758	3,596	627	722	2,735	565	122	259	27,490	2,291
1967	337	386	351	220	3,178	295	207	5,841	297,939	5,722	9,387	1,527	325,388	27,116
1968	126,201	8,281	2,602	3,303	76,942	6,283	5,488	694	4,901	617	666	2,576	238,550	19,879
1969	647	11,036	1,310	3,551	21,479	3,063	313	1,397	632	9,161	555	892	54,036	4,503
1970	1,861	1,630	15,381	971	52,306	48,481	1,872	1,059	1,968	530	302	454	126,814	10,568
1971	434	417	416	293	138	948	72	18,177	4,054	20,362	1,082	1,231	47,623	3,969
1972	817	714	577	298	54,142	4,070	481	2,536	6,113	564	367	357	71,036	5,920
1973	564	2,910	766	10,226	1,190	171,475	4,059	1,659	26,023	34,882	2,901	1,392	258,046	21,504
1974	1,262	975	864	739	2,725	1,200	153	8,594	11,057	823	1,617	671	30,678	2,556
1975	582	588	543	1,462	40,405	13,970	3,353	802	904	689	434	410	64,142	5,345
1976	484	395	380	7,250	19,603	787	5,270	116	5,050	45,680	16,180	8,950	110,144	9,179
1977	6,550	2,120	1,150	136,755	15,789	2,410	650	125	1,641	558	1,710	418	169,874	14,156
1978	457	462	294	239	587	7,200	4,064	28,557	23,764	971	3,081	1,021	70,698	5,891
1979	7,238	1,500	866	14,625	3,924	20,884	1,389	528	685	56	177	1,335	53,204	4,434
1980	492	395	358	198	78,799	840	286	55,014	3,973	935	2,645	1,113	145,046	12,087
1981	1,423	884	1,938	2,568	2,581	5,821	1,718	1,260	13,528	2,807	1,276	830	36,632	3,053
1982	687	7,073	1,405	799	7,904	3,258	88	-19	1,081	4,542	552	408	27,775	2,315
1983	422	1,063	3,241	173	692	2,012	1,161	2,281	45,308	4,186	251	251	61,040	5,087
1984	2,354	416	323	42	-140	-451	-762	-510	-110	12,902	2,113	1,423	17,599	1,467
1985	2,367	695	2,870	14,404	2,110	2,014	5,436	-189	3,868	28,244	14,242	1,557	77,617	6,468
1986	704	542	162	-119	689	8,091	-520	-586	408	18,620	1,155	26,748	55,894	4,658
1987	2,975	11,121	5,036	437	1,616	70,920	875	-189	791	-32	62	487	94,099	7,842
1988	146	164	38	-99	406	80	962	-166	409	-109	-127	-145	1,559	130
1989	197	226	310	-18	-81	-449	-369	-387	-352	-109	1,200	212	381	32
1990	80	42	1,011	4,635	534	-509	69,667	782	2,500	157	147	180	79,227	6,602
1991	1,309	15,914	1,148	2,833	425	462	1,606	170	1,502	178	41	65,137	90,726	7,561
1992	28,255	91,482	7,021	40,542	23,070	26,558	1,080	466	263	255	22,142	1,436	242,571	20,214
1993	1,067	720	725	402	42,342	54,351	3,033	471	165	220	264	352	104,113	8,676
1994	424	409	3,024	10,301	24,227	5,746	87	1,595	615	1,164	249	1,782	49,624	4,135
1995	583	297	1,006	121	1,352	1,888	1,014	-176	157	4	16	117	6,377	531
1996	-27	-8	-19	-116	-179	2,091	237	7,906	9,494	91	148	91	19,711	1,643
AVG	5,824	5,151	1,717	8,215	15,709	14,205	3,476	4,393	14,287	6,017	2,624	3,873	85,490	7,124
MAX	126,201	91,482	15,381	136,755	78,799	171,475	69,667	55,014	297,939	45,680	22,142	65,137	325,388	27,116
MIN	-27	-8	-19	-119	-179	-509	-762	-586	-352	-109	-127	-145	381	32

🟦 LOSS OUTLIERS
🟨 GAIN OUTLIERS

	Complete Data Set *(acre-ft/mo.)*		Outliers Removed *(acre-ft/mo.)*		Complete Data Set *(ft^3/day/mile)*		Outliers Removed *(ft^3/day/mile)*	
	Mean	7,124	Mean	3,844	Mean	155,140	Mean	83,715
	Median	898	Median	830	Median	19,555	Median	18,064
	Std Dev	22,886						

CALCULATED GAINS AND LOSSES

BLACK CYPRESS BAYOU BASIN
HEADWATERS TO BLACK CYPRESS BAYOU AT JEFFERSON
1968-1998

TOTAL GAIN/LOSS	
64,198	FT^3/DAY/MILE

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	TOTAL	AVE
1948														
1949														
1950														
1951														
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1968	3,644	-363	12,469	6,922	77,671	9,514	-5,161	-554	-1,006	1,169	1,536	3,764	109,604	9,134
1969	3,893	-7,372	-5,480	20,440	1,462	2,550	-62	-11	-28	-5	3,056	766	19,207	1,601
1970	9,356	5,757	2,111	-5,544	7,426	11,575	1,950	436	-43	-526	1,251	2,257	36,006	3,000
1971	3,584	4,151	6,904	3,421	4,852	290	-597	2,161	436	112	-627	-2,776	21,909	1,826
1972	-9,686	3,909	2,557	4,090	4,050	-2,556	160	99	44	63	7,446	9,374	19,550	1,629
1973	4,161	3,491	3,276	-30,547	8,557	-11,755	2,653	174	-10,146	1,757	-8,135	15,004	-21,511	-1,793
1974	16,374	10,660	-1,072	29,515	3,925	27,296	935	640	-139	1,181	-5,466	-420	83,430	6,952
1975	-1,379	19,679	13,386	-7,795	24,105	2,804	577	637	216	152	482	1,351	54,216	4,518
1976	11,126	9,944	22,148	4,283	-1,705	4,943	-15,253	-118	-343	-238	794	4,388	39,968	3,331
1977	4,624	-2,775	-8,454	7,678	2,626	1,618	15	-4,712	-4,471	-840	1,017	9,326	5,652	471
1978	8,592	9,612	4,702	6,448	14,930	2,173	28	3	0	0	-603	5,684	51,570	4,297
1979	17,766	10,603	12,191	3,566	-18,878	16,881	-6,766	15,418	-20,103	243	3,292	-763	33,451	2,788
1980	14,059	3,598	5,391	8,826	589	4,659	534	29	28	335	2,983	4,454	45,484	3,790
1981	4,338	5,150	6,149	3,766	9,351	8,784	-540	-20	290	6,364	3,500	2,640	49,770	4,147
1982	4,069	11,023	3,661	7,197	9,053	15,357	4,176	1,617	0	0	370	30,863	87,385	7,282
1983	12,106	9,000	-11,342	3,601	6,141	3,187	6,787	561	0	0	260	6,597	36,898	3,075
1984	5,386	9,105	12,125	7,876	1,797	217	57	90	0	10,996	15,857	20,175	83,681	6,973
1985	11,837	6,781	5,922	4,922	-1,053	2,971	1,275	234	0	372	790	9,225	43,275	3,606
1986	2,669	-2,988	3,913	8,939	11,687	22,294	14,347	223	430	1,642	11,166	33,806	108,126	9,010
1987	14,959	10,126	-21,213	6,013	73	-7,394	-296	238	192	342	11,948	17,577	32,564	2,714
1988	14,898	3,681	336	8,159	1,593	52	324	92	0	396	6,127	24,573	60,232	5,019
1989	12,859	7,117	44,230	20,935	-12,683	23,740	14,309	4,344	944	430	1,551	3,678	121,454	10,121
1990	-4,456	4,821	19,784	-12,788	-14,062	-7,205	77	956	-888	1,508	-9,497	-5,481	-27,232	-2,269
1991	18,150	7,608	10,930	16,139	54,312	7,933	1,311	2,456	9,447	1,094	26,113	17,682	173,175	14,431
1992	7,369	32,114	10,262	5,850	8,587	173	10,529	5,444	4,873	884	1,033	3,045	90,164	7,514
1993	-3,919	-5,128	8,727	6,847	-4,275	-5,060	89	-1,182	427	-5,156	5,869	7,260	4,500	375
1994	4,885	1,933	10,445	5,300	6,616	28,943	1,524	1,409	142	10,767	4,364	-1,190	75,140	6,262
1995	35,006	16,054	18,465	-2,790	14,843	-253	748	-336	91	-457	416	3,316	85,103	7,092
1996	4,229	1,767	3,541	6,266	966	3,872	1,210	3,615	9,084	17,917	16,466	20,304	89,236	7,436
1997	15,272	-5,459	12,408	7,651	19,932	19,721	-6,294	-3,720	-877	-2,162	2,890	-9,644	49,720	4,143
1998	-15,078	1,279	8,169	6,991	1,327	-471	0	0	-522	3,909	-925	-78	4,600	383
AVG	7,442	5,964	6,988	5,231	7,865	6,027	924	975	-385	1,685	3,398	7,637	53,752	8,639
MAX	35,006	32,114	44,230	29,515	77,671	28,943	14,347	15,418	9,447	17,917	26,113	33,806	173,175	14,431
MIN	-15,078	-7,372	-21,213	-30,547	-18,878	-11,755	-15,253	-4,712	-20,103	-5,156	-9,497	-9,644	-27,232	-2,269

		Complete Data Set *(acre-ft/mo.)*		Outliers Removed *(acre-ft/mo.)*		Complete Data Set *(ft^3/day/mile)*		Outliers Removed *(ft^3/day/mile)*	
🟦	LOSS OUTLIERS								
🟨	GAIN OUTLIERS								
		Mean	4,492	Mean	3,736	Mean	132,702	Mean	110,381
		Median	2,557	Median	2,173	Median	75,551	Median	64,198
		Std Dev	9,709						

CALCULATED GAINS AND LOSSES
BRAZOS RIVER BASIN
BRAZOS RIVER NEAR HIGHBANK TO BRAZOS RIVER NEAR HEMPSTEAD
1965-1994

TOTAL GAIN/LOSS
159,763 FT^3/DAY/MILE

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	TOTAL	AVE
1940														
1941														
1942														
1943														
1944														
1945														
1946														
1947														
1948														
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1964														
1965	3,573	97,509	-12,581	19,396	-812,191	174,005	-9,106	-16,144	-30,451	-9,574	-71,148	60,279	-606,432	-50,536
1966	31,829	8,063	75,078	-457,582	219,390	30,504	21,529	-25,147	-217,793	76,994	6,538	-434	-231,031	-19,253
1967	4,037	1,275	375	-6,514	-12,087	-11,478	-17,488	2,115	-18,077	-61,114	-586	-24,593	-144,136	-12,011
1968	-333,533	23,046	-123,640	133,660	-5,759	451,686	306,148	33,629	57,765	40,987	72,558	180,287	836,833	69,736
1969	21,895	97,556	73,547	65,340	-221,251	78,534	34,959	13,520	2,543	-8,663	34,550	-3,072	189,459	15,788
1970	41,471	-52,050	-184,472	60,867	-40,843	-136	27,049	11,984	40,118	72,862	37,362	9,805	24,017	2,001
1971	12,539	-691	6,529	5,475	31,456	3,603	-89,312	15,268	1,471	-90,094	16,809	-51,497	-138,445	-11,537
1972	8,825	21,797	8,218	9,527	79,541	5,020	-12,832	9,653	-2,734	-35,080	45,296	22,317	159,548	13,296
1973	39,536	95,410	40,499	13,774	157,992	105,442	44,757	22,275	3,754	214,279	37,171	85,844	860,735	71,728
1974	116,790	104,450	17,037	12,762	-3,596	-8,500	12,374	-57,109	189,737	-22,424	-239,937	130,124	251,708	20,976
1975	39,308	-149,077	54,554	-10,542	-146,849	139,579	58,580	19,252	8,289	21,723	20,058	1,407	56,283	4,690
1976	-4,076	9,094	16,236	-97,577	122,674	61,901	-77,210	27,293	4,307	-45,597	51,411	179,394	247,850	20,654
1977	35,471	65,433	-70,437	-7,514	209,280	52,387	1,777	5,692	8,143	9,994	14,970	29,573	354,769	29,564
1978	65,503	56,034	13,195	6,662	-6,526	18,632	4,705	-21,787	62,950	4,651	30,921	21,053	255,994	21,333
1979	189,518	94,819	27,852	152,950	-139,949	339,669	31,835	124,123	54,638	31,575	35,297	8,000	950,326	79,194
1980	98,155	86,744	39,748	38,311	-42,083	44,322	20,267	9,648	1,583	-6,653	12,259	6,434	308,735	25,728
1981	10,938	15,340	-5,919	8,359	57,655	-92,755	77,633	15,159	9,736	-169,755	253,462	21,134	200,985	16,749
1982	-296	-208	-21,126	64,675	-39,085	-86,170	21,844	20,473	17,004	8,211	5,748	10,624	1,695	141
1983	59,497	18,936	66,811	65,566	157,376	73,486	15,200	32,040	67,099	16,750	16,067	48,700	637,529	53,127
1984	13,842	16,314	44,826	10,041	35,083	28,619	17,429	11,690	14,275	162,050	177,240	48,098	579,507	48,292
1985	124,002	-59,288	143,242	55,582	22,534	-2,999	26,117	1,154	1,774	-35,467	-11,221	132,984	398,414	33,201
1986	2,148	-122,584	28,546	2,512	90,586	-46,439	10,581	32,543	-2,072	-64,263	56,078	35,554	23,189	1,932
1987	92,569	-16,839	63,072	17,176	-127,094	86,190	57,645	12,696	18,443	19,888	24,820	28,071	276,637	23,053
1988	35,816	4,881	71,361	27,837	18,804	-67,702	17,352	14,610	8,050	6,327	3,148	1,919	142,402	11,867
1989	51,954	35,224	49,199	95,121	-310,344	-61,655	79,043	72,218	9,233	14,908	20,792	8,918	64,613	5,384
1990	24,605	32,492	-41,663	-188,242	-92,315	178,218	15,482	12,726	15,480	-5,621	17,138	15,289	-16,413	-1,368
1991	352,791	27,503	56,465	122,878	39,356	29,848	37,064	-9,695	26,020	-82,969	-53,950	-707,168	-161,859	-13,488
1992	401,971	-63,955	194,899	174,456	-32,234	195,043	37,890	21,005	13,722	31,377	25,104	108,282	1,107,560	92,297
1993	173,189	-34,319	26,384	93,938	268,683	308,373	121,781	29,867	688	-6,842	12,698	9,167	1,003,606	83,634
1994	40,887	-9,941	89,223	36,057	-170,704	28,356	11,463	23,098	4,848	781,272	-9,034	118,975	944,499	78,708
1995														
1996														
1997														
AVG	58,492	13,432	24,902	17,498	-23,083	68,519	30,152	15,462	12,351	28,991	21,387	17,849	285,953	43,993
MAX	401,971	104,450	194,899	174,456	268,683	451,686	306,148	124,123	189,737	781,272	253,462	180,287	1,107,560	92,297
MIN	-333,533	-149,077	-184,472	-457,582	-812,191	-92,755	-89,312	-57,109	-217,793	-169,755	-239,937	-707,168	-606,432	-50,536

🟦	LOSS OUTLIERS
🟨	GAIN OUTLIERS

	Complete Data Set *(acre-ft/mo.)*	Outliers Removed *(acre-ft/mo.)*	Complete Data Set *(ft^3/day/mile)*	Outliers Removed *(ft^3/day/mile)*
Mean	23,829	24,532	223,462	230,047
Median	17,087	17,037	160,236	159,763
Std Dev	113,628			

CALCULATED GAINS AND LOSSES
CIBOLO RIVER BASIN
CIBOLOR CREEK AT SELMA TO CIBOLO CREEK NEAR FALLS CITY
1946-1989

TOTAL GAIN/LOSS	
4,895	FT^3/DAY/MILE

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	TOTAL	AVE
1934														
1935														
1936														
1937														
1938														
1939														
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1946	-1,040	-1,085	-7,601	537	-328	348	43	1,867	-5,277	439	-2,426	-146	-14,668	-1,222
1947	352	74	166	100	517	71	49	60	36	32	40	45	1,543	129
1948	45	50	44	36	133	40	82	332	55	78	29	32	956	80
1949	38	97	40	-377	105	542	71	76	36	1,037	69	127	1,862	155
1950	54	60	47	103	41	533	40	40	40	24	25	31	1,037	86
1951	32	33	40	34	84	39	22	17	72	22	27	29	452	38
1952	31	56	33	93	121	35	27	14	-20,408	39	53	147	-19,760	-1,647
1953	53	36	36	102	144	29	20	199	321	57	36	79	1,111	93
1954	37	31	32	34	85	32	16	12	14	32	25	21	371	31
1955	26	77	106	26	97	137	18	37	50	22	16	29	642	54
1956	22	18	15	18	39	4	17	6	53	91	22	290	596	50
1957	23	45	-908	-10,828	-16,351	-7,427	52	31	913	-2,489	284	68	-36,588	-3,049
1958	608	-953	-1,006	86	-21,498	79	66	32	-1,004	-571	-895	51	-25,005	-2,084
1959	55	59	48	296	153	-62	51	803	804	11,038	1,290	993	15,527	1,294
1960	1,161	222	1,092	276	1,304	-11,088	-3,420	-3,863	345	-60,580	-20,068	2,647	-91,971	-7,664
1961	-8,158	-8,339	891	944	1,334	-30,746	9,161	1,590	-62	3,816	11,515	1,742	-16,313	-1,359
1962	1,487	1,340	1,471	1,011	1,030	593	916	452	-2,076	209	18	139	6,590	549
1963	654	-1,541	857	1,245	921	489	366	340	232	891	5,921	465	10,839	903
1964	2,231	2,186	-498	-3,417	34	-364	488	355	-5,062	1,386	7,116	718	5,173	431
1965	-17,043	-18,884	1,442	2,071	11,623	-20,541	1,262	1,093	723	-6,480	-339	3,553	-41,519	-3,460
1966	992	-2,625	2,672	-10,691	-18,169	-564	383	945	1,216	773	789	692	-23,587	-1,966
1967	930	610	681	372	-28	300	462	267	-157,401	-8,746	10,219	1,682	-150,652	-12,554
1968	34,538	2,758	1,776	9,664	-17,346	-34,641	241	1,006	5,214	944	2,615	3,439	10,207	851
1969	-135	-11,859	-20,829	-30,524	-5,412	4,052	1,062	397	113	628	1,084	116	-61,306	-5,109
1970	-1,254	399	-3,163	979	24,650	2,114	1,260	1,091	643	979	921	1,068	29,687	2,474
1971	849	843	768	454	473	-3,315	-182	16,323	-16,501	4,086	1,501	4,419	9,718	810
1972	-635	-288	870	818	-28,872	3,647	2,860	1,897	1,274	1,025	1,374	1,268	-14,762	-1,230
1973	1,427	988	-509	-18,134	-2,412	-36,740	-6,773	5,143	87,536	-30,550	4,299	3,874	8,149	679
1974	-42,043	1,020	2,348	2,053	2,354	-2,927	1,053	6,961	-13,865	487	4,522	2,680	-35,357	-2,946
1975	2,146	5,164	2,044	-9,951	-25,357	-3,497	-3,666	2,402	1,050	1,274	1,188	1,517	-25,685	-2,140
1976	1,136	694	1,475	-5,069	20,371	1,643	4,359	1,661	154	-1,393	-9,071	-45,342	-29,382	-2,449
1977	2,886	-5,895	3,060	1,337	5,644	2,752	2,371	1,660	11,632	1,630	16,726	2,146	45,949	3,829
1978	1,725	897	223	3,541	1,945	13,867	1,272	8,264	5,086	1,262	18,772	1,490	58,343	4,862
1979	-17,238	-2,967	980	10,535	-46,291	8,522	3,350	2,453	1,410	1,347	1,289	1,194	-35,415	-2,951
1980	1,069	614	1,123	825	6,211	670	556	1,739	13,665	694	649	803	28,618	2,385
1981	584	483	577	-1,821	-3,408	-43,683	-1,661	-4,121	-149,139	2,296	2,315	1,011	-196,567	-16,381
1982	787	-4,106	871	810	-11,479	850	318	166	445	2,248	-1,403	-995	-11,487	-957
1983	857	-2,985	-5,932	484	452	279	-847	-499	-4,639	-361	-2,152	75	-15,269	-1,272
1984	-1,029	43	-2,327	-56	86	36	-14	-25	-85	5,550	1,790	151	4,120	343
1985	-343	-1,469	1,378	-24	-1,875	-8,501	11,399	273	669	-903	2,439	-2,419	625	52
1986	536	-694	513	252	-439	17,637	782	292	1,054	2,800	-557	-3,177	18,999	1,583
1987	1,435	-7,263	-2,539	1,741	23,368	-62,365	2,179	3,100	2,254	1,524	1,259	732	-34,575	-2,881
1988	1,368	1,321	712	856	617	1,023	1,154	421	351	102	263	764	8,952	746
1989	685	-416	-406	-620	-2,815	1,069	351	369	-39	-300	302	569	-1,252	-104
AVG	-638	-1,162	-393	-1,131	-2,231	-4,660	718	1,265	-5,411	-1,443	1,452	-254	-13,888	-1,437
MAX	34,538	5,164	3,060	10,535	24,650	17,637	11,399	16,323	87,536	11,038	18,772	4,419	58,343	4,862
MIN	-42,043	-18,884	-20,829	-30,524	-46,291	-62,365	-6,773	-4,121	-157,401	-60,580	-20,068	-45,342	-196,567	-16,381

🟦	LOSS OUTLIERS	Complete Data Set		Outliers Removed		Complete Data Set		Outliers Removed	
🟨	GAIN OUTLIERS	*(acre-ft/mo.)*		*(acre-ft/mo.)*		*(ft^3/day/mile)*		*(ft^3/day/mile)*	
		Mean	-1,157	Mean	128	Mean	-23,964	Mean	2,661
		Median	166	Median	236	Median	3,435	Median	4,895
		Std Dev	13,015						

CALCULATED GAINS AND LOSSES

FRIO RIVER BASIN
FRIO RIVER UVALDE TO DERBY
1960-1996

TOTAL GAIN/LOSS	
12,926	FT^3/DAY/MILE

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	TOTAL	AVE
1934														
1935														
1936														
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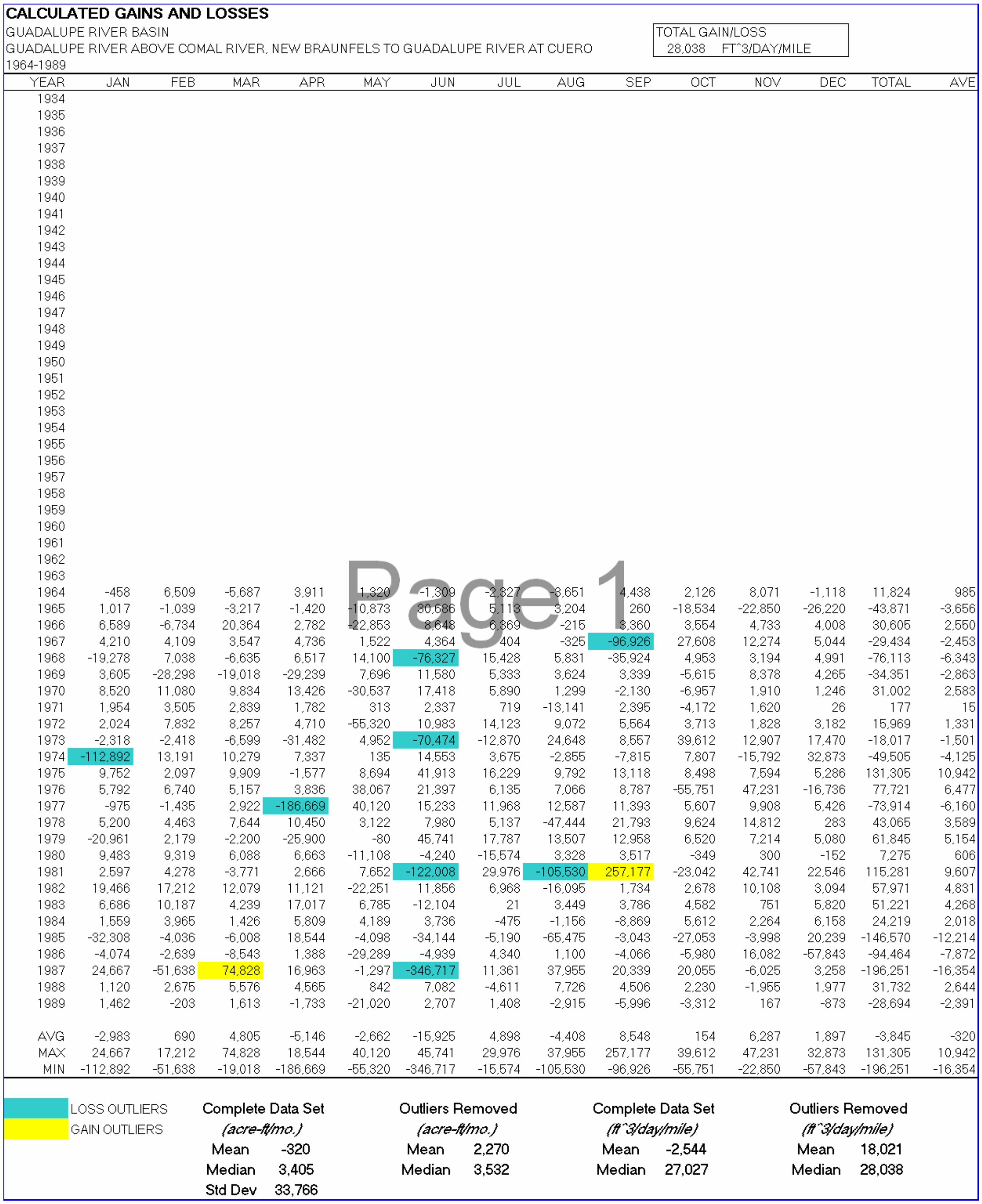
1964	-65	-73	444	-19	-75	5,129	-152	-1,023	-10,267	2,398	1,660	-208	-2,250	-187
1965	-136	119	-53	3,125	3,226	-1,980	-173	-100	-2,538	-8,422	-317	551	-6,700	-558
1966	-118	-54	-133	1,152	549	125	-686	-27,102	-8,292	-630	-260	-192	-35,642	-2,970
1967	-181	-153	-205	-504	-365	-366	-2,900	-182	2,566	-16,909	-8,697	-3,226	-31,122	-2,594
1968	-12,095	-7,021	-13,721	-3,404	-13,375	-4,524	-5,339	-281	106	-208	-182	-204	-60,249	-5,021
1969	-165	-108	-138	-137	-1,430	112	127	-303	-322	-37,140	692	1,397	-37,414	-3,118
1970	752	563	91	355	5,360	2,184	-21	-150	5,601	1,316	637	647	17,333	1,444
1971	760	182	62	5	-11	-133	3,945	-39,671	1,638	-27,760	173	2,164	-58,648	-4,887
1972	2,660	2,221	1,446	716	8,107	488	117	-19,349	2,226	1,239	907	1,547	2,323	194
1973	2,322	2,516	2,526	5,184	1,546	-13,994	-115,076	-2,887	27,570	-2,904	6,928	6,369	-79,902	-6,658
1974	6,466	5,070	4,877	3,148	5,357	2,300	486	-15,394	82,953	6,877	6,807	6,559	115,505	9,625
1975	6,970	17,511	7,294	8,110	16,123	8,729	7,923	4,601	4,860	4,321	4,653	4,398	95,493	7,958
1976	4,367	3,012	2,270	17,722	1,217	4,789	-44,634	2,703	8,033	12,611	13,116	13,784	38,990	3,249
1977	12,447	9,783	9,425	3,293	-159	5,384	4,715	2,820	2,630	-11,401	3,516	5,264	47,715	3,976
1978	5,130	3,476	2,821	2,158	1,320	4,920	182	-25,052	1,376	1,168	2,196	2,480	2,176	181
1979	4,025	2,928	-14,837	-6,757	2,360	-9,275	3,481	2,112	1,520	1,247	1,692	2,947	-8,555	-713
1980	3,089	1,529	877	580	32,466	1,130	-150	9,712	-50,387	5,898	-124	131	4,751	396
1981	718	621	-1,583	-53,021	-2,061	-49,648	-2,087	885	1,858	-1,405	3,808	3,984	-97,932	-8,161
1982	3,786	2,594	3,826	2,867	5,463	2,221	1,414	359	315	515	1,096	1,610	26,065	2,172
1983	2,280	1,725	1,847	1,384	-99	412	-3	526	276	243	-888	546	8,248	687
1984	1,237	664	58	-204	-652	-1,425	-1,254	-784	-500	29,631	-128	-65,739	-39,097	-3,258
1985	6,334	-2,275	-519	-1,333	-841	-820	-711	-440	-471	-8,254	1,709	1,514	-6,106	-509
1986	981	784	40	403	-532	29,629	-36	-1,013	1,852	20,460	2,158	-1,695	53,032	4,419
1987	-2,051	1,178	1,535	2,525	-152,444	-76,008	4,919	6,693	7,307	8,233	7,743	8,594	-181,776	-15,148
1988	8,903	7,018	5,728	4,266	2,712	-571	-6,215	529	1,250	1,817	2,535	2,109	30,080	2,507
1989	2,998	3,406	2,767	1,373	690	-742	-797	-631	-561	-501	-102	-195	7,704	642
1990	-141	-119	-94	-1,000	-3,089	-877	15,615	-1,692	-883	-533	-327	-312	6,547	546
1991	199	156	-438	9	-461	-1,001	-915	-793	-32,527	-2,150	1,890	-105,599	-141,628	-11,802
1992	-24,284	-48,166	-55,286	-21,035	-29,726	-60,102	2,638	5,105	3,523	3,532	6,581	8,447	-208,773	-17,398
1993	8,012	6,281	6,916	5,306	3,425	4,417	1,896	722	910	630	1,010	1,274	40,797	3,400
1994	1,408	1,097	891	1,483	8,339	701	-515	178	305	5,543	1,888	2,125	23,443	1,954
1995	2,352	1,514	2,582	2,544	1,123	1,022	1,857	-84	-8,651	254	894	1,331	6,739	562
1996	944	424	128	57	-338	240	-286	-253	-520	-40,583	2,961	-164	-37,390	-3,116
AVG	1,512	558	-865	-596	-3,220	-4,471	-4,019	-3,038	1,296	-1,541	2,007	-2,962	-15,341	-1,278
MAX	12,447	17,511	9,425	17,722	32,466	29,629	15,615	9,712	82,953	29,631	13,116	13,784	115,505	9,625
MIN	-24,284	-48,166	-55,286	-53,021	-152,444	-76,008	-115,076	-39,671	-50,387	-40,583	-8,697	-105,599	-208,773	-17,398

🟦 LOSS OUTLIERS
🟨 GAIN OUTLIERS

	Complete Data Set *(acre-ft/mo.)*	Outliers Removed *(acre-ft/mo.)*	Complete Data Set *(ft^3/day/mile)*	Outliers Removed *(ft^3/day/mile)*
Mean	-1,278	981	-23,070	17,706
Median	633	716	11,426	12,926
Std Dev	16,240			



CALCULATED GAINS AND LOSSES
GUADALUPE RIVER BASIN
GUADALUPE RIVER ABOVE COMAL RIVER, NEW BRAUNFELS TO GUADALUPE RIVER AT CUERO
1964-1989

TOTAL GAIN/LOSS
28,038 FT^3/DAY/MILE

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	TOTAL	AVE
1934														
1935														
1936														
1937														
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1964	-458	6,509	-5,687	3,911	1,320	-1,309	-2,327	-3,651	4,438	2,126	8,071	-1,118	11,824	985
1965	1,017	-1,039	-3,217	-1,420	-10,873	30,686	5,113	3,204	260	-18,534	-22,850	-26,220	-43,871	-3,656
1966	6,589	-6,734	20,364	2,782	-22,853	8,648	6,369	-215	3,360	3,554	4,733	4,008	30,605	2,550
1967	4,210	4,109	3,547	4,736	1,522	4,364	404	-325	-96,926	27,608	12,274	5,044	-29,434	-2,453
1968	-19,278	7,038	-6,635	6,517	14,100	-76,327	15,428	5,831	-35,924	4,953	3,194	4,991	-76,113	-6,343
1969	3,605	-28,298	-19,018	-29,239	7,696	11,580	5,333	3,624	3,339	-5,615	8,378	4,265	-34,351	-2,863
1970	8,520	11,080	9,834	13,426	-30,537	17,418	5,890	1,299	-2,130	-6,957	1,910	1,246	31,002	2,583
1971	1,954	3,505	2,839	1,782	313	2,337	719	-13,141	2,395	-4,172	1,620	26	177	15
1972	2,024	7,832	8,257	4,710	-55,320	10,983	14,123	9,072	5,564	3,713	1,828	3,182	15,969	1,331
1973	-2,318	-2,418	-6,599	-31,482	4,952	-70,474	-12,870	24,648	8,557	39,612	12,907	17,470	-18,017	-1,501
1974	-112,892	13,191	10,279	7,337	135	14,553	3,675	-2,855	-7,815	7,807	-15,792	32,873	-49,505	-4,125
1975	9,752	2,097	9,909	-1,577	8,694	41,913	16,229	9,792	13,118	8,498	7,594	5,286	131,305	10,942
1976	5,792	6,740	5,157	3,836	38,067	21,397	6,135	7,066	8,787	-55,751	47,231	-16,736	77,721	6,477
1977	-975	-1,435	2,922	-186,669	40,120	15,233	11,968	12,587	11,393	5,607	9,908	5,426	-73,914	-6,160
1978	5,200	4,463	7,644	10,450	3,122	7,980	5,137	-47,444	21,793	9,624	14,812	283	43,065	3,589
1979	-20,961	2,179	-2,200	-25,900	-80	45,741	17,787	13,507	12,958	6,520	7,214	5,080	61,845	5,154
1980	9,483	9,319	6,088	6,663	-11,108	-4,240	-15,574	3,328	3,517	-349	300	-152	7,275	606
1981	2,597	4,278	-3,771	2,666	7,652	-122,008	29,976	-105,530	257,177	-23,042	42,741	22,546	115,281	9,607
1982	19,466	17,212	12,079	11,121	-22,251	11,856	6,968	-16,095	1,734	2,678	10,108	3,094	57,971	4,831
1983	6,686	10,187	4,239	17,017	6,785	-12,104	21	3,449	3,786	4,582	751	5,820	51,221	4,268
1984	1,559	3,965	1,426	5,809	4,189	3,736	-475	-1,156	-8,869	5,612	2,264	6,158	24,219	2,018
1985	-32,308	-4,036	-6,008	18,544	-4,098	-34,144	-5,190	-65,475	-3,043	-27,053	-3,998	20,239	-146,570	-12,214
1986	-4,074	-2,639	-8,543	1,388	-29,289	-4,939	4,340	1,100	-4,066	-5,980	16,082	-57,843	-94,464	-7,872
1987	24,667	-51,638	74,828	16,963	-1,297	-346,717	11,361	37,955	20,339	20,055	-6,025	3,258	-196,251	-16,354
1988	1,120	2,675	5,576	4,565	842	7,082	-4,611	7,726	4,506	2,230	-1,955	1,977	31,732	2,644
1989	1,462	-203	1,613	-1,733	-21,020	2,707	1,408	-2,915	-5,996	-3,312	167	-873	-28,694	-2,391
AVG	-2,983	690	4,805	-5,146	-2,662	-15,925	4,898	-4,408	8,548	154	6,287	1,897	-3,845	-320
MAX	24,667	17,212	74,828	18,544	40,120	45,741	29,976	37,955	257,177	39,612	47,231	32,873	131,305	10,942
MIN	-112,892	-51,638	-19,018	-186,669	-55,320	-346,717	-15,574	-105,530	-96,926	-55,751	-22,850	-57,843	-196,251	-16,354

		Complete Data Set *(acre-ft/mo.)*		Outliers Removed *(acre-ft/mo.)*		Complete Data Set *(ft^3/day/mile)*		Outliers Removed *(ft^3/day/mile)*	
🟦	LOSS OUTLIERS								
🟨	GAIN OUTLIERS								
		Mean	-320	Mean	2,270	Mean	-2,544	Mean	18,021
		Median	3,405	Median	3,532	Median	27,027	Median	28,038
		Std Dev	33,766						

CALCULATED GAINS AND LOSSES

NAVASOTA RIVER BASIN
NAVASOTA RIVER ABOVE GROESBACK TO NAVASOTA RIVER AT BRYAN
1978-1997

TOTAL GAIN/LOSS	
5,223	FT^3/DAY/MILE

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	TOTAL	AVE
1940														
1941														
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1978	983	-2,684	-9,547	960	623	437	-446	-259	2,602	-311	-995	-3,513	-12,151	-1,013
1979	-359	11,456	91,091	1,717	-74,747	151,397	35,201	14,250	2,042	2,282	966	-26,554	208,741	17,395
1980	-554	-22,583	2,239	-12,860	-21,840	2,919	928	123	709	39	1,355	1,641	-47,882	-3,990
1981	3,264	6,465	8,346	4,226	17,594	25,767	-33,629	59	14,641	-18,269	3,180	213	31,857	2,655
1982	3,914	374	-8,675	24,729	8,852	30	-121	33	25	527	-645	-42,766	-13,722	-1,144
1983	12,508	4,663	27,571	8,421	36,724	6,604	2,225	20,574	4,380	2,553	3,825	2,230	132,277	11,023
1984	6,602	3,843	5,282	3,370	1,269	4,210	3,298	324	228	6,832	18,717	-837	53,136	4,428
1985	-3,367	25,199	21,135	4,505	7,977	684	644	1,716	2,001	3,058	9,015	26,870	99,437	8,286
1986	2,745	-19,678	4,665	-10,576	-15,746	9,442	1,702	1,034	1,111	-5,047	-18,433	-28,257	-77,039	-6,420
1987	-5,071	-38,928	28,250	2,553	-7,680	54,994	919	-255	-8,739	1,002	-6,371	-47,419	-26,744	-2,229
1988	-15,936	-12,288	-61,750	257	5,363	764	-284	151	698	-60	11	4,850	-78,223	-6,519
1989	3,273	2,915	-2,283	1,574	-43,887	-46,120	-7,118	-271	-3,617	-383	-284	-601	-96,801	-8,067
1990	-2,767	-4,138	-109,286	-46,908	-130,341	901	469	121	3,465	-4,398	-15,663	-21,946	-330,490	-27,541
1991	1,016	-62,355	-31,541	3,930	1,252	-17,081	213	-4,256	-18,293	-10,786	-35,463	-166,698	-340,061	-28,338
1992	-50,826	22,208	12,267	-3,859	-98,778	-5,018	-2,698	-5,041	-612	-500	-1,205	4,394	-129,666	-10,805
1993	16,500	-18,490	4,687	-4,853	33,951	-10,442	5,855	3,303	3,260	-701	1,820	3,833	38,723	3,227
1994	2,027	-48,382	3,271	-12,307	-71,911	17,038	744	4,648	339	-4,118	-25,970	-57,540	-192,163	-16,014
1995	-12,295	-21,679	-19,050	1,233	6,739	-2,429	-3,813	33,810	6,236	-446	-11	-166	-11,871	-989
1996	-3,091	-1,160	-2,100	-7,931	2,336	0	4,206	-984	-652	-209	909	2,399	-6,276	-523
1997	-7,033	-68,185	-44,838	-128,785	6,882	-30,008	1,275	2,201	-398	-563	-1,450	-17,066	-287,968	-23,997
AVG	-2,423	-12,171	-4,013	-8,530	-16,768	8,204	478	3,564	471	-1,475	-3,335	-18,347	-54,344	-4,529
MAX	16,500	25,199	91,091	24,729	36,724	151,397	35,201	33,810	14,641	6,832	18,717	26,870	208,741	17,395
MIN	-50,826	-68,185	-109,286	-128,785	-130,341	-46,120	-33,629	-5,041	-18,293	-18,269	-35,463	-166,698	-340,061	-28,338

🟦 LOSS OUTLIERS
🟨 GAIN OUTLIERS

	Complete Data Set *(acre-ft/mo.)*		Outliers Removed *(acre-ft/mo.)*		Complete Data Set *(ft^3/day/mile)*		Outliers Removed *(ft^3/day/mile)*	
	Mean	-4,529	Mean	-1,813	Mean	-69,776	Mean	-27,932
	Median	221	Median	339	Median	3,399	Median	5,223
	Std Dev	27,830						

CALCULATED GAINS AND LOSSES

NECHES RIVER BASIN
NECHES RIVER NEAR NECHES TO NECHES RIVER NEAR TOWN BLUFF
1959-1979

TOTAL GAIN/LOSS
153,851 FT^3/DAY/MILE

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	TOTAL	AVE
1940														
1941														
1942														
1943														
1944														
1945														
1946														
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1962														
1963	47,812	174,663	190,311	-383,937	-138,431	49,754	29,022	12,761	26,686	6,656	27,109	27,347	69,752	5,813
1964	81,969	37,807	343,667	15,483	311,126	65,550	12,717	12,473	-5,128	9,820	11,336	41,015	937,835	78,153
1965	26,785	-189,085	164,926	171,042	-388,563	174,945	27,481	17,552	-37,716	11,537	-5,044	310,504	284,364	23,697
1966	188,596	606,440	124,949	-1,930,504	246,040	147,785	6,799	39,813	-496	27,878	22,601	-109,164	-629,263	-52,439
1967	-47,678	-73,967	64,119	-107,314	48,055	-107,250	-62,903	-50,844	-21,234	-1,208,536	-217,617	-451,303	-2,236,472	-186,373
1968	-129,431	-93,396	-274,842	846,738	-189,753	518,956	357,778	68,295	177,787	52,310	104,622	493,958	1,933,022	161,085
1969	153,565	204,781	735,226	707,255	-121,055	-220,466	-5,375	4,813	6,216	-66,481	49,330	-334,279	1,113,530	92,794
1970	52,611	-588,859	-782,852	-439,298	-376,349	6,524	9,025	3,372	-32,741	-398,445	46,590	63,166	-2,437,256	-203,105
1971	64,774	27,072	31,029	31,290	72,655	15,763	-660,095	-92,740	-844	-533,381	-75,601	-1,461,329	-2,581,408	-215,117
1972	-113,835	213,907	250,806	143,415	187,421	-10,347	19,631	11,712	13,862	22,673	143,374	280,188	1,162,807	96,901
1973	421,247	290,022	333,933	232,854	653,560	-292,350	377,870	106,237	212,576	88,786	207,447	638,727	3,270,909	272,576
1974	781,230	696,518	-5,793	19,477	-346,888	-588,769	24,067	20,437	34,751	-169,371	-1,087,082	140,933	-480,490	-40,041
1975	70,702	263,543	293,449	-83,568	703,686	398,205	208,598	98,940	-8,421	82,328	19,705	83,050	2,130,217	177,518
1976	117,337	-200,776	294,995	-1,331,616	-151,390	62,737	180,720	48,601	-29,501	-133,381	32,277	181,166	-928,832	-77,403
1977	211,579	-460,427	-6,460	39,644	114,307	-371,838	14,884	20,754	11,219	7,466	24,539	-1,989	-396,322	-33,027
1978	330,679	148,205	-150,530	-43,464	33,459	-16,588	-12,992	-23,218	85,692	8,284	12,961	190,564	563,052	46,921
1979	397,152	583,318	812,140	1,228,608	-387,759	833,837	170,643	156,696	292,374	148,865	270,680	208,940	4,715,494	392,958
1980	-463,469	-17,604	147,930	-112,898	116,007	-167,228	-170,193	-15,705	-224,511	-23,789	-67,351	-189,621	-1,188,433	-99,036
1981	-284,733	-62,183	-93,927	2,136	-632,138	-901,238	120,770	7,947	144,518	-101,274	81,101	27,747	-1,691,273	-140,939
1982	104,761	132,473	177,124	937,999	515,767	-668,786	-51,997	19,450	-15,067	-73,092	135,071	-462,439	751,261	62,605
1983	490,996	291,633	-28,210	60,142	542,281	-140,657	80,912	127,352	51,370	17,342	53,086	389,668	1,935,914	161,326
1984	290,254	224,719	163,386	228,579	-45,359	-12,527	30,036	8,860	12,998	235,058	296,310	-6,744	1,425,570	118,798
1985	259,964	463,807	497,525	20,900	140,680	38,120	11,442	15,136	3,703	-694,396	-65,416	-773,305	-81,841	-6,820
1986	13,119	-834,924	5,691	-153,205	6,925	169,702	127,812	23,357	30,017	-13,197	7,424	354,978	-262,303	-21,859
1987														
1988														
1989														
1990														
1991														
1992														
1993														
1994														
1995														
1996														
AVG	127,749	76,570	137,025	4,156	38,095	-42,340	35,277	26,752	30,338	-112,347	1,144	-14,926	307,493	25,624
MAX	781,230	696,518	812,140	1,228,608	703,686	833,837	377,870	156,696	292,374	235,058	296,310	638,727	4,715,494	392,958
MIN	-463,469	-834,924	-782,852	-1,930,504	-632,138	-901,238	-660,095	-92,740	-224,511	-1,208,536	-1,087,082	-1,461,329	-2,581,408	-215,117

🟦	LOSS OUTLIERS
🟨	GAIN OUTLIERS

Complete Data Set *(acre-ft/mo.)*		Outliers Removed *(acre-ft/mo.)*		Complete Data Set *(ft^3/day/mile)*		Outliers Removed *(ft^3/day/mile)*	
Mean	25,624	Mean	47,879	Mean	147,458	Mean	275,522
Median	24,303	Median	26,735	Median	139,855	Median	153,851
Std Dev	340,145						

CALCULATED GAINS AND LOSSES

NUECES RIVER BASIN
NUECES RIVER BELOW UVALDE TO NUECES RIVER NEAR THREE RIVERS
1964-1996

TOTAL GAIN
-18,924 FT^3/DAY/MILE

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	TOTAL	AVE
1934														
1935														
1936														
1937														
1938														
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1964	-166	-1,291	116	-294	3,373	-10,470	-516	9,873	15,510	224,710	1,684	-890	241,638	20,136
1965	434	6,722	-483	-7,706	119,810	-15,427	8,195	-1,265	40	1,214	346	-2,005	109,875	9,156
1966	60	4,130	368	15,270	196,535	35,712	1,062	-81,205	17,892	-1,404	-866	-843	186,711	15,559
1967	-352	-10	671	3,736	6,670	915	175	28,184	593,577	79,908	-17,951	-3,602	691,923	57,660
1968	-122,874	-8,805	-13,299	-8,840	-21,028	6,535	1,145	-2,631	2,917	9,415	-1,341	-3,159	-161,966	-13,497
1969	-1,417	-9,867	-1,230	-1,026	-27,115	-1,483	-1,155	-799	3,531	-65,296	69,621	16,395	-19,841	-1,653
1970	-746	-2,636	-20,184	-3,794	-61,256	39,404	-2,300	8,491	-27,837	14,134	-3,428	-3,483	-63,635	-5,303
1971	-3,298	-1,860	19	383	73	-858	338,579	-497,589	436,758	618,672	18,119	-2,588	906,411	75,534
1972	-2,112	-2,964	-1,793	-3,444	-55,271	-1,032	-2,724	-77,394	14,216	-212	-4,828	-5,631	-143,188	-11,932
1973	-6,331	-6,786	-4,716	-15,748	-5,854	-265,395	-312,224	-25,582	-67,669	59,560	2,647	-11,605	-659,703	-54,975
1974	-13,279	-10,276	20,426	-6,508	-22,152	-7,370	-4,201	48,907	-118,188	-17,894	-19,432	-13,319	-163,285	-13,607
1975	-13,465	-51,646	-17,258	-18,376	-23,704	60,317	21,461	-3,219	1,871	-6,961	-863	-9,392	-61,236	-5,103
1976	-9,152	-6,538	-5,451	-49,281	-55,703	-6,515	-105,018	15,600	42,534	-3,111	198,884	34,743	50,990	4,249
1977	-12,986	-24,811	-22,466	-155,945	-43,648	-7,288	-11,277	-9,834	-9,212	-29,989	-16,663	-14,854	-358,973	-29,914
1978	-11,751	-7,674	-6,548	-5,102	3,695	70,278	-5,564	-56,972	1,000	-1,861	-8,624	-6,362	-35,486	-2,957
1979	-15,661	-6,661	-34,593	-44,744	-13,304	-81,728	-10,897	-7,529	-5,593	-4,140	-4,600	-8,202	-237,652	-19,804
1980	-4,979	-3,522	-2,803	-1,922	-48,061	31,326	-250	153,423	-34,602	-21,816	-3,570	-1,496	61,728	5,144
1981	-2,206	-1,503	-1,226	-130,064	108,767	-14,340	43,200	-5,724	20,559	-130,120	12,500	-6,731	-106,888	-8,907
1982	-5,560	-13,602	-6,103	-5,738	21,497	-4,029	-6,704	-2,728	-1,907	22,015	-2,243	-3,672	-8,775	-731
1983	-4,904	-4,394	-3,935	-4,294	-4,104	-12,291	-4,090	-5,460	3,699	8,923	3,500	-3,475	-30,824	-2,569
1984	-4,508	-2,382	-1,421	-1,339	-1,568	-1,752	1,117	-840	-466	2,731	9,785	-31,911	-32,554	-2,713
1985	-58,711	-8,669	302	7,984	85,666	40,436	35,625	-1,427	14,073	61,057	69,102	2,890	248,329	20,694
1986	-4,445	-3,747	-2,091	-2,380	-1,412	4,008	-3,735	-2,035	3,953	-28,371	-10,127	-24,040	-74,423	-6,202
1987	-14,340	-24,379	-18,849	-15,261	-161,327	-322,791	-18,707	-21,702	-35,234	-15,764	-15,499	-17,403	-681,257	-56,771
1988	-16,440	-14,019	-12,389	-9,750	-3,929	-6,128	-9,309	-1,224	-2,000	-4,227	63	-2,737	-82,091	-6,841
1989	-5,010	-6,885	-7,160	-5,664	-3,947	-1,506	-1,800	-164	-735	-348	-809	-1,328	-35,357	-2,946
1990	-1,055	703	14,088	20,618	12,049	4,401	-48,945	69,540	696	939	2,102	-1,450	73,685	6,140
1991	-4,232	-6,421	-3,640	-357	4,158	-4,671	-3,218	-774	-94,152	-1,812	-10,469	-181,212	-306,800	-25,567
1992	-44,897	-126,213	-104,452	-72,117	-23,740	-97,965	-30,748	2,589	-8,472	-10,498	-27,530	-20,071	-564,113	-47,009
1993	-17,116	-13,054	-12,737	-13,622	-71,911	-64,215	8,263	-5,189	-5,450	-4,424	-4,097	-4,088	-207,640	-17,303
1994	3,565	-5,359	-5,126	-27,131	-46,918	7,402	-12,027	-6,147	-3,023	2,564	-356	-7,444	-100,000	-8,333
1995	-4,038	-5,567	-5,120	-4,117	4,797	1,396	386	-1,151	-13,601	-2,108	18,087	-3,389	-14,424	-1,202
1996	-3,580	-2,903	-2,142	-1,282	61	-5,603	-1,308	-13,059	20,678	-219,359	16,256	-3,596	-215,836	-17,986
AVG	-12,289	-11,300	-8,522	-17,208	-3,903	-19,113	-4,167	-15,001	23,193	16,246	8,164	-10,483	-54,384	-4,532
MAX	3,565	6,722	20,426	20,618	196,535	70,278	338,579	153,423	593,577	618,672	198,884	34,743	906,411	75,534
MIN	-122,874	-126,213	-104,452	-155,945	-161,327	-322,791	-312,224	-497,589	-118,188	-219,359	-27,530	-181,212	-681,257	-56,771

🟦 LOSS OUTLIERS
🟨 GAIN OUTLIERS

	Complete Data Set *(acre-ft/mo.)*		Outliers Removed *(acre-ft/mo.)*		Complete Data Set *(ft^3/day/mile)*		Outliers Removed *(ft^3/day/mile)*	
	Mean	-4,532	Mean	-6,421	Mean	-24,654	Mean	-34,930
	Median	-3,479	Median	-3,479	Median	-18,924	Median	-18,924
	Std Dev	73,855						

CALCULATED GAINS AND LOSSES

RIO GRANDE RIVER BASIN
RIO GRANDE RIVER AT PIEDRAS NEGRAS TO RIO GRANDE RIVER AT LAREDO
1940-2000

TOTAL GAIN/LOSS
-8,344 FT^3/DAY/MILE

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	TOTAL	AVE
1940	-1,625	-1,885	-2,913	-1,256	-16,396	-10,662	-6,639	-1,803	-2,134	-9,007	-1,556	-2,213	-58,088	-4,841
1941	-4,483	-2,295	-2,184	2,703	-15,434	-5,533	5,087	1,923	6,459	9,481	-3,497	-538	-8,311	-693
1942	-5,942	-4,298	-3,828	-4,817	-13,212	-4,468	-28,664	12,586	-1,303	-10,172	-2,697	-5,258	-72,072	-6,006
1943	-3,432	-2,257	-2,983	-3,078	-1,192	-12,178	118	-905	930	-1,802	-1,934	-838	-29,550	-2,463
1944	-2,870	-2,726	-1,817	-1,535	-4,816	-457	1,027	-38,816	-4,613	-2,015	-2,628	-3,161	-64,425	-5,369
1945	-1,660	-2,135	-1,980	-10,814	-1,640	-126	2,435	699	656	-24,036	-1,387	-1,891	-41,881	-3,490
1946	-933	-1,429	-835	-5,388	-16,326	-3,632	-3,357	-5,249	-1,437	-6,925	-2,761	-2,863	-51,134	-4,261
1947	-2,095	-1,843	-1,195	-737	-7,002	-16,656	-433	352	3,428	-2,686	-938	-899	-30,704	-2,559
1948	-1,612	-1,274	-2,137	-1,264	-307	12,928	6,502	1,838	-17,714	-736	-1,900	-1,840	-7,517	-626
1949	1,849	-4,509	-3,542	-8,034	-1,331	-13,694	5,184	2,277	7,682	1,095	1,201	-500	-12,321	-1,027
1950	2,061	1,547	386	882	-2,344	-3,015	5,958	3,236	3,612	1,190	491	1,211	15,215	1,268
1951	365	495	632	126	-14,586	-1,682	2,563	750	-2,813	481	-163	-98	-13,930	-1,161
1952	71	98	-312	506	-155	-293	4,276	792	501	758	-242	-552	5,447	454
1953	-862	-626	-2,214	-2,068	-3,470	550	3,564	-10,566	-13,908	-1,626	-618	-36	-31,881	-2,657
1954	-736	-1,019	-1,630	-3,541	-10,254	112,351	-52,737	1,671	-8,502	-4,301	-2,323	-2,987	25,991	2,166
1955	-1,898	-2,902	-802	-680	-117	666	-224	-579	5,676	498	-1,930	-1,585	-3,876	-323
1956	-1,507	497	-446	-975	-502	813	-4,019	1,216	-3,935	-1,073	-1,568	-1,209	-12,709	-1,059
1957	-549	690	-2,595	-7,334	-33,978	-5,050	1,159	1,580	-6,364	-2,493	-1,251	-1,112	-57,298	-4,775
1958	-4,716	-2,482	-756	-1,344	366	6,734	-32	3,927	27,774	-2,643	-4,295	-2,060	20,475	1,706
1959	-1,474	-2,763	-3,264	-2,708	28	884	165	6,031	-1,871	-2,422	-3,736	-2,638	-13,769	-1,147
1960	1,453	-640	-1,066	297	-1,404	1,288	1,505	4,424	-3,304	-15,819	-4,280	-1,919	-19,464	-1,622
1961	-2,628	-1,764	-1,076	-2,387	-1,899	15,308	-2,068	-609	668	-269	-2,241	-1,016	19	2
1962	440	957	963	-2,014	1,766	1,713	3,453	408	2,993	653	-626	397	11,105	925
1963	14	-128	627	-2,645	-1,152	-1,974	648	4,698	2,170	-3,924	31	573	-1,061	-88
1964	721	-1,801	-1,830	-694	-1,806	-685	139	-6,020	12,149	-11,163	-4,320	-2,156	-17,466	-1,455
1965	-528	80	-735	227	-16,273	-548	1,423	4,598	2,664	-519	-1,750	-711	-12,072	-1,006
1966	-807	-344	8	3,809	-23,013	3,058	1,075	14,194	-2,611	-2,268	-1,123	-551	-8,572	-714
1967	605	-4	-546	-2,744	923	2,789	1,077	-1,299	-12,760	-2,139	-1,341	-1,150	-16,589	-1,382
1968	-308	297	108	-154	-3,460	263	11,835	6,748	10,303	-631	1,403	-960	25,444	2,120
1969	231	137	-171	-1,696	-2,105	1,202	4,332	-5,261	-311	-1,087	-892	-1,275	-6,897	-575
1970	-623	847	-3,435	1,018	-1,795	-1,341	-1,648	2,663	8,828	2,058	1,242	38	7,851	654
1971	1,762	-5,568	-1,183	206	1,278	-61,985	-14,166	-711	-12,653	-46,751	-4,375	-3,208	-147,355	-12,280
1972	-1,680	-955	-407	-83	-6,088	1,257	3,080	9,144	8,645	-4,162	-743	-2,016	5,990	499
1973	-972	-1,209	454	-3	-756	-1,838	1,653	9,232	-1,788	-7,904	-2,617	-1,275	-7,024	-585
1974	-452	1,359	-2,903	538	-2,378	-389	2,360	2,749	37,452	-10,712	-6,027	-5,695	15,902	1,325
1975	-2,496	-4,155	-3,257	-3,669	-13,855	-6,740	9,004	-867	177	-1,078	-6,384	-1,403	-34,723	-2,894
1976	-2,136	-1,606	-4,558	-2,401	-7,476	-2,078	5,304	-13,199	-9,986	-8,345	-6,010	-5,054	-57,545	-4,795
1977	-5,812	-4,523	-3,634	-356	-15,885	-1,741	1,256	540	-1,408	-379	-70	-419	-32,433	-2,703
1978	-228	-34	-618	-751	-2,715	-4,602	746	8,004	12,771	8,535	-816	-4,198	16,095	1,341
1979	-3,745	-1,687	-3,843	-8,482	-4,023	-18,970	-5,788	4,392	-195	1,497	530	-85	-40,398	-3,366
1980	850	466	798	-632	-12,113	2,231	-4,907	-7,974	14,347	691	-2,355	-2,832	-11,430	-953
1981	-2,514	-2,810	-1,254	-8,756	-9,447	-13,510	-3,829	4,793	2,790	4,617	1,273	-1,222	-29,869	-2,489
1982	-588	-1,563	-36	-1,124	-7,653	-6,921	498	1,808	-3,449	-728	-1,312	-1,516	-22,583	-1,882
1983	-184	103	1,627	1,206	2,411	-3,065	-1,122	3,310	678	2,297	-475	1,780	8,566	714
1984	457	2,331	2,154	-2,188	-3,220	8,360	3,643	8,480	1,271	-584	962	2,662	24,329	2,027
1985	750	935	-2,000	-1,243	-7,826	-2,024	1,082	3,625	8,116	-6,574	-377	1,826	-3,710	-309
1986	1,240	-1,216	-2,010	-2,195	-12,019	-9,094	9,292	8,696	6,065	6,905	-1,481	229	4,413	368
1987	1,725	2,518	1,895	5,543	3,167	-7,473	-4,243	328	-4,905	-2,126	-2,930	-457	-6,959	-580
1988	-348	-1,219	223	261	306	-1,701	4,838	4,832	380	-6,416	-1,028	-374	-246	-21
1989	-1,333	1,828	-5,108	-7,974	-5,512	-3,555	3,844	6,051	7,357	-5,050	-1,935	-2,099	-13,487	-1,124
1990	-4,306	-10,907	-2,131	-6,244	-9,814	-3,291	-1,616	18,880	9,258	-5,407	-6,001	-174	-21,752	-1,813
1991	2,868	4,478	3,158	-4,655	-4,894	-5,368	8,836	14,321	9,318	-8,871	-2,343	3,815	20,663	1,722
1992	1,798	-5,465	-7,946	-11,213	-5,084	-12,614	-4,525	-2,177	1,255	-791	-1,850	3,536	-45,077	-3,756
1993	-403	-1,757	-2,397	-1,502	-7,157	-8,475	-86	-116	5,704	2,687	4,216	-5,107	-14,393	-1,199
1994	-6,817	-4,850	-6,627	-7,153	-15,847	-4,851	-1,986	-951	-1,987	889	446	-182	-49,915	-4,160
1995	794	-1,254	-3,576	-5,162	-14,015	-858	-2,084	1,134	-3,648	-1,021	-1,379	2,854	-28,216	-2,351
1996	-715	-2,068	-1,182	-961	-4,251	-3,591	-27	7,874	2,511	2,043	876	2,158	2,666	222
1997	499	1,184	-275	-90	-251	1,405	5,891	8,975	5,901	282	3,153	2,432	29,104	2,425
1998	333	582	314	330	-4,002	1,364	958	21,491	-2,038	501	1,842	1,283	22,957	1,913
1999	1,184	1,331	1,980	143	-3,392	3,148	4,684	-9,129	663	-869	-416	-418	-1,092	-91
2000	-642	-137	-2,654	537	-6,625	1,919	2,483	-1,530	-384	1,985	1,254	2,023	-1,772	-148
AVG	-895	-1,137	-1,419	-2,072	-6,099	-1,418	-184	1,926	1,723	-2,924	-1,377	-868	-14,743	-1,229
MAX	2,868	4,478	3,158	5,543	3,167	112,351	11,835	21,491	37,452	9,481	4,216	3,815	29,104	2,425
MIN	-6,817	-10,907	-7,946	-11,213	-33,978	-61,985	-52,737	-38,816	-17,714	-46,751	-6,384	-5,695	-147,355	-12,280

🟦 LOSS OUTLIERS
🟨 GAIN OUTLIERS

	Complete Data Set *(acre-ft/mo.)*	Outliers Removed *(acre-ft/mo.)*	Complete Data Set *(ft^3/day/mile)*	Outliers Removed *(ft^3/day/mile)*
Mean	-1,229	-1,141	-12,638	-11,736
Median	-825	-811	-8,490	-8,344
Std Dev	7,743			

CALCULATED GAINS AND LOSSES

SABINE RIVER BASIN
SABINE RIVER NEAR MINEOLA TO SABINE RIVER NEAR BECKVILLE
1974-1996

TOTAL GAIN
41,845 FT^3/DAY/MILE

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	TOTAL	AVE
1940														
1941														
1942														
1943														
1944														
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1971														
1972														
1973														
1974	-115,608	204,978	63,002	-148,888	138,197	58,458	18,136	788	-8,722	40,342	-419,032	206,363	38,015	3,168
1975	55,092	-24,145	-61,551	-85,531	-37,214	-28,534	17,210	1,808	-3,124	-7,813	1,451	-290	-172,640	-14,387
1976	35,234	22,690	5,979	-349,591	35,254	7,774	-2,047	1,946	13,810	6,922	7,204	36,535	-178,289	-14,857
1977	23,239	-61,503	-40,760	52,674	108,353	-1,000	7,713	-10,538	13,306	2,298	7,840	28,878	130,499	10,875
1978	11,027	-1,449	-15,063	25,708	-6,815	10,827	2,561	-1,976	-949	-1,126	935	11,302	34,983	2,915
1979	132,263	83,461	60,183	257,704	-71,840	107,324	18,357	52,050	16,666	-60,826	12,448	-33,602	574,187	47,849
1980	-73,427	92,656	16,329	-26,793	-36,942	25,657	548	-3,083	921	3,103	-12	7,779	6,737	561
1981	780	888	-3,583	13,863	-51,673	-142,632	82,496	7,757	28,550	-41,472	-1,968	26,239	-80,756	-6,730
1982	19,094	19,590	9,915	-33,299	-61,603	-6,450	22,480	2,507	-2,464	-4,016	2,667	-58,085	-89,663	-7,472
1983	35,120	17,850	124,190	41,993	31,816	17,770	19,049	10,783	1,133	5,286	10,895	31,453	347,337	28,945
1984	20,768	-6,153	-38,041	61,301	17,097	7,060	3,141	584	1,876	-27,628	-4	-110,234	-70,231	-5,853
1985	47,402	-161,960	61,276	-89,498	-71,467	28,375	7,115	-3,568	-729	28,727	39,742	20,063	-94,522	-7,877
1986	32,519	-67,990	31,618	-53,427	70,946	-23,026	125,583	-524	5,633	12,111	-9,605	65,320	189,157	15,763
1987	18,830	36,166	-9,478	114,245	923	-20,637	6,730	-753	81	-10,899	5,650	-210,533	-69,675	-5,806
1988	218,122	-35,414	63,706	21,768	7,980	-4,274	-53,526	3,711	-1,878	-5,885	-222,801	26,131	17,639	1,470
1989	-34,479	-119,273	76,223	187,846	-344,716	220,522	69,481	22,732	645	4,122	5,084	-4,121	84,063	7,005
1990	-41,601	27,761	-347,388	8,667	-172,949	42,969	470	2,926	9,086	13,177	-4,158	15,752	-445,288	-37,107
1991	27,070	14,152	120,285	91,403	215,261	29,537	16,407	8,352	16,646	-82,222	-85,286	-366,288	5,317	443
1992	234,234	53,893	85,131	57,783	-2,809	-83,568	-100,997	-33,376	12,722	357	11,362	-63,334	171,399	14,283
1993	43,551	-95,069	122,318	-17,371	21,799	111,185	14,161	-9,528	-10,023	-180,315	49,001	-41,913	7,796	650
1994	-15,472	-146,384	206,237	36,195	57,000	30,998	-213,277	72,265	-972	61,327	-69,147	-161,457	-142,688	-11,891
1995	9,683	168,991	-46,038	-26,509	-57,648	8,346	4,208	-1,504	-1,199	-4,650	-3,198	16,456	66,937	5,578
1996	-4,017	-5,838	2,976	6,751	-12,216	3,032	-13,129	-10,660	124	7,107	-117,878	26,475	-117,273	-9,773
1997														
1998														
AVG	29,540	778	21,194	6,391	-9,707	17,379	2,299	4,900	3,963	-10,521	-33,861	-23,092	9,263	772
MAX	234,234	204,978	206,237	257,704	215,261	220,522	125,583	72,265	28,550	61,327	49,001	206,363	574,187	47,849
MIN	-115,608	-161,960	-347,388	-349,591	-344,716	-142,632	-213,277	-33,376	-10,023	-180,315	-419,032	-366,288	-445,288	-37,107

🟦 LOSS OUTLIERS
🟨 GAIN OUTLIERS

Complete Data Set *(acre-ft/mo.)*		Outliers Removed *(acre-ft/mo.)*		Complete Data Set *(ft^3/day/mile)*		Outliers Removed *(ft^3/day/mile)*	
Mean	772	Mean	3,592	Mean	8,248	Mean	38,387
Median	3,916	Median	3,916	Median	41,845	Median	41,845
Std Dev	83,983						

CALCULATED GAINS AND LOSSES

SAN ANTONIO RIVER BASIN
SAN ANTONIO RIVER AT ELMENDORF TO SAN ANTONIO RIVER AT FALLS CITY
1962-1989

TOTAL GAIN
25,690 FT^3/DAY/MILE

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	TOTAL	AVE
1934														
1935														
1936														
1937														
1938														
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1962	1,345	1,443	1,508	1,757	1,792	4,557	1,864	2,275	2,036	325	-260	499	19,142	1,595
1963	350	-374	2,770	1,633	1,290	1,089	1,738	999	778	-465	-549	737	9,996	833
1964	-3,180	3,384	-62	1,340	188	542	784	613	-4,963	-1,606	-8,062	388	-10,635	-886
1965	528	-9,905	-4,380	1,179	-17,444	-4,964	295	546	-670	-6,915	-1,162	-9,904	-52,795	-4,400
1966	-205	155	-720	-917	-1,864	203	941	-1,537	-883	-119	268	217	-4,459	-372
1967	954	553	1,051	1,187	956	748	260	384	12,894	2,032	-1,032	936	20,923	1,744
1968	-14,033	1,857	-823	-3,382	12,983	3,257	1,426	570	8,564	1,017	-1,415	-1,414	8,604	717
1969	-48	-2,275	-901	-346	8,415	3,638	781	48	2,617	-1,571	231	-2,458	8,129	677
1970	734	-192	-664	-761	-6,977	4,166	405	151	-454	-327	800	209	-2,912	-243
1971	362	-297	1,773	426	1,891	-990	2,281	-14,219	-3,145	786	2,218	39	-8,876	-740
1972	842	1,314	-1,436	-867	-41,587	1,114	-1,532	646	593	739	-338	-323	-40,833	-3,403
1973	-292	832	-1,376	-6,107	1,226	9,720	-29,178	6,411	-15,457	2,989	10,236	2,470	-18,526	-1,544
1974	1,105	1,346	1,185	1,146	1,442	3,776	1,022	-20,843	11,528	2,332	-4,274	539	304	25
1975	5,216	-855	6,357	573	20,104	12,614	2,158	-925	-551	-1,103	-1,217	388	42,761	3,563
1976	8,889	2,620	2,949	-6,512	-11,855	3,713	2,690	2,890	2,129	-19,693	12,734	5,560	6,114	510
1977	1,994	6,429	5,335	-6,685	11,956	8,456	3,965	283	-5,797	457	-20,885	-1,097	4,410	368
1978	-1,499	182	1,656	628	2,915	-4,531	685	-16,260	-8,908	1,018	-3,954	1,341	-26,727	-2,227
1979	-1,708	1,566	-1,580	-12,541	8,138	-3,476	613	1,741	2,881	1,161	410	18	-2,777	-231
1980	2,623	3,096	992	1,236	5,653	1,335	891	4,413	-5,160	1,628	1,812	1,573	20,092	1,674
1981	1,245	129	-1,679	-3,385	-4,425	-32,654	8,731	-2,386	-511	-9,807	-1,182	-1,190	-47,115	-3,926
1982	749	2,287	335	878	-10,037	2,489	1,652	1,040	1,593	6,265	10,493	13,134	30,876	2,573
1983	11,467	9,153	14,601	9,437	7,321	10,171	7,394	10,340	14,229	8,688	8,073	10,392	121,265	10,105
1984	9,738	9,177	9,861	8,146	5,203	5,686	5,858	6,839	7,030	-1,081	2,454	1,340	70,251	5,854
1985	7,114	2,855	2,019	4,340	2,449	-3,388	1,839	1,888	714	6,416	5,575	2,120	33,943	2,829
1986	1,399	1,004	2,089	1,170	-857	-11,684	3,590	3,766	-3,930	-2,397	-289	-5,404	-11,543	-962
1987	3,835	-7,002	-5,599	2,723	-62,856	18,632	-607	2,959	2,983	1,294	3,140	4,441	-36,056	-3,005
1988	4,581	3,374	2,929	3,677	2,630	707	-1,835	1,220	3,336	1,685	2,950	2,595	27,849	2,321
1989	4,167	1,241	582	2,466	3,945	4,180	1,416	3,380	1,273	-191	4,986	2,582	30,029	2,502
AVG	1,724	1,182	1,385	87	-2,050	1,397	719	-99	884	-230	777	1,062	6,837	570
MAX	11,467	9,177	14,601	9,437	20,104	18,632	8,731	10,340	14,229	8,688	12,734	13,134	121,265	10,105
MIN	-14,033	-9,905	-5,599	-12,541	-62,856	-32,654	-29,178	-20,843	-15,457	-19,693	-20,885	-9,904	-52,795	-4,400

🟦 LOSS OUTLIERS
🟨 GAIN OUTLIERS

Complete Data Set *(acre-ft/mo.)*		Outliers Removed *(acre-ft/mo.)*		Complete Data Set *(ft^3/day/mile)*		Outliers Removed *(ft^3/day/mile)*	
Mean	570	Mean	1,422	Mean	14,198	Mean	35,430
Median	996	Median	1,031	Median	24,811	Median	25,690
Std Dev	7,166						

CALCULATED GAINS AND LOSSES
SAN MARCOS RIVER BASIN
HEADWATERS TO SAN MARCOS RIVER, LULING
1957-1989

TOTAL GAIN/LOSS
-33,111 FT^3/DAY/MILE

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	TOTAL	AVE
1934														
1935														
1936														
1937														
1938														
1939														
1940														
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1957	-1,442	-918	-5,886	-14,661	30,290	19,375	3,100	2,617	-19,750	-15,488	3,246	4,641	5,124	427
1958	-919	16,691	10,848	5,771	3,902	2,342	-1,730	-1,238	-2,920	2,051	4,601	1,153	40,552	3,379
1959	-131	-7,032	-439	-3,767	1,102	-117	185	-559	-1,536	5,126	1,564	1,761	-3,842	-320
1960	1,627	1,024	1,957	-30,242	3,120	31,308	8,435	2,939	3,145	-61,155	7,740	786	-29,316	-2,443
1961	-6,543	-15,219	1,014	833	-1,964	-60,280	-1,905	-265	-8,073	-211	460	-315	-92,468	-7,706
1962	-614	-1,805	-2,316	-3,917	-5,623	-9,700	-5,012	-3,550	-1,379	-3,468	-1,983	-5,618	-44,987	-3,749
1963	-2,401	-7,680	-5,125	-8,628	-7,724	-9,637	-7,702	-6,658	-6,194	-6,699	-5,564	-4,459	-78,469	-6,539
1964	-3,188	-3,432	-3,445	-1,921	-958	-3,315	362	-1,343	-15,151	-2,518	-1,996	-5,213	-42,119	-3,510
1965	-31,145	-26,465	4,686	2,352	-22,438	2,973	3,535	1,134	308	-119	-6,576	-16,546	-88,300	-7,358
1966	2,542	-7,075	-5,105	-6,470	-6,261	-2,274	-5,339	-4,964	-4,513	-8,978	-9,973	-8,081	-66,492	-5,541
1967	-6,304	-6,103	-4,145	-4,465	-6,474	-5,773	-4,342	-3,806	-4,882	-16,230	-15,340	-5,792	-83,657	-6,971
1968	-30,529	-1,392	-18	-8,915	-7,280	-30,160	-6,002	-4,083	-3,369	-3,864	-8,789	-23,942	-128,343	-10,695
1969	-2,969	-18,554	-14,419	-14,073	-12,710	-1,562	-3,044	-2,609	-3,624	-5,241	-9,857	-13,709	-102,371	-8,531
1970	-10,338	-25,331	-22,699	-9,753	-8,604	1,891	3,267	2,501	0	-4,176	451	1,040	-71,750	-5,979
1971	841	-456	-681	-287	-102	-1,083	-680	-5,251	889	-2,001	-2,161	-795	-11,768	-981
1972	-834	-3,708	-4,971	-6,365	23,873	836	-833	-2,235	-2,789	-1,451	-406	-116	1,000	83
1973	125	-299	632	8,780	7,602	-11,715	9,322	10,725	12,045	-31,182	11,273	9,742	27,049	2,254
1974	-2,653	3,769	5,171	3,910	-2,616	-5,331	-7,512	-20,067	-8,921	-2,900	-23,463	-10,373	-70,985	-5,915
1975	3,055	-12,089	7,346	2,306	-77,092	-11,316	6,046	11,848	6,960	131	3,866	2,885	-56,053	-4,671
1976	2,109	1,211	615	-70,465	-45,510	-6,209	7,828	6,724	5,075	-9,269	-4,069	1,598	-110,363	-9,197
1977	11,158	-494	13,698	-27,397	16,319	5,944	9,446	6,412	5,385	3,261	3,798	2,081	49,611	4,134
1978	273	-2,031	-3,085	-3,882	-2,631	-14,682	-8,250	-6,459	-4,967	-2,610	-4,347	-5,385	-58,056	-4,838
1979	-11,429	-15,459	-4,443	15,414	958	-984	652	3,553	1,208	-501	-1,208	-2,335	-14,574	-1,214
1980	-6,307	-4,453	-6,798	-5,943	-21,833	-14,660	-12,601	-11,166	-6,713	-5,363	-3,027	-3,465	-102,330	-8,528
1981	-1,759	-2,560	-1,657	-445	283	8,271	18,092	19,521	14,633	9,103	15,208	3,027	81,719	6,810
1982	2,286	813	1,957	-651	-28,025	3,629	2,139	1,477	1,532	1,515	1,163	1,784	-10,381	-865
1983	7,683	2,065	762	13,676	3,783	29,435	16,202	12,155	10,870	10,957	7,908	8,705	124,201	10,350
1984	-11,394	-13,714	-12,459	-16,085	-21,839	-21,158	-13,160	-8,628	-8,753	-16,412	-9,764	-6,862	-160,229	-13,352
1985	-68,643	-47,825	-22,470	-49,808	-67,352	-22,409	-32,703	-3,037	-6,761	-56,531	-51,589	-10,336	-439,463	-36,622
1986	15,836	14,039	8,884	6,183	7,758	24,240	12,360	7,978	21,897	31,341	23,044	35,721	209,282	17,440
1987	43,050	18,491	35,861	24,500	26,557	95,744	49,331	26,193	19,616	16,366	34,216	20,498	410,423	34,202
1988	16,530	13,750	12,288	10,467	12,700	14,921	11,016	9,256	6,719	6,322	5,709	6,180	125,858	10,488
1989	6,901	6,415	6,352	7,753	-425	10,736	6,588	5,844	4,979	5,134	5,459	5,484	71,220	5,935
AVG	-2,592	-4,419	-245	-5,642	-6,340	584	1,730	1,362	150	-5,002	-921	-493	-21,827	-1,819
MAX	43,050	18,491	35,861	24,500	30,290	95,744	49,331	26,193	21,897	31,341	34,216	35,721	410,423	34,202
MIN	-68,643	-47,825	-22,699	-70,465	-77,092	-60,280	-32,703	-20,067	-19,750	-61,155	-51,589	-23,942	-439,463	-36,622

🟦 LOSS OUTLIERS
🟨 GAIN OUTLIERS

Complete Data Set *(acre-ft/mo.)*		Outliers Removed *(acre-ft/mo.)*		Complete Data Set *(ft^3/day/mile)*		Outliers Removed *(ft^3/day/mile)*	
Mean	-1,819	Mean	-1,199	Mean	-68,767	Mean	-45,337
Median	-919	Median	-876	Median	-34,727	Median	-33,111
Std Dev	15,730						

CALCULATED GAINS AND LOSSES
SULPHUR RIVER BASIN
SOUTH SULPHUR NEAR COOPER TO WRIGHT PATTMAN NEAR TEXARKANA
1953-1996

TOTAL GAIN/LOSS
-557 FT^3/DAY/MILE

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	TOTAL	AVE
1940														
1941														
1942														
1943														
1944														
1945														
1946														
1947														
1948														
1949														
1950														
1951														
1952														
1953	41,679	183,004	-2,548	-328,295	486,471	6,315	-72,808	-4,498	-13,833	-3,679	-19,684	-88,137	183,986	15,332
1954	-64,641	4,624	11,726	19,348	208,674	21,766	178	-178	-177	-151,575	-50,998	5,618	4,364	364
1955	-3,761	-3,942	50,336	77,261	4,630	3,914	12,145	1,856	28,285	78,006	698	1,416	250,845	20,904
1956	361	93,258	6,844	-6,206	-10,664	2,311	3,013	1,807	1,418	1,380	-40,893	-288	52,342	4,362
1957	13,376	46,799	15,000	-170,216	261,804	304,531	-2,593	-12,439	-68,493	9,858	-35,095	-2,694	359,839	29,987
1958	-13,859	-5,131	-48,952	-277,653	250,291	-123,544	20,588	-122	14,105	2,214	41,808	105	-140,149	-11,679
1959	11,733	36,097	-17,648	22,453	4,674	81,015	31,115	4,666	2,400	9,621	27,120	108,983	322,230	26,852
1960	14,824	-38,489	-35,203	-8,302	5,802	-6,617	107,520	1,568	102,176	50,860	9,288	67,063	270,491	22,541
1961	1,371	-12,452	1,684	174,838	25,138	-12,521	8,235	-5,888	-8,528	2,132	-71,411	84,271	186,869	15,572
1962	62,245	113,494	121,730	6,420	23,063	-64,529	10,713	987	-86,619	11,621	-131,325	-27,475	40,326	3,360
1963	1,997	4,106	88,217	-5,702	-40,503	-12,241	-2,294	-521	-115	636	35	3,262	36,877	3,073
1964	3,376	-1,808	-5,292	56,065	65,517	-56,969	17	3,376	-109,645	16,216	-47,019	43,529	-32,637	-2,720
1965	42,703	59,737	15,436	18,017	-222,502	-48,360	924	1,637	-21,197	34	-669	4,281	-149,959	-12,497
1966	-4,107	48,157	-3,546	-538,711	358,207	-992	-3,599	-20,440	-12,292	30,720	-660	-782	-148,045	-12,337
1967	-2,921	-3,578	-10,291	263,270	-133,967	301,086	85,857	-590	-50,905	-14,204	111,401	89,927	635,085	52,924
1968	16,059	-11,988	-176,526	-42,213	-53,646	-60,305	-70,553	4,628	-81,393	-11,556	44,541	-30,154	-473,107	-39,426
1969	-45,210	97,777	-79,658	35,314	-181,497	-8,234	-600	2,702	-25,656	-17,441	510	-39,364	-261,357	-21,780
1970	-17,140	-122,220	12,754	-155,633	80,891	2,185	-9,845	-1,235	-43,514	-97,615	-13,496	6,228	-358,640	-29,887
1971	-1,601	-7,752	16,645	4,320	14,338	3,760	-12,723	13,466	-8,811	-279,897	75,766	-63,845	-246,334	-20,528
1972	28,192	-20,089	-1,210	4,778	4,794	-11,626	6,528	157	8,630	-88,756	-98,935	4,324	-163,213	-13,601
1973	-15,451	13,645	64,031	84,891	104,020	52,878	-7,023	-214	-86,716	-193,333	8,137	35,409	60,275	5,023
1974	956	52,214	-8,268	-219,248	79,715	36,497	-1,828	-3,492	-39,652	-56,977	-158,486	141,150	-177,419	-14,785
1975	-25,666	-99,941	42,202	-18,165	-83,923	-151,579	-10,482	-3,212	-490	-280	5,805	1,879	-343,852	-28,654
1976	10,031	11,803	67,417	-172,745	30,735	59,250	-258,698	-2,587	4,332	-21,391	-2,441	6,510	-267,784	-22,315
1977	36,108	50,918	-129,591	152,974	24,321	-29,610	-840	-2,655	-250	-231	-128,418	-389	-27,664	-2,305
1978	-8,118	-24,053	69,878	764	5,497	-20,371	-76	-45	0	-3	-17,377	-41,236	-35,141	-2,928
1979	206,720	74,619	2,537	146,282	297,669	204,154	-13,046	-22,162	-9,084	-2,983	-2,919	54,922	936,710	78,059
1980	-475,112	85,263	23,793	45,420	-99,060	14,519	-3,865	-4,442	-54,221	-168	8,686	-41,167	-500,356	-41,696
1981	5,972	27,571	-7,006	676	-20,214	-281,872	45,715	-1,009	-7,572	-300,318	34,980	1,452	-501,624	-41,802
1982	1,665	43,909	10,966	23,708	53,433	214,974	-68,908	10,438	-107	-407	56,164	65,725	411,561	34,297
1983	-29,384	-159,850	8,833	26,065	18,668	-26,727	-52,136	699	-143	-801	-7,235	-98	-222,109	-18,509
1984	2,115	-109,168	-68,168	109,021	-19,446	-18	250	612	240	-82,894	124,785	-124,818	-167,489	-13,957
1985	-2,581	30,205	82,561	19,946	-34,857	7,129	-291	-83	-10	-23,258	-63,111	-17,729	-2,080	-173
1986	5,955	-35,607	23,087	-84,085	-31,112	-27,704	43,468	1,111	-9,679	-13,429	-133,449	37,795	-223,649	-18,637
1987	-7,633	-32,555	142,457	6,173	-15,645	-16,919	-17,939	-757	-93,253	-28,347	-230,084	201,569	-92,933	-7,744
1988	83,087	5,533	10,345	15,650	-1,104	-86	-123,685	-1,672	-2,703	-11,970	-223,955	56,571	-193,991	-16,166
1989	13,164	-11,631	44,557	31,535	41,404	-160,680	-4,739	1,459	-10,975	90	-906	1,593	-55,129	-4,594
1990	30,028	-41,086	44,739	2,365	-162,754	-150,191	-23,220	-30,558	3,149	-19,820	-45,845	29,542	-363,652	-30,304
1991	40,124	-43,440	76,220	22,568	153,797	-67,937	-7,637	4,412	228	-82,578	-39,423	-26,697	29,637	2,470
1992	-79,122	58,964	-14,799	-10,008	-90,154	-136,806	-435,523	4,083	36,675	1,815	-66,415	66,242	-665,049	-55,421
1993	59,175	-181,005	119,456	-7,469	1,455	-4,003	-509	1,438	4,069	-52,430	8,235	37,799	-13,791	-1,149
1994	38,143	-29,249	57,531	-32,276	-131,217	-39,940	-70,408	-10,531	6,972	6,318	-29,319	36,892	-197,084	-16,424
1995	83,239	90,458	-38,353	66,168	-156,596	21,030	-3,261	-119	-5,510	1,472	-513	3,216	61,231	5,103
1996	-3,457	-28	4,298	3,207	70,930	23,164	-3,054	-9,705	37,597	15,589	-22,987	-28,699	86,854	7,238
AVG	1,242	5,389	13,369	-14,487	26,979	-3,634	-20,589	-1,774	-13,665	-29,949	-25,571	15,084	-47,607	-3,967
MAX	206,720	183,004	142,457	263,270	486,471	304,531	107,520	13,466	102,176	78,006	124,785	201,569	936,710	78,059
MIN	-475,112	-181,005	-176,526	-538,711	-222,502	-281,872	-435,523	-30,558	-109,645	-300,318	-230,084	-124,818	-665,049	-55,421

🟦 LOSS OUTLIERS
🟨 GAIN OUTLIERS

Complete Data Set *(acre-ft/mo.)*		Outliers Removed *(acre-ft/mo.)*		Complete Data Set *(ft^3/day/mile)*		Outliers Removed *(ft^3/day/mile)*	
Mean	-3,967	Mean	-2,785	Mean	-49,561	Mean	-34,795
Median	-60	Median	-45	Median	-755	Median	-557
Std Dev	86,690						

CALCULATED GAINS AND LOSSES
TRINITY RIVER BASIN
TRINITY RIVER AT TRINIDAD TO TRINITY RIVER NEAR CROCKETT
1967-1987

TOTAL GAIN/LOSS
202,366 FT^3/DAY/MILE

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	TOTAL	AVE
1940														
1941														
1942														
1943														
1944														
1945														
1946														
1947														
1948														
1949														
1950														
1951														
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1962														
1963														
1964														
1965														
1966														
1967	19,578	12,864	15,747	41,293	14,337	-83,393	3,203	846	-58,902	-269,292	-19,351	-1,061	-324,131	-27,011
1968	-125,736	12,924	-250,445	148,243	-295,768	-76,386	72,845	16,329	15,959	6,995	17,268	83,174	-374,598	-31,216
1969	41,564	2,068	-78,321	406,425	-636,254	87,676	24,393	-3,395	3,094	-10,350	36,955	-4,194	-130,338	-10,862
1970	59,902	-172,223	-291,418	-938	43,741	8,760	312	76	-47,006	-189,385	63,885	5,993	-518,301	-43,192
1971	14,366	19,743	25,929	-3,559	-2,557	10,818	-17,176	29,989	3,041	-366,836	153,746	-260,796	-393,293	-32,774
1972	147,459	83,394	28,805	122	29,007	22,648	5,670	2,252	6,911	16,946	47,327	55,173	445,713	37,143
1973	-39,175	55,749	68,718	-701,148	555,154	-169,521	53,470	42,800	-53,582	-65,070	100,262	167,050	14,707	1,226
1974	176,065	111,149	70,877	38,382	46,426	-30,946	16,812	-4,669	-37,776	-199,776	-540,896	357,077	2,726	227
1975	107,457	-98,288	50,008	-181,810	-456,329	151,524	18,700	48,145	4,886	18,265	15,651	26,742	-295,049	-24,587
1976	43,246	32,787	81,185	-529,786	185,572	372,677	16,204	11,804	-34,208	-42,575	63,840	117,609	318,355	26,530
1977	44,314	-85,227	-313,914	34,055	181,798	177,121	7,408	6,335	10,571	6,507	4,786	19,923	93,679	7,807
1978	44,678	41,191	23,898	34,458	-8,719	28,879	4,880	6,233	22,063	-2	22,796	8,813	229,168	19,097
1979	88,934	34,370	114,360	253,858	-639,124	175,277	132,901	53,807	75,504	21,564	31,374	17,039	359,866	29,989
1980	-69,842	134,522	35,536	-114,665	-200,934	42,977	19,541	5,186	-4,445	2,519	4,861	8,139	-136,604	-11,384
1981	20,348	35,263	7,961	46,350	49,490	-227,395	95,846	19,850	44,889	-282,640	-14,904	94,056	-110,887	-9,241
1982	83,575	-9,520	25,018	81,327	-530,498	-18,556	57,433	23,074	30,988	1,399	6,029	147,171	-102,559	-8,547
1983	88,757	-60,655	218,142	92,054	156,901	-237	45,896	9,536	15,591	5,711	24,770	51,429	647,895	53,991
1984	33,182	21,726	-6,109	46,058	7,909	34,950	22,712	28,272	11,889	36,685	41,196	-365,848	-87,377	-7,281
1985	46,725	16,692	100,837	-116,568	25,014	40,118	20,368	6,939	15,293	-274,958	94,957	-34,723	-59,306	-4,942
1986	53,492	-25,822	29,608	53,501	5,479	51,549	85,408	14,979	-12,166	-82,898	-314,722	222,395	80,803	6,734
1987	-32,895	-145,431	263,485	84,341	-102,579	-3,984	124,768	3,656	8,824	-126	1,465	-9,007	192,516	16,043
1988														
1989														
1990														
1991														
1992														
1993														
1994														
1995														
1996														
AVG	40,286	823	10,472	-13,715	-74,854	28,312	38,647	15,335	1,020	-79,396	-7,557	33,627	-7,001	-583
MAX	176,065	134,522	263,485	406,425	555,154	372,677	132,901	53,807	75,504	36,685	153,746	357,077	647,895	53,991
MIN	-125,736	-172,223	-313,914	-701,148	-639,124	-227,395	-17,176	-4,669	-58,902	-366,836	-540,896	-365,848	-518,301	-43,192

🟦 LOSS OUTLIERS
🟨 GAIN OUTLIERS

	Complete Data Set *(acre-ft/mo.)*		Outliers Removed *(acre-ft/mo.)*		Complete Data Set *(ft^3/day/mile)*		Outliers Removed *(ft^3/day/mile)*
Mean	-583	Mean	16,325	Mean	-6,645	Mean	185,950
Median	16,752	Median	17,767	Median	190,812	Median	202,366
Std Dev	147,198						

APPENDIX C

Standard Operating Procedures (SOPs) for Processing Historical Pumpage Data

TABLE OF CONTENTS

FIGURES

APPENDICIES

1. Source Data - Historical groundwater use data for the period 1980 to 2000 is derived primarily from seven tables provided by the Texas Water Development Board (TWDB) in MS Excel format, each corresponding to one of the seven major water use categories (with 3-letter abbreviation):

    i. irrigation use (IRR) - "Irrigation_Master_Post1980_062602.xls"

    ii. livestock use (STK) - "Livestock_Master_Post1980_072602.xls"

    iii. county-other/rural domestic use (C-O) - "RuralDomestic_Master_Post1980_042902.xls"

    iv. mining use (MIN) - "Mining_Master_Post1980_052402.xls"

    v. manufacturing use (MFG) - "Manufacturing_Master_Post1980_052402.xls"

    vi. steam electric power generation use (PWR) - "Power_Master_Post1980_052402.xls"

    vii. city-municipal domestic water use (MUN) - "CityMunicipal_Master_Post1980_081402.xls"

1.1. Water use in the first three categories (IRR, STK, and C-O) is reported as annual summary estimates of groundwater use (in gallons and acre-feet per year) in each county-basin geospatial unit. A county-basin is the area created by the intersection of counties and river basins. For instance, because portions of Crosby County fall within the Red and Brazos River basins, there are two county-basins within Crosby County (Crosby-Red and Crosby-Brazos). Sources of groundwater are identified for irrigation and livestock water use categories but not for county-other. No specific wells are identified for these three categories, nor are monthly sub-totals provided. Also, estimates for the years 1998, 1999, and 2000 are not provided for these three categories.

1.2. Water use in the other four categories (MIN, MFG, PWR, and MUN) is reported as annual and monthly self-generated groundwater use totals, in gallons, from each manufacturing, power generation, mining, or municipal water user for the years 1980 to 2000. The name, county, basin, alphanumeric code (alphanum), source aquifer, and the number of wells from which the groundwater was pumped is also provided in most cases. This data is primarily derived from the TWDB's water use surveys.

1.3. The use categories "City/Municipal" and "County-Other/Rural Domestic" deserve additional discussion to avoid confusion. Both are considered domestic, i.e., household water uses, and for this reason they have often been pooled together and given the 3-letter abbreviation 'MUN" or "DOM". However, because specific groundwater source location information is available from municipal and community water suppliers, but not for private rural well owners, they have been split into two use categories. To minimize confusion the abbreviation "MUN" will refer only to City/Municipal uses. Rural domestic use will be referred to as "County-other" and abbreviated "C-O."

1.4. Accessory data required to complete and spatially distribute historical groundwater pumpage data for use in the groundwater model include the following data:

1.4.1. Well information

1.4.1.1. TWDB's state well database - http://www.twdb.state.tx.us/publications/reports/GroundWaterReports/GWDatabaseReports/Database in ASCII/All Counties/weldta.txt

1.4.1.2. TWDB well followup survey - GAM_WellLocationFollowup_100101.xls

1.4.1.3. TCEQ's public water utilities database - retrieved on CD-ROM. Updates may be available at http://www2.TCEQ.state.tx.us/iwud/. (dbPDWS_GAM.mdb)

1.4.1.4. USGS source information data - http://waterdata.usgs.gov/tx/nwis/inventory, and http://waterdata.usgs.gov/ok/nwis/inventory

1.4.2. irrigation monthly distribution estimates for 1980's and 1990's - IRR_GAM_MONTHLY_DISTRIBUTION.xls

1.4.3. Annual groundwater use data for Miller County, Arkansas for water years 1985-2000 (Miller Co 85-00.txt).

1.4.4. Annual groundwater use data for the Sparta aquifer (qryDataRequestForSparta.xls) and Cane River Formation (CRVRPumpage.xls) in Louisiana for water years 1980, 1985, 1989, 1994, 1995, and 1999.

1.4.5. GIS data layers (as polygon shapefiles unless otherwise specified)

1.4.5.1. Texas counties (county_tx.shp)

1.4.5.2. Louisiana parishes and Arkansas counties (parishes_la.shp, county_ar.shp)

1.4.5.3. Texas river basins (river_basins.shp)

1.4.5.4. 1990 census population data at block level for Texas, Louisiana and Arkansas (census90_all.shp)

1.4.5.5. 2000 census population data at block level for Texas, Louisiana and Arkansas (census00_all.shp)

1.4.5.6. municipal boundaries for Texas (cities_urban_tx.shp)

1.4.5.7. municipal boundaries for Louisiana and Arkansas (citiesla.shp, cities_urban_ar.shp)

1.4.5.8. lake and reservoirs – Texas, Louisiana and Arkansas (reservoirs_gam.shp, reservoirs_la.shp, reservoirs_ar.shp & lakes_ar.shp)

1.4.5.9. MRLC NLCD land use/land cover for north Texas (texas_sw.nlcd.tif.gz, texas_se.nlcd.tif.gz, texas_n.nlcd.tif.gz)

1.4.5.10. USGS 1:250,000 GLIS land use/land cover data for north Texas, Louisiana and Arkansas (lulc.shp, lulc_la.shp, lulc_ar.shp)

1.4.5.11. Texas irrigated farmlands 1989 survey polygons (irrfarm89_gam.shp)

1.4.5.12. Texas irrigated farmlands 1994 survey polygons (irrfarm94_gam.shp)

1.4.5.13. 30-m digital elevation models for northeast Texas, Louisiana and Arkansas (grid) (dem_ne_ft)

1.4.5.14. Queen City and Sparta aquifer boundaries (minor_aquifers.shp)

1.4.5.15. Northern, central and southern model grids (modgrd_n.shp, modgrd_c.shp, modgrd_s.shp)

2. Initial Processing

2.1. Create and populate an historical pumpage database in MS Access.

2.1.1. The original downloaded executable file **Post1980andPre2000.exe**, containing seven Excel files, one for each use category (city/municipal, power, mining, manufacturing, livestock, irrigation, and rural domestic/county-other) is used to create a new database **QCSPHistPumpage.mdb**.

2.1.2. Import each of the seven MS Excel files into the new project database **QCSPHistPumpage.mdb**:

Original Excel File	Access Project Database Table
CityMunicipal_Master_Post1980_081402.xls	MUN_1980to2000
Manufacturing_Master_Post1980_052402.xls	MFG_1980-2000
Mining_Master_Post1980_052402.xls	MIN_1980to2000
Power_Master_Post1980_052402.xls	PWR_1980-2000
Livestock_Master_Post1980_072602.xls	STK_1980-1997
Irrigation_Master_Post1980_062602.xls	IRR_1980-1997
RuralDomestic_Master_Post1980_042902.xls	C-O_1980-1997

2.1.3. Limit records to aquifers of interest and create a one join identifier column for future database manipulation and a second column to join database tables to GIS shapefiles.

2.1.3.1. For each table, **MIN_1980to2000, MFG_1980-2000, PWR_1980-2000, CityMunicipal_1980to2000**, create a new make-table query that will select only those pumpage records reported for the aquifers of interest. The aquifers of interest include: Carrizo-Wilcox (10), Other (22), Queen City (24), and Sparta (27). At the same time, create a new database join identifier to simplify relationships and queries within the historical pumpage database. The join id should be created using following formula:

JoinID = SO_COUNTY_ID*1000000+SO_BASIN_ID*1000+AQUIFER_ID

2.1.3.2. In addition, create a more generic identifier that will allow for the linkage between the database tables and the GIS county-basins shapefile using the following formula:

Shapefile!CtyBsn = DatabaseTable!Shpctybsn =SO_COUNTY_ID* 1000 + SO_BASIN_ID

2.1.3.3. The resulting recordsets are saved in the project database **QCSPHistPumping.mdb**:

Output Database Table	Count of Source County/Basin/Aquifer	Count of WUG Users
MUN_1980to2000_QCSP	68	126
MIN_1980to2000_QCSP	46	37
MFG_1980to2000_QCSP	68	52
PWR_1980to2000_QCSP	17	16

2.1.4. Add a Boolean field **NullFill** to each of the four database tables listed above. Query the database for those records that contain at least one null monthly withdrawal value. In a discussion with Cindy Ridgeway of the Texas Water Development Board (TWDB), it was determined that null withdrawal values actually represent zero withdrawal. Export these records to Excel and calculated the total annual withdrawal to verify that null values represent zero withdrawal in these records. Then for each record, replace the null value with the more appropriate zero value and toggle the **NullFill** field to true.

2.1.5. Add a Boolean field, **MonCalc** to the spreadsheet, with **False** entered in those records containing original, reported monthly pumpage values, and **True** for those records with no distributed monthly pumpage values in any of the twelve months January through December. Those records where **MonCalc** = **True** are those records for which average monthly distribution factors are used to calculate the monthly pumpage estimates (see section 2.5)

2.1.6. Import the table **z_county** from the TWDB Groundwater Database (GWDB.mdb) that includes 254 Texas Counties. Two integer codes are present to identify counties in Texas: **old_code** and **county_code**. The **old_code** corresponds to the **SO_County_ID** while **county_code** is a FIPS code, or a new code. The **old_code** is preserved and appended to all database tables and shapefiles where appropriate, to provide a linkage between the relational and spatial databases. Adding Louisiana and Arkansas data will duplicate FIPS codes and thus **county_code** will be non-unique and **old_code** must be maintained as a unique field. Prior to appending out of state data, add a field **StateFIPS** for the State

FIPS code. Give all Texas counties a **StateFIPS** of 48. Twenty records are added to represent the counties of Arkansas and parishes of Louisiana and are given **old_code** values ranging from 501 to 520. The original County FIPS codes are appended to the **county_code** field for the out of state data. The **StateFIPS** code for Arkansas is 5 and Louisiana is 22. The resulting **z_county** table will contain 274 records. Add three Boolean fields: **North**, **South**, and **Central**. These fields will be used to track those counties within the three model domains. See Section 2.2 below for more information regarding the identification of out of state counties of interest within the model domain.

2.1.7. Import the table **z_basin** from the TWDB Groundwater Database (GWDB.mdb). This table includes 23 river basins in Texas with one additional null basin field. Two records are added for the counties in Arkansas and Louisiana. These counties are not divided by basin but are considered as a single basin per state. These two records are added and given basin codes of 24 (Arkansas) and 25 (Lousiana).

2.1.8. Import the tables **z_aquifer** and **z_aquifer_id** from the TWDB Groundwater Database (GWDB.mdb). The **z_aquifer** table contains 432 records with **aquifer_code** (e.g. 124 ALVM) and an **aquifer_name** (e.g. alluvium). The **z_aquifer_id** contains 30 records or aquifers. The integer ID field (1-30) is used in each of the use type pumping data tables to track the aquifer from which water is pumped.

2.1.9. Identify which **aquifer_codes** in the **z_aquifer** table correlate to one of the thirty aquifers in the **z_aquifer_id field** using a method of highest frequency code matches found in the Groundwater Database **z_welldata** table. The **z_welldata** table contains a record for each well. Each well is attributed with the **aquifer_code** (corresponding to the **z_aquifer** tables) and three aquifer id fields (**aquiferid1**, **aquiferid2**, **aquiferid3**). The resulting table will contain an **aquifer_id** of 1-30 with each of the 432 aquifer codes, **AquiferCodes**.

2.1.9.1. Query the count of the **aquifer_code** and **aquifer_id** combinations in the well data table, **z_welldata**:

```
Query1:  SELECT z_welldata.aquifer_code, z_welldata.aquifer_id1, Count(z_welldata.aquifer_id1) AS CountOfaquifer_id1
FROM z_welldata GROUP BY z_welldata.aquifer_code, z_welldata.aquifer_id1;
```

2.1.9.2. Query the **aquifer_code** and the maximum count of the **aquifer_id/aquifer_code** combinations:

```
Query 2:  SELECT Query1.aquifer_code, Max(Query1.CountOfaquifer_id1) AS MaxOfCountOfaquifer_id1
FROM Query1 GROUP BY Query1.aquifer_code;
```

2.1.9.3. Finally combine the results of the two queries above and the original **z_aquifer_id** and **z_aquifer** tables to get the resulting **AquiferCodes** table.

```
Query 3:  SELECT Query1.aquifer_id1, Query1.aquifer_code FROM Query1 INNER JOIN Query2 ON
(Query1.CountOfaquifer_id1 = Query2.MaxOfCountOfaquifer_id1) AND (Query1.aquifer_code = Query2.aquifer_code);
```

2.2. Preparing a county-basin ArcView shapefile for Texas, Arkansas, and Louisiana.

2.2.1. The reported pumpage is uniquely defined in the water-use survey tables by county-basin-aquifer units. Spatially the pumpage may be divided into county-basin units for Texas counties, Arkansas counties and Louisiana parishes. County-basin units consist of the area in the same county and river basin. Many counties are split between two or more river basins, thus, county-basins are equal to in size or smaller than counties.

2.2.2. To create a county-basin shapefile, in ArcView, load shapefiles of Texas counties and river basins in GAM projection (These were borrowed from the data model for the northern Carrizo-Wilcox GAM). Intersect these two layers using the Geoprocessing Wizard to create a new shapefile **countybasin_TX.shp**.

2.2.2.1. The Texas county file contains the FIPS county identifier. The **old_code** (**SO_COUNTY_ID** is based on the **old_code**) corresponds to the **TXCNTY_DD1** field. A field must be added to provide a unique identifier on which to link with database records:

CtyBsn = TXCNTY_DD1 (or Old_Code) * 1000 + Basin_Num

2.2.3. Create the out-of-state county shapefiles and select out-of-state Arkansas counties and Louisiana parishes within the northern model domain.

2.2.3.1. Load the out-of-state counties shapefiles, **parishes_la.shp** and **county_ar.shp**, into ArcView along with the northern model grid boundary. Out-of-state regions intersect the northern model grid only. Select only those counties/parishes that intersect the northern model domain using a spatial query. Twenty counties are selected. These twenty polygons represent the out-of-state counties within the model domain and must be appended to the database table **z_county**. Delete all but these polygons from the shapefile. Add a **WUG_County_ID** field and number the records 501-520. Add a basin field and for each Arkansas county and set basin equal to 24 and set each Louisiana parish basin equal to 25. Add a **StateFIPS** field and set to 5 for Arkansas and 22 for Louisiana. Finally merge these records with the county basin shapefile for Texas, **countybasin_tx.shp** to create **CtyBsn.shp**. Remember to complete the unique identifier field:

CtyBsn = Old_Code * 1000 + Basin_Num

2.2.3.2. Be sure that each unique county in the county-basin shapefile **CtyBsn.shp** has a matching county record in **z_county** database table.

2.3. Limit water use records to those counties intersecting the model domain. Get rid of pumping records for each use category from counties contained in the “Other” aquifer that are outside of the model domain.

2.3.1. Select the unique county-basin units for the “Other” aquifer in each of the use type pumpage tables (e.g. **MUN_1980to2000_QCSP**). Include the **shpctybsn** field which contains the unique value on which to join the shapefiles to the database tables (**shpctybsn** = **ctybsn**). Export the results of the following query to a dBase file that can be used in ArcView:

```
SELECT DISTINCT MUN_1980to2000_QCSP.JoinID, MUN_1980to2000_QCSP.ShpCtyBsn,
MUN_1980to2000_QCSP.AQUIFER_ID
FROM MUN_1980to2000_QCSP WHERE  (((MUN_1980to2000_QCSP.AQUIFER_ID)=22));
```

2.3.2. Add the **CtyBsn.shp** county-basin shapefile created in Section 2.2 to ArcView and create a join to the dBase table from the previous step using the **ctybsn** field (shapefile) and the **shpctybsn** field (dBase table).

2.3.3. Create a spatial query that will select those counties that DO NOT intersect the northern, southern, or central model domains. Export this list of county-basins to dBase and import it into the project database.

2.3.4. Run a delete query that will delete all of the pumping records associated with county-basins that DO NOT intersect the model domain from the **MUN_1980to2000_QCSP** pumping data table.

2.3.5. Repeat for the MFG, MIN, and PWR use categories.

2.4. Associate each model grid cell (for each of the three model grids: northern, central and southern) with the county-basin it falls primarily within. This will be useful when we need to determine monthly distribution factors and water user group IDs (**WUG IDs**) for non-well-specific pumpage categories (IRR, STK, C-O). These monthly distribution factors are estimated as averages within a county-basin. **Note**: The primary county-basin is not used to spatially distribute pumpage among grid cells because it is inexact. A grid cell may be part of multiple county-basins. For spatial distribution purposes, this grid cell should be split by county-basin – then later aggregated.

2.4.1. Load the model grid shapefile in GAM projection. Union this shapefile with county-basins shapefile

(**CtyBsn.shp**) using the Geoprocessing Wizard. Using XTools calculate the area of each polygon in the newly created shapefile. In ArcCatelog add a numeric field, **frarea**, to the attribute table, and use the field calculator function to enter its values (**frarea** = area/27878400). Here, 27878400 is the area, in square feet, of each grid cell. Export the table as a dbf file.

2.4.2. Import the dbf file into MS Access as a new table. The goal is to identify, for each grid cell, the county-basin with which it is primarily associated. Select by query the records with no value for the field **CtyBsn**. Delete these records, as they are grid cells over Mexico or the ocean. Next select by query the records with 0 row and 0 column and delete these as they are counties outside of the model domain.

2.4.3. Create a query to select for each unique grid cell the county-basin unit with the maximum area:

```
Query1: SELECT central.ROW, central.COLUMN, central.GRID_ID, central.GRIDID, Max(central.FRAREA) AS
MaxOfFRAREA FROM central GROUP BY central.ROW, central.COLUMN, central.GRID_ID, central.GRIDID;
```

2.4.4. Create a query to link the necessary information for the database table. Note that **MasterTable** was imported to this project database from the Carrizo-Wilcox Historical Pumpage Database:

```
Query2:  SELECT Query1.GRIDID, Query1.ROW, Query1.COLUMN, Query1.GRID_ID, central.BASIN_NUM,
central.BASIN_NAME, central.OLD_CODE, central.COUNTY_NAM, central.CNTYBSN, MasterTable.[RWPG number],
MasterTable.[RWPG letter] FROM (Query1 LEFT JOIN central ON (Query1.GRIDID = central.GRIDID) AND
(Query1.MaxOfFRAREA = central.FRAREA)) LEFT JOIN MasterTable ON central.OLD_CODE = MasterTable.countynum;
```

2.4.5. Format the primary key **Grid_id** as well as a few additional fields and create the database table:

```
Query3:  SELECT 1000000+[GRIDID] AS GRID_ID, "CCW" AS MODEL, Query2.COUNTY_NAM AS CNTY,
Query2.BASIN_NAME AS RIVERBASIN, Query2.OLD_CODE AS ctynum, Query2.BASIN_NUM AS basinnum,
Query2.[RWPG number] AS RWPGnum, Query2.[RWPG letter] AS RWPGlet INTO Grid_lkup_CCW FROM Query2;
```

2.4.6. The result of this process is a new database table containing for each grid cell a primary county-basin in which the majority of the grid cell resides. Repeat as necessary for each model grid.

Model Grid	**Output Database Table**
Central Carrizo-Wilcox	Grid_lkup_CCW
Northern Carrizo-Wilcox	Grid_lkup_NCW
Southern Carrizo-Wilcox	Grid_lkup_SCW

2.5. Completion of monthly pumpage estimates for MUN, MFG, MIN, and PWR use categories.

2.5.1. In database tables **MUN_1980to2000_QCSP**, **MFG_1980to2000_QCSP**, **MIN_1980to2000_QCSP**, and **PWR_1980to2000_QCSP** monthly pumpage estimates are reported for the majority, but not all, of the water users. For other users, only the annual total pumpage is reported. It is necessary to estimate the monthly pumpage totals for some water users via the following procedure.

2.5.2. Calculate one set of twelve monthly pumping distribution fractions for each unique county-basin-aquifer unit for each reported year in each of the four tables listed in 2.5.1 above.

2.5.2.1. Begin by creating a query to calculate the mean annual pumpage, for each year 1980-2000, for each unique county-basin-aquifer unit, **qryMUNMeanAnnualPumpPerCBA**:

```
SELECT MUN_1980to2000_QCSP.JoinID, MUN_1980to2000_QCSP.ShpCtyBsn,
MUN_1980to2000_QCSP.SO_COUNTY_ID, MUN_1980to2000_QCSP.SO_BASIN_ID,
MUN_1980to2000_QCSP.AQUIFER_ID, MUN_1980to2000_QCSP.ShpCtyBsn, MUN_1980to2000_QCSP.YEAR,
Avg(MUN_1980to2000_QCSP.[MUNICIPAL_CITY(ACFT/YR)]) AS [AvgOfMUNICIPAL_CITY(ACFT/YR)],
Avg(MUN_1980to2000_QCSP.[MUNICIPAL_CITY(GAL/YR)]) AS [AvgOfMUNICIPAL_CITY(GAL/YR)]
FROM MUN_1980to2000_QCSP
GROUP BY MUN_1980to2000_QCSP.JoinID, MUN_1980to2000_QCSP.ShpCtyBsn,
MUN_1980to2000_QCSP.SO_COUNTY_ID, MUN_1980to2000_QCSP.SO_BASIN_ID,
MUN_1980to2000_QCSP.AQUIFER_ID, MUN_1980to2000_QCSP.ShpCtyBsn, MUN_1980to2000_QCSP.YEAR
ORDER BY MUN_1980to2000_QCSP.JoinID;
```

2.5.2.2. Create a second query to calculate the mean monthly pumpage, for each year 1980-2000, for each unique county basin aquifer unit, **qryMUNMeanMonthlyPumpPerCBA**:

```
SELECT MUN_1980to2000_QCSP.JoinID, MUN_1980to2000_QCSP.ShpCtyBsn,
MUN_1980to2000_QCSP.SO_COUNTY_ID, MUN_1980to2000_QCSP.SO_BASIN_ID,
MUN_1980to2000_QCSP.AQUIFER_ID, MUN_1980to2000_QCSP.YEAR,
Avg(MUN_1980to2000_QCSP.Jan_inGallons) AS AvgOfJan_inGallons,
Avg(MUN_1980to2000_QCSP.Feb_inGallons) AS AvgOfFeb_inGallons,
Avg(MUN_1980to2000_QCSP.Mar_inGallons) AS AvgOfMar_inGallons,
Avg(MUN_1980to2000_QCSP.Apr_inGallons) AS AvgOfApr_inGallons,
Avg(MUN_1980to2000_QCSP.May_inGallons) AS AvgOfMay_inGallons,
Avg(MUN_1980to2000_QCSP.Jun_inGallons) AS AvgOfJun_inGallons,
Avg(MUN_1980to2000_QCSP.Jul_inGallons) AS AvgOfJul_inGallons,
Avg(MUN_1980to2000_QCSP.Aug_inGallons) AS AvgOfAug_inGallons,
Avg(MUN_1980to2000_QCSP.Sep_inGallons) AS AvgOfSep_inGallons,
Avg(MUN_1980to2000_QCSP.Oct_inGallons) AS AvgOfOct_inGallons,
Avg(MUN_1980to2000_QCSP.Nov_inGallons) AS AvgOfNov_inGallons,
Avg(MUN_1980to2000_QCSP.Dec_inGallons) AS AvgOfDec_inGallons
FROM MUN_1980to2000_QCSP
GROUP BY MUN_1980to2000_QCSP.JoinID, MUN_1980to2000_QCSP.ShpCtyBsn,
MUN_1980to2000_QCSP.SO_COUNTY_ID, MUN_1980to2000_QCSP.SO_BASIN_ID,
MUN_1980to2000_QCSP.AQUIFER_ID, MUN_1980to2000_QCSP.YEAR
ORDER BY MUN_1980to2000_QCSP.JoinID, MUN_1980to2000_QCSP.AQUIFER_ID;
```

2.5.2.3. Create a third query based on the previous two above to calculate the monthly pumping distribution factor, for each year 1980-2000, for each unique county-basin-aquifer unit by dividing the mean monthly pumping in gallons by the mean annual pumping in gallons, **qryMUNMonthlyFactorperCBA**:

```
SELECT qryMUNMeanMonthlyPumpPerCBA.JoinID, qryMUNMeanAnnualPumpPerCBA.ShpCtyBsn,
qryMUNMeanAnnualPumpPerCBA.SO_COUNTY_ID, qryMUNMeanAnnualPumpPerCBA.SO_BASIN_ID,
qryMUNMeanMonthlyPumpPerCBA.AQUIFER_ID, qryMUNMeanAnnualPumpPerCBA.YEAR,
CDbl(FormatNumber(qryMUNMeanMonthlyPumpPerCBA!AvgOfJan_inGallons/qryMUNMeanAnnualPumpPerCB
A![AvgOfMUNICIPAL_CITY(GAL/YR)],4)) AS JanFactor,
CDbl(FormatNumber(qryMUNMeanMonthlyPumpPerCBA!AvgOfFeb_inGallons/qryMUNMeanAnnualPumpPerC
BA![AvgOfMUNICIPAL_CITY(GAL/YR)],4)) AS FebFactor,
CDbl(FormatNumber(qryMUNMeanMonthlyPumpPerCBA!AvgOfMar_inGallons/qryMUNMeanAnnualPumpPerC
BA![AvgOfMUNICIPAL_CITY(GAL/YR)],4)) AS MarFactor,
CDbl(FormatNumber(qryMUNMeanMonthlyPumpPerCBA!AvgOfApr_inGallons/qryMUNMeanAnnualPumpPerC
BA![AvgOfMUNICIPAL_CITY(GAL/YR)],4)) AS AprFactor,
CDbl(FormatNumber(qryMUNMeanMonthlyPumpPerCBA!AvgOfMay_inGallons/qryMUNMeanAnnualPumpPerC
BA![AvgOfMUNICIPAL_CITY(GAL/YR)],4)) AS MayFactor,
CDbl(FormatNumber(qryMUNMeanMonthlyPumpPerCBA!AvgOfJun_inGallons/qryMUNMeanAnnualPumpPerCB
A![AvgOfMUNICIPAL_CITY(GAL/YR)],4)) AS JunFactor,
CDbl(FormatNumber(qryMUNMeanMonthlyPumpPerCBA!AvgOfJul_inGallons/qryMUNMeanAnnualPumpPerCB
A![AvgOfMUNICIPAL_CITY(GAL/YR)],4)) AS JulFactor,
CDbl(FormatNumber(qryMUNMeanMonthlyPumpPerCBA!AvgOfAug_inGallons/qryMUNMeanAnnualPumpPerC
BA![AvgOfMUNICIPAL_CITY(GAL/YR)],4)) AS AugFactor,
CDbl(FormatNumber(qryMUNMeanMonthlyPumpPerCBA!AvgOfSep_inGallons/qryMUNMeanAnnualPumpPerC
BA![AvgOfMUNICIPAL_CITY(GAL/YR)],4)) AS SepFactor,
CDbl(FormatNumber(qryMUNMeanMonthlyPumpPerCBA!AvgOfOct_inGallons/qryMUNMeanAnnualPumpPerCB
A![AvgOfMUNICIPAL_CITY(GAL/YR)],4)) AS OctFactor,
CDbl(FormatNumber(qryMUNMeanMonthlyPumpPerCBA!AvgOfNov_inGallons/qryMUNMeanAnnualPumpPerC
BA![AvgOfMUNICIPAL_CITY(GAL/YR)],4)) AS NovFactor,
CDbl(FormatNumber(qryMUNMeanMonthlyPumpPerCBA!AvgOfDec_inGallons/qryMUNMeanAnnualPumpPerC
BA![AvgOfMUNICIPAL_CITY(GAL/YR)],4)) AS DecFactor
FROM qryMUNMeanAnnualPumpPerCBA LEFT JOIN qryMUNMeanMonthlyPumpPerCBA ON
(qryMUNMeanAnnualPumpPerCBA.JoinID = qryMUNMeanMonthlyPumpPerCBA.JoinID) AND
(qryMUNMeanAnnualPumpPerCBA.YEAR = qryMUNMeanMonthlyPumpPerCBA.YEAR);
```

2.5.2.4. Export the results of the monthly pumping query to a spreadsheet program and calculate the sum and mean of all monthly factors per year. Then in a second spreadsheet, calculate the normalized monthly distribution factors by dividing each monthly factor by the sum of all factors for each year. Calculate the mean and sum of all normalized distribution factors as a QA measure (sum = 1 and mean = 0.08333 [1/12, or even distribution]). Copy the mean and sum of the raw distribution factors into the spreadsheet with the normalized distribution factors. These fields will be used to determine outliers.

2.5.2.5. Import the spreadsheet containing normalized distribution factors and raw factor statistics into the project database. Add a Boolean field **Outlier** to the database table. Open the table and filter for all records with null monthly distribution factors. For each resulting record toggle the **Outlier** field to **True**. Next filter the records with mean raw distribution factors that fall outside of the range 0.035 to 0.15. Review each of these records to determine additional outliers by checking for anomalous normalized monthly distribution factors. If any additional outliers are noted, toggle the value of the **Outlier** field to **True**.

2.5.3. Calculate one unique set of twelve mean monthly pumping distribution fractions for each unique county-basin-aquifer unit in each of the four tables listed in 2.1.3.3. above

2.5.3.1. Query the normalized monthly factor tables to find the average monthly distribution factor for the entire 21 year period using only those records that are NOT outliers (**Outliers** = **False**), **qryCityMunMFacMean**:

```
SELECT CityMun_MFac_Fin.JoinID, CityMun_MFac_Fin.ShpCtyBsn, CityMun_MFac_Fin.SO_COUNTY_ID,
CityMun_MFac_Fin.SO_BASIN_ID, CityMun_MFac_Fin.AQUIFER_ID, Avg(CityMun_MFac_Fin.Jan) AS
AvgOfJanFactor, Avg(CityMun_MFac_Fin.Feb) AS AvgOfFebFactor, Avg(CityMun_MFac_Fin.Mar) AS
AvgOfMarFactor, Avg(CityMun_MFac_Fin.Apr) AS AvgOfAprFactor, Avg(CityMun_MFac_Fin.May) AS
AvgOfMayFactor, Avg(CityMun_MFac_Fin.Jun) AS AvgOfJunFactor, Avg(CityMun_MFac_Fin.Jul) AS
AvgOfJulFactor, Avg(CityMun_MFac_Fin.Aug) AS AvgOfAugFactor, Avg(CityMun_MFac_Fin.Sep) AS
AvgOfSepFactor, Avg(CityMun_MFac_Fin.Oct) AS AvgOfOctFactor, Avg(CityMun_MFac_Fin.Nov) AS
AvgOfNovFactor, Avg(CityMun_MFac_Fin.Dec) AS AvgOfDecFactor, CityMun_MFac_Fin.Outliers INTO
MUN_MonthlyFactorsperCBA
FROM CityMun_MFac_Fin
GROUP BY CityMun_MFac_Fin.JoinID, CityMun_MFac_Fin.ShpCtyBsn, CityMun_MFac_Fin.SO_COUNTY_ID,
CityMun_MFac_Fin.SO_BASIN_ID, CityMun_MFac_Fin.AQUIFER_ID, CityMun_MFac_Fin.Outliers
HAVING (((CityMun_MFac_Fin.Outliers)=No));
```

2.5.3.2. Export the results of this query to a spreadsheet program and calculate the sum and mean of all monthly factors per year. If for any records sum does not equal one then in a second spreadsheet, calculate the normalized monthly distribution factors by dividing each monthly factor by the sum of all factors for each year. Calculate the mean and sum of all normalized distribution factors as a QA measure (sum = 1 and mean = 0.08333 [or 1/12, an even distribution]). Copy the mean and sum of the raw distribution factors into the spreadsheet with the normalized distribution factors.

2.5.3.3. Import the results of 2.5.3.2 above into the project database, **MUN_MonthlyFactorsperCBA** and add a Boolean field, **GIS**, and a double field **Nearest**. These fields will be used to track sources of monthly factors for those county-basin-aquifer units for which no valid monthly distribution factors were calculated.

2.5.4. For county-basin-aquifer units with no valid monthly distribution factors, use the monthly distribution factors from the nearest adjacent county-basin. If more than one adjacent county-basin exists, pick one that contains information for the same aquifer. If more than one adjacent county-basin contains distribution factors for the same aquifer then give priority to the adjacent county-basin unit in the same basin or the same county.

2.5.4.1. Query for those records that are not outliers making sure to add a new Boolean field to the query **Valid** and set all records to **True**, **qryCityMunMfacValid**:

```
SELECT DISTINCT CityMun_MFac_Fin.JoinID, CityMun_MFac_Fin.ShpCtyBsn, CityMun_MFac_Fin.Outlier,
"True" AS ValidMFac FROM CityMun_MFac_Fin WHERE (((CityMun_MFac_Fin.Outlier)=No));
```

2.5.4.2. Export the results of the query in step 2.5.4.1 above to a dBase file for use in ArcView (refer to section 2.5.4.6.).

2.5.4.3. Query the database table, **MUN_MonthlyFactorsperCBA**, for those records that are outliers, **qryCityMunMFacOutliers**:

```
SELECT DISTINCT MUN_MonthlyFactorsperCBA.JoinID, MUN_MonthlyFactorsperCBA.Outlier,
MUN_MonthlyFactorsperCBA.ShpCtyBsn
FROM MUN_MonthlyFactorsperCBA WHERE (((MUN_MonthlyFactorsperCBA.Outlier)=Yes));
```

2.5.4.4. To determine which county-basin-aquifer units do not have valid calculated monthly distribution factors, select those county-basin-aquifer units are that in the outliers query and NOT in the valid query, **qryCityMunMFacGIS**.

```
SELECT qryCityMunMFacOutliers.JoinID, qryCityMunMFacOutliers.ShpCtyBsn,
qryCityMunMFacOutliers.Outlier
FROM qryCityMunMFacOutliers LEFT JOIN qryCityMunMFacValid ON qryCityMunMFacOutliers.JoinID =
qryCityMunMFacValid.JoinID WHERE (((qryCityMunMFacValid.JoinID) Is Null));
```

2.5.4.5. The results of the query in 2.5.4.4. above are the county-basin-aquifer units for which monthly distribution factors cannot be calculated. Append these records into the monthly factors table **MUN_MonthlyFactorsperCBA**, making sure to fill in the appropriate values and fields. For each of the appended records, be sure to toggle the **GIS** field **True**.

2.5.4.6. Open ArcView and add the county-basin shapefile (**CtyBsn.shp**). Add the dBase file from step 2.5.4.2 above. Join the dBase table containing counties with valid calculated monthly distribution factors to the county-basin shapefile based on the **shpctybsn** and **ctybsn** (county-basin) text fields. Render the polygons such that all of those county-basins with valid monthly factors are one color and the rest of the county-basins another.

2.5.4.7. Query the county-basin shapefile (**CtyBsn.shp**) for those county-basin units resulting from the query in 2.5.4.5 above. These are the county-basins for which no valid monthly distribution factors were calculated. Find the nearest county-basin with valid calculated monthly distribution factors and record this county-basin-aquifer unit the **Nearest** field of the appropriate record appended to the monthly factors table, **MUN_MonthlyFactorsperCBA**. That is to say, this represents the nearest county-basin-aquifer unit from which calculated monthly distribution factors are borrowed.

2.5.4.8. Check the resulting monthly distribution factors table, **MUN_MonthlyFactorsperCBA**, to be sure there is exactly one record for each unique county-basin-aquifer unit present in the pumping data table, **MUN_1980to2000_QCSP**.

2.5.5. Distribute the annual pumping into monthly pumping using the monthly distribution factors and fill in the appropriate values in the pumping data table, **MUN_1980to2000_QCSP**

2.5.5.1. Query the pumping database table, **MUN_1980to2000_QCSP** for those records where **MonCalc** is **False**. These are records for which monthly pumping has already been distributed. Append these records into a new table, **MUN_1980to2000_QCSP_Final**.

2.5.5.2. Query the pumping database table, **MUN_1980to2000_QCSP** for those records where **MonCalc** is true and append them to the new pumping data table **MUN_1980to2000_QCSP_Final**, **qryMUNPumpDistribution**:

```
INSERT INTO MUN_1980to2000_QCSP_Final ( JoinID, ShpCtyBsn, ID, WUG_ID, WUG_NAME, DATA_CAT,
WUG_RWPG, WUG_COUNTY_NAME, WUG_BASIN_NAME, CITY_ID, SO_TYPE_ID_NEW, watertype,
WUG_COUNTY_ID, WUG_BASIN_ID, alphanum, [Supplier Information], ADDRESS_LINE2, SO_RWPG,
SO_COUNTY_ID, SO_BASIN_ID, AQUIFER_ID, SO_ID, SO_NAME, numwells, [YEAR],
[MUNICIPAL_CITY(ACFT/YR)], [MUNICIPAL_CITY(GAL/YR)], Jan_inGallons, Feb_inGallons, Mar_inGallons,
Apr_inGallons, May_inGallons, Jun_inGallons, Jul_inGallons, Aug_inGallons, Sep_inGallons, Oct_inGallons,
Nov_inGallons, Dec_inGallons, MonCalc )
SELECT DISTINCTROW MUN_1980to2000_QCSP.JoinID, MUN_1980to2000_QCSP.ShpCtyBsn,
MUN_1980to2000_QCSP.ID, MUN_1980to2000_QCSP.WUG_ID, MUN_1980to2000_QCSP.WUG_NAME,
MUN_1980to2000_QCSP.DATA_CAT, MUN_1980to2000_QCSP.WUG_RWPG,
MUN_1980to2000_QCSP.WUG_COUNTY_NAME, MUN_1980to2000_QCSP.WUG_BASIN_NAME,
```

```
MUN_1980to2000_QCSP.CITY_ID, MUN_1980to2000_QCSP.SO_TYPE_ID_NEW,
MUN_1980to2000_QCSP.watertype, MUN_1980to2000_QCSP.WUG_COUNTY_ID,
MUN_1980to2000_QCSP.WUG_BASIN_ID, MUN_1980to2000_QCSP.alphanum, MUN_1980to2000_QCSP.[Supplier
Information], MUN_1980to2000_QCSP.ADDRESS_LINE2, MUN_1980to2000_QCSP.SO_RWPG,
MUN_1980to2000_QCSP.SO_COUNTY_ID, MUN_1980to2000_QCSP.SO_BASIN_ID,
MUN_1980to2000_QCSP.AQUIFER_ID, MUN_1980to2000_QCSP.SO_ID, MUN_1980to2000_QCSP.SO_NAME,
MUN_1980to2000_QCSP.numwells, MUN_1980to2000_QCSP.YEAR,
MUN_1980to2000_QCSP.[MUNICIPAL_CITY(ACFT/YR)], MUN_1980to2000_QCSP.[MUNICIPAL_CITY(GAL/YR)],
MUN_1980to2000_QCSP![MUNICIPAL_CITY(GAL/YR)]*MUN_MonthlyFactorsperCBA!Jan AS Jan_inGallons,
MUN_1980to2000_QCSP![MUNICIPAL_CITY(GAL/YR)]*MUN_MonthlyFactorsperCBA!Feb AS Feb_inGallons,
MUN_1980to2000_QCSP![MUNICIPAL_CITY(GAL/YR)]*MUN_MonthlyFactorsperCBA!Mar AS Mar_inGallons,
MUN_1980to2000_QCSP![MUNICIPAL_CITY(GAL/YR)]*MUN_MonthlyFactorsperCBA!Apr AS Apr_inGallons,
MUN_1980to2000_QCSP![MUNICIPAL_CITY(GAL/YR)]*MUN_MonthlyFactorsperCBA!May AS May_inGallons,
MUN_1980to2000_QCSP![MUNICIPAL_CITY(GAL/YR)]*MUN_MonthlyFactorsperCBA!Jun AS Jun_inGallons,
MUN_1980to2000_QCSP![MUNICIPAL_CITY(GAL/YR)]*MUN_MonthlyFactorsperCBA!Jul AS Jul_inGallons,
MUN_1980to2000_QCSP![MUNICIPAL_CITY(GAL/YR)]*MUN_MonthlyFactorsperCBA!Aug AS Aug_inGallons,
MUN_1980to2000_QCSP![MUNICIPAL_CITY(GAL/YR)]*MUN_MonthlyFactorsperCBA!Sep AS Sep_inGallons,
MUN_1980to2000_QCSP![MUNICIPAL_CITY(GAL/YR)]*MUN_MonthlyFactorsperCBA!Oct AS Oct_inGallons,
MUN_1980to2000_QCSP![MUNICIPAL_CITY(GAL/YR)]*MUN_MonthlyFactorsperCBA!Nov AS Nov_inGallons,
MUN_1980to2000_QCSP![MUNICIPAL_CITY(GAL/YR)]*MUN_MonthlyFactorsperCBA!Dec AS Dec_inGallons,
MUN_1980to2000_QCSP.MonCalc
FROM MUN_1980to2000_QCSP INNER JOIN MUN_MonthlyFactorsperCBA ON MUN_1980to2000_QCSP.JoinID =
MUN_MonthlyFactorsperCBA.JoinID
WHERE (((MUN_1980to2000_QCSP.MonCalc)=Yes));
```

Results of this process are stored in the following database tables:

Input Database Table	Monthly Distribution Factors	Output Database Table
MUN_1980to2000_QCSP	MUN_MonthlyFactorsperCBA	MUN_1980to2000_QCSP_Final
MIN_1980to2000_QCSP	MIN_MonthlyFactorsperCBA	MIN_1980to2000_QCSP_Final
MFG_1980to2000_QCSP	MFG_MonthlyFactorsperCBA	MFG_1980to2000_QCSP_Final

Note that there were no water-use survey records for the Queen City or Sparta aquifers in the PWR use category therefore this record set is omitted from further processing.

2.6. Predict historical pumpage for 1998-2000 for IRR, STK, C-O use categories.

2.6.1. For the use categories IRR, STK, and C-O, groundwater use summaries are not reported for the years 1998 through 2000. The groundwater use for these years must be obtained by interpolation from existing data.

2.6.2. Prepare STK, IRR, and C-O tables for regression:

Use Category	Access Project Database Table
IRR	IRR_1980-1997
STK	STK_1980-1997
C-O	C-O_1980-1997

2.6.2.1. For each table, **MIN_1980to2000, MFG_1980-2000, PWR_1980-2000, CityMunicipal_1980to2000**, create a new make-table query that will select only those pumpage records reported for the aquifers of interest. The aquifers of interest include: Carrizo-Wilcox (10), Other (22), Queen City (24), and Sparta (27).

2.6.2.2. Create an identifier that will allow for the linkage between the database tables and the GIS county-basins shapefile using the following formula:

Shpctybsn =SO_COUNTY_ID* 1000 + SO_BASIN_ID

However, the C-O water survey records do not contain the fields **CO_COUNTY_ID** and **SO_BASIN_ID**. Instead these records contain only the **WUG_COUNTY_ID** and **WUG_BASIN_ID** fields. It was determined for all water use records:

SO_COUNTY_ID = WUG_COUNTY_ID and
SO_BASIN_ID = WUG_BASIN_ID

Therefore, the **WUG_COUNTY_ID** and **WUG_BASIN ID** fields were used in the formula above to generate the field **shpctybsn**.

2.6.2.3. Pivot tables were used to organize the non-point water use data by aquifer, year, and county-basin (**shpctybsn**) for the STK, IRR use categories and year, county-basin (**shpctybsn**) for the C-O use category. Note that there is no aquifer associated with pumpage records in the C-O water-use survey database.

2.6.3. Each county-basin was associated with the nearest weather gage using GIS.

2.6.4. Precipitation and temperature data were summarized by county-basin and various regressions were explored using the statistical software "R". It was determined that temperature was not correlated to pumping, thus temperature was ignored as a parameter.

2.6.5. A regression or extrapolation of data for years 1998, 1999, and 2000 was completed based on data from the previous 10 years (i.e. 1988-1997) for STK and IRR. A similar process was completed for C-O except using years 1985-1994 to predict data for 1995-2000 based on recommendation from TWDB staff for overcoming the anomaly in 1995 C-O pumpage data. Regression results are stored in the database tables: **IRRRegression**, **C-ORegression**, and **STKRegression**.

2.6.6. Create a make table query based on the original pumping data table (e.g. **IRR_1980-1997**), **qryIRR_1980to2000_QCSP**, restrict the data table to those records in the aquifers of interest Carrizo-Wilcox, Other, Queen City, and Sparta. In addition, create the shapefile county-basin join field **shpctybsn** and the unique id field **JoinId**. Create a **codectybsn** join field to be used temporarily to join the processed data for 1998 through 2000.

```
SELECT [IRR_1980-1997].ID, [IRR_1980-1997]!WUG_COUNTY_ID*1000+[IRR_1980-1997]!WUG_BASIN_ID
AS ShpCtyBsn, [IRR_1980-1997]!WUG_COUNTY_ID*1000000+[IRR_1980-
1997]!WUG_BASIN_ID*1000+[IRR_1980-1997]!AQUIFER_ID AS JoinId,
z_county!county_code*1000+[IRR_1980-1997]!SO_BASIN_ID AS CodeCtyBsn, [IRR_1980-1997].WUG_ID,
[IRR_1980-1997].WUG_NAME, [IRR_1980-1997].DATA_CAT, [IRR_1980-1997].WUG_RWPG, [IRR_1980-
1997].WUG_COUNTY_NAME, [IRR_1980-1997].WUG_BASIN_NAME, [IRR_1980-1997].CITY_ID,
[IRR_1980-1997].SO_TYPE_ID_NEW, [IRR_1980-1997].WUG_COUNTY_ID, [IRR_1980-
1997].WUG_BASIN_ID, [IRR_1980-1997].SO_RWPG, [IRR_1980-1997].SO_COUNTY_ID, [IRR_1980-
1997].SO_BASIN_ID, [IRR_1980-1997].AQUIFER_ID, [IRR_1980-1997].SO_ID, [IRR_1980-1997].SO_NAME,
[IRR_1980-1997].YEAR, [IRR_1980-1997].[IRRIGATION(ACFT/YR)], [IRR_1980-
1997].[IRRIGATION(GAL/YR)], [IRR_1980-1997].Comments INTO [IRR_1980-1997_QCSP] FROM [IRR_1980-
1997] INNER JOIN z_county ON [IRR_1980-1997].WUG_COUNTY_ID = z_county.old_code WHERE
((([IRR_1980-1997].AQUIFER_ID)=22 Or ([IRR_1980-1997].AQUIFER_ID)=24 Or ([IRR_1980-
1997].AQUIFER_ID)=27 Or ([IRR_1980-1997].AQUIFER_ID)=10));
```

2.6.7. Import the reformatted results for 1998 through 2000 for each use category (STK and IRR). Create an append query to append the records for the Queen City and Sparta aquifers, **qryIRR1998to2000**:

```
INSERT INTO [IRR_1980-1997_QCSP] ( CodeCtyBsn, ShpCtyBsn, JoinId, WUG_ID, WUG_NAME,
DATA_CAT, WUG_RWPG, WUG_COUNTY_NAME, WUG_BASIN_NAME, CITY_ID, SO_TYPE_ID_NEW,
WUG_COUNTY_ID, WUG_BASIN_ID, SO_RWPG, SO_COUNTY_ID, SO_BASIN_ID, AQUIFER_ID, SO_ID,
SO_NAME, [YEAR], [IRRIGATION(ACFT/YR)] ) SELECT DISTINCT sparta_irr.CodeCtyBsn, [IRR_1980-
1997_QCSP].ShpCtyBsn, [IRR_1980-1997_QCSP].JoinId, [IRR_1980-1997_QCSP].WUG_ID, [IRR_1980-
1997_QCSP].WUG_NAME, [IRR_1980-1997_QCSP].DATA_CAT, [IRR_1980-1997_QCSP].WUG_RWPG,
[IRR_1980-1997_QCSP].WUG_COUNTY_NAME, [IRR_1980-1997_QCSP].WUG_BASIN_NAME, [IRR_1980-
1997_QCSP].CITY_ID, [IRR_1980-1997_QCSP].SO_TYPE_ID_NEW, [IRR_1980-
1997_QCSP].WUG_COUNTY_ID, [IRR_1980-1997_QCSP].WUG_BASIN_ID, [IRR_1980-
1997_QCSP].SO_RWPG, [IRR_1980-1997_QCSP].SO_COUNTY_ID, [IRR_1980-1997_QCSP].SO_BASIN_ID,
```

[IRR_1980-1997_QCSP].AQUIFER_ID, [IRR_1980-1997_QCSP].SO_ID, [IRR_1980-1997_QCSP].SO_NAME, sparta_irr.YEAR, sparta_irr.[AcreFt/Yr] FROM sparta_irr LEFT JOIN [IRR_1980-1997_QCSP] ON (sparta_irr.AquiferID = [IRR_1980-1997_QCSP].AQUIFER_ID) AND sparta_irr.CodeCtyBsn = [IRR_1980-1997_QCSP].CodeCtyBsn)
GROUP BY sparta_irr.CodeCtyBsn, [IRR_1980-1997_QCSP].ShpCtyBsn, [IRR_1980-1997_QCSP].JoinId, [IRR_1980-1997_QCSP].WUG_ID, [IRR_1980-1997_QCSP].WUG_NAME, [IRR_1980-1997_QCSP].DATA_CAT, [IRR_1980-1997_QCSP].WUG_RWPG, [IRR_1980-1997_QCSP].WUG_COUNTY_NAME, [IRR_1980-1997_QCSP].WUG_BASIN_NAME, [IRR_1980-1997_QCSP].CITY_ID, [IRR_1980-1997_QCSP].SO_TYPE_ID_NEW, [IRR_1980-1997_QCSP].WUG_COUNTY_ID, [IRR_1980-1997_QCSP].WUG_BASIN_ID, [IRR_1980-1997_QCSP].SO_RWPG, [IRR_1980-1997_QCSP].SO_COUNTY_ID, [IRR_1980-1997_QCSP].SO_BASIN_ID, [IRR_1980-1997_QCSP].AQUIFER_ID, [IRR_1980-1997_QCSP].SO_ID, [IRR_1980-1997_QCSP].SO_NAME, sparta_irr.YEAR, sparta_irr.[AcreFt/Yr];

The following tables result from the procedure outlined above:

Input Database Table	Output Database Table
IRR_1980-1997	IRR_1980to2000_QCSP
STK_1980-1997	STK_1980to2000_QCSP
C-O_1980-1997	C-O_ 1980to2000

2.7. Temporally distribute STK, IRR, and C-O pumpage.

2.7.1. Temporal distribution of livestock pumpage was completed using the methods below. During database development, it was decided that an annual time step would be used for the groundwater model, thus temporal distribution of C-O and IRR water use categories was not completed for a monthly time step.

2.7.2. Livestock pumpage was provided in annual totals and monthly estimates for 1980-1997. Using methods outlined in Section 2.6 above, the annual pumpage was estimated for 1998 through 2000 using historical data. According to TWDB GAM Technical Memo 02-02, annual total livestock pumpage may be distributed uniformly to months.

2.7.3. In the project database select all of the records in the livestock pumping data table with null monthly pumping estimates and copy to a separate database table and remove these records from the livestock pumping table.

2.7.4. For all records with null monthly estimates, calculate the annual total pumping in gallons using the following equation:

$$\text{Livestock(gal/yr)} = \text{Livestock(acre ft/yr)} * 325851$$

2.7.5. Next, using the annual pumping in gallons per year, calculate the monthly estimates for January through December using the following equation:

$$\text{Month\_inGallons} = \text{Livestock(gal/yr)} / 12$$

2.7.6. Append these records back into the Livestock pumping data table with the following comment: “Annual pumping was distributed into monthly pumping evenly for each month of the year as per Tech-Memo 02-02”. The resulting table is **STK_1980to2000_QCSP**.

2.7.7. Finally, add a Boolean field **MonCalc** and toggle to yes for those records with the comment from Section 2.7.6. above.

2.8. Coordinates and projection

2.8.1. Longitude and latitude are provided in the source well tables in either of the following formats: DDMMSS (or degrees minutes seconds) or DD.DDDD (decimal degrees). Decimal degrees are readily converted to the custom Texas Albers projection using ArcToolbox **Project Shapefile** utility. If the DDMMSS format is provided, the degrees, minutes, and seconds must be parsed using the left, mid, and right functions in MS Excel or MS Access. Once parsed the following equation is applied to calculate DDLAT and DDLON:

DD.DD = ((SS/60)+MM)/60)+DD

2.8.2. All well locations have been provided in a geographic coordinate system with North American Datum 1983 (NAD83). The X- and Y-coordinates in the project coordinate system are added using ArcCatalog, ArcToolbox, and ArcView. Export the database table with at least one unique identifier field and the X- and Y-coordinate values in DDLON, DDLAT format to a dBase file. Open the file in ArcView and **Display the XY Events**. Export the resulting event theme to shapefile. Be sure to define the geographic coordinate system, NAD83. Using the **Project Shapefile** utility in ArcToolbox, project the wells into GAM Coordinate System. The GAM coordinate system is defined in ArcView as follows:

Projection: Albers Equal Area Conic
Units: Feet
Datum: NAD83
Spheroid: GRS80
1st Standard Parallel: 27 30 00 (27.50000)
2nd Standard Parallel: 35 00 00 (35.00000)
Central Meridian: -100 00 00 (-100.00000)
Latitude of Projection: 31 15 00 (31.25000)
False Easting: 4921250.00000 (US Survey Feet)
False Northing: 19685000.00000 (US Survey Feet)

2.8.3. Projection parameters are reviewed in GAM technical memo 01-01 (rev a) by Roberto Anaya (February 28, 2001). Add X- and Y-coordinate fields to the projected well file using ArcCatalog and edit the field values in ArcView. Calculate the value of the X coordinate using the following VBA code:

```
 Dim dblX As Double
 Dim pPoint As IPoint
 Set pPoint = [Shape]
dblX = pPoint.X
Value = dblX
```

2.8.4. Calculate the value of the Y coordinate using the same code, however substitute **pPoint.X** with **pPoint.Y**. The resulting fields will be the X- and Y-coordinates of the well features in the shapefiles defined coordinate system. For additional help with VBA for ArcView see ArcView desktop or on-line help. Store the well locations in the database in both geographic and Albers-custom coordinate systems.

3. Point Source Groundwater Use Categories (MFG, MIN, MUN, PWR)

Groundwater use from the categories MFG, MIN, MUN, and PWR is considered point source data to be matched with specific wells from which water is pumped. Annual and monthly reported groundwater withdrawal for these uses is provided for each water user, **alphanum** for each year from 1980 to 2000 in the water use surveys provided by the TWDB. Included for each record, is the county and river basin as well as the water user group ID, regional water planning group, number of wells from which water is drawn and the primary aquifer from which the groundwater was pumped. These water use survey tables do not indicate the specific location of the wells, well elevation, well depth, a specific aquifer name needed for groundwater modeling. Specific well data must be retrieved from other sources. The primary source of well data is the state well database (GWDB.mdb) maintained by the TWDB. Secondary sources include well data found in the TCEQ public drinking water supply database (PWDS), USGS site inventory, the EPA Envirofacts database and the OSHA Establishment Search. A supplemental source, the follow-up survey provided by the TWDB, was reviewed however, contained no additional information for the water users of the Queen City and Sparta aquifers. In the absence of well information, the withdrawal location may be approximated based on facility location, where available.

The water use surveys were summarized per use category per aquifer to get a sense of the number of water users and total number of pumping records per aquifer to guide the efforts of locating production wells. Aquifers of interest for the purpose of this exercise are the Carrizo-Wilcox (10), Other (22), Queen City (24), and Sparta (27). Note that "Other" aquifer in this case has been narrowed down to only those wells located within the model domain.

Power (PWR) Water Use Survey

Aquifer	Count Pump Recs.	Count County-Basins	Count User Groups (alphanum)	Min # of user groups per county basin	Max # of user groups per county basin
Carrizo-Wilcox (10)	271	15	18	1	2
Other (22)	27	2	2	1	1
Queen City (24)	0	0	0	0	0
Sparta (27)	0	0	0	0	0

Municipal (MUN) Water Use Survey

Aquifer	Count Pump Recs.	Count County-Basins	Count User Groups (alphanum)	Min # of user groups per county basin	Max # of user groups per county basin
Carrizo-Wilcox (10)	2137	51	109	1	6
Other (22)	302	11	18	1	5
Queen City (24)	41	2	2	1	1
Sparta (27)	84	4	4	1	1

Manufacturing (MFG) Water Use Survey

Aquifer	Count Pump Recs.	Count County-Basins	Count User Groups (alphanum)	Min # of user groups per county basin	Max # of user groups per county basin
Carrizo-Wilcox (10)	835	42	94	1	8
Other (22)	296	17	30	1	5
Queen City (24)	42	5	8	1	4
Sparta (27)	42	4	4	1	1

Mineral Extraction (MIN) Water Use Survey

Aquifer	Count Pump Recs.	Count County-Basins	Count User Groups (alphanum)	Min # of user groups per county basin	Max # of user groups per county basin
Carrizo-Wilcox (10)	702	37	61	1	7
Other (22)	13	3	3	1	1
Queen City (24)	30	3	3	1	1
Sparta (27)	24	3	5	1	2

The water use surveys summaries above show that there are very few user groups and thus wells to locate when considering the Queen City (24) and Sparta (27) aquifers exclusively. There are no PWR users withdrawing water from these two aquifers. There are two user groups in two county-basins withdrawing water from the Queen City (24) aquifer for municipal use. Likewise, there are four user groups in four county-basins withdrawing water from the Sparta (27) aquifer for municipal use. There are eight user groups in five county-basins withdrawing water from the Queen City (24) aquifer and four user groups in four county-basins withdrawing water from the Sparta (27) aquifer for manufacturing. Finally, there are three user groups in three county-basins withdrawing water from the Queen City (24) aquifer and 5 user groups in three county-basins withdrawing water from the Sparta (27) aquifer for mineral extraction. Water for each user group may be withdrawn from several wells. The next step is to link the water use survey data to individual well locations and ultimately assign this withdrawal to a model grid cell.

3.1. Locate MUN, MFG, and MIN production wells.

3.1.1. State Well Database and Municipal Water Use : TWDB GWDB

3.1.1.1. Download the state well database for from the TWDB website http://www.twdb.state.tx.us/publications/reports/GroundWaterReports/GWDatabaseReports/GWdatabaserpt.htm. Unzip and store a copy of the original database in a readily accessible location.

3.1.1.2. Import the following tables from the state well database (GWDB.mdb) into the project database: **z_welldata**, **z_welltype**, **z_wdremarks**, and **z_wateruse**. The **z_welldata** table contains all of the wells for the state of Texas and can be linked to the **alphanum** field of the pumping data tables using the **user_code_econ** field. The remaining three tables are lookup tables for values in the **z_welldata**.

3.1.1.3. To link water use records to state wells, create a query that relates the **alphanum** field of the water use survey table (e.g. **MUN_1980to2000_QCSP_Final**) to the **user_code_econ** field of the state well database table **z_welldata**. To check the number of water user-well matches made per aquifer the following query can be used:

```
SELECT MUN_1980to2000_QCSP_Final.alphanum, z_welldata.user_code_econ,
MUN_1980to2000_QCSP_Final.AQUIFER_ID  FROM z_welldata INNER JOIN MUN_1980to2000_QCSP_Final
ON z_welldata.user_code_econ = MUN_1980to2000_QCSP_Final.alphanum  GROUP BY
MUN_1980to2000_QCSP_Final.alphanum, z_welldata.user_code_econ,
MUN_1980to2000_QCSP_Final.AQUIFER_ID HAVING (((MUN_1980to2000_QCSP_Final.AQUIFER_ID)=24));
```

In this example, the query will identify all municipal water user groups for which a corresponding well is present in the state well database in the Queen City aquifer (24).

3.1.1.4. Each water-use survey record must be assigned to the location of the corresponding well or wells in the state well database. Using a make-table query to create a new table **MUNMatchPump**, all fields from the water use survey (**MUN_1980to2000_QCSP_Final**) are merged with all fields from the state well database (**z_welldata**) by joining the water user group, **alphanum** and **user code econ**, fields. In many cases, several different wells may have the same **user code econ**, making a one-to-many match (this is expected, since one city may own multiple wells). Add a flag field to track records that should be deleted prior to permanent removal. In addition, add a **Source** field to track the source of the well location data. For each of these records **Source** = “TWDB GWDB”.

3.1.1.5. Check the resulting table (**MUNMatchPump**) to ensure that the wells are of the appropriate type (e.g., primary water use = "public supply" or "unused" for MUN use) and the well drill date precedes the withdrawal date. If a well is drilled in the middle of a year, assume that pumping begins in the following year. Next, verify that the aquifer listed in the state well database agrees with that in the water use survey. There are three fields in the state well database table, **z_welldata**, that contain information regarding the aquifer: **aquifer_id1** (primary aquifer), **aquifer_id2** (secondary aquifer), and **aquifer_id3** (tertiary aquifer). Finally, review the well remarks table, **z_wdremarks**, for indication of a cessation in withdrawal from a well using the following query for example:

```
SELECT MUNMatchPump.state_well_number, z_wdremarks.group_number, z_wdremarks.remarks_1,
z_wdremarks.remarks_2 FROM MUNMatchPump LEFT JOIN z_wdremarks ON
MUNMatchPump.state_well_number = z_wdremarks.state_well_number GROUP BY
MUNMatchPump.state_well_number, z_wdremarks.group_number, z_wdremarks.remarks_1,
z_wdremarks.remarks_2;
```

3.1.1.6. As a final quality assurance measure, the locations of individual wells are plotted in a GIS. A table of unique well locations is generated from the **MUNMatchPump** table. The following query is run to construct the **MUNWells** table:

```
SELECT MUNMatchPump.state_well_number, MUNMatchPump.LatCalc, MUNMatchPump.LongCalc,
MUNMatchPump.own1, MUNMatchPump.[Supplier Information], MUNMatchPump.ADDRESS_LINE2,
MUNMatchPump.SO_COUNTY_ID, MUNMatchPump.SO_COUNTY_ID, MUNMatchPump.AQUIFER_ID,
MUNMatchPump.aqfid1 FROM MUNMatchPump GROUP BY MUNMatchPump.state_well_number,
MUNMatchPump.LatCalc, MUNMatchPump.LongCalc, MUNMatchPump.own1, MUNMatchPump.[Supplier
Information], MUNMatchPump.ADDRESS_LINE2, MUNMatchPump.SO_COUNTY_ID,
MUNMatchPump.SO_COUNTY_ID, MUNMatchPump.AQUIFER_ID, MUNMatchPump.aqfid1;
```

The resulting table of wells is imported into ArcView and displayed with the state municipality coverage (**cities_urban_tx.shp**), the county-basin shapefile (**CtyBsn.shp**), and the aquifer extents (**minor_aquifers.shp**). Well locations are compared with these GIS layers to ensure agreement.

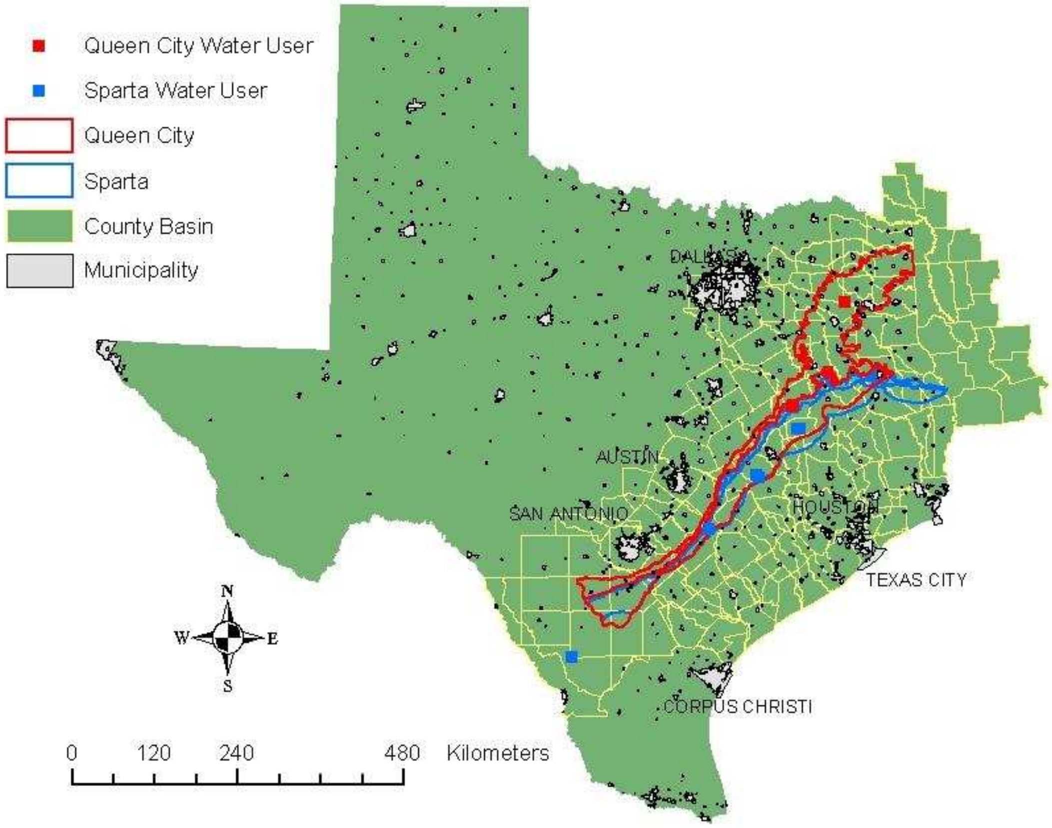

Figure 1. Location of Municipal Water Users' Wells (Queen City = 2 user groups, Sparta = 4 user groups).

3.1.1.7. Using this method, all of the municipal water use records for the Queen City (24) and Sparta (27) aquifers were matched to at least one well record in the state well database. In some cases, multiple wells were identified. Manufacturing and mineral extraction water user groups for the Queen City (24) and Sparta (27) aquifers were not matched to any wells in the state well database by the water user group criteria alone.

3.1.2. State Well Database, Manufacturing, and Mineral Extraction Water Use: TWDB GWDB

3.1.2.1. The water user groups, **alphanum**, in the manufacturing (MFG) and mineral extraction (MIN) use categories are not listed in the corresponding **user_code_econ** field of the state well database (GWDB) well table **z_welldata**. Therefore to find these wells, limit the list to the aquifer of interest (e.g. 24 for Queen City) and search for the source county-basin and **supplier information** in the appropriate fields of the state well database table. Take note of any wells that are within the same county-basin to further inspect locations using GIS. If an owner is identified, record the **alphanum** of the water use survey records into the **user_code_econ** of the **z_welldata** table to facilitate the creation of the **MFGPumpMatch** and **MINPumpMatch** database tables. Verify the use codes prior to updating the water user group, **user_code_econ**.

3.1.2.2. If unmatched withdrawal records remain, lift the aquifer constraint on the state well table, **z_welldata**, and search for the **supplier information** in the **own1** and **own2** fields. If a match is found, verify the county-basin prior to updating the water user group, **user_code_econ**. Matched wells can be used to generate **MFGMatchPump** and **MINMatchPump** in the same way that **MUNMatchPump** is constructed.

3.1.3. Public Drinking Water Supply Database: TCEQ PDWS

3.1.3.1. To receive data from the public drinking water supply database a written request on company letter head must be sent to TCEQ along with a project description including the purpose of the data request. Send the letter to:

Public Drinking Water Section MC 155
Texas Commission on Environmental Quality
PO Box 13087
Austin, TX 78711-3087
Attn: Mr. John Meyer

3.1.3.2. In response to this request, the TCEQ sent a CD-ROM containing a database (dbPDWS_GAM.mdb) and database schema diagram. Before any extensive work was completed with this dataset, a preliminary search was done for pumping records lacking a corresponding well in the state well database. A quick search by owner revealed that remaining MFG and MIN pumping records were not available in the public water supply database.

3.1.4. EPA Envirofacts, Manufacturing and Mineral Extraction Use: EPA Envirofacts

3.1.4.1. The EPA Envirofacts facility database can be queried on-line at http://www.epa.gov/enviro/html/fii/fii_query_java.html. A search for a county in the state of Texas will reveal all of the noted facilities within the county. This list can be reviewed for **supplier information** and **address_line2** values. The location of a facility can be found in the **Facility Detail Report**. Latitude and longitude are provided where available. In some cases this coordinate value is approximated by a zip code centroid. Thus, a better location may be obtained. However, it is better to use this approach rather than omitting the withdrawal from the model entirely. In some cases, coordinates are not provided but a street address is available. This data can be used to geocode facility locations.

3.1.4.2. Create a database table, identical in structure to the **z_welldata** table, called **AddWells**. For well locations found via this method add corresponding records to the **AddWells** table providing as much well data as possible. Add a **Source** field to this table and add the value “EPA Envirofacts” for all wells identified in this database.

3.1.5. For remaining withdrawal records that cannot be located, try an establishment search on the U.S. Department of Labor website (http://www.osha-slc.gov/cgi-bin/est/est1) or via a business search on www.switchboard.com for example. Though these sources provide street addresses, this data can be used to geocode a facility location.

3.1.6. Unique well locations were queried for each of the use categories MFG and MIN. These wells were displayed and locations were verified using GIS.

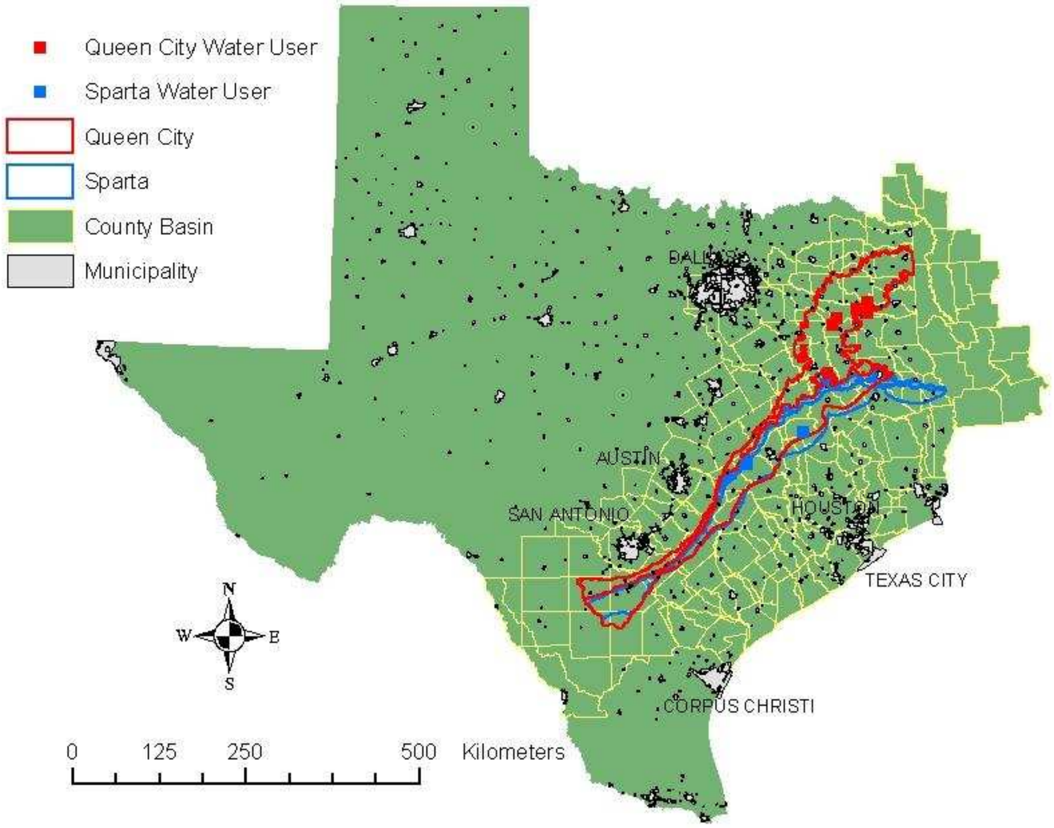

Figure 2. Location of Manufacturing Water Users' Wells (Queen City = 3 user groups, 5 wells Sparta = 2 user groups, 3 wells).

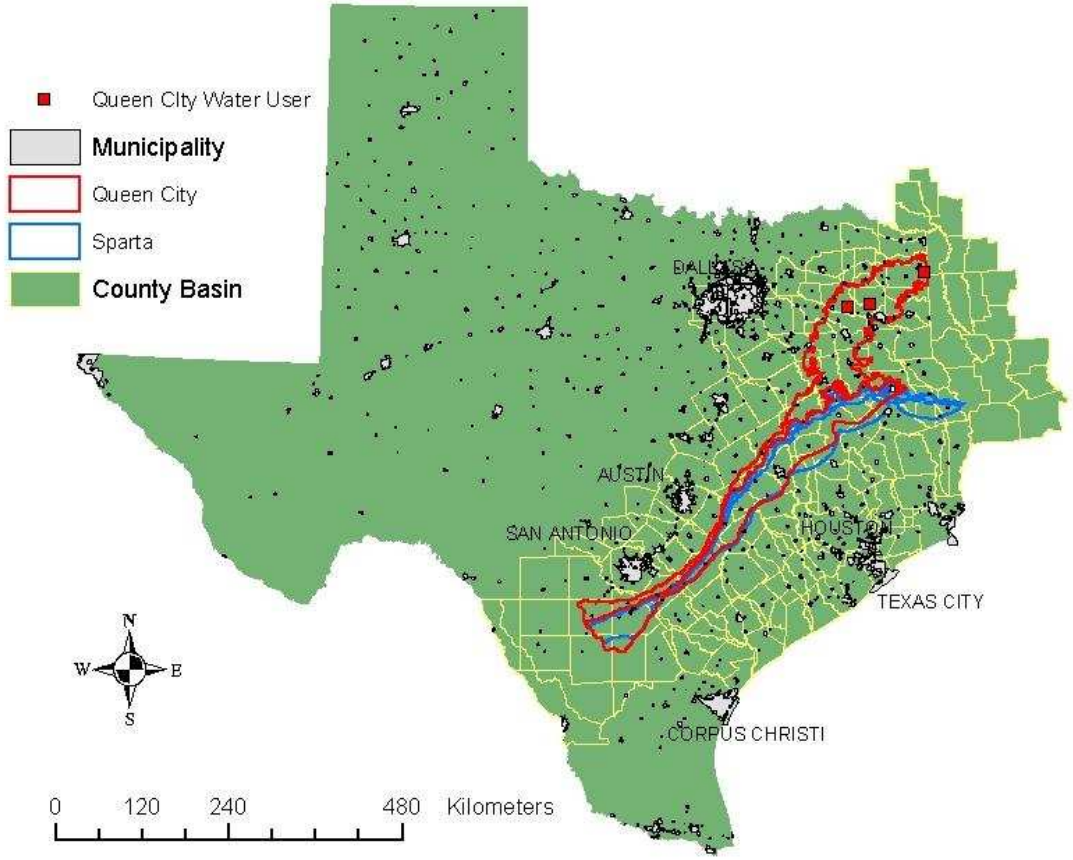

Figure 3. Location of Mineral Extraction Water Users' Wells (Queen City = 3 user groups)

3.2. Review matched wells. The following table displays the percentage of withdrawal from each aquifer per use category that was not assigned to a specific point of withdrawal, or well, using any of the above databases.

Table: Percent Reported Withdrawal from the Queen City Aquifer (24)

Use Category	% Located	% Not Located	Total Withdrawal (gal/yr)
Municipal (MUN)	100	0	2,616,631,067
Manufacturing (MFG)	76	24	471,082,600
Mineral Extraction (MIN)	100	0	6,704,558,571

Table: Percent Reported Withdrawal from the Sparta Aquifer (27)

Use Category	% Located	% Not Located	Total Withdrawal (gal/yr)
Municipal (MUN)	100	0	9,733,591,703
Manufacturing (MFG)	80	20	1,542,423,790
Mineral Extraction (MIN)	0	100	37,408,200

3.2.1. Detailed county-basin maps were generated to try and identify any missing well locations. The USGS site inventory data (http://waterdata.usgs.gov/tx/nwis/inventory) was posted on the maps, however there is little available to validate a potential match to this dataset.

3.3. Methods for locating remaining withdrawal

3.3.1. Match pumping to a street address. Download TIGER data from the US Census Bureau website (http://www.census.gov/prod/cen2000) Load this dataset into ArcView and run preliminary queries to determine potential geocode address matches. Street addresses of interest were not found in the TIGER Line file thus there we no wells located using this technique. However, if data are available, this is the recommended approach for approximating well locations.

3.3.2. Match pumping to a zip code centroid. A table of zip codes and corresponding zip code region centroid locations can be downloaded from the US Census Bureau website (http://www.census.gov/geo/www/tiger/zip1999.html). Import this table into the project database and query the appropriate zip codes to determine the zip code centroids for a given water user group. The zip code file contains 5-digit zip codes for Texas defined as of November 1, 1999. The location in the zip code file is developed using the Bureau TIGER database.

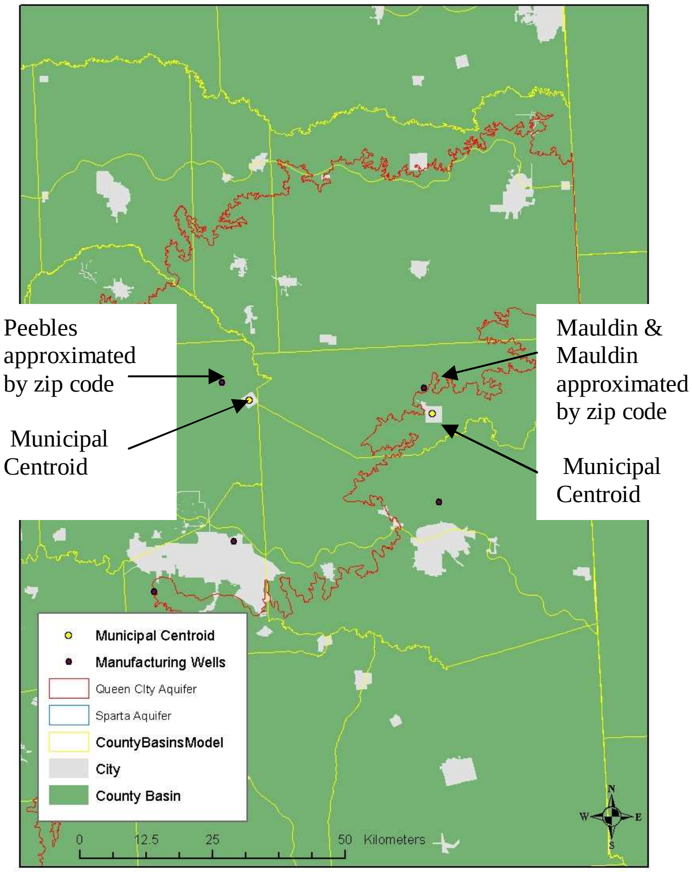

Figure 4. Well Locations for Water Users Groups: Zip code vs. Municipal Centroids.
The map above shows the two water user groups for which
both zip code and municipal centroids were found.

3.3.3. Match Pumping to a Municipal Centroid. Create centroids of the municipal coverage (**cities_urban_tx.shp**), obtained from the TWDB website, using ArcView XTools Shape to Centriod tool. Add two fields to the resulting city centroids shapefile (**citycenter.shp**) and calculate the X- and Y-coordinates. Import the associated dBase file (**citycenter.dbf**) into the project database. Query this database table for a particular city name and copy the coordinate values into a new table for each water user (see example below).

ShpCtyBsn	AQUIFER_ID	Supplier Information	X	Y
21012	27	NORTHRUP GRUMMAN	6081424.19817654	19489579.612124
89018	27	CAL-MAINE FOODS	5716589.51868412	19040040.65322
102004	24	WRIGHT WASHATERIA	6658126.47303317	20225563.866659
158004	24	MAULDIN & MAULDIN LUMBER CO	1528379.07463753	1189960.9952
212006	24	BORAL BRICKS, HENDERSON DIVISION	1430636.1252	1157554.3725
212006	24	TEXAS PARKS & WILDLIFE DEPT.	6376349.13687689	20091648.398229
230004	24	PEEBLES LUMBER COMPANY	1493719.0396	1192672.6432

Additional municipal locations can be queried from the USGS Geographic Names Information System (http://geonames.usgs.gov).

3.3.4. Match Pumping to a County Basin Centroid. If no other location source is available, a water user may be mapped to the centroids of the source county-basin from which water is withdrawn. Though this method can be misleading it is perhaps better than omitting the withdrawal from the model entirely. Using this method, 100% of the remaining unallocated pumping was allocated for each use category for the Queen City and Sparta aquifers. Create centroids of the county-basin shapefile (**ctybsn.shp**) using

ArcView **XTools Shape to Centroid** tool. Add two fields to the resulting county-basin centroids shapefile (**ctybsncenter.shp**) and calculate the X- and Y-coordinates. Import the associated dBase file (**ctybsncenter.dbf**) into the project database. Query this database table for a particular county-basin and copy the coordinate values into a new table for each water user (see example above).

Five mineral extraction water user groups withdrawing water from Sparta aquifer, constituting 100% of the total withdrawal* from this aquifer were located using centroids

Supplier	Water User Group (alphanum)	County Basin Centroid	Municipal Centroid
Union Pacific Resources	146444		X
Union Pacific Resources	146470	X	X
Texaco, USA Burleson	322910	X	
Home Petroleum Corp	392780	X	X
Sun Exploration and Production	830215	X	

Five manufacturing water user groups withdrawing water from the Queen City aquifer, constituting 24% of the total withdrawal* from this aquifer were located using centroids.

Supplier	Water User Group (alphanum)	County Basin Centroid	Municipal Centroid	ZipCode Centroid
Boral Bricks, Henderson Division	380608		X	
Mauldin & Mauldin Lumber	543802		X	X
Peebles Lumber Co	654391		X	X
Texas Parks and Wildlife – Smith Co. Fish Hatchery	854207	X		
Wright Washateria	957570	X		

Two manufacturing water user groups withdrawing water from the Sparta aquifer, constituting 20% of the total withdrawal* from this aquifer were located using centroids.

Supplier	Water User Group (alphanum)	County Basin Centroid
Cal-Maine Foods	129601	X
Northrup Grumman	931897	X

*As reported in the water use surveys.

3.4. Apportion water use between matched wells

3.4.1. For that water use matched to more than one well, compare the number of matched wells to the number of wells reported as used in the water use survey. If the number of matched wells exceeds the number reportedly used, inspect the well data, including the county, basin, aquifer, well type, drill date, and other fields to see if some of the wells can be excluded from consideration as the source form which the water was reportedly pumped. If so, remove that well from the table.

3.4.2. Next, apportion the reported pumpage among the wells matched. Since data does not indicate otherwise, pumpage is divided equally between wells. Create a new query that 1) adds a column to the **MatchPump** tables indicating the number of wells matched to the table (**wellsmatch**), and 2) if one or more wells are matched, divide the reported pumpage in the fields **annual total in gallons** and **jan** – **dec** by the number of wells matched.

3.4.3. To check for error summarize total annual water use by county-basin-year in the **MatchPump** tables. Make sure that these match the corresponding totals from the original source tables (i.e., **MUN_1980-2000_QCSP**). If not, correct the situation, which may occur by double-matching some water use records to wells.

3.5. Calculate additional fields

3.5.1. Calculate latitude and longitude as decimal degrees from degrees-minutes-seconds in new fields **DDLAT** and **DDLON**. Also in the same query, calculate water use in acre-feet from gallons in new fields **AcreFt**, **JanAcreFT**, **FebAcreFt**,…., **DecAcreFt**.

3.6. Summarize well-specific matching completeness. Perform queries to calculate the sum of matched water use by county-basin-year, and the total water use (matched and unmatched) by county-basin-year. Based on these queries, calculate the volumetric percent completeness of matching by county, basin, and year. Completeness should be high (e.g., >90%) to facilitate accurate accounting for water use in the model. One hundred percent of the pumpage from the Queen City and Sparta aquifers was matched to at least one well location or approximate location.

3.7. Arkansas pumping and well data preparation and well location

3.7.1. The file **Miller Co 85-00.txt**, sent from Mike Guess of Arkansas Soil and Water Conservation Commission on 4/15/03, contains all of the pumping data for Miller County, Arkansas for 1985 - 2000. All pumpage is matched to a water supply well in this file. Each record has geographic coordinates provided in DDMMSS (degree, minutes, and seconds) format. See Section 2.8 for information regarding coordinate value processing and projections.

3.7.2. The data table was provided in a flat table structure and imported into the project database (**tblASWCCGwWell**), thus spatial matching was already provided. Though major suppliers are identified, there is no information on individual domestic water users. For ease of use in ArcView the well data was extracted into a separate table containing one record per well (**tblASWCCGwWellChr**). The time series information was retained in a time series table (**tblASWCCGwWellTS**). The tables are related by the **Owner ID #**.

3.7.3. The Sparta and Claiborne aquifers supply the public water system in Miller County, Arkansas. No additional point source water use categories (PWR, MFG, or MIN) are reported in this county. The original table was filtered to retain only wells and pumping from the Sparta (124SPRT) and Claiborne (124CLBR) aquifers. Two new database tables were added containing only those records from the aquifers of interest (**tblASWCCGwWellChrSP** and **tblASWCCGwWellTSSP**) Of the original 105 wells, only two withdraw from the Sparta aquifer and one withdraws from the Claiborne aquifer. Further inspection reveals that only one of the wells contains non-zero pumping values. Records for the two wells containing zero reported pumping were eliminated from the database table. Data were provided from 1985 through 1999. It is assumed that pumping from 1980 through 1984 is zero, as is the case for 1985 through 1987. Data were disaggregated to monthly values based on the monthly distribution factor from the nearest Texas county-basin unit having withdrawal from the same aquifer, Sparta, for the same use category, MUN.

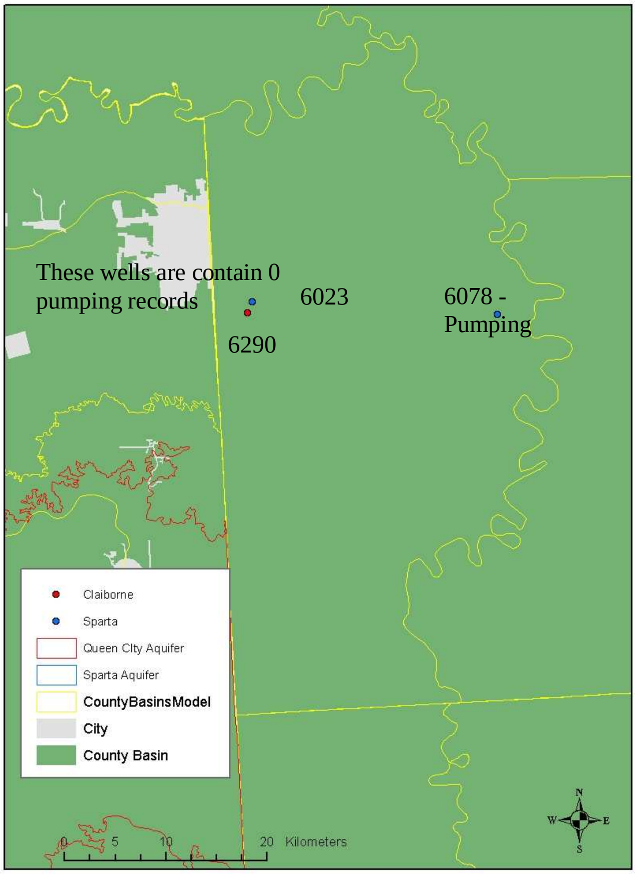

Figure 5. Sparta and Claiborne Production Wells in Miller County, Arkansas.

3.8. Louisiana pumping and well data preparation and well location

3.8.1. A file containing Sparta aquifer water use per category per parish per year, **qryDataRequestForSparta.xls** was sent by Pierre Sargent of the US Geological Survey, Baton Rouge Louisiana, on March 31, 2003. In general, data in this table are provided for 1980, 1985, 1989, 1994, and 1999. Data table fields include: Parish, Aquifer, Use Category, Amt (MGD). Use categories provided include Aquaculture, General Irrigation, Industry, Livestock, Power Generation, Public Supply, Rice Irrigation and Rural Domestic.

3.8.2. A second spreadsheet including Cane River water use, **CRVRPumpage.xls**, was provided by Pierre Sargent of the US Geological Survey, Baton Rouge Louisiana, on April 29, 2003. This table includes the fields: Aquifer Code (124CRVR), Parish, Category, Year, Pumpage (Mgal/day).

3.8.3. These spreadsheets were imported into the project database (**LADOTD**). A query was employed to limit the Louisiana withdrawal data to that within the model domain or Caddo, Sabine, and Natchitoches.

3.8.4. Time series data were generally maintained and provided about every five years. In some cases, aquifer specific withdrawal data were not provided for a given year. In these cases, historical water use data was used to estimate withdrawal for the Cane River Formation or Sparta Aquifer for “missing” years. Total historical ground and surface water use, **HistoricData65-Present.xls**, was provided per water use category per parish for the years: 1960, 1965, 1970, 1975, 1980, 1985, 1990, and 1995. This workbook is made up of two spreadsheets for each use category: one surface-water and one groundwater withdrawals. Each spreadsheet contains historical data as the total withdrawal per county per use. Aquifer specific withdrawal is not provided but can be estimated based on known withdrawals in other years. Methodology for this estimated withdrawal allocation is preserved in the database table **Sparta-CRVR_pumpingCalcs**. An additional field (**Est**) was added to the database table (**LADOTD**) to store comments pertaining to an estimation approach (e.g. "Estimated as 23.7% of 1980 total of 0.36", or "Estimated as 0"). Finally, linear interpolation was employed to develop annual withdrawal data from the five year data. Interpolated values are flagged, "Linear Interpolation" in the appropriate field (**Est**). In addition the delta X, delta Y, and DY/DX are stored in the database table (**LADOTD**) for each interpolated record. Withdrawal time series data were separated by use category prior to point and non-point source spatial matching. LADOTD use categories were matched to corresponding GAM water use categories using the following table (**tblLADOTDUse**):

LADOTD	GAM
Aquaculture	LIVESTOCK
General irrigation	IRRIGATION
Industry	MANUFACTURING
Livestock	LIVESTOCK
Public supply	MUNICIPAL
Rice Irrigation	IRRIGATION
Rural domestic	COUNTY-OTHER

3.8.5. Query the water-use records for each individual use category and store each in a separate database table.

Water Use Category	Louisiana Pumpage Table
MUN	tblLADOTDPumpMUN
MFG	tblLADOTDPumpMFG
IRR	tblLADOTDPumpIRR
C-O	tblLADOTDPumpC-O
STK	tblLADOTDPumpSTK

3.8.6. Louisiana well data was downloaded from http://www.dotd.state.la.us/intermodal/wells/home.asp. All wells were downloaded one township at a time. Each file was imported into the project database. X- and Y-coordinates were provided in longitude/latitude DDMMSS (degree, minutes, and seconds) format. See Section 2.8. for information regarding coordinate value processing. Data was queried so as to retain wells from which withdrawal is made for the point source use categories (MUN, MFG) in Sabine, Caddo, and Natchitoches parishes from the Sparta (124SPRT) or Cane River (124CRVR) geologic units. Manufacturing wells are stored in **tblLADOTDWellMFG** while municipal supply wells are stored in **tblLADOTDWellMUN** in the project database.

3.8.7. Match pumpage records to all LA wells based on aquifer and parish. Create a table of results and add a field **YRDelete**, a Boolean field to track date violations. For example, if a well is pumped before it is installed (pump date < drill date) or after it is abandoned (pump date > abandoned date). Quality check each well for year violations and flag appropriate records. Delete these records from the table and count the number of wells matched per parish per year. Record this value in a new column **wellmatch**. Apportion pumping evenly among all wells of a particular use category, per county per aquifer, provided they are active. Store manufacturing well – water use matches in **tblLADOTDPumpMFG** and municipal supply matches in **tblLADOTDPumpMUN**. Quality check all remark fields.

3.8.8. For pumping records unmatched to the public water supply wells provided, look for towns, or municipal centroids, within the Sparta aquifer outcrop. The municipal centroids for Rodessa and Ida were used to allocate municipal withdrawal in Louisiana. Withdrawal should be evenly distributed to the appropriate municipal wells or centroids per parish-aquifer.

3.9. Spatial Allocation of Groundwater Pumpage to the Model Grid. Each model grid is comprised of an equal-spaced grid with a size of one mile by one mile. The grid has 3 dimensions- row, column, and model layer.

Each cell of the model grid is labeled with a 7-digit integer **grid_id**. The first digit represents the model layer. Digits 2 through 4 represent the row number. Digits 5 through 7 represent the column.

3.9.1. This section describes the spatial allocation of well-specific groundwater pumpage from the categories MUN, MFG, and MIN to each of the model grids: central, northern and southern (CMG, NMG, SMG).

3.9.2. Individual well records are stored in the following database tables:

Database Table	**Table Description**
MFGWells	Manufacturing wells with matched withdrawal records
MINWells	Mineral extraction wells with matched withdrawal records
MUNWells	Municipal supply wells with matched withdrawal records
tblLADOTDWellMFG	Louisiana manufacturing wells with matched withdrawal records
tblLADOTDWellMUN	Louisiana municipal supply wells with matched withdrawal records
tblASWCCGwWellChrSP	Arkansas wells with matched withdrawal records

3.9.3. Plot wells from each of the tables listed above in ArcView. If not already done, be sure to project the wells shapefiles into the GAM coordinate system and add X- and Y-coordinate values to associated attribute tables and corresponding database table. For more information regarding projections and coordinate processing see Section 2.8.

3.9.4. Load each model grid shapefile into the ArcView map document. Intersect each of the well tables with each of the model domains and maintain attributes for row, column, and layer for each model grid (e.g. **Row_NMG**, **Col_NMG**, **Layer_NMG**).

3.9.5. Import the resulting attribute tables for each of the well tables into the project database and using an update query, append the model row, column, and layer values into the corresponding well table.

Use Category	Database Table Containing Wells with Matched Withdrawal	Database Table Containing Unique List of Wells
Manufacturing (MFG)	MFGMatchPump	MFGWells
Mineral Extraction (MIN)	MINMatchPump	MINWells
Municipal (MUN)	MUNMatchPump	MUNWells
Louisiana Manufacturing (MFG)	tblLADOTDPumpMFG	blLADOTDWellMFG
Louisiana Municipal (MUN)	tblLADOTDPumpMUN	tblLADOTDWellMUN
Arkansas Municipal (MUN)	tblASWCCGwWellTSSP	tblASWCCGwWellChrSP

3.9.6. Refer to section 5 for vertical allocation procedure, or the assignment of the model layer property.

3.9.7. Lastly, for each use category and model grid combination, create a query to join the model grid cell properties (e.g. **ROW_CMG**, **COL_CMG**, and **LAYER_CMG**) in the wells table (e.g. **MFGWells**) to the corresponding water use records in the matched pumpage table (e.g. **MFGMatchPump**). Summarize the results by row, column, layer, and year and append these summarized records to a new database table (e.g. **MFG_CMG**). This summarized result represents the total withdrawal from a grid cell for each use category. The following database tables result:

Use Category	Model Grid	Database Table with Allocated Well-Specific Pumping
Manufacturing (MFG)	Central (CMG)	MFG_CMG
Manufacturing (MFG)	Northern (NMG)	MFG_NMG
Manufacturing (MFG)	Southern (SMG)	MFG_SMG
Louisiana Manufacturing (MFG)	Northern (NMG)	MFG_LA_NMG
Municipal (MUN)	Central (CMG)	MUN_CMG
Municipal (MUN)	Northern (NMG)	MUN_NMG
Municipal (MUN)	Southern (SMG)	MUN_SMG
Louisiana Municipal (MUN)	Northern (NMG)	MUN_LA_NMG
Arkansas Municipal (MUN)	Northern (NMG)	MUN_AR_NMG
Mineral Extraction (MIN)	Central (CMG)	MIN_CMG
Mineral Extraction (MIN)	Northern (NMG)	MIN_NMG

3.9.8. Note there is no mineral extraction withdrawal in the southern model domain, Louisiana, or Arkansas.

3.9.9. Finally, compile all of the northern model grid tables into one per use category summarizing withdrawal by row, column, layer, and year (e.g. **MFG_NMG**, **MUN_NMG**, **MIN_NMG**).

4. Non-Point Source Groundwater Use Categories (IRR, STK, C-O)

4.1. Prepare the county-basin coverage for non-point water use spatial allocation

4.1.1. For non-point water-use spatial allocation the county-basin must be used in conjunction with at least one additional coverage. It is important to note that non-point groundwater use should not be allocated to areas of open water or to municipalities. Instructions for the preparation of the county-basin coverage for non-point water use allocation are provided below.

4.1.1.1. Merge polygon shapefiles representing Texas, Arkansas, and Louisiana lakes and reservoirs (**reservoirs_gam.shp**, **reservoirs_ar.shp**, **lakes_ar.shp**, and **reservoirs_la.shp**) to create a reservoirs shapefile using the Geoprocessing Wizard.

4.1.1.2. Merge polygon shapefiles representing Texas, Arkansas, and Louisiana municipalities (**cities_urban_tx.shp**, **cities_urban_ar.shp**, and **citiesla.shp**) to create a municipality shapefile using the Geoprocessing Wizard.

4.1.1.3. Clip the county-basin shapefile with the reservoirs and municipalities shapefiles from the two previous steps. The resulting shapefile (**CtyBsnMod.shp**) will be referred to as "the county-basin coverage" used for all non-point water-use spatial allocation.

4.2. Spatial allocation of livestock groundwater pumpage. Technical Memo 02-02 states that livestock groundwater use must be evenly distributed to all rangeland within each county-basin. Though all livestock groundwater use can be allocated to rangelands in the southern model domain, there are some county-basins reporting livestock withdrawal in the northern and central domains for which rangeland is not present in the LULC dataset. Figure 6 show the rangeland distribution over the three model domains. There is a distinct line where rangeland density decreases in the central model domain resulting in a low density of rangeland in eastern Texas according to LULC data. Livestock withdrawal was distributed to the appropriate aquifer outcrop within each county-basin reporting withdrawal for which there is no rangeland. Additionally, there are two county-basins, both in the northern and central model domains, for which neither rangeland nor the appropriate outcrop are present. In these cases, the livestock water use was allocated to the appropriate aquifer extent.

4.2.1. Preparation of the rangeland shapefile for livestock water use distribution.

4.2.1.1. Livestock groundwater use within each county-basin is distributed evenly to all rangeland: Anderson Level II land use codes 31 (herbaceous rangeland), 32 (shrub and brush rangeland), and 33 (mixed rangeland) of the USGS 1:250,000 GLIS land use land cover data set (http://edcwww.cr.usgs.gov/glis/hyper/guide/1_250_lulc), where possible.

4.2.1.2. In ArcView, create a rangeland-only land use shapefile by loading the USGS land use shapefiles by quadrangle, merging them as required to cover the model domain, selecting the land use codes 31, 32, and 33 in a query, then saving the theme as a new shapefile **Rangeland.shp**.

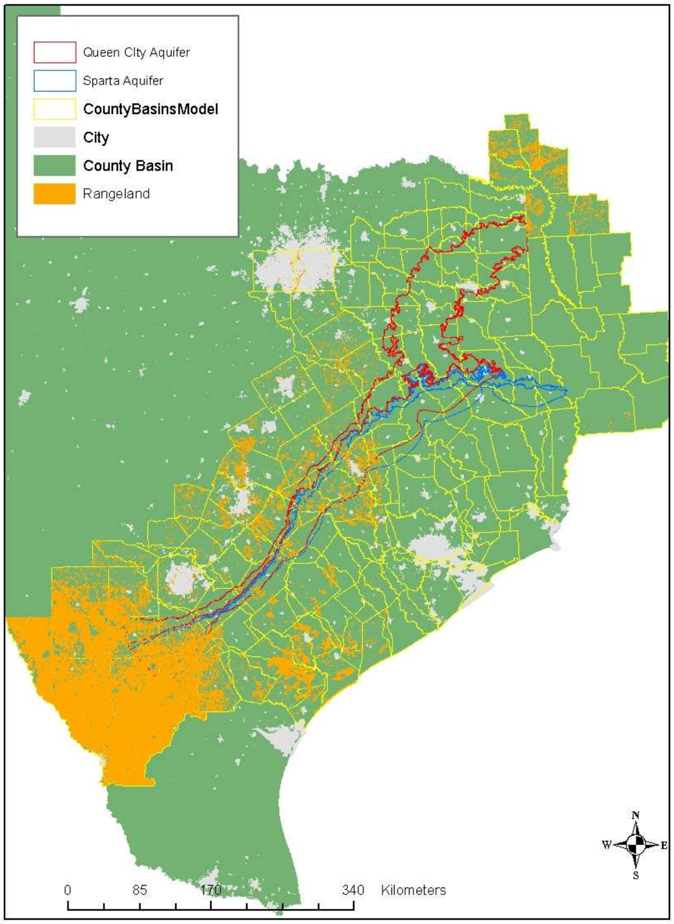

Figure 6. Rangeland in Texas, Arkansas, and Louisiana.
(Rangeland in Texas and Louisiana include land use codes 31 (herbaceous rangeland), 32 (shrub and brush rangeland), and 33 (mixed rangeland);
Arkansas rangeland is denoted by the group "Herbaceous/pasture/forage".)

4.2.1.3. Using the Geoprocessing Wizard, intersect the Rangeland shapefile with the county-basin shapefile (make sure to use **CtyBsnMod.shp**) to make a new shapefile **range_countybasin.shp**.

4.2.1.4. Calculate the unique area (in square miles) of the new intersected polygons, **area_un1**, using the field calculator (area_un1=shape.returnarea/27878400).

4.2.1.5. Summarize the unique area by county-basin (total area of rangeland within county-basin) using the summary button.

4.2.1.6. Link the summary table back to the **range_countybasin.shp** and migrate it into a new field, **rg_cb_tot**, using the field calculator.

4.2.1.7. Determine weighted area factor, **w_area1**, for each polygon using the field calculator (w_area1=area_un1 / rg_cb_tot). **W_area1** is, for each rangeland polygon, the fraction of the total rangeland area within the county-basin.

4.2.2. Intersect the rangeland/county-basin polygons with the Northern, Central, and Southern model grids and set up for unique pumpage calculations.

4.2.2.1. Using the Geoprocessing Wizard, intersect the shapefiles range_countybasin and Northern, Southern, and Central Model Grids to create a new shape files:

Model Grid	Rangeland-County-Basin-Grid file
Northern	rng_cb_Nmg.shp
Central	rng_cb_Cmg.shp
Southern	rng_cb_Smg.shp

4.2.2.2. Calculate the unique area of "intersected" polygons, **area_un_grid**, using the field calculator (area_un_grid=shape.returnarea/27878400). Double check that no values are greater that 1.

4.2.2.3. Determine the weighted area factor, **w_area_grid**: (w_area_grid = area_un_grid/area_un1).

4.2.3. Calculate unique withdrawal for each grid cell for every year (80-00).

4.2.3.1. At this point, we need to ensure that we don't allocate pumping to areas of the active aquifer that are unlikely to have pumping, i.e. below the bad water line. Grids were created that define the "actively pumped" portion of each layer, for each model. This "actively-pumped" area is bounded by the updip limit of the aquifers and the TWDB defined bad water line. A grid would consist of all of the model cells in all layers, with a 1 or a 0 defining whether the cell is likely to be actively pumped.

4.2.3.2. Because it is difficult to carry fractions of cells, given the differing actively pumped areas for each model grid, we summed the weights for each grid cell to yield a single weight for each block for each layer.

4.2.3.3. Again, to keep everything on a grid cell basis, we developed a county basin – gridblock coverage for each model that defined which cells were in each county-basin. We did not carry fractions of cells, i.e. each cell is in one county-basin only. The error created by this should be small over the entire model region.

4.2.3.4. At this point, we can just normalize the weights for each cell by dividing each cell weight by the sum of all cell weights in the county-basin. Note that for a cell to be considered, it must be in the actively pumping region of a county-basin. So a county-basin may have 1000 cells, but since the bad water line runs through the middle of the county, only 500 cells may be considered in the normalization calculation.

4.2.3.5. Now we have weights for each cell for each model. If we sum all of the weights for the cells in a county-basin, they will sum to one. So we can just multiply the total pumping in the aquifer in each county-basin by each cell weight to determine the amount of pumping in that particular cell.

4.3. Spatial allocation of irrigation groundwater pumpage. Irrigation pumpage is distributed between the MRLC NLCD land use types 61 (orchard/vineyard), 82 (row crops), and 83 (small grains) within each county-basin based on area. The distribution is further weighted based on proximity to the irrigated farmlands mapped from the 1989 or 1994 irrigated farmlands survey. The weighting factor is the natural logarithm of distance in miles to an irrigated polygon. However, this weighting factor is manually constrained to be between 0.5 and 2, in order to limit the effect of weighting to a factor of 4. All grid cells further than roughly 7.4 miles from an irrigated polygon will have a weight of 0.5, while all grid cells nearer than 1.6 miles from an irrigated polygon will have a weight of 2. Irrigation groundwater use for Louisiana was evenly distributed to the aquifer outcrop using methods described in Section 4.2.5. Irrigation withdrawal was assumed negligible in Miller County, Arkansas.

4.3.1. Create “distance grids” for the irrigated farmlands 89 and 94 shapefiles. These will be grid files that contain the distance from each grid cell to the nearest irrigated farmlands polygon.

4.3.1.1. Add **irr_farms89.shp** to a view, and make it active. With Spatial Analyst extension activated, select **find distance** from the **analysis** menu. Choose a grid cell size of 1 mile, and set the extent to the model domain. This will generate a grid of distance values to the nearest irrigated farm. Repeat for **irr_farms94.shp**. Call them **dist_irr*yy***.

4.3.2. Create shapefile for MRLC land use categories 61, 82, and 83.

4.3.2.1. In ArcView, load MRLC grid. Resample grid with a larger grid size to make the file more manageable (use x4 factor and set the analysis extent to the model domain). Select, in the new resampled grid, values 61, 82, and 83, and convert to shapefile. Call it **mrlc_irrigated.shp**.

4.3.2.2. Using the Geoprocessing Wizard, intersect county-basin boundaries with **mrlc_irrigated.shp** to create **mrlc_cb.shp**. Create a unique id **cb_irr_id** so that, if necessary, these unique polygons can be queried.

4.3.2.3. Intersect **mrlc_cb.shp** with the 1 mi. sq. grid cells.

4.3.2.4. Select only the 1 mile grid cells that are above the aquifer of concern’s extents. The county-basin irrigation pumpage totals are aquifer specific, so the pumpage should only be distributed where the proper underlying aquifer is present.

4.3.2.5. It is necessary to distribute across the entire county-basin area where the underlying aquifer is present, and not limited to that portions of the aquifer and county-basin within the model domain. Therefore, if a county-basin is intersected by the model domain boundary, the pumpage total must be distributed across the entire county-basin so that only the proper percentage gets distributed inside the model domain. To insure that this happens, select the county-basins on the perimeter that get intersected by the model domain boundaries. With the Geoprocessing Wizard, intersect these county-basins with the subsurface aquifer boundaries, the resulting file will be county-basins above the aquifer. Clip out the areas that reside inside the model domain (Union with model domain and delete that which is inside). What is left, (county-basins above aquifer of concern and outside of model domain) can be dissolved into one polygon and merged with the 1 mile grid cells. Give this new polygon a **grid_id** of “9999999” (later when pumpage values are summed by grid id the “9999999” values will fall out).

4.3.2.6. Add the new record “9999999” to the selected set from 4.3.4.1. Using Geoprocessing Wizard, intersect the selected 1 mile grid cells with the **mrlc_cb.shp** file. The result will be all of the irrigated land with the proper **grid_id** and county-basin name. Call it **mrlc_cb_*grid*.shp** (e.g. **mrlc_cb_nmg.shp**).

4.3.2.7. Add field **un_area_gd** and calculate the polygons’ areas in sq. miles using the field calculator (“un_area_gd” = [shape].returnarea/27878400).

4.3.3. Determine weighting factor for each polygon based on area and proximity with irrigated farms.

4.3.3.1. Add fields **dist_irr89**, **dist_fact89**, **ardisfac89**, **sumcbfac89**, **w_ar_dis89**.

4.3.3.2. Populate the distance to irrigated farmland field (**dist_irr89**) using the values from the **dist_irr89** grid file.

4.3.3.3. Calculate the distance to irrigated farms factor using the field calculator (dist_fact89=1/(1+[dist_irr89]).ln + 0.0001). Select all values that are greater than 2 and change them to 2, and select all values that are less than 0.5 and change to 0.5 so that the range is 0.5 – 2.

4.3.3.4. Calculate the area-distance factor using the field calculator (ardisfac89 = un_area_gd * dist_fact89).

4.3.3.5. Create a summary table by county-basin that summarizes the **ardisfac89** field. Link the summary table back up by county-basin and migrate the summed values into **sumcbfac89**.

4.3.3.6. Calculate the distribution weighting factor for area of irrigated land (mrlc land use) and distance to irrigated farmland (farmland survey) using the field calculator (w_ar_dis89 = ardisfac89 / sumcbfac89). This is basically the fraction of the total county-basin pumpage that will be distributed to a specific polygon.

4.3.3.7. Repeat section 4.3.5 for irrigated farmland 94.

4.3.4. Calculate unique withdrawal for each grid cell for every year (80-00).

4.3.4.1. We used the same “actively pumped” grids that were created for the livestock distribution to define possible areas of pumping for each layer. This time, we used the weights defined by the W_AR_DIS89 field for 1980-1989 and the W_AR_DIS94 field for 1990-2000.

4.3.4.2. As with the livestock distribution, we normalized each cell weight by dividing it by the sum of all cell weights for a county basin. After we had these normalized weight grids for each time period, it was a simply matter of multiplying the total pumping for the county-basin for each year by the weight grid to yield the cell pumping.

4.3.4.3. For each model domain and aquifer combination, summarize the allocated withdrawal by county-basin unit per aquifer per year.

4.3.4.4. Compare these values to the values reported in the original groundwater use survey table. Review county-basin units for which allocation is not approximately 100%. In some cases, a county-basin unit lies on the edge of a model domain. Allocation appears to be quite small for these units. This is because the groundwater use is distributed over the entire region but only a small portion falls within the model domain. Resolve any errors in matching before moving on.

4.3.5. Refer to section 5 for vertical allocation procedure, or the assignment of the model layer property.

4.3.6. Summarize all unique withdrawal by model grid row, column, layer and year.

4.4. Spatial allocation of rural domestic groundwater pumpage. Note that rural domestic withdrawal allocation is completed in the same fashion for Texas, Louisiana, and Arkansas data. Arkansas rural domestic pumpage is estimated based on Bowie County, Texas withdrawals. Estimated Arkansas rural domestic withdrawal is stored in the project database table **tblARCOApprox**.

4.4.1. Calculate the population in each 1 mile grid cell.

4.4.1.1. In ArcView, load the 1990 block-level census population shapefile.

4.4.1.2. Load ArcView polygon shapefiles for cities. Select census blocks that fall with in city boundaries and delete those records so that rural domestic pumpage does not get distributed to cities. (Note: assume that city boundaries are good surrogates for the extent of the area served by public water supply systems, whose pumpage is reported under the category **MUN**). Repeat this process for the reservoir areas.

4.4.1.3. Calculate the area of census blocks in sq. miles in a new field **blk_area** using the Field Calculator function (blk_area=shape.returnarea / 27878400).

4.4.1.4. Load the model grid, model domain, and county-basins shapefile. Select all county-basins that are intersected by the model domain boundary. Union the selected county-basins with the model domain boundary. In the resulting shapefile, delete the polygons that are inside the model domain, leaving only areas of the county-basins that are outside of the model domain. Dissolve these polygons into one and merge with the model grid shapefile. Give this new record a **grid_id** of 9999999. (Adding this new area will insure that, when the county-basin total populations are calculated, the population outside of the model domain will be included).

4.4.1.5. In the Geoprocessing Wizard, intersect the census block shapefile with the model grid shapefile to create a new shape file **intrsct*90*.shp**. (Note: Because the model grid size is 1 square mile, no intersected polygon (inside the model domain) should be larger than 1 square mile. Make sure that this is the case before proceeding).

4.4.1.6. Calculate the unique area of all intersected polygons in square miles as a new field **area_un1** using the Field Calculator function (area_un1=shape.returnarea / 27878400). (One grid cell should have an area of 1).

4.4.1.7. Add a new numeric field **pop_un1**, the unique Population of the intersected polygons. Using the Field Calculator, calculate its value as (POP_un1 = pop*90* * area_un1 / blk_area) where **pop*90*** is the block population from the census file.

4.4.1.8. Sum the field **pop_un1** by grid_id using the **Field Summarize** function to calculate the total population within each grid cell. Join this summary table to the original grid table by **grid_id** and copy value into new field **pop_90**.

4.4.1.9. Repeat steps 4.5.1.1 – 4.5.1.8 (no need to repeat step 4.5.1.4, just use the grid file that was used for previous iteration) for the 2000 block-level census population shapefile.

4.4.2. Calculate the rural domestic pumpage for each 1 mile grid cell.

4.4.2.1. We used a procedure similar to irrigation and livestock allocation from this point, creating a normalized weight grid for each of the time periods based on pop_90 and pop_00 by dividing each cell population by the total population in the active part of the county-basin.

4.4.2.2. In the historical period, rural domestic pumping in the TWDB database is not specified by aquifer, so we made vertical allocation estimates for each county basin based on 1) the allocations in the predictive period, 2) looking at nearby rural domestic wells in the TWDB database, and 3) considering measured head levels.

4.4.2.3. After the vertical allocation was made, allocating pumping to each grid cell was just a matter of multiplying the pumpage for a county-basin allocated for a particular layer by the weight for a particular cell.

4.4.3. Review allocated groundwater use records for percentage allocated.

4.4.3.1. For each model domain, summarize the allocated withdrawal by county-basin unit per year.

4.4.3.2. Compare these values to the values reported in the original groundwater use survey table. Review county-basin units for which allocation is not approximately 100%. In some cases, a county-basin unit lies on the edge of a model domain. Allocation appears to be quite small for these units. This is because the groundwater use is distributed over the entire region but only a small portion falls within the model domain. Resolve any errors in matching before moving on.

4.4.4. Refer to section 5 for vertical allocation procedure, or the assignment of the model layer property.

4.4.5. Summarize all unique withdrawal by model grid row, column, layer and year.

4.4.5.1. For each model grid (northern, central, and southern) and each aquifer, summarize the withdrawal per grid row, column, layer and year. Compile and save all results in the following database tables. Remember to include Louisiana and Arkansas rural domestic withdrawals in the northern model grid.

Model Grid	**Allocated Livestock Withdrawal**
Central	CO_CMG
Northern	CO_NMG
Southern	CO_SMG

5. Vertical Distribution of Groundwater Pumpage (all uses).

The vertical distribution of pumping for the Queen City and Sparta aquifers was either based upon the water use data as defined in the TWDB database. This is also true for well-specific pumping. Rural domestic was vertically allocated based upon the vertical allocation weights of rural domestic pumping as defined by county-basin in the predictive pumping data sets. In a few cases the allocation weights were changed by the modeler if a particular county basin allocation was strongly inconsistent with adjoining county-basins.

5.1. Sparta Aquifer

5.1.1. Set the **LAYER** field of each table equal to 1 to indicate withdrawal from the Sparta aquifer.

5.2. Queen City Aquifer

5.2.1. Set the **LAYER** field of each table equal to 3 to indicate withdrawal from the Queen City aquifer.

5.3. Cane River Formation

5.3.1. Set the **LAYER** field of each table equal to 3 to indicate withdrawal from the Queen City aquifer.

APPENDIX 1:
DATABASE TABLES

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APPENDIX 1: DATABASE TABLES

Table Name	Table Description	Table Source
AddWells	Envirofacts additional well locations	INTERA - SOP Section 3.1.4.2.
AquiferCodes	Major and minor aquifer codes from z_aquifer and z_aquifer_id	INTERA - SOP Section 2.1.9
C-Oregression	Rural Domestic Regression Results	INTERA - SOP Section 2.6
C-O_1980-1997	Rural Domestic Groundwater Use (1980-1997) as provided by TWDB in RuralDomestic_Master_Post1980_042902.xls	INTERA - SOP Section 2.1.2
C-O_1980to2000	Rural Domestic Groundwater Use (1980-2000) includes extrapolated data values for all aquifer withdrawals	INTERA - SOP Section 2.6
CalMaineDB	Cal-Maine Foods well locations stored in TWDB database tables	INTERA
CalMaineNew	Additional Cal-Maine Foods well locations provided by Van Kelley	INTERA
CO_AR_NMG	Allocated Arkansas rural domestic withdrawal for the northern model grid	INTERA - SOP Section 2.4
CO_CMG	Allocated rural domestic withdrawal for the central model grid	INTERA - SOP Section 2.4
CO_LA_NMG	Allocated Louisiana rural domestic withdrawal for the northern model grid	INTERA - SOP Section 2.4
CO_NMG	Allocated Texas, Louisiana, and Arkansas rural domestic withdrawal for the northern model grid	INTERA - SOP Section 2.4
CO_SMG	Allocated rural domestic withdrawal for the southern model grid	INTERA - SOP Section 2.4
CtyBsnCMG	County-basin units that intersect the Central Model Domain	INTERA
CtyBsnNMG	County-basin units that intersect the Northern Model Domain	INTERA
CtyBsnSMG	County-basin units that intersect the Southern Model Domain	INTERA
Grid_lkup_CCW	Central model grid cell associated with the county-basin it falls primarily within	INTERA - SOP Section 2.4
Grid_lkup_NCW	Northern model grid cell associated with the county-basin it falls primarily within	INTERA - SOP Section 2.4
Grid_lkup_SCW	Southern model grid cell associated with the county-basin it falls primarily within	INTERA - SOP Section 2.4
IRRRegression	Irrigation Regression Results	INTERA - SOP Section 2.6
IRR_1980-1997	Irrigation Groundwater Use (1980-1997) as provided by TWDB in Irrigation_Master_Post1980_062602.xls	INTERA - SOP Section 2.1.2.
IRR_1980to2000_QCSP	Irrigation Groundwater Use (1980-2000) includes extrapolated data values for Queen City and Sparta aquifer withdrawals	INTERA - SOP Section 2.6
IRR_CMG	Allocated irrigation withdrawal for the central model grid	INTERA - SOP Section 4.3

IRR_MRLC_QC24_CMG	Irrigation MRLC and area weighting/distance weighting for Queen City withdrawal in the central model grid	INTERA - SOP Section 4.3
IRR_MRLC_QC24_NMG	Irrigation MRLC and area weighting/distance weighting for Queen City withdrawal in the northern model grid	INTERA - SOP Section 4.3
IRR_MRLC_QC24_SMG	Irrigation MRLC and area weighting/distance weighting for Queen City withdrawal in the southern model grid	INTERA - SOP Section 4.3
IRR_MRLC_SP27_CMG	Irrigation MRLC and area weighting/distance weighting for Sparta withdrawal in the central model grid	INTERA - SOP Section 4.3
IRR_MRLC_SP27_NMG	Irrigation MRLC and area weighting/distance weighting for Sparta withdrawal in the northern model grid	INTERA - SOP Section 4.3
IRR_MRLC_SP27_SMG	Irrigation MRLC and area weighting/distance weighting for Sparta withdrawal in the southern model grid	INTERA - SOP Section 4.3
IRR_NMG	Allocated irrigation withdrawal for the northern model grid	INTERA - SOP Section 4.3
IRR_SMG	Allocated irrigation withdrawal for the southern model grid	INTERA - SOP Section 4.3
LADOTD	This dataset is used for Louisiana pumping data as it contains 1980, 1985, 1989, 1994, 1995, 1999; Imported original excel sheet, qryDataRequestForSparta.xls and CRVRPumpage.xls, containing pumping data for LA parishes. Emailed from P.Sargent at LAUSGS on 3/31/03.	INTERA - SOP Section 3.8.3
MasterTable	Table containing all Texas counties and associated Regional Water Planning Groups (RWPGs)	INTERA - SOP Section 2.4.4.
MFGAltLoc	Alternative manufacturing well locations	INTERA
MFGMatchPump	Manufacturing Groundwater Use (1980-2000) matched with a unique well record	INTERA - SOP Section 3.1.
MFGWells	Manufacturing Groundwater Use unique wells, locations and associated model grid cells	INTERA - SOP Section 3.1.
MFG_1980-2000	Manufacturing Groundwater Use (1980-2000) as provided by TWDB in Manufacturing_Master_Post1980_052402.xls	INTERA - SOP Section 2.1.2.
MFG_1980to2000_QCSP	Manufacturing Groundwater Use (1980-2000) filtered for just those aquifers of interest: Carrizo-Wilcox (10), Other (22), Queen City (24), and Sparta (27)	INTERA - SOP Section 2.1.3
MFG_1980to2000_QCSP_Final	Manufacturing Groundwater Use (1980-2000) filtered for just those aquifers of interest: Carrizo-Wilcox (10), Other (22), Queen City (24), and Sparta (27); with calculated monthly distribution	INTERA - SOP Section 2.5

MFG_CMG	Allocated manufacturing withdrawal for the central model grid	INTERA - SOP Section 3.9
MFG_LA_NMG	Allocated Louisiana manufacturing withdrawal for the northern model grid	INTERA - SOP Section 3.9
MFG_MonthlyFactorsperCBA	Calculated MFG monthly distribution factors per county-basin-aquifer unit	INTERA - SOP Section 2.5
MFG_NMG	Allocated composite (Louisiana and Texas) manufacturing withdrawal for the northern model grid	INTERA - SOP Section 3.9
MFG_SMG	Allocated manufacturing withdrawal for the southern model grid	INTERA - SOP Section 3.9
MFG_TX_NMG	Allocated Texas manufacturing withdrawal for the northern model grid	INTERA - SOP Section 3.9
MINAltLoc	Alternative Mineral Extraction well locations	INTERA
MINMatchPump	Mineral Extraction Groundwater Use (1980-2000) matched with a unique well record	INTERA - SOP Section 3.1.
MINWells	Mineral Extraction Groundwater Use unique wells, locations and associated model grid cells	INTERA - SOP Section 3.1.
MIN_1980to2000	Mineral Extraction Groundwater Use (1980-2000) as provided by TWDB in Mining_Master_Post1980_052402.xls	INTERA - SOP Section 2.1.2.
MIN_1980to2000_QCSP	Mineral Extraction Groundwater Use (1980-2000) filtered for just those aquifers of interest: Carrizo-Wilcox (10), Other (22), Queen City (24), and Sparta (27)	INTERA - SOP Section 2.1.3.
MIN_1980to2000_QCSP_Final	Mineral Extraction Groundwater Use (1980-2000) filtered for just those aquifers of interest: Carrizo-Wilcox (10), Other (22), Queen City (24), and Sparta (27); with calculated monthly distribution	INTERA - SOP Section 2.5
MIN_CMG	Allocated mineral extraction withdrawal for the central model grid	INTERA - SOP Section 3.9
MIN_MonthlyFactorsperCBA	Calculated MIN monthly distribution factors per county-basin-aquifer unit	INTERA - SOP Section 2.5
MIN_NMG	Allocated mineral extraction withdrawal for the northern model grid	INTERA - SOP Section 3.9
modgrd_c	Central model grid	INTERA
modgrd_n	Northern model grid	INTERA
modgrd_s	Southern model grid	INTERA
MUNMatchPump	Municipal Supply Groundwater Use (1980-2000) matched with a unique well record	INTERA - SOP Section 3.1.
MUNWells	Municipal Supply Extraction Groundwater Use unique wells, locations and associated model grid cells	INTERA - SOP Section 3.1.
MUN_1980to2000	Municipal Groundwater Use (1980-2000) as provided by TWDB in CityMunicipal_Master_Post1980_081402.xls	INTERA - SOP Section 2.1.2.

MUN_1980to2000_QCSP	Municipal Groundwater Use (1980-2000) filtered for just those aquifers of interest: Carrizo-Wilcox (10), Other (22), Queen City (24), and Sparta (27)	INTERA - SOP Section 2.1.3.
MUN_1980to2000_QCSP_Final	Municipal Groundwater Use (1980-2000) filtered for just those aquifers of interest: Carrizo-Wilcox (10), Other (22), Queen City (24), and Sparta (27); with calculated monthly distribution	INTERA - SOP Section 2.5
MUN_AR_NMG	Allocated Arkansas municipal withdrawal for the northern model grid	INTERA - SOP Section 3.9
MUN_CMG	Allocated municipal withdrawal for the central model grid	INTERA - SOP Section 3.9
MUN_LA_NMG	Allocated Louisiana municipal withdrawal for the northern model grid	INTERA - SOP Section 3.9
MUN_MonthlyFactorsperCBA	Calculated MUN monthly distribution factors per county-basin-aquifer unit	INTERA - SOP Section 2.5
MUN_NMG	Allocated composite (Louisiana, Arkansas, and Texas) municipal withdrawal for the northern model grid	INTERA - SOP Section 3.9
MUN_SMG	Allocated municipal withdrawal for the southern model grid	INTERA - SOP Section 3.9
MUN_TX_NMG	Allocated Texas municipal withdrawal for the northern model grid	INTERA - SOP Section 3.9
PWR_1980-2000	Power Groundwater Use (1980-2000) as provided by TWDB in Power_Master_Post1980_052402.xls	INTERA - SOP Section 2.1.2.
PWR_1980to2000_QCSP	Power Groundwater Use (1980-2000) filtered for just those aquifers of interest: Carrizo-Wilcox (10), Other (22), Queen City (24), and Sparta (27)	INTERA - SOP Section 2.1.3.
PWR_MonthlyFactorsperCBA	Calculated PWR monthly distribution factors per county-basin-aquifer unit	INTERA - SOP Section 2.5
RangeCentral	Rangeland in the Central Model Domain	INTERA - SOP Section 4.2.3.1
RangeNorth	Rangeland in the Northern Model Domain	INTERA - SOP Section 4.2.3.1
RangeSouth	Rangeland in the Southern Model Domain	INTERA - SOP Section 4.2.3.1
Sparta-CRVR_pumpingCalcs	Methodology for estimating withdrawal in Louisiana	INTERA - SOP Section 3.8.4.
STKRegression	Livestock Regression Results	INTERA - SOP Section 2.6
STK_1980-1997	Livestock Groundwater Use (1980-1997) as provided by TWDB in Livestock_Master_Post1980_072602.xls	INTERA - SOP Section 2.1.2.
STK_1980to2000_QCSP	Livestock Groundwater Use (1980-2000) includes extrapolated data values for Queen City and Sparta aquifer withdrawals	INTERA - SOP Section 2.6
STK_CMG	Allocated livestock withdrawal for the central model grid	INTERA - SOP Section 4.2
STK_NMG	Allocated livestock withdrawal for the northern model grid	INTERA - SOP Section 4.2
STK_SMG	Allocated livestock withdrawal for the southern model grid	INTERA - SOP Section 4.2

tblARCOApprox	Approximate rural domestic withdrawal from Miller County, Arkansas based on withdrawals in Bowie County, Texas.	INTERA - SOP Section 4.4.
tblASWCCGwWell	Pumping data for Miller Co., AR by well location (includes lat/longs). Emailed from Mike Guess at ASWCC on 4/15/03 as Miller Co 85-00.txt.	INTERA - SOP Section 3.7.2.
tblASWCCGwWellChr	Individual municipal supply well locations provided in Miller Co 85-00.txt	INTERA - SOP Section 3.7.2.
tblASWCCGwWellChrSP	Individual well locations provided in Miller Co 85-00.txt for the aquifers of interest	INTERA - SOP Section 3.7.3.
tblASWCCGwWellTS	Water use records provided in Miller Co 85-00.txt	INTERA - SOP Section 3.7.2.
tblASWCCGwWellTSSP	Water use records provided in Miller Co 85-00.txt for the aquifers of interest	INTERA - SOP Section 3.7.3.
tblLADOTDMFGMatchPump	Louisiana manufacturing water use records matched to individual wells.	INTERA - SOP Section 3.8.7.
tblLADOTDMUNMatchPump	Louisiana municipal supply water use records matched to individual wells.	INTERA - SOP Section 3.8.7.
tblLADOTDPumpC-O	Rural domestic withdrawal for Louisiana	INTERA - SOP Section 3.8.5.
tblLADOTDPumpIRR	Irrigation withdrawal for Louisiana	INTERA - SOP Section 3.8.5.
tblLADOTDPumpMFG	Manufacturing withdrawal for Louisiana	INTERA - SOP Section 3.8.5.
tblLADOTDPumpMUN	Municipal Supply withdrawal for Louisiana	INTERA - SOP Section 3.8.5.
tblLADOTDPumpSTK	Livestock withdrawal for Louisiana	INTERA - SOP Section 3.8.5.
tblLADOTDUse	LADOTD Use categories and associated GAM use categories	INTERA - SOP Section 3.8.4.
tblLADOTDWellMFG	Louisiana manufacturing well data was downloaded from http://www.dotd.state.la.us/intermodal/wells/home.asp.	INTERA - SOP Section 3.8.6.
tblLADOTDWellMUN	Louisiana municipal well data was downloaded from http://www.dotd.state.la.us/intermodal/wells/home.asp.	INTERA - SOP Section 3.8.6.
z_aquifer	z_aquifer table from TWDB Groundwater Database (GWDB.mdb); table of major and minor aquifers	INTERA - SOP Section 2.1.8.
z_aquifer_id	z_aquifer_id table from TWDB Groundwater Database (GWDB.mdb); table of major aquifers	INTERA - SOP Section 2.1.8.
z_basin	z_basin table from TWDB Groundwater Database (GWDB.mdb); table of TX river basins	INTERA - SOP Section 2.1.7.
z_county	z_county table from TWDB Groundwater Database (GWDB.mdb); table of TX counties	INTERA - SOP Section 2.1.6.
z_wateruse	z_wateruse table from TWDB Groundwater Database (GWDB.mdb); table of TX water use categories	INTERA - SOP Section 3.1.1.2
z_wdremarks	z_wdremarks table from TWDB Groundwater Database (GWDB.mdb); table of TX z_wdremarks	INTERA - SOP Section 3.1.1.2
z_welldata	z_welldata table from TWDB Groundwater Database (GWDB.mdb); table of TX wells	INTERA - SOP Section 3.1.1.2
z_welltype	z_welltype table from TWDB Groundwater Database (GWDB.mdb); table of TX well types	INTERA - SOP Section 3.1.1.2

C_C-OSPT	Rural domestic vertical allocation weights for all central model layers	INTERA - SOP Section 5.4
N_C-OSPT	Rural domestic vertical allocation weights for all northern model layers	INTERA - SOP Section 5.4
S_C-OSPT	Rural domestic vertical allocation weights for all southern model layers	INTERA - SOP Section 5.4

APPENDIX D

Standard Operating Procedures (SOPs) for Processing Predictive Pumpage Data

TABLE OF CONTENTS

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1. Background

These procedures were developed to further implement the guidance provided by the Texas Water Development Board (TWDB) in the Technical Memorandum 02-01 "Development of Predictive Pumpage Data Set for GAM." The information in that technical memorandum will not be repeated here, and the readers should first consult that document.

2. Groundwater Use Source Data

To the extent possible, procedures for predictive pumping distribution among model grid cells mimicked the procedures for historical pumpage data. Predicted future groundwater use estimates were provided by the TWDB in Excel spreadsheet files, as well as previously developed historical pumpage data sets. Use estimates were provided for the years 2000-2050. Water user groups are generally assigned for each water user category IRR, STK, MIN, MFG, PWR, MUN, and C-O in each county-basin. However, individual municipal water supplies within a county-basin are assigned identified as separate water user groups. The water use categories are listed below:

- IRR – irrigation
- STK – livestock
- MIN – mineral extraction
- MFG – manufacturing
- PWR – power generation
- MUN – municipal water supply, and
- C-O – county-other (rural domestic) use.

Historical groundwater use records from the categories MIN, MFG, PWR, and MUN are available for each specific water user group, each assigned an alphanumeric water user code (aka "alphanum") in historical water use data tables. Specific locations and wells from which this groundwater was pumped were identified in historical pumpage records. These are known as "well-specific" water use categories. However, the particular locations of historical groundwater pumpage were generally not known for the use categories IRR, STK, and C-O. These categories are known as "non-well-specific" water use categories. This pumpage was distributed spatially based on population density, land use, and other factors.

The following Excel spreadsheet files were downloaded from the TWDB web site within one executable file (FinalPredictive.exe):

- CityMunicipal_Master_Predictive_072202.xls
- Irrigation_Master_Predictive_072202.xls
- Livestock_Master_Predictive_072202.xls
- Manufacturing_Master_Predictive_072202.xls
- Mining_Master_Predictive_072202.xls
- Power_Master_Predictive_072202.xls
- RuralDomestic_Master_Predictive_072202.xls

3. Initial Processing

3.1 Create a sub-set of data for the modeled aquifers: All spreadsheet files were imported into Access and stored as separate database tables. Each water use category data table was queried for water use in the aquifer of interest based pm the aquifer's major aquifer code: 27 (Sparta) or 24 (Queen City). All other records were deleted.

3.2 Split water use between ground and surface water: Some records contain an aggregate of surface and ground water use, as indicated by a value of "04" in the field "SO_TYPE_ID_NEW." A new field

"PERCENT GROUNDWATER" was added to the table and assigned a value from 0 to 1 based on information in the field "ADDTL COMMENTS." All Queen City and Sparta records were reviewed and it was determined from the available data that there were no surface water records in the data set remaining after the previous step (3.1).

3.3 Transpose datasets: Code was written in a Visual Basic for Applications model within the Access database file to transpose time series data from columns to rows (Appendix A). Original data tables had one column per year. The code transposed the dataset such that there was one record per year.

4. Spatially Distribute Well-Specific Pumpage

Groundwater use from the categories MFG, MIN, MUN, and PWR is considered "well specific" data to be matched with specific wells from which water is pumped. Annual and monthly reported groundwater withdrawal for these uses is provided for each water user for each year from 2000 to 2050 in the water use surveys provided by the TWDB. Included for each record, is the county and river basin as well as the water user group ID, regional water planning group, number of wells from which water is drawn and the primary aquifer from which the groundwater was pumped. These water use survey tables do not indicate the specific location of the wells, well elevation, well depth, a specific aquifer name needed for groundwater modeling. Specific well data must be retrieved from other sources. The primary source of well data is the state well database (GWDB.mdb) maintained by the TWDB. Secondary sources include the EPA Envirofacts database and switchboard.com. In the absence of well information, the withdrawal location may be approximated based on facility location, where available.

4.1 Identify the location of new wells: If the field "Possible_New_Wells" contained a flag "NW", it was necessary to identify the location of new wells. All Queen City and Sparta records were reviewed and it was determined from the available data that there were no possible new well records in the data set remaining after the previous step (3.1).

4.2 Match predictive pumpage to well locations: It was assumed that a water user would tend to pump water in the future from the same locations from which they had historically pumped. It was recommended to identify each water use record alphanum from the field "WUG_Prime_Alpha" or "Seller Alpha". Unfortunately there were NULL values for each Queen City and Sparta record in both fields. If this was the case we followed the following approach to assign pumpage to well locations.

4.2.1 When the WUG was identified in the historic pumpage datasets, the alphanum from the historic database was added to the corresponding WUG in the predictive database. The WUG identified in the historic database was not always pumped from the same aquifer as in the predictive dataset. It was assumed in these cases that a water user would tend to pump water in the future from the same locations from which they had historically pumped. This only applied if the new aquifer existed at that geographical location. In a few cases multiple alphanum values were provided for a given WUG. Replicate copies of the record were added to the predictive pumpage table for each value of alphanum.

4.2.2 In many cases an alphanum was not provided in the historical water use records. In these cases, any owner information that may have been provided for a WUG was used to search the EPA envirofacts database and switchboard.com to identify an approximate location based on the facility address provided. If multiple wells were identified, the pumping was evenly distributed over all wells and the total number of wells was recorded in the database table.

4.2.3 There were several WUG values present in the predictive dataset but NOT in the historical dataset. In these cases, a land use coverage was used to identify an approximate well location.

4.2.4 In the event that a particular land use was not present in a county-basin for which pumpage was reported, the withdrawal was then applied to the center of the overlapping county-basin and aquifer extent area. Withdrawals located via this last resort method were relatively small.

4.2.5 Matching unique well records were compiled in database tables and the number of wells matched was stored in a field in the database tables.

A few examples of the methodology applied will be explained for LaGrange municipal pumping, Queen City and Sparta mining pumping and Lee-Colorado manufacturing.

In the case if the LaGrange municipal pumping, the current wells are in the Gulf Coast Aquifer. After conferring with the TWDB, it was decided to put the predictive Queen City and Sparta pumping at the same locations (five grid cells in an around LaGrange) as the current municipal wells.

For mining, there were 9 missing WUG IDs for the Queen City and 6 for the Sparta. For every case except the for a WUG in the Houston-Neches county-basin, the WUGs were associated with current mines (lignite). For the Houstin-Neches WUG the pumping was assigned to the centroid of the county-basin.

For Lee-Colorado county-basin manufacturing, the WUG identified was 071001144. The wells identified for this WUG were CW/OTHER. We assumed that the Queen City and Sparta wells would be located in a similar geographic location.

4.3 Create new tables for each well-specific water use category: For each use category a table of matched pumpage and well records was created. Six fields (e.g. NMG_ROW, NMG_COL, NMG_LAYER) were added to each table to store the i,j,k of model grid cells for each of the three model domains: central, northern, and southern. The reported pumpage total was divided by the number of wells matched to a particular WUG in a given county-basin and withdrawing from a particular aquifer to evenly distribute pumpage over all matched wells. Prior to identify model grid cells for each match pumpage record, the records were reviewed to ensure that the wells were plotting in the appropriate county-basin and within the reported aquifer extents. Finally the matched records were imported into ArcGIS and mapped with respect to the three model domains in order to populate the three i,j,k model grid database fields in each water use category matched pumpage table.

5. Vertical Distribution of Groundwater Pumpage (all uses)

5.1 Sparta Aquifer: Set the "LAYER" field of each table equal to 1 to indicate withdrawal from the Sparta aquifer.

5.2 Queen City Aquifer: Set the "LAYER" field of each table equal to 3 to indicate withdrawal from the Queen City aquifer.

6. Distribution of non-point pumping

6.1 Irrigation, livestock, and county-other pumping were distributed spatially just as in the historical period. For the predictive period (see Appendix C), and the weighting used for years 1990-1999 in the historical period were used going forward in the predictive.

6.2 The only difference in vertical allocation was for county-other, where the aquifers are actually specified in the predictive database, so no assumptions have to be made about layer allocation. In the case of counties in Arkansas and Louisiana, no county-other pumping was added in the predictive period for the Queen City and Sparta aquifers, as no data was available.

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Attachment 1

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```
Option Explicit

Public Sub TransposeGAMInput()

Dim db As DAO.Database
Dim rstIn As DAO.Recordset
Dim rstOut As DAO.Recordset
Dim intID As Long
Dim intYear As Long
Dim dblAcreft As Double
Dim i As Integer
Dim strField As String

Set db = CurrentDb()
Set rstIn = db.OpenRecordset("MIN_QCSP_Predictive")
Set rstOut = db.OpenRecordset("MIN_QCSP_Predictive_Trans")

rstIn.MoveFirst

Do Until rstIn.EOF
   intID = rstIn!UNIQUEID

   For i = 0 To 50
     intYear = 2000 + i
     strField = "[GAM" & intYear & "(ACFT/YR)]"
     dblAcreft = rstIn.Fields(strField)


     With rstOut
       .AddNew
       !UNIQUEID = intID
       !Year = intYear
       !ACRE_FT = dblAcreft
       .Update
     End With

   Next i

 rstIn.MoveNext

Loop

End Sub
```

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APPENDIX E

TWDB and Stakeholder Comments on the Draft Conceptual Model Report (7/31/03) and Responses

CONCEPTUAL DRAFT REPORT TECHNICAL/ADMINISTRATIVE COMMENTS:

DRAFT REPORT- SECTION 1.0: INTRODUCTION

No comments

DRAFT REPORT - SECTION 2.0: STUDY AREA

1. Section 2.1 Please include a discussion of evapotranspiration in the study area (Contract, Exhibit B, page 3, Section 3.1.1.). ***A discussion of ET was added.***

2. Page 2-11: Please include a figure showing the physiographic provinces. (Contract Exhibit B, Page 16, iv). ***A figure showing the physiographic provinces was added.***

DRAFT REPORT - SECTION 3.0: PREVIOUS INVESTIGATIONS

No comments

DRAFT REPORT - SECTION 4.0: HYDROGEOLOGIC SETTING

1. Chapter 4 General: Please break out rivers, springs, streams, and lakes into a separate report section as per contract Exhibit B., Page 14 (Final report sections). ***Done.***

2. Page 4-4, paragraph 1: Are the East Texas Embayment and East Texas Basin equivalent? Also are the Houston Embayment and Gulf of Mexico equivalent? One set of terms is used in text and another on Figure 4.2.1. Please clarify and update if necessary. ***These two terms are used interchangeably. We adopted the term East Texas Embayment consistent with Figure 4.2.1.***

3. Section 4.2.3: page 4-11, 1st paragraph, "However, leaving the Weches Formation out, there is an inversion …" Please clarify what "leaving the Weches Formation out" means. Suggest -- "Excluding the Weches Formation, there is an inversion …" (if that retains same meaning). ***This discussion was re-written to clarify the meaning.***

4. Section 4.3.5: page 4-33, relating to equation (2) and referring to Figure 4.3.8, should it be C_o = 0.15 and C_l = 0.17, rather than the reverse? Please verify and update as applicable. ***Corrected.***

5. Section 4.3.6: page 4-34, equation (3). Please clarify and update why TCEQ median K= 3.9 ft/d used rather than combined median 4.2 ft/d? ***Corrected.***

6. Page 4-54, paragraph 2: Please add evidence that the Queen City and Sparta aquifers are hydraulically separate or connected. ***This discussion was clarified to move away from the term hydraulically connected and to discuss the presence of confining units and juxtaposition of aquifer contacts.***

7. Please clarify why 1936 water-level data used for predevelopment water-level map even though hydrographs indicate stable water levels in more recent times when water-level data was more plentiful. Please explain why 1936 was selected rather than other predevelopment years. ***The water levels used for pre-development surfaces were not only derived from 1936 as can be seen in Tables 4.4.1 through 4.4.3. The rationale used for selecting predevelopment hydrographs was to use earliest head measurements available, which in most cases was 1936 data. These were augmented by later measurements and selected stable hydrographs.***

8. Page 4-60, paragraph 3: Please explain significance of slope, which slopes indicate downward flow, and whether there is spatial variation of slope. ***Done.***

9. Page 4-66, paragraph 2: Please consider making comparisons based only on water-level measurements made in the same well. ***Analysis has been modified to only consider measurements within a given well.***

10. Page 4-80, figure 4.4.2: Please add label (a) to Figure. ***Done.***

11. Page 4-82, figure 4.4.4: Please add label (a) to Figure. ***Done.***

12. Figures 4.4.14a, b: Suggest that contours not supported by data should be dashed and noted in legend. ***Done.***

13. Figures 4.4.15a, b: Suggest that contours not supported by data should be dashed and noted in legend. ***Done.***

14. Figures 4.4.16a, b: Suggest that contours not supported by data should be dashed and noted in legend. ***Done.***

15. Figures 4.4.23a, b: Suggest that contours not supported by data should be dashed and noted in legend. Please consider revising to reflect only water-level measurements in the same well. ***Analysis has been modified to only consider measurements within a given well.***

16. Figures 4.4.28a, b: Suggest that contours are not supported by data should be dashed and noted in legend. Also consider revising to reflect only water-level measurements in the same well. ***Analysis has been modified to only consider measurements within a given well.***

17. Section 4.6: Recharge. Please discuss use of SWAT to implement recharge in this section as well as what data sources will go into the process such as soils data, precipitation data and evaporation data. Also, maps of recharge potential or recharge coefficients should be shown. (contract, Exhibit B page 5, Section 3.1.6 Paragraph 1). ***The discussion of recharge and role of SWAT is included in Section 6.3.4.***

18. Section 4.7: Please include some stream-flow hydrographs if they are available (Contract Exhibit B, Page 17 xvii). ***Done.***

19. Section 4.7: Please include a discussion of how evapotranspiration (ET) will be implemented in the model. Also, please include information about data used to implement ET, for example vegetation types and root depths (Contract, Exhibit A, page 76, 3rd paragraph). ***The discussion of recharge and ET depths is included in Section 6.3.4.***

20. Section 4.8: Figures 4.8.5 – 4.8.7; please use bar charts rather than line graphs and also include graphs for predictive pumping (Contract Exhibit B, Page 17, xxiii). ***Agree to add bar charts of total pumping by aquifer from 1980 through 2050.***

SECTION 5.0: CONCEPTUAL MODEL OF GROUNDWATER FLOW IN THE AQUIFER

1. Section 5.0/page 5-2 through 5-3: Portions of the rejected recharge discussion may be misconstrued, please schedule a meeting with TWDB staff to discuss alternative ways of presenting this material. ***A meeting was held and the section has been modified to exclude the term rejected recharge and couch the discussion in terms of discharge and decrease in discharge.***

OVERALL

1. The following figures are difficult to interpret in a black and white printout (Contract Exhibit B, Page 16.) Please select gray-scale or other colors for these figures.

Figure 2.11
Figure 2.3
Figure 4.4.9
Figure 4.8.3
Figure 4.8.2
Figure 5.3

Corrected.

DRAFT REPORT EDITORIAL COMMENTS:

1. List of Figures page v: Figure 4.5.1 caption, aquifer is misspelled. ***Corrected.***

2. Page 1-3, paragraph 2, sentence 1: Please delete “recently”. ***Corrected***

3. Page 1-1, paragraph 1: Please add “respectively” at end of second sentence. “South ..” and “East..” should not be capitalized. ***Corrected.***

4. Page 2-1, paragraph 1: Please consider deleting last sentence in paragraph because it also appears in the introduction. ***Done.***

5. Page 2-3, paragraph 1: Please clarify why it is noteworthy that the Rio Grande, Brazos, … originate outside of Texas. ***This statement was deleted.***

6. Page 2-17, Figure 2.10a, b, c: Please explain the significance of the numbers in this figure. ***Done.***

7. Page 2-25, Figure 2.13a, b: The colors are difficult to distinguish, for example between the Cook Mountain, Goliad, and Weches formations. Please consider other colors. ***Figure was revised to include different colors and stiples and stripes.***

8. Page 4-1, paragraph 1: Please specify which units are referred to in the sentence “The Queen City and Sparta formations contain thicker, more continuous and more permeable fluvio-deltaic sands …”. Please delete sentence “Although the Reklaw…”. The sentence “The lower four units…” should be at the beginning of a new paragraph. ***This section was significantly re-written to clarify the text and fix grammatical errors.***

9. Section 4.5: Figure 4.5.1 caption, aquifer is misspelled. ***Corrected.***

10. Page 4-114, paragraph 1: Please reword Item 3 to “bacterially mediated oxidation ….”. ***Done.***

11. Page 4-125, paragraph 2: Suggest changing sentence from “Their estimates put the Queen City recharge…” to “Their estimates put the total Queen City recharge…”. ***Corrected .***

12. Section 4.6: page 4-126, 2nd paragraph, “There was only one natural lake in ~~the~~ Texas, Caddo Lake, ….”. ***Corrected.***

13. Section 5.0: Page 5-3, 2nd paragraph, “ Our conceptual model for the Queen City and Sparta aquifers is that …..” Typo -- please change “if” to “is”. ***Corrected.***

CONCEPTUAL DRAFT DATA SOURCE FILES COMMENTS:

Source data were reviewed for completeness, organization, and documentation in the form of metadata as specified in the Contract, Exhibit B, Pages 25 – 27. Most of the data were correctly organized and documented. Exceptions are noted for each main directory below. In addition each directory is to have a .LST file listing each file and its description. The lowest level subdirectories do not have listing files.

These comments will be addressed in the revised data.

DRIVE:\QCSP\scrdata\bndy

- No attributes are listed in county_tx_met.doc.
- Cities_urban_tx_met2.txt refers to cities_urban_tx1.met and cities_urban_tx2.met, neither of which is present in the directory.

- RWPG metadata is incomplete.

DRIVE:\QCSP\scrdata\clim

- No comments

DRIVE:\QCSP\scrdata\cnsv

- No comments

DRIVE:\QCSP\scrdata\geol

- The water quality folder should be in the subhyd folder.
- Are the structure data x and y values in GAM coordinates? If so please specify. If not, they should be.
- The structure data contained in the subdirectory /structure is an ascii text file whereas Exhibit B, page 25, second paragraph of the contract specifies that all ascii data must either be imported into ArcView or access.

DRIVE:\QCSP\scrdata\geom.

- qcsp_dem_met0.txt refers to sw_dem_met1.doc and sw_dem_met2.doc yet those files are not in the directory.

DRIVE:\QCSP\scrdata\soil

- Either all of the dbf files in the subdirectories \soil_data\ar\data ,\soil_data\la\data , and \soil_data\tx\data should be linked with the attribute, muid, to form one access database file with one metadata file or each individual dbf file should have its own metadata file.

DRIVE:\QCSP\scrdata\subhyd

- Water quality data should be in this folder.
- The specific capacity data contained in the subdirectory /hydraulic_ conductivity are ascii text files whereas Exhibit B, page 25, second paragraph of the contract specifies that all ascii data must either be imported into ARCView or access.

DRIVE:\QCSP\scrdata\surhyd

- The metadata listed in streams_la_met.doc is actually for rf1 data.

DRIVE:\QCSP\scrdata\tran

- No comments

PUBLIC REVIEW COMMENTS ON CONCEPTUAL DRAFT REPORT:

A stakeholder submitted the following comments:

1. Behavior of the Reclaw, Weches, and Cook Mountain Formations:

The Reclaw, Weches, and Cook Mountain formations are described as leaky aquitards (P. 4-1). Yet, in Section 4.4.3, Pressure Versus Depth Analysis, (P. 4-59 ff), the study of pressure head versus depth of the midpoint of the screened interval for those wells on the TWDB website having both types of data, yielded slopes near unity in the central GAM area, except for Bastrop County, suggesting little or no cross-formational flow. These two statements combined suggest that although the Reclaw, Weches, and Cook Mountain may be capable of functioning as leaky aquitards, but there is little or no pressure differential driving flow through the aquitards; i. e., pressures are so near hydrostatic that there is no evident cross-formational flow from the Queen City Aquifer to the Sparta Aquifer or vice versa. Thus, the conceptual model for the Queen City and the Sparta aquifers seems to differ from that for the Carrizo-Wilcox. Please explain why.

The discussion of the pressure density survey has been clarified to explain how it does support the Conceptual Model. Garza et al (1987) demonstrated that heads were still upward from oldest to youngest sediments in the Carrizo-Wilcox and Queen City and Sparta aquifers overmuch of Texas which is consistent with an elevation driven system and with the conceptual model.

Further along in Section 4, it is stated (P. 4-130) that under pre-development conditions, ground water flow is from topographically higher outcrops to topographically lower streams and to confined sections of the aquifers. Recharge is said to have been balanced by discharge to springs and streams in the outcrop and through cross-formational flow (see also P. 4-133). Here losses to streams are not considered rejected recharge, but natural discharge (see next comment). Here, too, cross-formational flow is said to be another form of natural discharge (see also P. 5-4). Yet, as indicated above, it was stated that analysis of pressure versus depth relationships did not reveal cross-formational flow, seemingly an unexplained inconsistency between observations and conclusions. Could the answer lie with different locations for the pressure versus depth analysis (fairly shallow in the confined portion of the aquifers) and the location of cross-formational flow (deeper portions of the confined aquifers)? Citation to Payne's (1968) conclusion on P. 4-133 that upward leakage from the Sparta begins a very short distance down dip from the outcrop suggests not. It appears that this seemed contradiction in how the Queen City and Sparta aquifer systems operate needs some explanation.

The discussion of the pressure versus depth analysis has been better discussed relative to the conceptual model.

No explanation was given (Pages 4-59 ff) for excepting Bastrop County, leading me to wonder if what was really meant was Brazos County. If Brazos County were not what was really meant to be excepted, then some explanation for excepting Bastrop County would be appropriate.

Checking the table again indicates that the text was correct as written.

2. Recharge versus Natural Discharge:

Ground water recharge would seemingly be a simple concept. The more time I spend practicing in the area of hydrogeology, however, the more complex I realize recharge is and that the term "recharge" is used by many in many different ways.

Recharge is defined in the Draft Report as water that enters the saturated zone at the water table (P. 4-124). It appears to me, based on this definition, which is a perfectly reasonable definition, that a given water molecule is either recharge or it is not. Any loses after recharge are some form of discharge. Yet, it is stated (P. 4-124) that some potential recharge will be rejected, relying on the assumptions that under undisturbed conditions, recharge is balanced by natural discharge and referencing Theis, 1940, and Domenico and Schwartz, 1990. Taking these two statements at face value implies that some water, for whatever reasons(s), that could reach the saturated zone does not; otherwise it would be recharge and wouldn't have been rejected. I doubt, though, that this is what the author(s) of the Draft Report actually meant. My sense is that they have defined recharge in one way and are using it in another way; i.e., rejected recharge is simply a form of discharge. Some explanation of what the authors actually meant seems appropriate.

The discussion of recharge has been revised to address this inconsistency.

Interestingly, under TAC §356.2.14, the term "recharge" also includes interformational leakage.

It is stated on P. 4-124, as Theis did, that to maintain a state of dynamic equilibrium, ground water withdrawals by pumping must be balanced by (1) an increase in recharge, (2) a decrease in natural discharge, (3) a reduction in storage, or (4) some combination of these three factors. It also is stated on P. 4-124 that balancing discharge by pumping through increased recharge implies that some potential recharge is being rejected, which can only occur where the water table is near the land surface, and that under pre-developed conditions, the aquifer is essentially full. It is presented on P. 4-124 that ground water discharge to streams (gaining streams) captures recharge from the inter-stream areas. In short, base flow discharge to streams is considered to be rejected recharge rather than natural discharge, which has the appearance to me of a logical inconsistency and implies a different meaning of the term "recharge" than stated earlier on P, 4-124. Additional consideration and explanation of how the term recharge is being used should be provided. Furthermore, do the water levels in the Queen City and Sparta support the concept that the aquifers are essentially full? No discussion is provided.

The discussion of recharge has been revised to address the issues raised.

The consequences of treating base flow discharges to streams and other near-surface losses as rejected recharge rather than natural discharge becomes apparent, and of real concern based on Section 5, Conceptual Model of Groundwater Flow in the Aquifer. On P. 5-2, it is stated that, "The onset of pumpage and concomitant water-level decline can induce an increase in recharge, because less water is captured by evapotranspiration as the water table declines below the root zone and vertical gradients in the recharge zone increase." Again, the use of the term "recharge" in this sentence appears to be different from how it was defined on P. 4-124. Dutton and others, 2003, (Groundwater Availability Model for the Central Part of the Carrizo-Wilcox Aquifer in Texas) found that the water table can be quite deep beneath topographic highs (>30 feet) and that downward movement of water through the unsaturated zone is controlled more by the hydrologic properties of the unsaturated zone than the annual precipitation rate. I infer from Dutton and others (2003) that the recharge rate at the water table is less a function of the annual precipitation, and even the differing amounts of annual precipitation along the outcrops of the aquifer units, than it is a function of the properties of the soils through which recharge must infiltrate. Fluctuations in precipitation result mainly in changes in the amount of water stored in the unsaturated zone (Dutton and others, 2003, P. 83). Fluctuations in precipitation also can result in the transient existence of perched zones or interflow. My own research into the soils literature indicates the existence of hard pans in the otherwise sandy soils developed on outcrops of the Simsboro and Carrizo aquifers in Bastrop and Lee counties. In short, except near stream courses crossing the outcrop of the aquifers, a relatively small portion of the total area encompassed by the model, recharge is not taking place (rejected) because the aquifer is actually full, but because hydraulic conditions in the unsaturated zone allow only so much water through the unsaturated zone almost regardless of the amount of precipitation and of the depth to the water table. If the conceptualization of recharge to the Queen City and the Sparta aquifers, especially in the central portion of the aquifer systems, is different from the conceptualization of recharge to the Carrizo-Wilcox aquifer system in the central portion of the state, please explain how and why. Please also explain the physical circumstances under which recharge to the Queen City and Sparta aquifers can be increased by lowering the water table and where this will occur.

The discussion of recharge has been revised with regards to issues of natural discharge and "rejected recharge". In contrast to the implication of reviewer's comment, the recharge model presented in Dutton et al. (2003) was not based upon data but was rather based upon an assumed conceptual model. The more recent work of Scanlon et al. (2003) does suggest that precipitation is a dominant factor in predicting recharge rates.

In support of the concept of induced recharge (P. 5-2 of the Conceptual Report), the authors of the report make reference to Freeze, 1971 (no bibliographic citation provided, but I presume the reference is to Freeze, R. A., 1971, "Three-dimensional, Transient, Saturated-unsaturated Flow in a Groundwater Basin," published in Water Resources

Research, Vol. 7, P. 347-366; there is also a reference to Freeze, 1969, for which a bibliographic citation is provided). Before totally buying into the concept of induced recharge based on thirty-year old literature, though, it is important to consider the more recent writings of Bredehoeft, Papadopulos, and Cooper, 1982 (Groundwater: The Water Budget Myth: in Scientific Basis of Water-Resources Management); Sophocleous, 1997 (Managing Water Resources Systems: Why "Safe Yield" is not Sustainable; Ground Water, Vol. 35, No. 4); Bredehoeft, 1997 (Safe Yield and the Water Budget Myth, Ground Water, Vol. 35, No. 6); Alley, Reilly, and Franke, 1999 (Sustainability of Ground-Water Resources: U. S. Geological Survey Circular 1186); Bredehoeft, 2002 (The Water Budget Myth Revisited: Why Hydrogeologists Model, Ground Water, Vol. 40, No. 4); Kendy, 2003 (The False Promise of Sustainable Pumping Rates: Ground Water, Vol. 41, No. 1); among others. The relevance of these articles should be analyzed and discussed in formulating a conceptual model for the Queen City and Sparta aquifers and tying them to the previous GAM effort for the Carrizo-Wilcox aquifer system.

Furthermore, it appears to me that citation of Freeze, 1971, in support of increased recharge with increased pumping overstates what Dr. Freeze was actually reporting. The overall intent of Dr. Freeze's paper was to describe a general finite difference code by which basin response (small basin) to development could be analyzed considering saturated and unsaturated flow and confined and unconfined conditions. The figure included in the Draft GAM Conceptual Model Report is Figure 11 in Freeze, 1971, and represents the response of a hypothetical basin where the water table in the recharge area is virtually at the ground surface. Under such a condition, recharge is limited by the rate at which ground water can move away from the recharge area and be discharged. Imposing withdrawals on the basin lowers the water table some, possibly allowing greater recharge. As Dr. Freeze notes, though, once the depth to the water table becomes sufficiently great; i.e., below a level at which ET losses cease to have any great influence over the rate of recharge, as it is overmuch of the outcrop area of the Carrizo Wilcox aquifer system, no greater amount of recharge can be captured except through reduction of base flow discharge and transition from gaining streams to losing streams. If I have misunderstood what dr. freeze was saying, please explain how. Please also explain how the behavior of Dr. Freeze's hypothetical basin is generally applicable to and representative of the behavior of the Queen City and the Sparta aquifers.

We have reviewed the suggested list of citations and appreciate the reviewer's comments on the subject. The recharge conceptual model write-up has been significantly revised based upon the comments above. The relevance of Dr. Freeze's citation is that he describes numerically perhaps the earliest example of demonstrating the concept of sustained yield.

Conceptualization of a GAM, which inherently presumes that significant amounts of "rejected recharge" can be captured to offset increased ground water withdrawals may not be representative of the actual system. I have no doubt that a numerical model, properly calibrated and verified, can be constructed that incorporates the concept of induced recharge. My concern is, as Ms. Kendy (2003) articulates, that we are making a "false promise," which will lead to unconservative predictions of ground water availability. Anyone applying a numerical model to make predictions knows he/she will be wrong. The model is a simplified representation of the natural ground water flow system and is non-unique. If we are to err, as we must though, let us err on the conservative side and preserve options for future generations.

The discussion has been revised based upon the comments.

A recently published article by Bredehoeft, 2003 (From Models to Performance Assessment: the Conceptualization Problem: Ground Water, Vol. 41, No. 5) is directly on point: "The intent of this paper is to explore philosophically the role of the conceptual model in analysis. Selection of the appropriate conceptual model is an a priori decision by the analyst. Calibration is an integral part of the modeling process. Unfortunately a wrong or incomplete conceptual model can often be adequately calibrated; good calibration of a model does not ensure a correct conceptual model" (abs) "My point is that we can choose the wrong conceptual model, fit the data, and get a wrong answer" (P. 572).

We agree that a poor conceptual model results in a poor numerical model. However, there are legitimate uncertainties regarding conceptual models of groundwater flow. The conceptual model presented in the draft conceptual model report is representative of the aquifer system of interest.

My overall concern here is that the conceptual model presented in the Draft Report seems fuzzy, incomplete, and perhaps incorrect. The implicit concept that somehow imposing greater demands on an aquifer can magically increase recharge not only appears erroneous, but misleading and will result in predictions of greater availability of ground water than may actually occur. Again, if we are to err, let us err on the side of conservatism. If through use of the GAMs, groundwater conservation districts (GCDs) project too little ground water available, that is fixable. If, though, GCDs project too much ground water available, that may not be fixable. In addition, I am concerned that the demands of the GAM effort have led to a focus on the process of creating a numerical model, unquestionably a daunting task, rather than the true purpose of effort, providing the tool by which the availability of ground water can be assessed.

We have revised the conceptual model discussion significantly to address the reviewer's comments regarding "rejected recharge" and we believe that the comments have been very constructive.

3. <u>Aquifer Discharge Through Pumping:</u>

Based on statements in the first paragraph in Section 4.8, Aquifer Discharge Through Pumping (P. 4-142), it appears that pumpage from particular wells was assigned based on the aquifer identifier in the TWDB database. It is not clear whether these aquifer designations were checked against the structure imbedded in the model layers. If not some pumpage could be attributed to the wrong aquifer, miss-representing the actual situation.

Our experience working with the GAMs is that the aquifer identifier is generally a more accurate identifier of what aquifer the well is in rather than the structure. This is largely because the structure data support is sparse for the large modeled area. For suspect wells, we do look at structure data and we agree with the reviewer that this is a valid concern.

4. <u>Aquifer Discharge Through Pumping:</u>

On P. 4-144 of the draft report, there are statements that, "In some cases, the RWPGs identified new well field locations for developing new water supplies. In such instances, the specific locations of the future well fields will be used to spatially distribute the groundwater pumping forecasts. However, in the absence of any data indicating otherwise, we will assume that the most recent past distribution of groundwater pumping represents the best available estimate of locations of future groundwater withdrawals." Again, on P. 4-145, it is stated that "Similarly for manufacturing, mining, and power generation, predicted future water pumping totals by county-basin will be distributed among the same wells and locations used by those water users in 1999." These statements are not very detailed and the process may, in some cases, lead to invalid assignments of pumpage. For example, if this process were used for the GAMs of the Carrizo-Wilcox aquifer system, the locations of ground water pumpage for mining in Milam and Lee Counties in 1999 would not be representative of the locations for ground water pumpage for the Three Oaks Mine to be opened in Lee and Bastrop counties. Isn't there some mechanism by which clear deviations from the results of applying the process of allocating pumpage can be recognized? Isn't there some tabular method by which these assumptions and decisions can be made clear to readers of the report and those who will use the model?

Pumping SOPs for historical and predictive are included as Appendix C and D. They include a detailed methodology, consistent with the GAM guidance for allocation of pumping. Carrizo-Wilcox pumping was not re-allocated in these models with the exception of county-other.

Thank for you attention to these questions and comments. I will appreciate learning your thoughts and responses to them.

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APPENDIX F

TWDB and Stakeholder Comments on the Draft Model Report and Responses

ATTACHMENT 1

Texas Water Development Board
Review of Final Draft Report & Model for Queen City-Sparta GAM
TWDB Contract No. 2003-483-482

Overall this report is very well written and relatively easy to follow considering its size. Text figures also are well done, but too much use is made of dark shading, which obscures underlying features. Many simple contour maps do not need shading. County lines and names should be added to maps. Figure display styles should be better standardized among the three models. Below is a list of detailed comments keyed to report section and page number. In your final report please include the review comments from the conceptual draft review with your responses, as well as your responses to the comments listed below. It will expedite the process if you include the new page number(s) and/or figure number(s) in your response.

Also, please note that the review of the source data files to be delivered with the final report may be a lengthy review process. TWDB staff will be reviewing source data content, metadata, and verifying all relevant materials were submitted in the prescribed folders outlined in Exhibit B Attachment 2. Therefore we encourage any support from our GAM consultants for an early delivery of these materials electronically.

Exhibit B, Attachment 1, Section 5.4, last paragraph states each report shall have an authorship list of persons responsible for the studies: firm or agency names as authors will not be acceptable. Please provide this information with the final report. In addition, with the new rules concerning geoscientists operating in the State of Texas working on state-related projects, please have the appropriate person or persons seal the final report using the guidance provided by the Texas Board of Professional Geoscientists (www.tbpg.state.tx.us).

Disclaimer: We reserve the right to make additional comments as additional concerns are brought to our attention.

FINAL DRAFT REPORT TECHNICAL/ADMINISTRATIVE COMMENTS:

TITLE PAGE

1. Please list authors per Exhibit B, Attachment 1, Section 5.4. Firms or agency names as authors will not be acceptable.

   Completed.

ABSTRACT

1. Please provide an abstract per Exhibit B, Attachment 1, Section 5.4.

   Completed.

TABLE OF CONTENTS

1. Section 6.3.5, Implementation of Pumpage Discharge should be 6.3.6
2. Section 8.1.3, Sensitivity Analysis is missing from TOC
3. Figure 4.2.2, caption, “logs” should be “log”
4. Figure 9.2.19, please correct spelling of “measured” and correct caption in text

SECTION 1.0: INTRODUCTION

1. We suggest changing future tense to past tense for all references to model development, e.g. Page 1-2 second paragraph "will be developed…" suggest "was developed…"

   Completed. See pages 1-2 and 1-3.

SECTION 2.0: STUDY AREA

1. Page 2-1, second paragraph, suggest changing " will be added…" to "were added…"

   Completed. See second paragraph on page 2-1.

2. Page 2-2, last paragraph, second sentence, please remove this sentence or reword that model boundaries intersect 16 of the 23 major river basins in Texas. (Lavaca-Guadalupe, Colorado-Lavaca, San Jacinto-Brazos, Trinity-San Jacinto, Neches-Trinity, Nueces-Rio Grande, and Canadian river basins are not within model boundaries).

   Completed. See last paragraph on page 2-2.

3. Figures 2.4 and 2.5, please correct spelling of "Bureau" in source reference

   Completed. See Figure 2.4 on page 2-7 and Figure 2.5 on page 2-8.

4. Please provide source references for Figures 2.1, 2.2, 2.3, 2.7 (also please add date reference), 2.8, 2.11, 2.13a-c, 2.15, 217a-c, and 2.19

   Completed. See Figure 2.1 on page 2-4, Figure 2.2 on page 2-5, Figure 2.3 on page 2-6, Figure 2.7 on page 2-10, 2.8 on page 2-11, Figure 2.11 on page 2-17, and Figures 2.13a-c on pages 2-19 through 2-21. On Figures 2.13a-c, the source is indicated as the NCDC (National Climatic Data Center) in the legend. The source for Figure 2.15 is also the NCDC. For the cross sections illustrated in Figure 2.20 (formerly Figure 2.19), the source is internal work done for this study.

5. Figure 2.5, please reword caption to specify minor aquifers <u>modeled</u> in the study area. Text discusses Yegua-Jackson aquifer in study area, please update text to mention Brazos River Alluvium also in study area.

   Completed. See Figure 2.5 on page 2-8 and last paragraph of text on page 2-1.

6. Figure 2.7, please reword caption to indicate <u>confirmed and pending</u> Groundwater Conservation Districts. Bluebonnet GCD does not include Washington and Waller counties, please adjust figure appropriately. Please remove Upshur GCD and Houston County GCD from figure, table 2.1, and text according to June 8, 2004 GCD status map. Also include month and year of base map in source reference of Figure 2.7.

   Completed. See Figure 2.7 on page 2-10, Table 2.1 on page 2-3, and second paragraph on page 2-2.

7. Page 2-14, last line, please change reference from (Candell et al., 1996) to (Canadell et al., 1996).

Completed. See last line on page 2-14.

8. Page 2-14, last paragraph, missing period after “pan evaporation rates”

   Completed. See last paragraph on page 2-14

9. Figure 2.10, please use a single color scale. High and low areas cannot be distinguished in a black and white print.

   Completed. See Figure 2-10 on page 2-16.

10. Figure 2.10, please include “not mapped” in legend to account for the areas shown around Houston and Corpus Christi. In addition, please correct spelling of “Geological” in reference source.

    Completed. See Figure 2.10 on page 2-16. Figure was modified to include mapped information in the areas around Houston and Corpus Christi.

11. Figure 2.16, please correct spelling of “Development” in reference source.

    Completed. See Figure 2.16 on page 2-24.

12. Per RFQ Section 3.1.2 and RFQ section 5.4, please include discussion and figures of net sand analyses in Chapter 2 Geology section or cross-reference to later discussions and Figures 4.2.13 and 4.2.14.

    Completed. See first and third paragraphs on page 2-27.

13. Per RFQ 3.1.2, please reference reader to Figure 4.2.1 when structural features in study area are discussed or move Figure 4.2.1 to this section.

    Completed. See Figure 2.17 on page 2-29. Figure of major faults and structural features moved to Section 2.0.

SECTION 3.0: PREVIOUS WORK

1. no comments

SECTION 4.0: HYDROLOGIC SETTING

1. Section 4.2 general, there is a lot of redundancy in this section. Let the figures do the talking. Focus on the hydrologically relevant. The emphasis should be methodology and justification for model layer bounds and elevations. These get lost in the geological details.

   Completed. In general we believe that Section 4.2, though very detailed, provides a good summary of the background, methods of interpretation, and procedures used in development of the model structure. We have deleted portions of the text which we agreed were either irrelevant or redundant on pages 4.5 and 4.7.

2. RFQ Section 5.4 states figures portraying bottom elevations and thicknesses should include control points. Please update Figures 4.2.3 through 4.2.12 with control points used. In addition, please use consistent nomenclature in key for elevations, such as:
   -6,000 to -4,000
   -4,000 to -2,000
   or
   -5,999 to -4,000
   -3,999 to -2,000

   Completed. See Figures 4.2.3 through 4.2.11 on pages 4-16 through 4-24.

3. Page 4-7, first paragraph, last sentence, should be "structural features produce"

   Completed. See last sentence on page 4-6.

4. Page 4-8, second paragraph, eighth sentence, leave out "one hand…other hand", use "relative to"

   Completed. See second paragraph on page 4-8.

5. Page 4-9, general, refer to stratigraphic sections and maps in section 2 as a reminder

   Completed. See second and third paragraphs on page 4-9.

6. Page 4-9, last paragraph, consider mentioning large anticline/syncline in Winter Garden

   Completed. See last paragraph on page 4-9.

7. Page 4-9, last line, reference sequence of figures as "Figures 4.2.4 to 4.2.7"

   Completed. See last sentence on page 4-9.

8. Page 4-10, third paragraph, first sentence, "centers" should be "is centered"

   Completed. See second paragraph on page 4-10.

9. Page 4-10, third paragraph, second sentence, "hovers" ???

   Completed. See second paragraph on page 4-10.

10. Page 4-10, last paragraph, second sentence, "could be" should be "locally reaches"

    Completed. See third paragraph on page 4-10.

11. Page 4-11, general, a lot of redundant description here, be more concise.

This discussion is consistent with the description of the aquifer/aquitard isopachs on page 4.10 so we have left the text the same excepting minor editorial comments.

12. Page 4-11, last paragraph, second sentence, "mimicking" ???

    Completed. See third paragraph on page 4-11.

13. Page 4-11, end of third paragraph, "can be follow…", should be "can be followed…"

    Completed. See third paragraph on page 4-11.

14. Page 4-11, last paragraph, last sentence, sentence unclear, should it be "cannot be traced"?

    Completed. See third paragraph on page 4-11.

15. Page 4-12, first paragraph, last sentence, maybe should be "definitions of the authors were maintained in this study"

    Completed. See first paragraph on page 4-12.

16. Page 4-13, second paragraph, third sentence, should be "is also apparent in decreasing sand thickness"

    Completed. See first paragraph on page 4-13.

17. Page 4-13, second paragraph, fourth sentence, end sentence after "embayment" (you "already mentioned" the last part)

    Completed. See first paragraph on page 4-13.

18. Page 4-13, second paragraph, last sentence, "import" should be "transport"

    Completed. See first paragraph on page 4-13.

19. Page 4-13, second paragraph, fourth sentence, end sentence after "embayment" (you "already mentioned" the last part)

    Completed. See first paragraph on page 4-13.

20. Page 4-13, second paragraph, last sentence, "import" should be "transport"

    Completed. See first paragraph on page 4-13.

21. Figure 4.2.9 caption, Page 4-22, please remove text "(insert new fig.)"

    Completed. See Figure 4.2.8 caption on page 4-21.

22. Page 4-26, Figure 4.2.13, the text states that the source of the information in the map is Guevara and Garcia (1972). Please include that citation in the figure caption.

    Completed. See Figure 4.2.12 caption on page 4-25.

23. Page 4-27, Figure 4.2.14, the text states that the map is from Ricoy and Brown (1977). Please include that citation in the figure caption.

    Completed. See Figure 4.2.13 caption on page 4.26.

24. Page 4-28, second paragraph, first sentence, "<u>Additional</u> hydraulic conductivity"? this is first mention of K

    Completed. See second paragraph on page 4-27.

25. Page 4-29, second paragraph, last sentence, reference to the "analytical method" is unclear

    Completed. See second paragraph on page 4-28.

26. Page 4-31, last paragraph, Queen City aquifer sand map is shown in Figure 4.2.13 (not Figure 4.2.12). Please correct.

    Completed. One figure moved from Section 4.0 to Section 2.0, so the Queen City aquifer sand map is shown in Figure 4.2.12 (see page 4-25).

27. Page 4-32, top of page, Sparta aquifer sand map is shown in Figure 4.2.14 (not Figure 4.2.13). Please correct.

    Completed. One figure moved from Section 4.0 to Section 2.0, so the Sparta aquifer sand map is shown in Figure 4.2.13 (see page 4-26).

28. Page 4-32, second paragraph, second sentence, Isaaks and Srivastava 1989 not in References

    Completed.

29. Page 4-35, end of third paragraph. Suggest changing "…aquifer will be used as the basis " to "….aquifer was used as the basis…."

    Completed. See second paragraph on page 4-34.

30. Page 4-36, table 4.3.2, use 10^{-2} instead of 0.01 for consistency

    Completed. See Table 4.3.2 on page 4-35.

31. Page 4-36, please correct spelling of citation "McReath et al. (1991)" to "McWreath et al. (1991)

    Completed. See second paragraph on page 4-35.

32. INTERA SOW Hydraulic Parameterization Section states information on hydraulic properties will be based on reports such as Hays et al (1998), Prudic (1991), Myers (1969), Payne (1968), and TWDB County reports. Hays et al (1998) and Myers (1969) not cited in text or references. Please explain why these references were not used.

    Both Hays et al. (1998) and Myers (1969) were reviewed as part of our work. The Hays et al. (1998) model of the Sparta is an extension of the work of McWreath et al. (1991) which is referenced and summarized in Table 4.3.2 of our report. Hays et al. (1998) did not alter the model properties from McWreath et al. (1991). The Myers (1969) database was incorporated by Mace et al. (2002) and we used this data through that report.

33. RFQ Section 3.1.5 states hydrographs will help define water-level declines and seasonal fluctuations. Please include discussion if seasonal fluctuations were observed throughout the model area, in particular in the unconfined portions of the aquifers.

    Completed. See second paragraph on page 4-67 and last paragraph on page 4-69.

34. Table 4.3.4 lists range of storativity of 0.00141 to 0.00052. Text lists range of 0.0001 to 0.00025. Please adjust so text and table agree or qualify range cited in text.

    Completed. See first paragraph on page 4-38.

35. Page 4-39, Table 4.3.4, suggest changing column heading of "Storage" to "Storativity"

    Completed. See Table 4.3.4 on page 4-38.

36. Page 4-41, Figure 4.3.1, use same horizontal scale for both graphs

    Completed. See Figure 4.3.1 on page 4-40.

37. Pages 4-49 – 4-53, Figures 4.3.9 – 4.3.13, please use different color pattern or gray scale. The colors cannot be distinguished in black and white.

    Completed. See Figures 4.3.9 through 4.3.13 on page 4-48 through 4-52.

38. Page 4-55, second paragraph, this paragraph does not belong in this section

    Completed. Paragraph removed. See page 4-55.

39. Page 4-59, last paragraph, last sentence, "Generation" does not really "consider", consider rephrasing

    Completed. See last paragraph on page 4-58.

40. Page 4-61, last sentence of second paragraph please change "has been significantly develop" to "has been significantly develop<u>ed</u>"

    Completed. See second paragraph on page 4-60.

41. Page 4-61, second paragraph, need literature reference for pressure-depth analysis

    Completed. See last paragraph on page 4-59.

42. Page 4-61, second paragraph, fourth sentence, “cases” should be “counties” and delete “in some counties”

    Completed. See second paragraph on page 4-60.

43. Page 4-62, second paragraph, fourth sentence, “less evident as they are.” is unclear

    Completed. See second paragraph on page 4-61.

44. Page 4-68, second paragraph, first sentence, “completed to” should be “completed in”

    Completed. See last paragraph on page 4-67.

45. Page 4-68, second paragraph, second to last sentence, “county” should be “counties”

    Completed. See first paragraph on page 4-68.

46. Page 4-70, second paragraph, second to last sentence, “1990” should be “1999”?

    Completed. Sentence removed. See second paragraph on page 4-69.

47. Page 4-83, Figure 4.4.4, please label top Figure (a). Not corrected from conceptual model comments.

    Completed. See Figure 4.4.4 on page 4-82.

48. Page 4-94, Figure 4.4.14b, please add space between Figure and 4.4.14b.

    Completed. See Figure 4.4.14b on page 4-93.

49. Per Conceptual Review comments 13 and 15, please update legends with dashed line in Figures 4.4.14a, 4.4.14b, 4.4.15a, 4.4.15b. 4.4.16a, and 4.4.16b

    Completed. See Figures 4.4.14a through 4.4.16b on pages 4-92 through 4-97.

50. Please add green line in legend for Figure 4.6.1

    Completed. See Figure 4.6.1 on page 4-126.

51. Page 4-100, Figure 4.4.17b, remove well numbers from map

    Completed. See Figure 4.4.17b on page 4-99.

52. Page 4-117, first paragraph, second sentence, “figure subtracts” unclear, what figure?

Completed. See first paragraph on page 4-116.

53. Please add green line in legend for Figure 4.6.1

    Completed. See Figure 4.6.1 on page 4-126.

54. Per RFQ 3.1.6, factors related to how the aquifer is recharged and effects of seasonal variations shall be examined and discussed. Please update section 4.6 with this discussion. In addition, please cross-reference to later discussions of recharge and ET distributions, such as section 6.3.5. (Conceptual Draft Review comments 18 and 20).

    Completed. See first paragraph on page 4-122 for discussion of recharge and effects of seasonal variations. See third paragraph on page 4-122 for cross reference to later discussions of recharge and ET distributions.

55. Page 4-129, second paragraph, first sentence, add “Colorado”

    Completed. See second paragraph on page 4-128.

56. Page 4-132, second paragraph, first sentence, “HDR” should be “HDR Engineering” since this is first occurrence of the name

    Completed. See second paragraph on page 4-131.

57. Page 4-132, third paragraph, fifth sentence, too many miles in “AFY/mile/mile”

    Completed. See third paragraph on page 4-131.

58. Page 4-143, Figure 4.7.2, 1981 should be 1982 on all graphs

    Completed. See Figure 4.7.2 on page 4-142.

59. Page 4-144, Figure 4.7.3, in Legend should be “Survey Point and Number” showing example dot and example number

    Completed. See Figure 4.7.3 on page 4-143.

60. Table 4.7.2, please update header from AFY to AFY/mile for consistency with other tables.

    Completed. See Table 4.7.2 on page 4-137.

61. Page 4-132, please replace QCS with “Queen City/Sparta” model.

    Completed. See third paragraph on page 4-131.

62. Page 4-149, fourth paragraph, Figure 4.8.8 and 4.8.9 should be Figures 4.8.8 and 4.8.9. And Tables 4.8.4 should be Table 4.8.4. Please correct.

    Completed. See third paragraph on page 4-148.

63. Page 4-149, last paragraph, “groundwater withdrawals from the Sparta aquifer..” should be “.groundwater withdrawals from the Queen City aquifer…”

    Completed. See last paragraph on page 4-148.

64. Page 4-163, Figures 4.8.2 and 4.8.3, please make the pumpage bar charts yearly rather than by decade, per Exhibit B, Attachment 1, page 17, xxiii.

    Completed. See Figures 4.8.2 and 4.8.3 on page 4-162.

65. Per RFQ Section 3.1.7, elevations of riverbeds, streambeds, spring orifices, and lake levels; stream conductance; channel widths; etc. shall be determined and discussed in section 4 of the report. Please update section 4 with this information or cross reference to later discussions that impart this information.

    Completed. See first paragraph on page 4-128.

66. Please correct captions in Figures 4.8.2 and 4.8.3 from “1980 to 1950” to “1980 to 2050”.

    Completed. See captions for Figures 4.8.2 and 4.8.3 on page 4-162.

67. Please change reference in last paragraph page 4-149 from groundwater withdrawals from the Sparta aquifer to withdrawals from the <u>Queen City</u> aquifer.

    Completed. See last paragraph on page 4-148.

SECTION 5.0: CONCEPTUAL MODEL OF GROUNDWATER FLOW IN THE AQUIFER

1. Page 5-1, first paragraph, third sentence, “artificial” would be better than “anthropological”

    Completed. Anthropological changed to anthropogenic.

2. Page 5-4, last paragraph, second sentence, “is” should be “are”

    Completed. Page 5-4.

3. Page 5-5, last paragraph, fifth and sixth sentences, symbols mentioned in text do not match those on Figure 5.2, “blue” is grey and “dot” is triangle

    Completed. Text has been corrected, Page 5-5.

4. Page 5-6, last sentence, “as a future state” is unclear, maybe should delete sentence (are you sure modeling is the only way to study this phenomena?)

    Completed. Sentence has been edited for clarity, Page 5-6.

5. Page 5-7, Figure 5.1, some arrows in wrong place or missing

    Corrected. Page 5-7.

6. Please update Figure 5.1 with ET. Please update caption in Figure 5.1 to indicate figure represents “predevelopment” conditions. Also please explain in text or correct in figure 5.1 how river-aquifer interaction occurs cross-formationally between the Queen City and Weches formations and not in the outcrop of the Queen City, Weches, and/or Sparta formations. Please review cross-formational flow especially top cross-section, which indicates downward flow at the base of the system. Also the diagram indicates downward flow in predevelopment. Is that consistent with the predevelopment system? Please also indicate where the head dependant boundaries are located.

   Completed. Page 5-7. The figure has been corrected to include post-development stresses and to include ET and spring discharge. Stream-aquifer discharge arrows have been corrected. The Figure has generally been corrected and made clearer based upon TWDB comments and further editing. Cross-formational flow both up and down could exist in predevelopment conditions in the East Texas Basin region.

7. Please update Figure 5.2 caption to indicate vertical head differences represent 1980 conditions.

   Completed, Page 5-8.

8. Per RFQ Section 5.4 states the conceptual model section shall also discuss important controls on groundwater flow, for example: faulting, lithology, boundaries. Please update section with discussion on possible impacts to flow due to faulting.

SECTION 6.0: MODEL DESIGN

1. Per the SOW, drains will be assigned at ground surface elevations where water tables could rise above land surface. Per RFQ Section 5.4, please include figure showing the locations of drains assigned in the models and discuss this in section 6.0

   Completed. See Page 6-13 and Figure 6.3.8 through 6.3.10.

2. Page 6-1, third paragraph, first sentence, “;” should be “:”

   Completed.

3. Please include discussion of solver used for each model when discussing model code.

   Completed, Page 6-1.

4. Page 6-3, second paragraph, second sentence, please correct to indicate the GAM standard requires that grid cells be square of a uniform dimension <u>no greater than </u>1 mile. (RFQ Section 3.2.1)

   Completed, see Page 6-3.

5. Page 6-10, Section 6.3.3, first paragraph, suggest avoiding use of term rejected-recharge and instead rewriting third sentence as -- The stream-routing package will

allow for no stream-related recharge during gaining conditions and for stream-related recharge to be induced during losing conditions.

Completed, see Page 6-11, Paragraph 3.

6. The legend for Figures 6.3.5 to 6.3.7 suggests a color coding schematic was used to show relationship between stream cells and model layers. This is difficult to see in the figures. Please adjust.

   Completed, see Figures 6.3.5 through 6.3.7. Figures edited to just show stream and reservoir cell.

7. Section 6.3.3 text discusses MODFLOW reservoir package, please include a figure showing location of grids using the reservoir package. (RFQ Section 5.4).

   Completed, see Figures 6.3.5 through 6.3.7. Figures edited to stream and reservoir cell.

8. Active cells in Figures 6.3.1 to 6.3.3 and faults in Figures 6.3.8 to 6.3.10 appear slightly different when figures are compared. To avoid possible confusion, suggest adding a disclaimer in the text where the figures are discussed or in the captions, that grid orientation causes slight variations between models.

   The issue of grid orientation is discussed in more than one place in the report and this point is true for streams, reservoirs, and faults.

9. Page, 6-11, third paragraph, first sentence, Hibbs and Sharp not in References

   Completed.

10. INTERA SOW discusses using USGS methodology for ungaged streams (Lanning-Rush, 2000), please discuss this in the text or explain why this was not applicable. In addition SOW discusses HYSEP for baseflow determination, please discuss this in the text or explain why this was not applicable.

    The model was found to be relatively insensitive to stream stage. For this reason, we deemed it not necessary to use more rigorous methods such as that of Lanning-Rush (2002) to estimate stream headwater stages. We used a WAM-based method to estimate stream gains and losses over HYSEP analyses because of the highly regulated nature of most stream gages in our model domains.

11. Page 6-11, third paragraph, last sentence, “RFI” should be “RF1”

    Completed, see Page 6-12.

12. Page 6-11, last paragraph, second to last sentence, “nearby ungaged” should be “nearby gaged”

    Completed, see Page 6-12.

13. Page 6-14, second paragraph, third sentence, “correlates” should be “correlate”

    Completed, see Page 6-15.

14. Page 6-14, last paragraph, second to last sentence, “empirical relationships” may be better than “functional relationships”

    Completed, see Page 6-15.

15. Page 6-17, third paragraph, “6.3.5” should be “6.3.6”

    Completed, see Page 6-18.

16. Page 6-22, Figures 6.3.1 to 6.3.3 “No Layers Active” symbol, legend does not match map

    Completed, see Figures 6.3.1 through 6.3.3.

17. Please clarify if Figure 6.3.14 was the basis for the initial recharge used in all the models.

    Completed. Figure title 6.3.17 clarified to explain that this is the calibrated steady-state recharge distribution.

18. Page 6-38, first paragraph, last sentence, please add “is described in the following sections.”

    Completed.

19. Page 6-40, second paragraph, last sentence, insert “(equation 6.2)” after “harmonic mean”

    Completed, Page 6-43.

20. Page 6-44, Figures 6.4.1 to 6.4.3, purple patterns make it hard to see data points

    Completed on Figures 6.4.1 through 6.4.3.

21. Page 6-46, Figure 6.4.3, could not find a reference to this figure in text

    Corrected, see Page 6-44.

22. Page 6-47, Figure 6.4.4 caption, please change Log 10 to Log_{10}

    Completed on Figure caption.

23. Page 6-48, Figure 6.4.5 caption, please change Log 10 to Log_{10}

    Completed on Figure caption.

24. Page 6-49, Figure 6.4.6 caption, please change Log 10 to Log_{10}

    Completed on Figure caption.

SECTION 7.0: MODELING APPROACH

1. In their SOQ page 78, the INTERA team proposed to use PEST to aid in calibrating the GAMs. If PEST was used please explicitly include a discussion of this method in section 7.1 of the report.
   If PEST was not used please discuss which method was used.

   A discussion of PEST and the method of calibration used is included on page 7-2.

2. Introduces ramp up from 1975 to 1980 before the start of the transient models. How were pumpage and 1975 water levels developed? The steady-state year(s), ramp up (parameters/approach/years), transient calibration years, and transient verification years should be introduced prior to this section. (Section 6.0?)

   Completed. This is explained in a new Section 6.2.3 Model Simulation Period, Page 6-5.

3. SOW Task 4 states a review of literature to define possible calibration constraints such as groundwater age dating will be conducted. Please discuss this in section 7.0.

   Completed on Page 7-6.

4. Page 7-6, second paragraph, please change “calibration criteria of 40 to 50 feet.” To “calibration criteria of 30 to 50 feet.” (If that is correct. Based on RMS range of 30 to 50 feet at top of page).

   Corrected on Page 7-7.

5. Page 7-7, Section 7-4, “Steam flow rates and recharge were applied with seasonal variation in the average conditions period.” All model scenarios have annual stress periods, so this sentence does not apply. Please remove if that is correct.

   Completed, see Pages 7-7 and 7-8.

SECTION 8.0: STEADY-STATE MODEL

1. Page 8-1, third paragraph, “we maintained the horizontal conductivity field from the calibrated Southern Carrizo-Wilcox GAM, except in the overlap region as described in Section 6.4.1.” The horizontal conductivity field of the Southern Carrizo-Wilcox GAM in the overlap was not discussed in 6.4.1. Please include that discussion, preferably in Section 6.

   Completed. The Carrizo conductivity fields were merged by a simple combined kriging of the original data/surfaces. The result is shown in Figure 6.4.3.

2. Page 8-1, first paragraph, second sentence, may be should leave off end of sentence “from the Carrizo-Wilcox….” that is not the only cross-formational flow, is it?

Completed. Changed to "from the confined aquifers". See page 8-1.

1. Page 8-4, Section 8.1.2.1, references Figures 8.2.1 to 8.2.6, please correct to Figures 8.1.1 to 8.1.6.

   Changed. See pages 8-4 and 8-5.

3. Page 8-2, last paragraph, it seems like recharge and confining unit Kv are directly correlated

   Completed. This comment is correct. Changed to "directly correlated" on page 8-2.

4. Figures 8.1.2, 8.1.4, 8.1.6, please use different symbols rather than different colors and provide a legend (SOW, Exhibit B, Attachment 1, page 16, figures shall be designed such that a black and white printout is readable and understandable).

   Completed. Updated.

5. Figure 8.1.8, inset figure too small to read. Suggest adding as full page Figure 8.1.8b.

   Completed. Rotated to landscape, Pearson and White picture enlarged.

6. Page 8-19, last paragraph and 8-20 second paragraph, be careful about drawing conclusion from negative results (did not see difference therefore coverage must be adequate), maybe replace "indicates" with "suggests"

   Completed. Suggested change made, page 8-19.

2. Please expand legends to include contour intervals in Figures 8.1.1, 8.1.3, 8.1.5, 8.2.1, 8.2.3, and 8.2.5. In addition, unable to see counties in figures, please adjust.

   Completed. Necessary figure changes made.

3. Please update the following figures with county boundaries: 8.1.2, 8.1.4, 8.1.6, 8.1.7, 8.2.2, 8.2.4, 8.2.6, 8.2.7, 8.3.1, 8.3.2, 8.3.3, 8.3.5, 8.3.7, 8.3.9, and 8.3.10.

   Completed. Necessary figure changes made.

4. The insert of study area in Figures 8.2.1 through 8.2.7 needs to be updated from the southern model area to the central model.

   Completed page 8-34 to 8-40

7. Page 8-28, last paragraph, second to last sentence, please spell out "CZWX"

   Completed page 8-28

8. Page 8-29, third paragraph, last sentence, something missing in "calibration the low conductance"

Completed page 8-29

9. Page 8-30, Section 8.2.2. Central Model Results. Please include an accounting of any dry cells in the discussion, (SOW, Exhibit B, page 10)

Completed page 8-30

10. Page 8-31, 8.2.2.2 Streams. “Non-adequate gage data may explain…” Suggest changing to “A shortage of gage data may explain….”

Completed page 8-31

11. Page 8-31, first paragraph, fourth sentence, spell out “CZWX”

Completed page 8-31

12. Page 8-53, first paragraph, first sentence, “8.1.3.1” should be “8.1.2.1”

Completed. See first paragraph on page 8-51.

13. Page 8-53, second paragraph, second sentence, “Queen City” should be “Sparta”?

Completed. See second paragraph on page 8-51.

14. Page 8-53, third paragraph, second sentence, “Sparta” should be “Queen City”?

Completed. See third paragraph on page 8-51.

15. Page 8-54, second paragraph, fifth sentence, “Figure 4.4.3” should be “Figure 13”

Completed. See second paragraph on page 8-52.

16. Page 8-56, last paragraph, last sentence, “Table 4.5.1” should be “Table 4.6.1”

Completed. See last paragraph on page 8-54.

17. Figure 8.2.2a and 8.2.6a, some of the labels overlap each other and are unreadable. Please separate so that they are all readable.
18. Figure 8.2.4a, please post labels, or use different symbols so that residuals can be distinguished in black and white (SOW, Exhibit B, Attachment 1, page 16, figures shall be designed such that a black and white printout is readable and understandable).
19. Page 8-53, first paragraph, please change figure reference. “Head targets were adjusted in the outcrop as described in 8.1.~~3~~2.1.

Completed. See first paragraph on page 8-51.

5. Unable to locate dry cells in Figures 8.3.4, 8.3.6, or 8.3.8 since color code for dry cells matches contour fills. Please adjust color code for dry cells so they are visible in figures.

Completed. Lighter colors were used for the color floods. See pages 8-57, 8-59, and 8-61.

6. Figures 8.3.13 and 8.3.15 are the same figure, please delete 8.3.15 and update text to reference 8.3.13.

   Completed.

20. Figures 8.3.5a, 8.3.7a, and 8.3.9a, only post labels if they are readable. If there are too many, use only symbols, or label only a few from each range.

    Completed. Labels were removed since it was not possible to post all without overlapping. Symbols were changed to make it easier to distinguish between posted classes. See pages 8-58, 8-60, and 8-62.

21. Figures 8.3.12 and 8.3.13, figures are too small. Please make each full page like the other figures in this section.

    Completed. See pages 8-67 and 8-68.

22. Tables 8.1.3, 8.2.2, and 8.3.2, please mention model (northern, central, or southern) in the Table heading.

    Completed. See page 8-56.

SECTION 9.0: TRANSIENT MODEL

1. For consistency and comparison purposes, please provide the same type figures for all three models. For example, the central and northern model sections include figures of stream leakance and gain/loss graphs which are missing in the southern; hydrographs in central model section include insert of the study area and southern and northern do not; and the central model area section includes a Figure 9.2.20 showing the change of model-wide rates and southern and northern model areas do not. Please include the same kind of figure for the Northern and Southern models.

   Completed. Model-wide rate graphs added to the Northern and Southern sections. Observed head maps for the Queen City and Sparta aquifers added to the Central Sections (pages 9-57, 9-59, 9-61, and 9-63)

2. Please include contour interval in legend for Figures: 9.1.1, 9.1.3, 9.1.5, 9.1.7, 9.1.9, 9.1.11, and 9.1.13.

   Completed.

3. Please update Figures 9.1.1 through 9.1.12 so county boundaries are visible.

   Updated.

4. Please use the same contour intervals in Figure 9.1.7 in the simulated and estimated water levels. Also please insert a space between “aquifer” and “heads” in the caption.

Completed.

5. Page 9-5, second paragraph, second sentence, “because” should be “became”

   Completed. Changed on page 9-5.

6. Page 9-6 states 99 cells were dry at the end of the verification run. Unable to locate dry cells in Figures 9.1.7, 9.1.9, or 9.1.11. Please verify if dry cells were plotted.

   Most of the 99 dry cells were in the Wilcox layers, which are not shown in the Queen City/Sparta model plots. The few dry cells in layers 1, 3, and 5 are shown on the plots.

7. Page 9-7, third paragraph, “HDR estimates, all of which are smaller…” (add of).

   Completed. See page 9-8.

8. Page 9-11, Table 9.1.3, third column, (1980 Reserv.) Sum should be 1,675

   Corrected.

9. Model flow budget for stress period 6 does not match Table 9.1.3 for 1980. Other years do match. Also, layers sums do not match sum row. Please correct table.

   Table corrected.

10. Tables 9.1.3, 9.2.1,9.2.2, 9.2.3, 9.2.4, 9.2.5, 9.3.1 and 9.3.2. Please mention model (northern, central or southern) in the Table heading.

    Completed.

11. Figures 9.1.2, 9.1.4, 9.1.6, 9.1.8, 9.1.10, and 9.1.12. Please use different symbols with a legend so that the Figures can be understood in black and white. Also, please ensure that residual labels are readable and that they aren’t overlapping.

    Completed. Residual labels removed due to number of overlapping points and for consistency with central and northern models. Different symbols used for positive and negative residuals.

12. Page 9-42, fourth paragraph, please clarify what is meant by the sentence “With this conductance, the imposed GHB heads have an effect of extending the model approximately 15 to 20 miles.”

    The following sentence is what was meant “With this conductance and the current transient pumping, the impact of the imposed lateral GHB heads extends approximately 15 to 20 miles from the boundary into the model relative to the no-flow case.” Completed page 9-48.

13. Page 9-43, second paragraph, (Figures 9.2.1 to 9.2.4) typos, please correct unnecessary periods.

Completed.

14. Section 9.2, please provide an accounting of dry cells. (SOW, Exhibit B, page 10).

    Completed on page 9-49

15. Page 9-44, third paragraph, suggest the following change "~~As for the steady-state m~~ Most models are gaining with little change through time."

    Completed on top of page 9-51

16. Page 9-45, second paragraph, suggest "changes in storage are ~~anti~~- negatively correlated…"

    Completed on page 9-51

17. Page 9-45, second paragraph, suggest "storage term ~~does not allow for~~ prevents a simple determination…"

    Completed on page 9-51

18. Page 9-45, third paragraph, "Queen City aquifers, but.." (please add comma)

    Completed on page 9-51

19. Page 9-45, third paragraph, "layers 1 and 3, but .." (please add comma)

    Completed on page 9-51

20. Figures 9.2.6, 9.2.8, 9.2.10, and 9.2.12 please don't overlap labels. Separate so that they are readable.

    Labels were suppressed and more convenient symbols were used instead.

21. Please insert update of study area in Figures 9.2.13a through 9.2.15b from the southern model to the central model study area.

    Figures updated

22. Figure 9.2.28, caption references steady-state sensitivity, please review and verify if figure represents transient or steady-state and either replace figure or correct caption as appropriate.

    Completed on page 9-84

23. Section 9.3, (Northern model) dry cell fill matches contour fill and difficult to locate. Please update dry fill with a contrasting fill so they are visible in the figure.

    Completed. See pages 9-98 to 9-108.

24. Page 9-70, Figure 9.2.19, caption typo “measure~~m~~ed” Please correct

    Completed on page 9-76

25. Page, 9-79, last paragraph, first sentence, “Section 6.3.4” should be “Section 6.3.5”.

    This paragraph was removed from the text.

26. Page 9-82, last paragraph, please indent.

    Completed. See page 9-90.

27. Please update caption of Figure 9.3.1 with year of comparison of gain/loss.

    Completed. Figure caption indicates that simulated gain/loss is the average over 1980-1999. See page 9-116.

28. Section 9.3.2.1, please provide an accounting of dry cells. (SOW, Exhibit B, page 10)

    Completed. See first paragraph on page 9-92.

29. Figures 9.3.8, 9.3.10, 9.3.12, and 9.3.14, please don’t overlap labels. Separate so that they are readable.

    Completed. Labels were removed since it was not possible to post all without overlapping. Symbols were changed to make it easier to distinguish between posted classes. See pages 9-103 to 9-109.

30. Page 9-88, Table 9.3.2, please add asterisk to 1988 in table (drought year?).

    Completed. See page 9-96.

31. Page 9-108, Figure 9.3.21, please label vertical axis.

    Completed. See page 9-116.

32. Page 9-111, Figures 9.3.22 and 9.3.23, please put each figure on full page.

    Completed. See pages 9-120 and 9-121.

33. Sections 9.1, 9.2, and 9.3, please include several figures showing sensitivities of a few hydrographs to various parameters (SOW, Exhibit B, page 17, xxxii)

    Completed. See pages 9-85 and 9-86 and pages 9-125 and 9-126.

SECTION 10.0: PREDICTIONS

1. As noted in the comments for Chapters 8.0, 9.0, and in general, please include contour intervals in legends in all figures showing contours, please redo county boundaries in the

figures in this chapter so they are visible, and please include legend or note in caption of hydrographs for the symbols used for simulated versus measured heads.

Completed. Figure changes made.

1. Page, 10-3, last paragraph, last sentence, "occurring the Wintergarden" should be "occurring in the Wintergarden"

   Completed. See page 10-4.

2. Please include in text for section 10.2, a discussion of the drawdown shown in the figures along the eastern model boundary in Figures 10.2.5, 10.2.6, 10.2.7, 10.2.11, 10.2.12, 10.2.13, and 10.2.14. Is this an artifact of the GHB? Pumpage within the model? Boundary effect?

   Completed. This is the edge of a drawdown cone from pumping in Fayette County that is outside the Southern model, but reflected in the GHB head. If you look at the Central model this effect is very clear. Page 10-3, first paragraph now states this.

2. Section 10.2, please define drawdown as 2000 heads minus heads at the end of the simulation. Note that negative values are rebound and positive values are drawdown.

   Completed. Added to page 10-2, third paragraph.

3. Tables 10.2.1, 10.3.1, and 10.4.1, please add the name of the model to the Table heading (northern, central or southern).

   Completed. Added to tables.

4. Section 10.2, please discuss any additional dry cells that occur in the predictive scenarios (SOW, Exhibit B, page 12, second paragraph).

   Completed. Discussion added to page 10-5, fourth paragraph.

5. Figures 10.2.2 – 10.2.21, please use either a only a 50 foot or only a 100 foot contour interval, don't mix. Combining intervals is misleading.

   All of the contours are at 25 ft intervals with the exception of the "transition" between drawdown and rebound, which is 10 ft. This single exception is necessary to show subtle changes.

6. Figure 10.2.11, page 10-16, what is the origin of the drawdown in Fayette and Lavaca Counties in the Queen City beginning in 2030? Is it due to pumping in Carrizo?

   This is the edge of a drawdown cone from pumping in Fayette and Lavaca counties that is outside the Southern model, but reflected in the GHB heads (boundary heads were updated between models). If you look at the Central model this effect is very clear. Page 10-3, first paragraph now states this.

7. Figures 10.2.2 – 10.2.21, please label all drawdown contours. In black and white prints it is difficult to distinguish drawdown versus rebound.

   Spacing of contours makes labeling difficult, so directional hatching has been added to discriminate between drawdown and rebound.

8. Table 10.2.1 2010 water budget does not match model results. Please verify which is correct and replace as necessary.

   Completed. Table has been updated and is consistent with model.

3. Page 10-18, discusses a 105-foot drawdown in the LaGrange well field. Figure 10.3.13 does not show a 100-foot contour to support this. Please verify if text and figure are in agreement and adjust as needed.

   After correction for pumping, both text (page 10-39, previously 10-38) and figure 10.3.13 are consistent.

4. For consistency between models please add a figure in section 10.3 showing the comparison between 2050 average recharge and 2050 DOR simulation for layers 1,3, and 5.

   Changes completed page 10-66 to 10-67.

9. Also, modeled heads for 2010 do not quite match Figures 10.2.2, 10.2.9, and 10.2.16. Please verify which is correct and replace as necessary.

   The model heads match the figures.

10. Section 10.3.1, please discuss any additional dry cells that occur in the predictive scenarios (SOW, Exhibit B, page 12, second paragraph).

    Changes completed page 10-40.

11. Page 10-37, first paragraph, “We also discuss~~ed~~ changes …” suggest changing tense.

    Changes completed page 10-38.

12. Page 10-37, third paragraph. “feature also appear~~ed~~s in Bastrop…” Suggest changing tense.

    Changes completed page 10-39.

13. Page 10-37, first paragraph, last sentence, “discussed” should be “discuss”

    See answer to comment 11 above.

14. Page 10-38, first paragraph, second sentence, explain the difference in scales on referenced drawdown plots

Consistent scale is now used throughout.

15. Page 10-39, second paragraph, first sentence, "chosen among" should be "chosen from among"

    Change completed page 10-40.

16. Please elaborate on the convergence problems with drought of record 2050 run and possible causes if known. Ideally this problem should be remedied in some way for the final model and report. Differences between results should not be based on solver differences. Also a run time of 50 hours (see model file review section) will make using the model difficult.

    Section added on page10-38.

17. Page 10-38, first paragraph, note that Figures 10.3.2b and 10.3.9b do not have the same scale as the other drawdown plots. They seem the same? Please clarify or correct.

    See answer to comment 14 above.

18. Figures 10.3.2 – 10.3.21, please label drawdown contours, so that drawdown and rebound can be distinguished in a black and white printout.

    Change completed page 10-43 and ff.

19. Figure 10.3.10a, it appears that two sets of contours are overlain. Please correct figure.

    Change completed page 10-51.

20. Page 10-67, third paragraph, "The <u>2000</u> simulated .." Please correct typo.

    Completed. See the third paragraph on page 10-73.

21. Page 10-70, third paragraph, "Drains remove ~~a~~ just over 20,000 …" Please correct typo.

    Completed. See the fourth paragraph on page 10-76.

22. Page 10-73, Table 10.4.1, "No DOR" section not distinguished

    Completed. No DOR water budget flagged. See page 10-80.

5. Section 10.4 for the northern model points out the drawdown along the western edge of the northern model for layer 5. When compared to the central model for the years 2010 and 2020, the cone of the depression does not extend as far as the overlap area. Please review and verify and adjust discussion as needed.

North model drawdowns were shown starting at 10 feet. The smallest drawdown shown for the Central model was 25 feet. Drawdowns along the western edge of the North model did not reach 25 feet until after 2020 and would, therefore, not be seen on the Central figures.

23. Section 10.4.1, Results - please discuss any additional dry cells that occur in the predictive scenarios (SOW, Exhibit B, page 12, second paragraph).

    Completed. See the second paragraph on page 10-75.

24. Figures 10.4.1 – 10.4.18, shading too dark in color. It actually looks better in black and white printout. Suggest using gray scale or lighter color for shading of head maps. Also, the dry cell markers do not show up with shading so no shading would be preferred, rather we recommend using only contours.

    Completed. Lighter colors were used for the color floods.

25. Figures 10.4.1 – 10.4.18. Scales opposite from southern and central for drawdown. Please use same scale. I.e. reds are drawdown and blues are rebound to avoid confusion.

    Completed. The same colors were used for the color floods for Northern, Central, and Southern drawdown maps.

SECTION 11.0: LIMITATIONS OF THE MODEL

1. Page 11-8, first paragraph, please spell out percent rather than using symbol.

   Completed, see Page 11-8.

2. Page 11-1, first paragraph, first sentence, Domenico, 1972, not in References

   Corrected.

3. Page 11-6, last paragraph, last sentence, “produces” should be “produce”

   Completed, see Page 11-6.

4. Page 11-8, second paragraph, first sentence, “GAMs model” should be “GAM models”

   Completed, see Page 11-9.

5. Please include a discussion of dry cells and calculations of aquifer volumes and/or the calculations of aquifer volumes in model areas with high residuals in section 11.3.

   Completed. The model sections 8, 9, and 10 plot and report the number of dry cells for each model. However, they were not a large percentage in these GAMs. A discussion of their significance on calculating aquifer storage in the unconfined model sections (outcrop) is included in Section 11.3, Page 11-8 and 11-9.

SECTION 12.0: FUTURE IMPROVEMENTS

1. Page 12-1, fourth paragraph, please spell out percent rather than using symbol, i.e. 48 percent.

   Completed, see Page 12-1.

2. Page 12-1, second paragraph, second sentence, "additional of water level monitoring and aquifer properties" should be "additional water level monitoring and aquifer property measurement"

   Completed, see Page 12-1.

SECTION 13.0: CONCLUSIONS

1. Page 13-3, first paragraph, "Southern Atascosa County <u>and</u> a broad drawdown …" Please add "and".

   Completed, see Page 13-3.

2. Page 13-1, second paragraph, second to last sentence, "modeled as individual model layers" should be "modeled as an individual model layer"

   Completed, see Page 13-1.

SECTION 14.0: ACKNOWLEDGMENTS

1. Page 14-1, first paragraph, "Southern Carrizo-Wilcox GAM…" should be Queen City Sparta

   Completed, see Page 14-1.

SECTION 15.0: REFERENCES

1. Page 15-1, Anderson, L.E., should there be a ? in the title. Please check and correct if necessary.

   The ? is part of the report title. No change.

2. Page, 15-4, Domenico and Schwartz, is a reference to both editions of this book necessary (1990 and 1998)?

   Completed. The reference to the 1990 version of this book was removed. See page 15-4.

3. Page 15-10, Mace et al., Aquifer misspelled in title. Please correct.

   Completed. See page 15-10.

4. Page 15-13, Toth, 1966, "interpretation of ~~of~~ field…" Typo. Please correct

   Completed. See page 15-13.

5. Page 15-13, Toth, 1966, "International Association of Science …" correct spelling of science.

   Completed. See page 15-13.

APPENDIX A: BRIEF SUMMARY OF HISTORICAL DEVELOPMENT OF THE QUEEN CITY AND SPARTA AQUIFERS ON A COUNTY BY COUNTY BASIS

1. Please change figure references in the second and third paragraph on page A-1 from Figure 2.3 to 2.5.

   Completed. See second and third paragraphs on page A-1.

2. Page A-1, second paragraph, please correct typo "between 1830 and ~~to~~ 1900."

   Completed. See second paragraph on page A-1.

3. Page A-12, first paragraph, "These later formations are rarely …". Please correct.

   Completed. See first paragraph on page A-12.

4. Page A-31, first paragraph, "were reported to go dry during …" Please correct.

   Completed. See page A-31.

APPENDIX B: APPLICATION OF WATER AVAILABILITY MODELS (WAM) FOR THE DEVELOPMENT OF STREAM GAIN-LOSS ESTIMATES

1. Page B-1, second paragraph, "the model boundary ~~and~~ which were selected .." Please correct.

   Completed. See Page B-1.

2. Page B-3, Section 4.0, "Black Cypress Creek were ~~unable to be~~ not studied.." Please replace "unable to be" with "not"

   Completed. See Page B-3.

3. Page B-5, Unit runoff rate equation. Please explain this equation in more detail. What are the variables in the equation?

   Completed. Simplified the equation to the following on Page B-5.

   UNIT RUNOFF RATE = $\sum_{j=1}^{n} \mathrm{NF}(j) \Big/ \sum_{j=1}^{n} \mathrm{DA}(j)$

   where the NF(j) is the Naturalized flow rate of tributary (j) and DA(j) is the drainage area of tributary (j). NF(j) is determined from the WAM model and the Drainage Area of tributary (j) is available from USGS or calculated. The unit runoff rate is the volume of runoff one square mile of land will produce with units of (acre-feet/square mile)

4. Page B-3, please justify the assumption is in the last sentence in section 3.0, “Any such losses are considered small”

   Completed, see Page B-3.

5. When naturalized flow method is used, the median estimate of gain/loss is given; when low-flow method is used, the estimate of gain/loss is under dry condition, which may not represent median condition. Please clarify and justify this approach because this is inconsistent.

   Completed, see Page B-3. The approach was based upon the availability of data and this is expanded upon in the appendix.

6. The gain/loss in the Colorado and in the Rio Grande is stacked on top of spring input. There is nothing wrong with this approach but it should be pointed out more clearly.

   Completed, see Page B-7.

APPENDIX C: STANDARD OPERATING PROCEDURES (SOPs) FOR PROCESSING HISTORICAL PUMPAGE DATA

The SOP is very informative and will be very helpful, especially the Appendix listing all of the database tables. However, there are a few items that should be corrected or clarified.

1. Page C-1, section 1.1, IRR and STK are tabulated by aquifer. Only C-O is not assigned to specific aquifers.

   Corrected, see Page C-1.

2. Page C-14, please correct the spelling of Carrizo (should have only one “z”) in all 4 water use survey tables.

   Completed, see Page C-14.

3. Page C-19, Section 3.2, Table - please add commas to total withdrawals number to separate 1,000s.

   Completed, see Page C-19.

4. Page C-20, Table, Please add commas to total withdrawals number to separate 1,000s

   Completed, see Page C-20.

5. Page C-21, Section 3.3.4, “Using this method 100% of the (remaining unallocated?) pumping was allocated for each used category…”. Should the text in parenthesis be added for clarity? Is it correct?

   Completed, see Page C-21 Used suggested clarification.

6. Page C-26, Section 3.9.1, incomplete sentence. Has something been left out? Please clarify.

Completed, see Page C-26.

7. Page C-29, Figure 6, please make rangeland darker and/or background lighter. The map is difficult to read.

   Completed, see Page C-29, Printed in Color.

8. Page C-34, Section 5, please expand discussion of vertical assignment of pumpage. Aquifer assignments are not listed for rural domestic use in the pumpage data. How was rural domestic assigned vertically? Was well specific data assigned based on intersection of the well depth with grid or based on water use data? Please clarify.

   Completed, see Page C-34.

APPENDIX D: STANDARD OPERATING PROCEDURES (SOPs) FOR PROCESSING PREDICTIVE PUMPAGE DATA

1. Page D-2, Section 4.2, please discuss the exceptions in the strategy for assigning predictive pumpage to well locations if wells could not located. For example discuss Municipal pumpage for LaGrange, Queen City Sparta mining, and Lee-Colorado Manufacturing.

   Completed, see Pages D-2 and D-3.

APPENDIX E: COMMENTS AND RESPONSES

1. Several of the conceptual model comments were not actually addressed even though they are listed as being addressed in this section. Please verify that all comments are addressed and describe how they have been addressed for both the final draft comments and for the conceptual model comments. It will expedite the final review process if you include the new page number(s) and/or figure number(s) in your responses.

   Completed. TWDB stated that any comments not dispositioned were identified. We have responded to all comments above with page number where applicable.

FINAL DRAFT MODEL COMMENTS

Since the Queen City – Sparta GAM consists of three separate models this section is separated into comments on the Northern, Central, and Southern models.

Northern GAM:

All files required to run the steady-state, transient (1975 – 1999), and predictive (2000 – 2050) models were included. With exceptions noted below for the most part the models ran with no problems and modeled heads matched those presented in the draft report. Also, it was noted that this was one of the few submitted models that actually had the files named correctly, by model and scenario. The borehole files were submitted as well.

1. The flow budget for the predictive runs 2010, 2020, 2030, 2040, 2050 and 2050 did not match the report table 10.4.1. The wells were about 10,000 acre-ft/year higher than

listed in the report, with most of the difference coming from storage and some coming from streams. In other words the well files included with the predictive model do not agree with the report. Please either correct the report or provide correct model files.

Completed. Table 10.4.1 was rebuilt.

2. The well file included with the transient model mostly agrees; however, wells in 1999 are off by 1,000 acre-ft/year most of the disagreement is in layer 8 (168,908 afy vs 167,930 afy in Table 9.3.2). It may be that the report table should be updated.

   Completed. Table 9.3.2 was rebuilt.

3. In addition, please include a readme file listing all special instructions, e.g., instructions to not re-write stream and reservoir packages and to use the included modflow executable if that is the case.

   Completed. An instruction file has been included.

4. Also, if the cell-by-cell flow is written for all 76 stress periods of the 2050 runs, then the 2.0 Gigabyte file limit will be exceeded. Those runs should have less frequent stress periods written and instructions to that effect should be listed in the readme.

   Completed. The output control files were modified to output only the last time step for each stress period and a note has been added to the instructions file.

5. Please include Autocad DXF map files with the models, per Exhibit B (SOW) Attachment 1 p. 14, and in addition, the coordinate system in all of the PMWIN files needs to be referenced to real world GAM coordinates (not local model coordinates) for the map DXF files to display. In other words,
   Xo = 5,794,171
   Yo = 2.015658E+07
   Ao = 29.10626
   With x1 and y1 corrected also to allow map to be seen in real world coordinates. Please update the PMWIN files.

   Completed. DXF files are included and coordinates have been set.

Review of Northern Model Pumpage
TWDB staff extracted pumpage from the input model files (wel.dat) for selected years for all layers and compared the summed results at the county level to the raw pumpage summed at the county level using Queen City, Sparta, and Carrizo-Wilcox designated pumpage and unassigned rural domestic (the unassigned rural domestic only applies to the historic review). A county was assigned to each grid cell centroid in GIS and the model pumpage was summed by county based on the county grid cell assignments. In the comparison, a ten percent difference in pumping in either direction was allowed to account for errors due to grid cells split across more than one county. The results are listed in the attached excel tables:

48_qcsp_NorthernComparison_1984to1997.xls and
QCSP_04_PredictCompareNorthernModelRaw.xls

In the northern model for the transient model seven counties fall outside of the 10 percent error range. Green indicates model pumpage too high, orange indicates model pumpage too low. A few counties have problems only for one or two years. In the predictive model nine counties fall out of range. In the predictive model, aquifers are specified for distributed pumpage therefore for livestock, irrigation, and rural domestic, even if the aquifers are over only part of the county, 100% of the pumpage should be in the model. The exception is if the county is not fully within the grid (between north and central and central and south). These exceptions are flagged in the spreadsheet analysis as "split". Some of the counties that are flagged as having too much pumpage in the predictive may be due to "regional" strategies that were not listed with sufficient detail in the raw datasets to query. Please check the pumpage assignment for those out of range counties. If there is a very good reason for the discrepancies please document the reason. Otherwise please correct the pumpage input and adjust all tables, discussions, and figures that are impacted in the report.

The TWDB identified pumping differences that exceeded 10 % in the following counties and requested that these differences be investigated:

Angelina - 1984-97, Predictive
Bowie - Predictive
Cass - Predictive
Franklin - Predictive
Hopkins - Predictive
Houston - 1984-97
Leon - 1987
Madison - 1987, 1992-97
Marion - Predictive
Nacogdoches - 1984-97, Predictive
Navarro – Predictive
Rains - 1997
Red River - 1984-97
San Augustine - 1986-97
Trinity - 1984-97
Upshur - Predictive

Pumping for the Northern model was reviewed in two steps. First, Sparta and Queen City pumping values for each county for each year were checked. This was done for all counties. After the review of the Sparta and Queen City pumping, which showed agreement between the TWDB data and the model pumping, we looked at the Carrizo-Wilcox pumping for the above listed counties.

Pumping for the Sparta and Queen City aquifers was summed by year (stress period) by county (grid cell assignments for each county can be found in the pumping source data in the data model) from the MODFLOW input "wel" file. These results were compared to pumping summed from the TWDB master pumping files. For the historical period, rural domestic was allocated to the individual aquifers based on allocation factors developed for each county. The file "North_model_Queen_City-Sparta_pumping _QA.xls", included with the data model, contains the comparisons for the Sparta and Queen City pumping. Comparisons were done for the historical pumping (1980-1997) and predictive pumping (2000-2050). 1998 and 1999 were not included because irrigation and livestock pumping were not available in the TWDB files for those years. It should be noted that there will be

some differences for the years 1995-1997 resulting from the extrapolation of rural domestic pumping performed for those years (see attached memorandum).

The summed pumping was compared for all counties that did not intersect a lateral boundary of the model. During the historical period, differences that exceeded 10% occurred in Trinity County (1995-1997), Henderson County (1997), and Morris County (1997). All of these occurred during the extrapolation period and are, therefore, not unexpected. During the predictive period, differences that exceeded 10% occurred in Leon County. However, this difference was less than 1.5 AFY for all years. Based on these results, it was determined that the pumping differences noted by the TWDB were the result of differences in the Carrizo-Wilcox pumping, which is based on the pumping datasets for the Carrizo-Wilcox GAMs (See Section 6.3.6 of this report).

Pumping differences in Angelina and Nacogdoches counties are the result of the paper mill pumping (Donohue Industries) near the Angelina-Nacogdoches county line. The pumping for Donohue Industries is assigned to Angelina County in the TWDB manufacturing pumping file (Manufacturing_Master_Post1980_052402.xls). However, the wells associated with this manufacturer are located in both Angelina and Nacogdoches counties. In order to check the model pumping in Nacogdoches County, pumping from Nacogdoches and Angelina counties was summed for each year. When this was done, the combined model pumping for both counties agrees for all years.

Differences in historical pumping noted in Houston, Madison, Red River, and Trinity counties are the result of rural domestic allocation factors for the three aquifers that sum to a value less than one. This happens in counties where some of the rural domestic pumping comes from formations older or younger than the modeled aquifers. For instance, almost all of Red River County is updip of the Wilcox, so none of the rural domestic pumping was assigned to the Wilcox.

The remaining differences are the result of differences carried through from the Carrizo-Wilcox GAMs. Carrizo-Wilcox pumping, other than the reallocation of rural domestic, is the same as the pumping in the Carrizo-Wilcox GAMs since modifying the Carrizo-Wilcox pumping was not within the Scope of Work for the Queen City and Sparta GAM.

Central GAM:
All files required to run the steady-state, transient (1975 – 1999), and predictive (2000 – 2050) models were included. With exceptions noted below, most of the models ran with no problems and modeled heads matched those presented in the draft report.

1. The predictive 2050 drought or record (DOR) run requires 50 hours to run on a 2.0 Gigabyte machine because the SIP solver is required since the run will not converge in the last stress period using the PCG2 solver. Please investigate and see if it is possible to remedy this convergence problem. Model users will primarily be using the 2050 DOR scenario to develop availability numbers and 50 hours for a single run will make this procedure very time consuming.

This is addressed in Section 10.3. The SIP solver is still necessary for complete convergence. The PCG2 solver is faster, but fails shortly before the end. Models with both solvers are included in the data model, with a short explanation.

2. Please include a readme file listing all special instructions, e.g., instructions to not re-write stream and reservoir packages and to use the included modflow executable if that is the case.

These instructions are part of the general model instructions in the root of the modflow directory.

3. Also the MODFLOW stream input (str1.dat), reservoir input (res1.dat), and output control files (oc.dat) should be included with the PMWIN files for each scenario since those files should not be regenerated by PMWIN.

Completed.

4. If borehole and observation data files are available we request that those also be included with the PM files.

Completed.

Review of Central Model Pumpage
TWDB staff extracted pumpage from the input model files (wel.dat) for selected years for all layers and compared the summed results at the county level to the raw pumpage summed at the county level using Queen City, Sparta, and Carrizo-Wilcox designated pumpage and unassigned rural domestic (the unassigned rural domestic only applies to the historic review). A county was assigned to each grid cell centroid in GIS and the model pumpage was summed by county based on the county grid cell assignments. In the comparison, a ten percent difference in pumping in either direction was allowed to account for errors due to grid cells split across more than one county. The results are listed in the attached excel tables:

47_qcsp_CentralComparison_1984to1997.xls and
QCSP_03_PredictCompareCentralModelRaw.xls

In the central model for the transient model six counties consistently fall outside of the 10 percent error range. Green indicates model pumpage too high, orange indicates model pumpage too low. A few counties have problems only for one or two years. In the predictive model twelve counties fall out of range. In the predictive model, aquifers are specified for distributed pumpage therefore for livestock, irrigation, and rural domestic, even if the aquifers are over only part of the county, 100% of the pumpage should be in the model. The exception is if the county is not fully within the grid (between north and central and central and south). These exceptions are flagged in the spreadsheet analysis as "split". Some of the counties that are flagged as having too much pumpage in the predictive may be due to "regional" strategies that were not listed with sufficient detail in the raw datasets to query. Please check the pumpage assignment for those out of range counties. If there is a very good reason for the discrepancies please document the reason. Otherwise please correct the pumpage input and adjust all tables, discussions, and figures that are impacted in the report.

The TWDB identified pumping differences that exceeded 10 % in the following counties and requested that these differences be investigated:

Angelina - 1984-97, Predictive
Bastrop - Predictive
Burleson – 2020
Falls – Predictive
Fayette – Predictive
Gonzales – Predictive
Grimes – Predictive
Guadalupe - 1997
Houston - 1984-97
Lee – 1994-97, Predictive
Madison - 1987-97
Milam – 1988, 1991, Predictive
Nacogdoches - 1984-97, Predictive
Navarro - Predictive
Robertson – 1984-93, 1997, Predictive
Wilson –Predictive

Pumping for the Central model was reviewed in two steps. First, Sparta and Queen City pumping values for each county for each year were checked. This was done for all counties. After the review of the Sparta and Queen City pumping, which showed agreement between the TWDB data and the model pumping, we looked at the Carrizo-Wilcox pumping for the above listed counties.

Pumping for the Sparta and Queen City aquifers was summed by year (stress period) by county (grid cell assignments for each county can be found in the pumping source data in the data model) from the MODFLOW input "wel" file. These results were compared to pumping summed from the TWDB master pumping files. For the historical period, rural domestic was allocated to the individual aquifers based on allocation factors developed for each county. The file "Central_model_Queen_City-Sparta_pumping _QA.xls", included with the data model, contains the comparisons for the Sparta and Queen City pumping. Comparisons were done for the historical pumping (1980-1997) and predictive pumping (2000-2050). 1998 and 1999 were not included because irrigation and livestock pumping were not available in the TWDB files for those years. It should be noted that there will be some differences for the years 1995-1997 resulting from the extrapolation of rural domestic pumping performed for those years (see attached memorandum).

The summed pumping was compared for all counties that did not intersect a lateral boundary of the model. During the historical period, differences that exceeded 10%

occurred in Bastrop County (1995-1997), Brazos County (1995-1997), Madison County (1996), and Trinity County (1995-1997). All of these occurred during the extrapolation period and are, therefore, not unexpected. During the predictive period, differences that exceeded 10% occurred in Lee and Leon counties. However, these differences were less than 1.5 AFY for all years for Leon County and less than 4.5 AFY for all years for Lee County. Based on these results, it was determined that the pumping differences noted by the TWDB were the result of differences in the Carrizo-Wilcox pumping, which is based on the pumping datasets for the Carrizo-Wilcox GAMs (See Section 6.3.6 of this report).

Pumping differences in Angelina and Nacogdoches counties are the result of the paper mill pumping (Donohue Industries) near the Angelina-Nacogdoches county line. The pumping for Donohue Industries is assigned to Angelina County in the TWDB manufacturing pumping file (Manufacturing_Master_Post1980_052402.xls). However, the wells associated with this manufacturer are located in both Angelina and Nacogdoches counties. In order to check the model pumping in Nacogdoches County, pumping from Nacogdoches and Angelina counties was summed for each year. When this was done, the combined model pumping for both counties agrees for all years.

Differences in historical pumping noted in Houston and Madison counties are the result of rural domestic allocation factors for the three aquifers that sum to a value less than one. This happens in counties where some of the rural domestic pumping comes from formations younger than the modeled aquifers.

The remaining differences are the result of differences carried through from the Carrizo-Wilcox GAMs. Carrizo-Wilcox pumping, other than the reallocation of rural domestic, is the same as the pumping in the Carrizo-Wilcox GAMs since modifying the Carrizo-Wilcox pumping was not within the Scope of Work for the Queen City and Sparta GAM.

Southern GAM:
All files required to run the steady-state, transient (1975 – 1999), and predictive (2000 – 2050) models were included. With exceptions noted below for the most part the models ran with no problems and modeled heads matched those presented in the draft report. Also, we should note that this was one of the few submitted models that actually has the files named correctly, by model and scenario. We also appreciate that the borehole files were submitted as well.

1. Please include AutoCAD DXF map files with the models, per Exhibit B (SOW) Attachment 1 p. 14.

   Completed. Maps now included.

2. Please contour all head plots with either only 50 foot or only 100-foot intervals. Combining intervals when not all contours are labeled is misleading.

   Addressed in report section.

3. Model flow budget does not match Table 9.1.3 for 1980 only. Other years match. Please correct table.

   Completed. Table corrected.

4. Please set stream unit output for cell-by-cell flow, ISTCB1 = 50, in str1.dat so that the streams will be included in the budget calculations.

   Corrected in steady-state model.

5. Scenario 2010 results including head plots and budget do not match the report. The storage, wells and ghb flows do not agree with Table 10.2.1. Please either correct table and figures or provide correct model file set.

   Completed. Table corrected.

Review of Southern Model Pumpage
TWDB staff extracted pumpage from the input model files (wel.dat) for selected years for all layers and compared the summed results at the county level to the raw pumpage summed at the county level using Queen City, Sparta, and Carrizo-Wilcox designated pumpage and unassigned rural domestic (the unassigned rural domestic only applies to the historic review). A county was assigned to each grid cell centroid in GIS and the model pumpage was summed by county based on the county grid cell assignments. In the comparison a ten percent difference in pumping in either direction was allowed to account for errors due to grid cells split across more than one county. The results are listed in the attached excel tables:

49_qcsp_SouthernComparison_1984to1997.xls and
QCSP_05_PredictCompareSouthernModelRaw.xls

In the southern model for the transient model one county consistently falls outside of the 10 percent error range. Green indicates model pumpage too high, orange indicates model pumpage too low. Two counties have problems only for one or two years. In the predictive model six counties fall out of range. In the predictive model, aquifers are specified for distributed pumpage therefore for livestock, irrigation, and rural domestic, even if the aquifers are over only part of the county, 100% of the pumpage should be in the model. The exception is if the county is not fully within the grid (between north and central and central and south).These exceptions are flagged in the spreadsheet analysis as "split". Some of the counties that are flagged as having too much pumpage in the predictive may be due to "regional" strategies that were not listed with sufficient detail in the raw datasets to query. Please check the pumpage assignment for those out of range counties. If there is a very good reason for the discrepancies please document the reason. Otherwise please correct the pumpage input and adjust all tables, discussions, and figures that are impacted in the report.

The TWDB identified pumping differences that exceeded 10 % in the following counties and requested that these differences be investigated:

Bexar – 1996
Gonzales - Predictive
Guadalupe – 1997
Karnes - Predictive
Live Oak - Predictive
Maverick - Predictive
McMullen - 1984-97, Predictive
Wilson – Predictive

Pumping for the Southern model was reviewed in two steps. First, Sparta and Queen City pumping values for each county for each year were checked. This was done for all counties. After the review of the Sparta and Queen City pumping, which showed agreement between the TWDB data and the model pumping, we looked at the Carrizo-Wilcox pumping for the above listed counties.

Pumping for the Sparta and Queen City aquifers was summed by year (stress period) by county (grid cell assignments for each county can be found in the pumping source data in the data model) from the MODFLOW input "wel" file. These results were compared to pumping summed from the TWDB master pumping files. For the historical period, rural domestic was allocated to the individual aquifers based on allocation factors developed for each county. The file "South_model_Queen_City-Sparta_pumping _QA.xls", included with the data model, contains the comparisons for the Sparta and Queen City pumping. Comparisons were done for the historical pumping (1980-1997) and predictive pumping (2000-2050). 1998 and 1999 were not included because irrigation and livestock pumping were not available in the TWDB files for those years. It should be noted that there will be some differences for the years 1995-1997 resulting from the extrapolation of rural domestic pumping performed for those years (see attached memorandum).

The summed pumping was compared for all counties that did not intersect a lateral boundary of the model. During the historical period, differences that exceeded 10% occurred in Frio County (1995 and 1996) and LaSalle County (1980-1997). The noted differences in Frio County occurred during the extrapolation period and are, therefore, not unexpected. The differences in LaSalle County were less than 1.5 AFY for all years. During the predictive period, no differences exceeded 10%.

Based on the results of the Sparta and Queen City pumping review, it was determined that the pumping differences noted by the TWDB were the result of differences in the Carrizo-Wilcox pumping, which is based on the pumping datasets for the Carrizo-Wilcox GAMs (See Section 6.3.6 of this report). Carrizo-Wilcox pumping, other than the reallocation of rural domestic, is the same as the pumping in the Carrizo-Wilcox GAMs since modifying the Carrizo-Wilcox pumping was not within the Scope of Work for the Queen City and Sparta GAM.

PUBLIC REVIEW COMMENTS OF FINAL DRAFT REPORT:

The following comments were received by e-mail from one stakeholder:

On the whole, I found the draft report very well written and no more confusing that I would expect a report on work of this magnitude and complexity. The graphics are good, if, of necessity, a little small. My greatest concern is that the models are so complex, underlain by a multitude of decisions and assumptions that few other than those who developed the models will really understand them. I worry, too, that our ability to process information numerically has outstripped our ability to comprehend fully what we are doing.

Minor Comments

1. P. 2-25, second paragraph: did you mean to use Paleogene rather than Paleocene? You use Paleocene in Figure 2.18 on P. 2-30.

   Checked. Paleocene was correct.

2. P. 4-4, top partial paragraph: before 4.2.2 heading, last sentence: did you mean antithetic rather than synthetic?

   Corrected. See Page 4-4.

3. P. 4-62, first full paragraph, first sentence: I still want to know why Bastrop is excepted?

   Text was clarified to say that Bastrop County is excepted because it had a slope of 0.84, see Page 4-61.

4. P. 5-5, first full paragraph, first sentence: something appears to be missing from this sentence.

   Corrected. See Page 5-5.

5. P. 6-13, second paragraph of Section 6.3.4: how does this treatment of the faults differ from that in the early GAM for just the Carrizo-Wilcox?

   This treatment is similar to what was done for the Southern and Northern Carrizo-Wilcox GAMs and is different from the Central Carrizo-Wilcox approach where they assumed all faults were barriers to flow.

6. P. 6-13, Section 6.3.5: something also appears to be missing from the next to the last sentence in the first paragraph of this section.

   Corrected. See Page 6-14.

7. P. 6-20, Table 6.3.5: Where is the information for Lee and Williamson counties?

   Lee and Williamson Counties are not in the GAM overlap regions so are not covered by this table.

8. P. 8-29, Section 8.2.1.4, last sentence: needs some editing.

   Sentence adjusted. Completed page 8-29

9. P. 8-31, Section 8.2.2.3: I presume that the figure of 44,000 AFY applied to all the aquifers modeled and not just the Queen City and Sparta.

   Yes, as stated in the report page 8-31: "It amounts to about 44,000 AFY for the 8 modeled layers."

10. P. 9-49, Table 9.2.4: this table appears to be a direct reflection on how MODFLOW looks at a water balance, but will be confusing to anyone unfamiliar with that because of the reversal of the signs; i.e., a positive change in storage is a decrease not an increase. Some explanation may help

    Mass balance tables can truly be confusing. The best way to sort things out is to look at parameters whose flux relative to the aquifer is well-known (i.e., recharge

water is always added to the aquifer while ET and wells remove water from the aquifer).

P. 9-71, Figure 9.2.20: is there some explanation for the rather odd, almost-mirror image changes in recharge and storage?

The figure shows a global mass balance (for clarity, side and boundary fluxes are not included because they are relatively small) with positive values indicating water added to the aquifer while negative values indicating water removed form the aquifer. Stream leakage, pumping, and ET are shown as negative on the plot and indicate that water is leaving the aquifer at a constant rate, at first approximation. On the other hand, recharge is always positive because water is added to the aquifer. The change in storage can be positive or negative and closely follows and balances recharge variations.