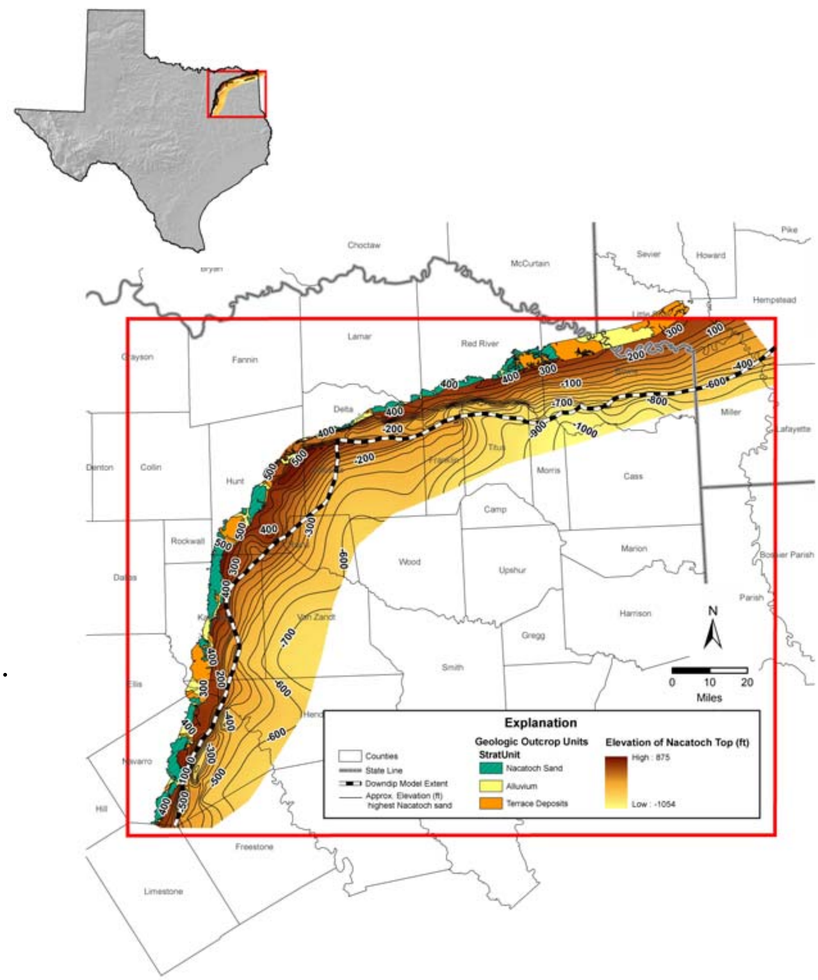
Final Report

Nacatoch Aquifer
Groundwater Availability Model



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Prepared for the

Texas Water Development Board

P.O. Box 1321, Capitol Station
Austin, Texas 78711-3231

January 2009

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This report documents the work of the following Licensed Texas Geoscientist or Licensed Texas Professional Engineer:

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Mr. Beach was the Project Manager and was responsible for overseeing the development of the conceptual model, and for development and calibration of the numerical model.

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EXECUTIVE SUMMARY

The Nacatoch aquifer occurs along a narrow band in northeast and north-central Texas. It is source of water for municipal, domestic and other users within its extent. The Nacatoch Groundwater Availability Model was developed as a tool to better understand the flow system within the aquifer and to support planning efforts.

The conceptual model divides the aquifer system into two layers. The top layer represents the Midway confining unit except in areas where river alluvium and terrace deposits overlay the Nacatoch sands. The bottom layer represents the Nacatoch sands. In areas where the alluvium and terrace deposits are present, they are generally interconnected with the Nacatoch. Underlying the Nacatoch is the Neylandville or Marlbrook unit, which is treated as no flow boundary in the model. The Nacatoch and alluvium deposits receive recharge from precipitation and groundwater discharges to local streams and rivers and is lost to evapotranspiration.

The groundwater flow model was developed with the MODFLOW-2000 groundwater flow code. The model is regional in scale and was calibrated for a predevelopment period and a transient period from 1980 through 1997. The interaction between surface water features and groundwater is simulated in the model using the MODFLOW stream package. Recharge into the Nacatoch aquifer was estimated through baseflow regression analysis and varies with annual precipitation. Evapotranspiration was simulated in the riparian area and a vegetation coefficient was used to adjust potential evapotranspiration for different types of vegetation. Initial estimates of aquifer hydraulic properties were estimated from existing aquifer test data, but the data were limited. Therefore, initial hydraulic property distributions were adjusted during calibration.

The mean absolute error (MAE) of the steady-state calibration targets for the Nacatoch (layer 2) was 22 feet over a range of 337 feet, resulting in a MAE/range ratio of 6.5%. The transient calibration was somewhat limited because most of the transient responses in the aquifer were due to local pumping. Calibration for some individual wells was not as good as calibration of the region. These limitations may be related to limited number of estimates or limited accuracy in the estimates of hydraulic conductivity, storage properties, or historical pumping

estimates. For the transient calibration in layer 2, MAE was 30 feet over a range of 386 feet for (a ratio of 7.8%). These statistics indicate that the model provides a reasonable historical match.

1.0 INTRODUCTION

The Nacatoch Aquifer of northeast Texas occurs in a narrow band of sandstone and clay beds that extend from central Texas north and eastward to and beyond the border with Arkansas and Louisiana. Limited in aerial extent and supply capacity, The Texas Water Development Board (TWDB) classifies the Nacatoch Aquifer as a “Minor Aquifer” (Ashworth and Hopkins, 1995a; Ashworth and Hopkins, 1995b; Texas Water Development Board, 2007b). However, to local citizens, the aquifer provides the primary source of groundwater for private domestic and livestock use, and is an important back-up supply for the community of Commerce to meet peak and drought demand. The Region D-North East Texas Water Planning Group recommends new and supplemental Nacatoch Aquifer groundwater wells as a water management strategy to meet future water needs. This report describes the hydrologic flow characteristics of the Nacatoch Aquifer that were evaluated to establish a conceptual model of the groundwater flow system that is the basis for a groundwater availability model (GAM).

The goal of the TWDB GAM program is to provide reliable information on groundwater availability to the citizens of Texas to ensure adequate supplies or recognize inadequate supplies over a 50-year planning period. The Nacatoch Aquifer GAM conceptual model was developed by assimilating and assessing available scientific information about the aquifers in the study area. The Nacatoch Aquifer model boundary encompasses the Nacatoch Aquifer formation outcrop and downdip subcrop extent north and west of the Mexia-Talco Fault Zone containing less than 3,000 mg/L total dissolved solids (TDS). For the current study, existing data was assimilated in the model area to define:

- Physiography, climate, vegetation, and land use
- Geology, hydrostratigraphy and structure
- Groundwater quality
- Hydraulic properties
- Surface water and groundwater interaction
- Recharge rates
- Water levels
- Pumping rates

The Nacatoch Aquifer GAM numerical computer model (constructed using the MODFLOW code) of the aquifer provides a scientific, quantitative tool to evaluate aquifer responses to current and projected pumping and to assist in regional water planning efforts and aquifer management decisions. The TWDB GAM program allowed stakeholders the opportunity to provide input and comments during the conceptual model development. The result is a standardized, thoroughly documented, and publicly available numerical groundwater flow model and support information.

The Nacatoch Aquifer GAM can be used as a water management evaluation tool by regional water planning groups, groundwater management areas, and groundwater conservation districts.

2.0 STUDY AREA

2.1 Location

The Nacatoch Aquifer of northeast Texas occurs in a narrow band that extends from near the Navarro-Limestone County line northward through the communities of Kaufman and Commerce, and then eastward through Bowie County and beyond into Arkansas (Figure 2.1.1) (Ashworth and Hopkins, 1995b). Shown in this figure, a boundary labeled “Study Area” was constructed encompassing the generalized area of interest in the model area. Geologic mapping of the Nacatoch Aquifer extends further southward through Limestone and Falls Counties; however, the Nacatoch Aquifer in this area is recognized as non-water bearing and is therefore not included in the aquifer delineation. The project area includes the Nacatoch Aquifer outcrop, local alluvium and terrace deposits, and its downdip / subsurface extent for a distance from zero to approximately 15 miles. Due to faulting, very little outcrop occurs in the central portion of the aquifer extent in the general area of the City of Commerce. The project area also extends a short distance across the State line into Arkansas.

Significant areas of the lateral outcrop are covered by silt and sand floodplain deposits shown in Figure 2.1.1 as alluvium and terrace deposits. These deposits are associated from east to west with the Red, Sulphur, Sabine, and Trinity Rivers; and in its southernmost extent in Navarro County, by Chambers and Richland Creeks. Figure 2.1.2 shows the river basins, major rivers and streams, and major reservoirs in the study area. The study area largely impacts five river authorities: (1) the Trinity River Authority, (2) the Angelina-Neches River Authority, (3) the Sabine River Authority, (4) the Sulphur River Basin Authority, and (5) the Red River Authority. A more detailed discussion of rivers, streams, and reservoirs is provided in Section 4.5 of this report.

The Nacatoch Aquifer occurs between other major and minor aquifers. Older aquifer formations in the area include the Woodbine and Blossom minor aquifers, which underlie the Nacatoch Aquifer. Separated primarily by the Midway formation, the Carrizo-Wilcox major aquifer overlies the Nacatoch Aquifer further downdip. These aquifer boundaries as established by the TWDB are available as ArcGIS shapefiles on the Texas Natural Resources Information System (TNRIS) website (http://www.tnris.state.tx.us/) and as PDF files on the TWDB website (http://www.twdb.state.tx.us/). Figure 2.1.3 shows a portion of two major aquifers, the Trinity and the Carrizo-Wilcox; while Figure 2.1.4 shows a portion of five minor aquifers including the Nacatoch, Woodbine, Blossom, Queen City, and Sparta.

The study area is contained within two water planning regions, Region C in the southwestern half and Regions D (North East Texas) in the northern half (Figure 2.1.5). Only the western Henderson County portion of the Neches and Trinity Valleys Groundwater Conservation District is impacted significantly by the study area, although Freestone County of the Mid-East Texas Groundwater Conservation District lies only slightly outside the area (Figure 2.1.6). The downdip limit of the Nacatoch Aquifer generally occurs at the eastern border of Groundwater Management Area 8, while Groundwater Management Area 11 lies immediately to the east (Figure 2.1.7).

Groundwater model boundaries are typically defined on the basis of surface or groundwater hydrologic boundaries. The study area encompassing the Nacatoch Aquifer GAM is laterally bounded by the aquifer extent in Nacatoch Aquifer outcrop and overlying units in the southwest and in southwestern Arkansas. Towards southeast and northeast, the model is bounded by Mexia-Talco Fault Zone containing less than 3,000 mg/L total dissolved solids (TDS). The lower vertical model boundary is the base of the lowest most sand unit in the Nacatoch Aquifer formation.

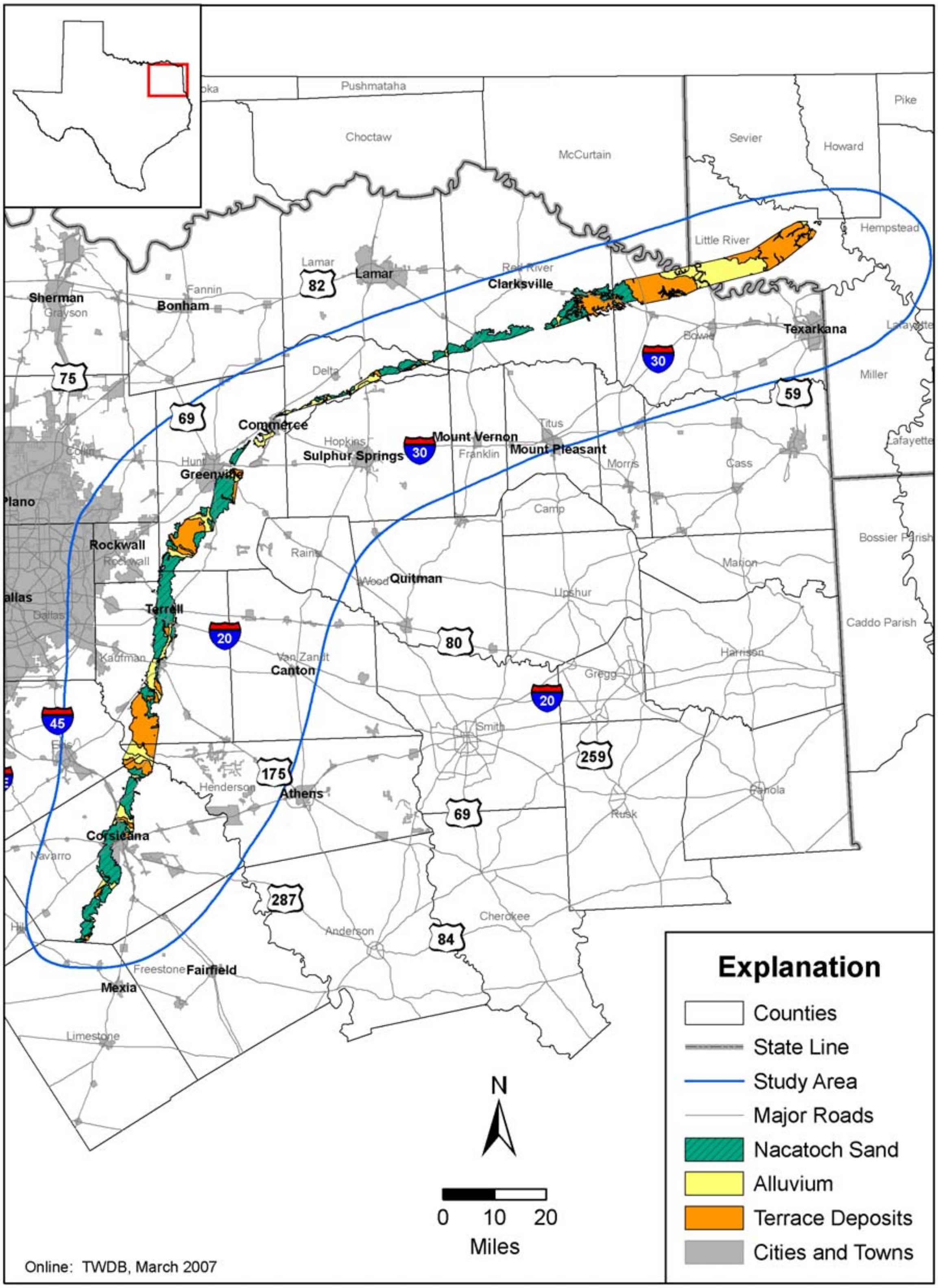


Figure 2.1.1 Location of the Nacatoch Aquifer GAM study area

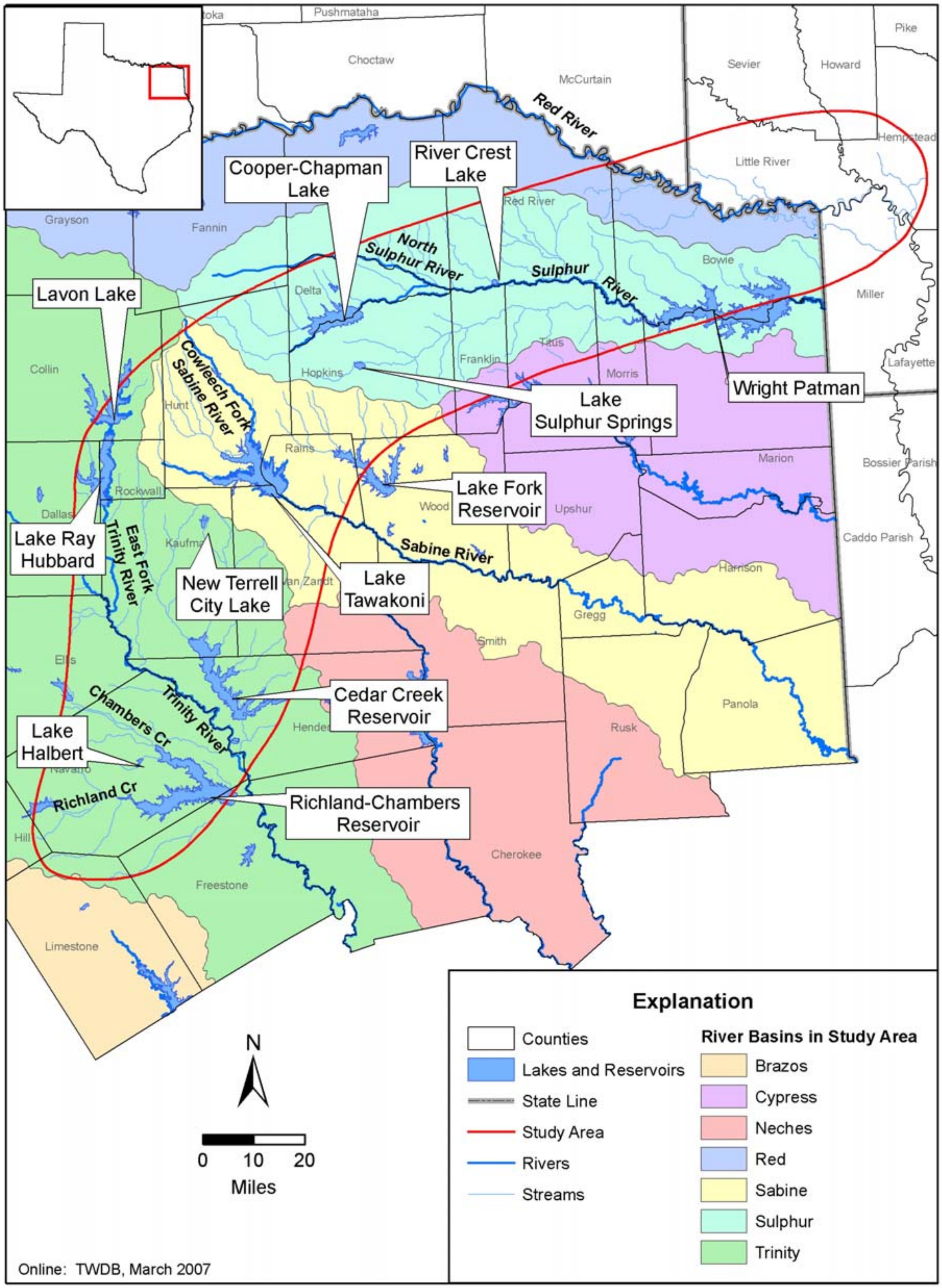


Figure 2.1.2 Location of river basins, rivers, significant streams, and reservoirs

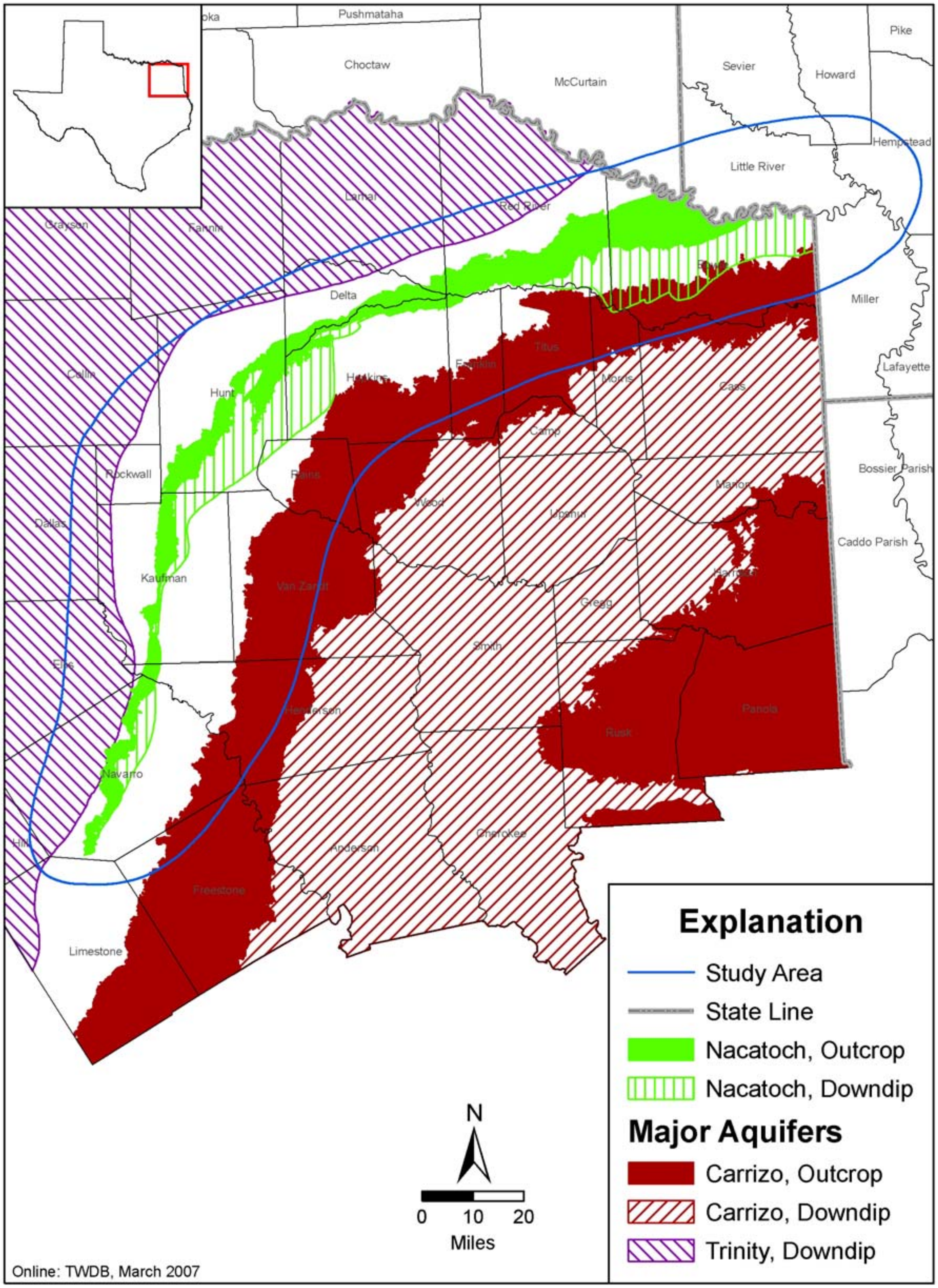


Figure 2.1.3 Areal extent of the Nacatoch and major aquifers in the study area

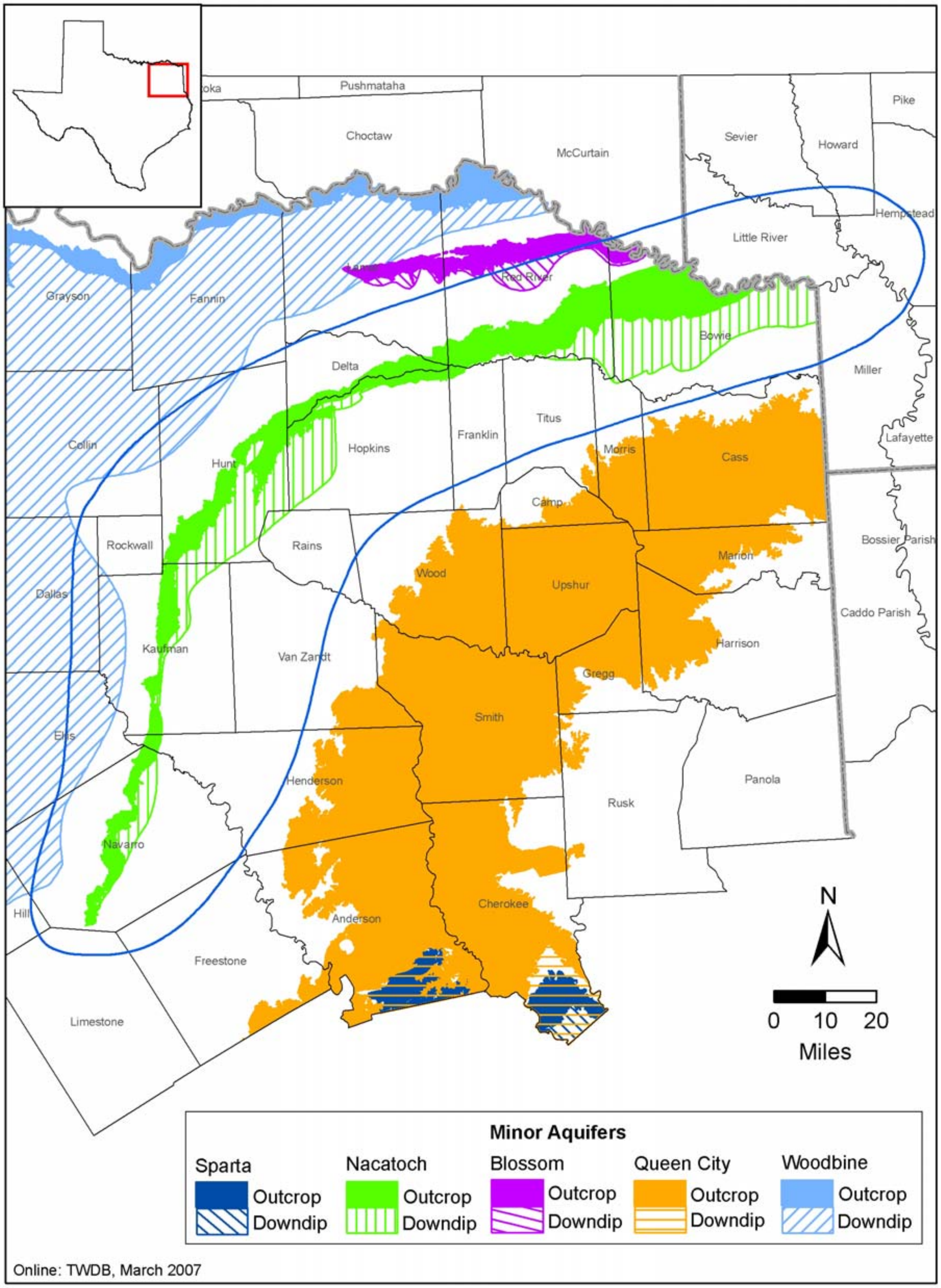


Figure 2.1.4 Areal extent of the minor aquifers in the study area

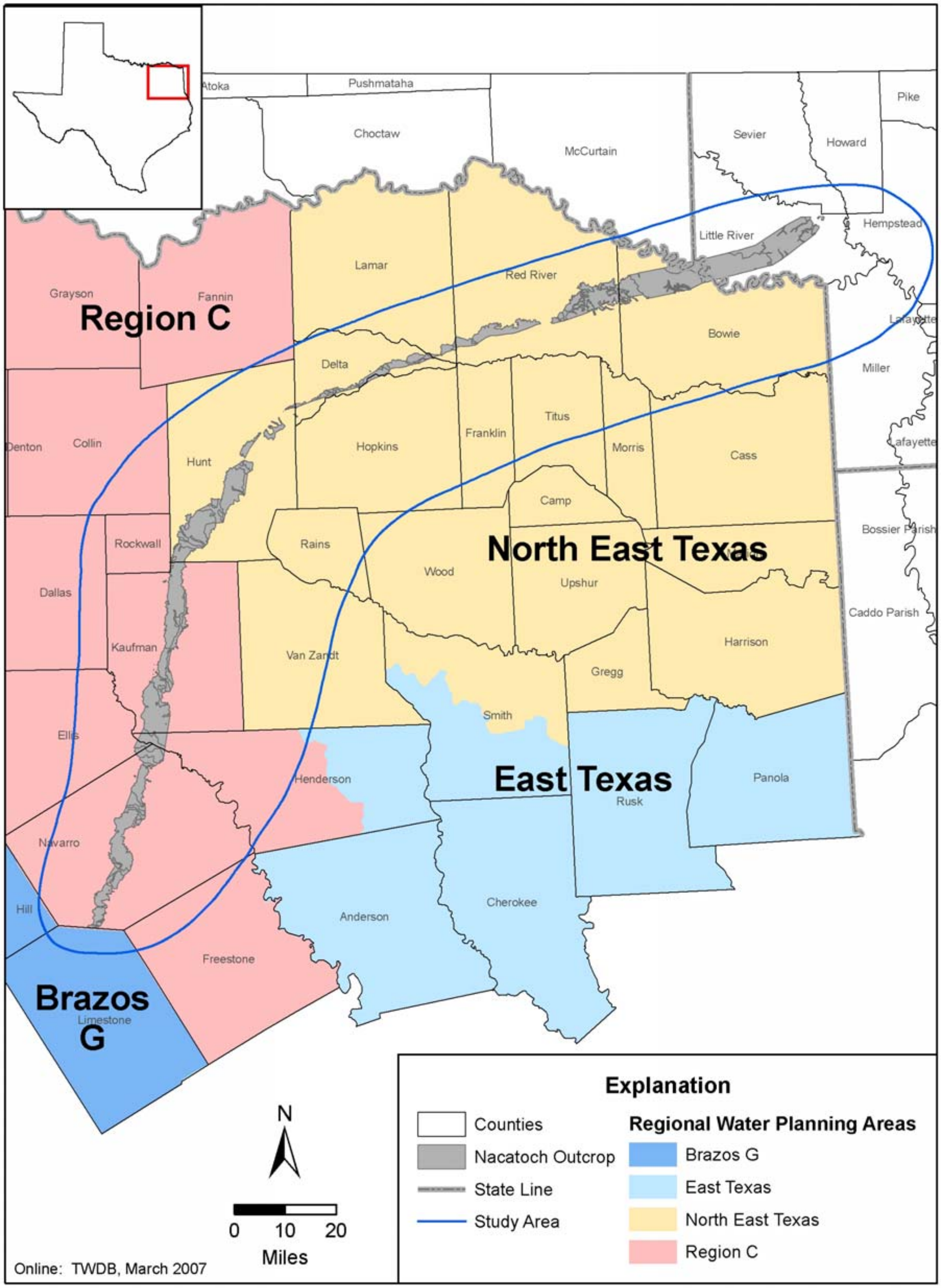


Figure 2.1.5 Location of Regional Water Planning Groups

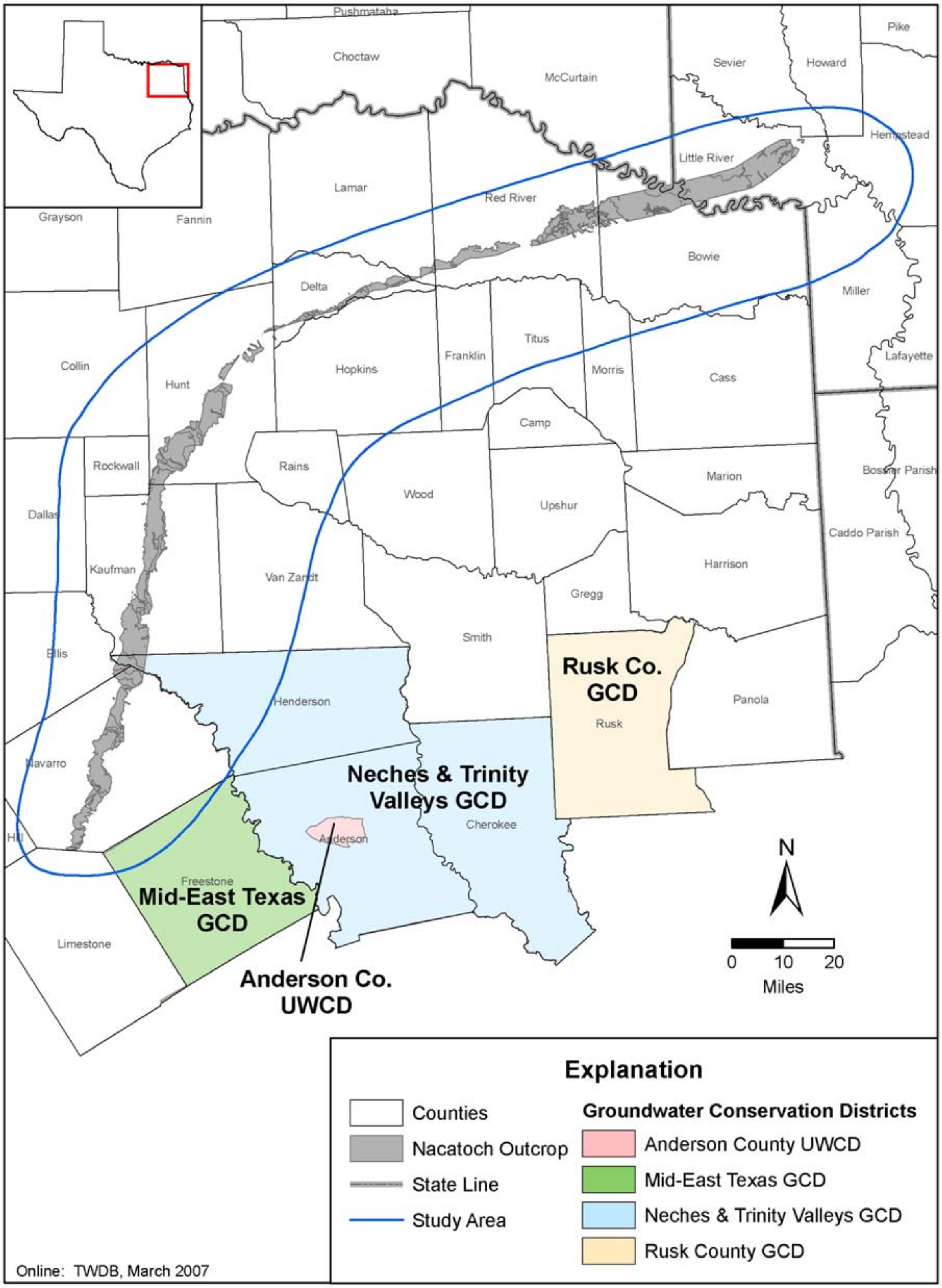


Figure 2.1.6 Location of Groundwater Conservation Districts

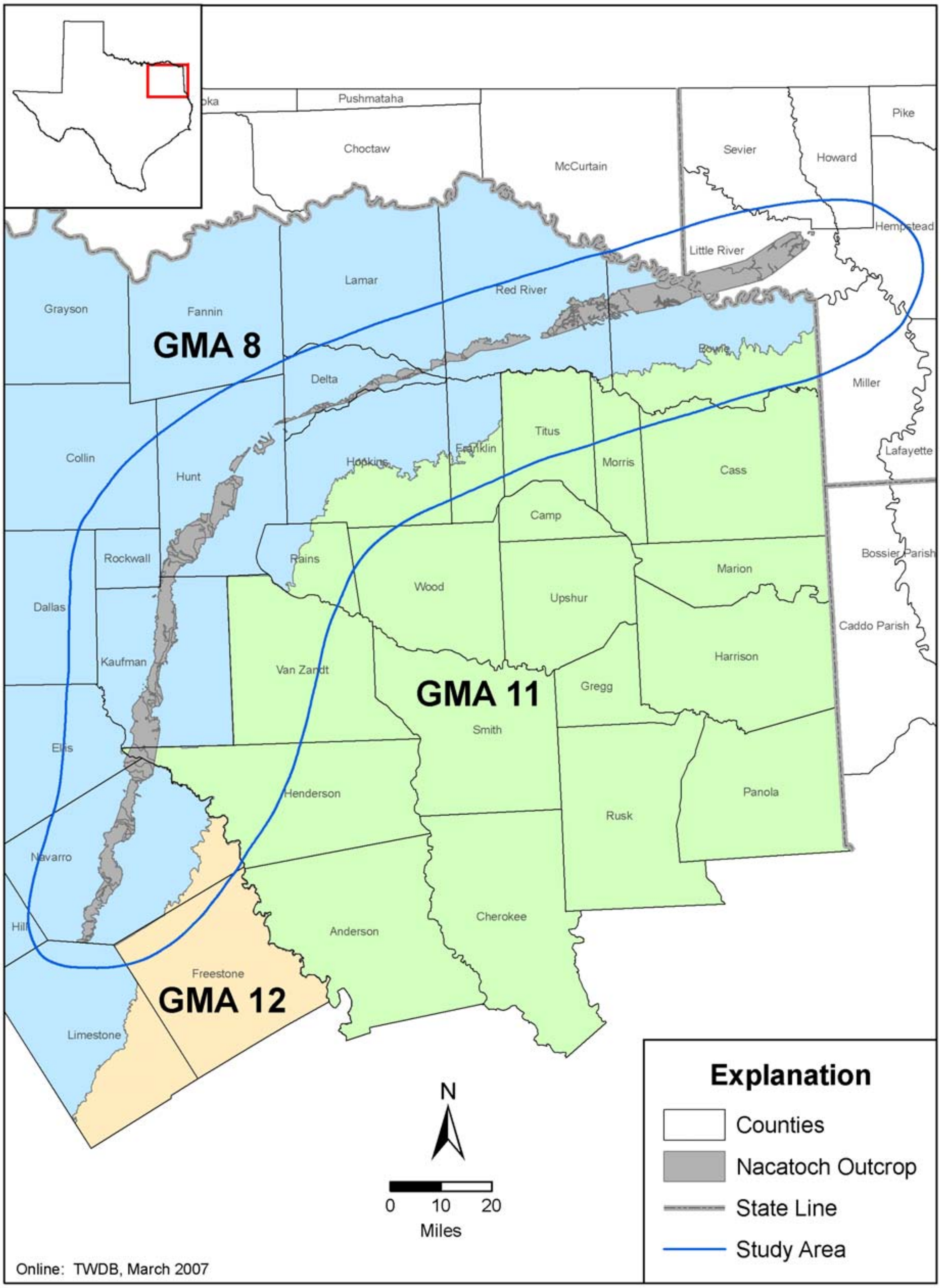


Figure 2.1.7 Location of Groundwater Management Areas

2.2 Physiography and Climate

The study area is located in the Blackland Prairies and the Interior Coastal Plains subprovinces of the Gulf Coastal Plains physiographic province (Figure 2.2.1) (Wermund, 1996). The Nacatoch Aquifer outcrop and most of the potable subcrop occur in the Blackland Prairie. The topography of the Blackland Prairie is generally described as low rolling terrain with soils derived from underlying chalks and marls. These soils can be characterized as black marine clays with high shrink-swell potential. 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.

The Dallas Morning News (Dallas Morning News, 1981), as reported in Ashworth (Ashworth, 1988), further subdivides the Nacatoch Aquifer outcrop into three physiographic subdivisions based on soil type and vegetation. The easternmost portion of the study region in the eastern portion of Bowie County falls within the East Texas Timberlands or "Piney Woods" Belt. The primary vegetation in this region is pine forest. From mid-Bowie to mid-Red River County the study area is typified by gently rolling woodlands and this region coincides with the Claypan-Post Oak Belt. The remainder of the Nacatoch Aquifer outcrop falls within the Blackland Prairies that is characterized as a treeless rolling prairie dissected by wooded stream valleys.

The United States Environmental Protection Agency (2004) divides the state into ecological regions according to areas of general similarity in ecosystems and in the type, quality, and quantity of environmental resources. Figure 2.2.2 shows the ecological regions that fall within the study area, which from west to east includes the Texas Blackland Prairies, the East Central Texas Plains, and the South Central Plains (data available through Texas Parks and Wildlife at http://www.tpwd.state.tx us/).

Figure 2.2.3 provides a topographic map of the study area. Generally, the area is characterized as having low relief with ground surface elevations highest in the center of the study region between the Trinity and Sulphur River Basins. Ground surface elevation varies from over 600 feet above sea level in portions of Hunt and Hopkins Counties in the central portion of the study area to less than 300 feet above sea level in the Sulphur and Red River valleys in the Northeast region of the study area. River valleys are broadly incised with terraced valleys that are hundreds of feet lower than the surface basin divide elevations.

Northeast Texas resides in the cool portion of the Temperate Zone of the Northern hemisphere. The study area intersects only one climatic zone in Texas, the Subtropical Humid division (Larkin and Bomar, 1983) and for this reason a figure showing climatic zones is not included. 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 Subtropical Humid climate zone extends from the Texas/Louisiana border in the northeastern part of the study area to the southwest end in Navarro County and is characterized as having warm summers. In the northern portion of the study area, the average annual temperature ranges from 64°F to 66°F and in the southwestern part the average annual temperature ranges from 68°F to 70°. Figure 2.2.4 plots the average annual air temperature for the study area. Average temperature varies seasonally throughout each year. In the northeast part of the study area, average monthly temperature varies from a low of 33°F in January to a high of 94°F in July and August. In the southwestern part of the study area, the average monthly temperature varies from a low of 34°F in January to a high of 96°F in August (Larkin and Bomar, 1983).

Within the outcrop area of the active model region, historical daily precipitation data are available at five stations from 1900 through 2000 (Figure 2.2.5) from the National Climatic Data Center. The spatial distribution is relatively dense in the model domain across the period of record given the small footprint of the study region. 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.

Figure 2.2.6 shows that historical average annual precipitation varies from a low of 38.7 inches in Navarro County to a high of 53.5 in Bowie County (Figure 2.2.6). 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 2.2.6 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. Figure 2.2.7 shows average monthly precipitation recorded at three precipitation gages with long periods of record located in Hunt, Navarro, and Bowie Counties. The long-term (period of record) average-annual precipitation depth is included for each gage. The three locations show similar seasonal patterns, with the highest precipitation occurring in months in spring and fall, while the lowest precipitation occurs in months in summer and winter.

Evapotranspiration (ET), including evaporation from bare soil and transpiration from plants, generally constitutes the second largest component of the water budget for the entire hydrologic cycle, after precipitation. The average annual net pan evaporation in the study area ranges from a low of 38.34 inches per year over the exposed portion of the aquifer in the far northeast portion of the study area to a high of 58.15 inches per year in the southwest corner of the study area (Figure 2.2.8) (Texas Water Development Board, 2007a). In the southwest part of the study area (Navarro County) the pan evaporation exceeds precipitation by as much as 20 inches. However in the northernmost potions of the study area (Bowie and Red River Counties), the annual rainfall generally exceeds pan evaporation rate by a couple of inches on average. Therefore, the greatest rainfall deficit with regards to the net evaporation rate occurs in the far southwestern portion of the study area and equals approximately 20 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. Figure 2.2.9 shows long-term monthly pan evaporation of three selected regions in the study area (Texas Water Development Board, 2007a). All three regions show seasonal fluctuation with low pan evaporation in the winter months and higher pan evaporation in the summer months.

ET directly from groundwater is caused primarily by deep-rooted phreatophytes and occurs primarily in riparian buffer strips adjacent to streams (Scanlon and others., 2005). Riparian zones are not specifically mapped in Texas. Groundwater ET can be a significant component of groundwater discharge for many aquifers and is expected to be a significant component for the Nacatoch Aquifer given that the aquifer is constrained to the outcrop over most of its extent. Scanlon and others (2005) summarizes the conceptual approach to groundwater ET. In general, if water tables are very near the surface, ET will be close to the potential evapotranspiration (PET), assuming there is some type of vegetative cover. In Section 4.7 of this report we used guidance developed for the GAM program to estimate groundwater ET rates and extinction depths (rooting depths) representative of the regions climate and vegetative cover.

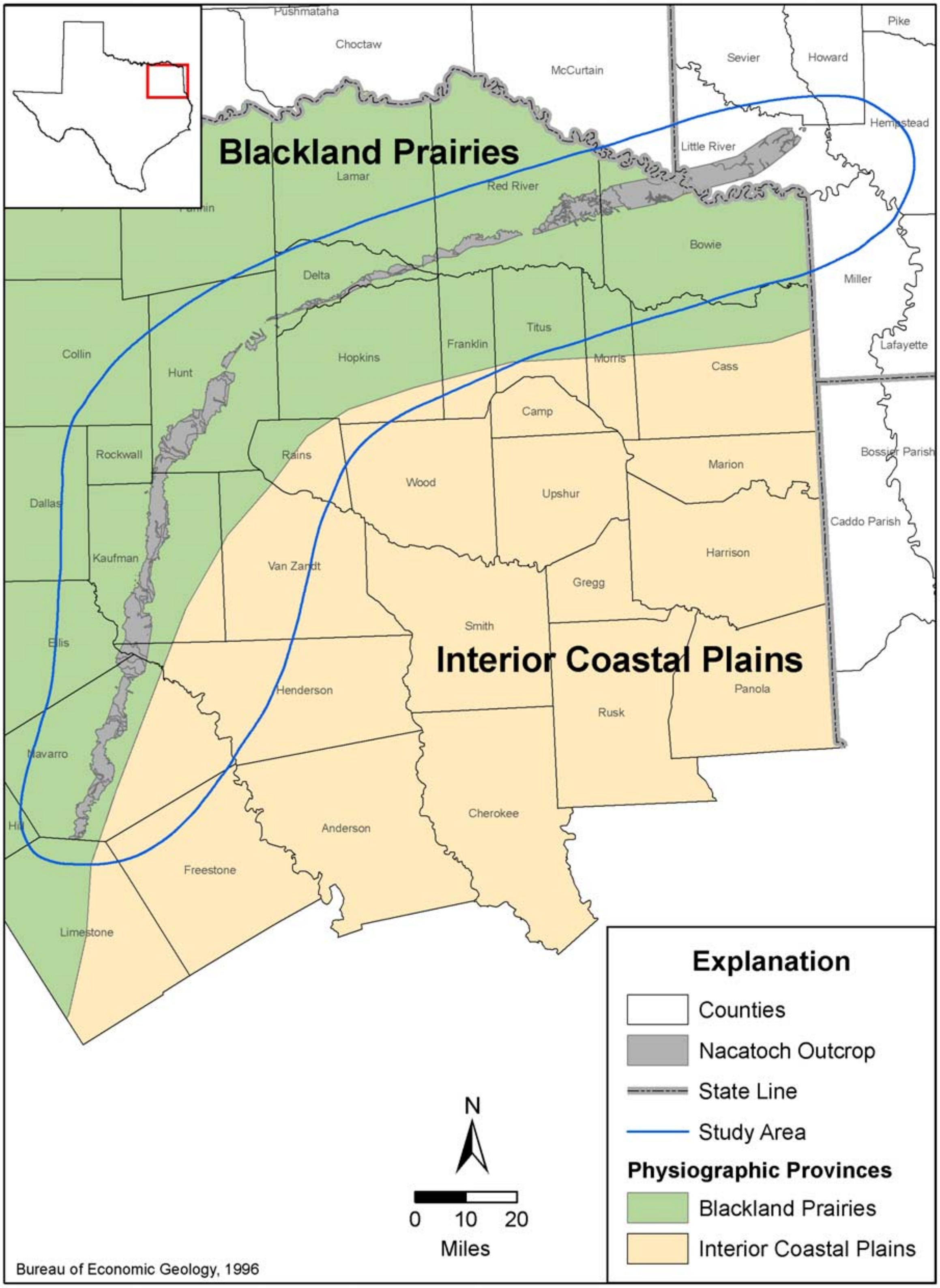


Figure 2.2.1 Physiographic provinces

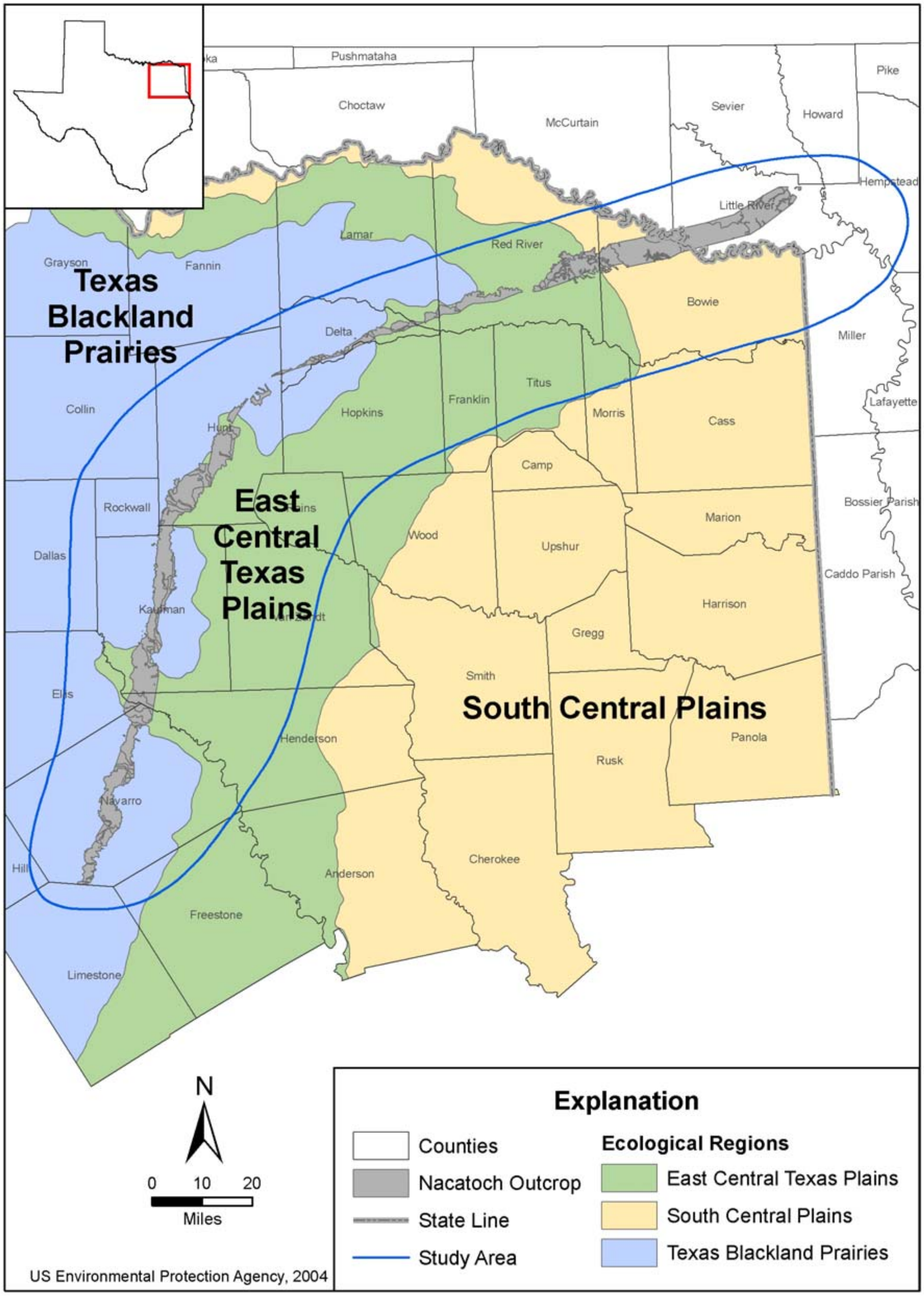


Figure 2.2.2 Ecological regions

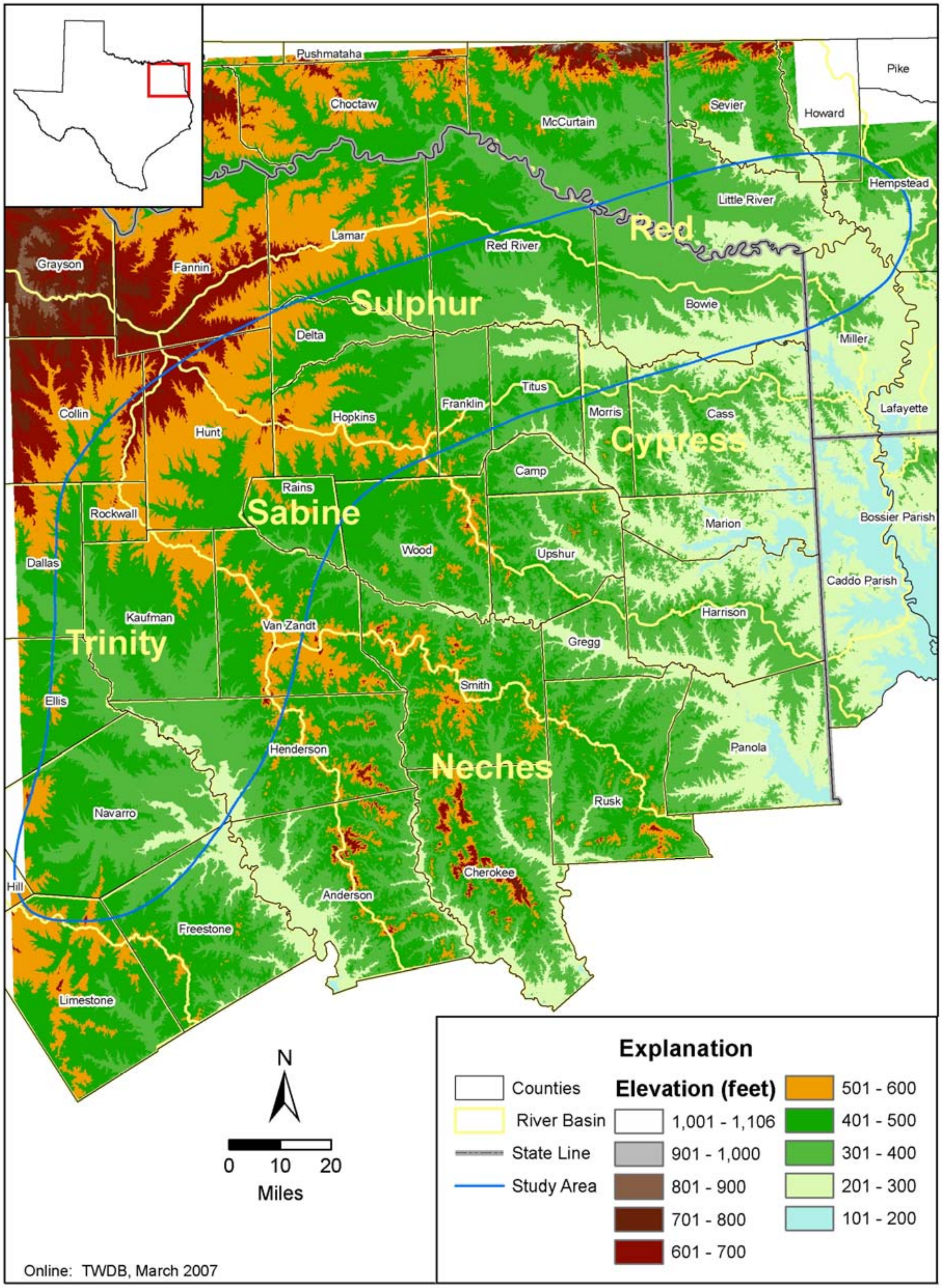


Figure 2.2.3 Topographic map

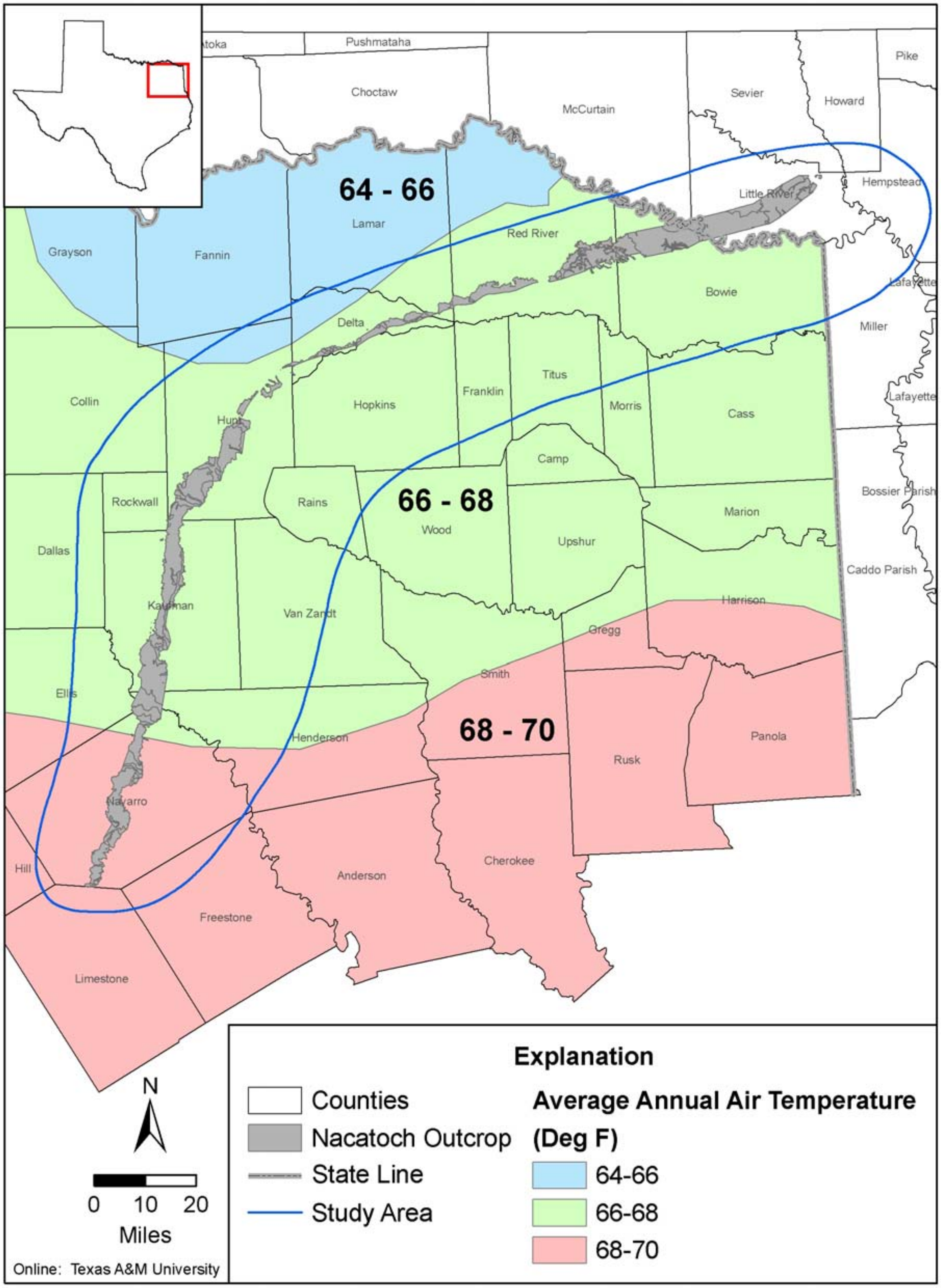


Figure 2.2.4 Average annual air temperature

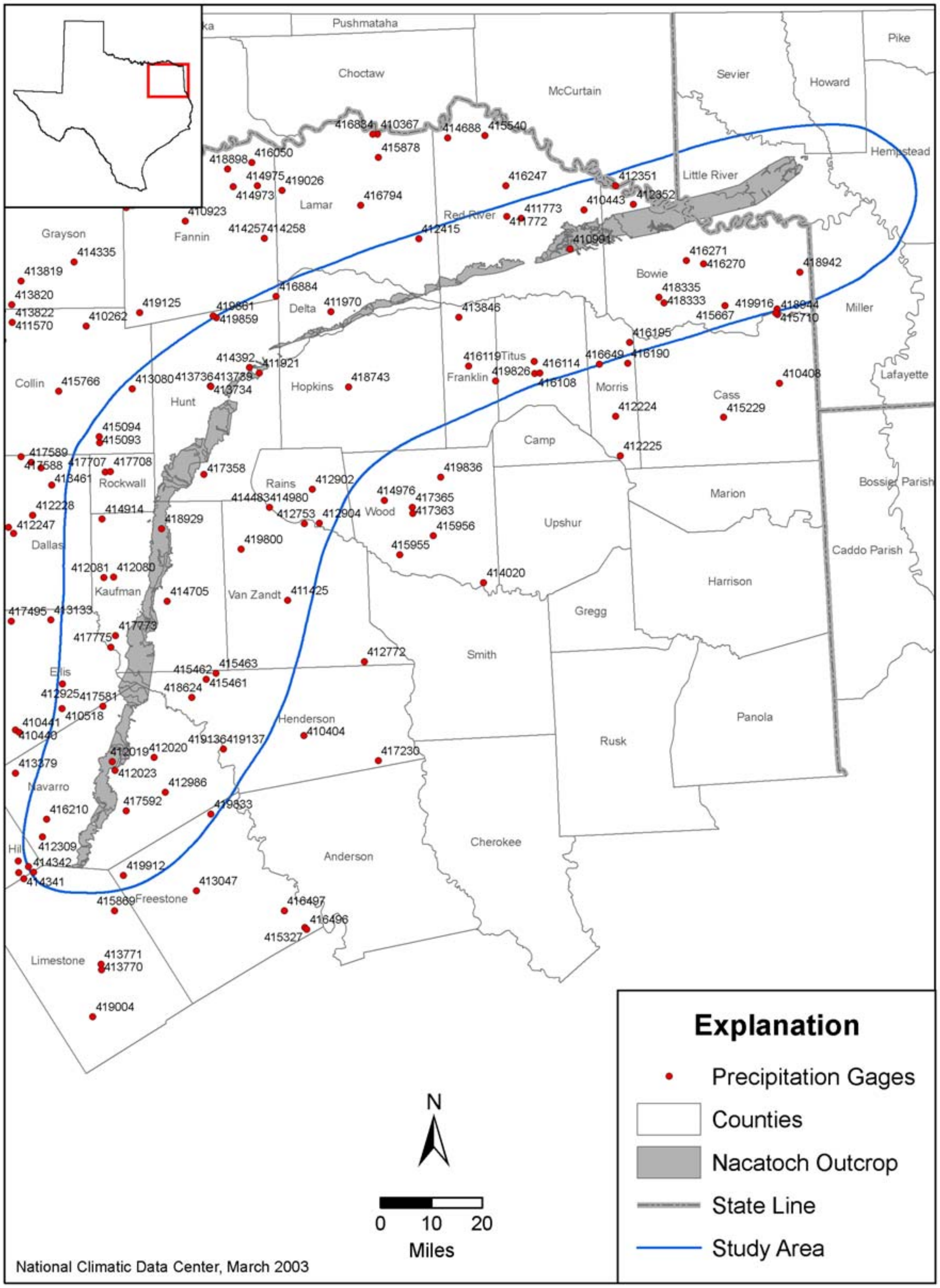


Figure 2.2.5 Location of precipitation gages

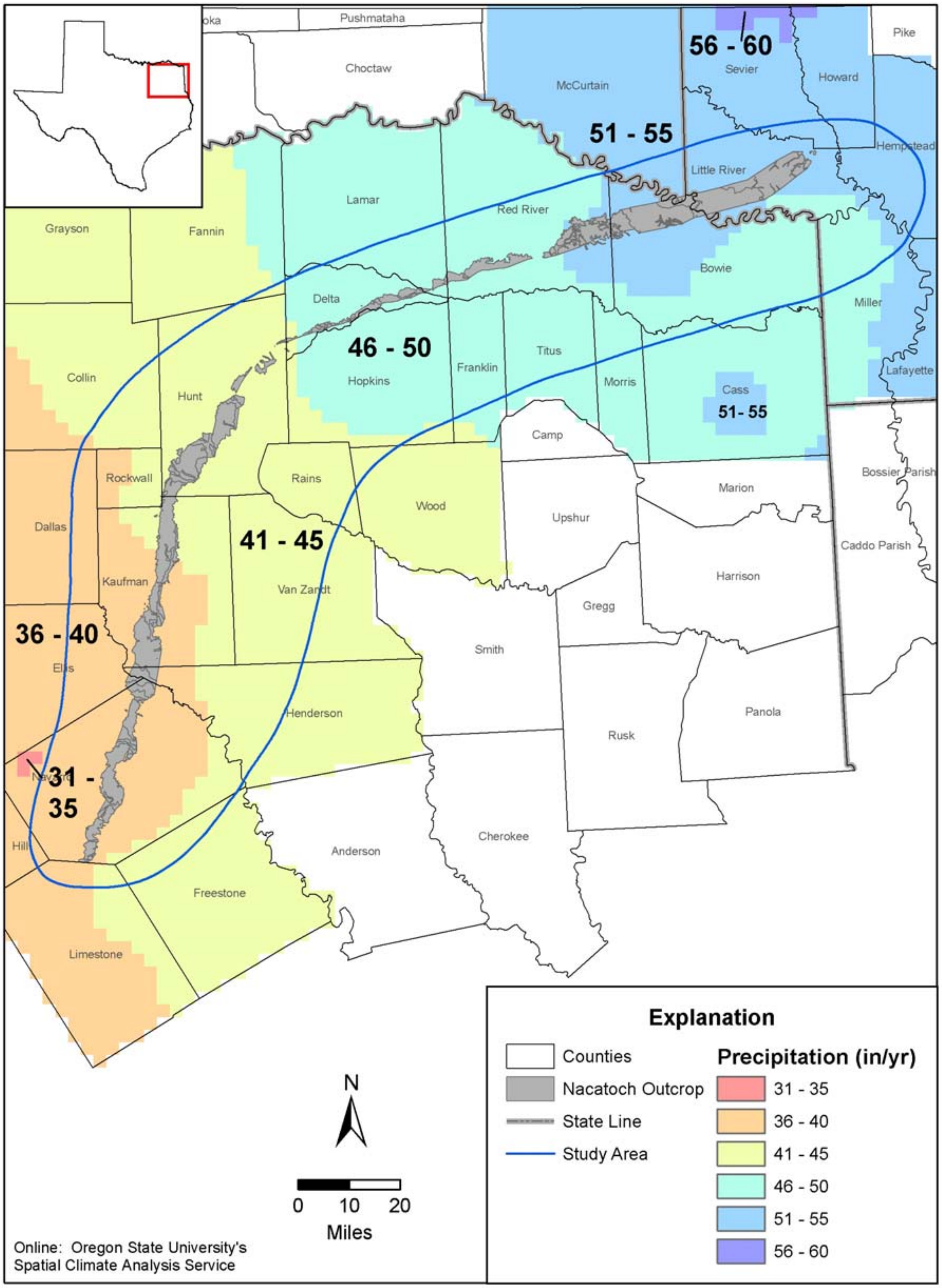


Figure 2.2.6 Average annual precipitation (1961-1990) in inches per year

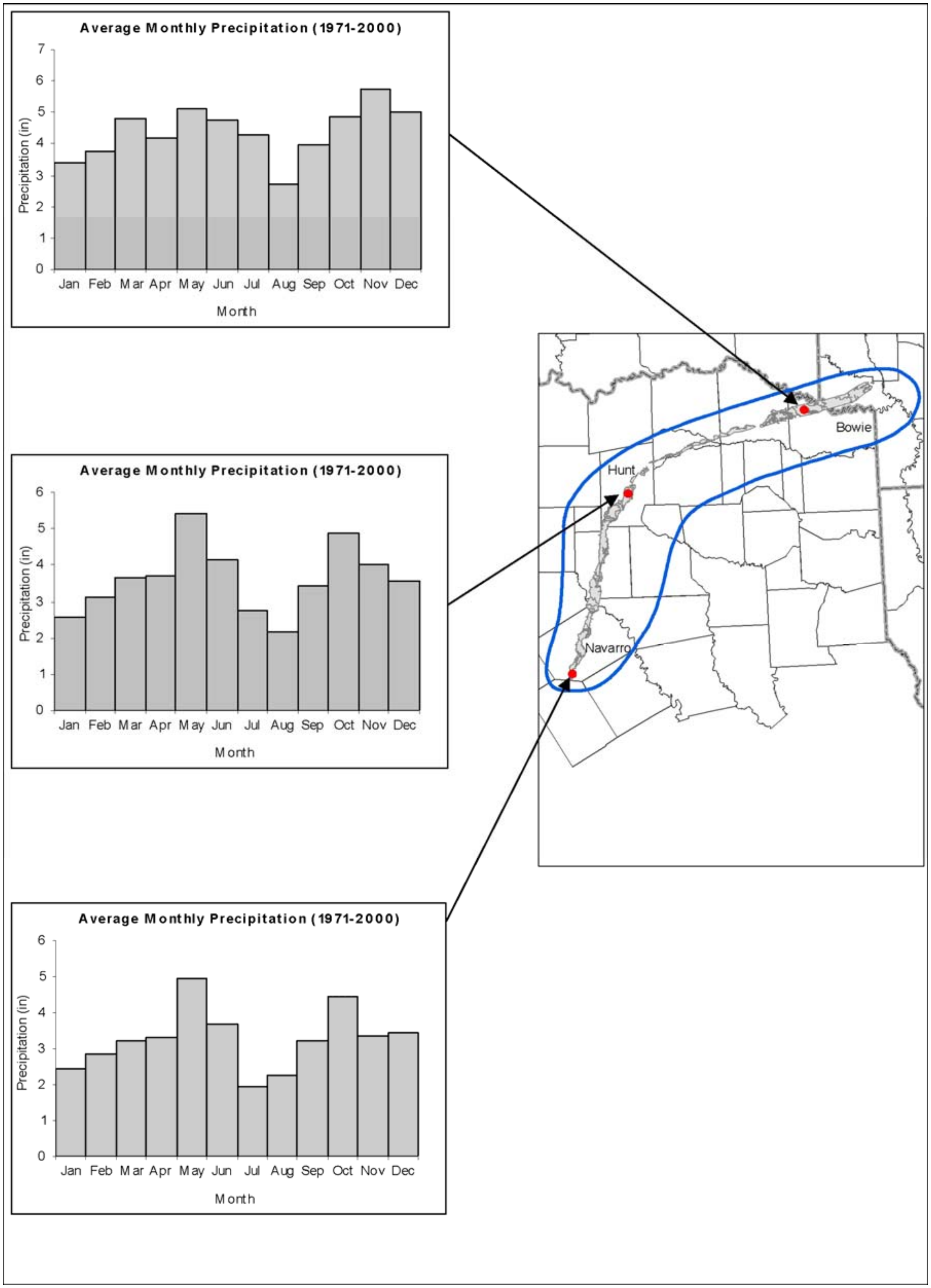


Figure 2.2.7 Representative monthly precipitation time series

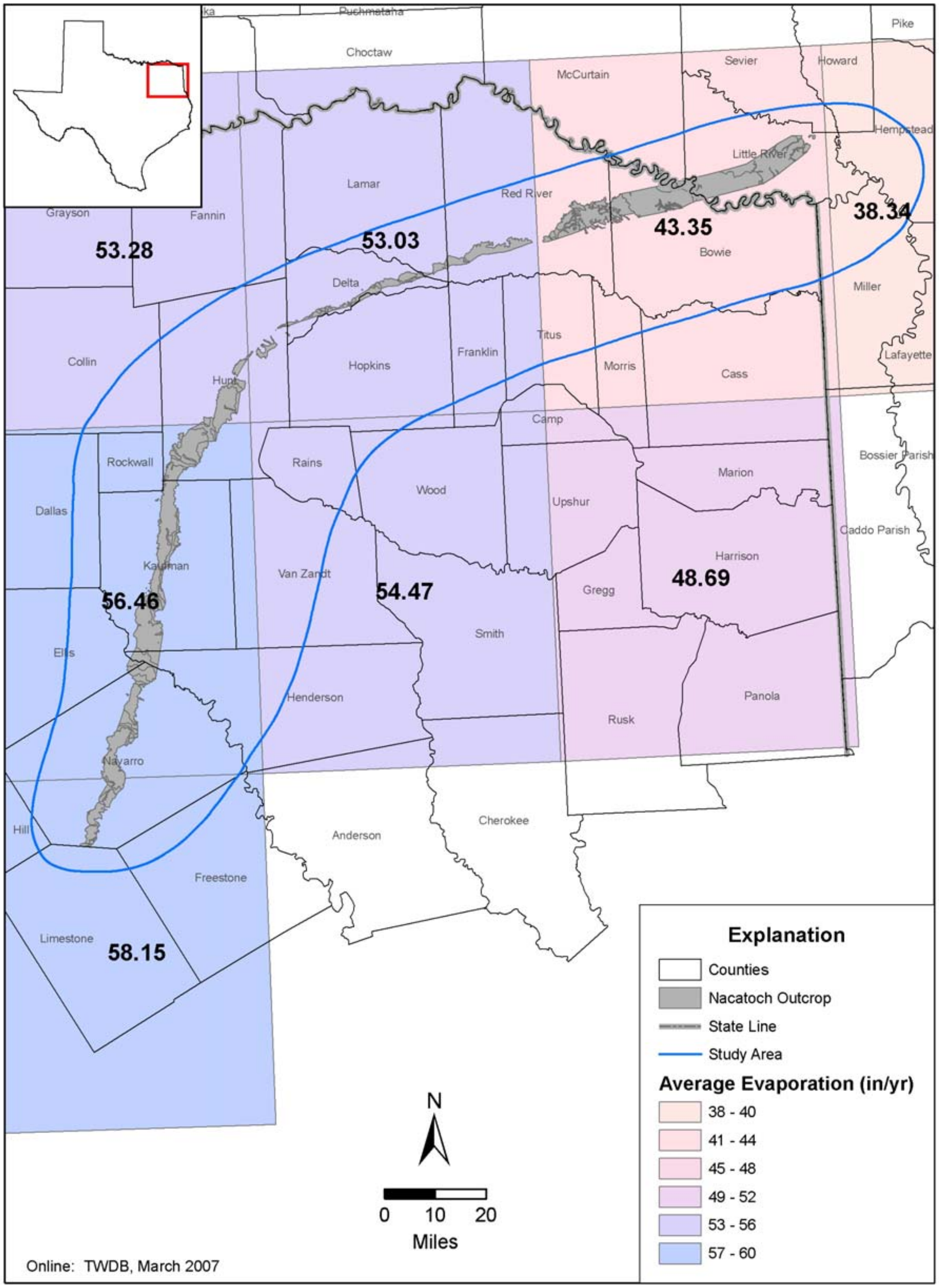


Figure 2.2.8 Average annual net pan evaporation rate in inches per year

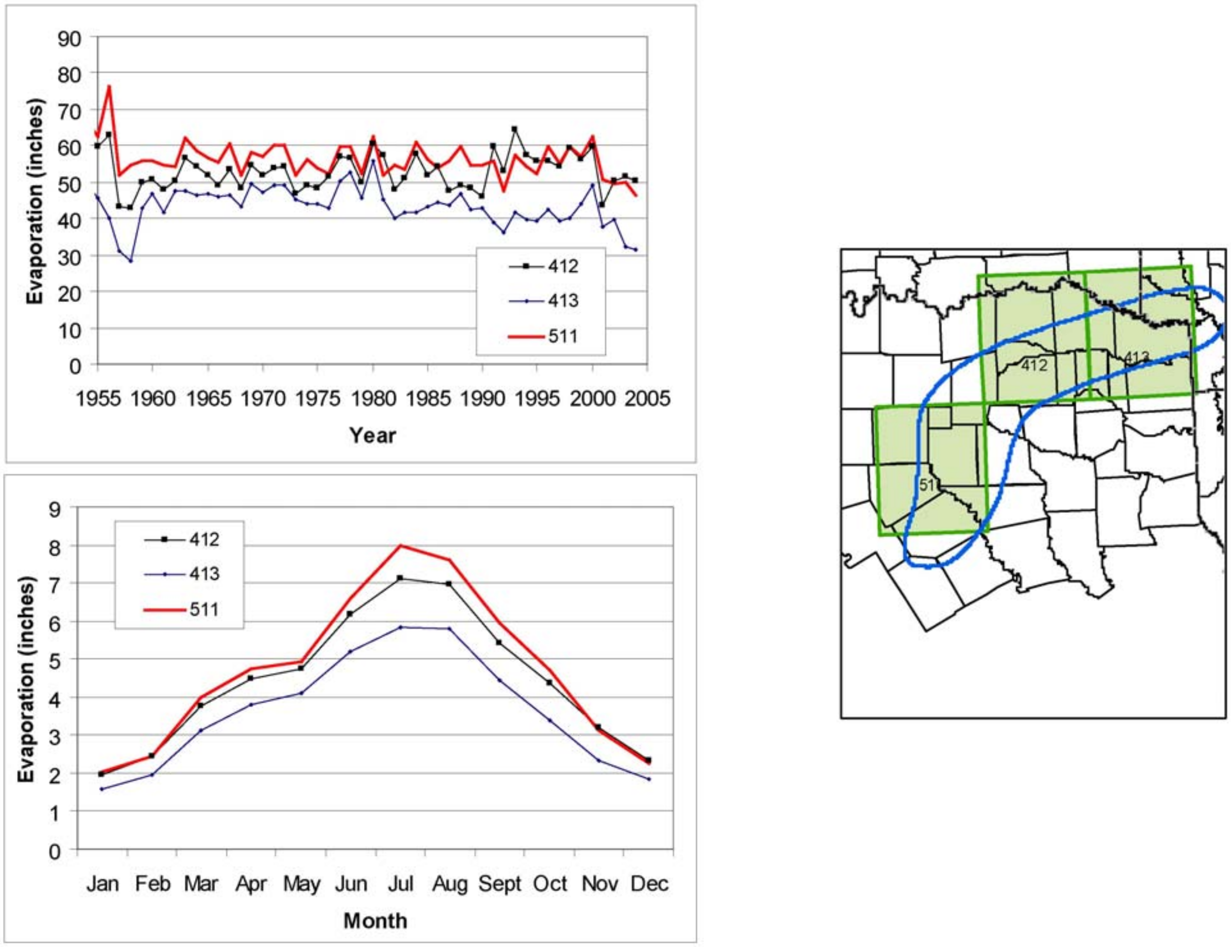


Figure 2.2.9 Long term monthly pan evaporation

2.3 Geology

The geologic history of Texas includes numerous episodes of sea-level fluctuations, with the last of these sea-level rises occurring during the Cretaceous. The Nacatoch Aquifer is the middle of the last three formations (Navarro Group) deposited in the East Texas embayment of the ancestral Gulf as the sea retreated in the waning period of the Cretaceous.

2.3.1 Pre-Nacatoch Structure and Tectonic History

The latter part of the Jurassic was a time of significant land surface erosion in Texas as the lowering of the ancestral Gulf of Mexico shifted drainage patterns to the east and southeast. As a result of this widespread erosion, the basal contact of the Cretaceous is everywhere in Texas marked by a major unconformity, as the Cretaceous rests upon a diverse patchwork of formations ranging in age from pre-Cambrian to Jurassic (Sellards and others., 1932). Hill (1901) referred to this relatively level erosional surface as the “Wichita Paleoplain”. Contemporaneously, a thick layer of evaporite sediments, the Louann Salt, was deposited in the Gulf Basin, and would later impact structural elements in the East Texas Basin.

Upon this land surface Cretaceous seas advanced inland from the south and east, and by Eagle Ford and Austin time, the Gulf (or Coloradian) Sea had transgressed northward to an area now occupied by Colorado, merged with the southern extent of the Artic Sea, and reached its maximum advancement over the Western Interior (Sellards and others., 1932). At the close of the Cretaceous, the Coloradian Sea had retreated gulfward marking the end of the last great epicontinental marine invasion.

During the latter part of the Cretaceous, Gulf waters were deepest and the sea remained the longest in the East Texas and Mississippi geosynclines (Sellards and others., 1932). The Mississippi geosyncline formed the most northerly extension of the sea and is referred to as the Mississippi Embayment. The deepest regions of these geosynclines represent the East Texas and North Louisiana Basins (Figure 2.3.1). The East Texas Basin axis generally plunges south-southwest with strata dipping into the basin from the Mexia-Talco fault zone on the north and west and the Sabine Uplift on the east.

A structurally high feature, the Sabine Uplift located along the Texas-Louisiana border, separates the two basins (Figure 2.3.1). The Pittsburg syncline, a relatively narrow passageway between the Sabine Uplift to the south and the highlands formed by the Ouachita belt to the north, provided a waterway connecting the East Texas and North Louisiana Basins (Granata, 1963; Murray, 1961)

Figure 2.3.2 shows in more detail the major tectonic features and grabens of the Mexia-Talco Fault Zone. This extensive zone of faulting just downdip of the Nacatoch Aquifer outcrop has significant impact on the movement of groundwater within this aquifer system, as will be described in more detail later in this section. For this reason, the Mexia-Talco fault zone contributes to the placement of the downdip boundary of this GAM (Figure 2.3.2).

2.3.2 Depositional Environment and Stratigraphy

Overlying the Marlbrook Marl of the Taylor Group and underlying the Tertiary-age Midway Group, the Navarro is the uppermost group of Cretaceous formations that, in northeast Texas, include in descending order the Kemp Clay, Nacatoch Aquifer, and Neylandville Formation (Table 2.3.1 and Figure 2.3.3). In the subsurface (beyond the extent of this project), the Navarro Group is informally subdivided by Guevara and Giles (1979) into the Upper Navarro Clay, Upper Navarro Marl, Nacatoch Sand, and Lower Navarro Clay. Where it exists within the project area, Ashworth (1988) included the Upper Navarro Marl in subsurface mapping of the Nacatoch Aquifer because of its similar traits displayed on geophysical logs. Across the state line in Arkansas and Louisiana, equivalent stratigraphic units of the Navarro are the Arkadelphia Marl, Nacatoch Aquifer, and Saratoga Chalk. For modeling purposes, the Nacatoch Aquifer is considered the Nacatoch Aquifer outcrop downdip to the first major offset in the Mexia-Talco fault zone or to a downdip point where water quality becomes a significant factor in terms of use.

The four units of the Navarro Group are mapped separately on the Geologic Atlas of Texas from approximately the City of Greenville in Hunt County southward. Although the southern terminus of the mapped extent of the Nacatoch Aquifer occurs approximately at the Falls-Milam county line, the southern end of the designated water-bearing Nacatoch Aquifer occurs at approximately the Navarro-Limestone county line. Model layer each formation is included in is also listed in Table 2.3.1. More on the development of model layer is included in Section 4.1.

Table 2.3.1 Stratigraphic units and aquifers

<table>
<tr><th rowspan="2">System</th><th rowspan="2">Group</th><th colspan="3">Stratigraphic Units</th><th rowspan="2">Model Layer</th></tr>
<tr><th colspan="2">Texas</th><th>Arkansas</th></tr>
<tr><td>Quaternary</td><td></td><td colspan="3">Alluvium and fluviatile terrace deposits</td><td rowspan="5">1[†]</td></tr>
<tr><td rowspan="2">Tertiary</td><td rowspan="2">Midway</td><td>Willis Point Formation</td><td rowspan="2">Midway, undifferentiated</td><td rowspan="2">Midway</td></tr>
<tr><td>Kincaid Formation</td></tr>
<tr><td rowspan="5">Cretaceous</td><td rowspan="4">Navarro</td><td>*Upper Navarro Clay</td><td rowspan="2">Kemp Clay</td><td rowspan="2">Arkadelphia Marl</td></tr>
<tr><td>*Upper Navarro Marl</td></tr>
<tr><td colspan="3">Nacatoch Sand</td><td>2</td></tr>
<tr><td>*Lower Navarro Clay</td><td>Neylandville Formation</td><td>Saratoga Chalk</td><td rowspan="2"></td></tr>
<tr><td>Taylor</td><td colspan="3">Marlbrook Marl</td></tr>
</table>

Water-bearing units

**Subsurface stratigraphic Nomenclature from Guervara and Giles (1979); Wood and Guervara (1981); and McGowen and Lopez (1983)*

[†] Alluvium and terrace deposits included in Layer 2 along Nacatoch outcrop

East of Greenville where the density of vegetation and the overlying alluvial soils with similar mineralogical characteristics have made it difficult to differentiate the Nacatoch Aquifer on the land surface, the geologic units are mapped collectively as the Navarro Group "undivided" on the Geologic Atlas of Texas sheets (not shown). For the purpose of this modeling project, the approximate location of Nacatoch Aquifer outcrop in this eastern "undivided" segment is estimated (Figure 2.3.4) by projecting updip the approximate thickness of the Nacatoch Aquifer as viewed in geophysical logs of wells located slightly downdip of the anticipated outcrop. Based on this estimation, the underlying Neylandville Formation in this segment is non-existent and the Nacatoch Aquifer rests directly on the Marlbrook formation.

From their outcrop in Texas, Nacatoch Aquifer dip south and southeast in the subsurface toward the central axis of the East Texas Basin; while in Arkansas, Nacatoch Aquifer dip east to southeast toward the axis of the Mississippi Embayment. In the southern part of the East Texas

Basin and over the Sabine Uplift Nacatoch Aquifer grade laterally into mudstones and thin, discontinuous sandstones.

McGowen and Lopez (1983) characterize the Nacatoch Aquifer as consisting of laterally discontinuous, coarsening upward, marine sandstones alternating with marine mudstones, and describe its origin as follows:

> *Nacatoch deposition followed an extended period of deposition of shelf mud, marls, and chalks during Taylor and early Navarro time and reflects a minor uplift in the landmass bordering the basin to the north. Terrigenous clastics supplied to the basin from the north and northeast accumulated on a relatively stable, shallow shelf. The rate of sediment influx was apparently slow enough to be significantly influenced by marine processes, such as tides and waves.*

Within the East Texas Basin, McGowen and Lopez (1983) divide the Nacatoch Aquifer into nearshore and shelf deposits (Figure 2.3.5). Nearshore environments along the northern basin boundary consist of thick net-sand deltaic units and interdeltaic areas of higher mudstone consistency. Some deltaic progradation is evident; however, basinward growth of the deltas was probably limited by slow sediment input and the lateral (southwestward) transport of sediment by the prevailing longshore current. McGowen and Lopez (1983) describe shelf sands in the southern outcrop extent and downdip of the northern nearshore facies as upper continuous sheet sands and lower discrete sand bodies interpreted to be inner shelf sand bars. Based on outcrop characteristics, lithology, and fossil content, Knight (1984) identified five depositional facies that correlate closely with the McGowen and Lopez's descriptions and include shoreface, delta-abandonment, reworked delta front, channel fill, and shelf environments.

Using sand grain analyses and core descriptions from five TWDB test holes (also described in Ashworth, 1988), along with geophysical log correlations, Knight (1984) describes up to five coarsening upward stratigraphic sequences in the Nacatoch Aquifer. Intervening mudstone units gradationally coarsen upward into overlying sand units, which likewise coarsen upward and generally terminate in a sharp contact (erosional surface) with the next overlying mudstone unit. The thickness of individual sand units vary from over 100 feet in deltaic areas to less than 20 feet in shelf deposits in the southern extent (Ashworth 1988). Thickness of intervening mudstone units similarly ranges from over 100 feet to only a few feet.

Net sand thickness is greatest (over 200 feet) within the Pittsburg syncline where it straddles the state line in eastern Bowie County in Texas and Miller County in Arkansas (Figure 2.3.6). McGowen and Lopez (1983) speculate that "this area underwent more rapid subsidence than did surrounding areas, thereby creating a sand sink that accumulated and preserved a thicker section of sand". However, much of the sand unit in this area contains groundwater of poor quality and is beyond the modeling limits of this project. Elsewhere, increased sand thickness in the range of 120 feet occur in southern Red River and northern Titus Counties, eastern Hunt and western Delta Counties, and in southern Hunt County. These areas of greater thickness indicate focal points of original sediment input into the East Texas Basin. Net sand thickness decreases to 100 feet or less between these sediment input areas, and from central Kaufman County southward, net sand thickness is reduced to approximately 20 feet. Figure 2.3.7 shows the location of lines of geologic cross sections. Net sand distribution parallel to the strike direction is illustrated in Figure 2.3.8, while total Nacatoch Aquifer thickness distribution in the downdip direction is shown in Figure 2.3.9, Figure 2.3.10, and Figure 2.3.11. Total thickness of the Nacatoch Aquifer is assumed to be the base of the lower-most sand package.

The Nacatoch Aquifer in Arkansas is described by Dane (1929) as "a complex unit made up of cross-bedded yellowish and gray fine-grained unconsolidated quartz sand; hard crystalline fossiliferous sandy limestone; coarse richly glauconitic sand; fine-grained, argillaceous blue-black sand; and pure light-gray clay and marl". Knight (1984) and Ashworth (1988) describe the mineralogical and textural characteristics of the Nacatoch Aquifer in Texas as follows:

> *Sandstone layers consist predominantly of rounded, moderately sorted to well-sorted, fine-grained sand and silt, which is moderately consolidated to unconsolidated with occasional thin, calcite-cemented layers. Original sedimentary structures are rare as a result of post depositional disturbance by burrowing marine fauna. The sands are various shades of gray in the subsurface but, when exposed at the surface, are commonly light-brown to yellow and often streaked with purple and orange. The mineralogical composition of cores taken*

from test holes drilled by the Department (TWDB) showed mostly quartz grains with lesser amounts of feldspar, chert particles, and glauconite. Mudstone layers separating the sand intervals are generally dark gray, fossiliferous, and very bioturbated with thicknesses often in excess of 100 feet.

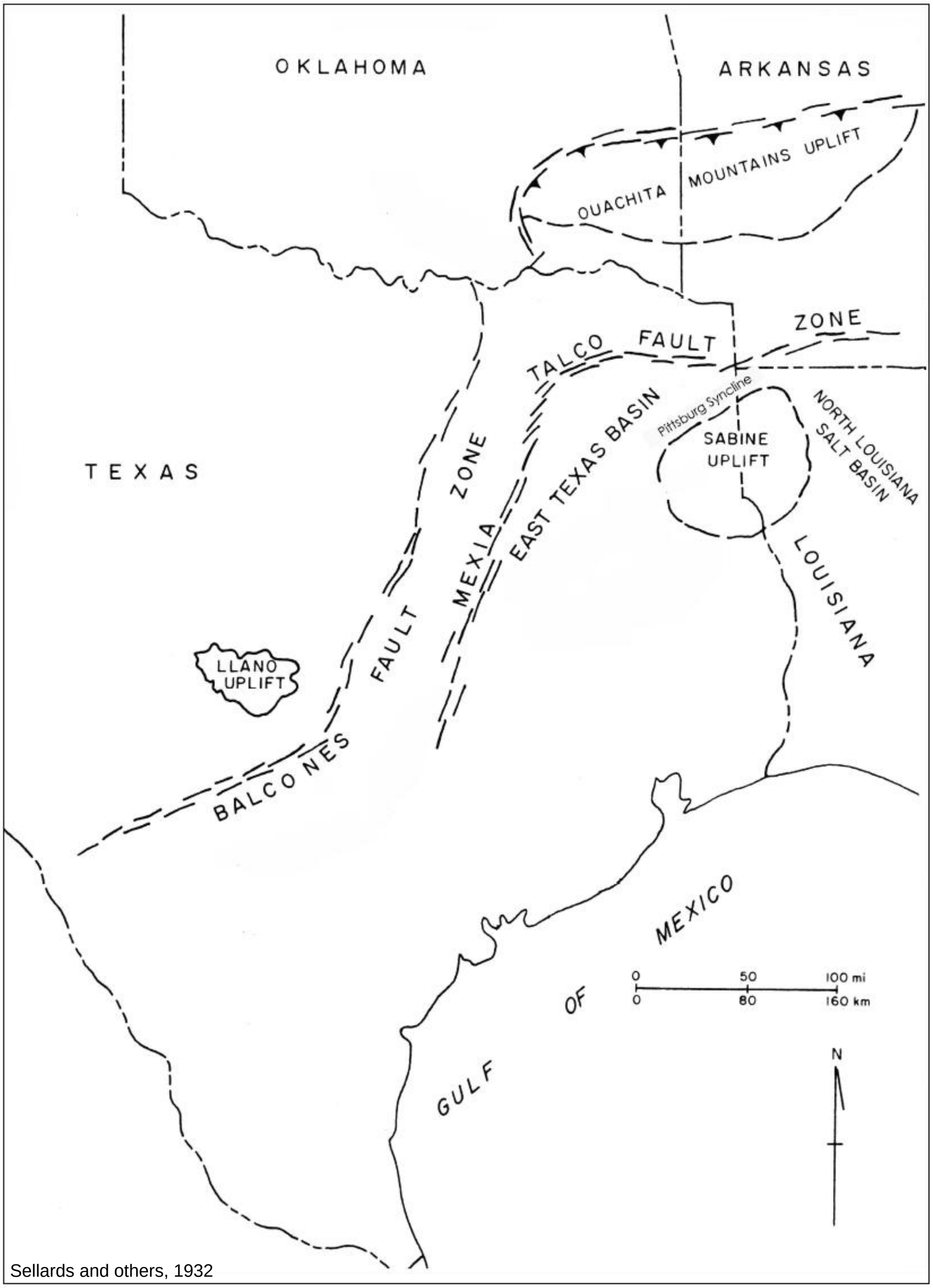


Figure 2.3.1 Major tectonic and structural features

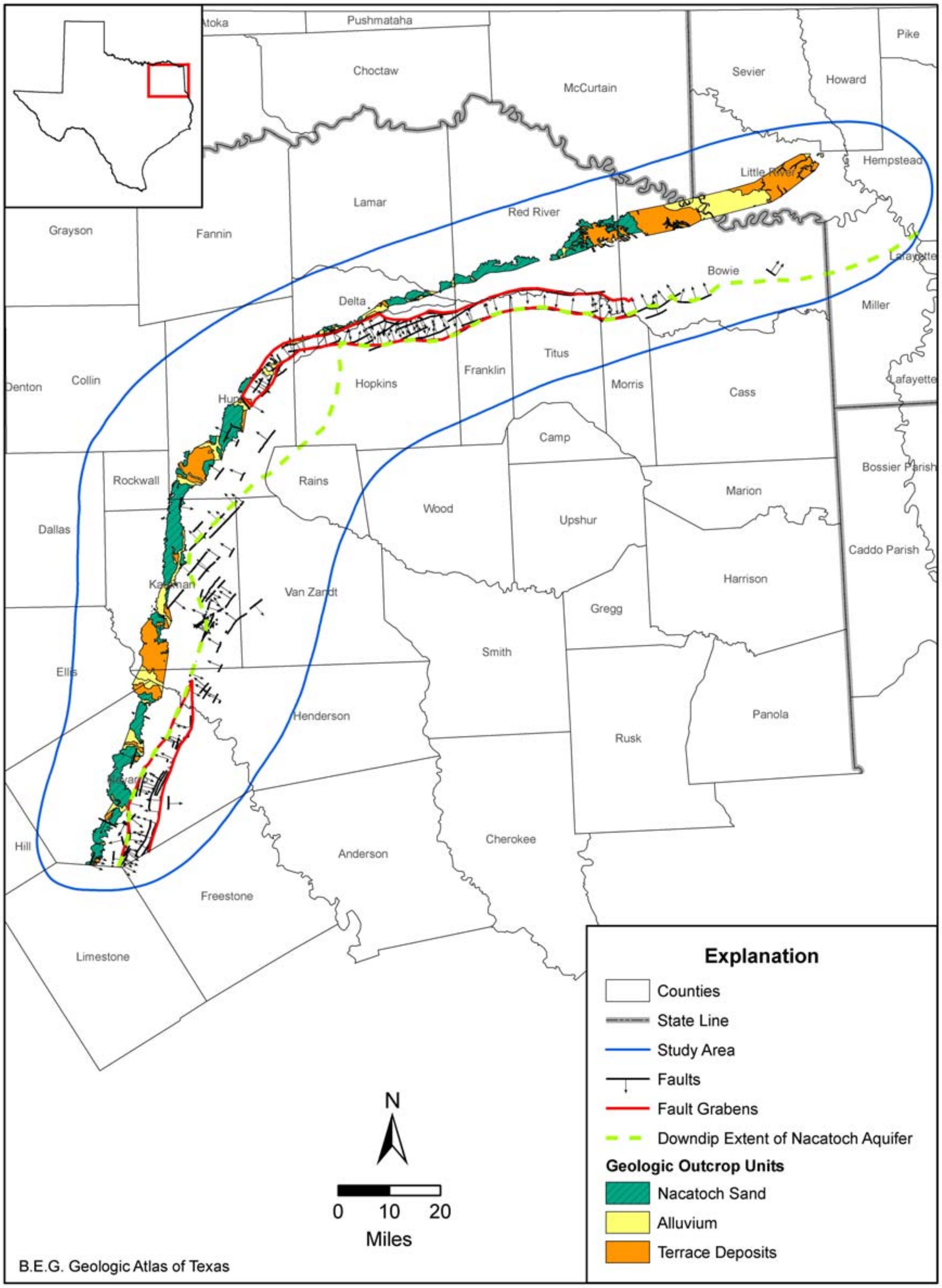


Figure 2.3.2 Mexia-Talco Fault Zone with Major Grabens

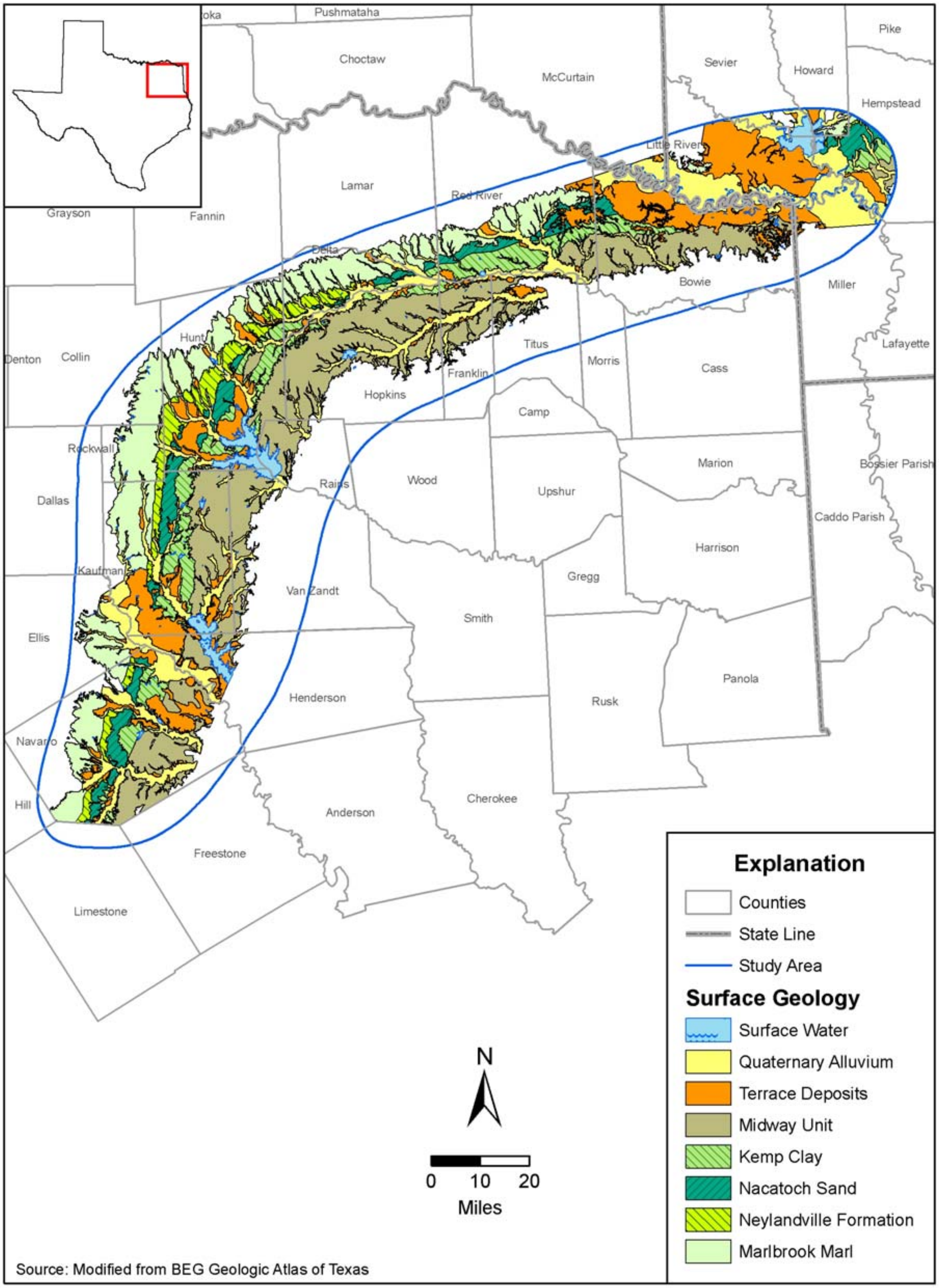


Figure 2.3.3 Surface geology

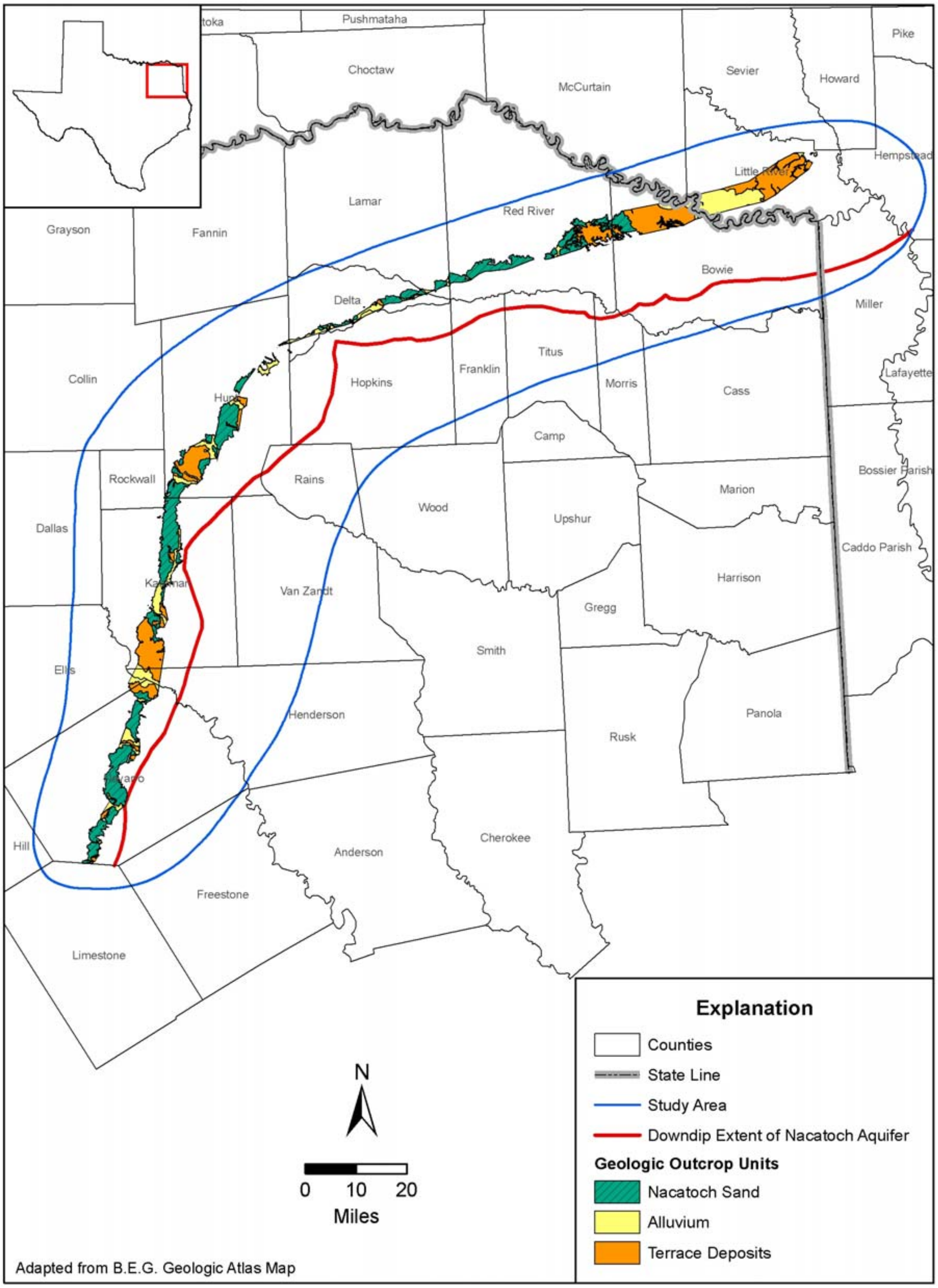
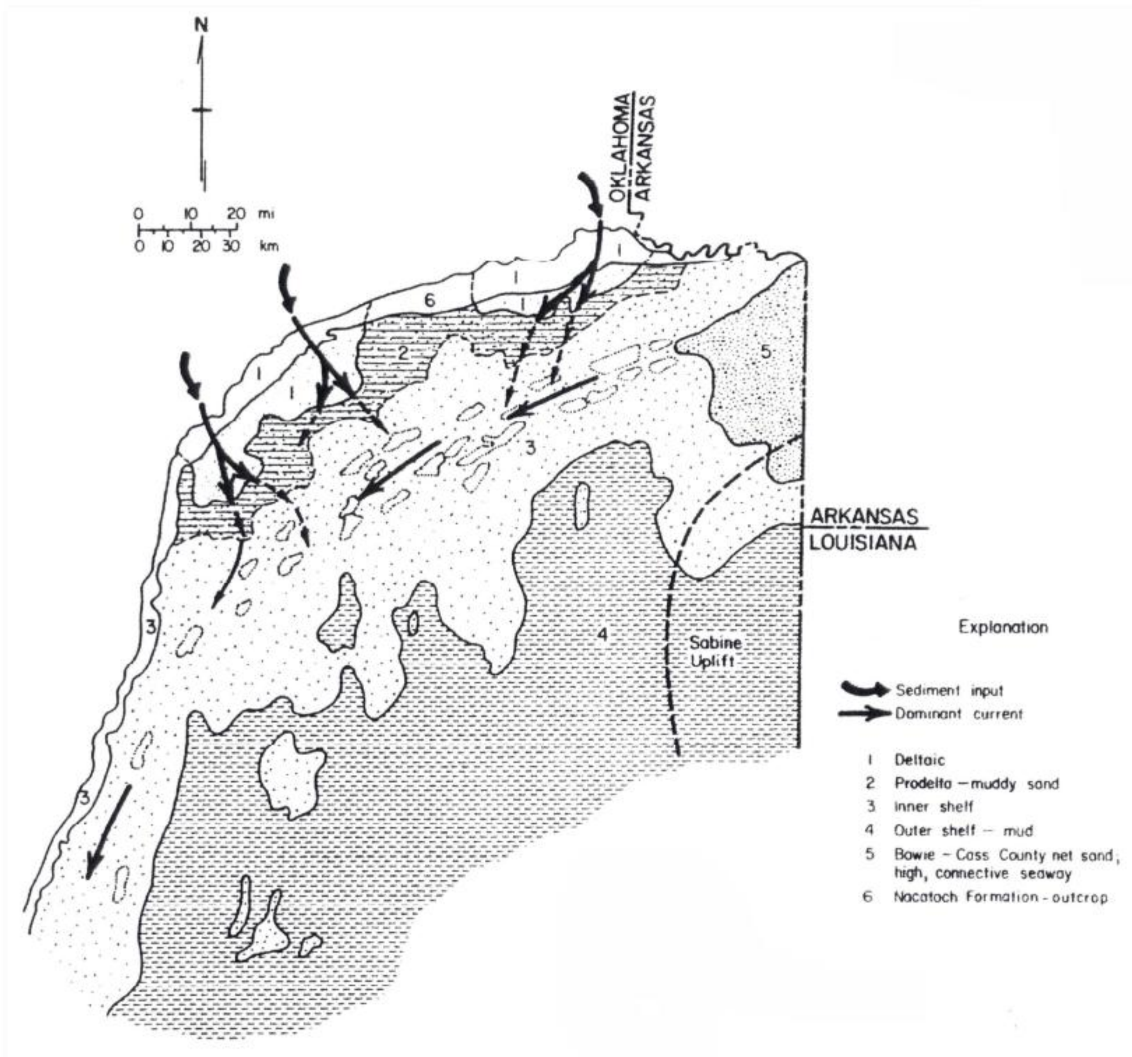


Figure 2.3.4 Nacatoch Aquifer outcrop



Modified from McGowen and Lopez, 1983

Figure 2.3.5 Nacatoch Aquifer facies distribution

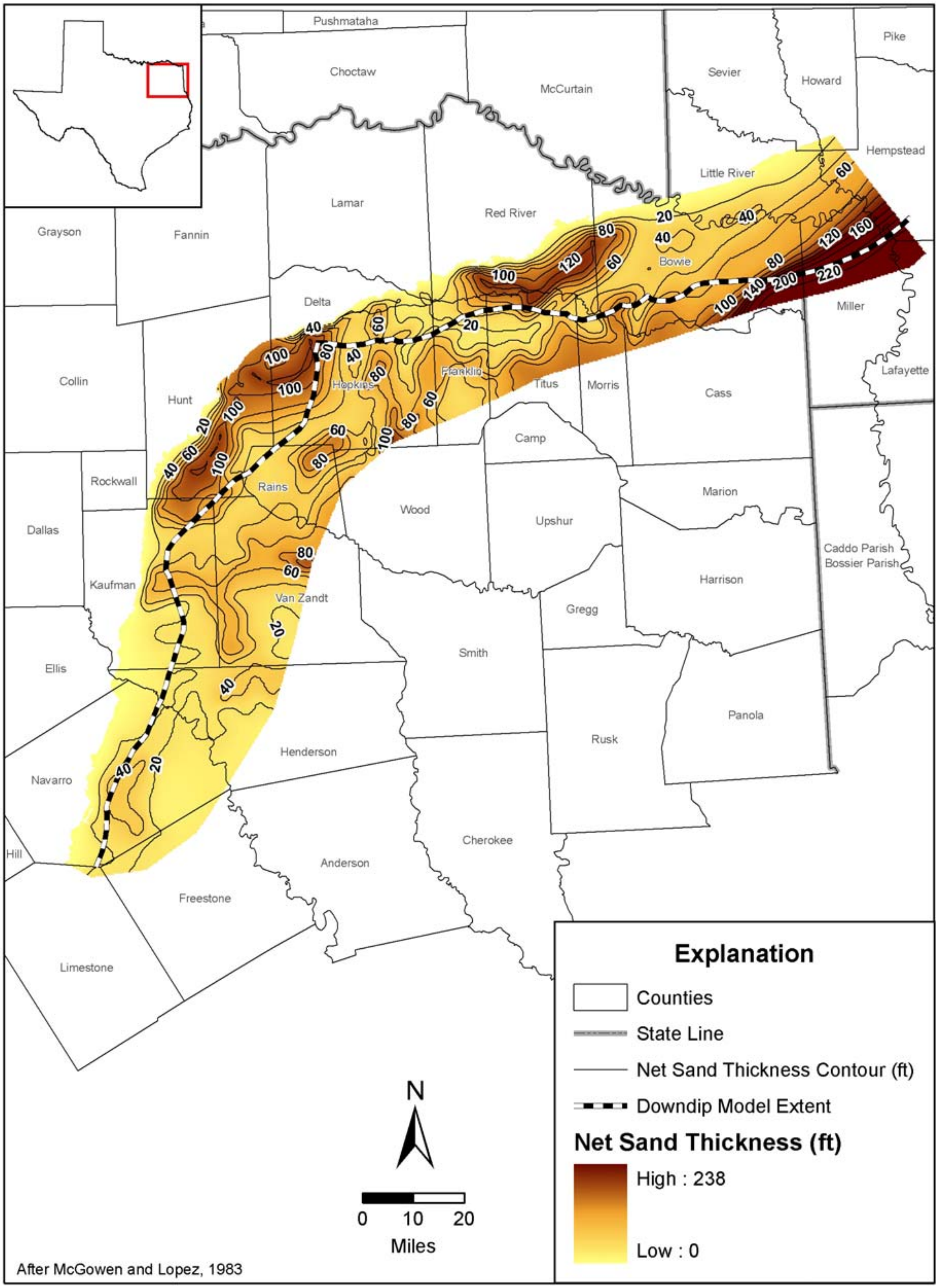


Figure 2.3.6 Net sand thickness (adapted from McGowen and Lopez, 1983)

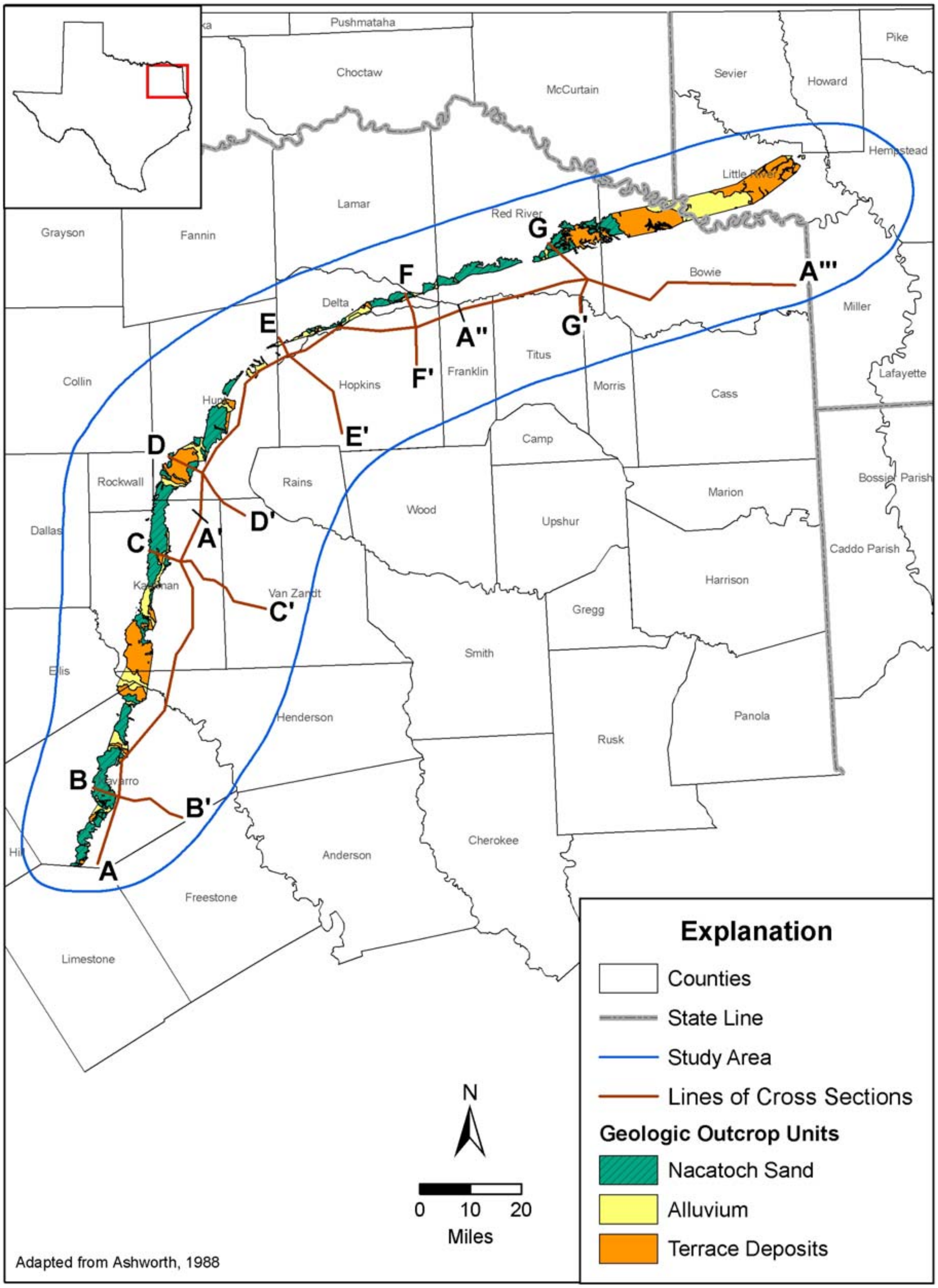


Figure 2.3.7 Location of lines of cross-section

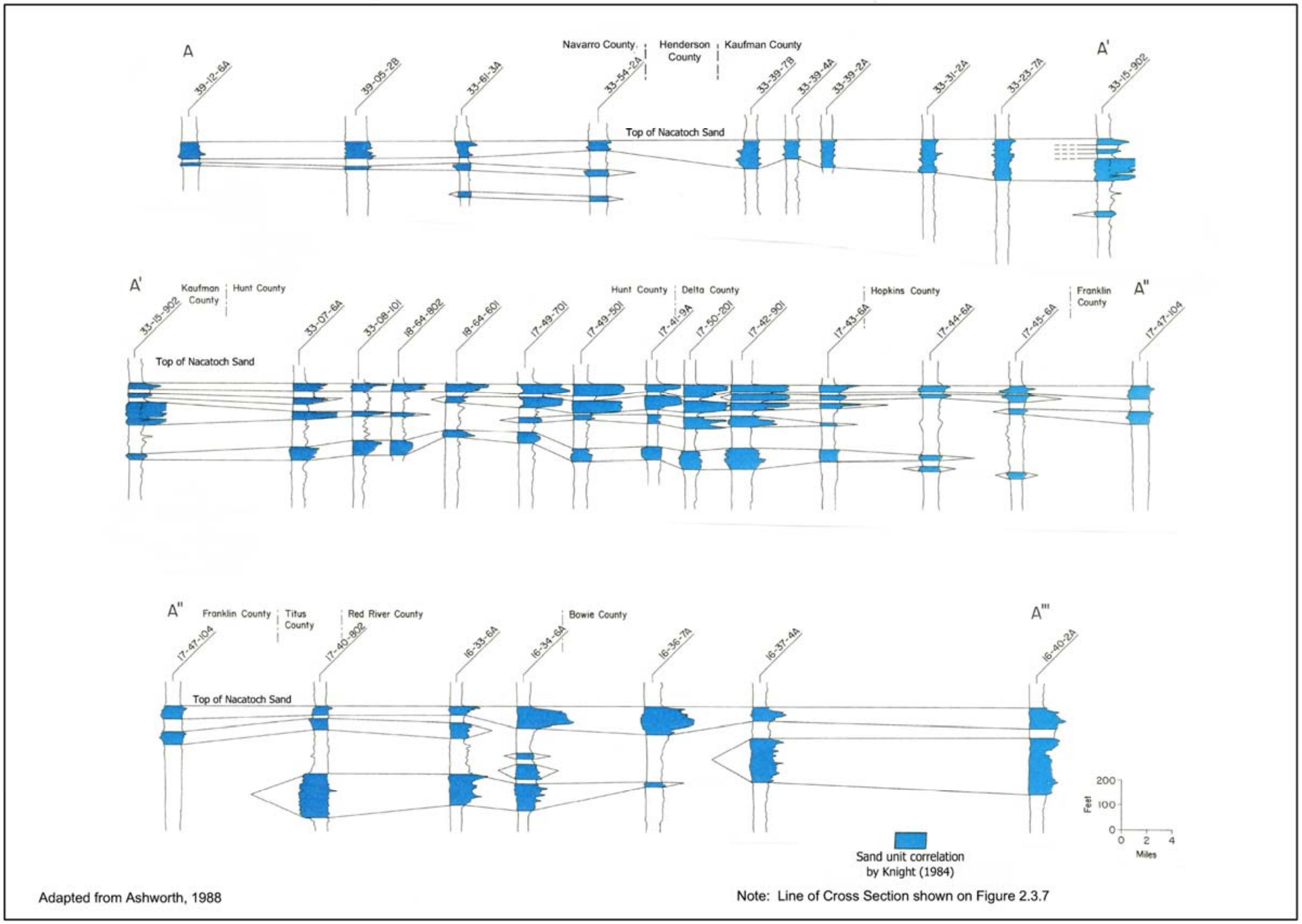


Figure 2.3.8 Geologic cross section A-A'"

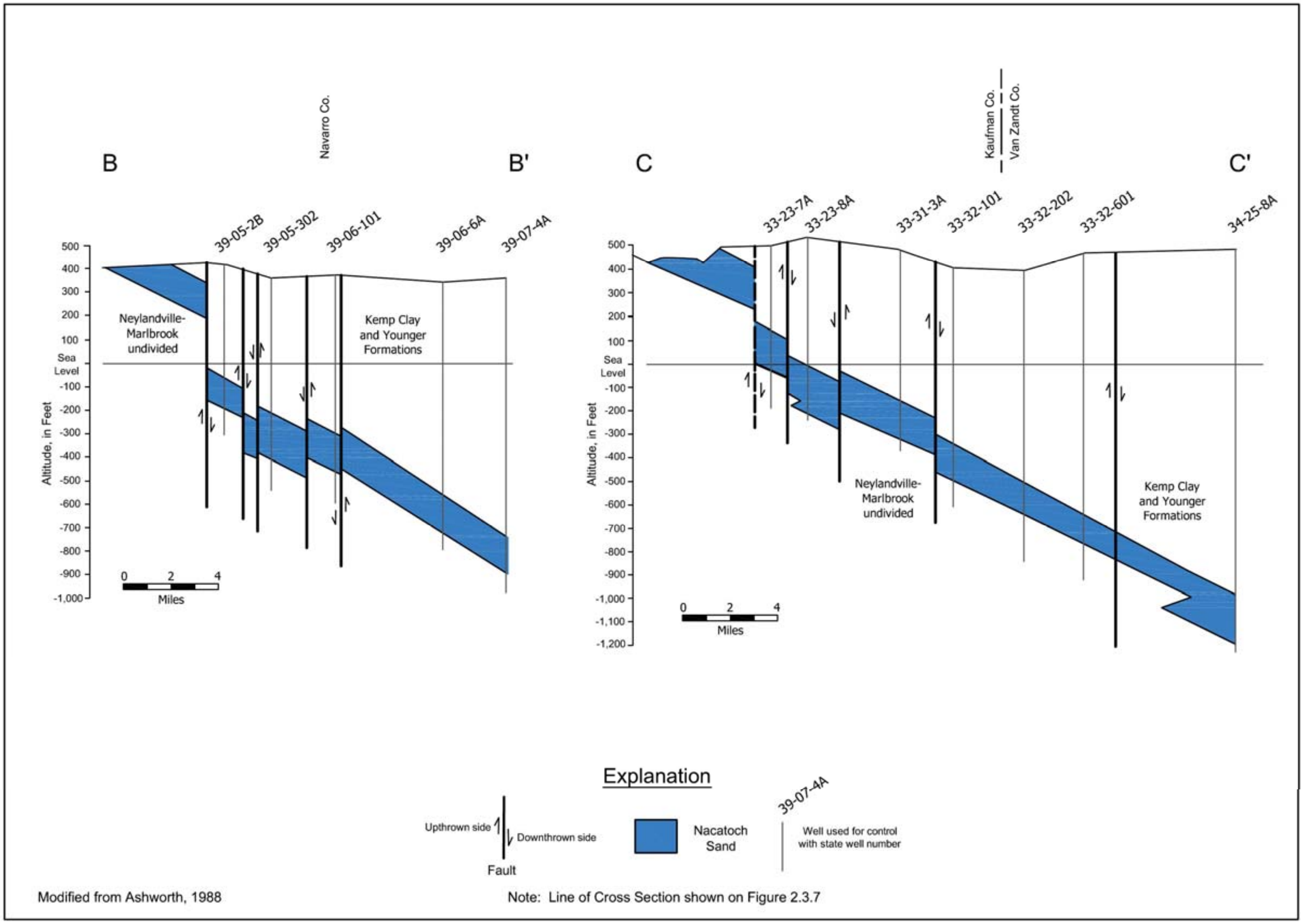


Figure 2.3.9 Geologic cross section B-B' and C-C'

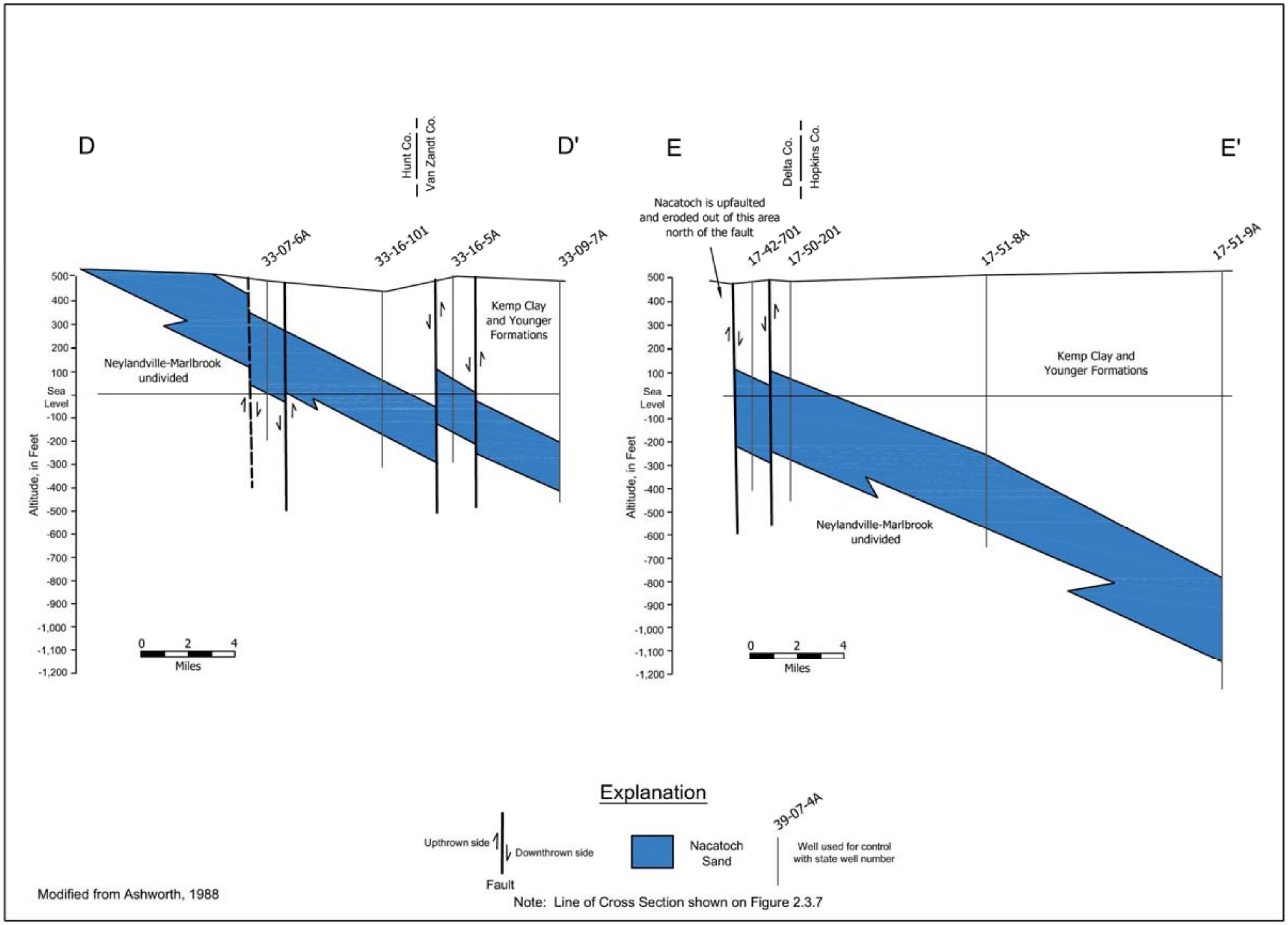


Figure 2.3.10 Geologic cross section D-D' and E-E'

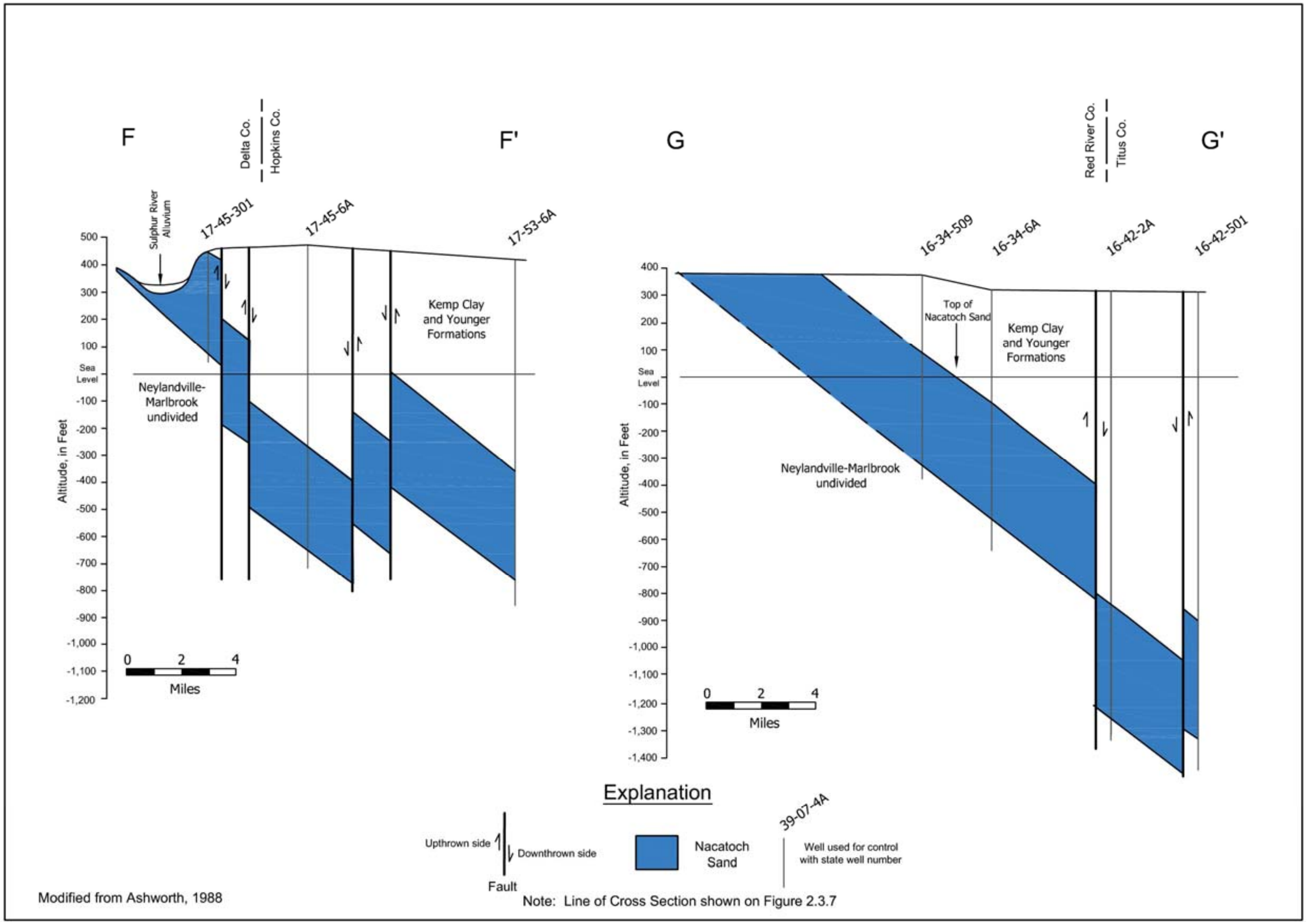


Figure 2.3.11 Geologic cross section F-F' and G-G'

2.3.3 Post-Nacatoch Erosion, Deposition of Younger Sediments, and Structural Faulting

Late Cretaceous time was marked by elevation of the land and retreat of the sea in central Texas, and early Tertiary by a new, but less intense, transgression of the sea (Sellards and others., 1932). Thus the interval between Cretaceous and Tertiary, as indicated on the outcrop, is an unconformity, the magnitude of which has not been well documented. Marine sediments and fossils of the Midway that overlie the Navarro formations mark the initial transgression of the sea during Tertiary time. Today the Nacatoch Aquifer outcrop has been incised by a number of surface streams and is overlain in many areas by river alluvium and flood plain deposits.

The paleoshoreline of the ancestral Gulf at the close of the Cretaceous from Hunt County eastward into southwestern Arkansas is documented by the stratigraphic occurrence of Nacatoch Sand near-shore sedimentary facies such as shoreface, tidal-flat, and deltaic deposits (McGowen and Lopez, 1983). From Kaufman County southward, the Nacatoch Sand outcrop is characteristic of a marine shelf environment, suggesting that the existing shoreline at the time was further inland to the west.

Basinward movement of the Jurassic-age Louann Salt occurred intermittently during the Mesozoic and more significantly during early Tertiary (Hager and Burnett, 1960) and had basin-wide structural implications. More than 35 salt structures (salt domes or diapers) have been identified in the central region of the East Texas Basin that often penetrate through the entire thickness of Cretaceous formations (Kreitler and others., 1981). Although these salt structures do not directly influence the updip fresh water extent of the Nacatoch Sand, they do create the potential for oil and gas reservoirs in Nacatoch Sand where fault closures occur along the flanks of the domes.

A secondary effect of the downdip migration of the Louann Salt was the development of the Mexia-Talco fault zone along the northern and western perimeter of the East Texas Basin (Figure 2.3.2). Basinward creep of overlying strata as the underlying salt was being displaced created strike-oriented normal faults that often formed grabens (Jackson, 1982). Cross sections BB' through GG' (Figure 2.3.9 through Figure 2.3.11) display this fault orientation. The faulting generally causes the normal downdip flow of groundwater to be halted or diverted, thus limiting the downdip extent of fresh water in the aquifer (Ashworth, 1988).

3.0 PREVIOUS INVESTIGATIONS

3.1 Hydrologic Investigations

Cretaceous strata in Texas are divisible into two distinguishable series, the lower Comanche Series and the upper Gulf Series (Sellards and others., 1932). Ferdinand Roemer (1849) and Benjamin Franklin Shumard (1863a; 1863b) provided early recognition of stratigraphic units that comprise the “Upper Cretaceous”. However, Robert T. Hill (1887) is credited with first using the name “Gulf Series” to include strata from the base of the Woodbine to the base of the Midway. The Navarro Group, which includes the Nacatoch Sand, occurs at the top of this Gulf Series.

In the mid-1800s, Shumard’s attempts at subdividing Cretaceous formations in Texas were based primarily on fossil observations. He introduced the name “Navarro beds” in 1861 for fossiliferous beds observed in Navarro County. Later, R.T. Hill (1901) used the name “Corsicana beds” for the basal, sandier portion of Shumard’s “Navarro beds” in Navarro County, which now likely correlates to the Nacatoch Sand and the underlying Neylandville Formation. Hill also introduced the name Kemp Clay for the upper Navarro clay unit overlying his “Corsicana beds”. W.L. Stephenson (Dane and Stephenson, 1928) originally identified the lower Navarro Clay below the Nacatoch Sand as the “Exogyra cancellata marls”. Sellards and others (1932) proposed Navarro as a Group name and, at Stephenson’s recommendation, revised the name of the lower Navarro unit to “Neylandville”.

Contemporaneously in southern Arkansas and northern Louisiana, workers were equally employed in developing Cretaceous stratigraphic subdivisions based on both lithologic and fossiliferous evidence. As in Texas, R.T. Hill was one of the prominent scientists in the field in Arkansas. In 1888, Hill made the first detailed investigation of the geology of southern Arkansas where he described a sandy rock unit that he called the “Washington Greensands”. Hill (1888; 1894; 1901) continued to revise his Upper Cretaceous nomenclature in subsequent papers. Taff (1891) followed with a more detailed map and cross sections depicting the extent of “Washington Greensands”.

A.C. Veatch (1906) is credited with introducing the name "Nacatoch Sand" in replacement of "Washington Greensands". In this report, Veatch provides the following narrative in describing this unit that included both the mid-Navarro sands and underlying Saratoga Chalk:

> <u>*Above the Marlbrook Marl is a series of sandy beds*</u> (stratigraphic definition)*, which are of vast economic importance to the strip of country along the Iron Mountain Railway between Arkadelphia and Texarkana, since they are the main water supply source of that region. - - -* <u>*The outcrop at Nacatoch Bluff, on the Little Missouri River, in Clark County*</u> (Arkansas) (type locality)*, is one of the most complete exposures occurring along this belt and shows the calcareous and quartzitic rocks which, when encountered in wells, are called "water rocks".*

C.H. Dane (1929) modified Veatch's previous nomenclature and developed the current formation names comprising the Navarro Group in Arkansas that are in use today; Arkadelphia Marl, Nacatoch Sand, and Saratoga Chalk. A number of researchers during this time, such as Adams (1901), attempted to correlate the upper Cretaceous formations of northeast Texas with the Arkansas section. In doing so nearly all are agreed that the Nacatoch Sand is not typically developed in Texas (Howe, 1924).

The "East Texas Basin" is the structural feature that most influenced the depositional environment within which the sands and clays of the Nacatoch were deposited. Numerous reports are listed in the reference section that pertain to the origin, development, and geometry of the East Texas Basin; bordering fault zones and their impacts on oil and gas production; and the Basin's internal salt tectonics. Wood and Guevara (1981) produced regional cross sections across the entire East Texas Basin, followed by McGowen and Lopez (McGowen and Lopez, 1983) who described the depositional systems of the Nacatoch Sand.

Surface geologic mapping of the Nacatoch Sand and its adjacent stratigraphic units is presented on the Dallas, Sherman, Texarkana, and Waco Geologic Atlas Sheets constructed and published by the University of Texas, Bureau of Economic Geology. However, the Nacatoch Sand is not shown individually but rather is included in the Navarro Group undivided on the Texarkana and a portion of the Sherman sheets.

Reports that discuss the hydrologic characterization of the Nacatoch Aquifer at specified locations include the following:

Baker (1971) – City of Commerce
Baker and others (1963a) – Sabine River Basin
Baker and others (1963b) – Red River, Sulphur River, and Cypress Creek Basins
Broadhurst (1944) – City of Commerce
Counts and others (1955) – Southwestern Arkansas
LBG-Guyton Associates (2003)– Brackish groundwater resources
Peckham and others (1963) – Trinity River Basin
Rettman (1987) – Limestone County
Rose (1945) – City of Greenville
Schrader and Scheiderer (2004) – Arkansas
Thompson (1972) – Navarro County
White (1973) – Rains and Van Zandt Counties

In 1988, John Ashworth developed the first regional comprehensive assessment of the groundwater availability of the Nacatoch Aquifer in Texas (Ashworth, 1988). Five cored test holes drilled for this project provided depositional stratigraphic information that assisted in understanding the lateral connectivity of individual sand beds, as well as yield and water quality characteristics of each sand bed. Ashworth also demonstrated the downdip groundwater flow restriction created by the offset faults of the Mexia-Talco Fault Zone. Working with Ashworth on the Nacatoch Aquifer project, Knight (1984) described the mineral content of the core and cutting samples, and developed his interpretation of Nacatoch Sand deltaic facies. Subsequent water-supply availability estimates have been developed for the regional water planning process and can be viewed in the 2007 Region C Water Plan and the 2007 North East Texas Regional Water Plan.

3.2 Modeling Investigations

No documentation was found regarding previous regional scale models of the Nacatoch Aquifer system.

4.0 HYDROLOGIC SETTING

Groundwater of variable quantity and quality occurs in the Nacatoch Aquifer. This section details the major hydrogeologic components of this area and their significance to the GAM model. Included is discussion of the hydrostratigraphy of the major water-bearing formations as well as the structure that defines them. The occurrence and flow of groundwater, recharge and discharge, and groundwater/surface water interaction are also described in this section.

4.1 Hydrostratigraphy

The Nacatoch Aquifer system lies within the Navarro Group, which is the uppermost group of Cretaceous formations that, in northeast Texas, include in descending order the Kemp Clay, Nacatoch Aquifer, and Neylandville Formation (Table 2.3.1 and Figure 2.3.3). As discussed in Section 2.3.2, the Nacatoch Aquifer is considered the Nacatoch Aquifer outcrop downdip to the first major offset in the Mexia-Talco fault zone or to a downdip point where water quality becomes a significant factor in terms of use.

Hydrostratigraphy in this area plays a major role in the development of the conceptual model and model layers. Table 2.3.1 also shows the units included in each model layer for the Nacatoch Aquifer GAM.

4.2 Structure

4.2.1 Development of Structure

The structural framework of the Nacatoch Aquifer can base its configuration on three principal components: deposition into the East Texas Basin, deltaic sedimentation processes, and stratigraphic off sets resulting from the Mexia-Talco Fault Zone. These depositional components were discussed earlier in Section 2.3. For modeling purposes, an understanding of these three components is critical to the establishment of elevation maps depicting the base and top of the Nacatoch Aquifer, and to addressing how groundwater flows through the aquifer system.

The Nacatoch Aquifer formation is not a single sand layer, but rather a sequence of sand layers separated by layers of mudstone that dip south and southeast in the subsurface toward the central axis of the East Texas Basin. The number of sand layers varies throughout the Nacatoch Aquifer extent, and the thickness of individual sand units varies from over 100 feet in deltaic areas to less than 20 feet in shelf deposits in the southern extent (Ashworth, 1988). Thickness of intervening mudstone units similarly ranges from over 100 feet to only a few feet.

Net sand thickness is greatest (over 200 feet) within the Pittsburg syncline where it straddles the state line in eastern Bowie and Cass Counties (Figure 2.3.6). Elsewhere, increased sand thickness in the range of 120 feet occur in southern Red River and northern Titus Counties, eastern Hunt and western Delta Counties, and in southern Hunt County. These areas of greater thickness indicate focal points of original sediment input into the East Texas Basin. Net sand thickness decreases to 100 feet or less between these sediment input areas, and from central Kaufman County southward, net sand thickness is reduced to approximately 20 feet. Net sand distribution parallel to the strike direction is illustrated in Figure 2.3.8, while total Nacatoch Aquifer thickness distribution in the downdip direction is shown in Figure 2.3.9, Figure 2.3.10, and Figure 2.3.11.

The Mexia-Talco fault zone consisting primarily of strike-oriented normal faults that often formed grabens disrupts the basinward dip of the Nacatoch Aquifer layers. The faulting generally causes the normal downdip flow of groundwater to be halted or diverted, thus limiting the downdip extent of fresh water in the aquifer (Ashworth, 1988).

For modeling purposes, the base of the Nacatoch Aquifer layer is the base of the lowest Nacatoch Aquifer interval (Ashworth, 1988). Figure 4.2.1, which illustrates this base, was constructed based on existing base contours shown in Figure 6 of Ashworth (1988). Figure 6 has contour gaps in areas where complex faulting occurs. Contours were added in these areas based on the existing data control provided in Figure 6 of Ashworth (1988). Although not all faults are honored by the added contours, a concerted effort was made to characterize the major faults that form the updip and downdip boundaries of the major grabens. The updip fault of the grabens generally represents the most pronounced offset of individual sand beds.

4.2.2 Construction of the Structural Surfaces

To develop a raster dataset for the structural surfaces and contours that were hand drawn, the following steps were completed.

1. Hand drawn contour lines of the base of the Nacatoch Aquifer were digitized from Figure 6 of Ashworth (1988) and georeferenced.
2. Each contour line was assigned the appropriate attribute (elevation, thickness, or percent sand).
3. Using the ESRI Spatial Analyst topo_to_raster algorithm, the contour lines were used to create a raster dataset with ¼-mile grid spacing.
4. Raster data were used to reproduce contour lines for comparison to digitized contour lines developed in step 3.
5. If regenerated contour lines did not match the digitized contour lines, additional contour lines and/or point data coverages were developed to help constrain the algorithm and thus reproduce the digitized contour lines. Additional points and/or lines were added to the constraining shapefile until digitized contour lines were reasonably reproduced.

The first surface developed was the base elevation of the Nacatoch Aquifer. The five-step process described above was used to recreate the base elevation that had been contoured by hand. To ensure that proper elevations were adhered to at the outcrop, two additional point shapefiles were also used in the interpolation. The first contained land surface elevation at the north and western outcrop extent (where the base of the Nacatoch Aquifer intersects the land surface) and was used as constrain the topo_to_raster algorithm to the correct topographic estimates along the outcrop. Points containing average land surface elevations (averaged over ¼-mile square grid blocks) were spaced at 500 feet to along the outcrop as data points for the topo_to_raster algorithm. These points were used all along the outcrop except where Nacatoch Aquifer does not outcrop in the graben in Hunt and Hopkins counties. The second set of data was the estimate of the Nacatoch Aquifer base elevation at the south and eastern outcrop extent (where the top of the Nacatoch Aquifer intersects the land surface). These estimates of the Nacatoch Aquifer base elevation were estimated by subtracting the estimated thickness of the Nacatoch Aquifer from the land surface elevation along the outcrop where the top of the

Nacatoch Aquifer intersects the land surface. The estimate of the Nacatoch Aquifer thickness is discussed in the next paragraph. After several iterations, the process yielded contours that compared relatively well to the original digitized contour lines and honored the land surface elevations as well. The topo_to_raster algorithm does not have a method for including the location of offsetting faults or for calculating the associated base elevation offset in a direct way. However, the base elevation transition from one side of the fault to the other is reproduced in a continuous but relatively abrupt fashion, which is probably more practical for model implementation than a 200-300 foot offset across the fault. Little to no data was found for the base of the Nacatoch Aquifer in the southwesternmost portion of the aquifer, therefore base is estimated in this area. Figure 4.2.1 illustrates the base of the Nacatoch Aquifer structure.

The second surface developed was the thickness Nacatoch Aquifer. Relatively little data exists to characterize the variation in Nacatoch Aquifer thickness over the model area. Therefore, using existing geologic cross-sections and our understanding of the depositional system, total thickness was estimated for downdip sections of the aquifer. In the outcrop, the thickness was adjusted to account for land surface elevation. Figure 4.2.2 shows the thickness of Nacatoch Aquifer over the model area, and highlights portion of the area in Bowie and Red River counties to show the thinning of the Nacatoch Aquifer units in the outcrop area.

To obtain the top elevation of the Nacatoch Aquifer, the thickness estimates were added to the base surface. In outcrop areas, the land surface elevation was used for the Nacatoch Aquifer top elevation. The land surface elevation in the outcrop areas was estimated by averaging all of the 90-meter NED data in each quarter-mile gridblock in the outcrop. Figure 4.2.3 shows the top of Nacatoch Aquifer unit.

Net sand thickness contours developed by McGowen and Lopez (1983) were digitized from the original maps. The net sand thickness contours on these original maps did not extend to the outcrop zone in many areas. Figure 2.3.6 illustrates the distribution of the net sand thickness in the study area.

The thickness of the overlying Midway and alluvium units was estimated by subtracting the top elevation of the Nacatoch Aquifer from land surface elevation or the base of the Wilcox formation (the top of the Midway). The base elevation of the Wilcox was taken from the northern Queen City and Sparta GAM (Kelley and others., 2004). Figure 4.2.4 shows the thickness of Midway and alluvium overlying the Nacatoch Aquifer.

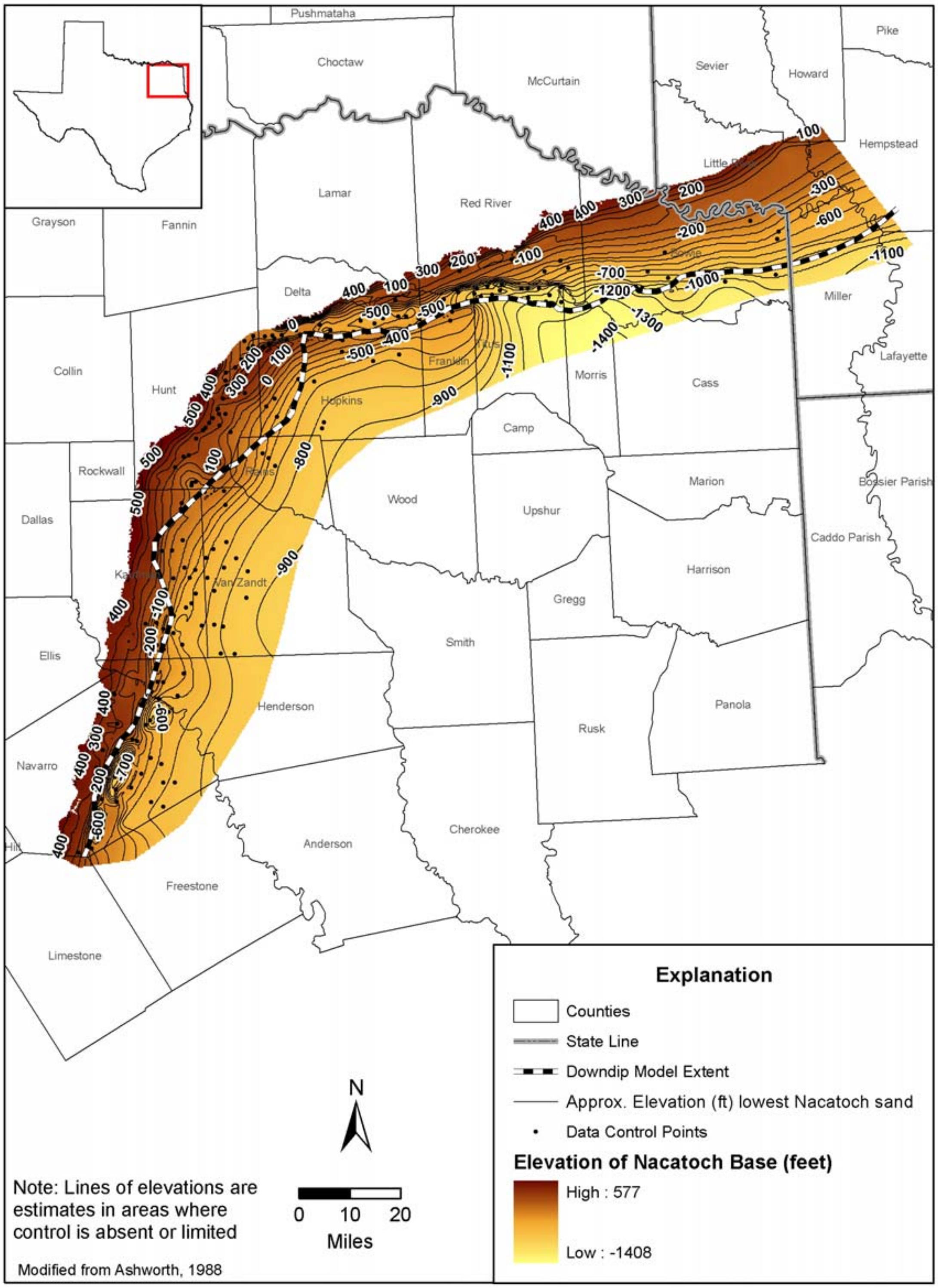


Figure 4.2.1 Base of Nacatoch Aquifer structure (developed using existing contours from Ashworth, 1988)

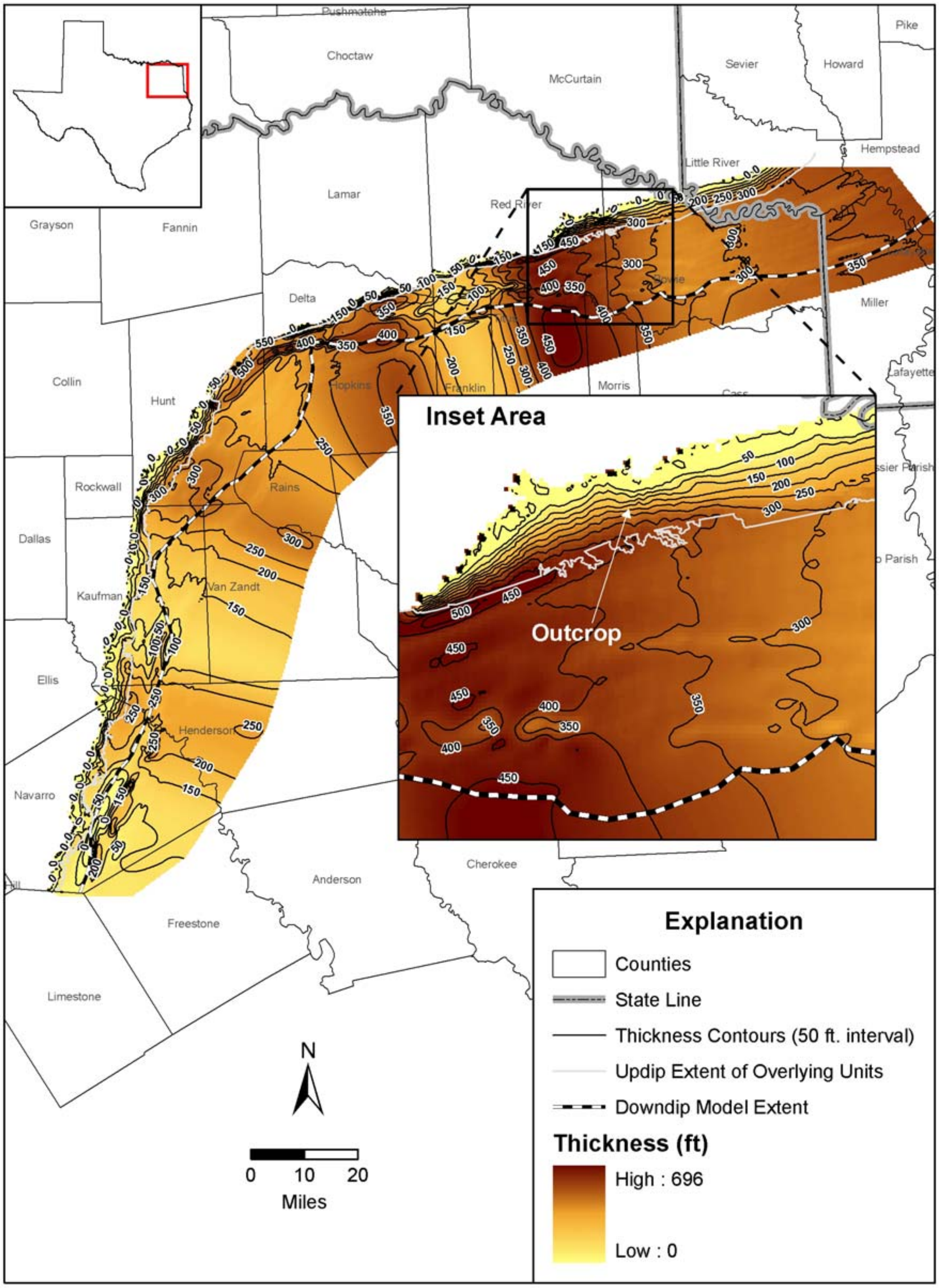


Figure 4.2.2 Estimated thickness of Nacatoch Aquifer structure

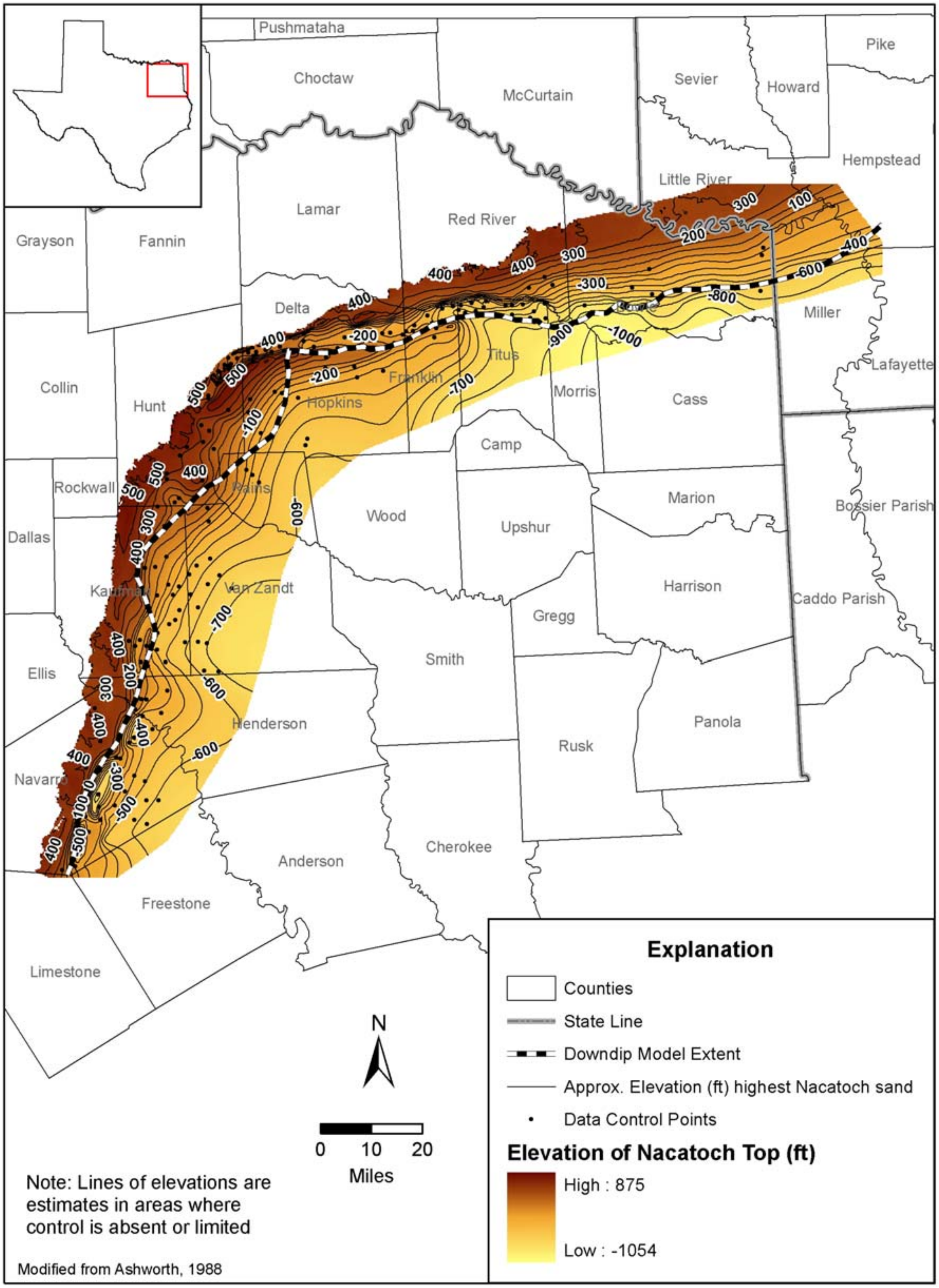


Figure 4.2.3 Estimated top of Nacatoch Aquifer structure

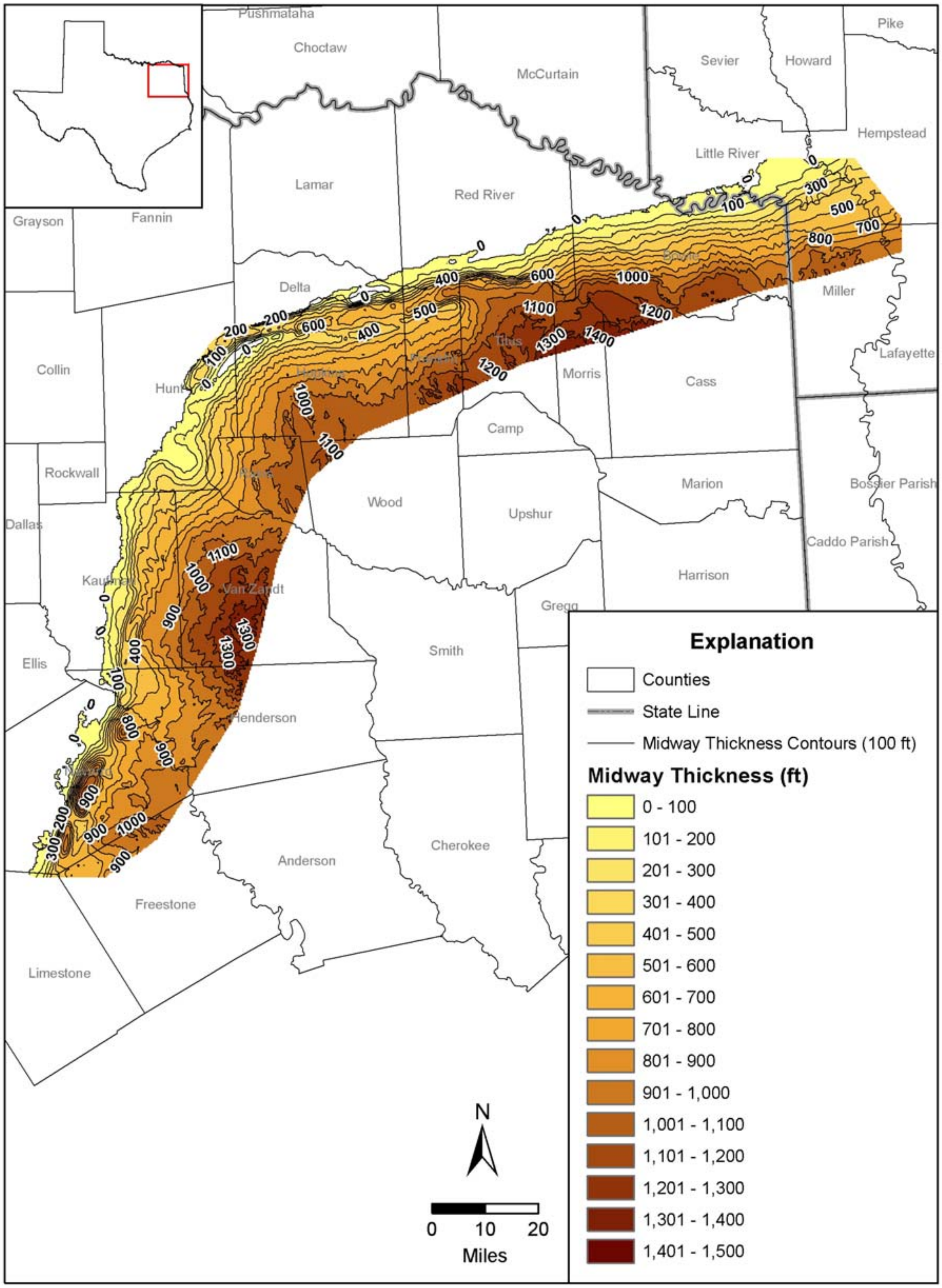


Figure 4.2.4 Estimated thickness of Midway and Alluvium

4.3 Water Levels and Groundwater Flow

A literature review was conducted to develop a conceptual understanding of regional groundwater flow in the Nacatoch Aquifer and the history of groundwater usage from the aquifer. The literature review included a review of available reports by the various past and present Texas state agencies responsible for water resources, the University of Texas-Bureau of Economic Geology, the U.S. Geological Survey (USGS), and reports by River Authorities. Water level data collected from these sources were used to develop water-level elevation contours for the steady-state period, considered representative of predevelopment conditions. In addition, three historical head surfaces were developed consistent with the GAM specifications. These include a head surface representative of 1980, 1990, and the end of the transient simulation time period (December 1997). Calibration head targets were developed for predevelopment, 1980, 1990, and 1997 time periods and transient hydrographs were develop to investigate transient water-level changes regionally and to be used in calibration. The analysis of water levels will be discussed in the remainder of this section.

4.3.1 Data Sources and Data Summary

The sources for the water-level data used for the Nacatoch Aquifer are the TWDB website: (http://www.twdb.state.tx.us/publications/reports/GroundWaterReports/GWDatabaseReports/GWdatabaserpt.htm), available TWDB county reports, and Ashworth (1988). Arkansas head data was obtained from the USGS website (http://waterdata.usgs.gov/nwis/). The Nacatoch Aquifer is commonly referred to as undifferentiated Navarro north of Hunt County and the Nacatoch Aquifer south of Hunt County. As a result, water levels from both of these aquifer designations were combined. In addition, there are significant alluvial aquifers overlying and in hydraulic contact with the underlying Nacatoch Aquifer in Bowie and Red River Counties. Alluvial aquifer water levels in the outcrop of the Nacatoch Aquifer were also included in the head database. Locations and hydrostratigraphic units for Texas wells with water-level data in the Nacatoch Aquifer are shown in Figure 4.3.1. A summary of the aquifer codes assigned to these wells along with the number of wells associated with each aquifer code is provided in Table

4.3.1. The locations for Arkansas wells with water-level data in the Nacatoch Aquifer are also shown in Figure 4.3.1.

According to the water-level data on the TWDB website, a total of 1,747 individual water-level measurements have been taken in 622 wells completed in the Nacatoch Aquifer in Texas. This includes measurements in the alluvial aquifers. The distribution of water level coverage by county is reasonably good. However, because of the limited downdip extent of the aquifer, there is a paucity of data in the confined section. The frequency of water-level measurements has varied significantly over time (Figure 4.3.2). Figure 4.3.2 shows that in the period from 1980 to 1985, the largest number of head measurements (381) were made and collected. This increase in water level measurements coincides with the TWDB study of the Nacatoch Aquifer documented in Ashworth (1988).

Groundwater usage in the Nacatoch Aquifer started in the late 1800s and early 1900s with the earliest municipal use in Hunt and Delta Counties to service the municipality of Commerce. From a review of Figure 4.3.2, one can see that very few water levels have been documented prior to 1935. The earliest water level recorded for the aquifer was recorded in 1907 in Hunt County.

Table 4.3.1 Summary of aquifer codes for wells in the formations comprising the Nacatoch Aquifer and the hydraulically connected alluvium

TWDB Aquifer Code	Description	Number of Wells from the TWDB Database	Number of Wells from the USGS Database
211NCTC	Nacatoch Aquifer	415	36
211NVRR	Navarro Group	39	0
211NVTY	Navarro and Taylor Group	50	0
100ALVM	Alluvium	41	41

4.3.2 Regional Groundwater Flow

Potable groundwater within the Nacatoch Aquifer occurs mostly in the outcrop under water-table conditions. Groundwater flow is highly controlled by faulting associated with the

Mexia-Talco Fault Zone. In many portions of the aquifer, downdip flow is precluded because of the discontinuity in aquifer sands caused by faulting. Because the aquifer predominantly exists in the outcrop under unconfined conditions, water-level elevations generally conform to topography with higher heads under higher surface elevations and lower heads in lower surface elevations.

In portions of the aquifer that are confined, the heads generally decrease as you move into the confined section with some continued expression of outcrop topography in areas with relatively high relief such as Red River County into Eastern Bowie County. The aquifer system and groundwater flow is topographically driven. As a result, under predevelopment conditions one would expect the groundwater that flows into the confined portions of the aquifer to discharge across the aquifer's upper boundary to the Midway Formation. To provide evidence of this flow system, we reviewed the available confined Nacatoch Aquifer heads and attempted to find Midway water level measurements in near proximity to the Nacatoch Aquifer head. The expectation would be that the confined Nacatoch Aquifer head would be higher than the Midway head indicating discharge from the confined Nacatoch Aquifer to the Midway. There were only three instances where we found well pairs that appeared to be minimally impacted by pumping and could provide an indication of the natural hydraulic gradient between the Nacatoch Aquifer and the Midway. One case was in an eastern Red River County well within the confined portion of the Nacatoch Aquifer. In this location, there was a 29-foot head difference from the Nacatoch Aquifer to the Midway. The second and third well pairs were located in Kaufman County. For these two well sets, the head difference between the Nacatoch Aquifer and the Midway were 24 and 17 feet. In all three cases heads in the Nacatoch Aquifer were found to be higher than Midway heads indicating that flow in the confined Nacatoch Aquifer section discharges through cross-formational flow to the Midway.

4.3.3 Predevelopment Conditions for the Nacatoch Aquifer

Predevelopment conditions are defined as those existing in the aquifer prior to any disturbances of natural groundwater flow due to artificial discharge from groundwater pumping. Predevelopment conditions are considered to be at steady state, which means that aquifer recharge equals aquifer discharge with no net change in aquifer storage. Before resource development, the aquifer did vary with changes in climate. However, it is assumed that there existed a long-term dynamic equilibrium where head variation was small relative to changes produced through aquifer development. Literature information on the historical development of the Nacatoch Aquifer is sparse. County reports exist for only a few of the counties in the aquifer region.

Development of the Nacatoch Aquifer first occurred in Red River County in 1885. Over a dozen wells were dug in this area between 1885 and 1915. Historically, the heaviest use of groundwater from the Nacatoch Aquifer is in the vicinity of the city of Commerce and in southwestern Red River County. The city of Commerce drilled its first well in 1914 (17-41-901, City of Commerce Well #1) and reported a water level 125 feet below land surface. In 1953, the water level in the well was reported to be 280.9 feet below land surface, a decline of 155.9 feet in the 39-year period. The city of Commerce Well #2 (17-41-902) located 250 feet from Well #1 was measured at 318.8 feet below land surface in 1971. The total head decline at the Commerce wells between 1914 and 1971 was reported to be 183.9 feet (Baker, 1971). Development of the Nacatoch Aquifer in Navarro County first occurred in the city of Corsicana in 1894 (Thompson, 1972). However, the first water levels on record in the Corsicana region were measured in 1961 by the city of Richland (TWDB, website). In general, there has been a slow transition from groundwater supplies to surface water supplies since 1980 (Baker and others., 1963b).

Given the early development of the aquifer and the lack of regional water levels prior to the 1960s, development of a predevelopment head surface is challenging. We used an iterative approach that included data from a variety of sources and time periods combined with professional judgment. The data used to develop the predevelopment head surface originates from the following sources; (1) ground surface elevation and its relation to unconfined aquifer heads, (2) the earliest water level measurements recorded, (3) the maximum water level measurements recorded, and water level trends taken from head time series data and particular wells (hydrographs).

To augment measured head values, we developed a relationship between land surface elevation based upon a 30-meter DEM and measured water level elevations in the outcrop portions of the aquifer. Because Hunt and Hopkins County heads have been so impacted by pumping, heads from these two counties were not included in the analysis. Figure 4.3.3 plots the linear relationship between land surface elevation and measured groundwater elevation in the outcrop. From Figure 4.3.3, one can see that the relationship is very strong with an R^2 of 0.85. It is also of interest to note that the relationship has a y-intercept of –18.8 feet which means that the average water level elevation is approximately 18.8 feet below average ground surface elevation.

Figure 4.3.4 plots the estimated unconfined head surface (proposed to be representative of predevelopment conditions) as calculated by the regression equation. The estimated head surface varies from approximately 230 to 460 feet above mean sea level. Figure 4.3.4 also plots the validation cross plot that demonstrates that the relationship honors the measurements reasonably well and that the residuals are not overly biased.

Through the use of the estimated head surface and the measured heads considered to be representative of predevelopment conditions, a predevelopment head surface was developed. Figure 4.3.5 plots the predevelopment Nacatoch Aquifer head surface with a 25-foot contour interval. The head contours again show close correlation with topography. Table 4.3.2 provides the targets used for control for the predevelopment head surface shown in Figure 4.3.5. One will note that of the 116 heads used as control, many have relatively modern measurement dates. These heads were only selected if we could be reasonably confident that historical pumping in that region was minimal.

An important aspect of the predevelopment contours is that major stream valleys and major topographic high regions create several groundwater flow system divides across the aquifer. In addition, the regions of high topography and head influence heads in the confined section with heads being under artesian conditions over most if not all of the confined section and heads at ground surface or above in regions of Red River, Bowie, and Hopkins Counties. The presence of flowing wells within the Nacatoch Aquifer in southwest Red River County was documented by Ashworth (1988) and is also documented in the TWDB wells database.

4.3.4 Water-Level Elevations for the Historical Period

GAM specifications require head surfaces generated for 1980, 1990, and 1997. Heads have not varied significantly through this time period because of relatively small variation in pumping across this period. As a result, the head surfaces for 1980, 1990, and 1997 show very little significant variation from each other. The GAM specified calibration period is from January 1, 1980 to December 31, 1997. The calibration process uses all available head targets to condition the model. We also used the predevelopment and the 1980, 1990, and 1997 head surfaces as general calibration guidance to make sure that head surfaces are consistent with their conceptualization.

Water-level data obtained from the TWDB website, from Ashworth (1988) and from the USGS website for Arkansas were used to develop water-level elevation contours for 1980, 1990 and at the end of the transient calibration period (December 31, 1997). Because the model simulates from predevelopment through 1997, the steady state calibration heads are the initial heads for transient calibration. The contour head surfaces aid in assessing the transient model's ability to represent observed conditions.

Water-level data are not available at regular time intervals in every well. Therefore, the coverage of water-level data for a particular month or even a year is very sparse. Since the amount of water-level data available for the times of interest were not sufficient to develop contours, data was integrated across time windows surrounding the year of interest. For example, for the 1980 head surface, we used heads from 1978 through 1982 (a five year period). The window of integration was expanded to 1982 to take advantage of the large number of head measurements collected in 1982 (see Figure 4.3.2). 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. Because of the relatively large number of head measurements available for 1982, we consider the 1982 head surface to be the most reliable head surface developed for the Nacatoch Aquifer.

Figure 4.3.6 shows the water-level elevation contours for the Nacatoch Aquifer representative of 1980 conditions. The contour map of head uses a 25-foot contour interval. The 1980 head surface is similar in morphology to the predevelopment head surface across most of the aquifer boundaries. However, there are two significant cones of depression in Hunt county extending into Delta and Hopkins Counties. The drawdown cone in Hunt and Delta Counties is associated with the city of Commerce wells. The Hopkins County cone of depression is associated with the city of Cumby. Figure 4.3.7 plots a net drawdown plot from estimated predevelopment heads to estimated 1980 heads. The calculation is made by subtracting predevelopment heads from 1980 heads which should generally result in a negative number representing feet of drawdown. One can easily see the significant drawdown cones discussed above. It is also apparent that the 1980 heads on average are largely unaffected (less than 25 feet of drawdown) in regions away from the big municipal users. Other significant water use in the study area includes irrigation pumped from the alluvial aquifers overlying the Nacatoch Aquifer. One would expect that drawdown from pumping the alluvial aquifers would be minimal given the volumes pumped, the high conductivity and unconfined nature of the alluvium, and the humid environment with ample rainfall. The rivers within the alluvium act as a source of capture.

Figure 4.3.8 and Figure 4.3.9 show the water-level elevations for the Nacatoch Aquifer for the 1990 and 1997 head surfaces. For the 1990 head surface, data was integrated from 1988 through 1991. For the 1997 head surface, data was integrated from 1996 through 1999. From a review of Figure 4.3.7 and Figure 4.3.9, one can see that heads show very little variation within the aquifer over this time frame. Many of the small differences between the 1980, 1990, and 1997 head surfaces probably originate from issues related to data control. As stated above, the 1980 head surface is considered to be the best head surface in the historical period because of much greater control.

4.3.5 Transient Water Levels

Transient water-level data was used along with the water-level elevation contours at specific time periods to calibrate the model. Figure 4.3.10 shows the locations of wells within the Nacatoch Aquifer for which transient water-level data exists. The figure distinguishes between those well that have less than seven measurements and those wells which have seven or greater water level measurements. There are 25 Nacatoch Aquifer wells within the study area that have seven or more documented water levels.

Figure 4.3.11 provides representative hydrographs from the northeastern portion of the study area in Bowie, Red River, Delta, and Hunt Counties. In Bowie and Red River Counties, the hydrographs are relatively stable. The Delta County hydrograph shows increasing head conditions, the result of decreased groundwater use in the near vicinity of that well. The Hunt County hydrograph shows significant drawdown over the period of record reflecting the continued use of groundwater by the City of Commerce through that time period. However, the total known drawdown in that portion of Hunt County (see Figure 4.3.7) of 100 to 200 feet is not reflected in the hydrograph.

Figure 4.3.12 provides representative hydrographs from the southwestern portion of the study area in Hunt, Kaufman, and Navarro Counties. These hydrographs display an upward trend. This is especially true for Well 17-57-201 in Hunt County that is seeing the affects of decreased pumping in its vicinity as the city added production wells to the east. Because upward trends are prevalent in the hydrographs for the aquifer, it is important to simulate transient heads from predevelopment until 1997 to have the ability to simulate increasing heads.

Table 4.3.2 Target values for calibration of the steady-state model to predevelopment conditions

Well Number	County/Parish, State	Measurement Date	Observed Water Level Elevation (ft)	Source
Nacatoch Aquifer				
1626903	Red River, TX	3/3/1960	435	TWDB website
1628708	Bowie, TX	NA	370[1]	TWDB website
1629803	Bowie, TX	6/17/1963	311	TWDB website
1631501	Bowie, TX	11/30/1957	266	TWDB website
1631701	Bowie, TX	4/12/1962	266.17	TWDB website
1631803	Bowie, TX	11/30/1955	273	TWDB website
1632701	Bowie, TX	11/30/1959	254	TWDB website
1632804	Bowie, AR	4/30/1974	239	TWDB website
1633301	Red River, TX	12/4/1959	334.9	TWDB website
1633701	Red River, TX	7/1/1972	310	TWDB website
1634107	Red River, TX	3/23/1978	431.7	TWDB website
1634109	Red River, TX	3/23/1978	365.7	TWDB website
1634304	Red River, TX	1/18/1974	390	TWDB website
1634508	Red River, TX	8/18/1976	330	TWDB website
1635101	Bowie, TX	NA	370[1]	TWDB website
1635304	Bowie, TX	NA	325[1]	TWDB website
1635401	Bowie, TX	3/25/1960	369.1	TWDB website
1635602	Bowie, TX	NA	338[1]	TWDB website
1636203	Bowie, TX	7/11/1960	326.1	TWDB website
1636301	Bowie, TX	7/7/1960	317.3	TWDB website
1636401	Bowie, TX	5/14/1958	343.1	TWDB website
1637102	Bowie, TX	12/29/1959	311.9	TWDB website
1637301	Bowie, TX	11/30/1955	281	TWDB website
1639107	Bowie, TX	2/22/1958	253	TWDB website
1639110	Bowie, TX	1/20/1968	248	TWDB website
1639202	Bowie, TX	6/28/1960	258.6	TWDB website
1639601	Bowie, TX	11/30/1982	221.6	TWDB website
1640102	Bowie, TX	5/17/1962	241	TWDB website
1643101	Bowie, TX	NA	300[1]	TWDB website
1644302	Bowie, TX	5/16/1962	339.8	TWDB website

Table 4.3.2 Target values for calibration of the steady-state model to predevelopment conditions

Well Number	County/Parish, State	Measurement Date	Observed Water Level Elevation (ft)	Source
1738401	Lamar, TX	12/24/1959	380.47	TWDB website
1738901	Red River, TX	4/26/1960	362.88	TWDB website
1739201	Red River, TX	4/27/1960	413.8	TWDB website
1739203	Red River, TX	4/27/1960	425.7	TWDB website
1739206	Red River, TX	2/11/1976	371.4	TWDB website
1739401	Red River, TX	6/2/1960	344	TWDB website
1739501	Red River, TX	2/11/1907	364.6	TWDB website
1739504	Red River, TX	4/26/1960	340.9	TWDB website
1739505	Red River, TX	4/26/1960	337.1	TWDB website
1739704	Red River, TX	7/31/1974	332	TWDB website
1739905	Red River, TX	12/8/1952	294	TWDB website
1740101	Red River, TX	4/27/1960	355	TWDB website
1740201	Red River, TX	10/21/1960	362.3	TWDB website
1740501	Red River, TX	11/30/1959	328.78	TWDB website
1740504	Red River, TX	10/21/1960	323.6	TWDB website
1741901	Hunt, TX	NA	530[1]	TWDB website
1743501	Delta, TX	12/2/1952	401.28	TWDB website
1749315	Hunt, TX	NA	465[1]	TWDB website
1750603	Hopkins, TX	6/19/1990	420	TWDB website
1758502	Hopkins, TX	6/10/1968	411	TWDB website
1856602	Hunt, TX	12/8/1982	510.7	TWDB website
1864301	Hunt, TX	NA	486[1]	TWDB website
1864602	Hunt, TX	12/8/1982	469.5	TWDB website
1864903	Hunt, TX	12/7/1982	423.9	TWDB website
3307501	Hunt, TX	7/29/1982	513.2	TWDB website
3307703	Hunt, TX	7/29/1982	479	TWDB website
3307802	Hunt, TX	10/20/1979	430	TWDB website
3308701	Hunt, TX	9/22/1983	439	TWDB website
3308702	Hunt, TX	9/30/1983	462	TWDB website
3308801	Hunt, TX	12/8/1982	402	TWDB website
3314601	Kaufman, TX	6/25/1979	559	TWDB website

Table 4.3.2 Target values for calibration of the steady-state model to predevelopment conditions

Well Number	County/Parish, State	Measurement Date	Observed Water Level Elevation (ft)	Source
3315101	Hunt, TX	7/29/1982	513.2	TWDB website
3315102	Kaufman, TX	12/9/1982	521.2	TWDB website
3315201	Hunt, TX	7/29/1982	457.9	TWDB website
3315401	Kaufman, TX	7/6/1961	482	TWDB website
3316104	Hunt, TX	11/18/1981	433	TWDB website
3316201	Hunt, TX	12/8/1982	436.2	TWDB website
3322305	Kaufman, TX	NA	479[1]	TWDB website
3322601	Kaufman, TX	6/24/1976	450.5	TWDB website
3322901	Kaufman, TX	12/9/1982	435	TWDB website
3323106	Kaufman, TX	7/6/1961	459	TWDB website
3330501	Kaufman, TX	12/9/1982	436.4	TWDB website
3330801	Kaufman, TX	12/9/1982	407.3	TWDB website
3338403	Kaufman, TX	12/9/1982	417.2	TWDB website
3345901	Navarro, TX	4/29/1968	382.9	TWDB website
3346204	Henderson, TX	9/2/1982	327.6	TWDB website
3353201	Navarro, TX	4/30/1968	439.1	TWDB website
3353202	Navarro, TX	7/10/1968	448.1	TWDB website
3353501	Navarro, TX	7/11/1968	392.8	TWDB website
3353801	Navarro, TX	7/11/1968	374.8	TWDB website
3360901	Navarro, TX	5/23/1968	409.5	TWDB website
3361401	Navarro, TX	5/21/1968	414.6	TWDB website
3904502	Navarro, TX	12/9/1982	428.1	TWDB website
3904603	Navarro, TX	7/5/1961	326	TWDB website
3905104	Navarro, TX	5/23/1968	351.5	TWDB website
3912201	Navarro, TX	5/28/1968	425.3	TWDB website
333204093595101	Miller, AR	10/23/1968	253.06	USGS
333215093581601	Miller, AR	6/4/1963	247.96	USGS
333318093412701	Hempstead, AR	4/30/1999	211.69	USGS
333724093492301	Hempstead, AR	2/15/1983	236.2	USGS
333913093423101	Hempstead, AR	4/28/1999	262.32	USGS
333920093455601	Hempstead, AR	4/4/1951	248	USGS

Table 4.3.2 Target values for calibration of the steady-state model to predevelopment conditions

Well Number	County/Parish, State	Measurement Date	Observed Water Level Elevation (ft)	Source
334334093432401	Hempstead, AR	12/13/1967	381.35	USGS
334405093531601	Hempstead, AR	3/29/1951	340.76	USGS
334641093344701	Hempstead, AR	10/24/1968	353.66	USGS
334731093304501	Hempstead, AR	3/26/1968	313.11	USGS
334834093362501	Hempstead, AR	10/24/1968	449.46	USGS
Navarro Group				
1740302	Red River, TX	10/21/1960	368.7	TWDB website
1744201	Hopkins, TX	NA	385[1]	TWDB website
3338402	Kaufman, TX	11/14/1975	381.98	TWDB website
3354401	Navarro, TX	4/23/1968	423.1	TWDB website
3354702	Navarro, TX	4/18/1968	384.7	TWDB website
3361302	Navarro, TX	7/15/1968	360.9	TWDB website
3361701	Navarro, TX	5/21/1968	390.9	TWDB website
3904801	Navarro, TX	5/28/1968	378.9	TWDB website
3905102	Navarro, TX	5/20/1968	329.9	TWDB website
Alluvium				
1627203	Bowie, TX	11/30/1958	346	TWDB website
1628101	Bowie, TX	2/28/1959	348	TWDB website
1628201	Bowie, TX	11/30/1959	317	TWDB website
1629101	Bowie, TX	8/31/1959	305	TWDB website
1629102	Bowie, TX	3/25/1960	330.2	TWDB website
333435094185301	Little River, AR	3/19/1968	282.46	USGS
333527094084101	Little River, AR	11/16/1967	268	USGS
333655094233401	Little River, AR	3/6/1958	305.71	USGS
333702094134301	Little River, AR	3/19/1968	274.14	USGS
333719093575001	Little River, AR	6/18/1963	254.12	USGS
333951094071501	Little River, AR	2/3/1959	329.45	USGS

[1] Adjusted water level

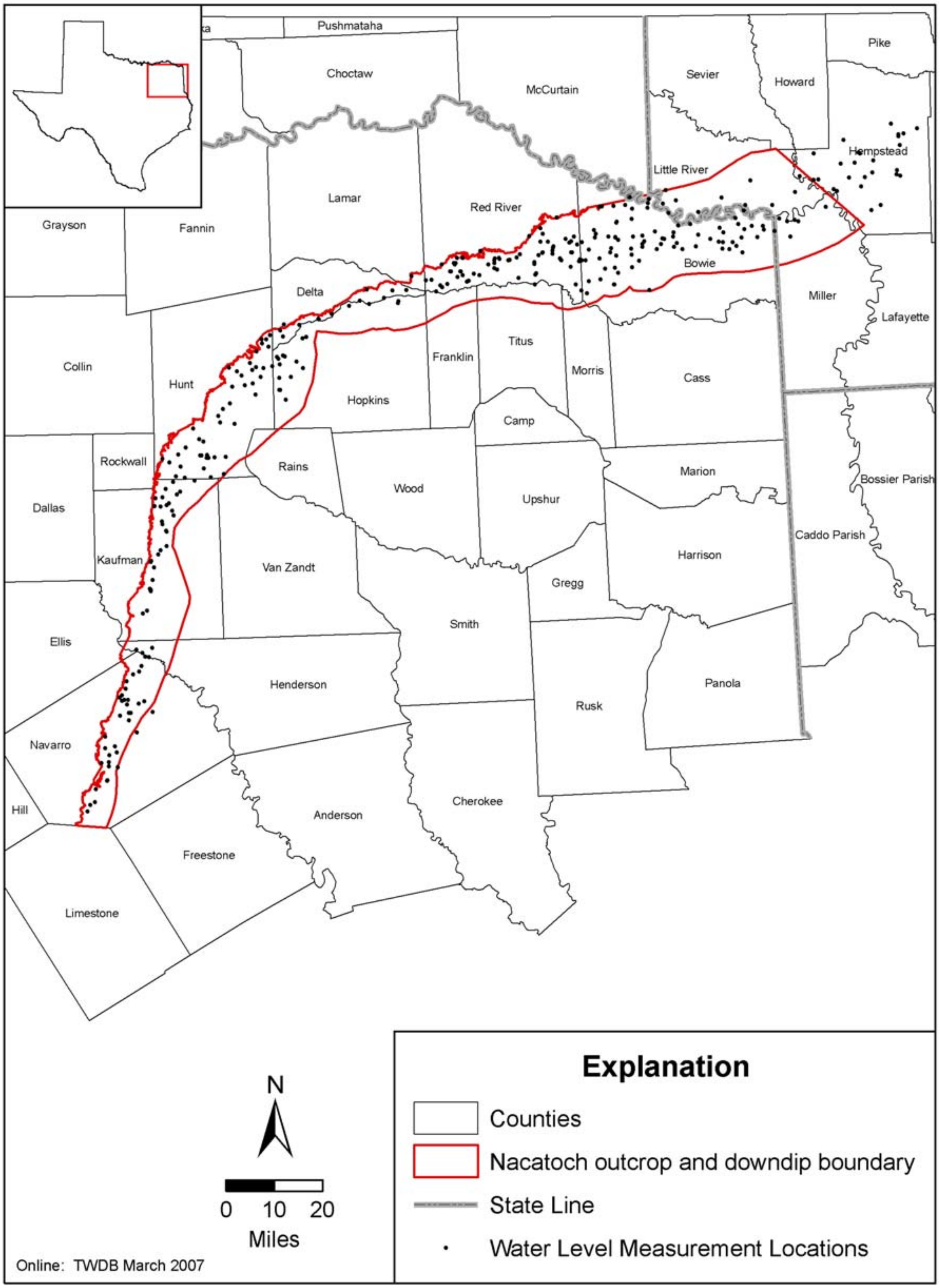


Figure 4.3.1 Water-level measurement locations for the Nacatoch Aquifer

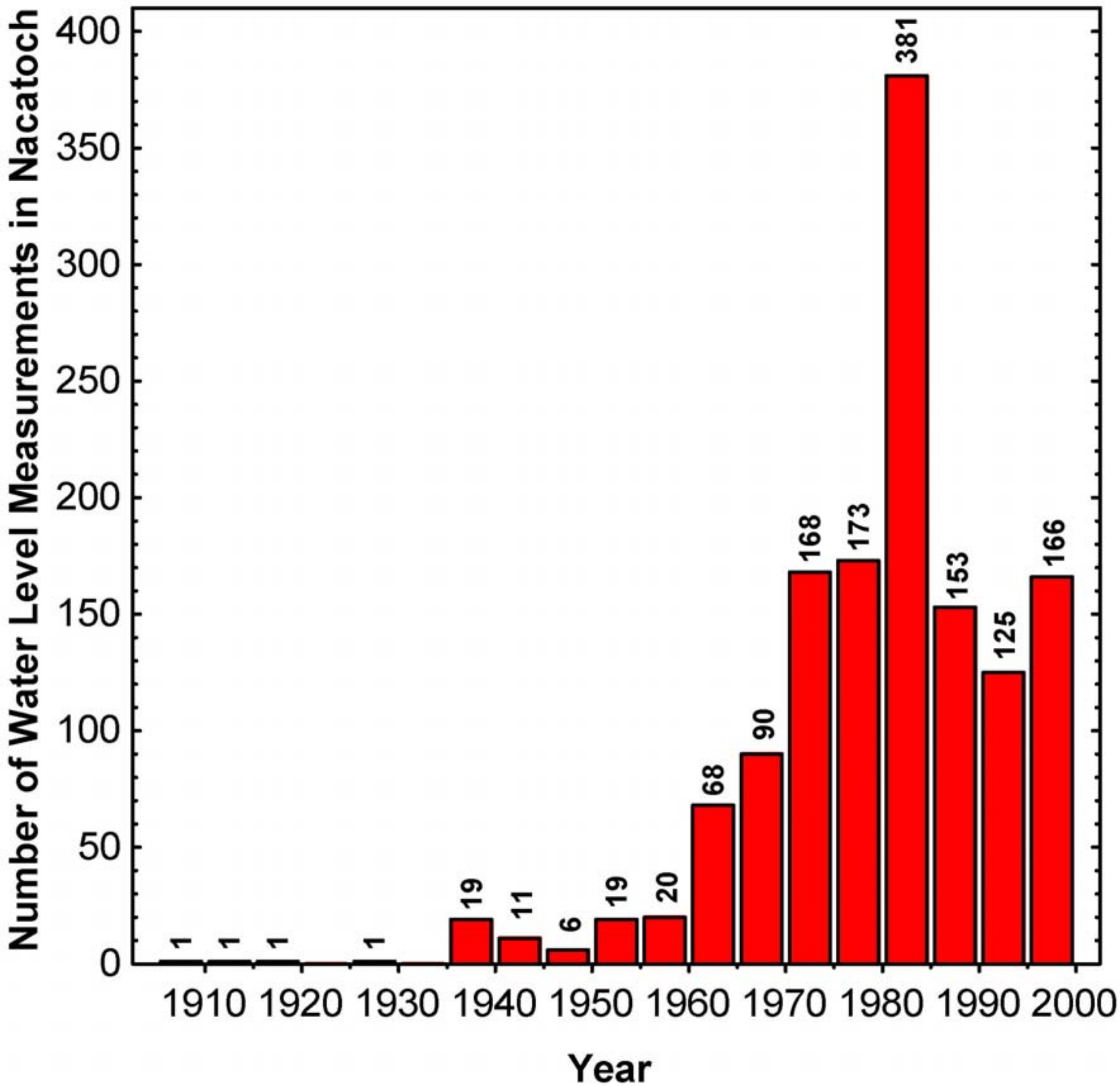


Figure 4.3.2 Temporal distribution of water-level measurements in the Nacatoch Aquifer

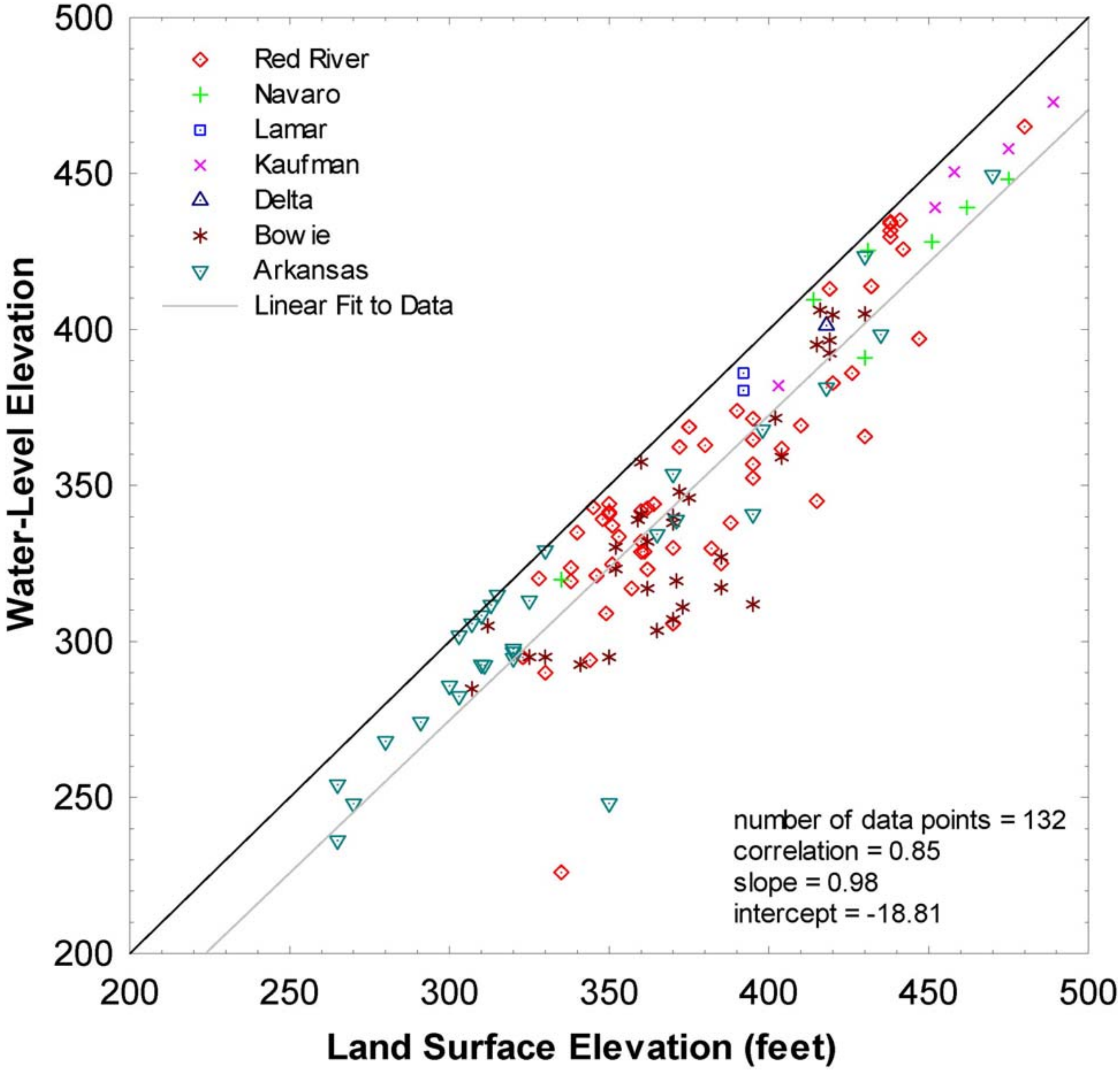


Figure 4.3.3 Regression between land surface elevation and water level elevation in the outcrop of the Nacatoch Aquifer

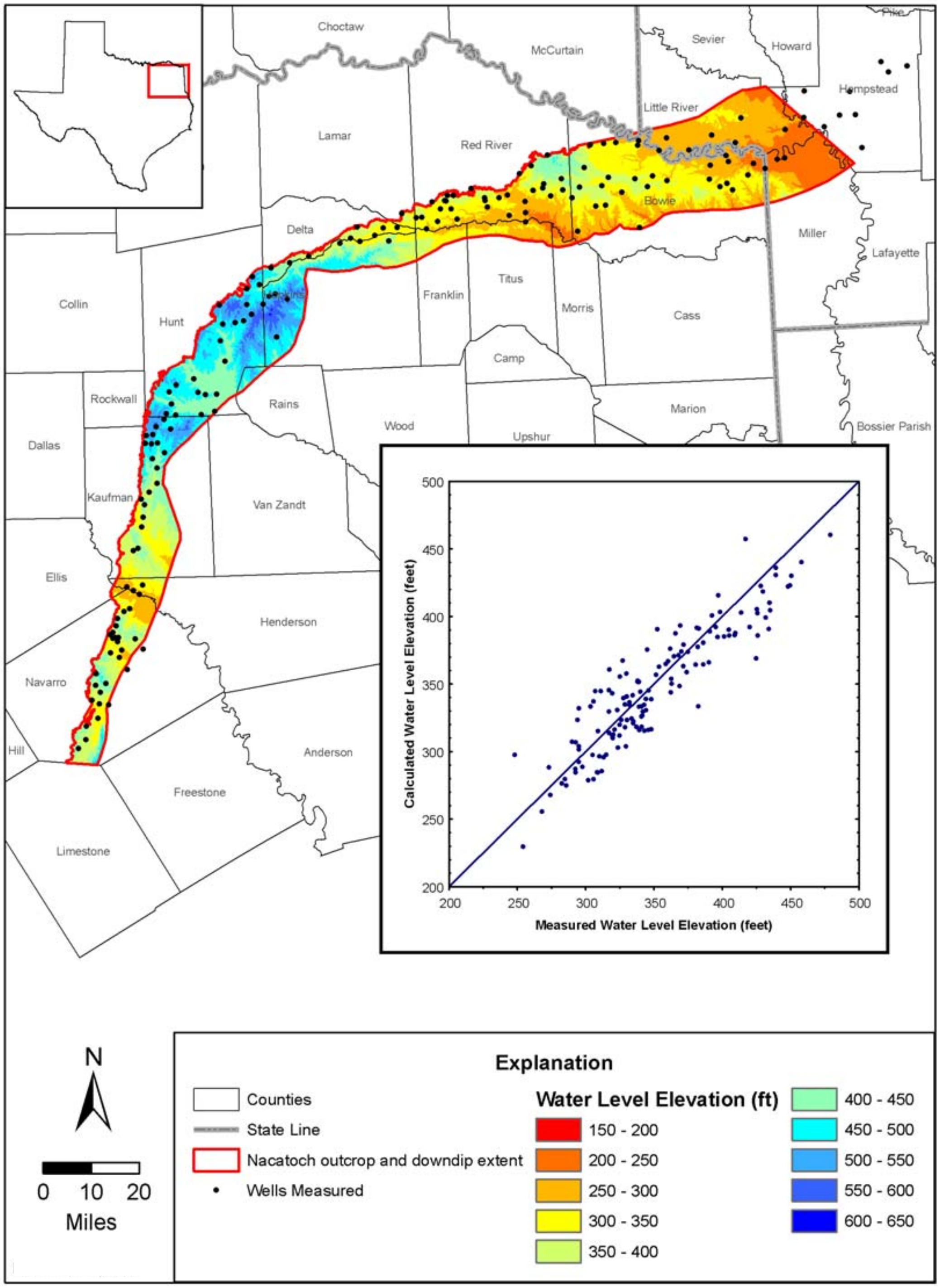


Figure 4.3.4 Estimated water-level elevation contours for the Nacatoch Aquifer during predevelopment conditions based on relationship between land surface elevation and water level elevation.

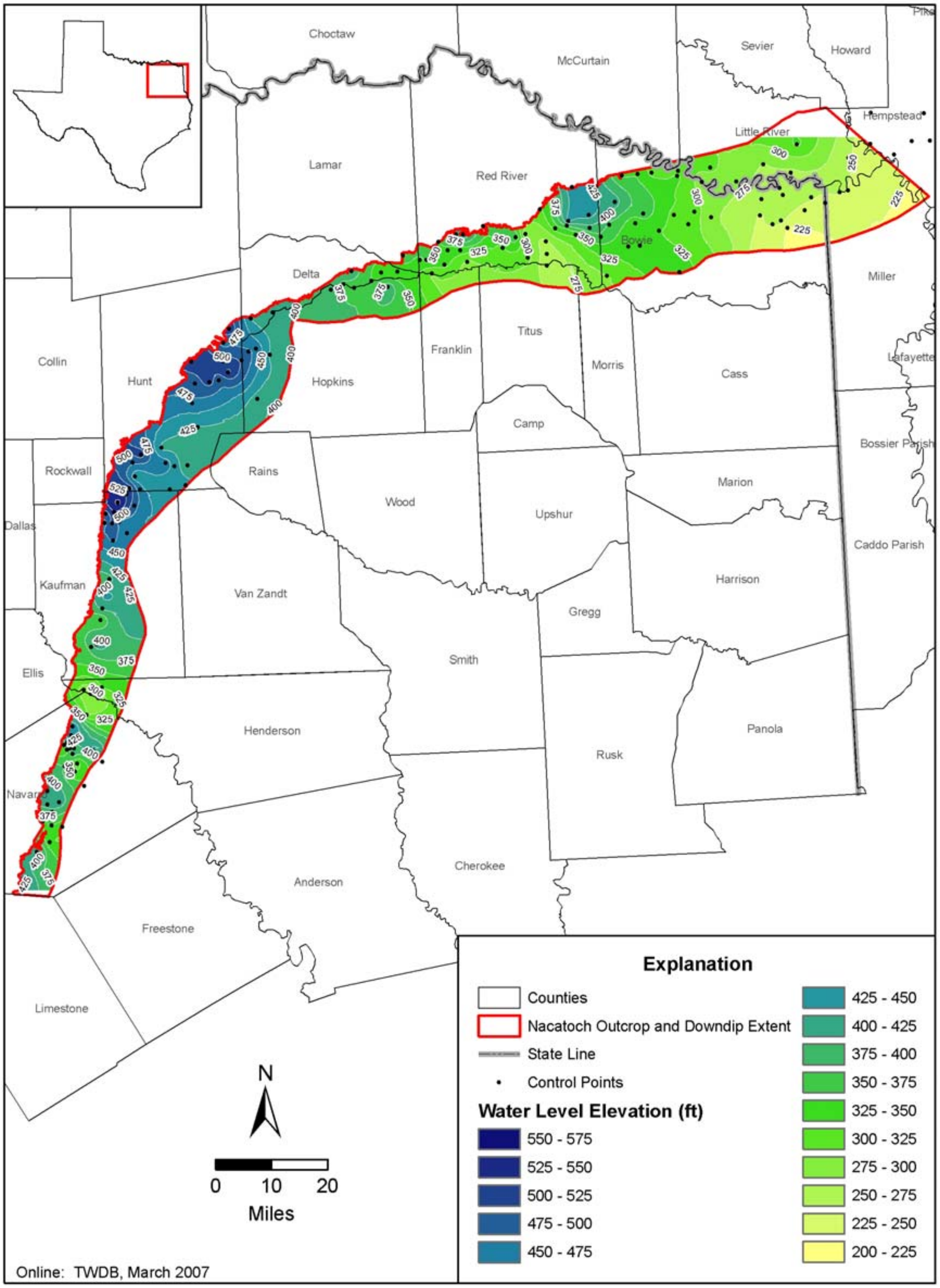


Figure 4.3.5 Estimated water-level elevation contours for predevelopment conditions in the Nacatoch Aquifer

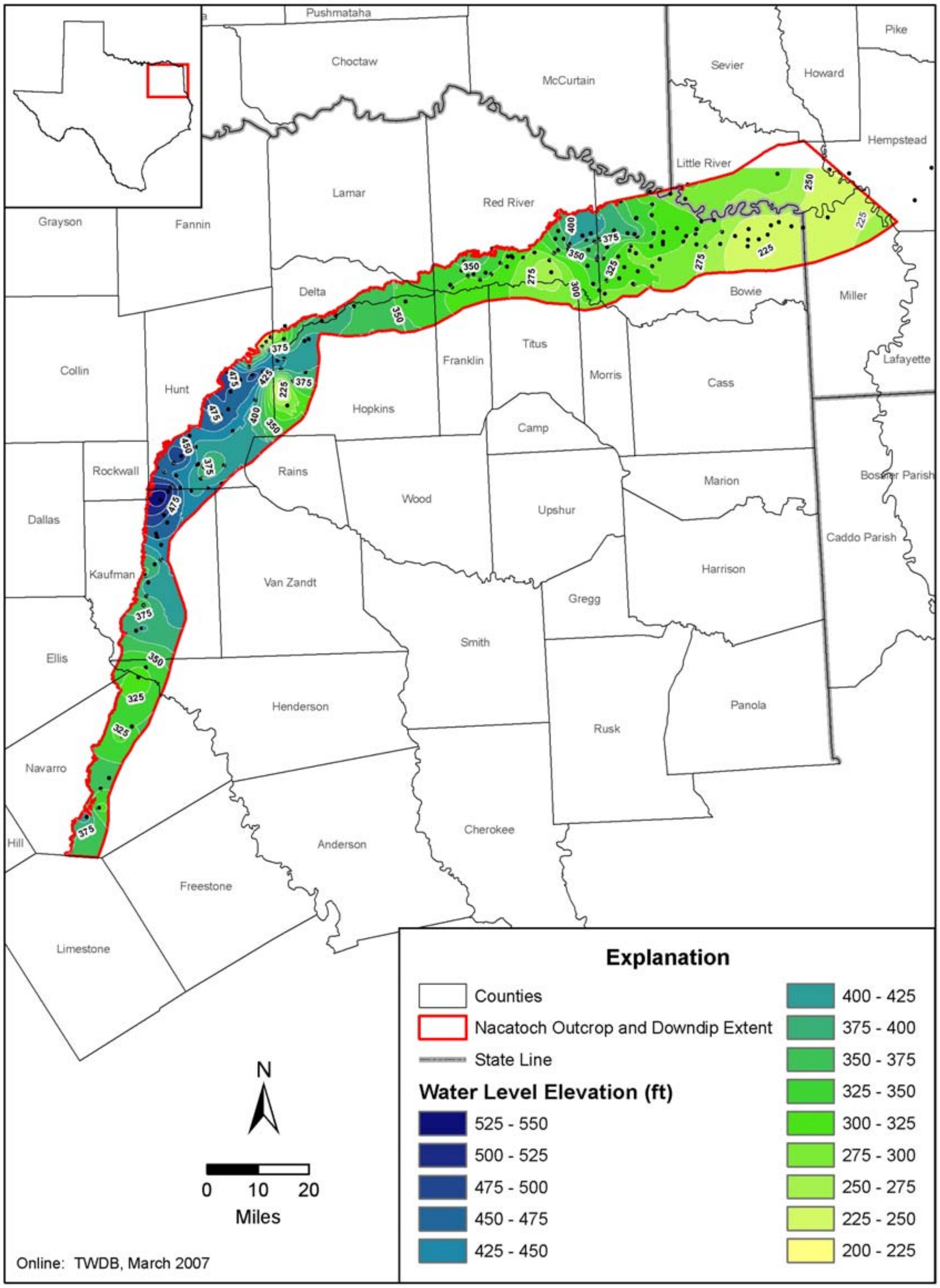


Figure 4.3.6 Water-level elevation contours for the Nacatoch Aquifer at the start of model calibration (1980)

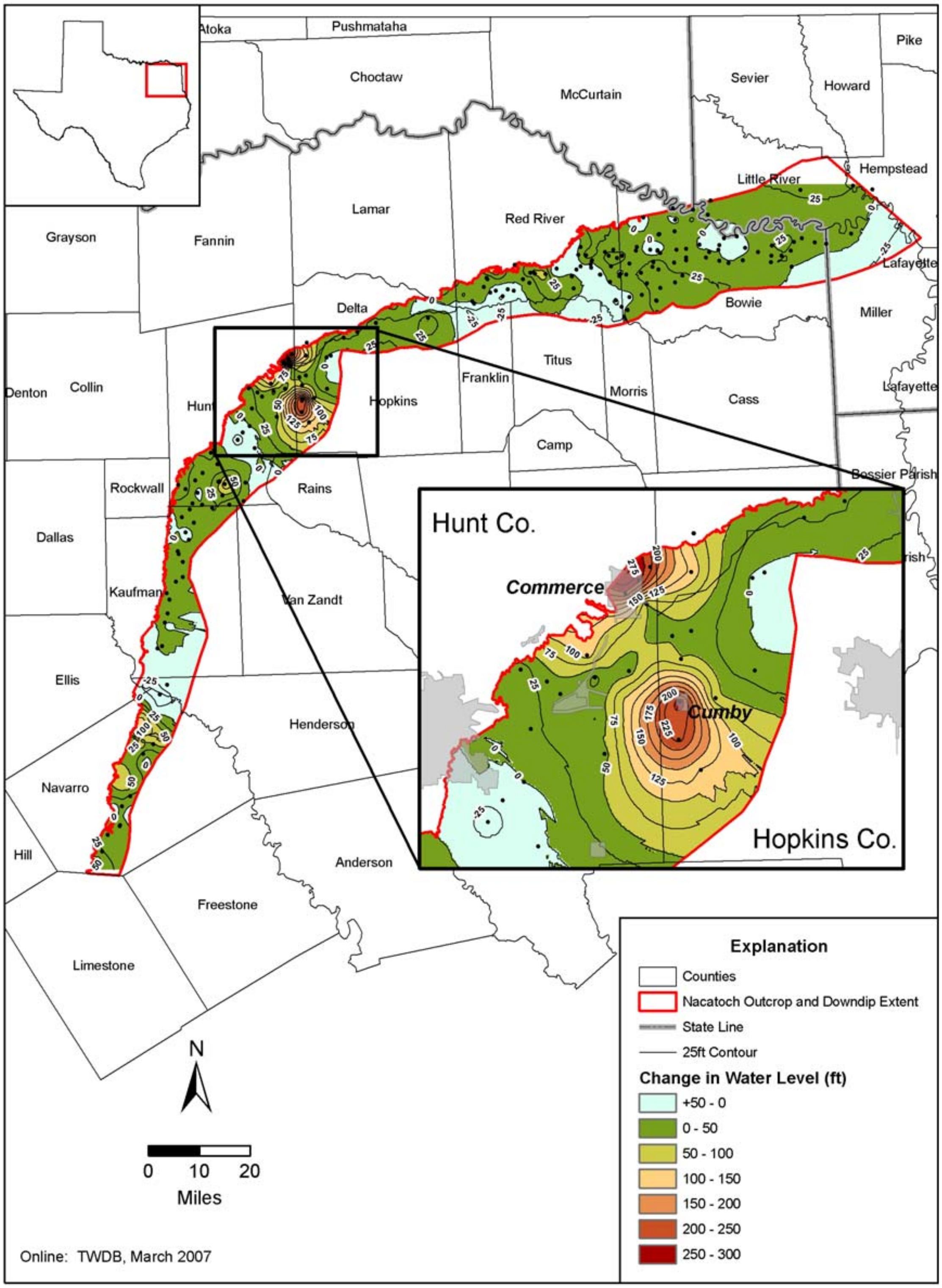


Figure 4.3.7 Estimated water level changes from predevelopment based upon the estimated 1980 Nacatoch Aquifer head surface (1980 heads minus predevelopment heads)

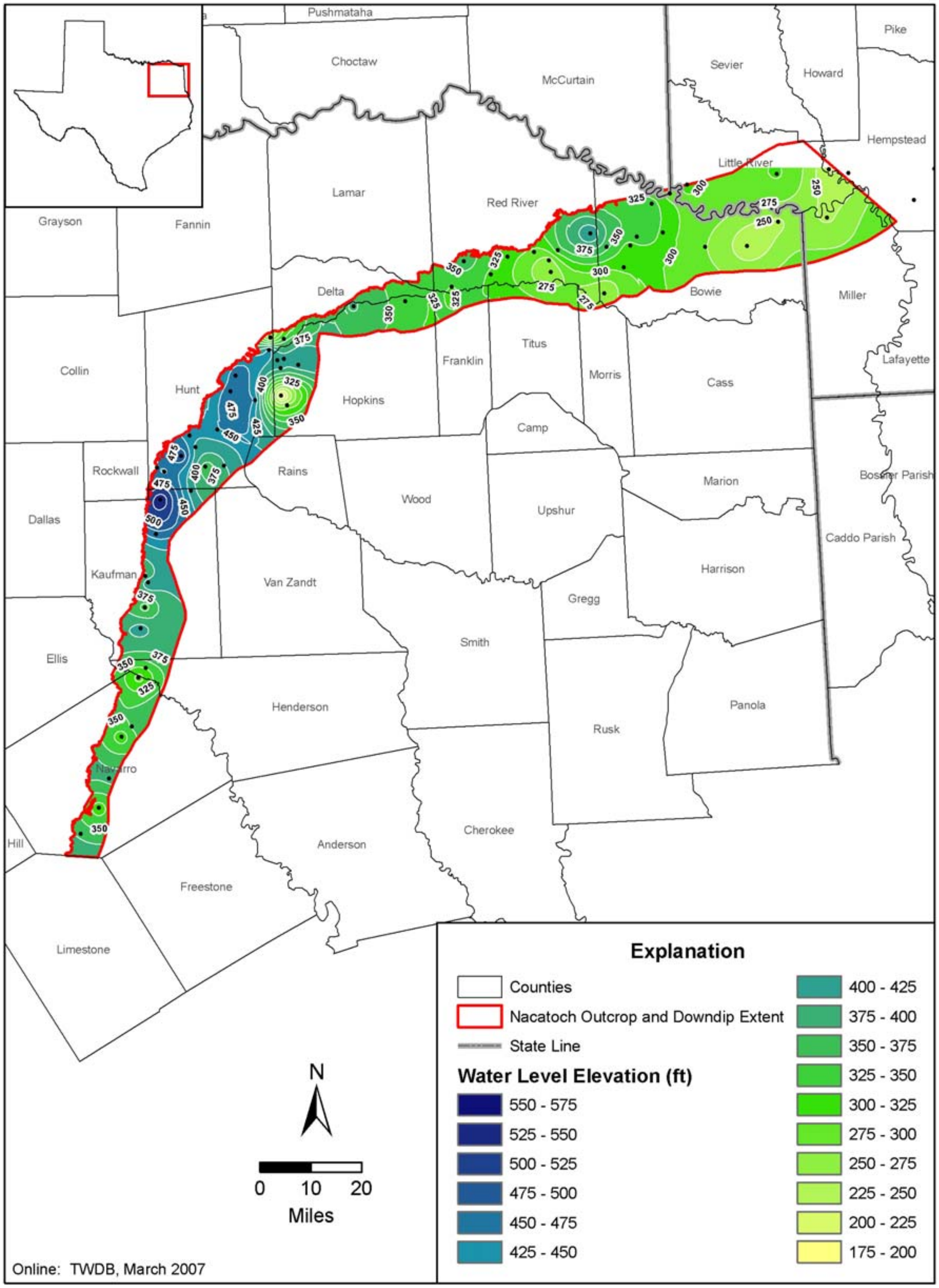


Figure 4.3.8   Water-level elevations for the Nacatoch Aquifer in 1990

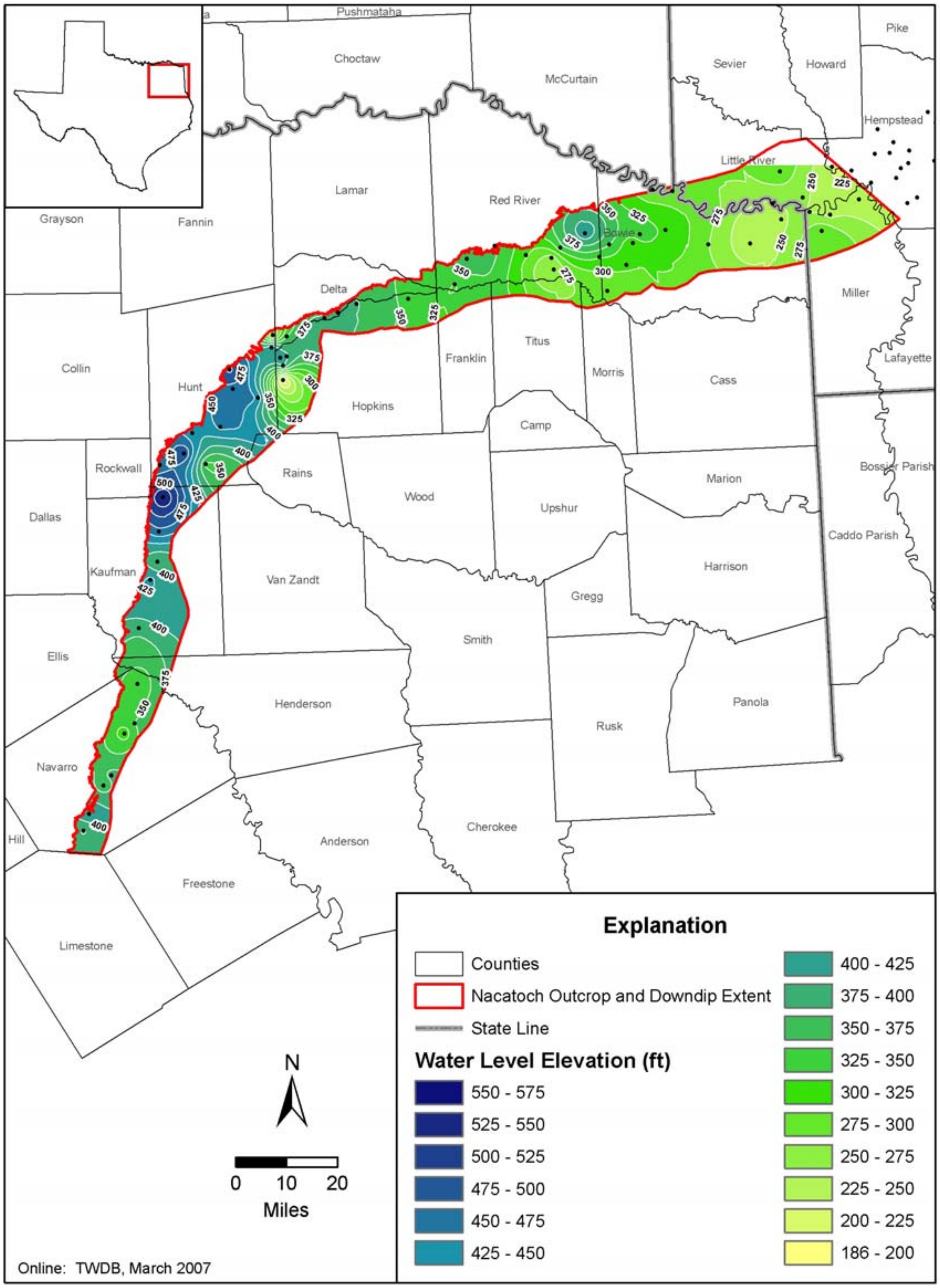


Figure 4.3.9 Water-level elevations for the Nacatoch Aquifer at the end of model calibration (1997)

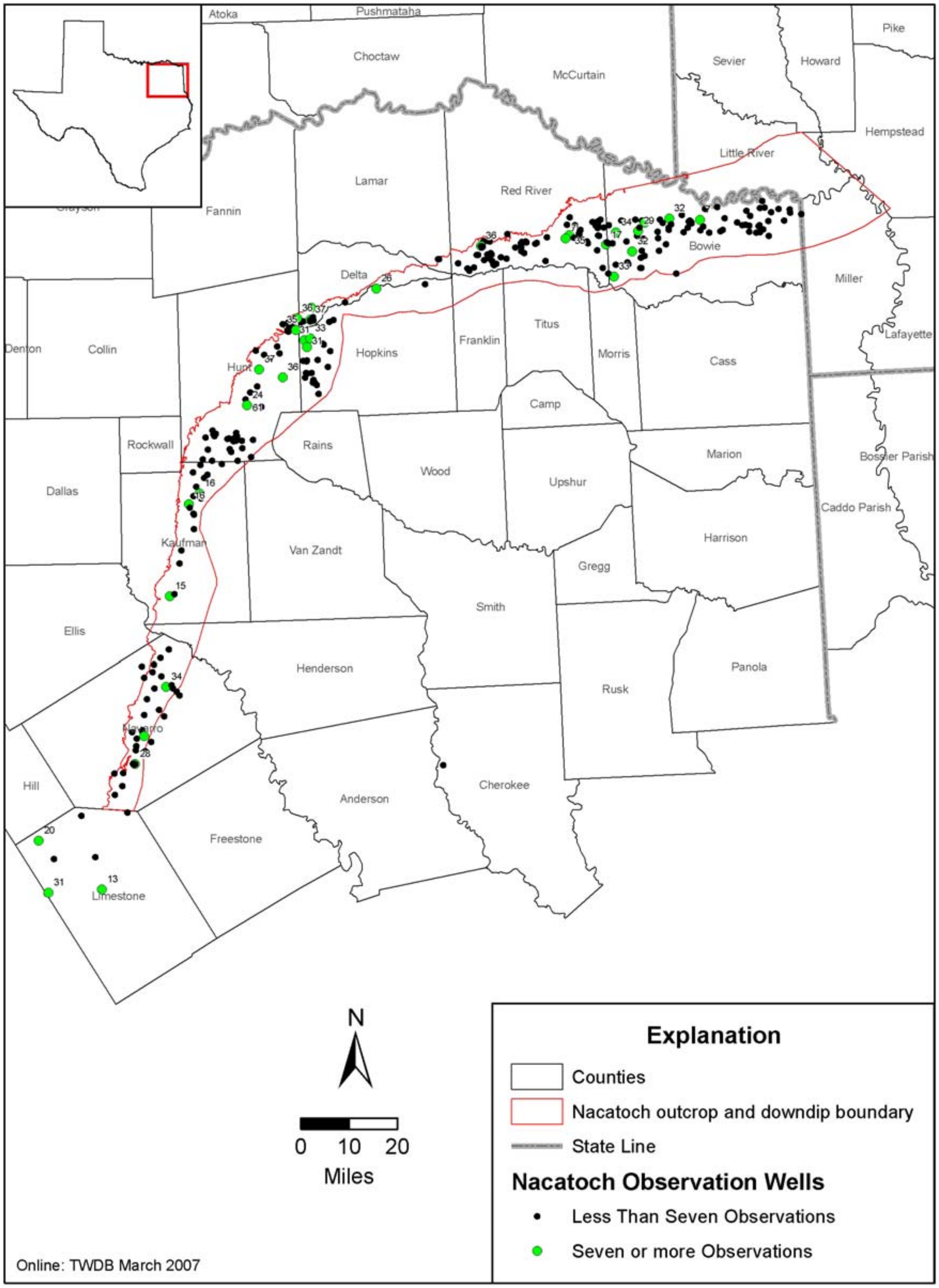


Figure 4.3.10 Locations with transient water-level data in the Nacatoch Aquifer and number of observations

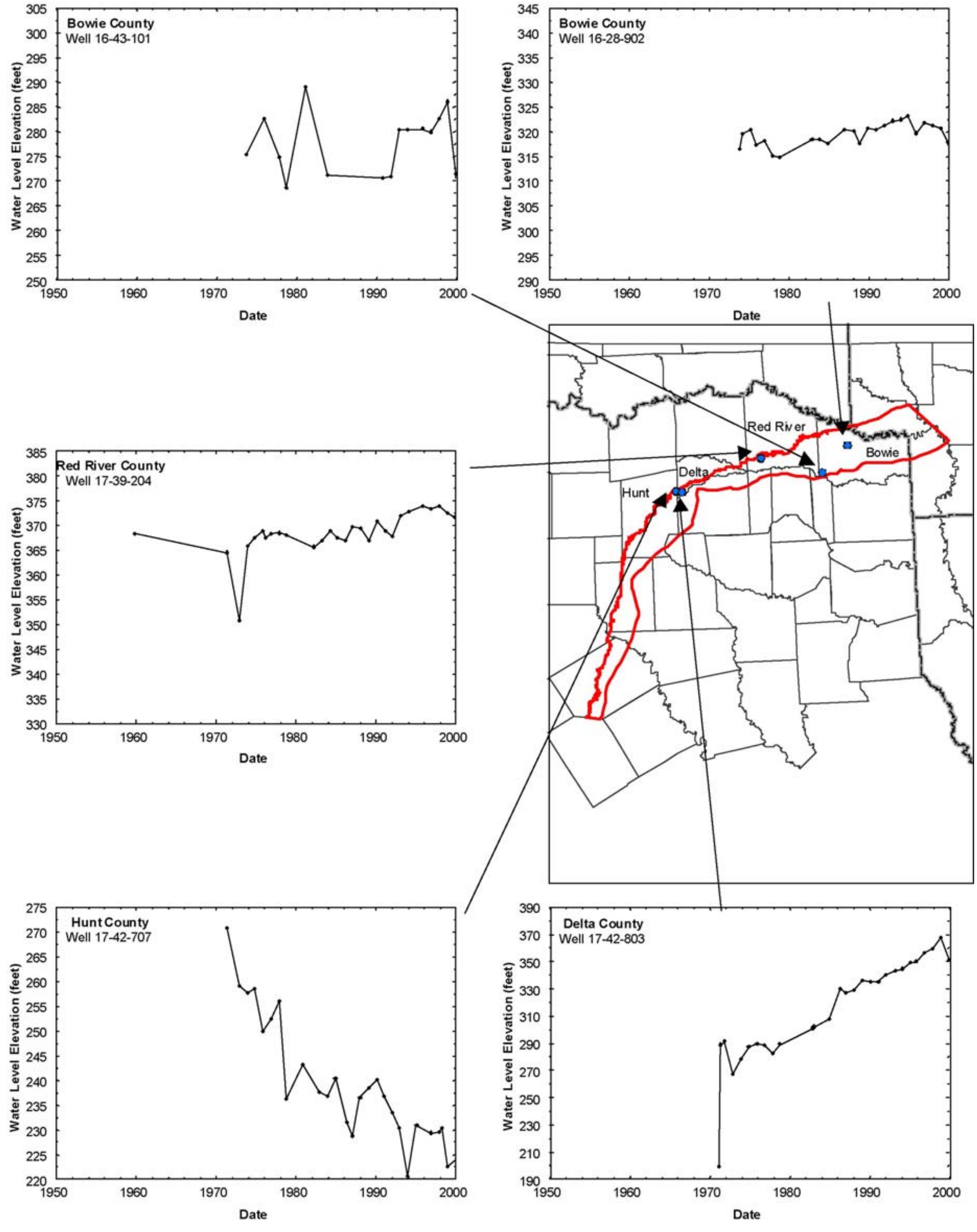


Figure 4.3.11 Example hydrographs for wells completed in the Nacatoch Aquifer in Bowie, Delta, Hunt and Red River Counties

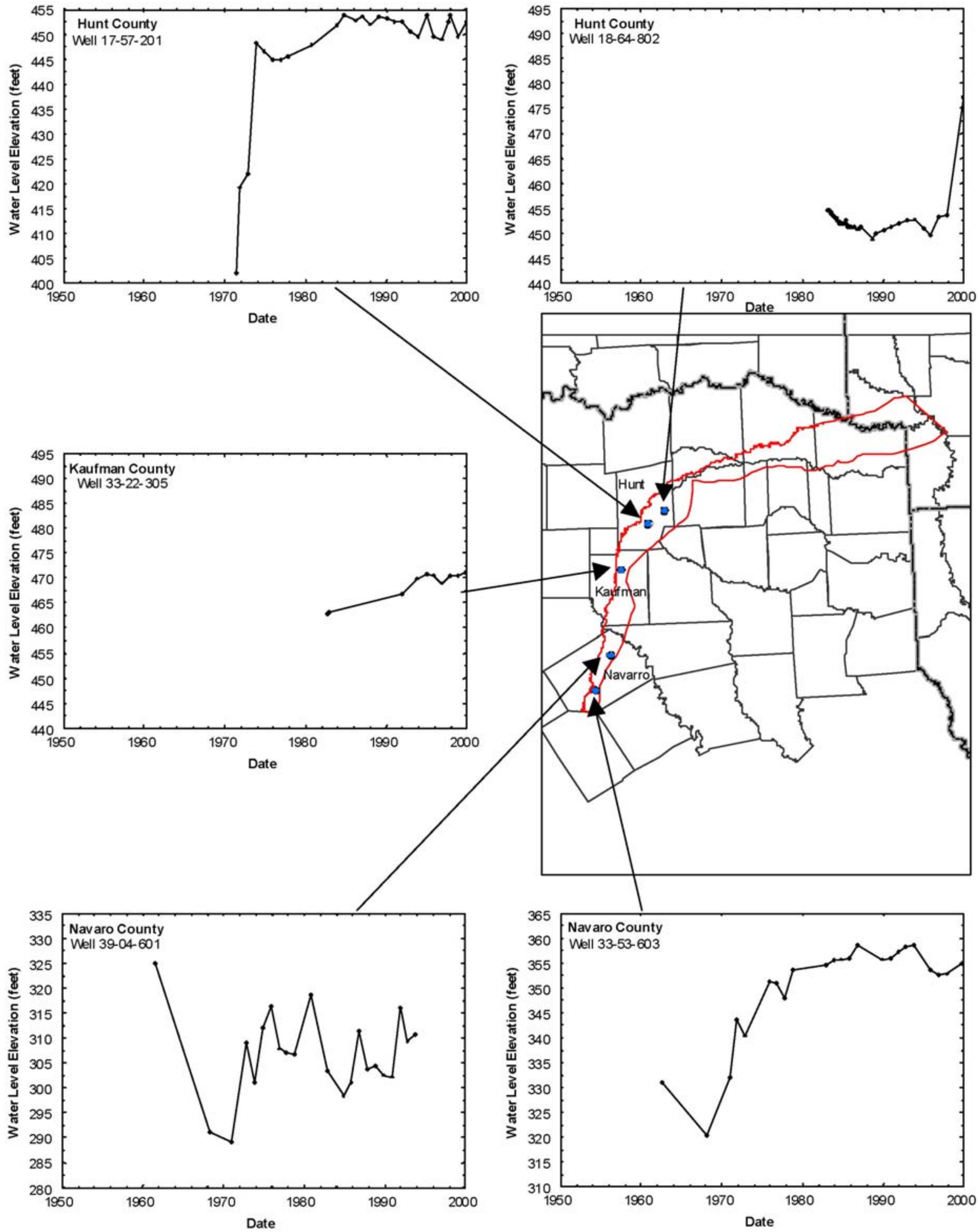


Figure 4.3.12 Example hydrographs for wells completed in the Nacatoch Aquifer in Hunt, Kaufman, and Navarro Counties

4.4 Recharge

In the following sections, we first discuss the conceptual framework describing groundwater recharge in the Nacatoch Aquifer. This discussion will be followed by the conceptual approach for estimating average recharge and for distributing recharge spatially and temporally in the Nacatoch Aquifer study area.

4.4.1 Conceptual Basics

Recharge can be defined as water that is made available at the water-table surface, together with the associated flow away from the water table within the saturated zone (Freeze, 1969). Recharge is a complex function of the rate and volume of precipitation, soil type, water level, soil moisture, topography, and ET (Freeze, 1969). Potential sources for recharge include precipitation, irrigation subsurface return flow, and stream or reservoir leakage. Precipitation and irrigation return flow are generally considered to be diffuse sources of recharge, while stream or reservoir leakage are considered to be focused source of recharge. For the Nacatoch Aquifer, we expect streams to be predominantly gaining, so they will primarily represent discharge processes. It is also expected that man-made reservoirs provide the potential for focused recharge in the study area in the aquifer outcrop. However, because reservoirs are necessarily located in topographically low areas, we conceptually would expect that most of the recharge associated with reservoirs would represent shallow recharge subject to evapotranspiration and discharge to wetlands and streams.

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

The groundwater system in the outcrop can often act as a classical topographically-driven recharge/discharge system, where recharge primary occurs in the areas of higher elevation, and discharge occurs in the areas of lower elevation through streams, seeps, and groundwater ET. The recharge to the water table that discharges relatively quickly in the surficial groundwater system does not have a significant impact on the deeper, confined aquifer system. Conceptually, recharge can be divided into two types, “shallow” recharge which discharges relatively quickly through baseflow and other surficial discharge components (such as groundwater ET), and “deep” recharge which moves into the confined system and exits through cross-formational flow or pumping after aquifer development. Of the former, the portion of recharge that exits through surficial discharge components is sometimes termed “rejected recharge”.

Figure 4.4.1 is a flow balance diagram depicting how precipitation partitions into the various components described above, under predevelopment conditions (i.e. no pumping). The values in this diagram represent estimates for an average precipitation of 45 in/yr over the Nacatoch Aquifer outcrop. This would be similar to what might occur in Hopkins County. In the following sections, we will discuss how similar values were estimated over the entire model region.

4.4.2 Average Recharge

Recharge in Texas aquifers has been studied by many investigators. Scanlon and others (2003) provides a summary of the studies for the major aquifers in Texas, which does not include the Nacatoch Aquifer. Only two previous estimates of average recharge could be found for the Nacatoch Aquifer. Muller and Price (1979) estimated, based on “a comparison of pumpage and water-level trends” that the effective annual recharge in the Nacatoch Aquifer was 1,500 acre-feet. They estimated that 200 acre-ft/year occurs in the Red River Basin and 1,300 acre-ft/year in the Sulphur River Basin. Ashworth (1988) used the trough method (based on Darcy’s law) to estimate 3,030 acre-ft/year of effective recharge for the Nacatoch Aquifer. Based on the assumed outcrop area, this equated to approximately 0.5% of precipitation in the area. If we assume an average precipitation of about 45 in/yr, this equates to just over 0.2 in/yr of recharge. We should note that this estimate is for the deep recharge only, since the trough method would not account for recharge that discharges locally in the shallow system.

For the current study, baseflow separation analyses were completed on several gages with subwatersheds (the catchment area above the gage) that intersected the Nacatoch Aquifer outcrop. These baseflow separation analyses as well as the location of the subwatersheds are detailed in Section 4.7.1. Baseflow can be used as a surrogate measure of shallow recharge, if we assume that most of the shallow recharge discharges through baseflow. In reality, some portion of shallow recharge will discharge through seeps and groundwater ET. So the baseflow estimates should be considered minimum shallow recharge estimates. The minimum recharge flux rate is determined by dividing the baseflow rate by the subwatershed area. Based upon the baseflow analysis (presented in Section 4.7.1), the area-weighted average shallow recharge for the Nacatoch Aquifer is a minimum of 0.5 in/yr.

Considerable difficulty lies in estimating how much shallow recharge would exceed the baseflow estimates due to other sources of discharge, such as groundwater evapotranspiration. There are no known estimates of groundwater ET based on field measurements in the general region (Scanlon and others., 2005). In Texas GAMs along the coast, groundwater ET is simulated to be as low as 3% to as high as 48% of the total discharge water budget (Scanlon and others., 2005). Our conceptual approach to groundwater ET is detailed in Section 4.7.1.

4.4.3 Precipitation

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

We first estimated monthly precipitation for each subwatershed by intersecting the boundary of the subwatershed with monthly precipitation grids from the PRISM dataset. Next we performed the same intersection of the subwatershed outlines with the monthly minimum and maximum temperature grids from the PRISM dataset. As discussed in section 2.2, 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 was used because it provides a good distribution of average annual precipitation across the model area based upon the period of record from 1961 to 1990. With the monthly minimum and maximum temperatures, we estimated potential evapotranspiration based on the Hargreaves method (Hargreaves and Samani, 1985). We then summed the daily baseflow values for each month, so that we had monthly total baseflow estimates along with corresponding monthly precipitation and evapotranspiration estimates for each subwatershed.

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

To estimate a best predictive model, we performed regressions of annual average baseflow versus a 12-month average precipitation, with a time lag varying from zero to ten months. Note that in the regressions, our response variable was the logarithm of baseflow while the predictor was untransformed precipitation, since annual average baseflow is approximately lognormally distributed, while annual precipitation is approximately normally distributed, as seen in Figure 4.4.2. After performing the regressions for each of the lag times, we then took the regression model with the best fit based on the coefficient of variation (R^2) and noted the corresponding lag. A summary of the results is shown in Table 4.4.1.

Table 4.4.1 Summary of baseflow regression analyses

Gage	Lag (months)	Intercept	Slope	R^2
7342465	1	-1.86	0.027	0.45
7342470	2	-1.27	0.016	0.62
7342500	3	-2.06	0.031	0.42
7343200	2	-1.86	0.033	0.60
8017300	3	-1.73	0.013	0.04
8062900	6	-3.74	0.076	0.80
8063500	4	-2.24	0.042	0.39
8064500	5	-2.43	0.053	0.41

With the exception of subwatershed 8017300, all of the regressions produced models with a coefficient of variation ranging from about 0.4 – 0.8. Figure 4.4.3 and Figure 4.4.4 show plots of precipitation versus baseflow for each of the subwatersheds. Note that the southern locations (gages starting with 80) have a greater slope and lesser intercept than the more northern locations (gages starting with 73).

Our objective in the analysis is to produce a single equation describing the relationship for the entire outcrop, since creating multiple equations would be needlessly complex given the overall uncertainty in the base data. An additional constraint is that the average precipitation (approximately 45 in/yr) should produce our best estimate of average recharge (approximately 0.7 in/yr, which includes 0.5 in/yr shallow and 0.2 in/yr deep). Using coefficients in the range of those produced from the regression, and adding an offset of 0.2 in/yr for deep recharge resulted in the following equation.

Recharge = 10^(0.033*precipitation-1.8)+0.2

The results of this equation predicted over the expected range of annual precipitation is shown in Figure 4.4.5. Note that the minimum recharge is approximately equal to the average deep recharge, and the maximum recharge does not exceed the maximum observed annual baseflow of approximately 3.5 inches/year (see baseflow histogram in Figure 4.4.2).

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

Although this relationship was derived from temporal data, it also provides a convenient way of distributing recharge spatially, for a long-term average precipitation distribution. This would be appropriate for the steady-state predevelopment model, where precipitation and recharge do not vary temporally, but will vary spatially. For the model region, long-term average precipitation varies from approximately 40-50 inches/year, which would produce a long-term average recharge of approximately 0.5-0.9 inches/year over the model domain, based only on precipitation. Figure 4.4.6 shows an example of this distribution of recharge. Other considerations, such as topography, will provide for further distribution of recharge spatially, as described in the following sections.

4.4.4 Irrigation Return Flow

Irrigation pumping in the Nacatoch Aquifer is limited to two counties, Bowie and Kaufman. The average irrigation pumping from Bowie County from 1978 through 1997 is approximately 687 acre-feet/year with 20% (137 acre-feet/year) of that total being considered to be from the alluvium. In Kaufman County, the irrigation pumping average from 1980 through 1997 is approximately 5 acre-feet/year.

Irrigation return flow can be a significant source of recharge, depending on the concentration of irrigation activities and the type of crops being grown. For example, a crop that requires constant flooding, such as rice, will provide more groundwater return flow than a crop that is irrigated more intermittently, such as corn. In general, current good agricultural management practices for most crops include balancing irrigation application with plant evapotranspiration requirements (e.g., Allen and others., 1998), so that the amount of water that likely moves beyond the root zone to the water table below is minimized. It is expected that some percent of the total groundwater pumped to supply irrigation water over the Nacatoch Aquifer outcrop makes its way back to the water table as shallow groundwater recharge. However, most of this water likely exits the groundwater system as shallow system discharge.

4.4.5 Topography

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

We developed a grid that reflected the relative topography in a given area by taking a 5-mile neighborhood average of the DEM and subtracting this from the original DEM. Because the neighborhood average DEM is locally smoothed (i.e. the highs are lower and the lows are higher), the difference between the two grids represents a local topographic indicator. Figure 4.4.7 shows an example of this grid.

4.4.6 Surface Soils

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

The SSURGO soils database from the NRCS has estimates of soil properties throughout most of the nation. One of the physical properties of the soils estimated in the database is saturated hydraulic conductivity, or Ksat. The SSURGO dataset provides a spatial coverage of delineated areas, called map units, of soils with similar properties. For each of these map units, there can be up to six soil components, including an estimate of what fraction of the map unit is comprised of each component. In addition, each component can have up to four soil horizons (layers of soil which common physical characteristics). Each horizon of each component will generally have an associated estimate of Ksat, as well as the thickness of that particular horizon.

Because we are interested in an integrated estimate of infiltration capacity, the Ksat values from the soil horizons were harmonically averaged (weighted by the thickness of the layers) for each component. An estimate of Ksat was made for each map unit by areally geometrically averaging the integrated component Ksat values, using the provided area fractions. Figure 4.4.8 shows the estimate of surface soil saturated conductivity in the model area. Note the increase in Ksat at the southern border of the study area in the area where the Midway contacts the Carrizo-Wilcox formations. This indicates that the surface soils of the Nacatoch Aquifer are less permeable than those of the Carrizo-Wilcox, based on the SSURGO data. The transition from the Midway to the Nacatoch Aquifer is not well-defined by the Ksat estimate. The most well-defined surface geology features expressed in the Ksat map are the alluvium areas, especially for the Red River on the Texas border. In general, the alluvial areas have the highest conductivity, and therefore would be expected to have the highest infiltration rates.

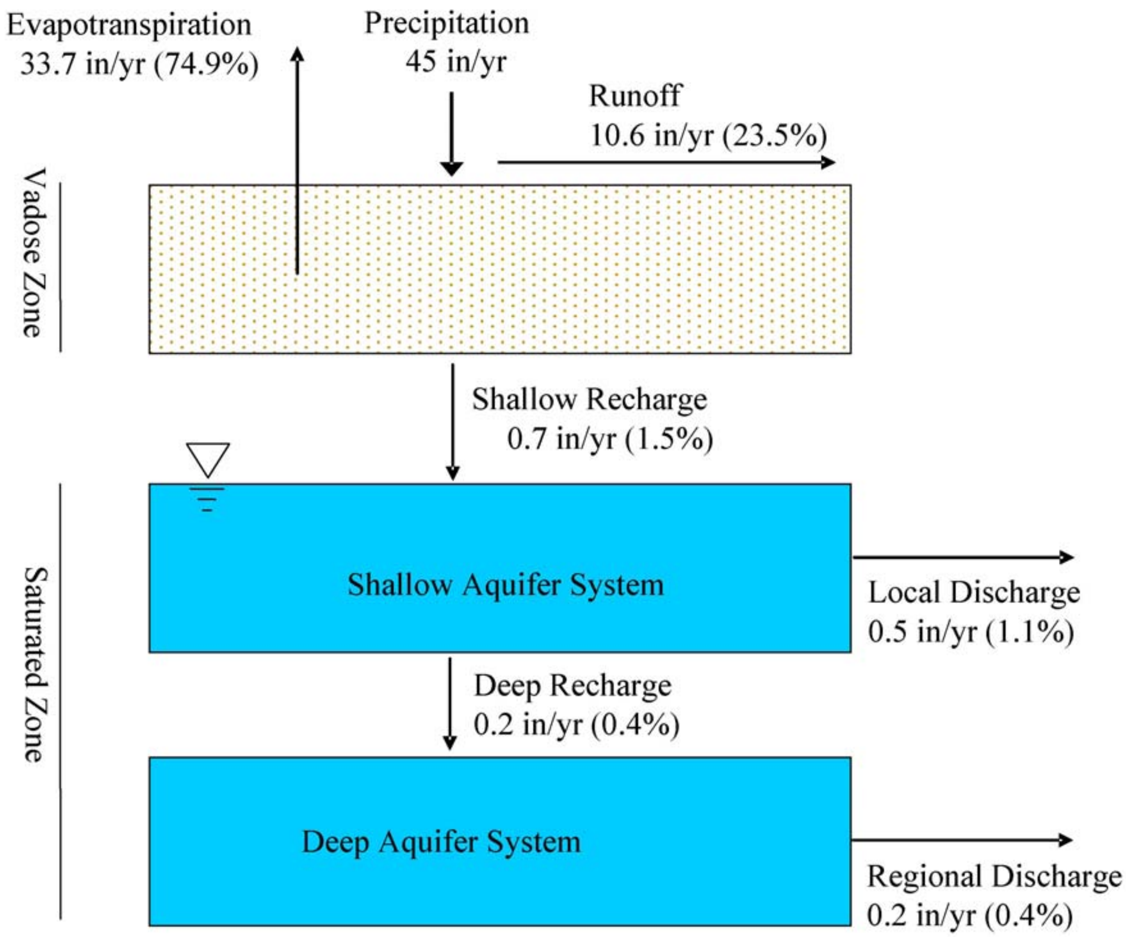


Figure 4.4.1 Block diagram of precipitation partitioning into various components of the hydrologic system. Flux rates are examples of what might occur in the model area

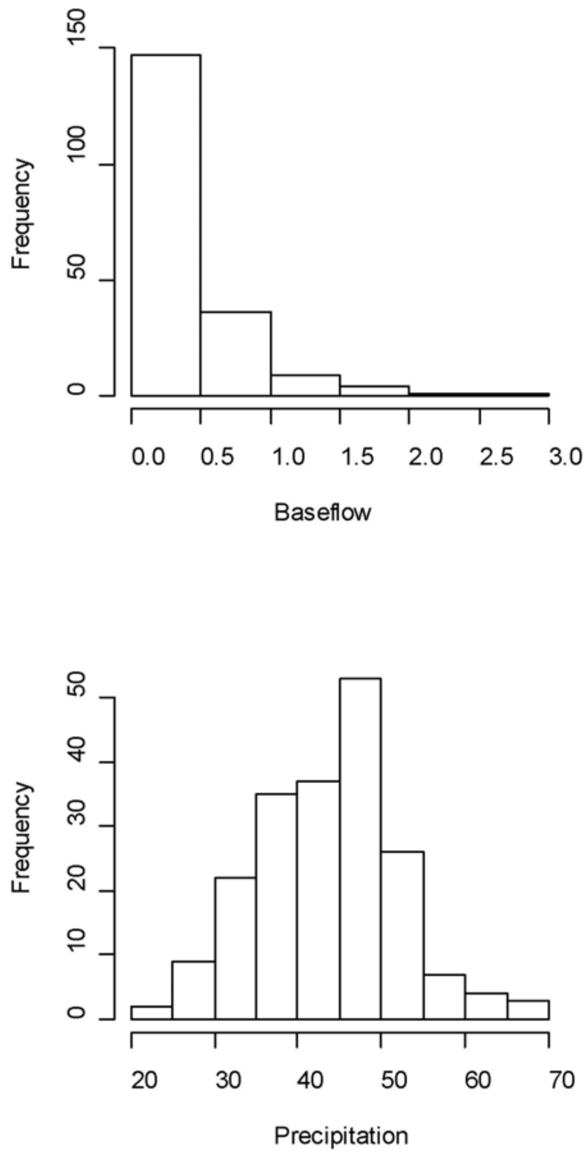


Figure 4.4.2 Histograms of annually averaged precipitation and baseflow

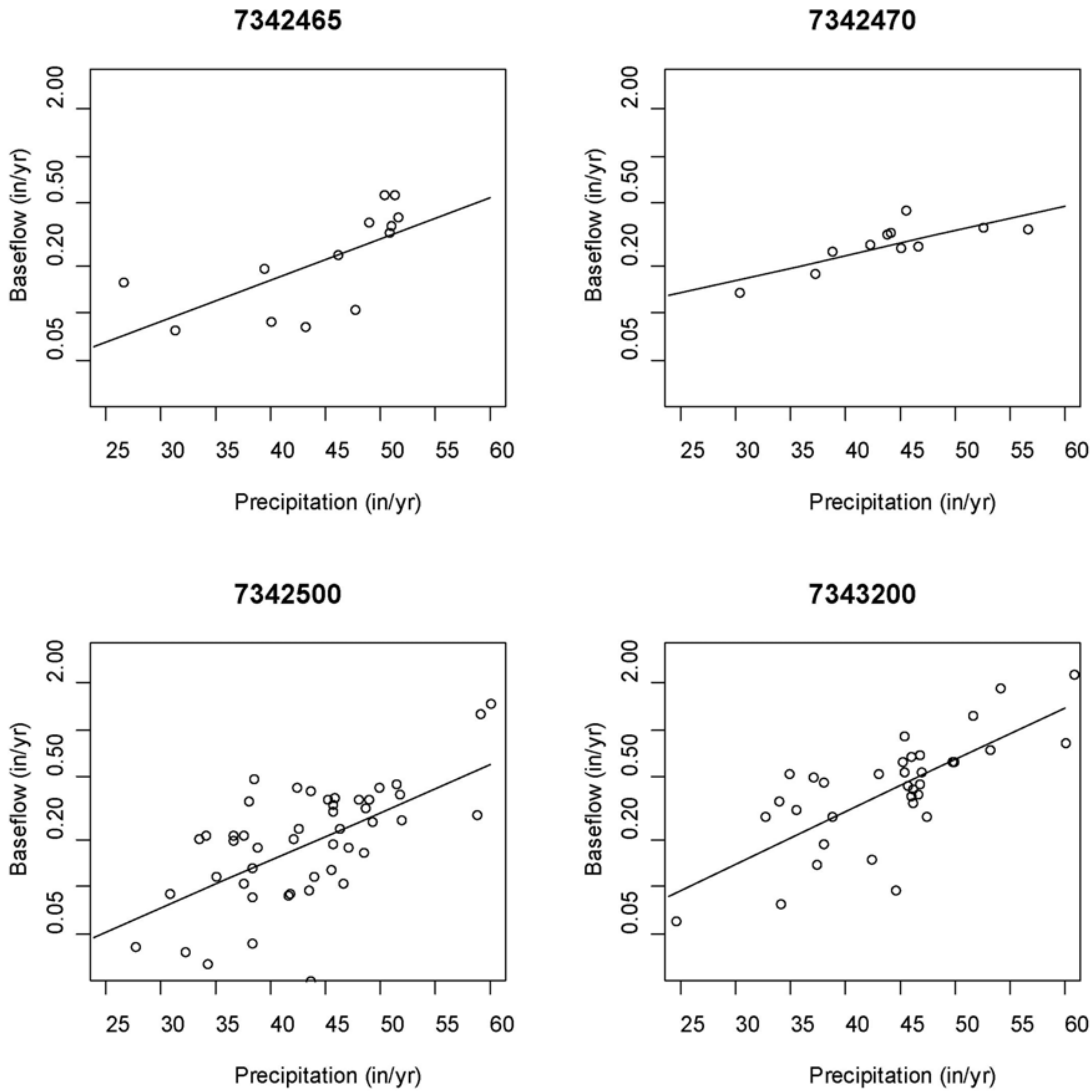


Figure 4.4.3 Plots of precipitation versus baseflow with regression lines

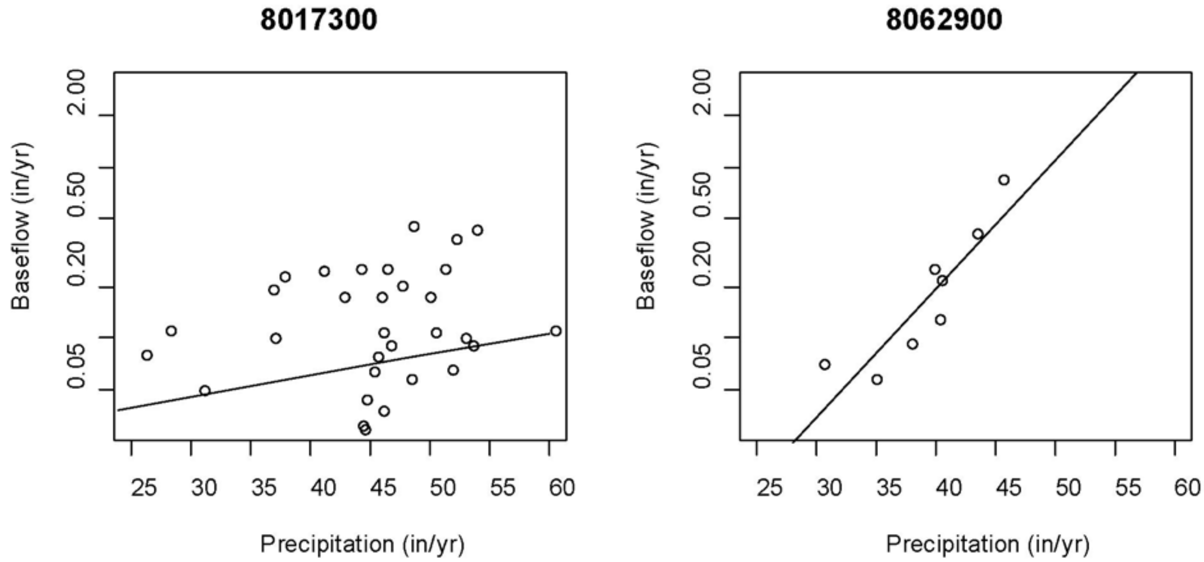


Figure 4.4.4 Plots of precipitation versus baseflow with regression lines

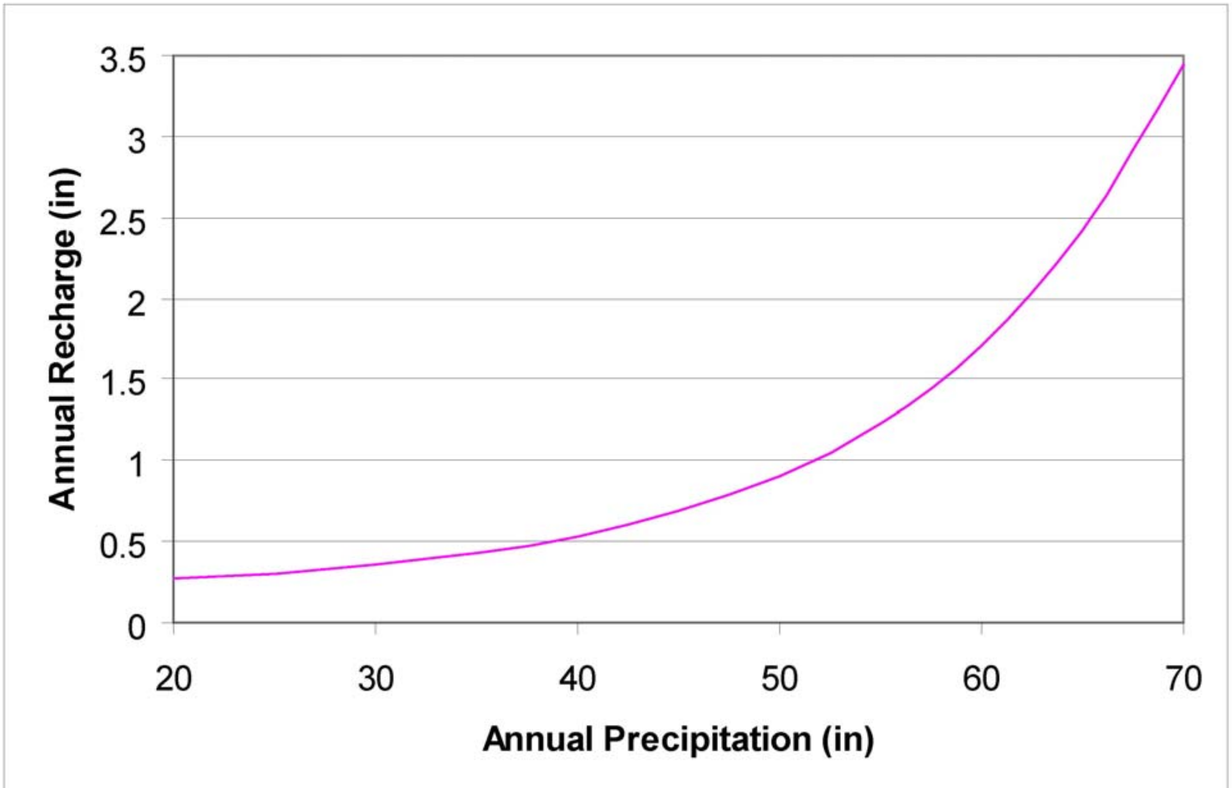


Figure 4.4.5 Relationship between annual recharge and annual precipitation used to estimate recharge in the model area

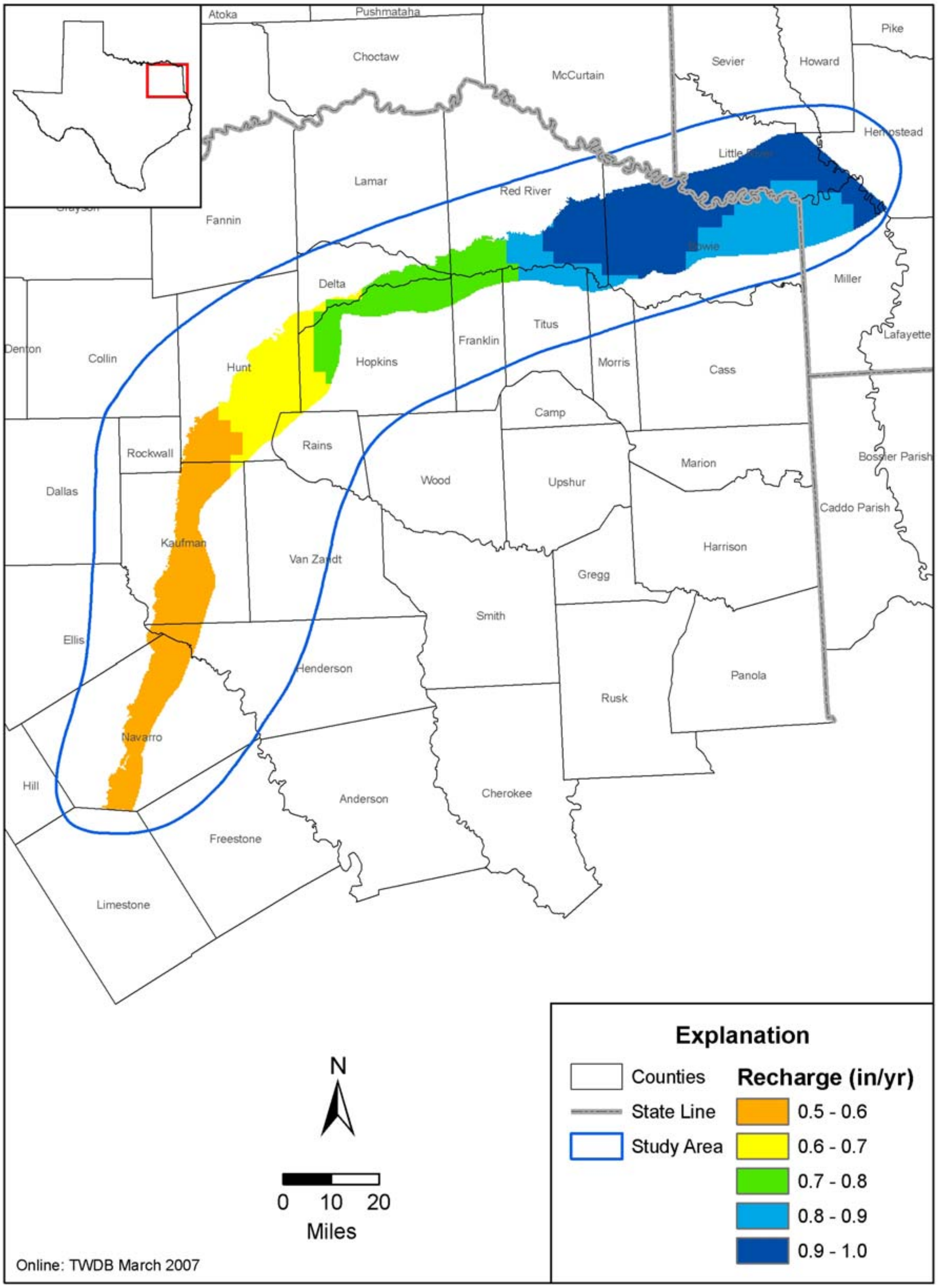


Figure 4.4.6 Average recharge for the model area

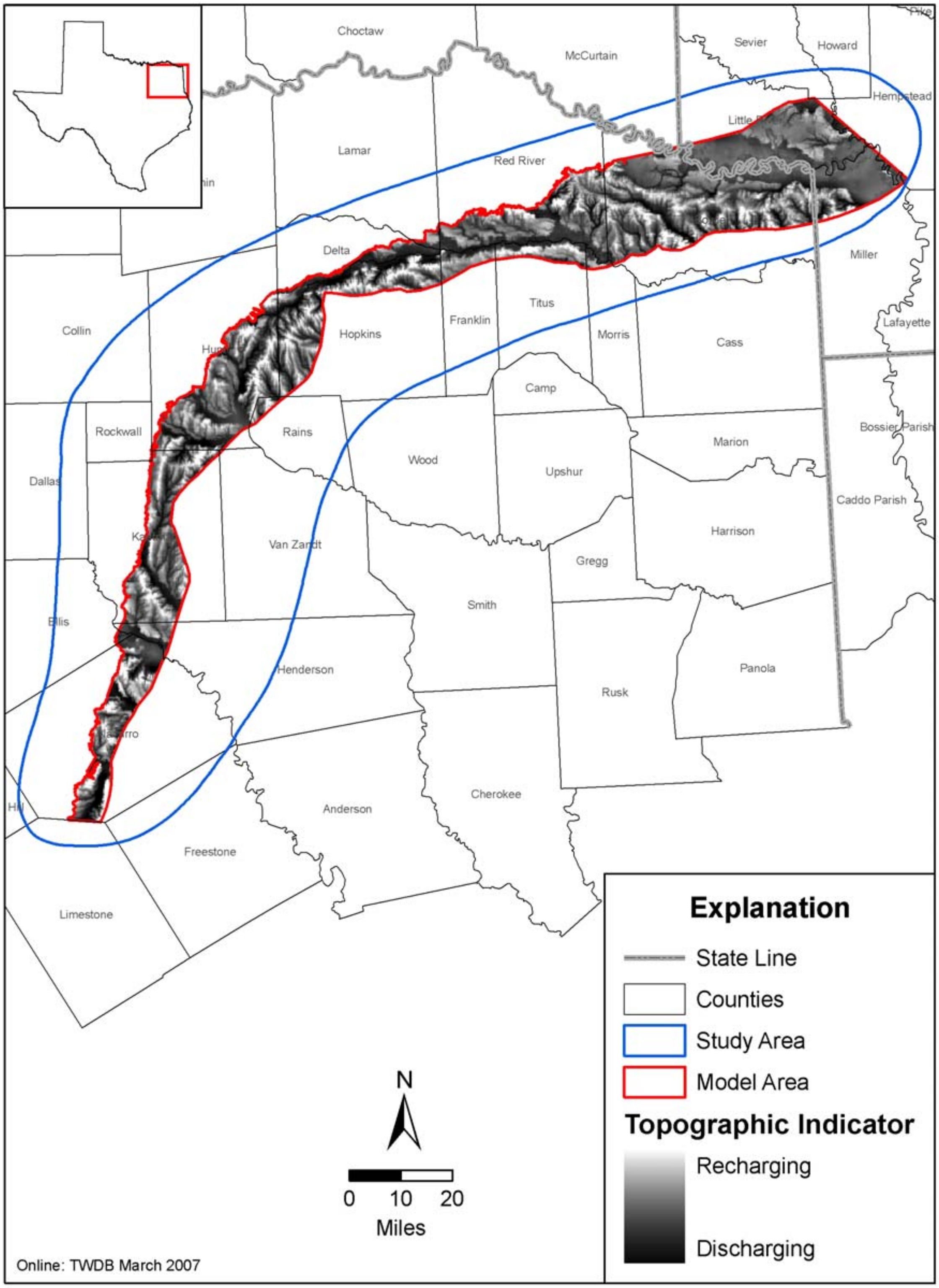


Figure 4.4.7 Recharge trends with topography

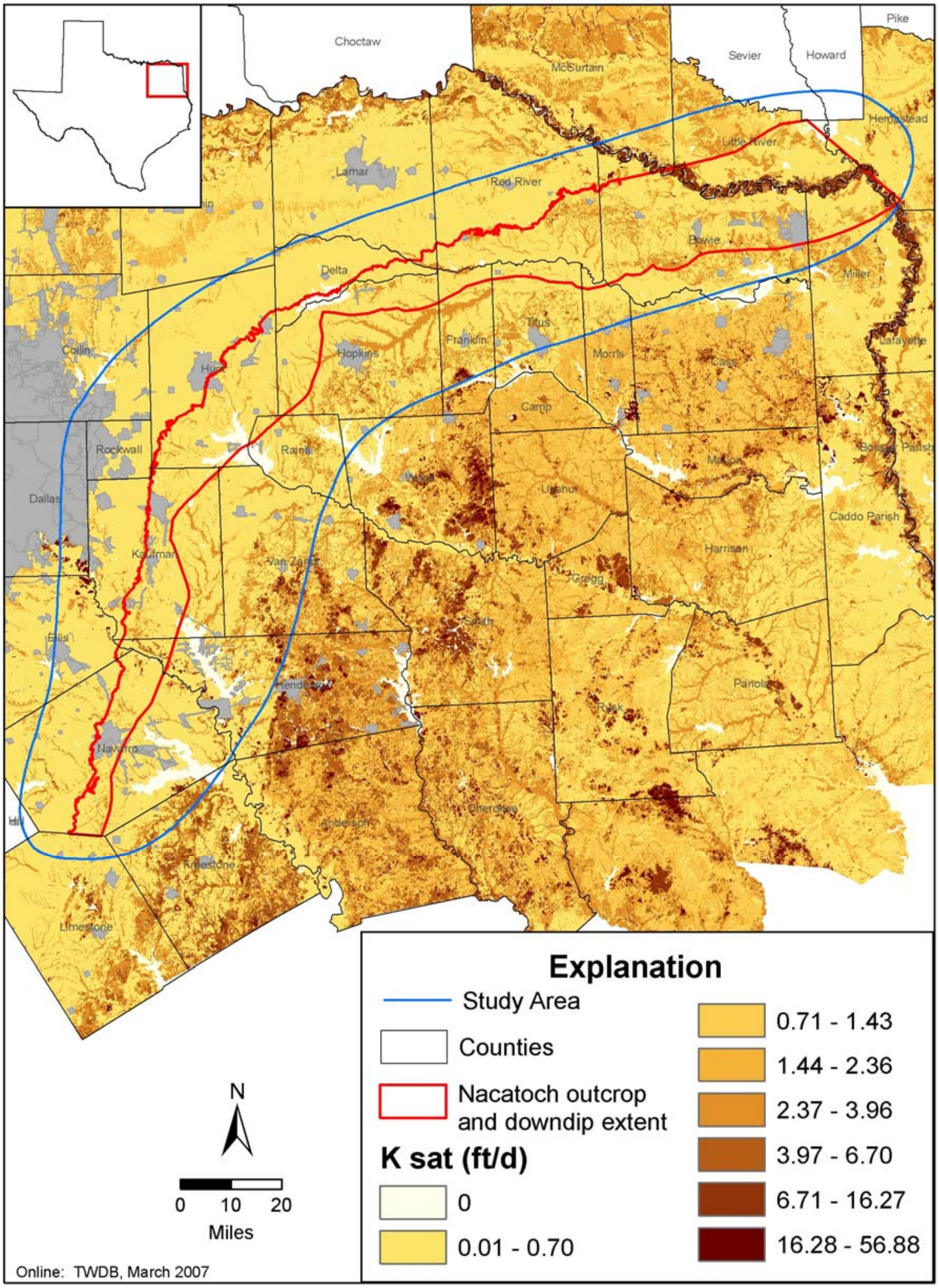


Figure 4.4.8 Estimate of surface soil saturated conductivity

4.5 Rivers, Streams, Springs and Lakes

Four major rivers intersect the Nacatoch Aquifer active model boundary, as shown in Figure 2.1.2. From southwest to northeast, they are the Trinity River, Sabine River, Sulphur River and the Red River. Figure 4.5.1 shows selected hydrographs from rivers and streams in the model area. The major rivers in the model area tend to flow year around, and are typically considered to be gaining (i.e. groundwater flows into the rivers most of the time). The discharge of groundwater into rivers in the model area is discussed in more detail in Section 4.7.1.

Discharge also occurs in areas where the water table intersects the land surface resulting in 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 4.5.2 shows the documented springs located within the model area. The primary source for spring data is Brune (1981), Heitmuller and Reece (2003), and the TWDB groundwater database. While there are over one hundred documented springs in the northeast region of the study area, the number of springs documented in the outcrop areas of the active model domain (those relevant to the model) is quite low. The rate of discharge of groundwater through springs in the model area is discussed in more detail in Section 4.7.1.

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, Figure 4.5.3 indicates that there are 8 significant reservoirs in the active model boundary, one (Cooper-Chapman) that occurs on the Nacatoch Aquifer outcrop and seven on the Midway outcrop (indicated in this figure as the unshaded region within the Nacatoch outcrop and downdip boundary). Table 4.5.1 lists the names, owners, and year impounded for these reservoirs. Figure 4.5.4 shows the lake stage elevations of four 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 4.5.4 shows that the reservoirs generally have stages that do not vary greatly over the time period of interest. Reservoirs, by necessity are constructed in topographic lows. As a result, it expected conceptually that any shallow recharge to groundwater that occurs as a result of these reservoirs would have a high potential for discharge through evapotranspiration and stream/bottomland discharge. Therefore, we believe that their contribution to deep recharge would be negligible.

Table 4.5.1 Reservoirs in the active model outcrop

Reservoir Number	Reservoir Name	Reservoir Owner	Year Impounded
1	Wright Patman Lake	U S Army Corps Of Engineers	1956
2	River Crest Lake	Texas Utilities Generating Co	1953
3	Cooper-Chapman Lake	U S Army Corps Of Engineers	1991
4	Lake Tawakoni	Sabine River Authority	1960
5	New Terrell City Lake	City Of Terrell	1955
6	Cedar Creek Reservoir	Tarrant County WCID #1	1965
7	Richland-Chambers Reservoir	Tarrant County WCID #1	1987
8	Lake Halbert	City Of Corsicana	1921

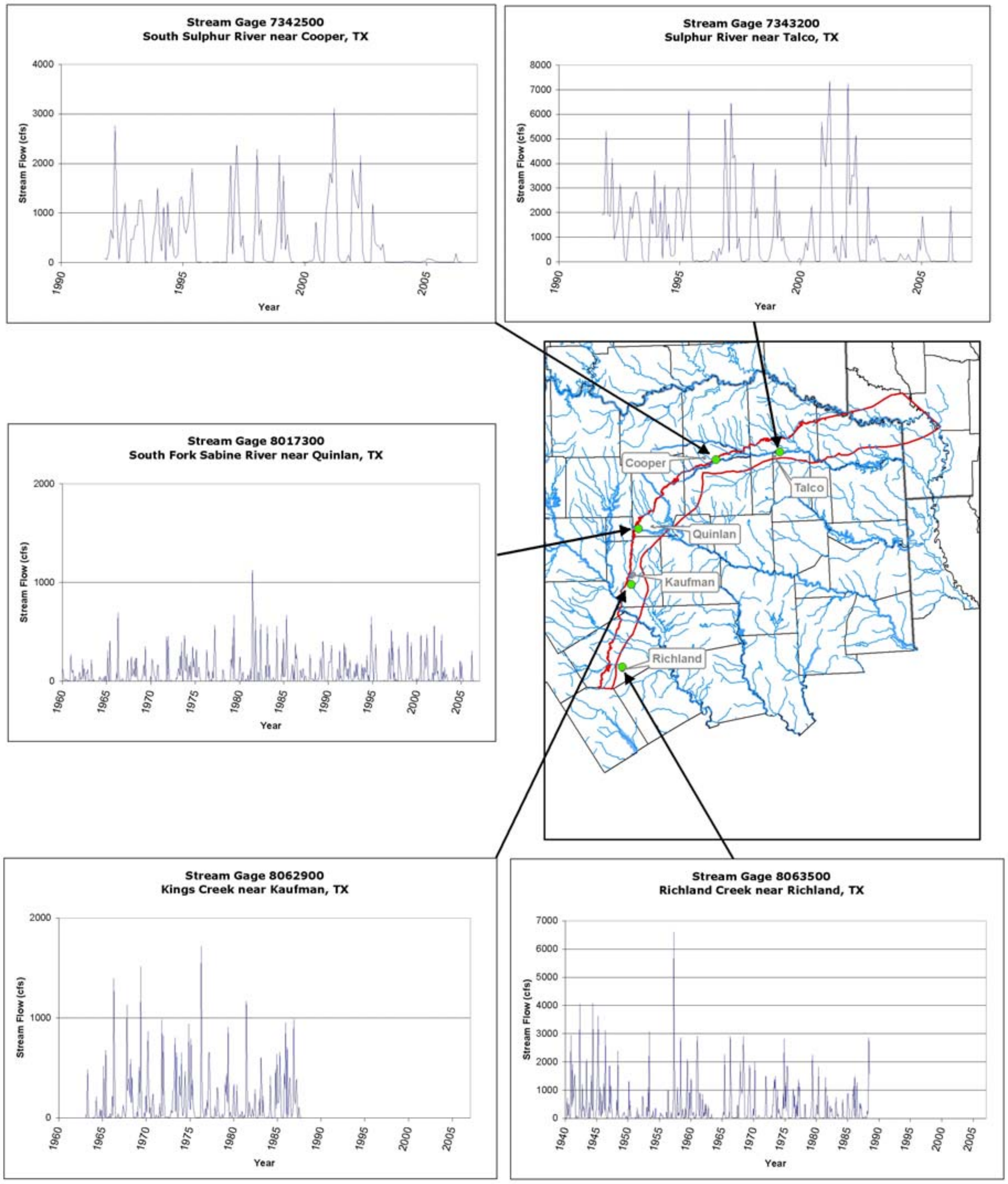


Figure 4.5.1 Selected stream hydrographs in the model area

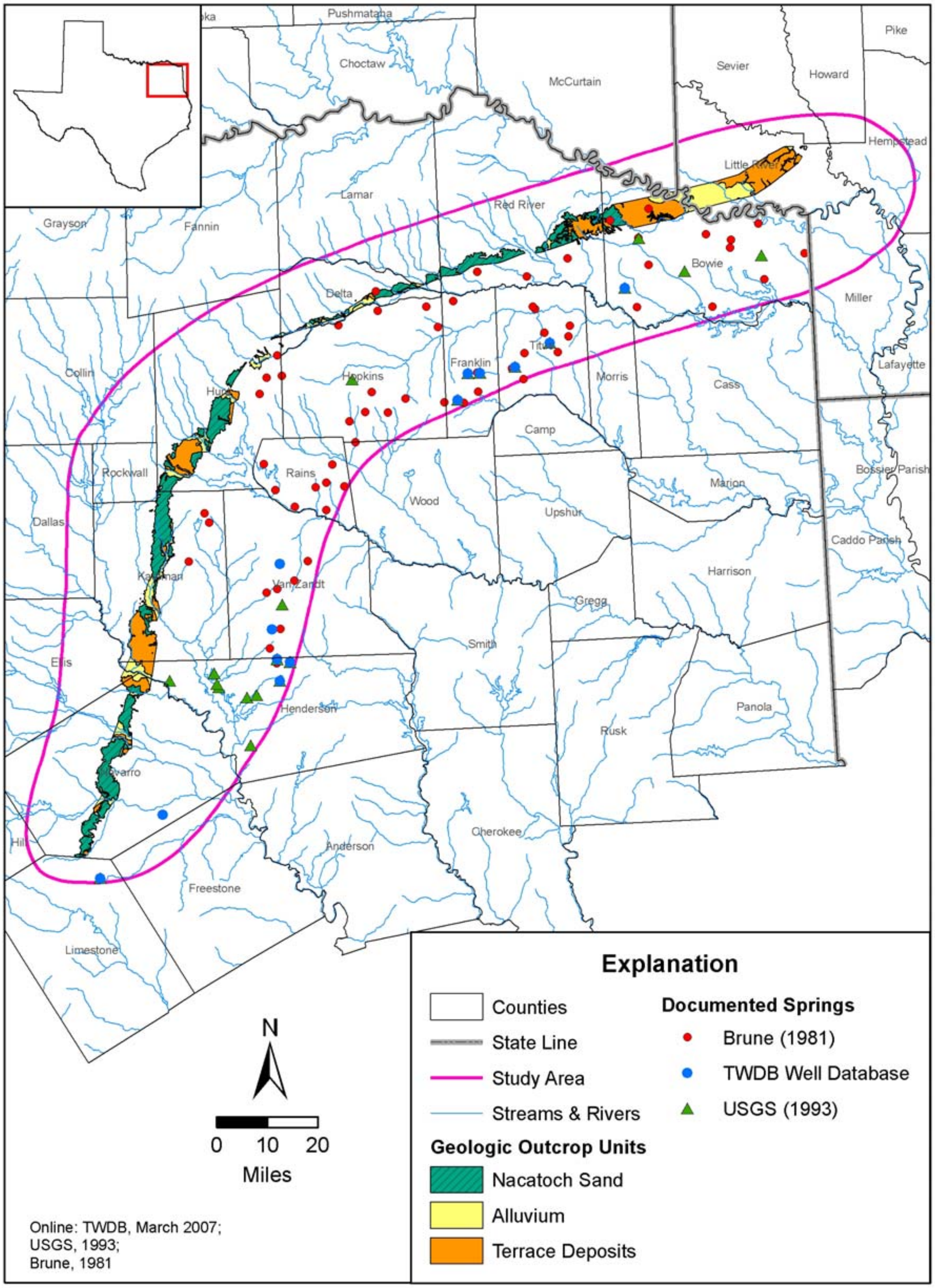


Figure 4.5.2 Documented springs

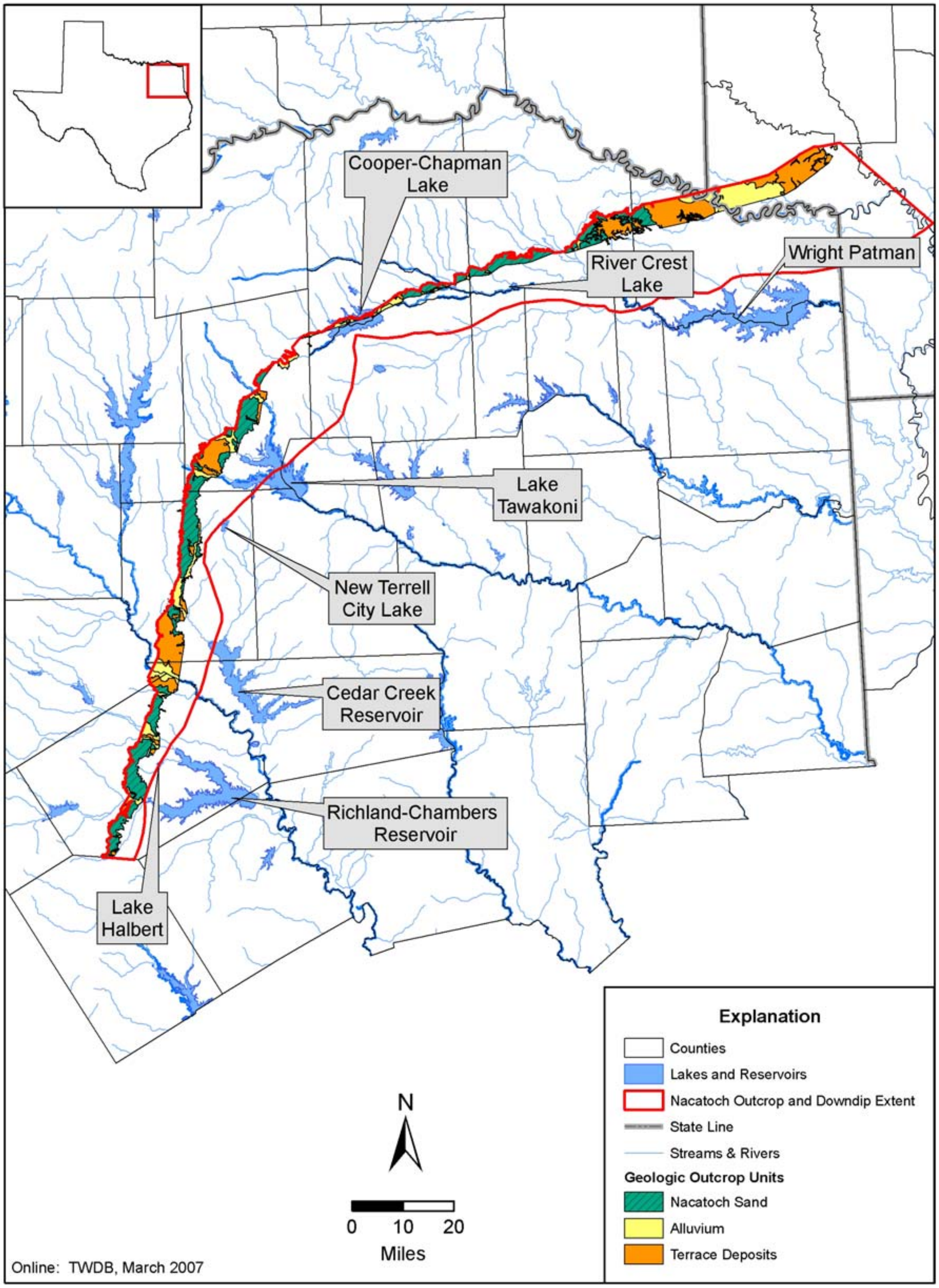


Figure 4.5.3 Significant reservoirs and lakes in the model area

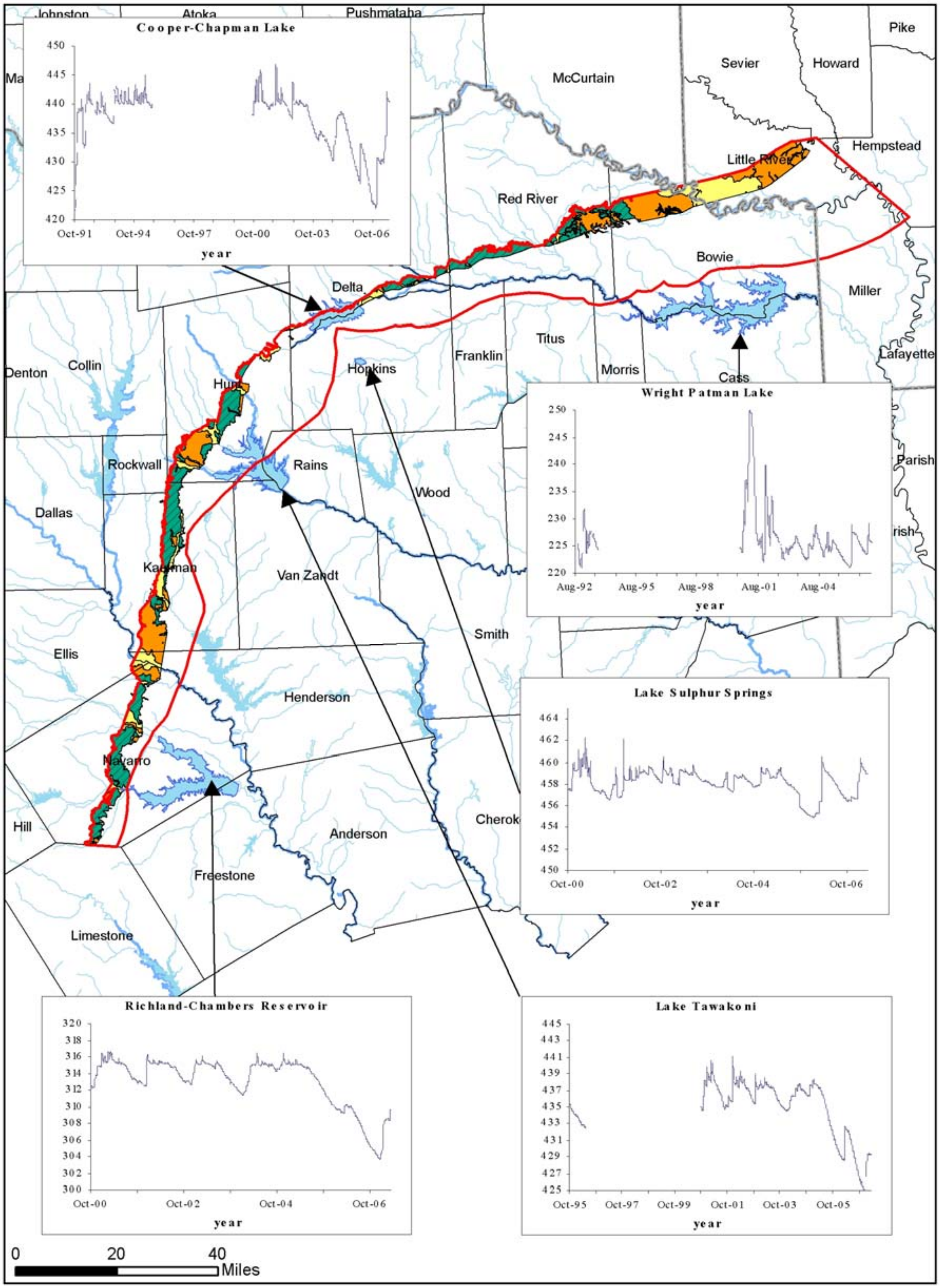


Figure 4.5.4 Hydrographs for select reservoirs in the model area

4.6 Hydraulic Properties

Specific capacity data for 65 wells completed in the Nacatoch Aquifer was compiled from TWDB records. Of these, 10 wells also had transmissivity calculated from pumping tests in Myers (1969) or Ashworth (1988). A linear relationship was derived from specific capacity and transmissivity data from these 10 wells and used to estimate transmissivity in the remaining wells for which there was only specific capacity data.

Hydraulic conductivity was estimated using screened interval thickness as equivalent to aquifer thickness (from Ashworth, 1988) for all wells, and the locations of the wells with hydraulic conductivity estimates is presented in Figure 4.6.1. The specific capacity and transmissivity data with linear regression is given in Figure 4.6.2. Although more data would be preferred, line of fit for this comparison was developed with the best data available. Using this linear relationship, transmissivity was calculated for other wells in the model area using specific capacity estimates. A histogram of the logarithm of estimated hydraulic conductivity for these wells is presented in Figure 4.6.3. Figure 4.6.4 depicts the relationship between net sand thickness and estimated transmissivity.

Specific capacity, transmissivity, and hydraulic conductivity data for the Nacatoch Aquifer wells are summarized in Table 4.6.1 below.

Table 4.6.1 Summary of Nacatoch Aquifer hydraulic properties

	Specific Capacity (gpm/ft)	Transmissivity (gal/day-ft)	Hydraulic Conductivity (ft/day)
Average	1.22	1,686	4.98
Maximum	13.80	13,127	56.60
Minimum	0.04	206	0.49
Median	0.50	1,220	2.95

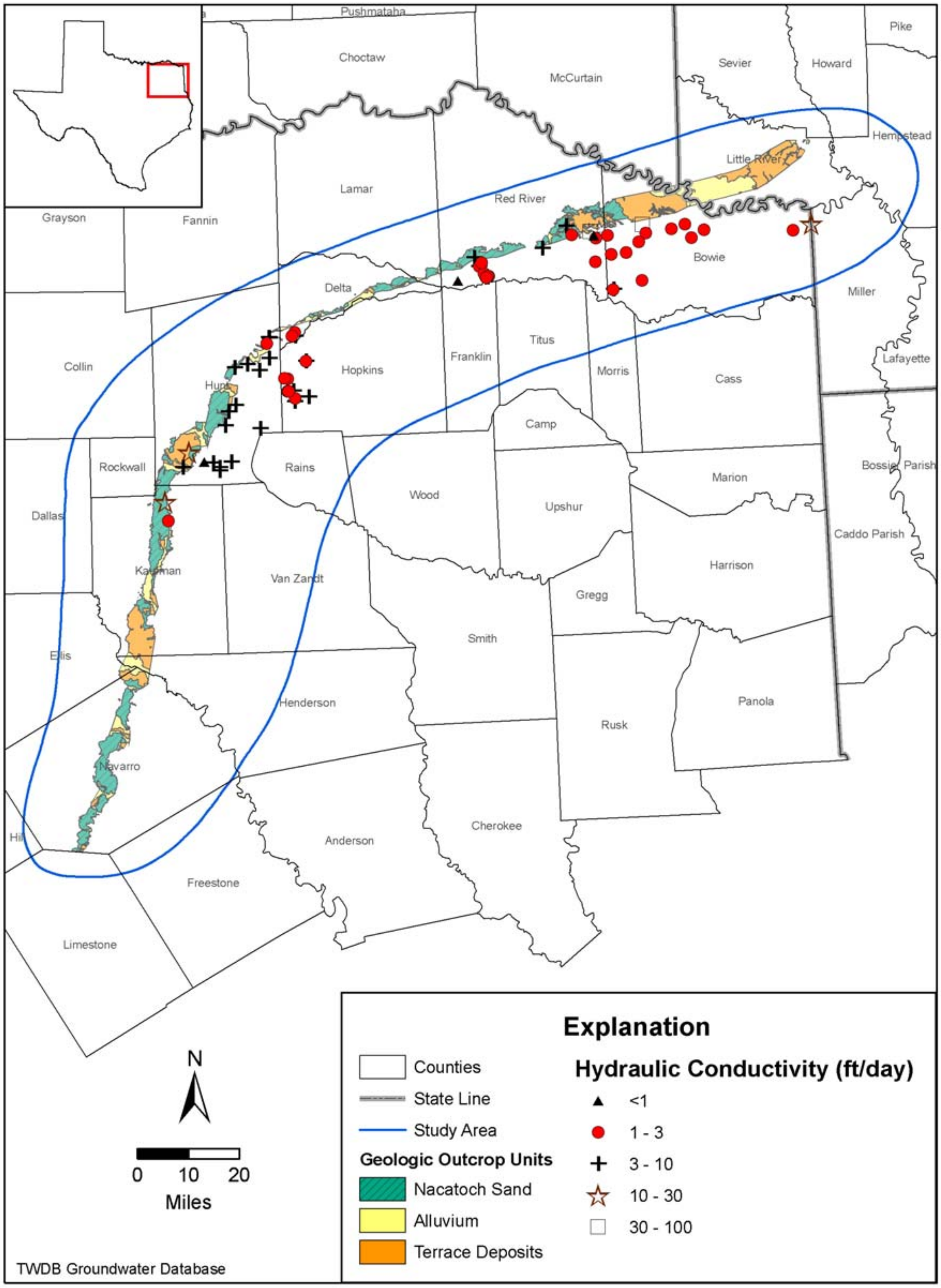


Figure 4.6.1 Nacatoch Aquifer hydraulic conductivity estimates

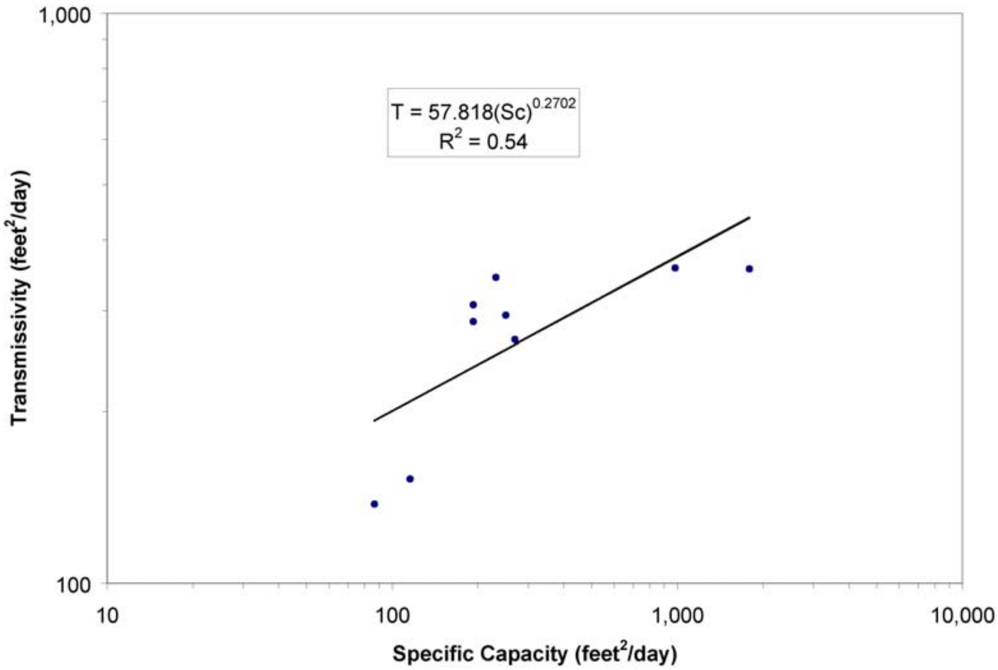


Figure 4.6.2 Relationship between Nacatoch Aquifer transmissivity and specific capacity

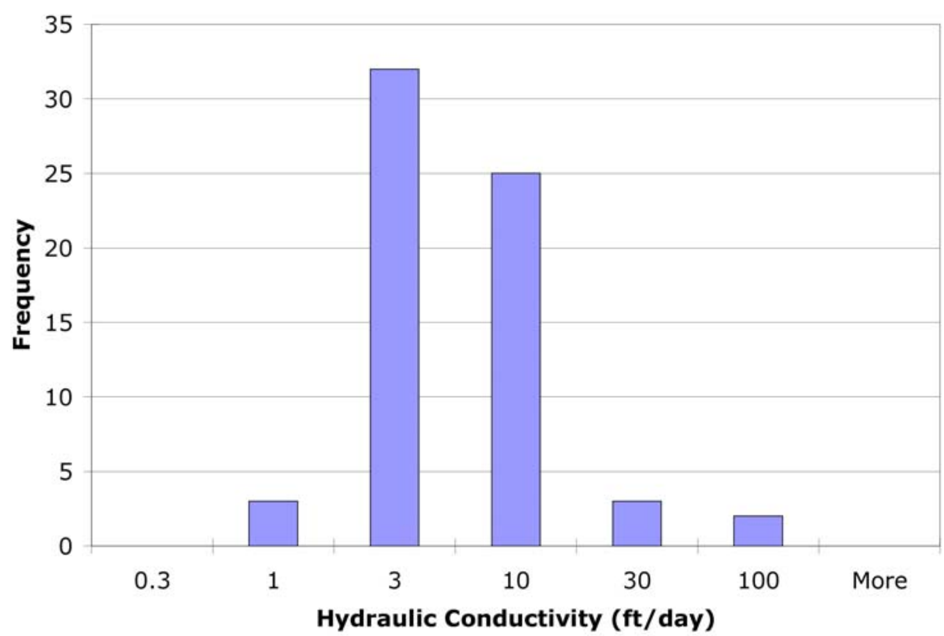


Figure 4.6.3 Histogram of Nacatoch Aquifer hydraulic conductivity estimates

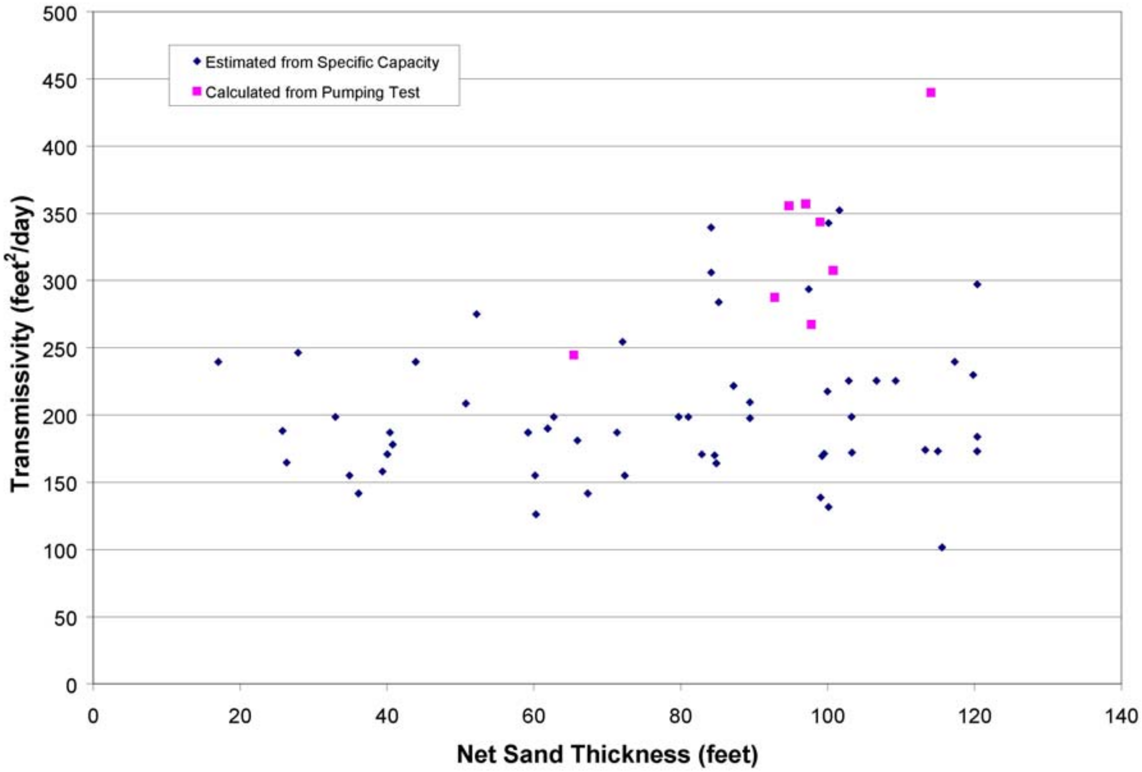


Figure 4.6.4   Relationship between transmissivity and net sand thickness

A much smaller data set (seven wells) was available for wells with specific capacity data completed in alluvium in the model area. All of the alluvium hydraulic property data came from wells completed in the northeastern portion of the model area. Of these seven wells, only one had transmissivity calculated from a pumping test in Myers (1969). Therefore transmissivity for the six wells completed in alluvial deposits with only specific capacity data was estimated using the relationship given in Driscoll (1986) for unconfined aquifers:

specific capacity (gpm/ft) = transmissivity(gpd/ft)/1500

This relationship is approximate because it is based on assumed values in the log term of the modified non-equilibrium equation of Cooper and Jacob (1946). Taking the logarithm of these assumed values tends to mute inaccuracies in the assumptions, leading to the approximation above.

Hydraulic conductivity was estimated using screened interval thickness as equivalent to aquifer thickness for these seven wells, and the locations and estimated hydraulic conductivities of the wells are presented in Figure 4.6.5. Specific capacity, transmissivity, and hydraulic conductivity data for the alluvial wells are summarized in Table 4.6.2 below.

Table 4.6.2 Summary of alluvium hydraulic properties

	Specific Capacity (gpm/ft)	Transmissivity (gal/day-ft)	Hydraulic Conductivity (ft/day)
Average	1.76	3,528	33.58
Maximum	4.63	13,127	56.61
Minimum	0.50	750	16.71
Median	0.60	900	30.99

No storativity values calculated from pumping tests were found in the TWDB data or in Myers (1969). Freeze and Cherry (1979) indicate that the storativity in confined aquifers usually range in value from 0.005 to 0.00005. The specific yields of unconfined aquifers are much higher than the storativities of confined aquifers, and generally range from 0.01 to 0.30 (Freeze and Cherry, 1979)

We found no data regarding the vertical hydraulic conductivity or estimated anisotropy in the hydraulic conductivity tensor. Regional estimates of horizontal to vertical hydraulic conductivity ratios range from 10 to 10000.

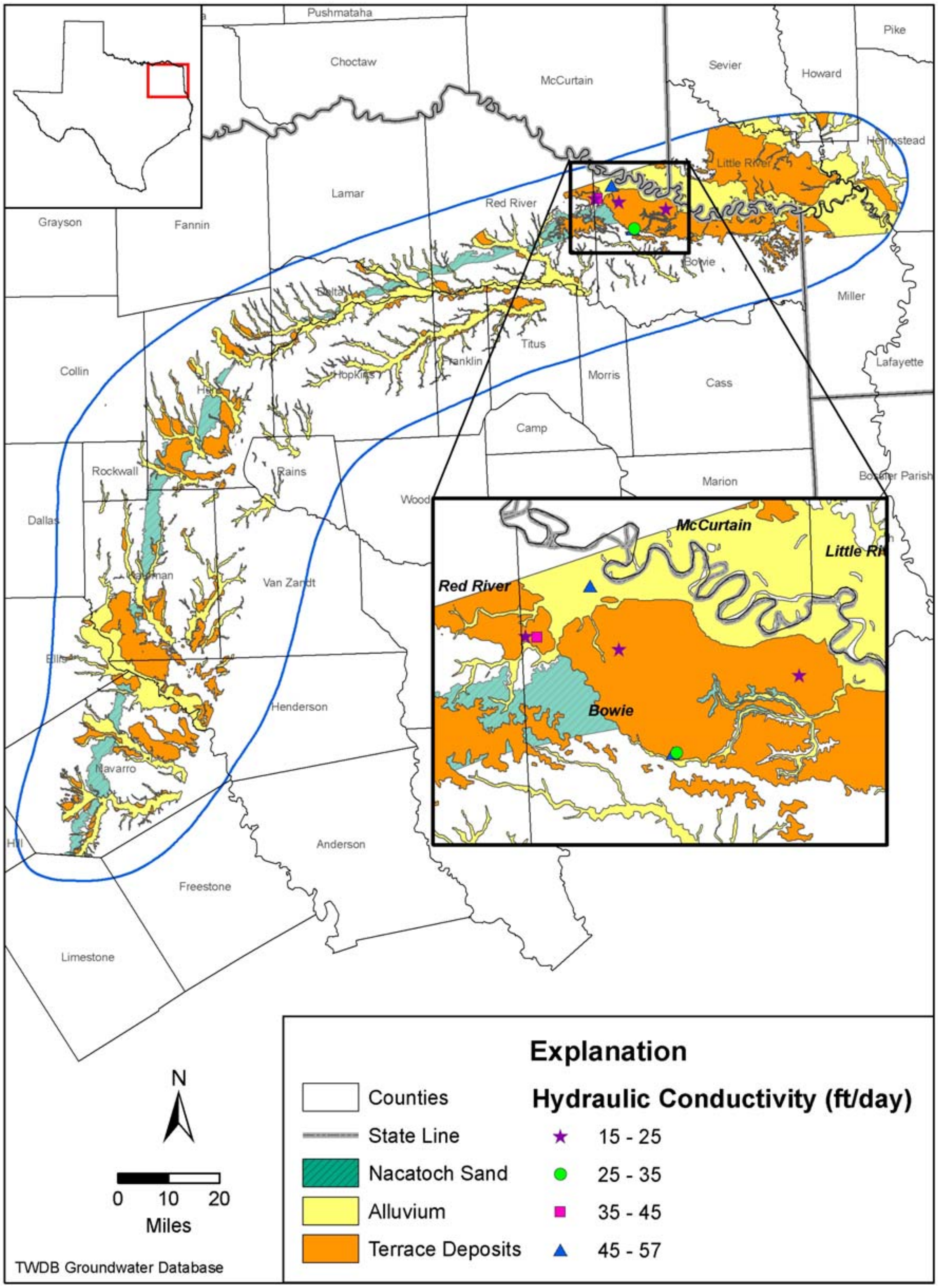


Figure 4.6.5 Alluvium hydraulic conductivity estimates

4.7 Aquifer Discharge

4.7.1 Natural Aquifer Discharge

Under predevelopment conditions, groundwater flow in the Nacatoch Aquifer is elevation driven from the higher elevation outcrops to the lower elevation stream valleys and, in areas where faulting does not disturb aquifer continuity, 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.

<u>Rivers and Streams</u>

As noted in Section 4.5, major rivers intersecting the model area include the Trinity, Sabine, Sulphur, and Red. In addition to the major rivers, numerous smaller streams occur in the model area. Figure 4.7.1 shows the location of stream gages 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. As shown in Figure 4.5.1, major rivers in the model area tend to flow year round.

Base flow is the contribution of groundwater to gaining reaches of a stream. After runoff from storm events has drained away, along with secondary sources such as interflow or bank-storage, the natural surface-water flow that continues over the long term is predominately base flow from groundwater. Streams can have an intermittent base flow, which is usually associated with wet winters and dry 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 our conceptual model that most streams and all rivers throughout the model area were gaining streams. With resource development, some percent of baseflow to streams may have been captured in areas where drawdowns have been significant.

Stream-aquifer interaction can be quantified through several means including low flow studies, hydrograph separation studies, and by modeling studies. The USGS documented a survey on low flow studies performed in Texas (Slade and others., 2002), but this report does not include any measurements in the Nacatoch Aquifer outcrop. To augment the lack of studies on aquifer-stream interaction in the model area, we have performed a hydrograph separation analysis.

Hydrograph separation is a methodology whereby streamflow hydrograph data is analyzed and surface runoff is partitioned from the stream baseflow component. The basic premise is that in the streamflow hydrograph, sharp peaks will represent surface runoff events, whereas the smooth, constant portion of the streamflow hydrograph represents baseflow. Figure 4.7.2 shows an example of this technique for streamflow gage 7342465 in Hunt County. There are several automated methods available to perform the separation. The utility of this method is that it provides a means to estimate the amount of groundwater discharging in a stream segment, thus providing bounds on shallow recharge estimates. The estimates of groundwater discharge can then be used in groundwater model calibration for the stream-aquifer boundary.

Baseflow separation studies were performed on 8 stream gages in the model area that had some historical unregulated period. The gages were chosen both for the availability of unregulated streamflow measurements, and for their proximity to the Nacatoch Aquifer outcrop. We selected gages with subwatersheds that intersected some of the outcrop area. Figure 4.7.3 shows the subwatersheds analyzed in the model area, along with the corresponding gages. The locations of the subwatersheds were determined using the 30m DEM and the ArcHydro toolset.

The code BFI (Wahl and Wahl, 1995) was used to perform the automated separation analysis. BFI is a similar baseflow separation tool to HYSEP. In our opinion, BFI provides a more convenient interface for data processing. Table 4.7.1 shows the gages that were analyzed and the regulated and unregulated years. The reporting of regulated and unregulated years was based on Slade and others (2002).

Table 4.7.1 also gives a summary of the results of the hydrograph separation analysis performed for the current study. In this table, total drainage area is equal to the total contributing gage drainage area, as reported by the USGS (these areas compare favorably to the calculated subwatershed areas from the ArcHydro analysis when properly combined). The runoff number is the surface runoff only (sometimes the term “runoff” is used to indicate the surface runoff and baseflow combined). To convert the baseflow and runoff numbers to a flux rate, the flow rates were divided by the drainage area. This is necessary, since only a portion of the total drainage area is actually over the outcrop of the Nacatoch Aquifer. The weighted average baseflow was 0.5 inches/year. These baseflow estimates can be used as guidance for calibration of the groundwater model.

Table 4.7.1 Summary of hydrograph separation analysis

Gage	Station Name	Unregulated Years	Total Drainage Area (mi^2)	Baseflow (in/yr)	Runoff (in/yr)
7342465	S Sulphur River at Commerce	1992-Present	150	0.28	13.7
7342470	S Sulphur River near Commerce	1980-1991	189	0.27	11.1
7342500	S Sulphur River near Cooper	1943-1992	527	0.29	10.6
7343200	Sulphur River near Talco	1957-1992	1405	0.58	12.8
8017300	S Fork Sabine River near Quinlan	1960-Present	78.7	0.18	17.1
8062900	Kings Creek near Kaufman	1964-1972	233	0.24	8.6
8063500	Richland Creek near Richland	1940-1963	734	0.45	8.1
8064500	Chambers Creek near Corsicana	1940-1961	963	0.69	6.4

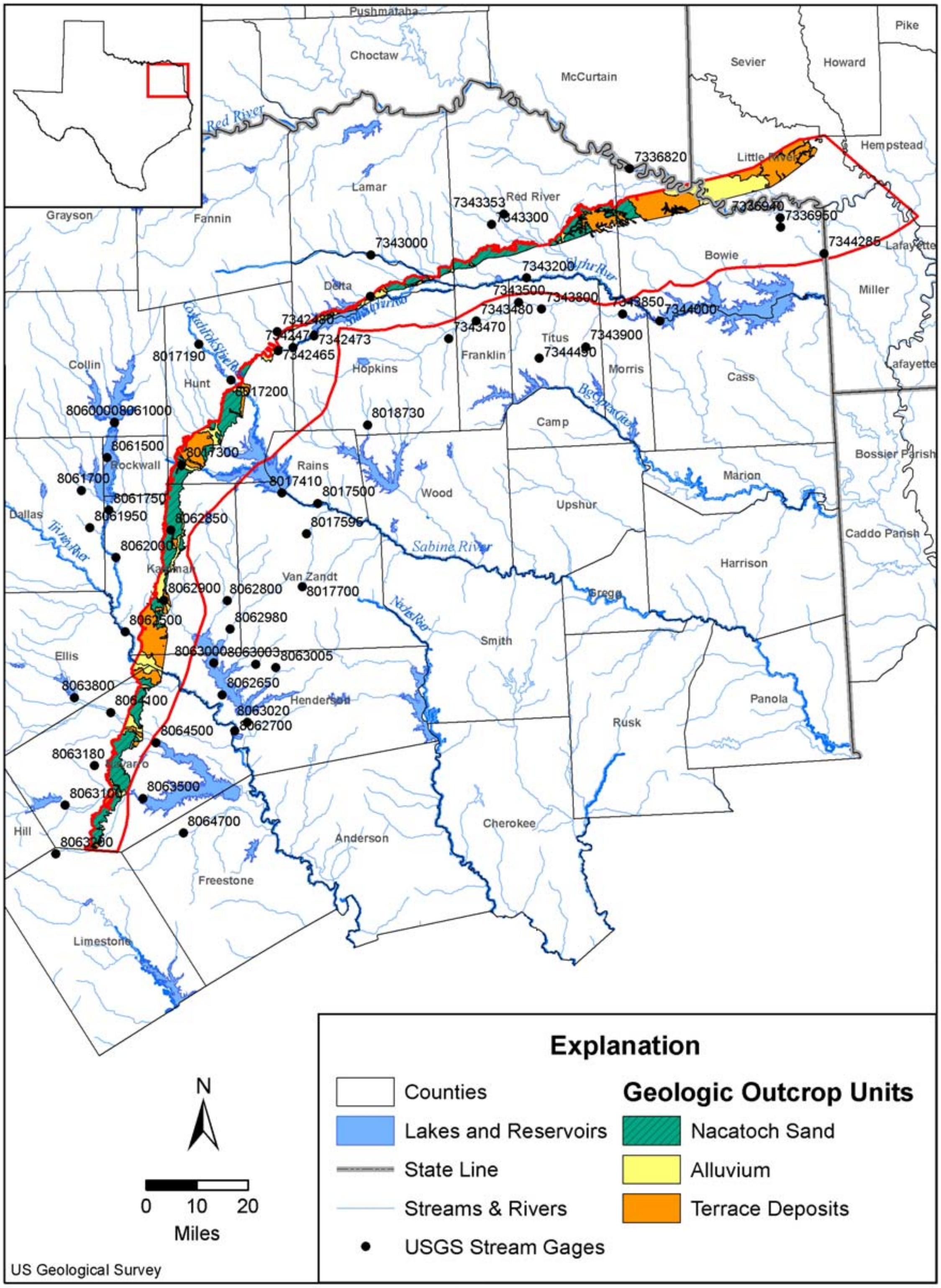


Figure 4.7.1 Stream gages in the model area

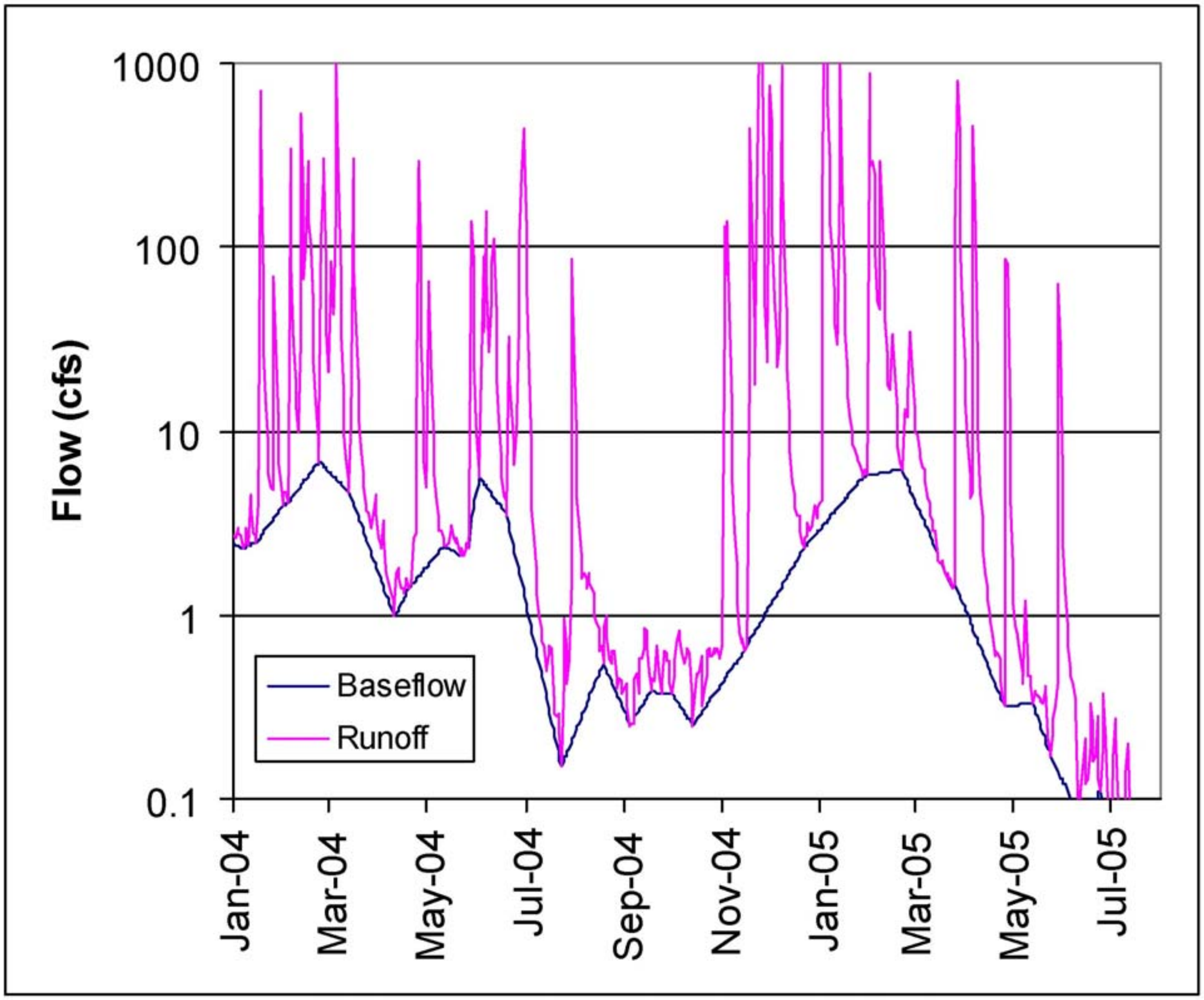


Figure 4.7.2 Example of hydrograph separation for gage 7342465 in Hunt County

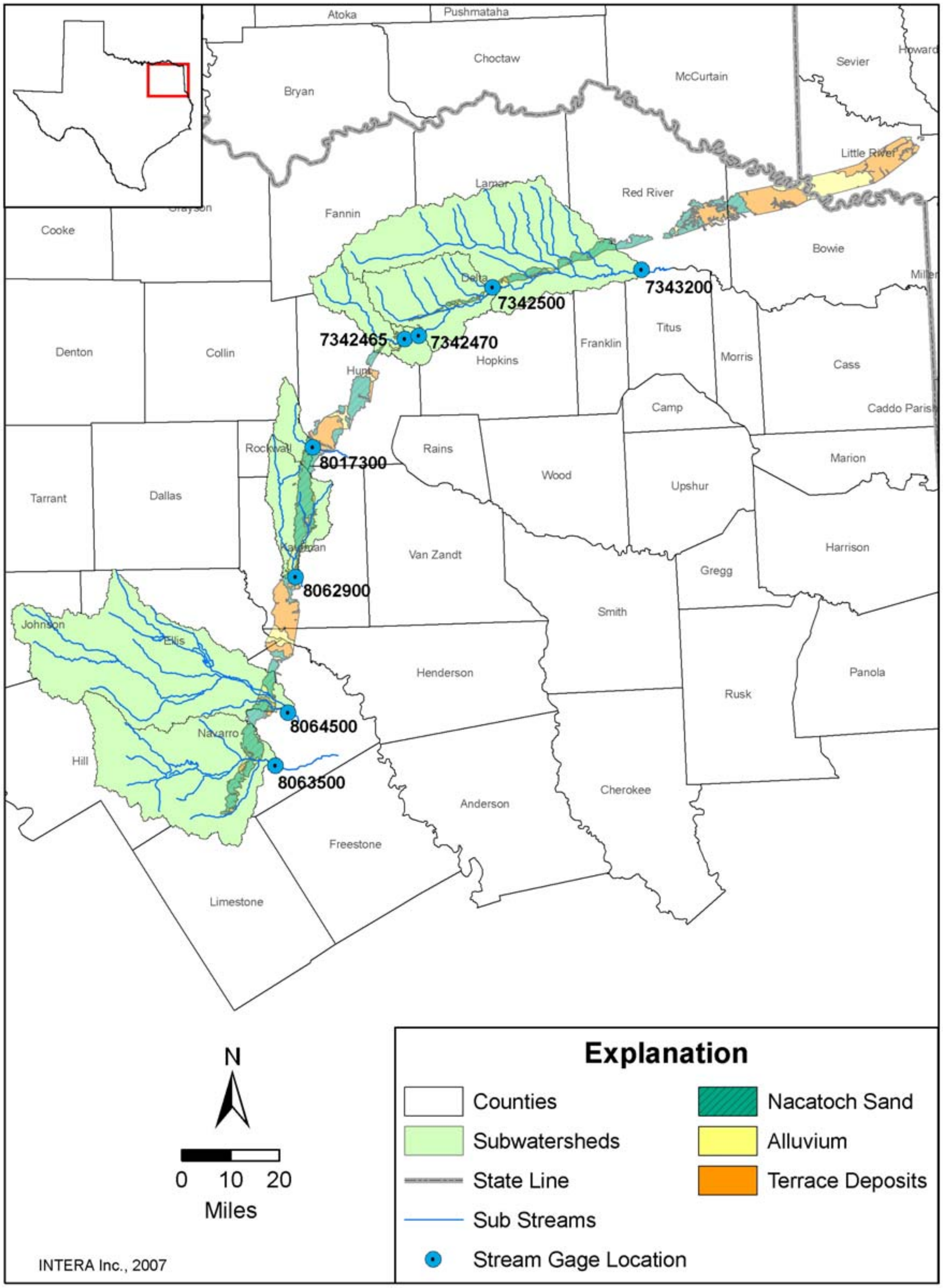


Figure 4.7.3 Location of subwatersheds and gages for baseflow separation analysis

Springs

Figure 4.5.2 shows the locations of documented springs in the model area. The available measured spring flow rates range from the springs being dry to a high of 97.6 gpm (0.2 cfs) at Woodbury Spring. Time series data are not available for the springs in the study outcrop area. However, in notes written by Brune (1981) Heitmuller and Reece (2003)) they note that some springs dry up in the summer while others flow year round. This implies that many of the smaller springs in the Nacatoch Aquifer and Midway are generally fed by the shallow groundwater system and that they would exhibit a variation in flow correlated to precipitation. Consistent with this conceptualization, this implies that the springs are capturing flow from shallow flow systems, which may even be at a scale below the GAM grid size. As a result, small springs are hard to accurately model using a regional model.

Throughout much of the State, including the model area, spring flows have shown a general decline over time. Most information regarding spring declines across the state for minor springs is anecdotal and undocumented. However, Ashworth (1988) noted that in areas of the Nacatoch Aquifer where drawdown has been significant, spring discharge has declined and the presence of flowing wells has ceased. Table 4.7.2 also indicates that several springs have dried up in the area including many in Hunt and Bowie Counties as early as the 1920s when pumping in these counties began.

Brune (1981) noted that declining groundwater levels due to pumping and unrestricted flowing wells have resulted in thousands of smaller springs that no longer flow and reduced flows in many of the larger springs in Texas. In areas of the Nacatoch Aquifer where drawdown has been minimal, we would expect spring flows to have been maintained because of the humid climate, dissected topography, and fault-bound aquifer architecture.

Table 4.7.2 Documented springs within the model boundary

County	Spring	Formation	Flow Rate (LPS[1])	Flow Rate (GPM[2])	Flow Rate (CFS[3])	Date of Measurement	DEM (Feet AMSL[5])	Source
Bowie	La Harpe	Terrace sands	Seeps	Seeps	Seeps	1/76	285.0	Brune (1981)
Bowie	Myrtle	NR[4]	3.0	47.6	0.1	1/12/76	357.4	Brune (1981)
Bowie	Cedar	Terrace gravels	Dry	Dry	Dry	Since 1920	340.9	Brune (1981)
Bowie	Nanatsoho	Terrace gravels	1.3	20.6	0.06	Since 1920	347.2	Brune (1981)
Bowie	Indian	Terrace sands	6.1	96.7	0.2	11/13/76	361.7	Brune (1981)
Bowie	Gay	Terrace sands	0.52	8.2	0.02	11/13/76	381.1	Brune (1981)
Bowie	Ghio	Terrace gravels	1	15.9	0.06	11/13/76	343.9	Brune (1981)
Bowie	Pine	NR[4]	0.33	5.2	0.01	12/1/76	420.8	Brune (1981)
Bowie	DeKalb	Terrace sands	0.32	5.1	0.01	11/13/76	381.8	Brune (1981)
Bowie	Dalby	Wilcox	0.06	0.95	0.002	1/76	298.6	Brune (1981)
Bowie	Red	Wilcox	Dry	Dry	Dry	1/76	302.4	USGS (2004)
Delta	Kichai	Terrace Sands	Seeps	Seeps	Seeps	11/77	410.1	Brune (1981)
Delta	Miller	Nacatoch Aquifer	Dry	Dry	Dry	11/77	371.6	Brune (1981)
Franklin	Red Branch	Navarro Sands	Weeps	Weeps	Weeps	NR[4]	355.2	Brune (1981)
Henderson	LT-33-48-607	NR[4]	0.63	10	0.02	NR	347.8	USGS (2004)
Hopkins	Sulphur Bluff	Navarro Sands	Seeps	Seeps	Seeps	12/77	418.5	Brune (1981)
Hopkins	Valley	Terrace Sands	Seeps	Seeps	Seeps	12/77	398.7	Brune (1981)
Hunt	Riley	Nacatoch Aquifer	Dry	Dry	Dry	Since 1917	481.1	Brune (1981)
Hunt	Stewart	Nacatoch Aquifer	Dry	Dry	Dry	Since 1925	552.4	Brune (1981)
Hunt	Smith	Nacatoch Aquifer	Dry	Dry	Dry	Since 1925	552.4	Brune (1981)
Hunt	Babb	Nacatoch Aquifer	0.07	1.1	0.002	11/1/77	552.7	Brune (1981)
Hunt	Allen	Nacatoch Aquifer	Dry	Dry	Dry	NR	514.0	Brune (1981)
Hunt	Hooker	Eocene Kincaid	Dry	Dry	Dry	NR	468.8	Brune (1981)
Kaufman	Ables	Tehuacana Ls.	0.52	8.2	0.02	9/29/79	544.7	Brune (1981)
Kaufman	Cottonwood	Terrace Sands	NR[4]	NR[4]	NR[4]	10/79	412.9	Brune (1981)
Kaufman	Unnamed	Terrace Sands	0.35	NR[4]	NR[4]	10/20/79	412.9	Brune (1981)

Table 4.7.2 Documented springs within the model boundary

County	Spring	Formation	Flow Rate (LPS[1])	Flow Rate (GPM[2])	Flow Rate (CFS[3])	Date of Measurement	DEM (Feet AMSL[5])	Source
Red River	Maple	Navarro Sand	0.25	4	0.009	1976	328.6	Brune (1981)
Red River	Cuthand	Navarro Sand	0.15	2.4	0.005	1976	296.4	Brune (1981)
Red River	Coleman	Navarro Sand	3.0	47.6	0.1	1976	357.1	Brune (1981)

Notes:

[1] LPS = liters per second
[2] GPM = gallons per minute
[3] CFS = cubic feet per second
[4] NR = not recorded
[5] AMSL = above mean seal level

Evapotranspiration

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

Groundwater ET occurs primarily in riparian buffer strips adjacent to streams (Scanlon and others., 2005). Riparian zones are not specifically mapped in Texas. We will consider two alternatives for defining the location of groundwater ET in the model region. Either we can define some fixed buffer around the streams as riparian areas, or we can assume that the discharging areas would be likely regions of groundwater ET. In general, we are trying to create the potential for groundwater ET in regions where the water table is near ground surface, and either approach will likely serve this purpose.

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

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

$$ETV_{max} = PET * K_c$$

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

Borrelli and others (1998) provides an estimate of long-term potential evapotranspiration, based on the Penman-Monteith method, as reproduced in Figure 4.7.4. Figure 4.7.4 shows that long-term average PET ranges from about 53 to 60 inches/year, increasing from east to west. Although ET varies considerably with seasons, it does not vary as dramatically on an annual average basis. Figure 4.7.5 shows average annual PET estimated with the Hargreaves method for Hunt County. Note that PET rarely varies more than 5% from the mean in any given year. For this reason, we may make the assumption that PET is constant throughout a transient simulation.

The most detailed vegetation map in Texas comes from the Texas Gap Analysis Project (Parker and others., 2003). Their estimates are based on a combination GIS analysis and ground truthing. Figure 4.7.6 shows an example of the vegetation coverage near Hunt County. The vegetation types are labeled by their broad National Vegetation Classification System (Federal Geographic Data Committee, 1997) categories. The TX-GAP report names several possible subcategories for each main category that provide information on the specific types of vegetation in Texas that might be representative. However, they do not specifically identify riparian vegetation or riparian zones in their analysis.

To determine if different types of vegetation are identified in areas near known streams, we intersected the stream coverage in the area (including a quarter-mile buffer) with the vegetation coverage, and calculated the frequency of each vegetation type for this subset, compared to the entire model region. Figure 4.7.7 shows a comparison of the frequency of occurrence for each vegetation type between the two datasets (Parker and others, 2003). The relative frequency of each vegetation type is very similar, indicating that either markedly atypical vegetation does not occur near streams, or the vegetation coverage does not contain sufficient resolution to discriminate the riparian areas.

Given these results, there are four major vegetation types: grassland, cold-deciduous woodland (post oak, blackjack oak), evergreen forest (loblolly pine), and temporarily flooded cold-deciduous woodland (cottonwood). The cropland and temperate broadleaved evergreen woodland (live oak) are minor types, and the rest have a small enough contribution to be safely ignored.

Scanlon and others (2005) provides a database of estimates of vegetation coefficient and rooting depths for many types of vegetation. Table 4.7.3 shows estimates for some the types relevant to this region.

Table 4.7.3 Estimates of vegetation coefficient and rooting depth for several vegetation types in the region

Vegetation Type	Kc	Rooting Depth (ft)
Cottonwood	0.37	10.
Grassland	0.70	2.
Pine	0.53	7.
Live Oak	0.5*	5.*
Post Oak	0.5*	5.*
Cropland	0.6*	1.

*estimated from analogs (Scanlon and others, 2005)

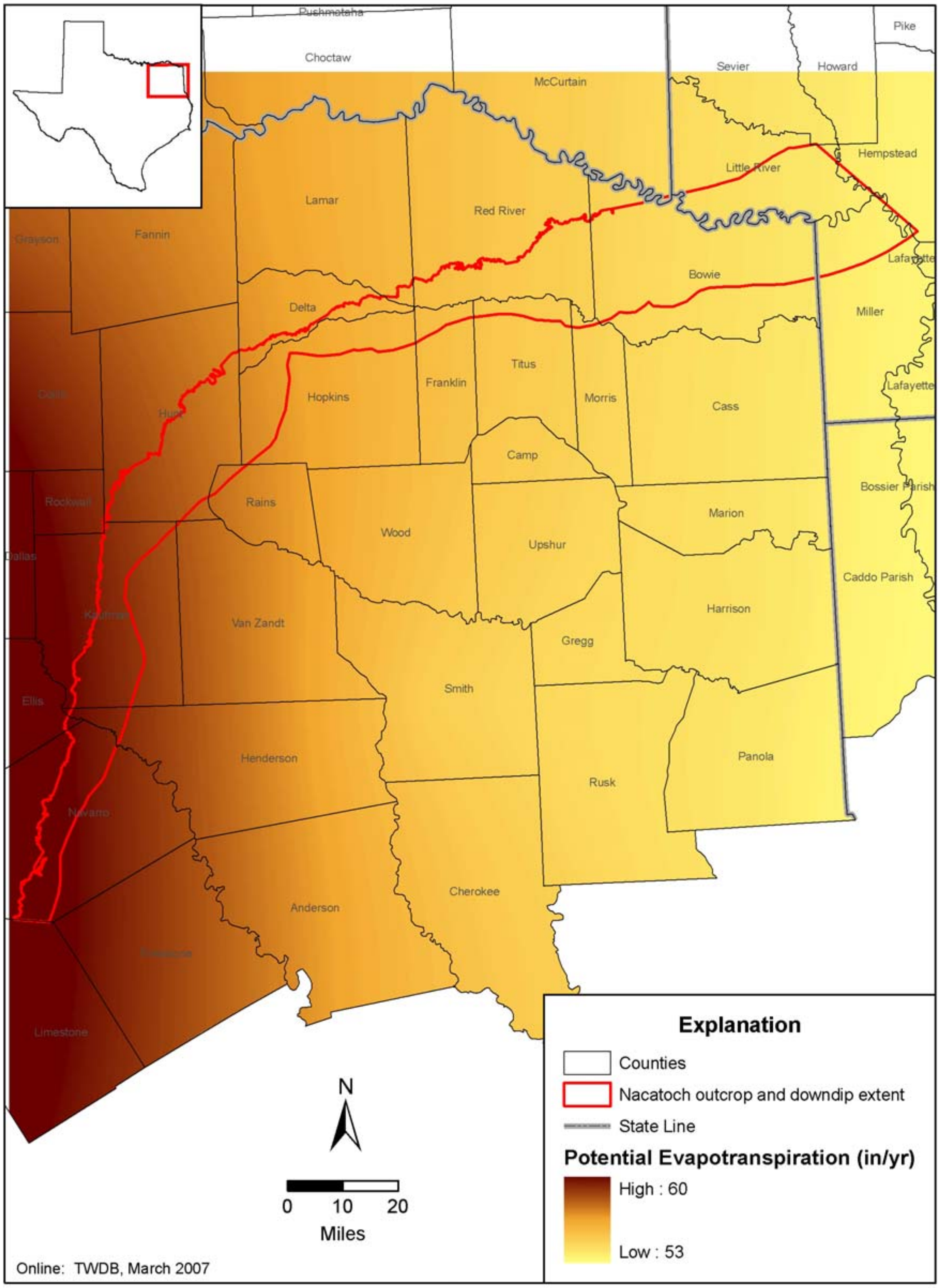


Figure 4.7.4 Potential ET in the region based on Penman-Monteith approach

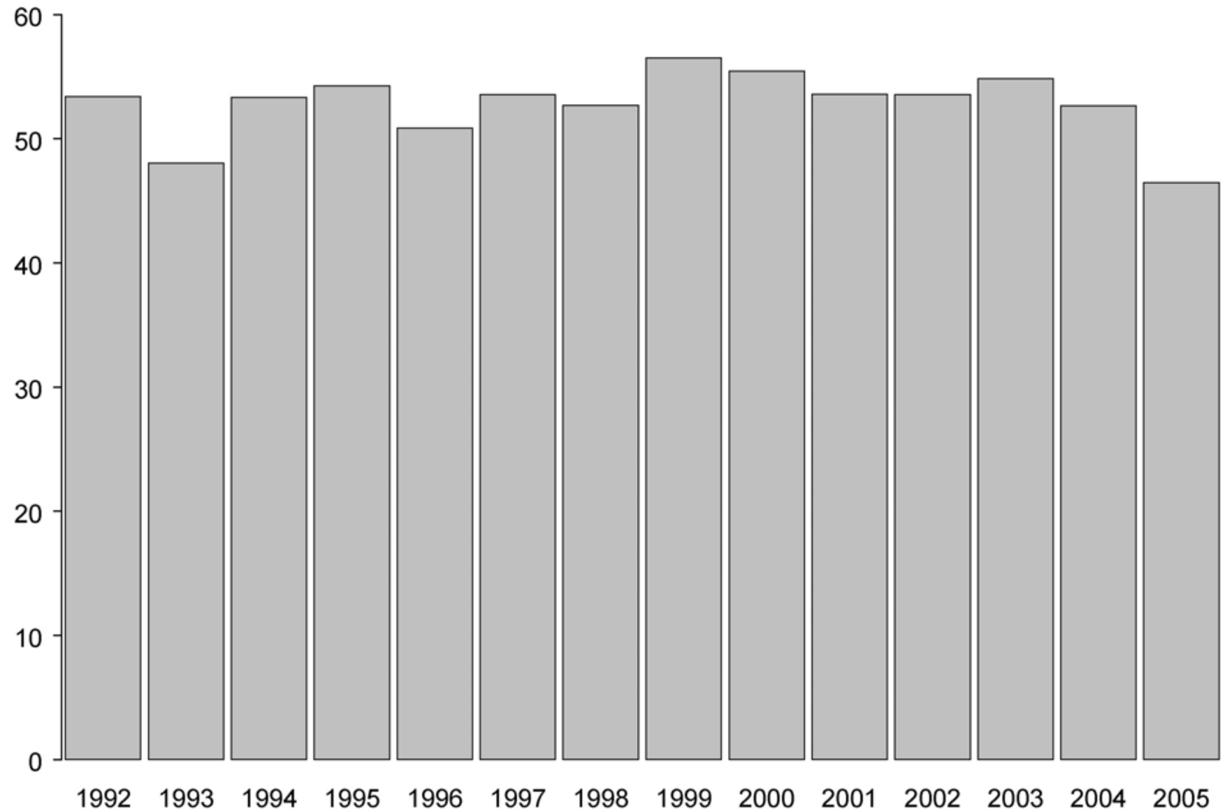


Figure 4.7.5 Variation of annual average ET in Hunt County, estimated from Hargreaves method

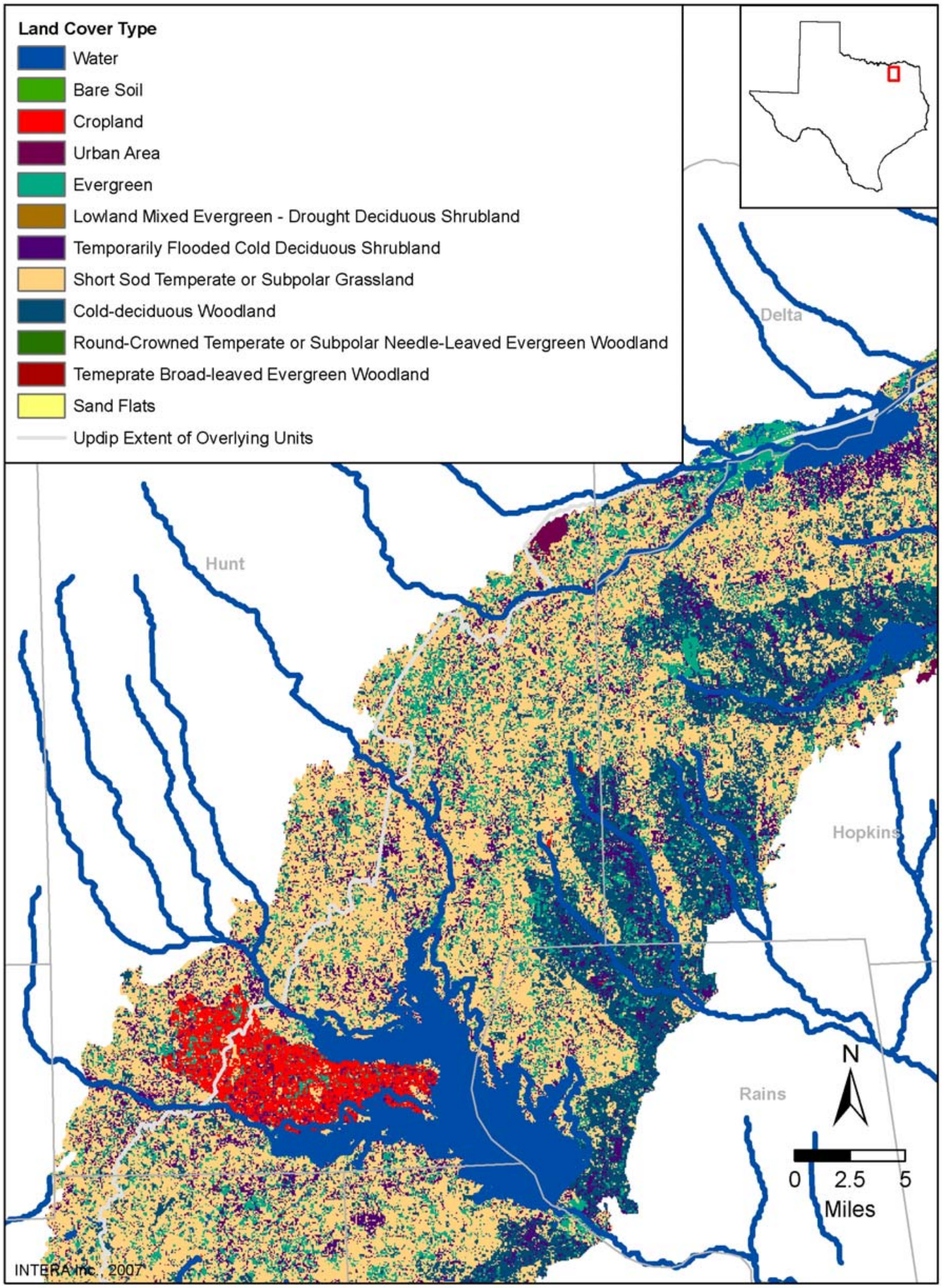


Figure 4.7.6   Example of vegetation coverage for subregion of model area

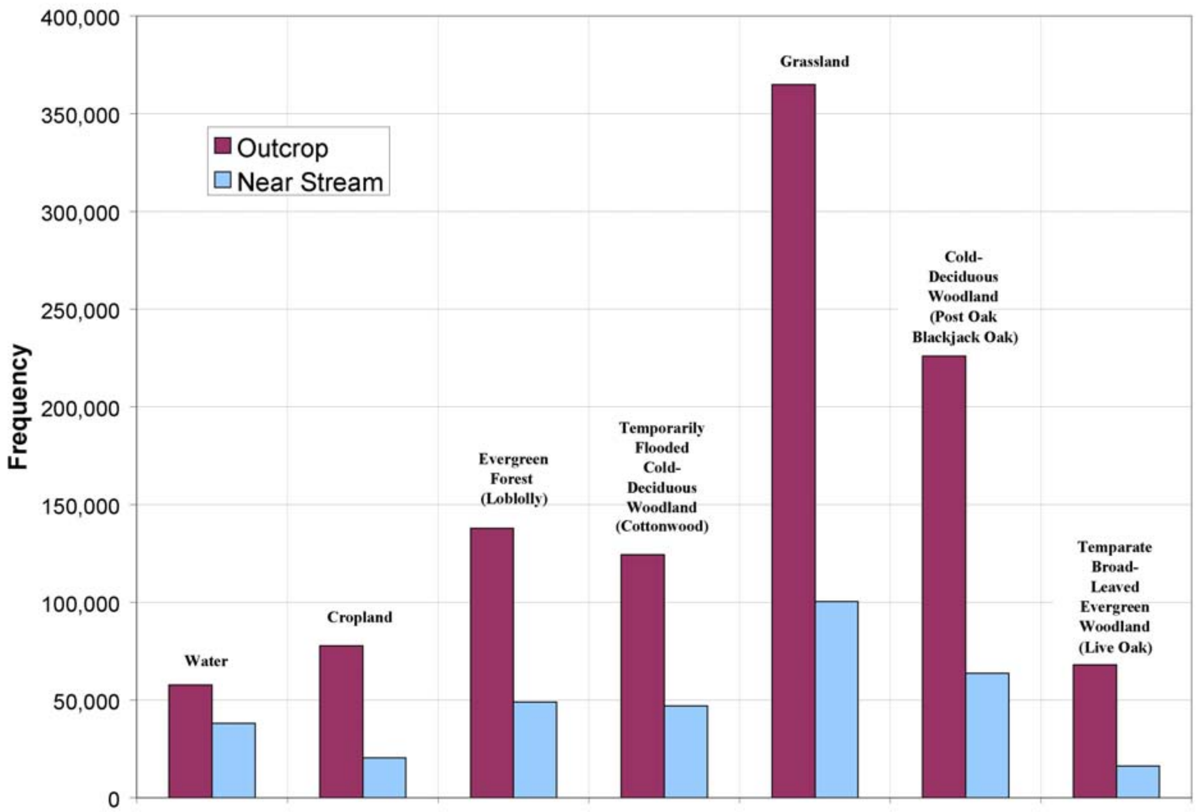


Figure 4.7.7 Frequency of vegetation types in the model outcrop region based on GAP vegetation coverage

Cross-formational Flow

Cross-formational flow is a natural mechanism for inflow and outflow of groundwater between the Nacatoch Aquifer and over- or underlying aquifers. The characterization of cross-formational flow has been well documented and studied in Tertiary aquifers in the East Texas Embayment (Fogg and Kreitler, 1982; Fogg and others., 1983). Cross-formational flow under natural conditions in dipping sedimentary aquifers is generally the result of topographic driven flow systems where heads in the outcrop are at their highest and they drive some groundwater flow into the confined portions of the aquifer. The flow within the confined portions of the aquifer would be a small percent of recharge and would generally slowly discharge through cross-formational flow to overlying sediments.

Groundwater flow, and subsequent cross-formational flow, in the Nacatoch Aquifer is highly controlled by faulting. In many portions of the aquifer faulting completely interrupts the continuity of transmissive portions (sands) of the aquifer (Ashworth, 1988). As a result, some portions of the Nacatoch Aquifer have almost zero groundwater flow from outcrop to confined sections of the aquifer and thus effectively zero vertical cross-formational flow. Other areas of the aquifer, where faulting does not bound the outcrop, flow to the confined section occurs and cross-formational flow to the Midway occurs. Figure 4.7.8 shows the location and orientation of faults and the approximate 3000 ppm TDS limit (downdip extent of freshwater) in relation to the Nacatoch Aquifer outcrop. Inspection of Figure 4.7.8 identifies good correlation between faulting in the outcrop and poor migration of fresh groundwater to the confined section. East of Delta and Hopkins Counties there is a lack of faulting in the outcrop and the potable portions of the aquifer extend into the subsurface. Fault swarms in Delta County within and immediately downdip of the Nacatoch Aquifer outcrop tends to prevent significant downdip groundwater flow as evidenced by the Nacatoch Aquifer downdip extent in that area. In these regions, cross-formational flow is negligible and recharge and discharge largely occurs within the outcrop of the aquifer.

In areas of the Nacatoch Aquifer where significant downdip flow is occurring, cross-formational flow is expected to occur largely between the outcrop and the bad water line. Under predevelopment conditions, this flow would naturally be upward across the Midway. The quantity of vertical cross-formational flow under predevelopment conditions is constrained to be at least equal to the amount of recharge reaching the downdip (confined) portions of the aquifer which could be in the tenths of an inch per year expressed as a rate. The process of vertical cross-formational flow is driven by the hydraulic gradient and the vertical conductance of the overlying formations. The hydraulic gradient is essentially defined by the heads in the confined portions of the Nacatoch Aquifer and the shallow water table in the overlying wedge of younger formations. Measurements of vertical conductance of the Midway and the overlying younger sediments are not available at the scale of this study (see Section 4.6). It is generally accepted that groundwater models provide the best means for estimating vertical conductances at a regional scale (Anderson and Woessner, 1992).

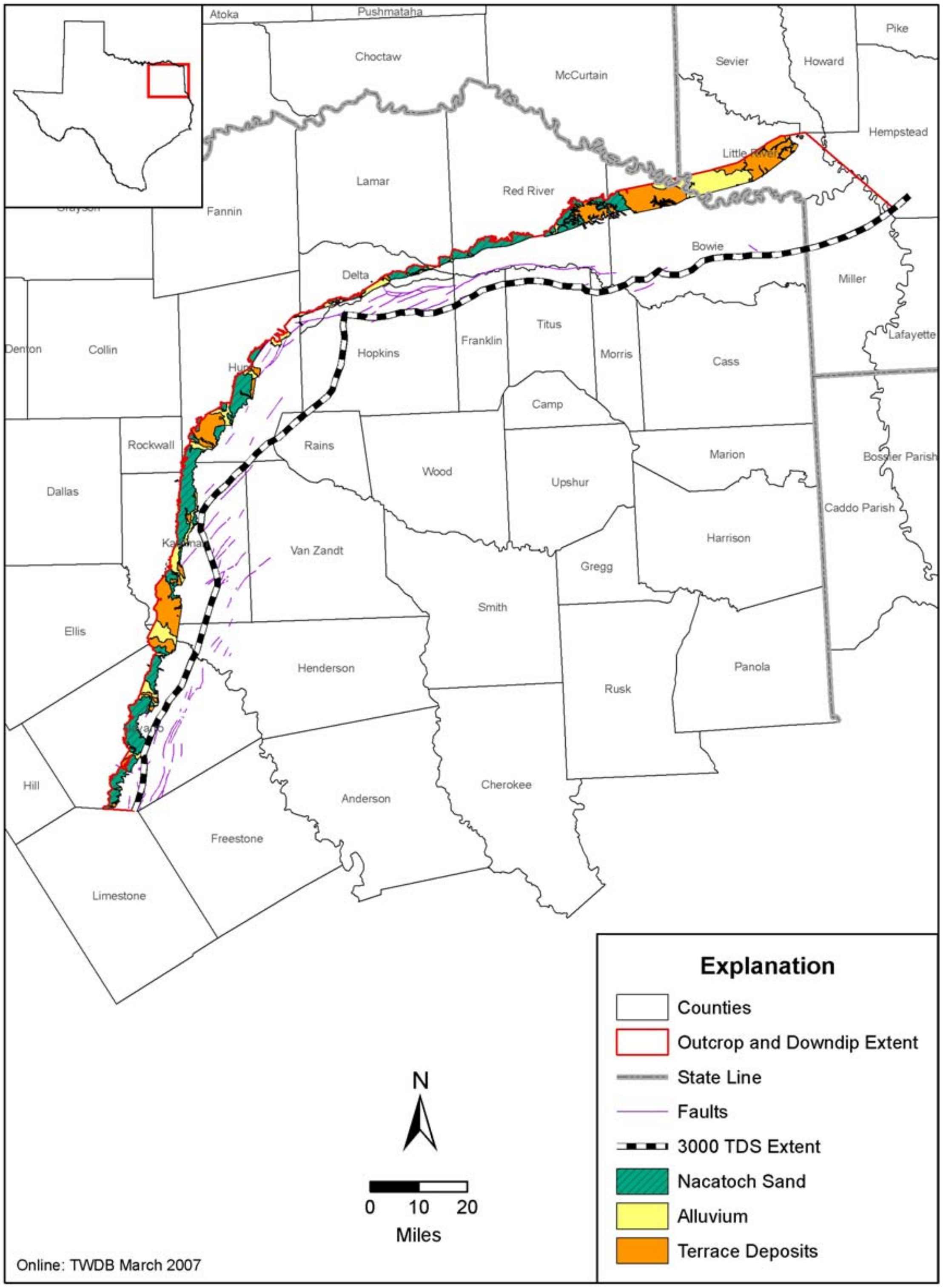


Figure 4.7.8 Mexia-Talco Fault Zone with location of approximate 3000 ppm TDS limit (Nacatoch Aquifer downdip extent of freshwater)

4.7.2 Aquifer Discharge Through Pumping

Pumping discharge estimates for each county in the active model area are developed for the historical period (1980 to 1997) and for early aquifer use (1963 to 1979). Historical (1980 to 1997) estimates of groundwater pumping throughout Texas have been provided by the TWDB as master pumpage tables contained in a pumpage geodatabase. The six water use categories defined in the TWDB database are municipal (MUN), manufacturing (MFG), power generation (PWR), mining (MIN), livestock (STK), and irrigation (IRR). Each water use record in the database carries an aquifer identifier that is used to select pumping records for the Nacatoch Aquifer. Pumping that is allocated to "OTHER AQUIFER" in the TWDB database was also reviewed to determine if it should be included with the Nacatoch Aquifer pumping. Rural domestic (RurDom) pumping, which consists primarily of unreported domestic water use, is estimated based on population density data provided by the TWDB. Groundwater pumping estimates for the part of the model area in Arkansas were based on pumping estimates in USGS (2004), which covered the period from 1965 through 2000 in five year increments.

The TWDB municipal, manufacturing, mining, and power generation pumping estimates, which are available for 1980 through 2000, are based on actual water use records reported by water users. The pumpage geodatabase also includes historical annual pumping estimates for livestock and irrigation 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, Bowie County, which is intersected by both the Sulphur River Basin and the Red River Basin, contains two county-basins. Figure 4.7.9 shows the spatial distribution of pumping ultimately developed using the data further detailed in this section for the year 1997.

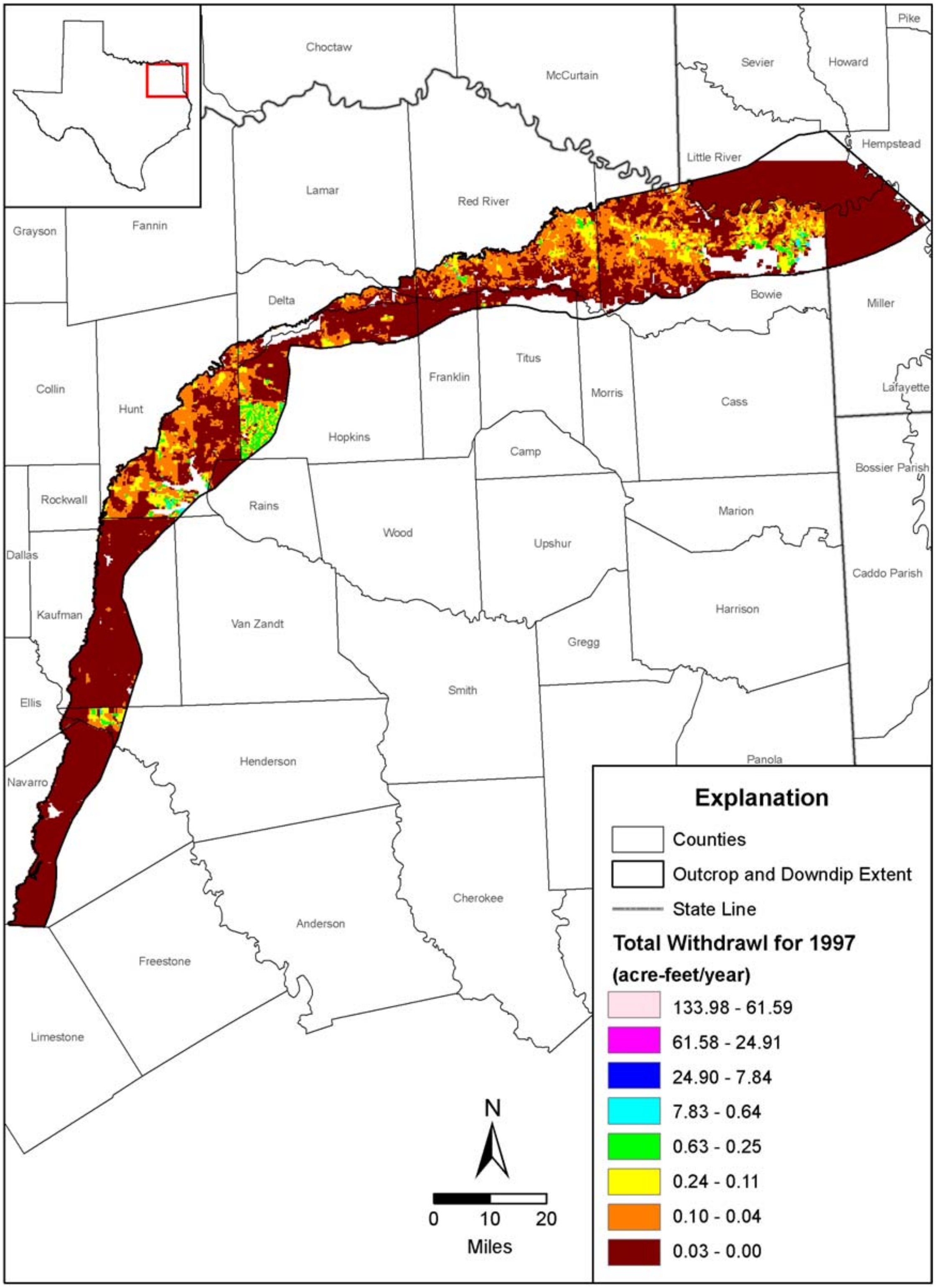


Figure 4.7.9 Pumping distribution for 1997

Reported historical pumping for municipal, manufacturing, mining, and power generation water uses was matched to the specific wells from which it was pumped to identify the withdrawal location in the aquifer (latitude, longitude, and depth below land surface) based on the well's reported properties. The well properties were obtained primarily from the TWDB groundwater database, with some additional information from the TCEQ's Public Water System database, the USGS's National Water Information System, or various other sources. When more than one well is 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".

Rural domestic pumping was distributed based on U.S. census block population density in non-urban areas (Figure 4.7.10). The TWDB has provided a polygon feature class of census blocks, based on the 1990 U.S. census, and a table of factors for converting rural population density into annual groundwater use. Urban areas will be excluded from rural population calculations and groundwater pumpage. All rural domestic pumping within the areal extent of the Nacatoch Aquifer will be allocated to the Nacatoch Aquifer, with the exception of a small area in Bowie, Morris, and Red River Counties where portions of the Wilcox Formation overlie the Nacatoch Aquifer. Based on well completions in this overlap area (TWDB groundwater database), it was estimated that 40 percent of the rural domestic use for the overlap area comes from the Nacatoch Aquifer.

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.

Pumping that was allocated to "OTHER AQUIFER" in the TWDB pumpage geodatabase and that fell within the areal extent of the Nacatoch Aquifer was reviewed to determine if it should be included with the Nacatoch Aquifer pumping. Based on water user information and well locations, it was determined that irrigation and manufacturing pumping in Bowie County and power generation pumping in Red River County should be included with the Nacatoch Aquifer pumping. Irrigation well locations in Bowie County indicate that most irrigation occurs in the area underlain by the Quaternary alluvium and terrace deposits associated with the Red River. Since these deposits overlie the Nacatoch Aquifer throughout most of their extent in Bowie County, it was assumed that 80 percent (based on areas) of the "OTHER AQUIFER" irrigation pumping in Bowie County would be included in model pumping. Well locations for "OTHER AQUIFER" manufacturing pumping in Bowie County and power generation pumping in Red River County indicate that the water source is the Nacatoch Aquifer. This agrees with Ashworth (1988) who includes power generation pumping in Red River County in the table of Nacatoch Aquifer pumping.

Pumping prior to the historical period (1980-1997) was estimated based on pumping listed in Ashworth (1988) and extrapolation of historical period pumping. Ashworth (1988) provides estimates of public supply and industrial pumping in Bowie, Hunt, Hopkins, Navarro, Red River, and Titus Counties for 1963 through 1982. Public supply pumping in Ashworth (1988) was assumed to be equivalent to municipal pumping in the TWDB pumpage geodatabase. Ashworth (1988) indicates that the industrial pumping in Red River County is related to operations of a power generation site. The industrial pumping in Navarro County was assumed to be equivalent to manufacturing pumping in the TWDB pumpage geodatabase.

Livestock pumping prior to 1980 was extrapolated back to 1963 for each county that had livestock pumping in 1980 based on the TWDB pumpage geodatabase. Irrigation pumping prior to 1980 was extrapolated back to 1963 for Bowie County. Bowie County was the only county that had irrigation pumping in 1980, based on the TWDB pumpage geodatabase. Extrapolations were based on linear regression of TWDB pumping rates for 1980 through 1984. Pumping prior to 1963 was estimated and adjusted based on model calibration.

Pumping for the Nacatoch Aquifer is summed by county and summed over the entire model area Table 4.7.4. Counties with less than 10 acre-feet of total pumping between 1980 and 1987 were not included. Table 4.7.4 lists total groundwater withdrawals by county for the years

1963, 1965, 1970, 1975, 1980, 1985, 1990, 1995 and 1997; while Table 4.7.5 lists groundwater withdrawals from the Nacatoch Aquifer by category for the Texas counties. Mining was not listed because total pumping was less than one acre-foot.

Figure 4.7.11 provides a bar chart summary of pumping totals for the Nacatoch Aquifer in the model region in Texas and Arkansas by year from 1963 through 1997. Pumping was relatively stable from 1963 through 1976 at about 3,500 to 4,000 acre-feet/year. Between 1976 and 1986, pumping increased to over 6,700 acre-feet/year. Following 1986, pumping decreased rapidly until 1991, after which pumping continued to decrease at a slower rate. In 1997, estimated pumping was about 2,730 acre-feet/year.

Figure 4.7.12 shows a bar chart of pumping by use category for the Nacatoch Aquifer in the model region in Texas and total pumping for Arkansas. Pumping in Little River and Miller Counties in Arkansas is not available by use category. From this chart, it can be seen that only a small fraction of the total pumping is from the Arkansas counties and that the Arkansas pumping was highest in the earlier years and generally declined over time. Very little Arkansas pumping occurred after 1984.

Pumping in the Texas counties was predominately for irrigation, municipal, rural domestic, and livestock. Most of the increase in total pumping between 1976 and 1986 is the result of irrigation pumping which reached a maximum of 3,301 acre-feet/year in 1986. Municipal pumping increased slightly from 1963 to 1970 to a maximum value of 2,314 acre-feet/year, and then decreased throughout the remainder of the time to a value of 1,133 acre-feet/year in 1997. Rural domestic pumping increased slightly until 1989 when it reached a maximum of 1,041 acre-feet/year. From 1989 to 1997, rural domestic pumping was relatively stable. Livestock pumping remained below 1,000 acre-feet/year, with a maximum value of 860 acre-feet/year. Power generation pumping averaged just over 400 acre-feet/year until 1980 when it dropped to less than 200 acre-feet/year. Power generation pumping ended in 1995. Mining and manufacturing pumping were negligible throughout the time period.

Figures 4.7.13 through 4.7.18 show pumping for the Texas counties by category. Most of the pumping came from five counties: Bowie, Delta, Hopkins, Hunt, and Red River. Total pumping in the other seven counties did not exceed 100 acre-feet/year at any time. Almost all of the irrigation pumping for the Nacatoch Aquifer came from Bowie County.

Table 4.7.4 Estimated rate of total groundwater withdrawal (acre-feet/year) from the Nacatoch Aquifer by county

Year	1963	1965	1970	1975	1980	1985	1990	1995	1997
Texas Counties									
Bowie	396	483	708	530	1372	2709	2353	643	581
Delta	466	406	563	490	480	497	540	273	268
Franklin	1	1	1	1	1	1	1	1	1
Henderson	5	5	6	8	9	11	13	15	14
Hopkins	189	243	308	360	367	260	303	411	361
Hunt	1086	963	1296	1172	1041	1317	1125	1045	909
Kaufman	77	77	78	80	82	61	66	75	59
Lamar	0	0	0	0	2	2	1	1	1
Navarro	25	24	28	29	15	15	15	14	11
Rains	3	3	3	4	4	2	4	5	5
Red River	922	924	954	996	750	556	632	549	507
Titus	0	0	0	0	68	80	0	0	1
Texas Total	**3170**	**3131**	**3945**	**3670**	**4192**	**5511**	**5054**	**3031**	**2716**
Arkansas Counties									
Little River	300	224	34	45	69	0	0	0	0
Miller	211	160	34	45	69	0	0	0	13
Arkansas Total	**511**	**384**	**67**	**90**	**139**	**0**	**0**	**0**	**13**
Texas and	**3681**	**3516**	**4013**	**3759**	**4331**	**5511**	**5054**	**3031**	**2730**

All withdrawals rounded to the nearest acre-foot per year (acre-feet/year)

Table 4.7.5 Rate of groundwater withdrawal (acre-feet/year) by category from the Nacatoch Aquifer for Texas counties

Type/County	Year								
Irrigation	1963	1965	1970	1975	1980	1985	1990	1995	1997
Bowie	0	0	0	0	927	2230	1688	55	40
Kaufman					0	0	8	11	1
Total Irrigation	0	0	0	0	927	2230	1696	66	41
Manufacturing	1963	1965	1970	1975	1980	1985	1990	1995	1997
Bowie					3	3			
Navarro	2	2	2	2	0				
Total	2	2	2	2	3	3	0	0	0
Municipal	1963	1965	1970	1975	1980	1985	1990	1995	1997
Bowie	175	258	410	160					
Delta	440	374	519	433	409	427	465	234	234
Hopkins	46	88	124	143	117	87	82	140	104
Hunt	880	750	1040	867	687	892	750	654	556
Navarro	18	16	18	16					
Red River	151	163	203	234	208	213	239	239	239
Titus					67	79			
Total Municipal	1710	1650	2314	1852	1488	1698	1536	1267	1133
Power	1963	1965	1970	1975	1980	1985	1990	1995	1997
Red River	411	407	413	415	187	2	127	29	
Total Power	411	407	413	415	187	2	127	29	0
Rural Domestic	1963	1965	1970	1975	1980	1985	1990	1995	1997
Bowie	220	226	240	253	266	285	428	370	351
Delta	21	20	18	18	18	14	14	9	10
Franklin	1	1	1	1	1	1	1	1	1

Table 4.7.5 Rate of groundwater withdrawal (acre-feet/year) by category from the Nacatoch Aquifer for Texas counties

Henderson	5	5	6	8	9	11	13	15	14
Hopkins	57	58	62	68	75	67	78	105	102
Hunt	205	214	234	252	270	328	298	315	292
Kaufman	20	20	21	23	25	11	10	16	17
Lamar					2	2	1	1	1
Navarro	6	6	5	6	6	5	6	7	5
Rains	3	3	3	4	4	2	4	5	5
Red River	227	223	212	226	239	213	154	143	152
Titus	0	0	0	0	1	1	0	0	1
Total Rural	765	776	804	860	918	939	1008	987	951
Livestock	1963	1965	1970	1975	1980	1985	1990	1995	1997
Bowie	0	0	59	117	176	191	236	218	190
Delta	6	12	26	39	53	56	61	30	23
Hopkins	86	96	123	149	175	106	143	166	155
Hunt	0	0	22	53	84	98	77	76	61
Kaufman	57	57	57	57	57	50	48	48	41
Navarro	0	1	3	6	8	10	9	7	6
Red River	133	131	126	121	116	128	112	137	116
Total Livestock	282	297	414	542	669	639	686	682	592

All withdrawals rounded to the nearest acre-foot per year (acre-feet/year)

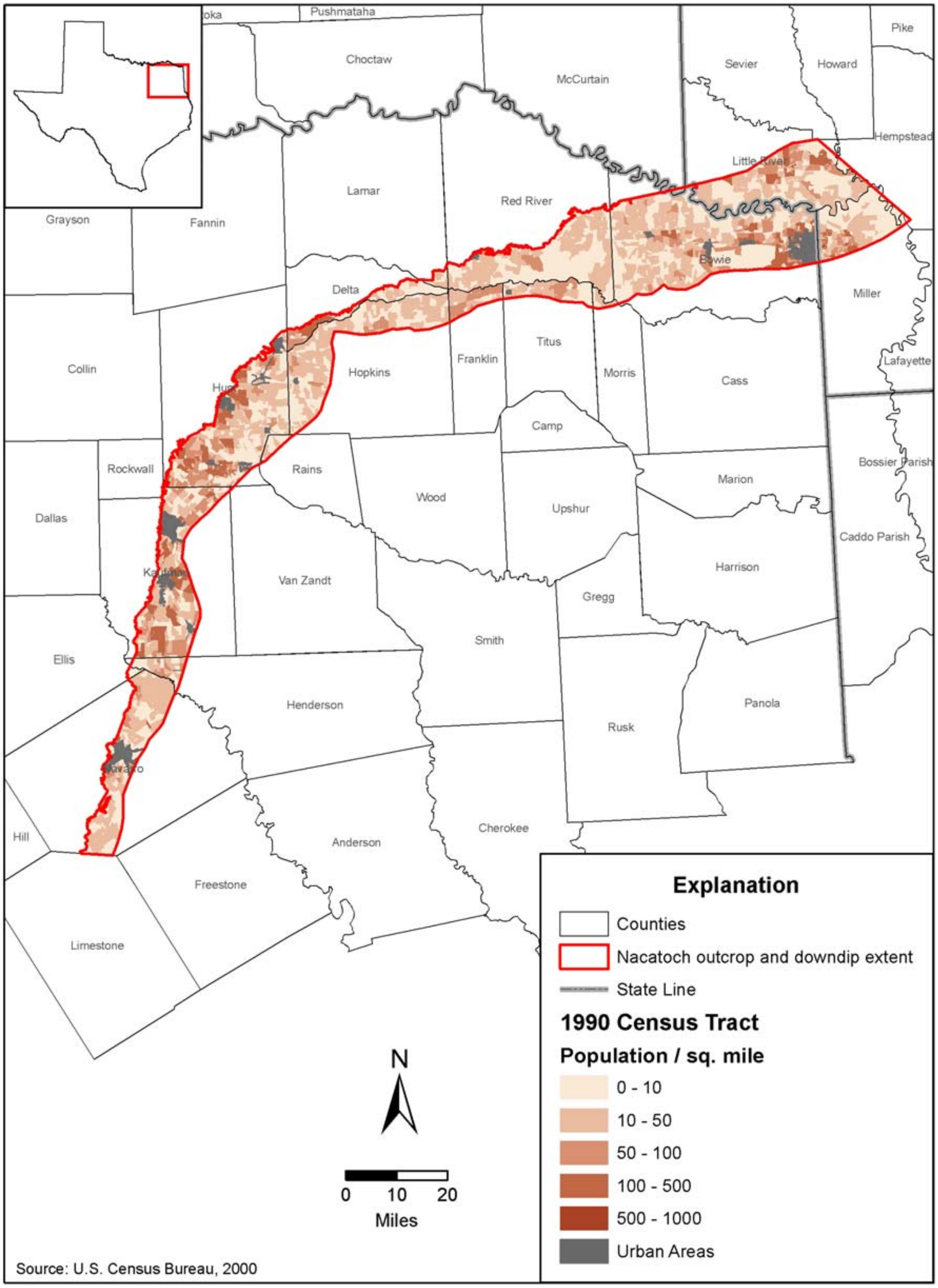


Figure 4.7.10 U.S Census Population Data for the Model Area

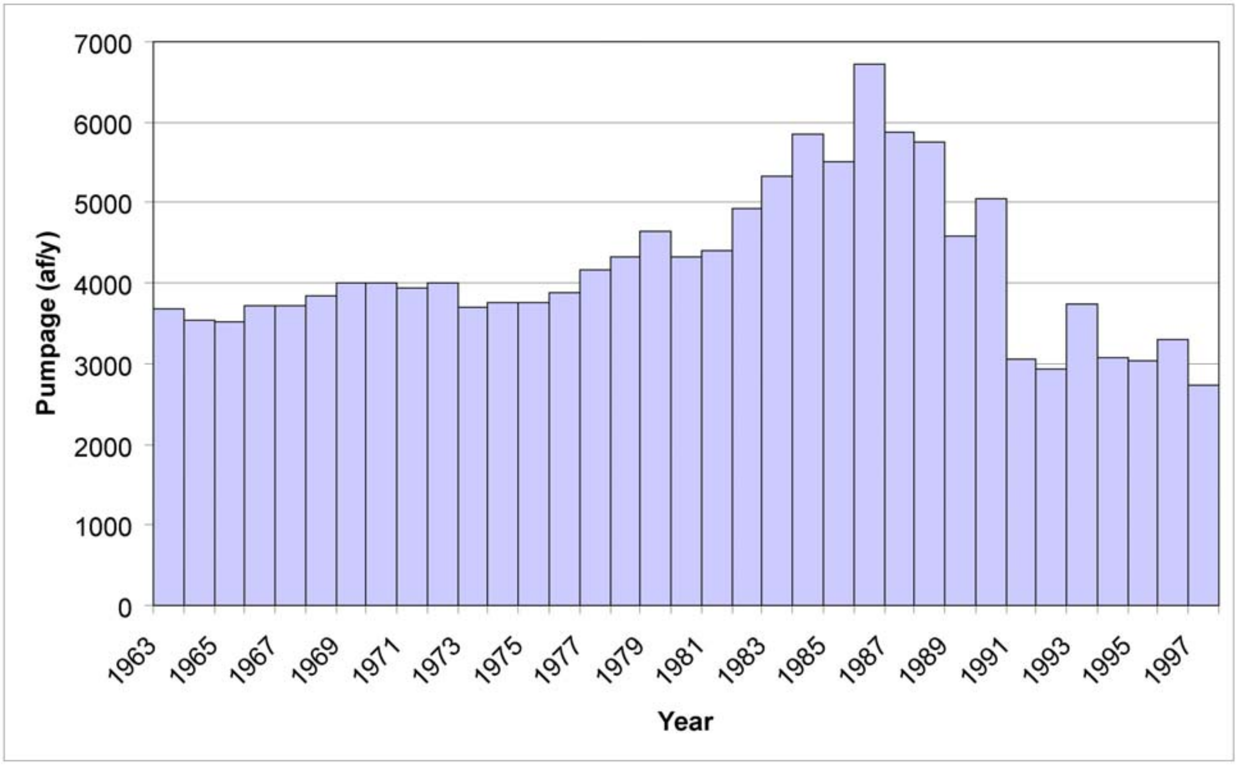


Figure 4.7.11 Total groundwater withdrawals for the Nacatoch Aquifer for 1963 through 1997 (Includes Texas and Arkansas pumping)

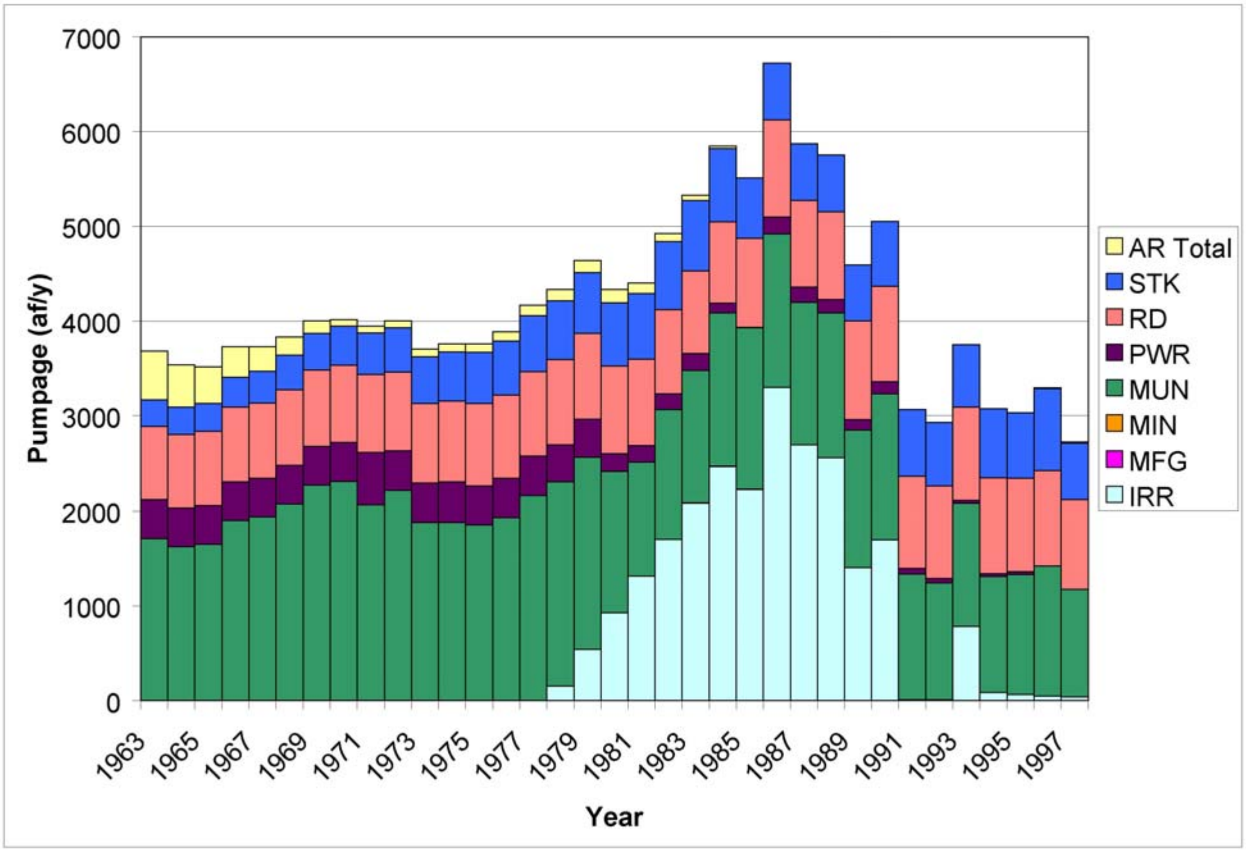


Figure 4.7.12 Total groundwater withdrawals for the Nacatoch Aquifer in Texas by category and total groundwater withdrawals for the Nacatoch Aquifer in Arkansas

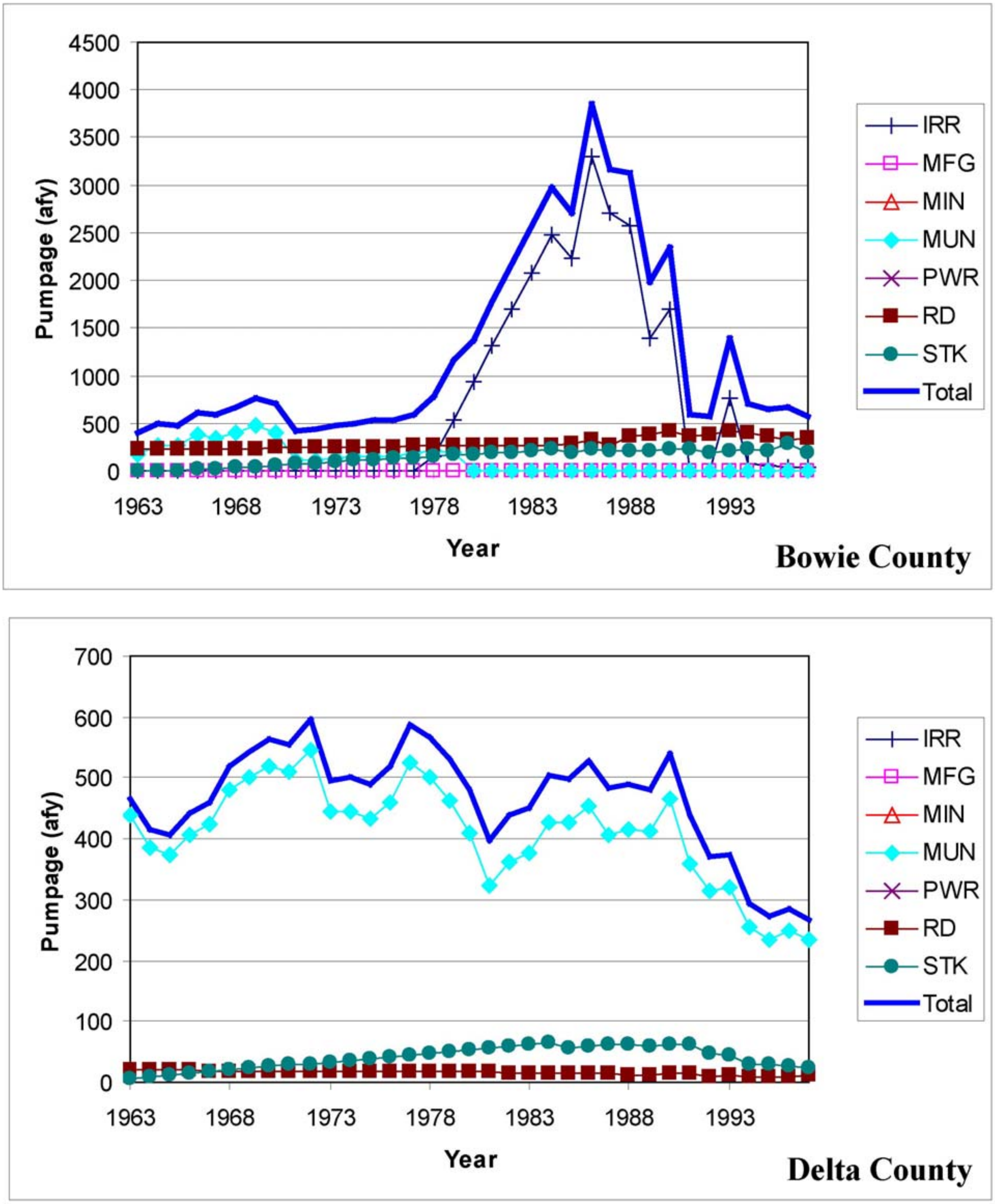
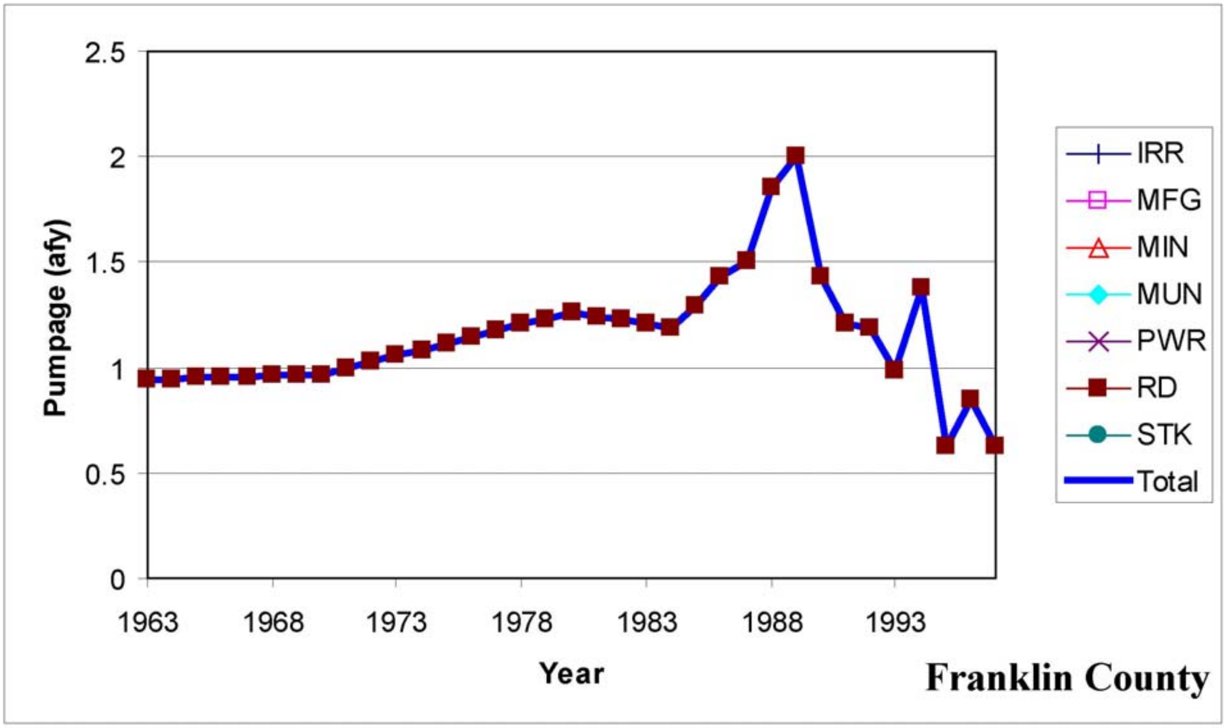


Figure 4.7.13 Total groundwater withdrawals for Bowie (top) and Delta (bottom) counties by category for 1963 through 1997



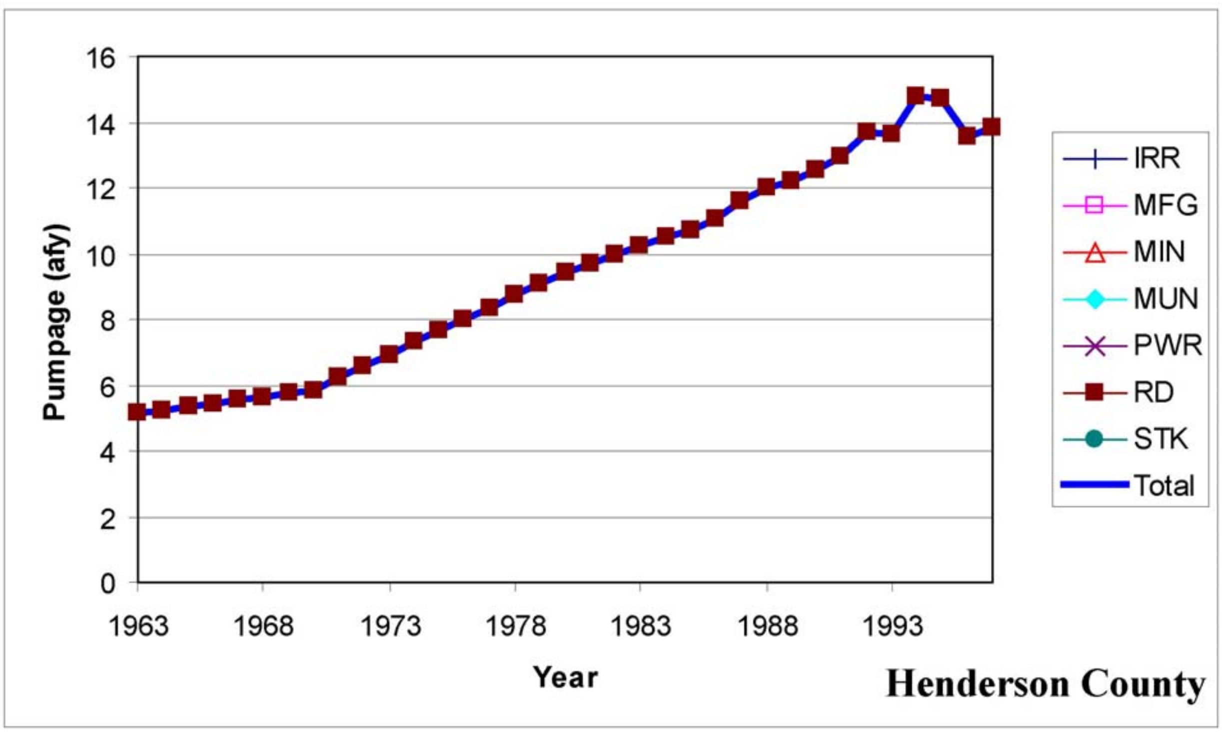


Figure 4.7.14 Total groundwater withdrawals for Franklin (top) and Henderson (bottom) counties by category for 1963 through 1997

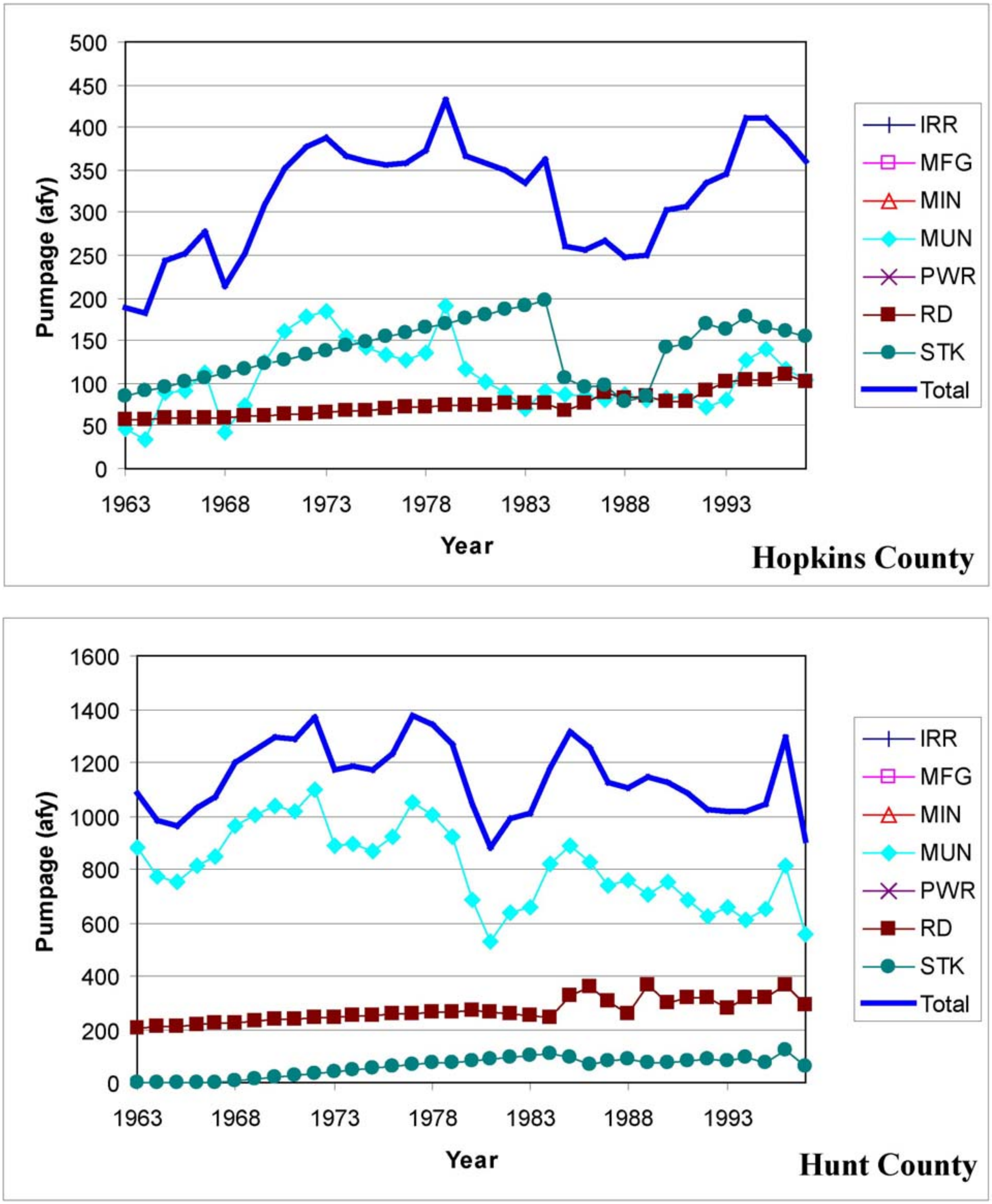
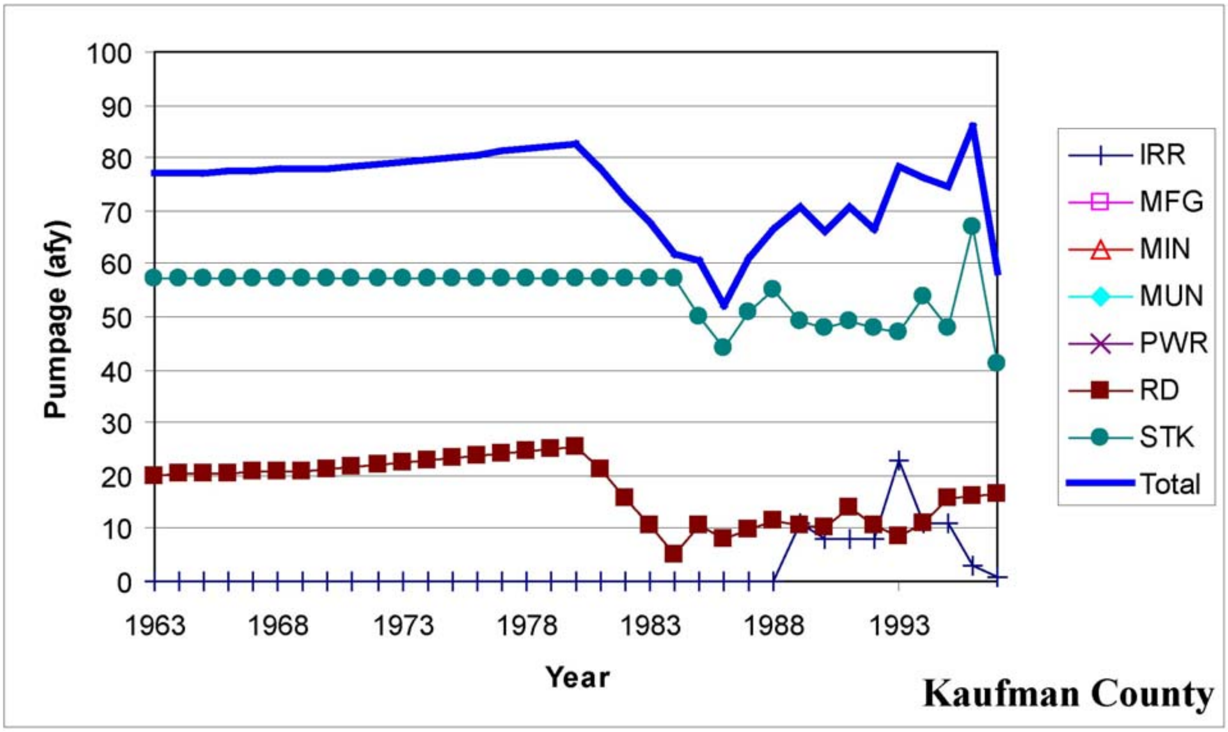


Figure 4.7.15 Total groundwater withdrawals for Hopkins (top) and Hunt (bottom) counties by category for 1963 through 1997



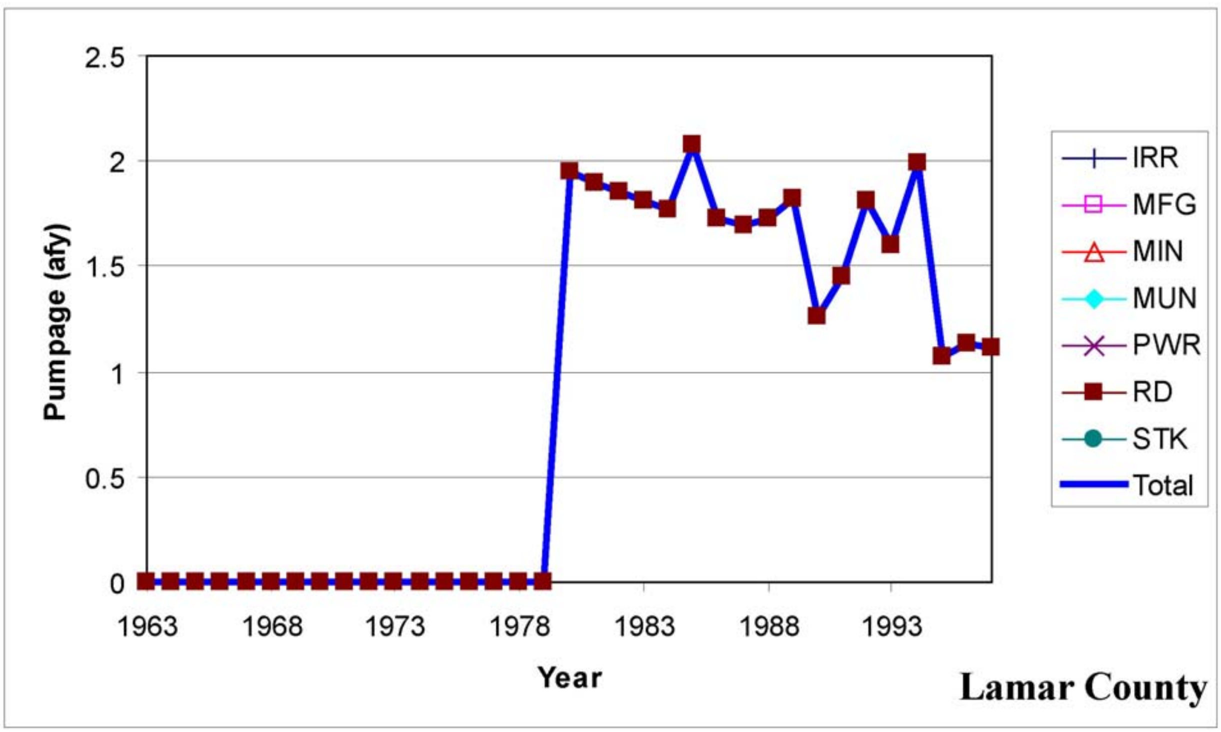
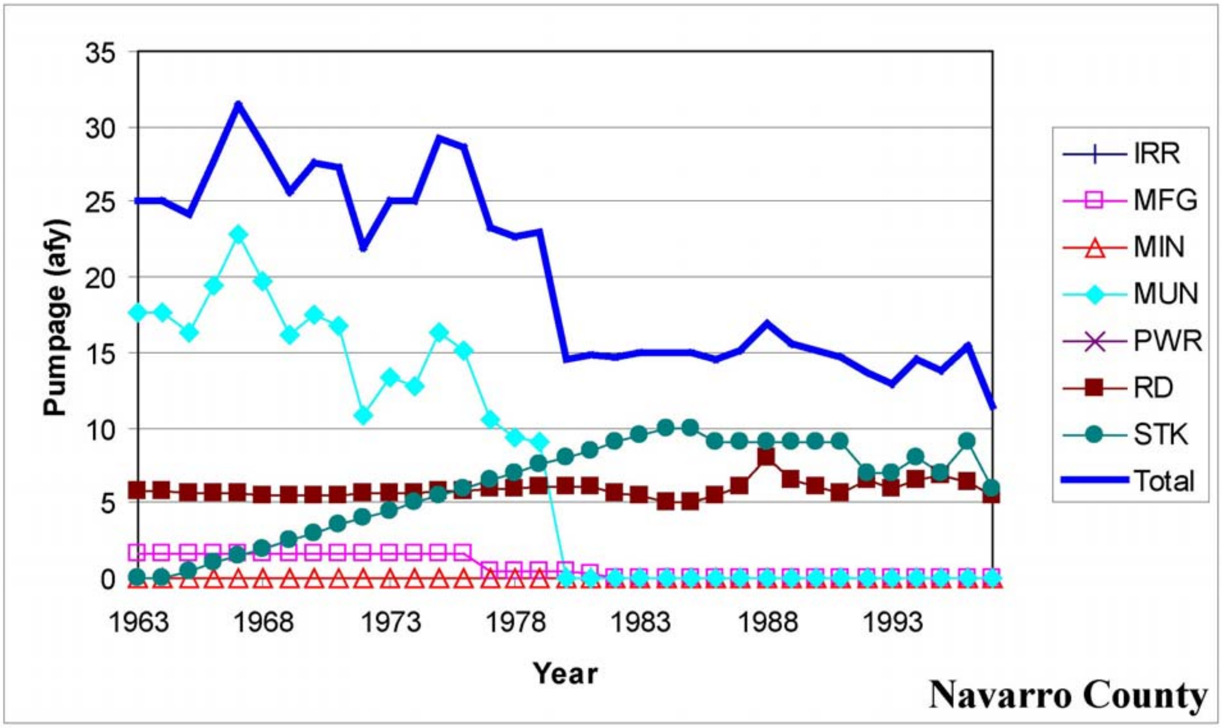


Figure 4.7.16 Total groundwater withdrawals for Kaufman (top) and Lamar (bottom) counties by category for 1963 through 1997



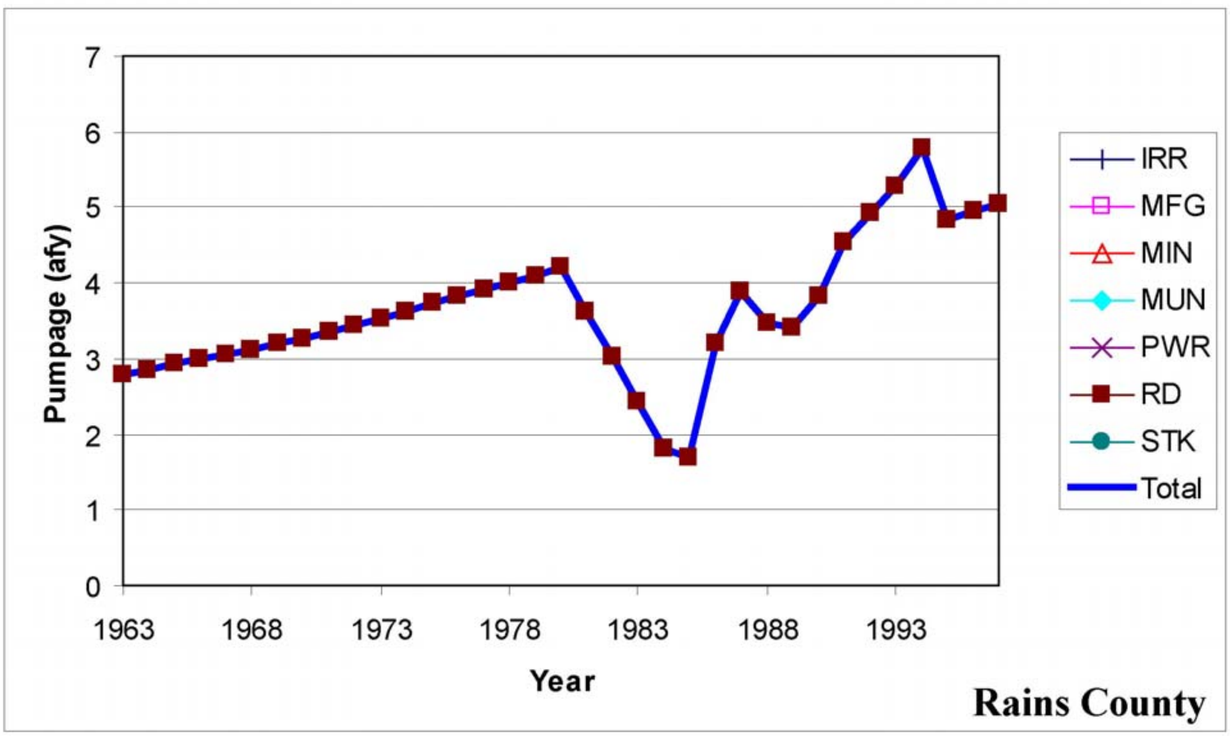
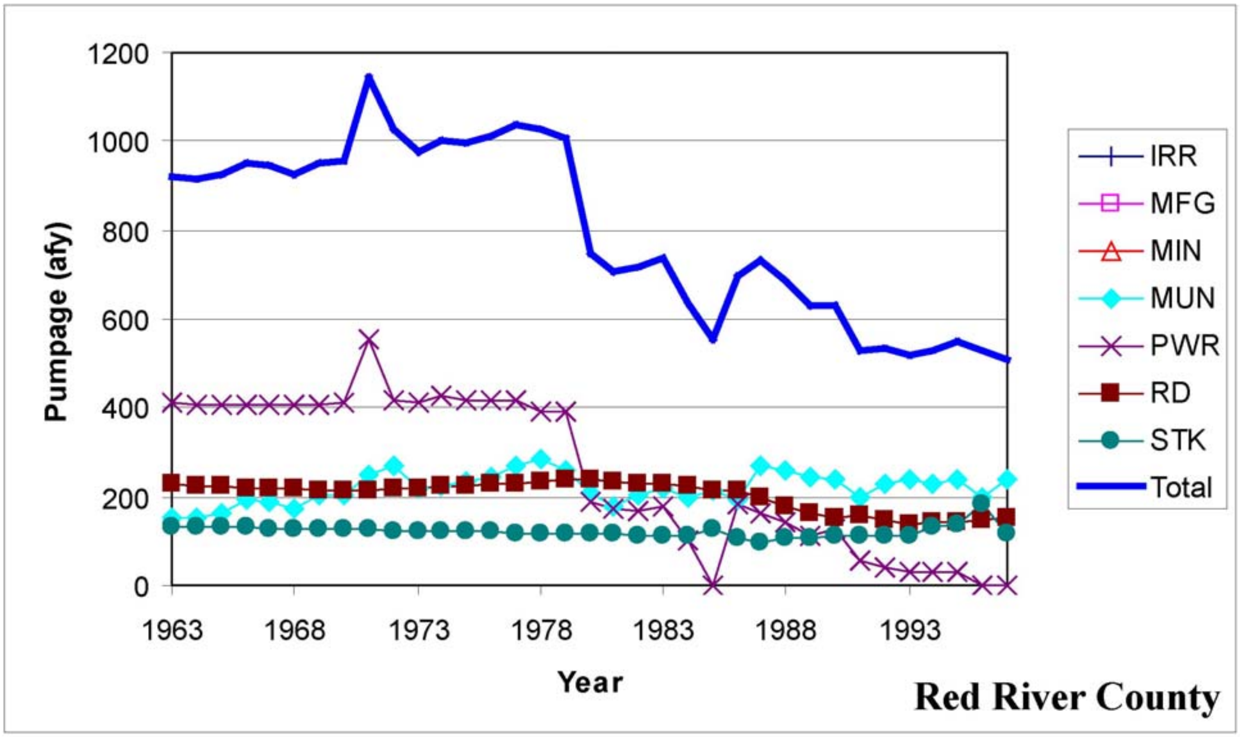


Figure 4.7.17 Total groundwater withdrawals for Navarro (top) and Rains (bottom) counties by category for 1963 through 1997



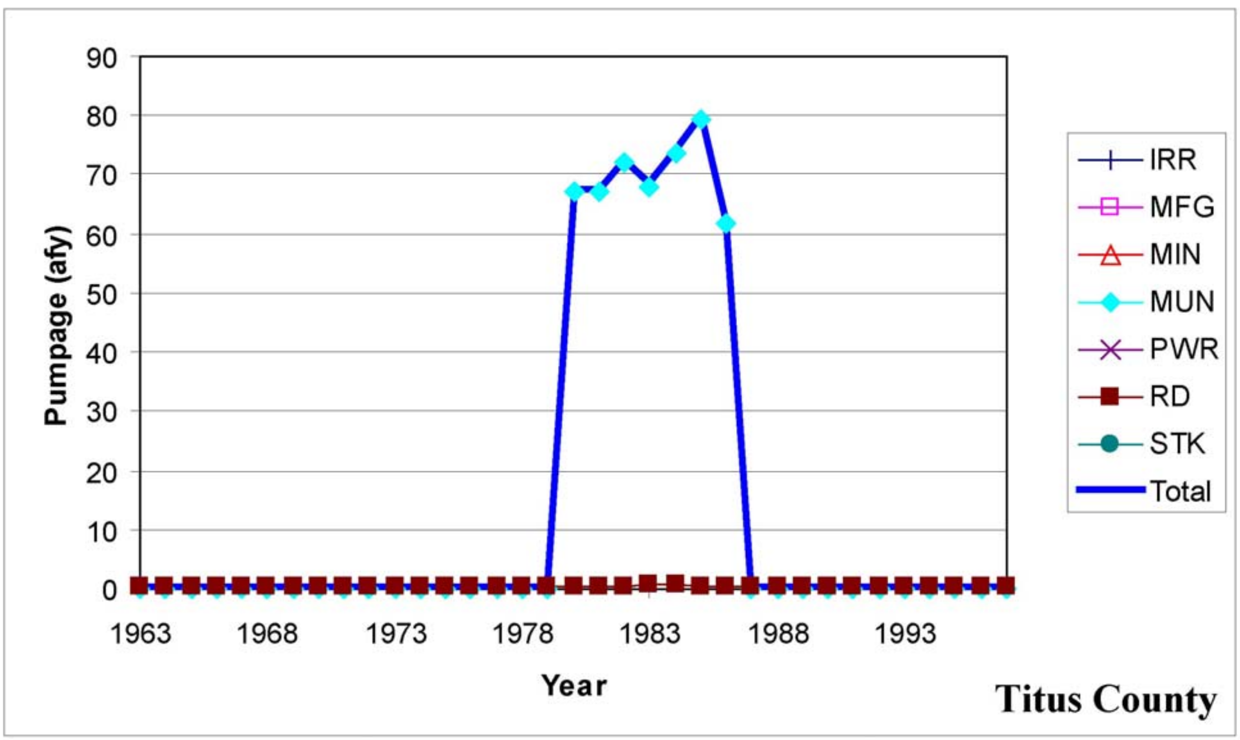


Figure 4.7.18 Total groundwater withdrawals for Red River (top) and Titus (bottom) counties by category for 1963 through 1997

4.8 Water Quality

The quality of groundwater in the model area was evaluated to help potential users of the model assess the quality of available groundwater. Water-quality data was compiled from the TWDB groundwater database. One of the main indicators of overall water quality is total dissolved solids (TDS). TDS is a measure of the salinity of groundwater, and is the sum of the concentrations of all of the dissolved ions, mainly sodium, calcium, magnesium, potassium, chloride, sulfate, and bicarbonate. The TWDB has defined aquifer water quality in terms of dissolved-solids concentrations expressed in milligrams per liter (mg/L) and has classified water into four broad categories:

- fresh (less than 1,000 mg/L);
- slightly saline (1,000 - 3,000 mg/L);
- moderately saline (3,000 - 10,000 mg/L); and
- very saline (10,000 - 35,000 mg/L).

A total of 241 of the most recent water-sample data points from wells completed in the Nacatoch Aquifer or more generally in the Navarro Group were used for the analysis of groundwater quality for these aquifer classifications. A few of these wells are reportedly completed in both the Navarro and Taylor groups. Figure 4.8.1 presents the TDS distribution for these wells. The groundwater is generally fresh near the outcrop, becoming slightly saline in downdip portions of the model area. There are no wells in the area reporting “very saline” water quality.

Figure 4.8.2 illustrates the hydrochemical facies of groundwater from wells completed in the Nacatoch Aquifer and the Navarro and/or Taylor Groups. Water from these wells is predominantly a sodium-bicarbonate water, with a smaller number of sodium-chloride and sodium-mixed anion types.

Several other parameters may be of interest from the standpoint of water quality for drinking-water supplies and irrigation. A summary of the available data for these parameters for wells completed in the Nacatoch Aquifer and Navarro-Taylor is included in Table 4.8.1 and Table 4.8.2, respectively.

Sodium adsorption ratio (SAR) is a measure of sodium hazard relating to irrigation water quality, and has been classified from low to very high in the United States Department of Agriculture Agricultural Handbook No. 60 (U.S. Salinity Laboratory, 1954). Figure 4.8.3 illustrates the distribution of sodium hazard in samples from wells completed in the Nacatoch Aquifer and Navarro and Taylor Groups.

Groundwater quality data was also compiled for wells completed in alluvial deposits in the model area. The most recent data available for 74 wells was used in this analysis. Figure 4.8.4 presents the TDS distribution for these alluvial wells. The water from these wells is generally fresh as can be seen in the figure. Only one well reported a TDS value over 3,000 mg/L at 9,949 mg/L in western Henderson County.

A summary of other analytes available for the alluvial well samples with drinking water supply and irrigation screening levels is given in Table 4.8.3.

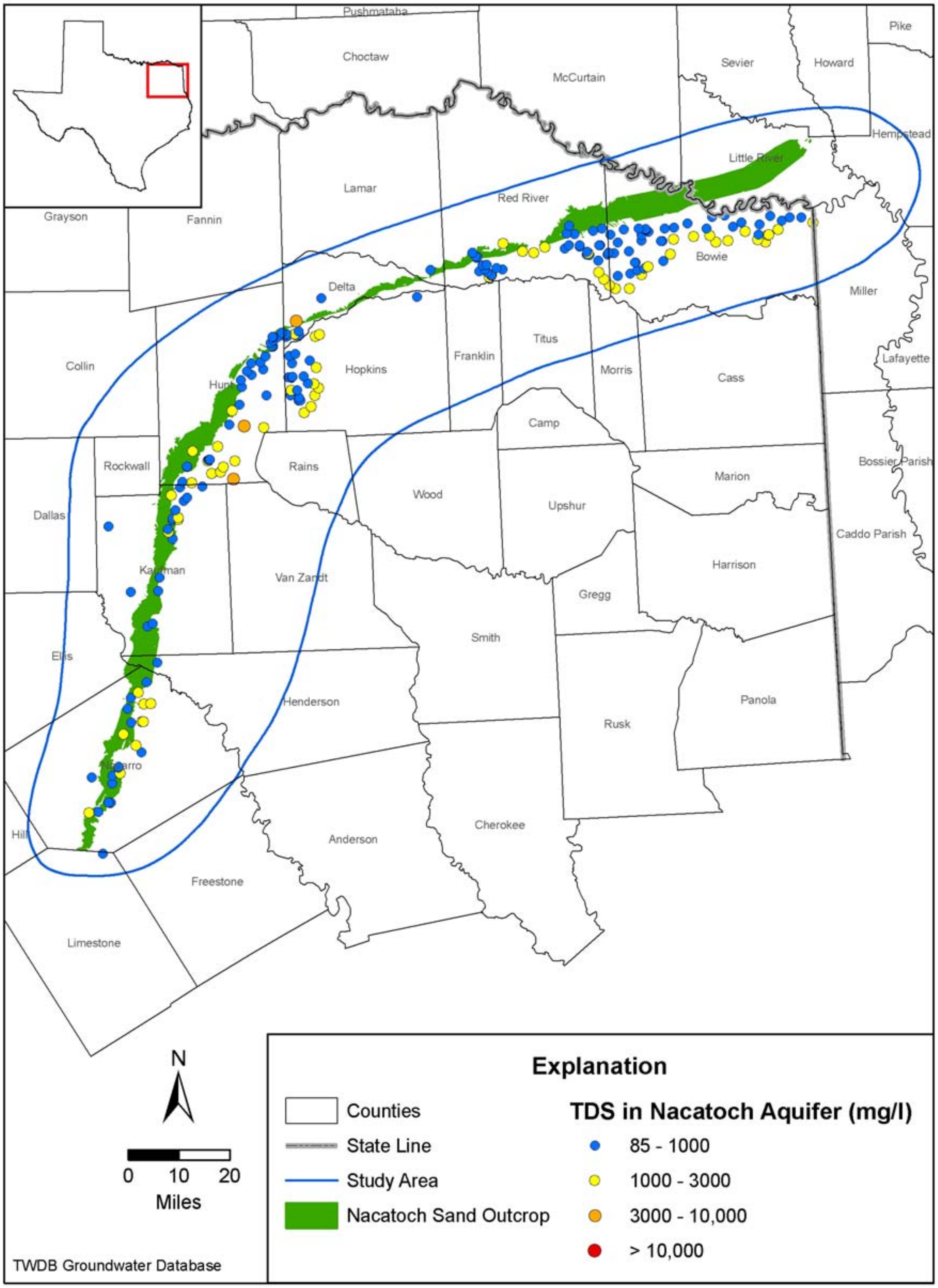


Figure 4.8.1 Map of Nacatoch Aquifer total dissolved solids

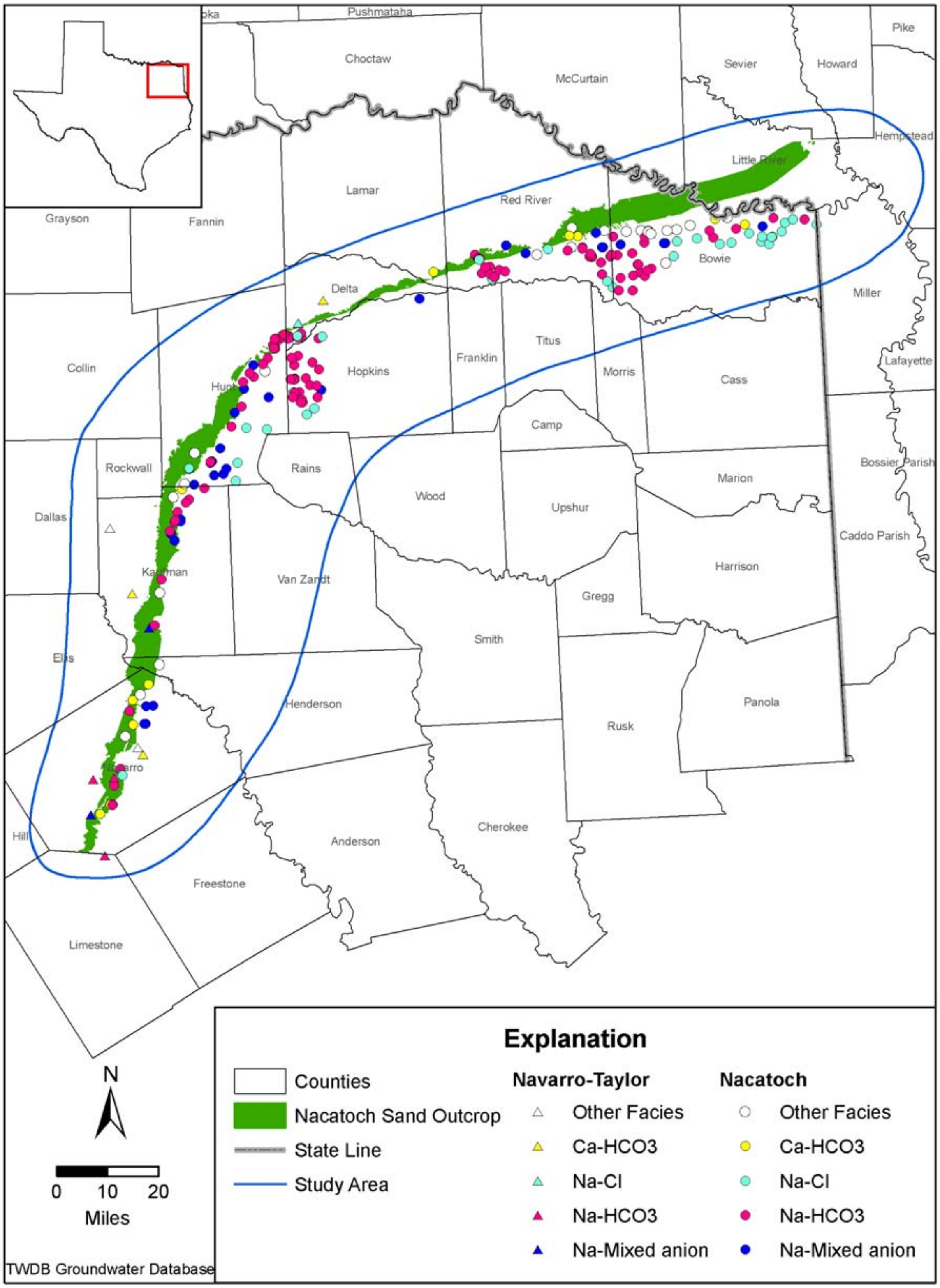


Figure 4.8.2 Map of Nacatoch Aquifer hydrochemical facies

Table 4.8.1 Summary of Nacatoch Aquifer water quality

Constituent	Type of Standard*	Screening Level	Units	Number of Results	Number of Results Exceeding Screening Level	Percent of Results Exceeding Screening Level	Result < Reporting Limit > MCL
Fluoride	Primary MCL[1]	4	mg/L	200	11	6%	0
Nitrate	Primary MCL[1]	10	mg/L as N	207	14	7%	0
PH	Secondary MCL[1] (lower bound)	7		211	10	5%	0
Chloride	Secondary MCL[1]	300	mg/L	215	50	23%	0
Fluoride	Secondary MCL[1]	2	mg/L	200	39	20%	0
Sulfate	Secondary MCL[1]	300	mg/L	215	20	9%	0
TDS	Secondary MCL[1]	1000	mg/L	208	62	30%	0
SAR	Irrig. Sodium Hazard - Medium[2]	10		209	150	72%	0
SAR	Irrig. Sodium Hazard - High[2]	18		209	140	67%	0
SAR	Irrig. Sodium Hazard - Very High[2]	26		209	131	63%	0
Specific Conductance	Irrig. Salinity Hazard - High[2]	750	µmhos/cm	203	175	86%	0
Specific Conductance	Irrig. Salinity Hazard - Very High[2]	2250	µmhos/cm	203	39	19%	0
Chloride	Irrig. Hazard[3]	1000	mg/L	215	4	2%	0

1. 30 TAC Chapter 290 Subchapter F

2. United States Salinity Laboratory (1954)

3. Tanji (1990)

Table 4.8.2 Summary of Navarro-Taylor water quality

Constituent	Type of Standard*	Screening Level	Units	Number of Results	Number of Results Exceeding Screening Level	Percent of Results Exceeding Screening Level	Result < Reporting Limit > MCL
Fluoride	Primary MCL[1]	4	mg/L	11	0	0%	0
Nitrate	Primary MCL[1]	10	mg/L as N	13	3	23%	0
pH	Secondary MCL[1] (lower bound)	7		25	3	12%	0
Chloride	Secondary MCL[1]	300	mg/L	25	1	4%	0
Fluoride	Secondary MCL[1]	2	mg/L	11	1	9%	0
Sulfate	Secondary MCL[1]	300	mg/L	25	3	12%	0
TDS	Secondary MCL[1]	1000	mg/L	12	3	25%	0
SAR	Irrig. Sodium Hazard - Medium[2]	10		12	2	17%	0
SAR	Irrig. Sodium Hazard - High[2]	18		12	2	17%	0
SAR	Irrig. Sodium Hazard - Very High[2]	26		12	2	17%	0
Specific	Irrig. Salinity Hazard - High[2]	750	µmhos/cm	25	12	48%	0
Specific	Irrig. Salinity Hazard - Very High[2]	2250	µmhos/cm	25	3	12%	0
Chloride	Irrig. Hazard[3]	1000	mg/L	25	1	4%	0

1. 30 TAC Chapter 290 Subchapter F
2. United States Salinity Laboratory (1954)
3. Tanji (1990)

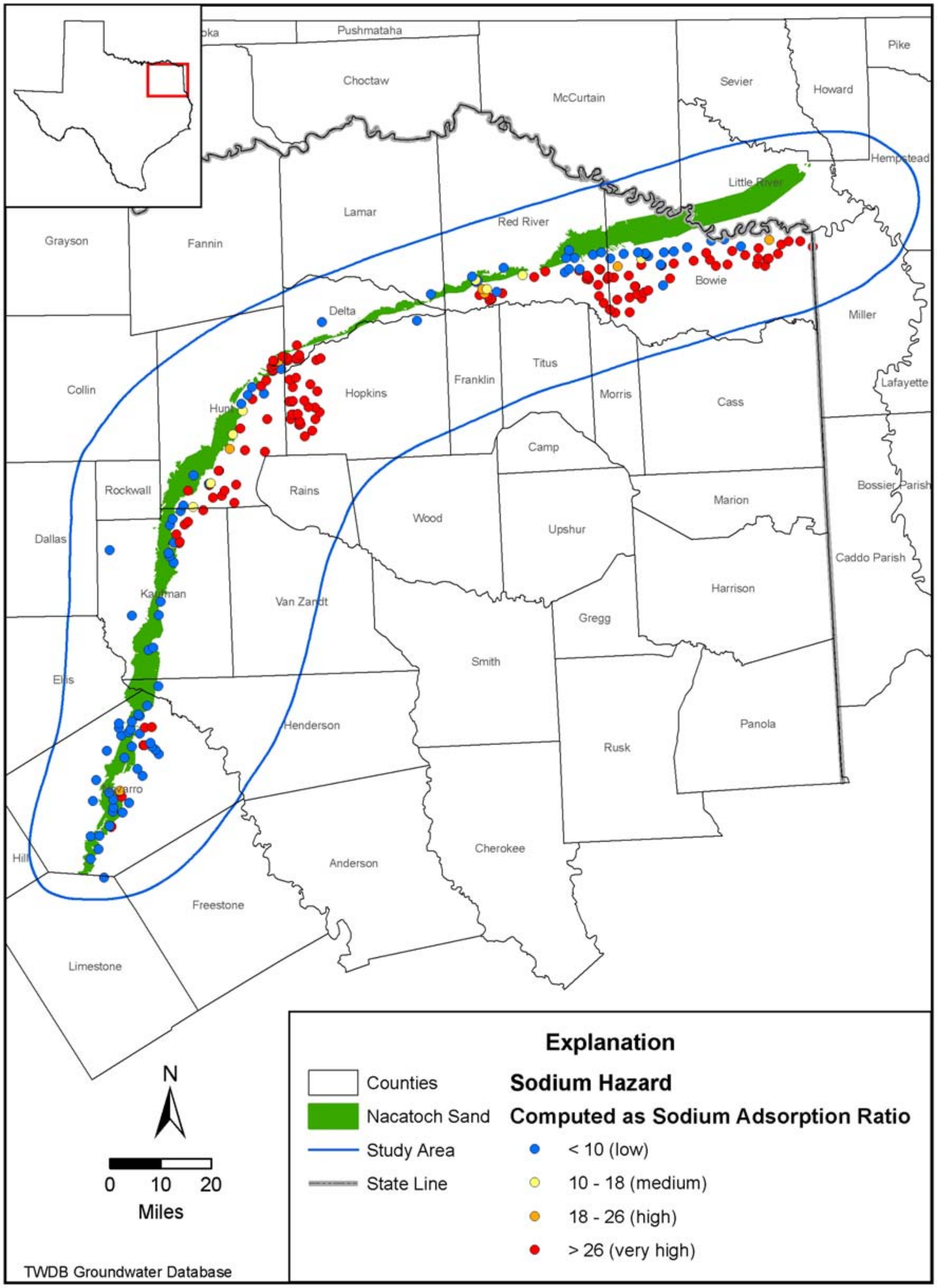


Figure 4.8.3 Map of Nacatoch Aquifer sodium adsorption ratio (SAR)

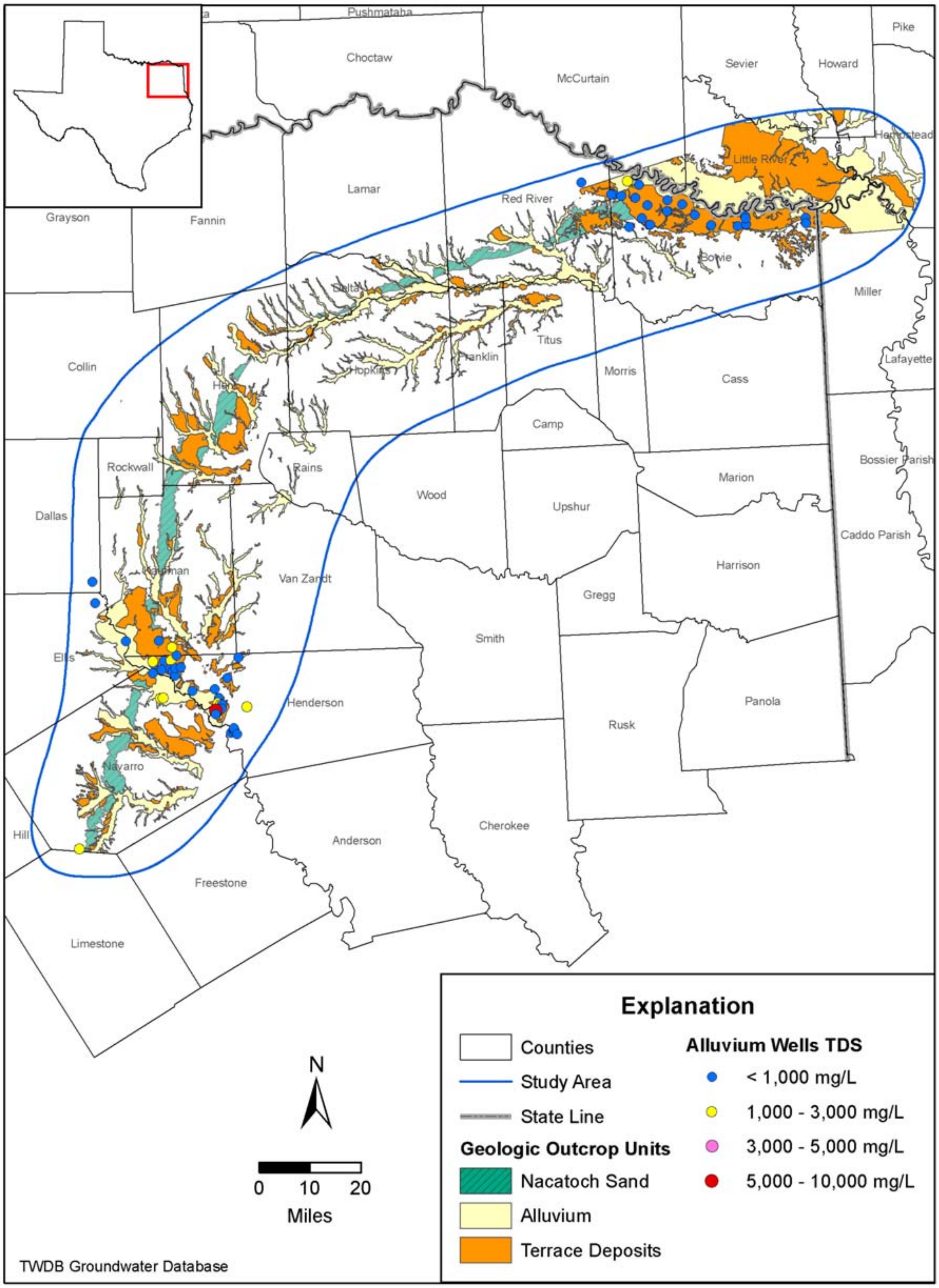


Figure 4.8.4 Map of alluvium total dissolved solids

Table 4.8.3 Summary of Alluvium water quality

Constituent	Type of Standard*	Screening Level	Units	Number of Results	Number of Results Exceeding Screening Level	Percent of Results Exceeding Screening Level	Result < Reporting Limit > MCL
Fluoride	Primary MCL[1]	4	mg/L	39	0	0.0%	0
Nitrate	Primary MCL[1]	10	mg/L as N	41	16	39.0%	0
PH	Secondary MCL[1] (lower bound)	7		46	16	34.8%	0
Chloride	Secondary MCL[1]	300	mg/L	74	7	9.5%	0
Fluoride	Secondary MCL[1]	2	mg/L	39	0	0.0%	0
Sulfate	Secondary MCL[1]	300	mg/L	73	8	11.0%	0
TDS	Secondary MCL[1]	1000	mg/L	66	11	16.7%	0
SAR	Irrig. Sodium Hazard - Medium[2]	10		65	1	1.5%	0
SAR	Irrig. Sodium Hazard - High[2]	18		65	1	1.5%	0
SAR	Irrig. Sodium Hazard - Very High[2]	26		65	0	0.0%	0
Specific Conductance	Irrig. Salinity Hazard - High[2]	750	µmhos/cm	47	18	38.3%	0
Specific Conductance	Irrig. Salinity Hazard - Very High[2]	2250	µmhos/cm	47	4	8.5%	0
Chloride	Irrig. Hazard[3]	1000	mg/L	74	1	1.4%	0

1. 30 TAC Chapter 290 Subchapter F

2. United States Salinity Laboratory (1954)

3. Tanji (1990)

5.0 CONCEPTUAL MODEL OF GROUNDWATER FLOW IN THE NACATOCH AQUIFER

5.1 Purpose of a Conceptual Model

A groundwater conceptual model of an aquifer represents the foundation for the numerical model. The conceptual model describes the basic structure of the flow system, the hydrologic processes that are important to the water budget of the system, the occurrence and movement of groundwater, and the inflow and outflow components. The components of the conceptual model include the hydrostratigraphy, hydraulic properties, hydraulic boundaries, recharge and natural discharge, and anthropogenic stresses such as pumping. Anderson and Woessner (1992) describe a conceptual model as a pictorial representation of the groundwater flow system, frequently in the form of a block diagram or a cross section. The conceptual model for the Nacatoch Aquifer system provides a regional perspective of the aquifer system dynamics, which is consistent with the objectives of this model.

Chapters 2 through 4 document and summarize available hydrologic and hydrogeologic data for the study area. While it is evident that there is still much to learn about the aquifer system, the assimilated data provide a foundation for developing a more quantitative understanding of the aquifers and a numerical model that can be improved as more data become available.

5.2 Nacatoch Aquifer Conceptual Model

Figure 5.2.1 shows two different depictions of the conceptual model for the Nacatoch Aquifer. All of the hydrostratigraphic units are connected and under natural conditions, the combination of the driving force caused by higher heads in recharge areas, variable hydraulic properties, and the location of discharge areas determines groundwater movement. Aquifer pumping may also influence water levels and the direction of groundwater flow.

The conceptual model for the Nacatoch Aquifer includes two productive layers, Layer 2 includes solely Nacatoch Aquifer deposits downdip from their outcrop but where exposed, also includes overlying minor alluvial and terrace deposits (Figure 2.3.4). Layer 1 includes the overlying Midway and Upper Navarro Group as well as major alluvium and terrace deposits downdip of the Nacatoch Aquifer outcrop, including Red River deposits.

These two aquifers are generally hydraulically connected and are difficult to differentiate. Underlying these two productive units is the Neylandville and Marlbrook units, which serve as an effective aquitard between the Nacatoch Aquifer and underlying units. Overlying the Nacatoch Aquifer is the Kemp Clay and Midway units, which serve as an effective aquitard between the Nacatoch Aquifer and the overlying productive units of Layer 1.

Recharge occurs mainly in the outcrop areas of Nacatoch Aquifer and on the alluvium overlying the Nacatoch Aquifer. Less recharge is expected to occur in the aquitards lying above and below the Nacatoch Aquifer. Recharge is a complex function of precipitation, soil type, geology, water levels, evapotranspiration and other factors. Precipitation on the outcrop either runs off as surface water, infiltrates and is lost to ET and/or springflow, or infiltrates into the subsurface and recharges the aquifer. Preliminary calculations indicate that recharge is a small percentage of the average precipitation, and like many areas in this region, much of the precipitation is removed via evapotranspiration or runoff, leaving less than 5 percent for shallow and deep recharge.

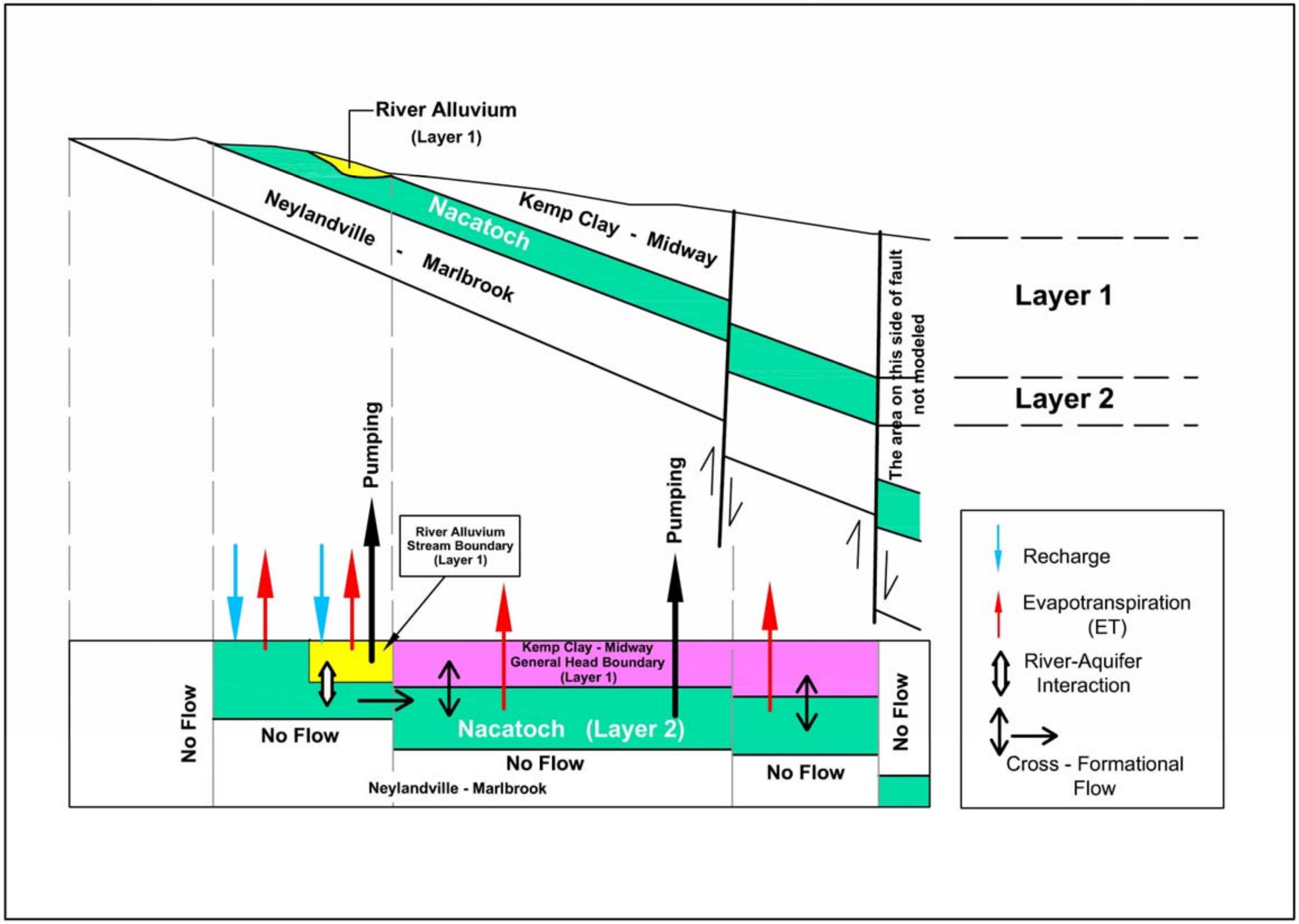


Figure 5.2.1 Conceptual flow model for the Nacatoch Aquifer

Cross-formational flow occurs between all the overlying or underlying layers, but because the amount of flow from the underlying Neylandville-Marlbrook is expected to be very small, it is considered a no-flow boundary. Upward flow to the Midway occurs due to the driving pressure of Nacatoch Aquifer water in the outcrop. Although this flow is relatively small, it is an important factor in properly simulating downward flow through the aquifer under the natural conditions.

Faults greatly affect groundwater flow patterns in the Nacatoch Aquifer. Throughout the study area, downdip portions of the Nacatoch Aquifer are largely separated from the updip flow regime due to extensive faulting and the resulting vertical offset of the more permeable sand units as described in Chapters 2 and 4. These faulted areas will be simulated using no-flow or low flow hydraulic flow barriers based on the offset of the faults. Where available, water quality data indicate a significant increase in dissolved solids in several downdip sections, which confirms the hydrogeologic indications that there is limited flow between the fresher updip sections and the more saline downdip sections.

Nacatoch Aquifer groundwater discharges to local creeks and major streams throughout the area, contributing to the baseflow of the major streams. The interaction of the alluvium and the Nacatoch Aquifer is important, especially near the Red River. This interaction will be handled by simulating the alluvium and the Nacatoch Aquifer in separate model layers.

Historical pumping from the Nacatoch Aquifer has been large enough to cause drawdown in some regions of the aquifer. Incorporating the drawdown and aquifer responses from these areas will be a key part of calibrating the model to improve the predictive capability of the model. All of these components will be appropriately assimilated into the groundwater flow model for the Nacatoch Aquifer.

6.0 MODEL DESIGN

A numerical groundwater flow model uses a computer code to simulate groundwater flow based on data developed for the conceptual model. Design of the numerical model consists of choosing a computer modeling code, developing a model grid (horizontal extent and vertical layers), assigning model parameters and stresses, and determining boundary conditions, types and values in the model grid. Each of these components of model design and their implementation are described in this section.

6.1 Code and Processor

The TWDB selected the MODFLOW-2000 (Harbaugh and others., 2000) to be used for the Nacatoch Aquifer GAM. MODFLOW-2000 is a multi-dimensional, finite-difference, block-centered, saturated groundwater flow code which is supported by a variety of boundary condition packages to handle recharge, streams, drainage, ET, and wells. Some of the benefits of using MODFLOW are (1) MODFLOW is the most widely accepted groundwater flow code in use today, (2) MODFLOW was written and is supported by the United States Geological Survey (USGS) and is public domain, (3) MODFLOW is well documented (Harbaugh and McDonald, 1996; McDonald and Harbaugh, 1988), and (4) there are several graphical user interface programs written for use with MODFLOW.

As mandated by the TWDB, Groundwater Vistas (Rumbaugh and Rumbaugh, 2007) was used to develop the MODFLOW datasets. The version of Groundwater Vistas used was 5.19. The model was developed and executed on x86 compatible (i.e. Pentium class) computers equipped with the Windows XP Professional operating system. The type of computer and memory required to use the model will vary depending on the type of pre- and post-processing software used.

The solver used was a geometric multigrid solver (GMG). The solver convergence criteria were determined by trial and error approach, judged by whether the solver can solve the equations and provide a satisfactory mass balance.

6.2 Model Layers, Grid and Simulation Time Periods

Based on the conceptual hydrostratigraphy detailed in Section 4 and the conceptual flow model described in Section 5, two model layers were used in the Nacatoch Aquifer GAM model. Each of the model layers is described below in the order in which MODFLOW-2000 numbers the model layers, which is from top (nearest to ground surface) to bottom.

Layer 1 represents the Midway, alluvium and terrace deposits, layer 2 represents the Nacatoch Aquifer. The model layers are shown with the model hydrostratigraphy in Figure 5.2.1.

As shown in Figure 6.2.1, a rectangular grid covers the model area. The model area covers the entire extent of the Nacatoch Aquifer in Texas from northeastern Bowie County to southwestern Navarro County. The grid also extends into Arkansas a sufficient distance to limit boundary condition affects near the state border. However, the model does not cover the full extent of the Nacatoch sands in Arkansas because it was not necessary for the Texas model. Generally, the northwest extent of the model was bounded by the outcrop of the Nacatoch sand and the southeastern extent was defined by the Mexia-Talco Fault Zone (Figure 2.3.2).

MODFLOW-2000 requires a rectilinear grid and also requires an equal number of rows for each column. One axis of the model grid is typically aligned parallel to the primary direction of flow. In general, the Nacatoch Aquifer receives recharge from the outcrop area and water moves southeasterly in a downdip direction. Because of the variations in the orientation of the Nacatoch Aquifer, the concept of principal flow direction is less obvious here. In addition, the flow pattern in the Nacatoch Aquifer is often altered by local geological controls, such as mountains in Hunt County and the Red River to the northeast. Therefore, a model grid with a general direction towards east and south is applied here. The model grid origin (the lower left-hand corner of the grid) is located at GAM Coordinates (5963200,19899800).

The grid cells are square with a uniform dimension of 1/4-mile on each side and contain 1/16 square miles or 40 acres. The model has 545 rows and 670 columns, totaling 365,150 grid cells per layer. Only those cells overlaying part of the aquifer that the layer represents have to be active cells. Figure 6.2.2 and Figure 6.2.3 show the active cells (shown as white/clear regions within the model boundary) and spatial distribution of certain boundary conditions in layers 1 and 2, respectively. Layers 1 and 2 contain 31,745 and 43,575 active cells, respectively, totaling 75,320 active cells for the entire model. Other boundary conditions such as GHB and stream package are described in detail in the following sections. The length units of the model are in feet and time units in days.

The model was simulated for a pre-development period and a calibration period (Table 6.2.1). The pre-development period is assumed to be a period where the aquifer is at steady-state. During this period, there was no major pumping stress and therefore, no pumping is included in simulation for this period.

The transient model calibration period was from 1980 through the end of 1997. The initial conditions for the transient calibration period are poorly known. However, it is known that there has been some significant pumping in the City of Commence and the surrounding areas in Hunt County prior to 1980. To account for this, a warm up period (a short transient period from 1978 to 1979) was added to obtain better approximation of the initial heads.

Table 6.2.1. Simulation time period set up

Time period	Number of stress periods	Length of each stress period (years)
Pre-development: steady state (Prior to major pumping)	1	274
Pre-1980: calibration (Focus on City of Commence area)	2	1
1980 – 1997: calibration	18	1

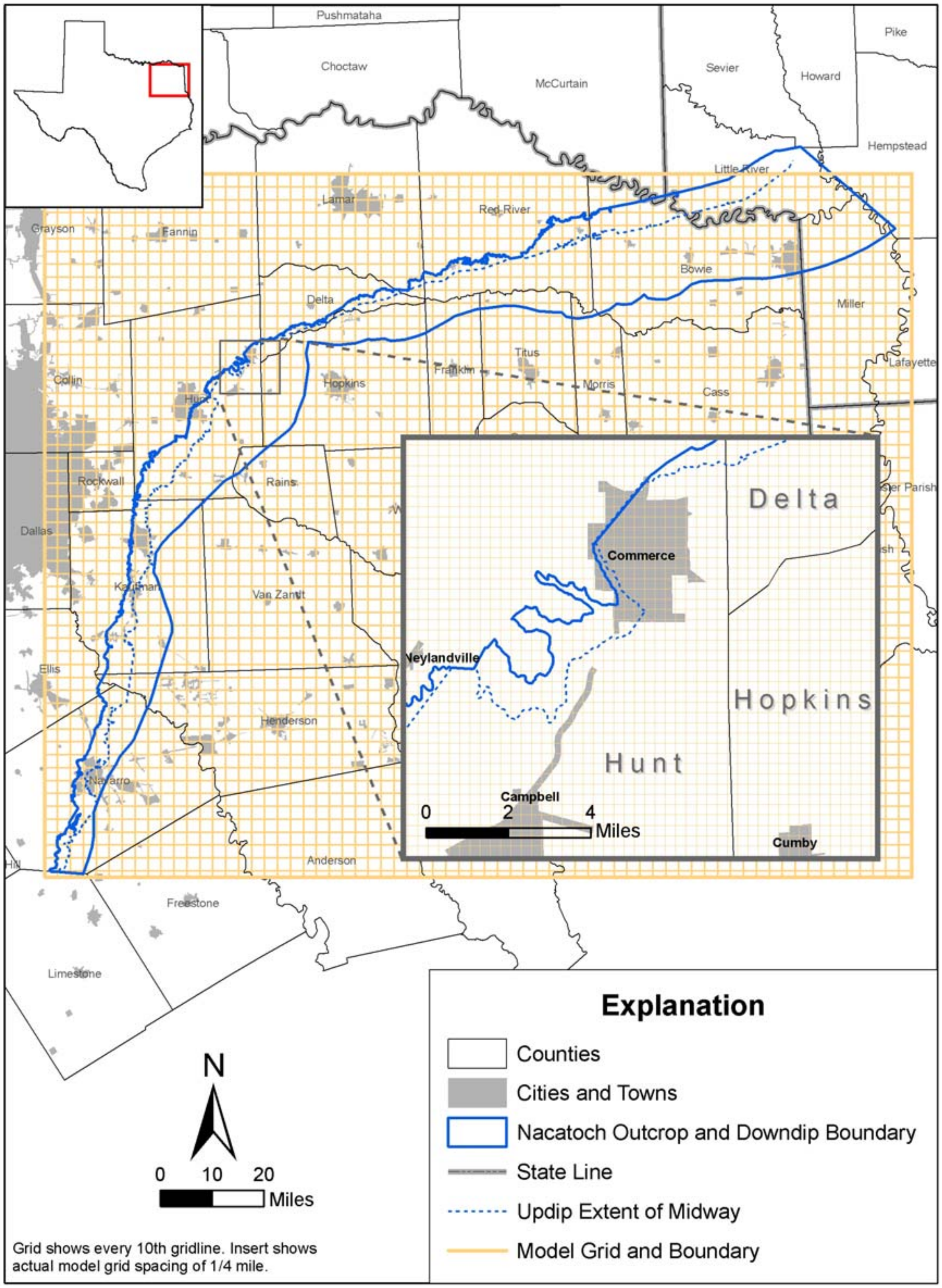


Figure 6.2.1 Model grid

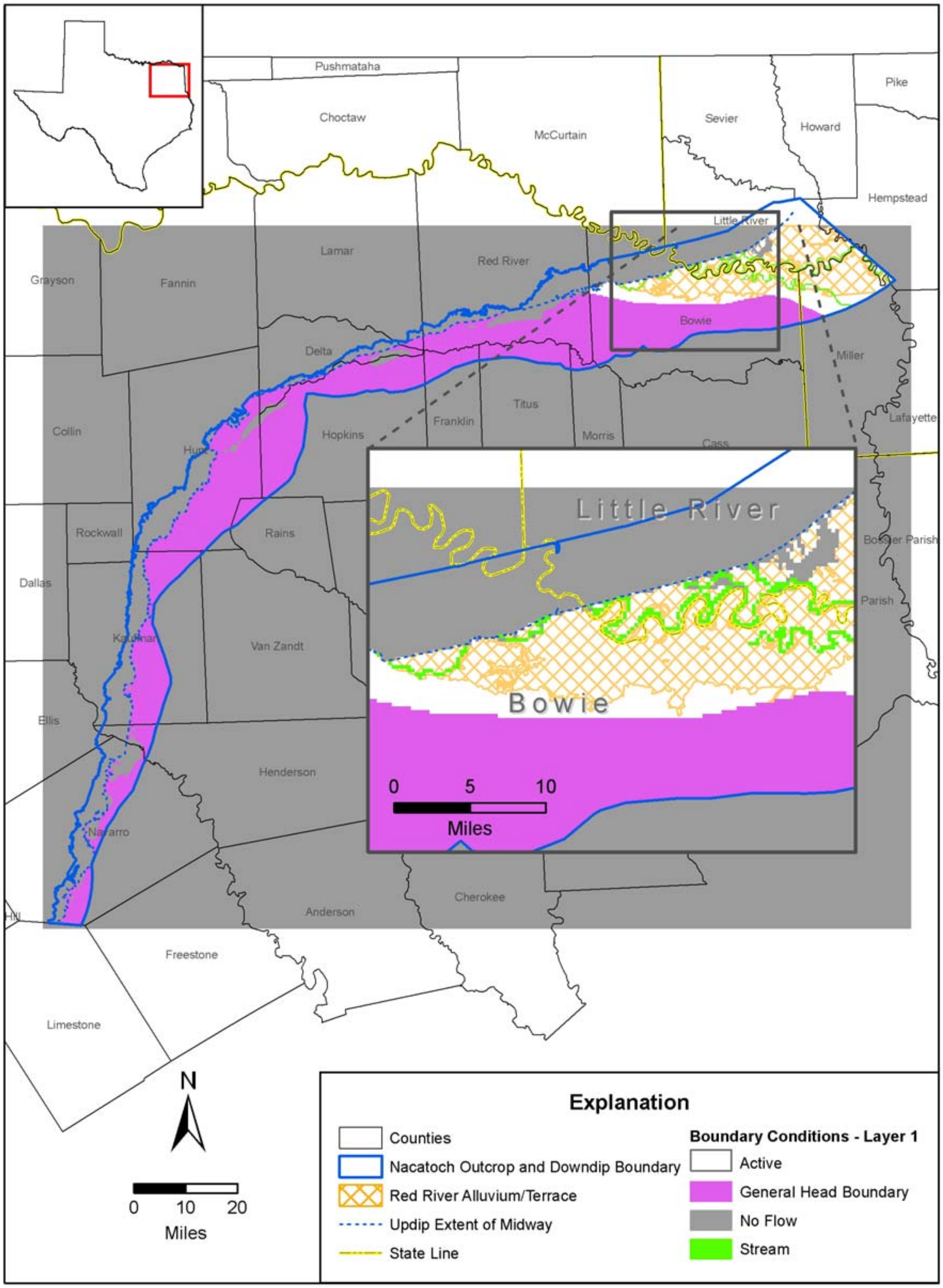


Figure 6.2.2 Active cells and boundary conditions in layer 1

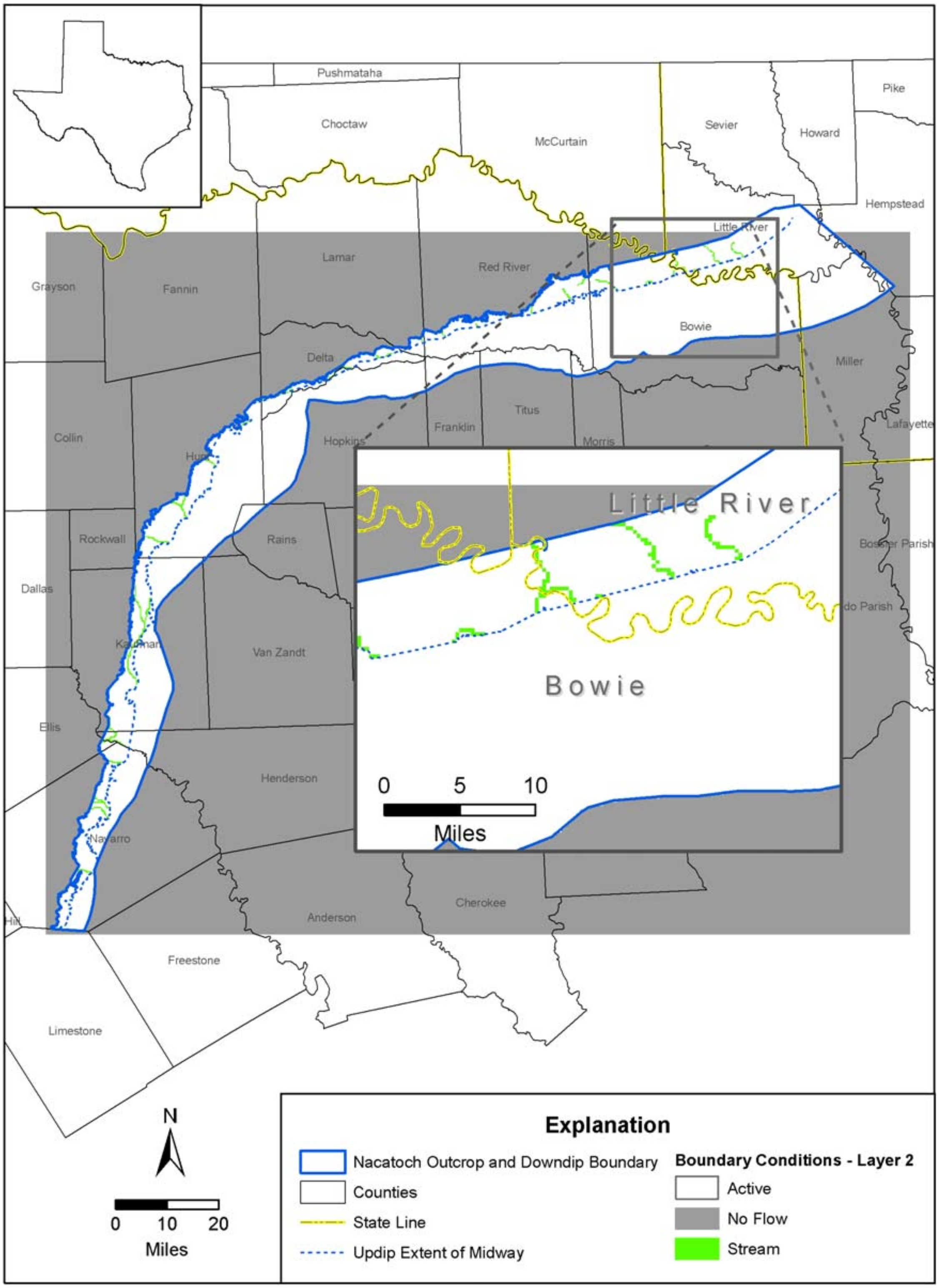


Figure 6.2.3 Active cells and boundary conditions in layer 2

6.3 Boundary Condition Implementation

Boundary conditions constrain a model by representing physical components in the system such as wells, evapotranspiration, or cross-formational flow. Boundary conditions are also used to permit the interaction between the active simulation grid domain (modeled area) and the hydrologically connected system surrounding the model area. Anderson and Woessner (1992) identify three general types of boundary conditions; specified head, specified flow, and head-dependent flow. Boundaries can be steady (does not change with time) or transient (does change with time). In MODFLOW, a stress period is time over which it is assumed that boundary conditions in the model are steady and do not change appreciably. Within a given stress period, there may be many computational time steps. Based on the level of data available in the model area regarding pumping rates, precipitation, measured water levels, and other hydrologic conditions, the stress period for this model was set equal to one year.

6.3.1 Vertical Boundaries

Underlying the Nacatoch Aquifer is a layer of Marlbrook Marl of the Taylor Group that serves as a no-flow boundary for the base of layer 2. The groundwater movement between the Midway and Nacatoch Aquifer is limited by assigning small vertical hydraulic conductivity in layer 1. In the Red River area, because of extensive alluvium deposits, the vertical connections are stronger between the two layers. GHB in layer 1 is shown in Figure 6.2.2.

6.3.2 Streams and Springs

Major rivers in the model area have been incorporated into the model as stream boundary conditions in the format of a streamflow routing package. This package has the capacity to keep track of the flow in streams which interact with groundwater. Both groundwater discharge to the stream and the stream leakage to the aquifer are limited. The stream cells were identified and routed using the EPA RF1 coverage (Figure 6.2.3).

The mean flow for the headwaters was also estimated using the PMEANFLOW attribute of the RF1.

6.3.3 Recharge

Average recharge was estimated based on a baseflow-precipitation relationship (as detailed in the conceptual model report section 4.2.2). Recharge was adjusted locally for topography by increasing recharge in the highlands and decreasing it in the lowlands. No impact of surficial geology was included since we are recharging a single outcrop, and the soils Kv analysis was inconclusive. Recharge is not included in stream cells, but is allowed to occur in ET cells. The spatial distribution of the recharge was not modified from the initial assessment.

6.3.4 Pumping Discharge

Estimation and implementation of pumping is important in model development because it represents a stress similar in nature and magnitude to the stresses the model is being developed to simulate. Historical pumping and the observed changes in the aquifer due to that pumping offer some of the best available historical data from which to develop a useful model. Both historical pumping and earlier water use were researched and factored into the model.

The methodology and data used to estimate and allocate pumping are summarized in Section 4.7.2. Because the stress period length used in the transient simulations was one year, all pumping was averaged throughout the year, and seasonal impacts were not accounted for in the model.

6.4 Hydraulic Properties

Hydraulic conductivity is one of the most important parameters to be estimated and distributed across the model because in part, it determines the rate at which water flows through the system. The storage coefficient is important in determining the rate of water level change when the aquifer is pumped.

6.4.1 Hydraulic Conductivity

The first step in estimating hydraulic conductivity is to compile the existing estimates. As discussed in Section 4.6, there is a small number of hydraulic conductivity estimates for the Nacatoch Aquifer. In determining the utility of locally determined hydraulic conductivity estimates (generally, from pump and specific capacity tests), it is important to consider the nature of the aquifer and the type of rocks which make up the aquifer. Although a pumping test can be used to estimate local hydraulic conductivity, these estimates are still small in scale compared with regional flow systems. The effective hydraulic conductivity incorporated into the model depends on aquifer geometry, hydraulic conductivity, and the scale at which variations in hydraulic conductivity occurs.

In the model development process, it was assumed that the available Nacatoch Aquifer hydraulic conductivity and transmissivity data, or interpreted hydraulic conductivity data, typically represent the highest permeability porous media tested and that these estimates could be used as a guide for estimating effective model hydraulic conductivity. However, direct estimates of vertical hydraulic conductivity meaningful to the general modeling process are almost never available, and that is true for this study. The distribution and estimated values of vertical hydraulic conductivity for the model are usually determined mainly through the model calibration process. This can lead to non-unique parameterization and may introduce a potentially large degree of uncertainty into the model results. The type and amount of available calibration data (water level measurements and discharges) and the degree to which it is implemented usually determine the degree of success in reducing this uncertainty. For this study, there was very little information regarding vertical head differences in the aquifers being simulated. This lack of data is not uncommon, but it does hinder the model calibration process.

The Nacatoch Aquifer in the model represents Nacatoch Aquifer as well as other materials and geologic features, thus a composite system. Hydraulic conductivity estimates from short duration pumping tests are very helpful in estimating local scale hydraulic conductivity, but the estimates are likely to be biased toward high values for several reasons. First, pumping tests are not performed in “dry boreholes”. Second, pumping tests are usually not performed in wells which don’t produce much water. These biases are enough to skew the estimates of hydraulic conductivity. In addition, the connection of the fracture network on a regional basis is unknown, and many surface water and groundwater interactions are controlled by more local hydrogeologic structures. These local structures are not represented in the data or the conceptual model, nor can they be incorporated into the numerical model at the regional scale. Therefore, estimates of hydraulic conductivity in the aquifer are biased toward high values.

6.4.2 Storativity

As discussed in Section 4.6, several estimates of storativity are based on pumping tests in the aquifer. These data are reasonable estimates of confined storage properties and are within typical ranges documented for confined aquifer system. Those estimates were used as a guide in calibrating the model.

7.0 MODELING APPROACH

Calibration of a groundwater flow model is the process of adjusting model parameters until the model reproduces field-measured values of water levels (heads) and/or flow rates. Successful calibration of a flow model to observed heads and/or flow conditions is usually a prerequisite to using the model for prediction of future groundwater availability. Parameters that are typically adjusted during model calibration are hydraulic conductivity, storativity, and recharge. Model calibration typically includes completion of a sensitivity analysis. Sensitivity analysis entails running the model with a systematic variation of the parameters and stresses in order to determine which parameter variations produce the most change in the model results. Those parameters which change the simulated aquifer heads and discharges the most are considered important parameters to the calibration. The sensitivity analysis guides the process of model calibration by identifying potentially important parameters but does not in itself produce a calibrated model.

7.1 Calibration

7.1.1 Approach

Groundwater models are inherently non-unique. Non-uniqueness refers to the characteristic of a model that allows many combinations of hydraulic parameters and aquifer stresses to reproduce measured aquifer water levels. To reduce the impact of non-uniqueness on model results, several approaches were used. Where possible, the model incorporated parameter values (i.e., hydraulic conductivity, storativity, recharge) that were consistent with measured values. In addition, a relatively long calibration period was selected to incorporate a wide range of hydrologic conditions. Finally, to the degree possible, two different calibration performance measures, hydraulic heads, and aquifer flow rate, were used to reduce non-uniqueness in the model.

Measured hydraulic conductivity and storativity data were initially incorporated into the model based on the data described in Chapter 4. In areas where measured data were not available, estimates were incorporated from similar aquifers for which data exist. As mentioned in Chapter 6, there are no available measurements of vertical hydraulic conductivity. Therefore, vertical hydraulic conductivity was estimated based on professional judgment. Storativity is estimated from measured specific storage data in combination with aquifer thickness. Initial estimates of recharge were based on the redistribution method.

Model parameters were held to within reasonable ranges during calibration based on available data and relevant literature. Adjustments to parameters from initial estimates were minimized to the extent possible to meet the calibration criteria. As a general rule, parameters that have few measurements were adjusted preferentially as compared to parameters that have a good supporting database.

The model was calibrated for two hydrologic conditions, one representing steady-state conditions (i.e., prior to major pumping, year 1960 in this case) and the other representing transient conditions after pumping started. A steady-state model is a representation of pre-development conditions and therefore, no pumping stresses were applied to the steady-state model. The required transient calibration period ran from 1980 to 1997, when most observations were available. Given the fact that some groundwater development occurred prior to 1980, mainly in City of Commence area of Hunt County, a short transient period (1978-1979) was added to better approximate 1980 heads. All stress periods in the calibration period were one year long.

The advantage of calibrating the model to 18 years of historical data is that this period incorporates a wide range of hydrological and stress conditions. The goal of the steady-state pre-development model was to simulate a period of equilibrium where aquifer recharge and discharge are equal. The goal of the transient calibration was to adjust the model to appropriately simulate the water-level changes that were occurring in the aquifers due to pumping. The steady-state and transient model periods may show sensitivity to different parameters.

7.1.2 Calibration Targets and Measures

In order to calibrate a model, targets and calibration measures must be developed. The primary type of calibration target is hydraulic head (water level) and this is the only type of calibration targets available for this model.

Model calibration is judged by quantitatively analyzing the difference (or residual) between observed and model computed (i.e., simulated) values. Several graphical and statistical methods are used to assess the model calibration. These statistics and methods are described in detail in Anderson and Woessner (1992). The mean error is defined as:

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

where:
h_m is measured hydraulic head, and
h_s is simulated hydraulic head, and
$(h_m - h_s)$ is known as the head error or residual.

A positive mean error (ME) indicates that the model has systematically underestimated heads, and a negative error, the reverse. It is possible to have a mean error near zero and still have considerable errors in the model (i.e., errors of +50 and -50 give the same mean residual as +1 and -1). Thus two additional measures, the mean absolute error and the root mean square of the errors, are also used to quantify model goodness of fit. The mean absolute error is defined as:

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

The standard deviation (SD) of errors or root mean squared (RMS) error is defined as:

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

A large SD means that there is wide scattering of errors around the mean error.

These statistics were calculated for the calibration period. In addition, the distribution of residuals was evaluated to determine if they are randomly distributed over the model grid and not spatially biased. Head residuals were plotted on the simulated water-level maps to check for spatial bias. Scatter plots were used to determine if the head residuals are biased as compared to the observed head surface.

7.1.3 Calibration Target Uncertainty

Groundwater elevation measurements have an inherent error component due to several factors, including measurement error, instrument error, sampling scale limitations, and recording errors. In order to know when the model calibration is acceptable, a level of reasonable uncertainty in the observed head data should be recognized and estimated. This uncertainty in observed data provides some guidance regarding setting calibration goals to avoid over-calibrating the model. Over-calibration of a model occurs when parameters are modified too much in order to match observed conditions.

The TWDB GAM standard for calibration criteria for head is an MAE less than or equal to 10% of head variation within the aquifer being modeled. Head differences across the Nacatoch Aquifer are about 425 feet. This leads to an acceptable MAE of about 45 feet for the entire model. This MAE can be compared to an estimate of the head target errors to consider what level of calibration the underlying head targets can support.

Although they can vary significantly, measurement errors in water levels are usually tenths of feet, and are considered insignificant at the scale of this regional aquifer model. However, estimates of measuring point elevation can be significant because these data are sometimes estimated from topographic maps based on the estimated location of the well. These data can easily be 5 to 10 feet in error, and sometimes more in mountainous areas. Instrument errors also exist but are hard to document.

Seasonal variations in water level create another challenge for measurements. When there are enough observations, a trend plus seasonal variations will be demonstrated and an average value will be better reflected in simulated heads. When only a few points of observation are available, it is hard to know whether the sampling point is at a seasonal high or low. The data then contains errors when compared to simulated average conditions. In the Nacatoch Aquifer, this error is judged at 10 to 20 feet for most wells. For wells close to a major withdrawal point, it could be higher.

Another conceptual translation error arises when complex lithology is assumed to be adequately represented by a single grid block. This type of simplification may occur for the Nacatoch Aquifer units and therefore, the simulated head for those layers contain some potential error because the simulated water level is "vertically averaged" as opposed to the water level in individual zones in which the wells are screened and the water levels are measured. The magnitude of this error is difficult to quantify, but could range from a relatively small value in areas that have good vertical connection to a significantly larger error in areas that have poor vertical connection.

Accumulation of all these potential errors provides an estimate of the error in the simulated heads, and ranges from about 15 to more than 50 feet in most cases and could be even higher in some observation points. Based on this analysis, a minimum calibration MAE value of 50 feet for the Nacatoch Aquifer was reasonable. Calibrating the model to MAE values less than 15 feet would potentially result in an over parameterized model. That level of parameterization was not justified by the available data and model architecture.

7.2 Sensitivity Analyses

A sensitivity analysis was performed on the steady-state and transient calibrated models to determine how changes in a parameter affect the results of the calibrated model. The sensitivity analysis was completed such that each of the hydraulic parameters or stresses was adjusted from its calibrated value by a small factor while all other hydraulic parameters were held at their calibrated values. The results of each sensitivity simulation were evaluated by calculating the average head change in the model and also by assessing the change in the hydrographs for selected wells.

8.0 STEADY-STATE MODEL

The calibration of the steady-state model involved adjusting some of the model input parameters in order to get a good fit to the observed target data. The process of calibrating the Nacatoch Aquifer GAM was iterative and involved both a trial-and-error approach and automated parameter estimation techniques. Because the steady-state and transient periods are contained in the same model, the parameter adjustments for the steady-state model will propagate to the transient model as well. This section describes the final steady-state calibration results.

8.1 Calibration

8.1.1 Calibration Targets

Figure 8.1.1 shows the locations of the wells with water levels that were used for the steady-state calibration. A total of 102 water level measurements were used for steady-state calibration. Those targets are all located in layer 2 (Nacatoch Aquifer). Layer 1 was not calibrated because no target data was available.

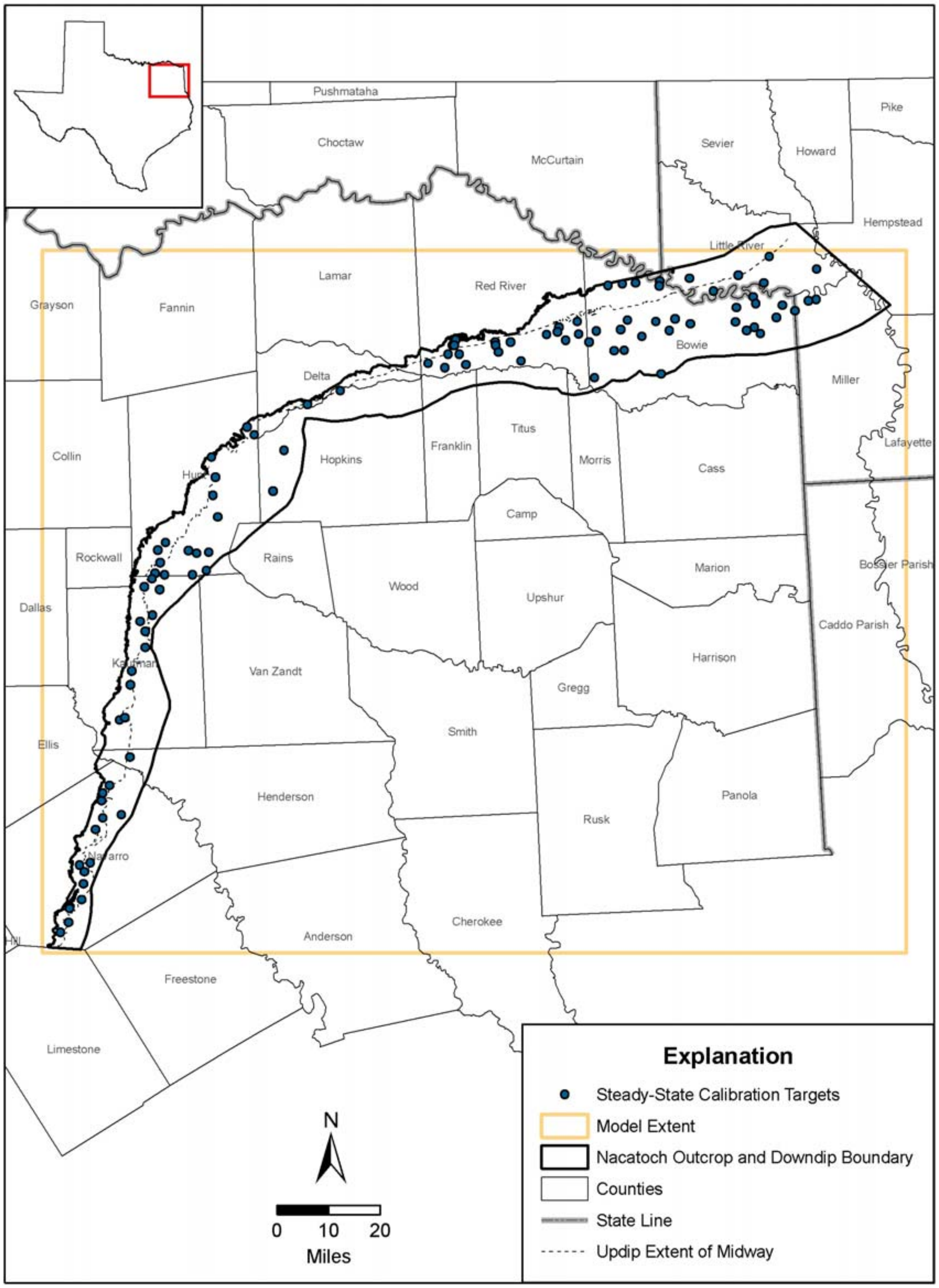


Figure 8.1.1 Location of wells used for steady-state calibration targets

8.1.2 Horizontal and Vertical Hydraulic Conductivities

The initial distribution of hydraulic conductivity was based on the measured data as discussed in Chapter 4. In order to facilitate calibration, the distribution of the hydraulic conductivity was zoned and the zones were generally consistent with the pattern observed from the measured data. Initial hydraulic conductivity values were adjusted during the calibration period of the steady-state and transient model. Table 8.1.1 summarizes the range of calibrated hydraulic conductivity values used in each layer. The final distribution of hydraulic conductivity values for layer 1 and 2 are shown in Figure 8.1.2 and Figure 8.1.3, respectively. Also shown on each figure is the ratio of horizontal to vertical hydraulic conductivity for each zone.

Table 8.1.1 Summary of hydraulic properties used in model

Layer	Horizontal Hydraulic Conductivity (ft/day)	Vertical Hydraulic Conductivity (ft/day)	Specific yield (-)	Specific Storage (-)
1	0.01 - 1	$1x10^{-4}$ – $1x10^{-3}$	0.01 - 0.03	$1x10^{-8}$ – $1x10^{-5}$
2	0.1 – 9.5	$1x10^{-3}$ – 0.9	0.01 – 0.03	$1x10^{-7}$ – $1x10^{-5}$

Compared to the rest of the model area, lower hydraulic conductivity for the Nacatoch Formation was observed and assigned to southwest Hopkins County. This can be explained partially by the extensive faults in the region, which may act as flow barriers and decrease effective hydraulic conductivity.

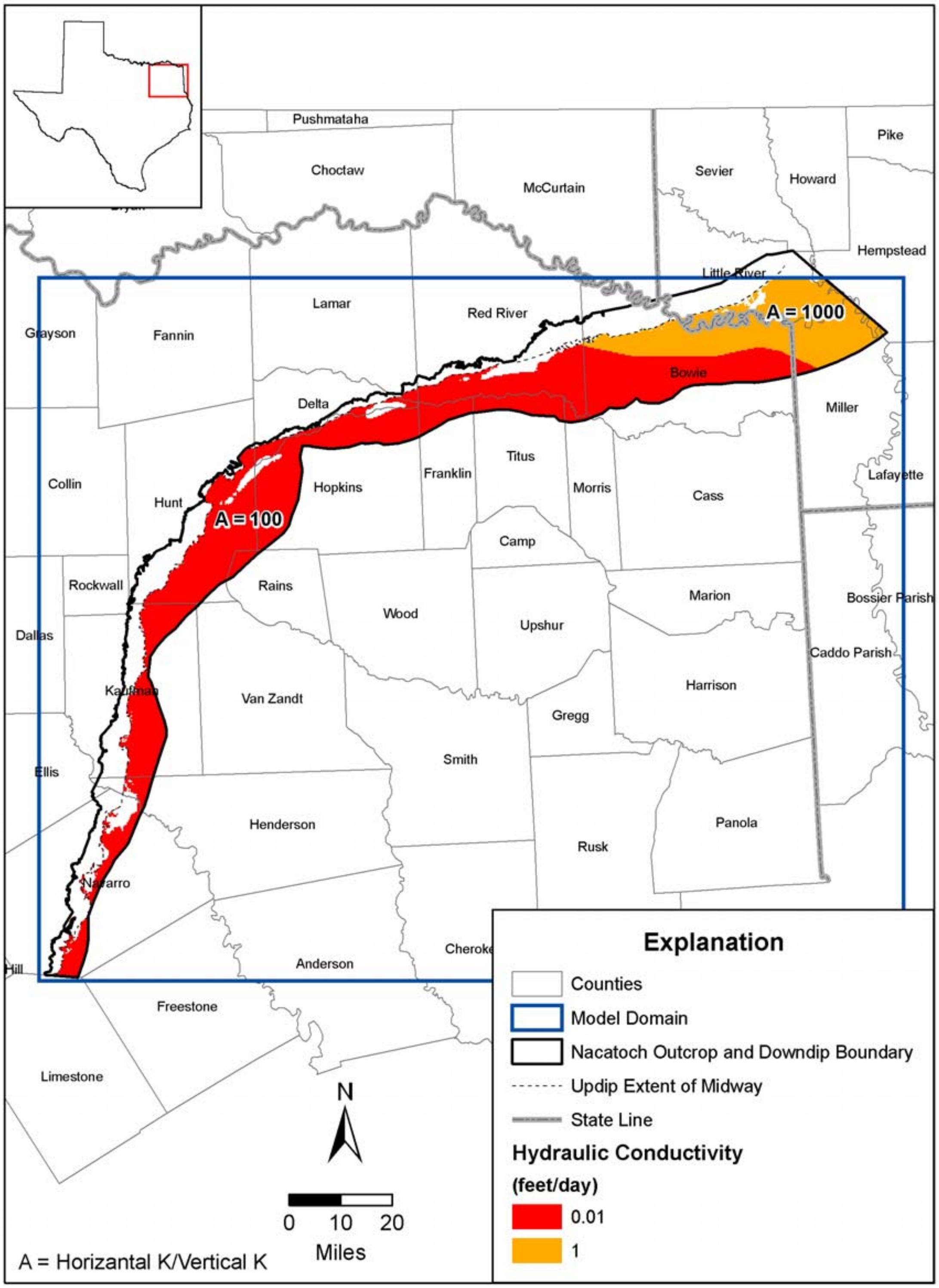


Figure 8.1.2 Final distribution of hydraulic conductivity in layer 1

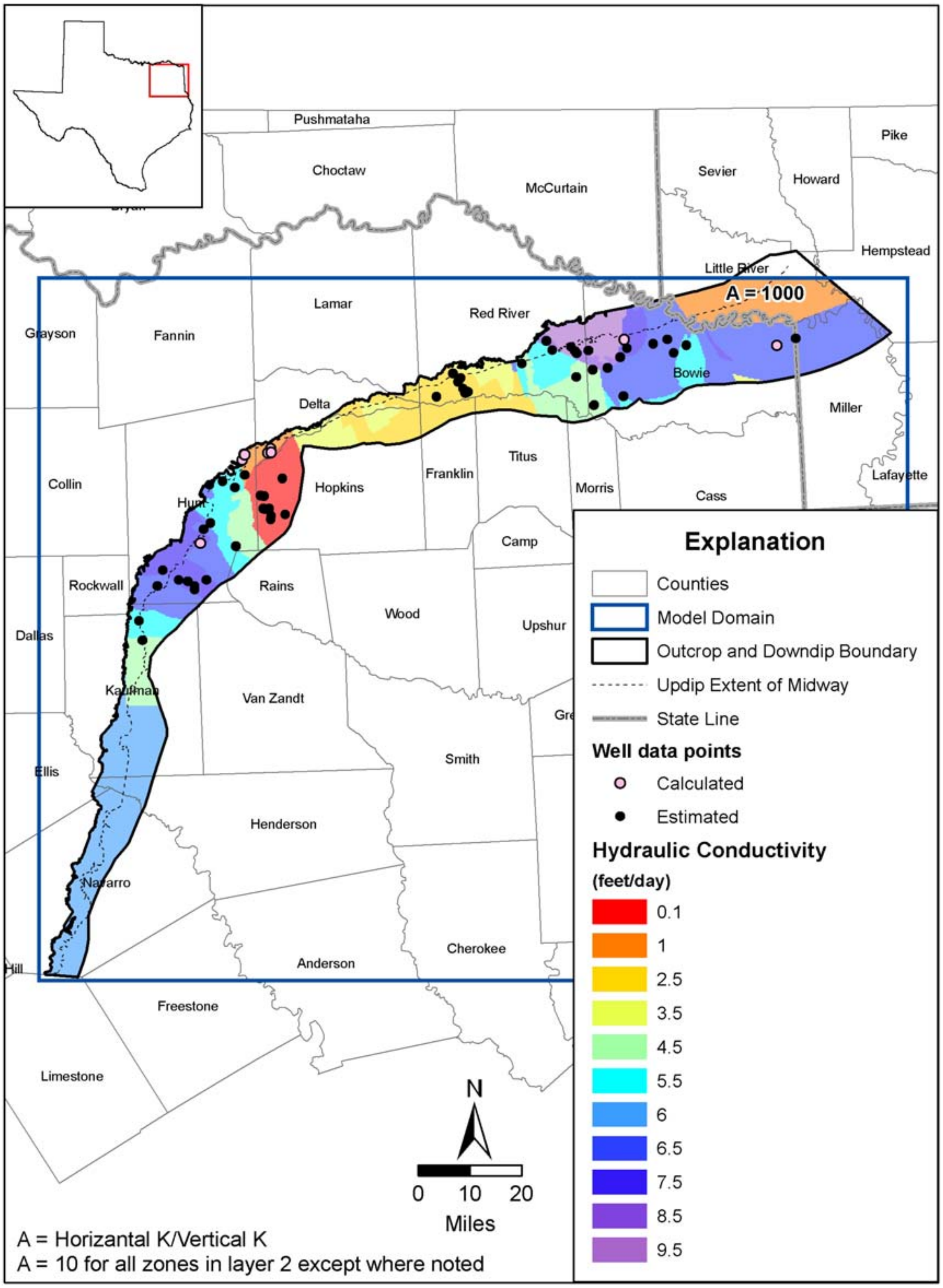


Figure 8.1.3 Final distribution of hydraulic conductivity in layer 2

8.1.3 Recharge

As discussed in Section 4.4, initial estimates of recharge were based on the results of baseflow-precipitation regression analysis.

For the steady-state period, these average recharge estimates were incorporated into the model. The spatial distribution of final calibrated recharge in the steady-state model is shown in Figure 8.1.4. Recharge is applied to the outcrop area only except in the Red River alluvium area, where recharge in each cell is also assigned using the procedure outlined in Section 4.4. The recharge estimates range from 0 to about 2 inches/year.

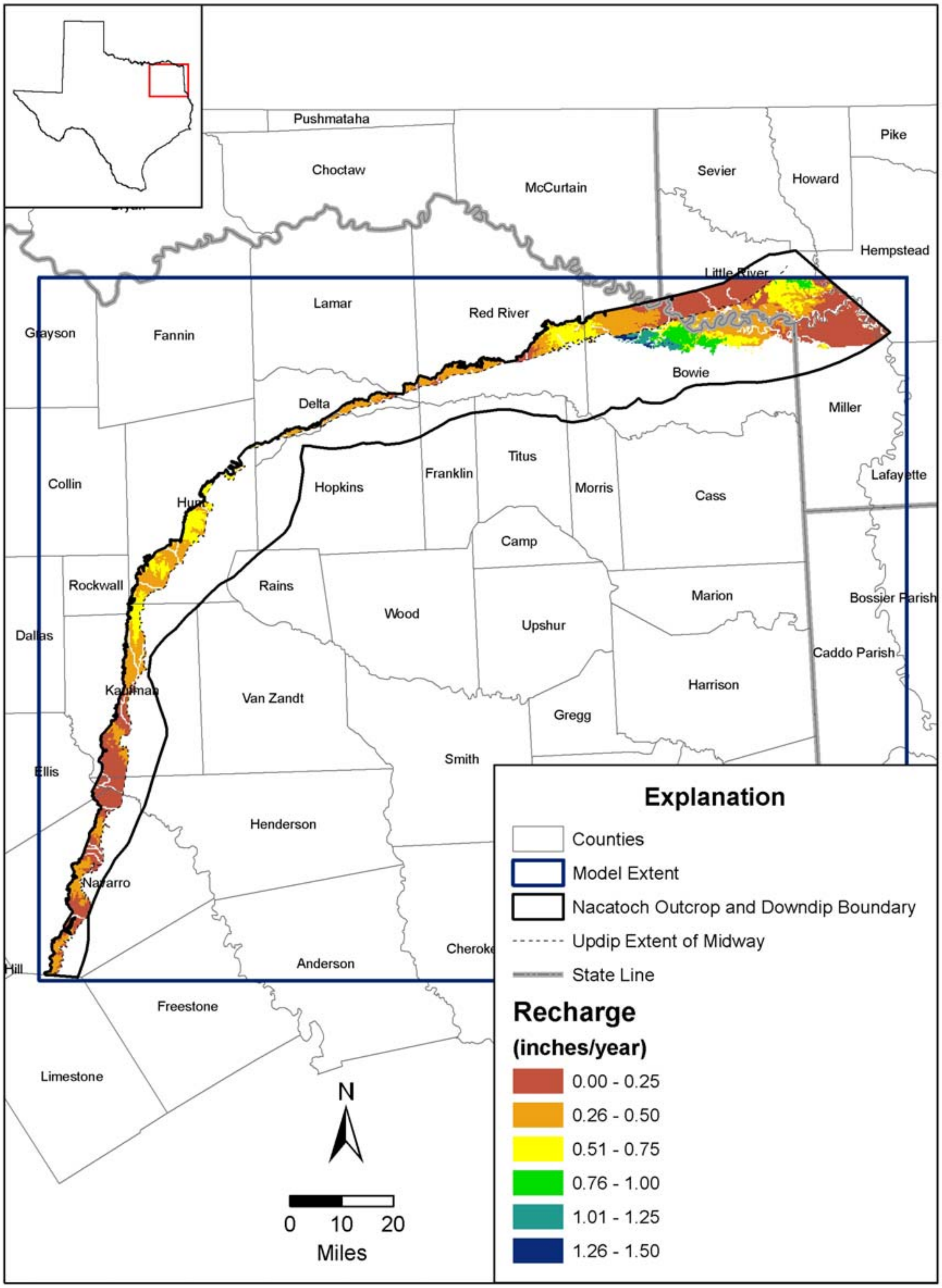


Figure 8.1.4 Final distribution of recharge rate in the steady-state model

8.1.4 Groundwater Evapotranspiration

Evapotranspiration (ET) was activated in the riparian area only (approximately one cell width adjoining the streams). The maximum ET rate was estimated based on multiplying the average potential ET by the appropriate vegetation coefficient. The potential ET and vegetation coefficient data comes from a TWDB report by Scanlon and others (2003). The rooting depth varies between 1 to 10 feet, tied to the vegetation type for each cell. The ET surface was set to the ground surface.

The final extinction depth and rate implemented in the calibrated model are shown in Figure 8.1.5 and Figure 8.1.6. Simulated evapotranspiration rates in the steady-state calibrated model are shown in Figure 8.1.7.

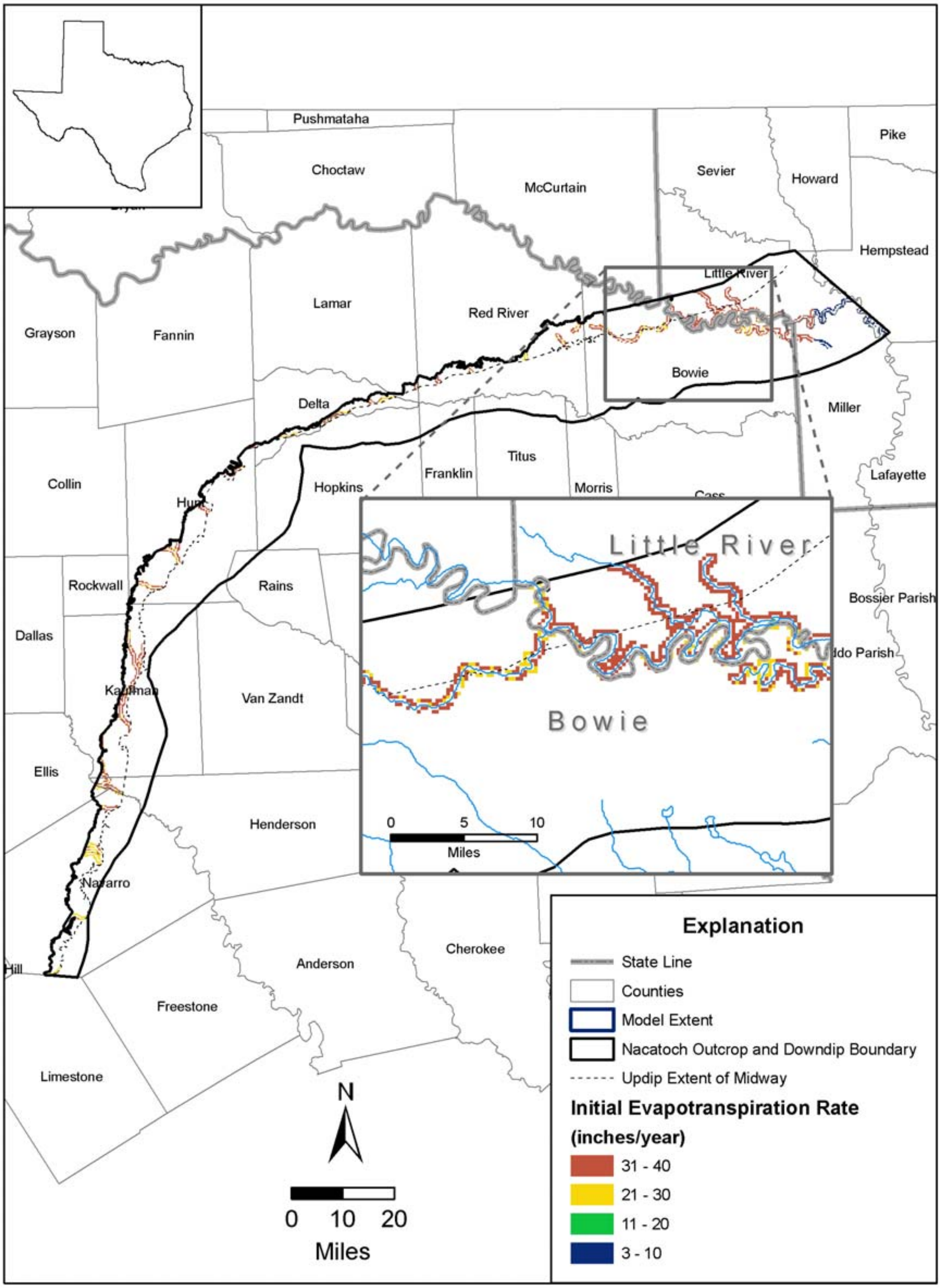


Figure 8.1.5 Final distribution of evapotranspiration rate

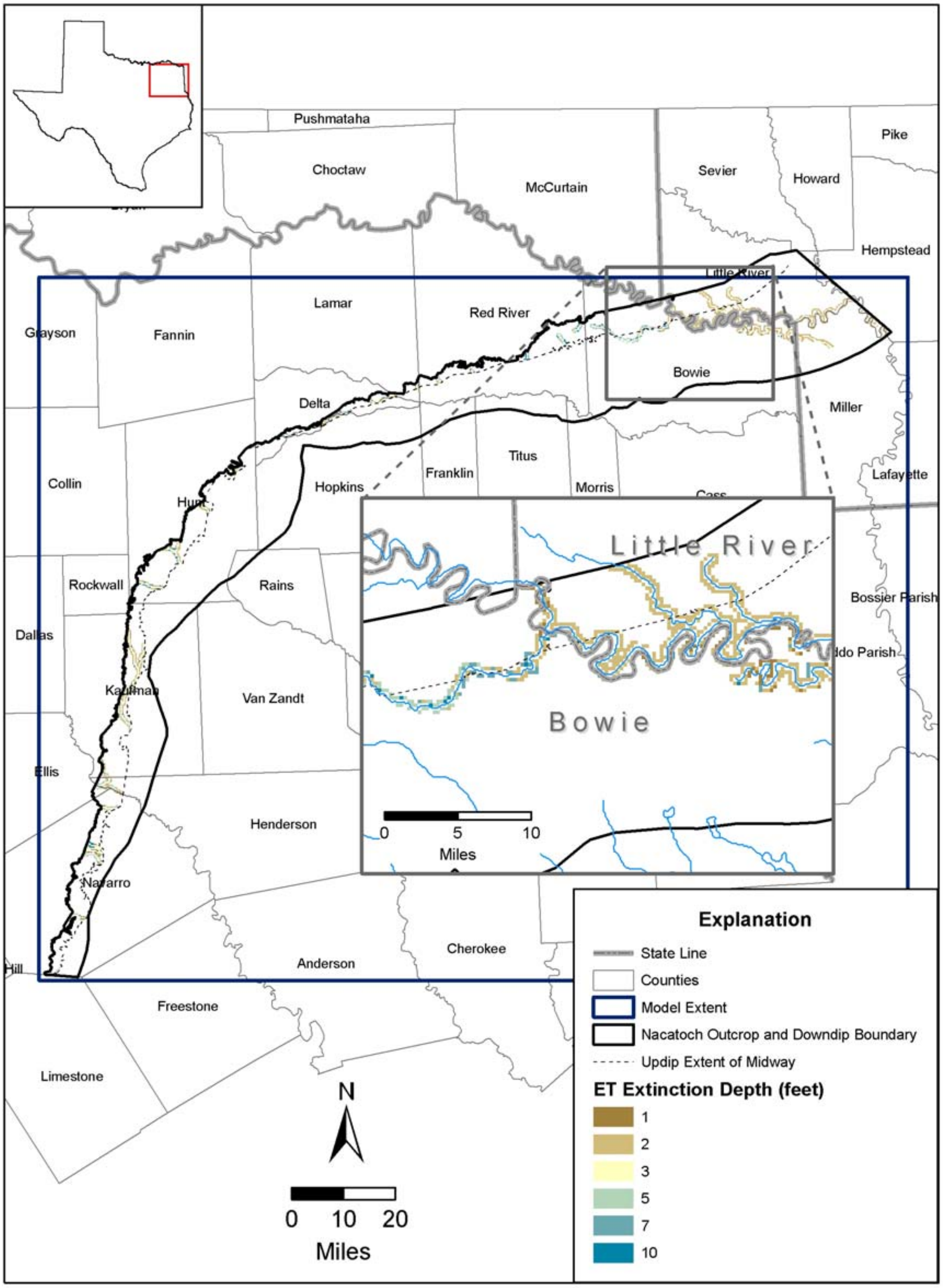


Figure 8.1.6 Final distribution of evapotranspiration extinction depth

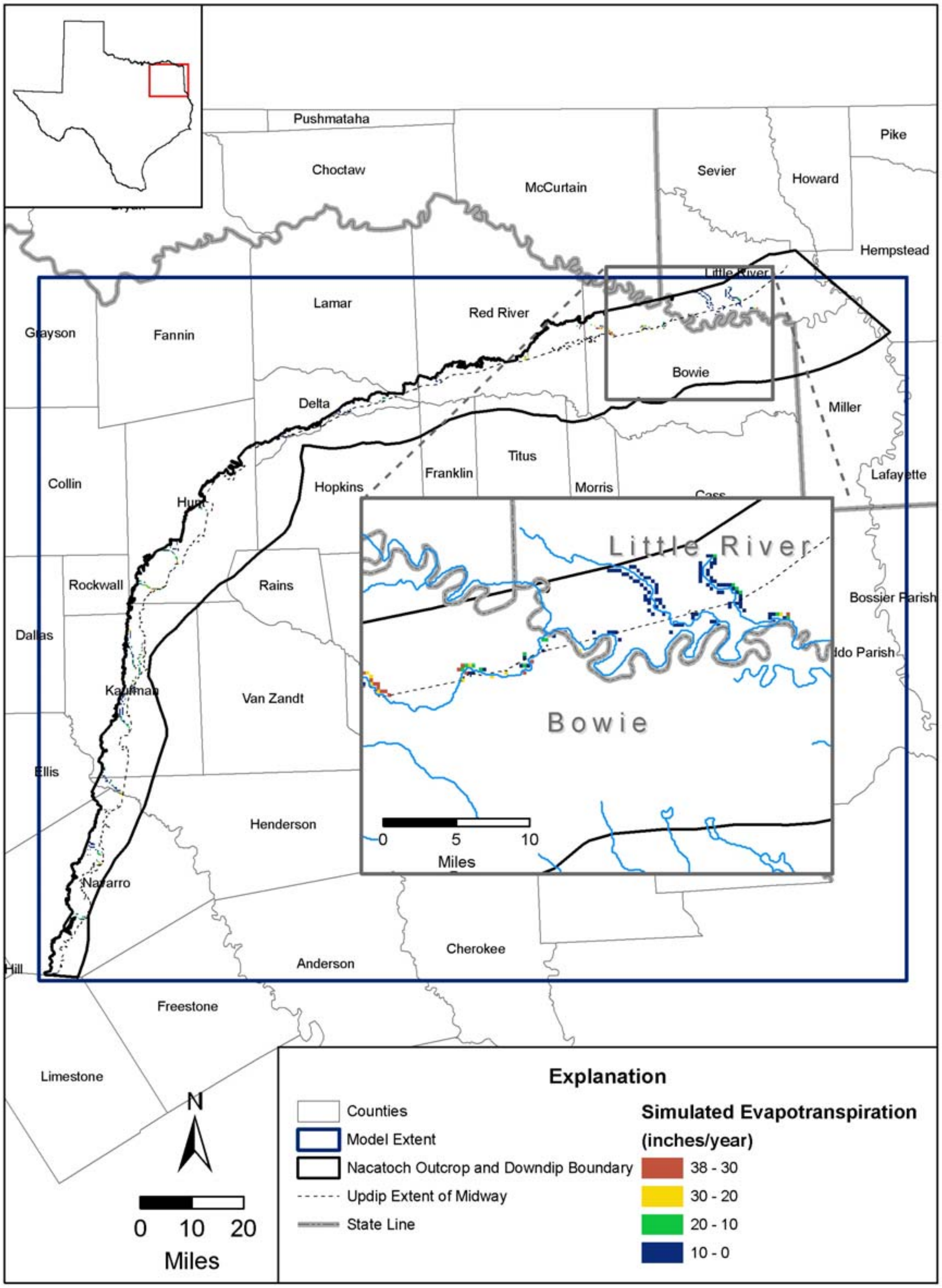


Figure 8.1.7 Simulated evapotranspiration rates in the steady-state model

8.1.5 General Head Boundaries

General head boundaries (GHBs) were used to simulate cross-formational flow into and out of the Nacatoch Aquifer (layer 2) to the overlying Midway. GHB is applied to all the active cells in layer 1 except cells in the Red River alluvium area. Head for GHB cells was based on estimated head from the Midway layer and was adjusted to the point between the top and bottom of the Midway layer (Figure 8.1.8). GHB conductance in these cells was treated as a calibration parameter. Some of the heads were modified during calibration to better simulate regional flow patterns discussed in Chapter 4.

8.1.6 Streams

Rivers across the outcrop area are simulated using the stream package. Average flow was used as inflow for entering each segment. The stage of stream was calculated by the stream package.

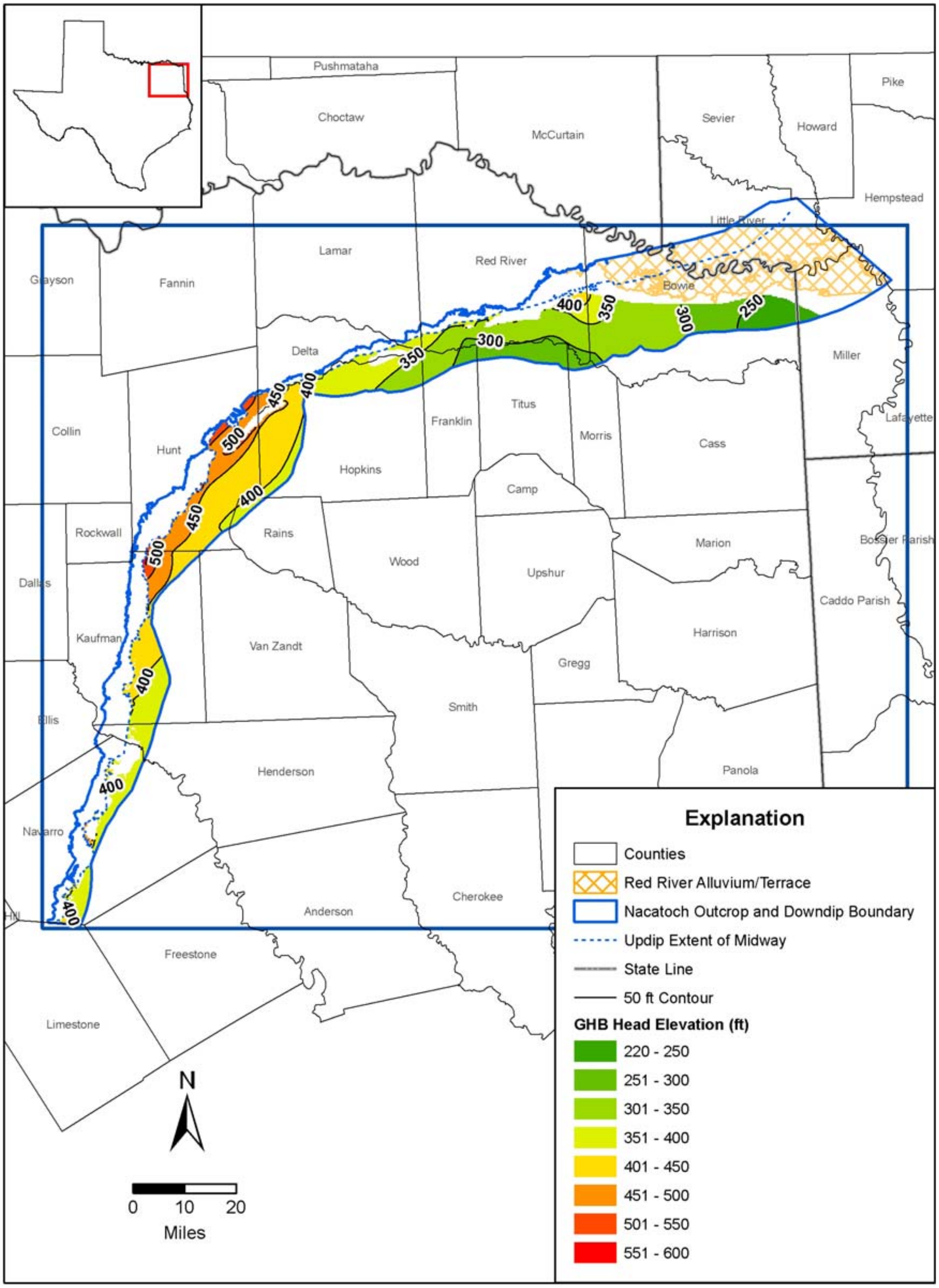


Figure 8.1.8 General head boundary water level (ft above mean sea level) in layer 1

8.2 Results

This section describes some of the observations that were made during the calibration of the model and presents results of the calibration of the steady-state portion of the model.

The steady-state model was assumed to represent pre-development conditions. The steady-state condition was approximated by simulating a long stress period. In this case, 100,000 days. During the transient runs, steady-state and transient (1980-1997) water level measurements were used to calibrate both the steady-state and transient models. Therefore, calibration occurred in a coupled fashion.

In the first attempt of steady-state calibration, it was discovered that simulated heads are consistently higher than observed values in the Red River alluvium area. This resulted in spatially biased error distribution. Subsequently, GHBs in layer 1 in the Red River area were removed and ET, recharge, and stream packages were updated to explicitly represent alluvium conditions.

In the steady-state calibration process, transmissivity is the main parameter that has been adjusted. The model is also sensitive to GHB conditions, and the GHB conductance has been estimated through the calibration process.

8.2.1 Calibration Statistics

Table 8.2.1 shows a summary of the calibration statistics for the calibrated steady-state model. The mean absolute error (MAE) is 22 feet. Given the range of 337 feet, the ratio of MAE over the range is about 6.5%. Calibration statistics were not calculated for layer 1 because there were no available water level measurements.

Table 8.2.1 Summary of steady-state head calibration statistics

Layer	Count	ME (feet)	MAE (feet)	RMS (feet)	Range (feet)	MAE/Range
Nacatoch Aquifer	102	1	22	28	337	6.5%

8.2.2 Hydraulic Heads

Figure 8.2.1 shows a crossplot of the simulated heads versus the observed heads for the steady-state model. The figure indicates that there is a good agreement in all areas of the model. Figure 8.2.2 and Figure 8.2.3 show maps of the simulated hydraulic head results from the calibrated steady-state model as well as the head residuals by layer. Residuals greater than zero indicate that the simulated head is lower than the measured head, and residuals less than zero indicate that the simulated head is higher than the measured head. As indicated in Figure 8.2.3, the flow direction and gradients are very similar to those shown in Figure 4.3.6.

A few cells near the edge of the Nacatoch Aquifer outcrop and some cells near the shallow Red River alluvium went dry in the steady-state simulation. The rewetting option was not used in the steady-state period because it was unstable. Dry cells in MODFLOW can be indicative of model instability during solver iterations or may indicate that the layer has a small saturated thickness or is dry. In this case, the dry cells are probably indicative of actual dry zones or areas where the saturated thickness is so small that the flow in the cells is relatively insignificant to the overall flow dynamics. Therefore, it is assumed the dry cells do not have a significant impact on model results.

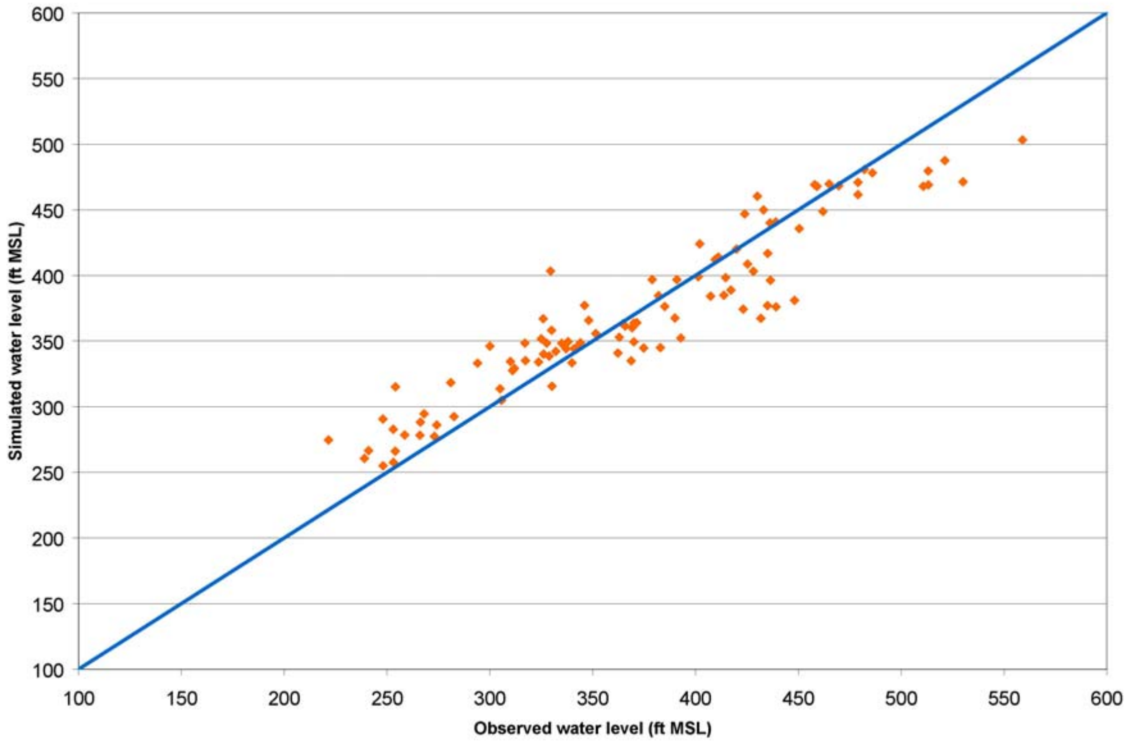


Figure 8.2.1 Simulated versus observed heads in the steady-state model

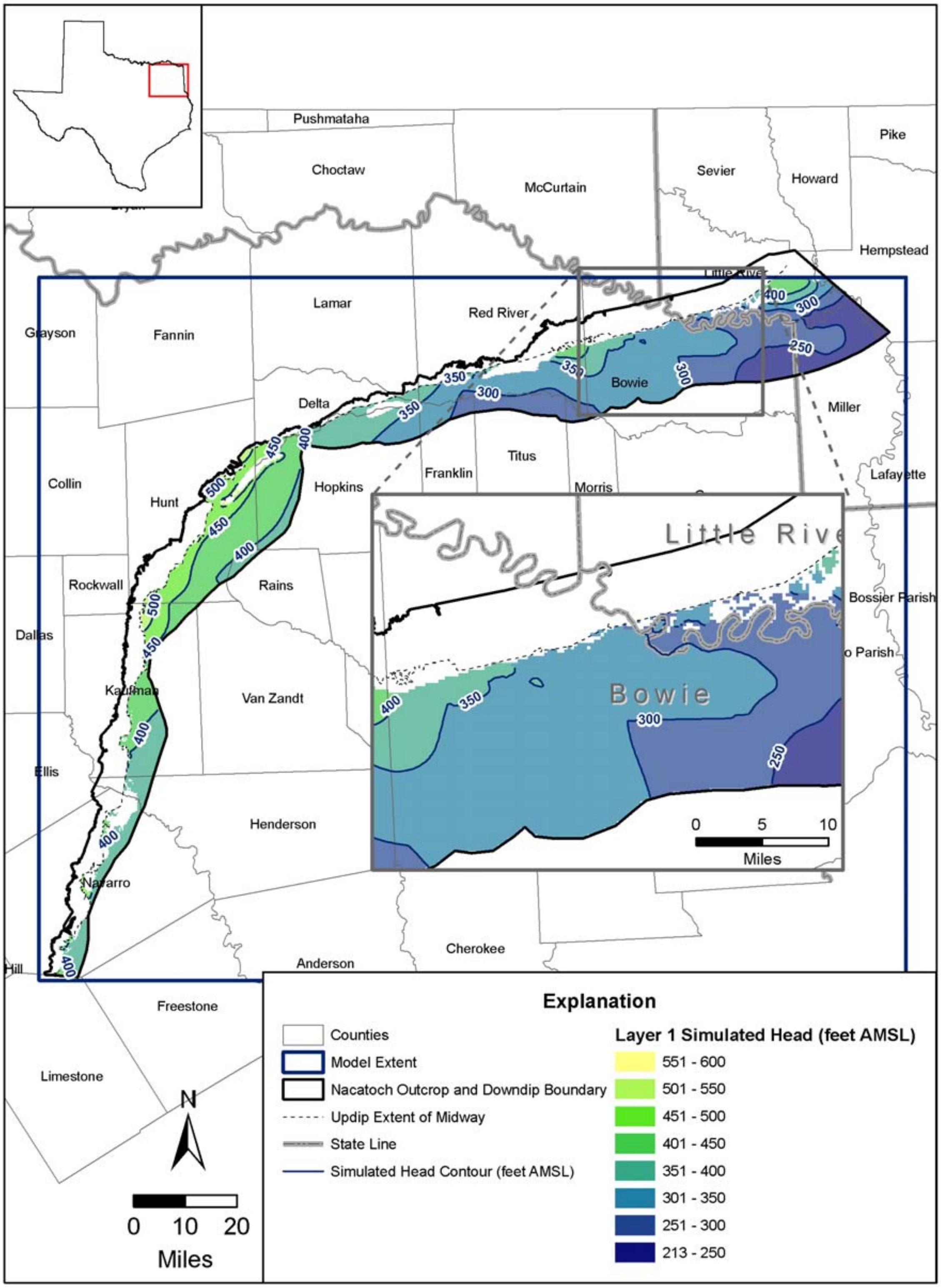


Figure 8.2.2 Simulated steady-state hydraulic heads in layer 1

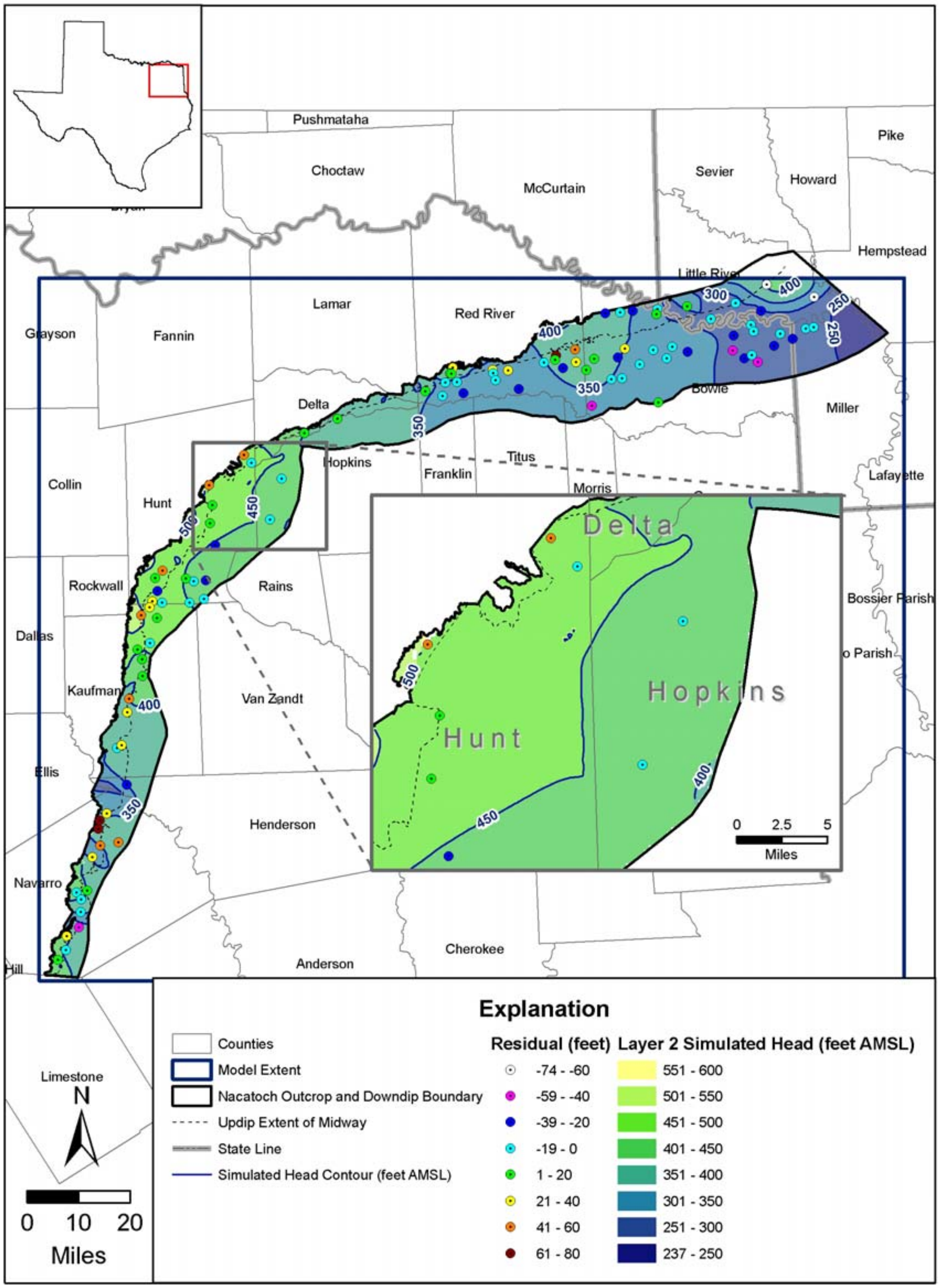


Figure 8.2.3 Simulated steady-state hydraulic heads and residuals in layer 2

8.2.3 Water Budget

Table 8.2.2 provides a summary of the water budget for the steady-state model in terms of volume. The water budget numbers were obtained by using USGS Zone Budget program (Harbaugh, 1990). As indicated in this table, on an annual basis, the Nacatoch Aquifer layer has a balance of flow of about 7,700 acre-feet moving upward to the upper layer. About 14,000 acre-feet of the 18,000 acre-feet of recharge is lost to ET. Streams gain about 6,300 acre-feet of flow.

Figure 8.2.4 illustrates the steady-state budget components for each layer in graphical form. Appendix A contains a summary of the steady-state water budget for each county in Texas.

Table 8.2.2 Summary of steady-state water budget components

	Layer	Top	Bottom	ET	Stream	GHBs	Recharge
IN	1	0	7,750	0	44	8,960	7,344
	2	13,290	0	0	5	0	10,440
	Sum	13,290	7,750	0	49	8,960	17,785
OUT	1	0	13,290	598	4,034	6,043	0
	2	7,750	0	13,789	2,332	0	0
	Sum	7,750	13,290	14,387	6,366	6,043	0

Note: Units are in acre-feet per year. A positive number indicates water entering the aquifer system or layer while a negative number indicates water leaving the aquifer system or layer

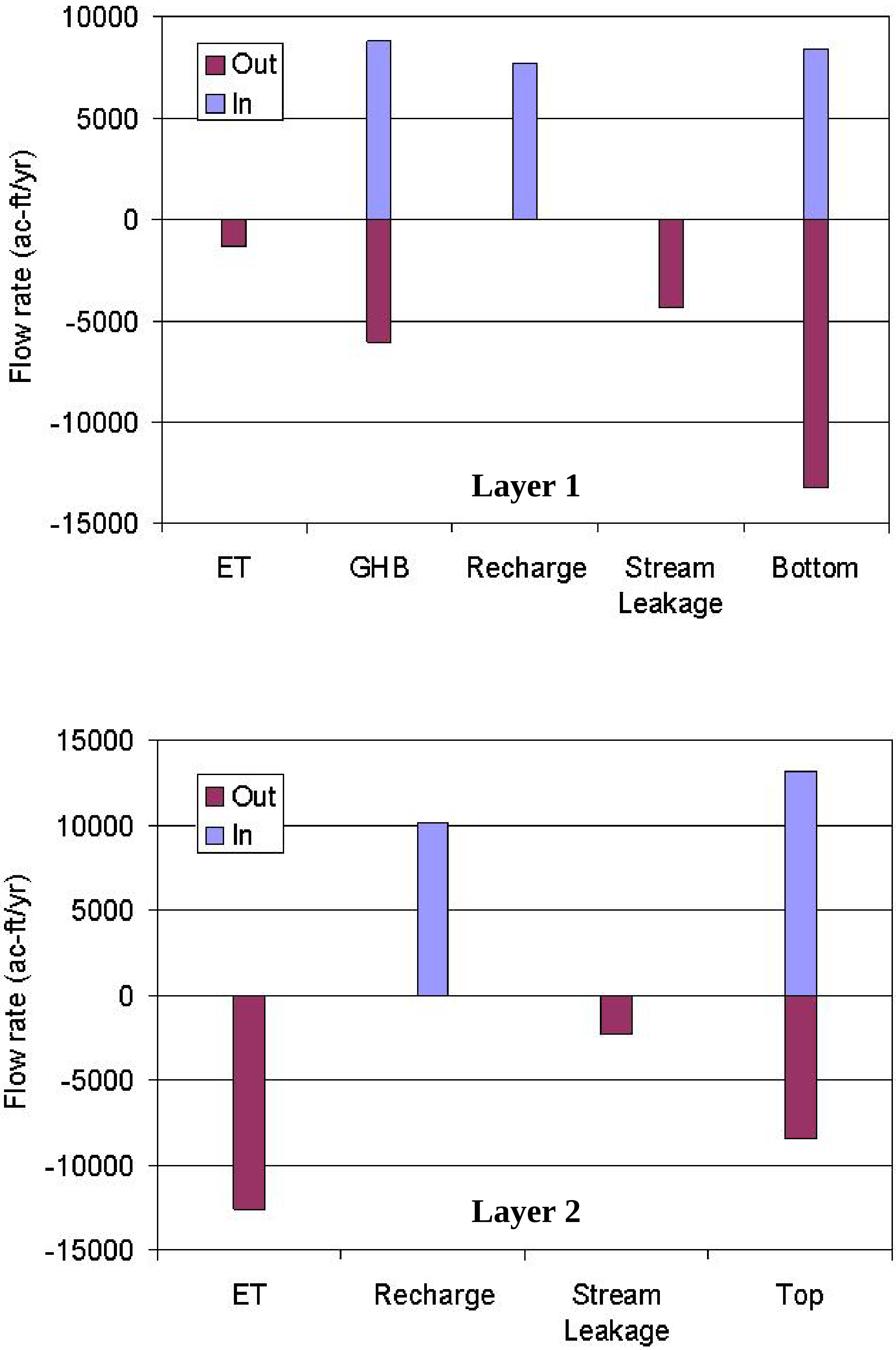


Figure 8.2.4 Water budget components in the steady-state model in layers 1 and 2

8.3 Sensitivity Analysis

A sensitivity analysis was completed for the calibrated steady-state model. One purpose of a sensitivity analysis is to quantify the impact on the model results when input parameters are varied. For this evaluation, hydraulic parameters were systematically increased and decreased from their calibrated values while the average change in head was calculated for the individual layers. For each parameter that was varied, four simulations were completed. The sensitivity factors were 0.5, 0.9, 1.1, and 1.5.

For the steady-state analysis, the sensitivity of seven parameters was evaluated. The seven parameters are:

1. Horizontal hydraulic conductivity (Kx)
2. Vertical hydraulic conductivity (Kz)
3. Recharge (RCH)
4. GHB head (GHBh)
5. GHB conductance (GHBc)
6. Stream conductance (C Str)
7. Pumping (P)

Figure 8.3.1 indicates that when hydraulic conductivity is decreased, average head increases, showing a negative correlation. The most sensitive positively correlated parameter is GHB head. Variations of GHB head of 0.5 and 1.5 factor were not included in the graph. A factor of 1.1 caused many cells to be flooded and a factor of 0.9 resulted in a lot of dry cells, both of which skewed the model results. Another parameter that is positively correlated to a lesser degree is recharge. Cutting recharge in half would bring average head down about 10 feet.

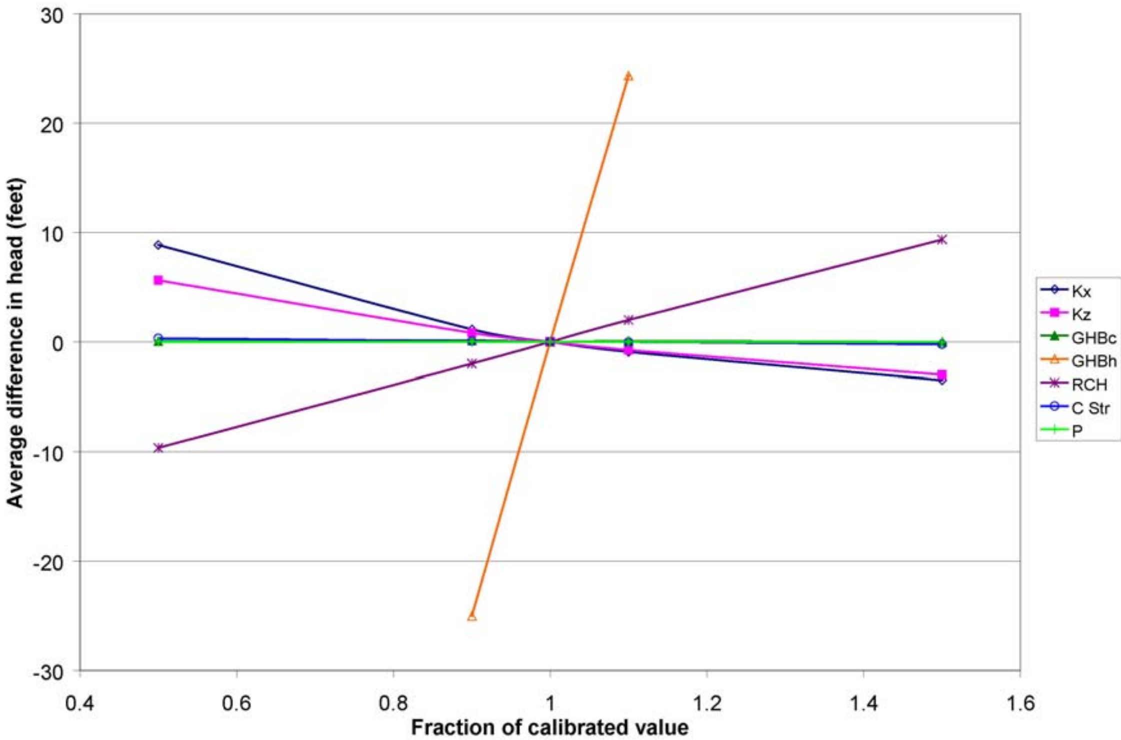


Figure 8.3.1 Steady-state sensitivity results

9.0 TRANSIENT MODEL

This section documents the calibration of the transient model and presents the transient model results. This section also details the sensitivity analysis completed for the transient model.

9.1 Calibration

The primary focus of the transient period is between 1980 and 1997. The short transient period (1978 to 1979) used estimated pumping in those two years but with average recharge, ET and other boundary conditions as in the steady-state phase.

Some of the aquifer storage properties, which were less sensitive during the long steady-state stress period, were more sensitive during the transient calibration and were adjusted to improve calibration. Because the calibration of the steady-state and transient model were coupled, the transient calibration also resulted in adjustment of hydraulic conductivity values and zonation as well as adjustment in the specific yield estimates. The hydraulic conductivity estimates within each zone were also adjusted to better calibrate the simulated response to the measured water level response between 1980 and 1997. In addition, recharge and pumpage are varied each year in the transient model. A discussion of these stresses and parameters is included below.

9.1.1 Calibration Targets

Water level measurements collected between 1980 and 1997 were used to calibrate the model. Figure 9.1.1 shows the locations of the wells containing water level measurements that were used for the transient calibration. There were 160 locations and 454 measurements in total. Some of the wells have one-time monitoring while others have water level measurements on an ongoing basis.

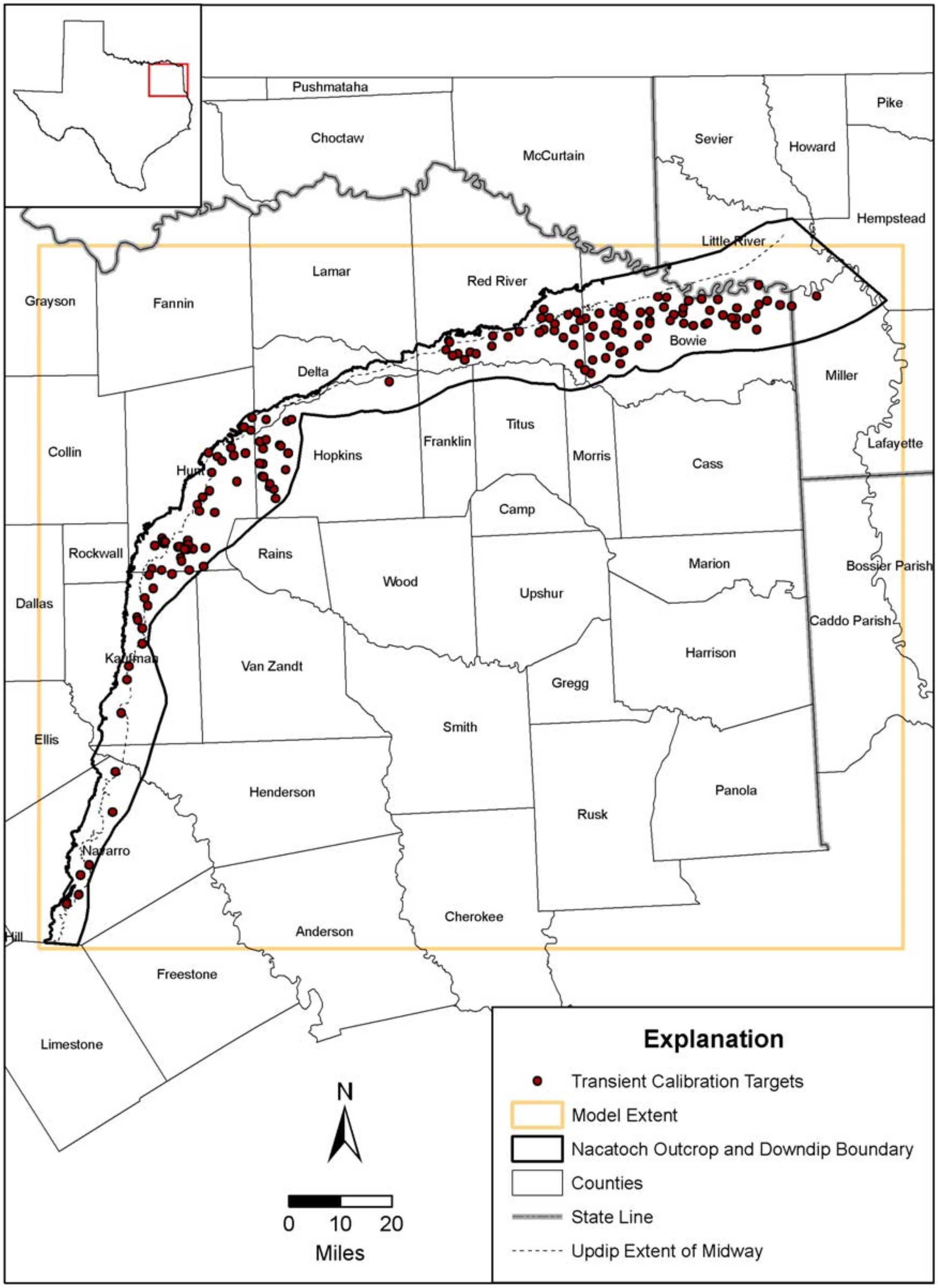


Figure 9.1.1 Location of wells used for transient calibration targets

9.1.2 Storage Properties

MODFLOW requires estimates of confined and unconfined aquifer storage properties, also referred to as storativity and specific yield, or primary and secondary storage coefficients. There are very few estimates of storativity and specific yield in the model area. Section 4.6 discussed the available information. Based on the relative lack of data, storativity and specific yield values were minimally zoned in each layer. The distribution of storage coefficients and specific yield for each layer of the model is shown in Figure 9.1.2 and Figure 9.1.3. The selection of these values was based on a combination of previous estimates and the calibration results.

9.1.3 Recharge and Pumpage

Figures 4.7.11 and 4.7.12 illustrate the estimated pumping that has occurred in the model area between 1980 and 1997. Figure 4.7.9 specifically shows spatial distribution of pumping entered into the transient model for the year 1997. For the transient calibration periods, it was assumed that the recharge was variable and was directly correlated to yearly precipitation.

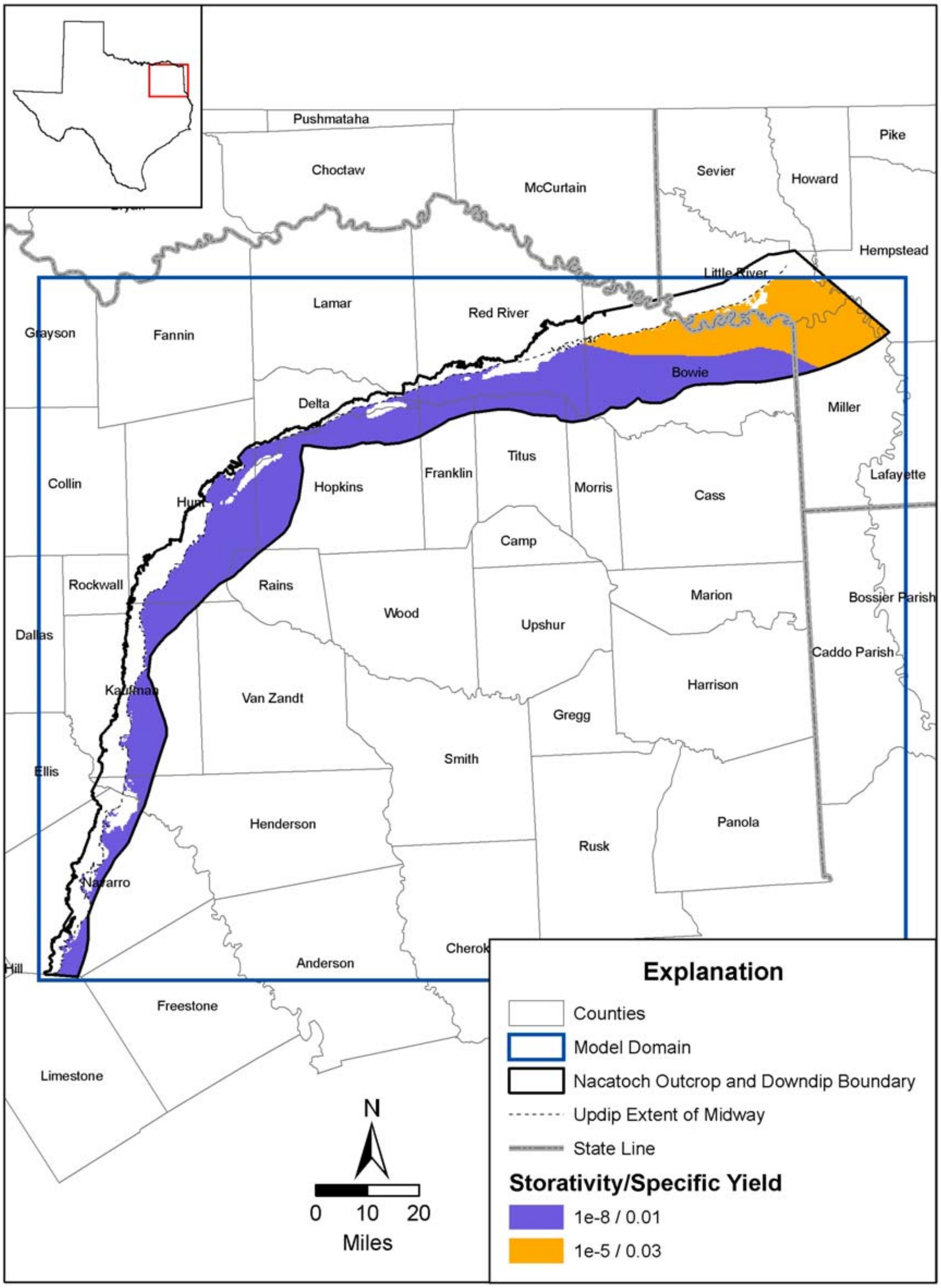


Figure 9.1.2 Final distribution of storage properties in layer 1

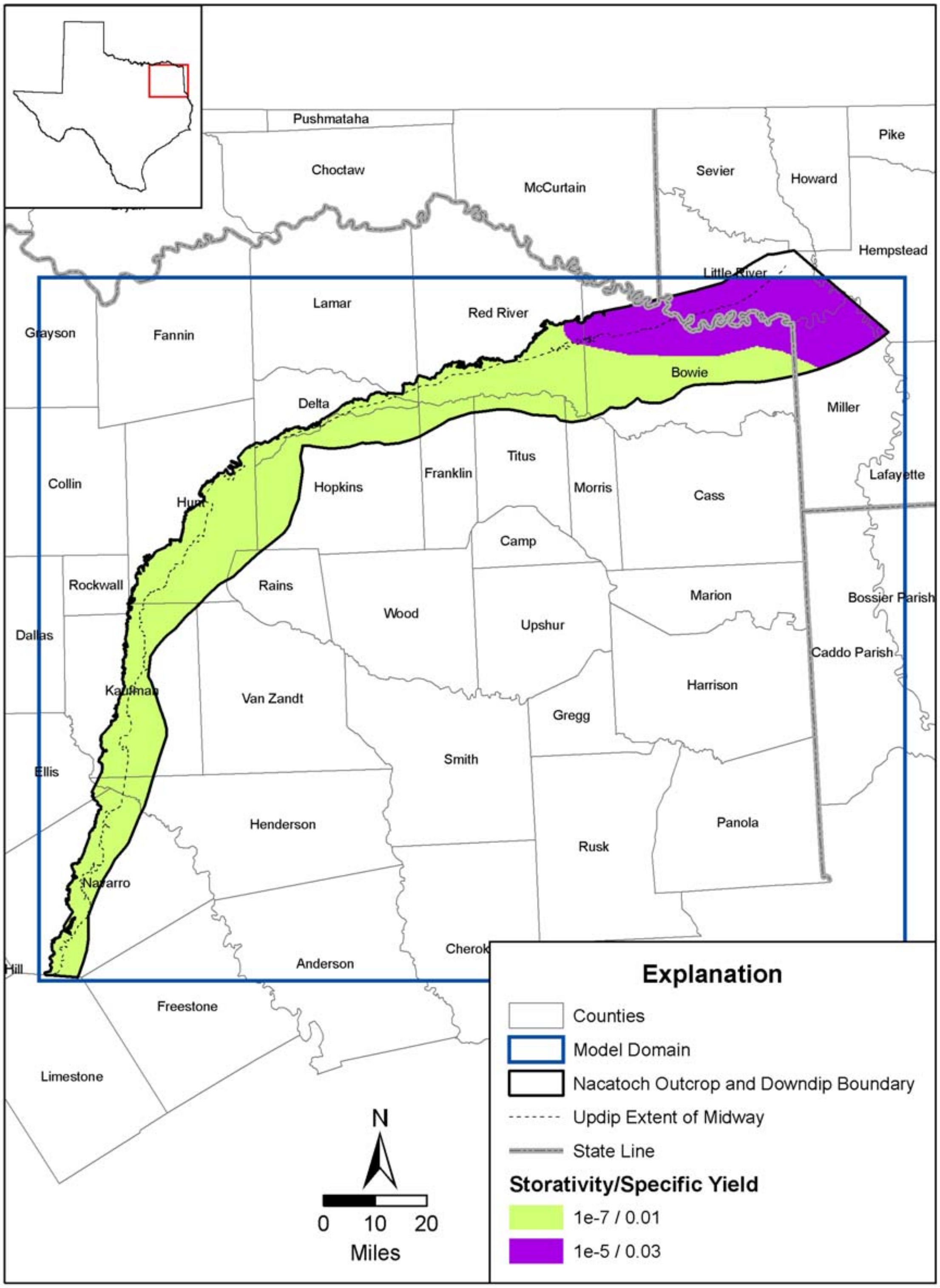


Figure 9.1.3 Final distribution of storage properties in layer 2

9.2 Results

As described in Section 8, the calibration of the transient model was iterative, and was coupled with the calibration of the steady-state model. This section will describe the results of the calibration phase of the model.

9.2.1 Calibration Statistics

Table 9.2.1 summarizes the statistics for the available head targets during the calibration period of the transient model. The statistics show that the model is capable of simulating heads and the change in head through time relatively well. The ratio of MAE to range for layers 1 and 2 are about 8 percent for each layer during the transient calibration period. The RMS for layers 1 and 2 during the transient calibration period are 4 and 38 feet, respectively.

Figure 9.2.1 shows the crossplot of the simulated and observed heads during the transient calibration period. Figure 9.2.2 shows the crossplot of residuals versus the observed heads during the transient calibration period. The trends in the observed water level hydrographs in the Nacatoch Aquifer are simulated well, in general. Also note, the residuals are high when the number of observation points are very low. Wells having high residuals include state well numbers (SWN) 1742707, 1749306, 1750705, 1750706, 1758102, 1758104 and 3307505. All have only one observation point except well 1742707, which has 14. Having only one observation may question the validity of the data, such as whether the measurement was taken during a seasonal low or high, or whether it was taken when nearby wells were pumping. Wells 1742707 and 1749306 are also located very close to the edge of the outcrop area. Sometimes, transmissivity cannot be adequately represented in that region. Another possibility is that there are local flow control features that cannot be represented in the model, such as a localized fault zone. Figure 9.2.3 shows average residuals for all water level measurements in each target well for the transient calibration period.

Table 9.2.1 Head calibration statistics for the calibration period

Calibration period (1980 - 1997)

Layer	Count	ME (feet)	MAE (feet)	RMS (feet)	Range (feet)	MAE/Range
1	16	-1	4	4	50	8.5%
2	438	-18	30	38	386	7.8%
All	454	-18	29	38	386	7.5%

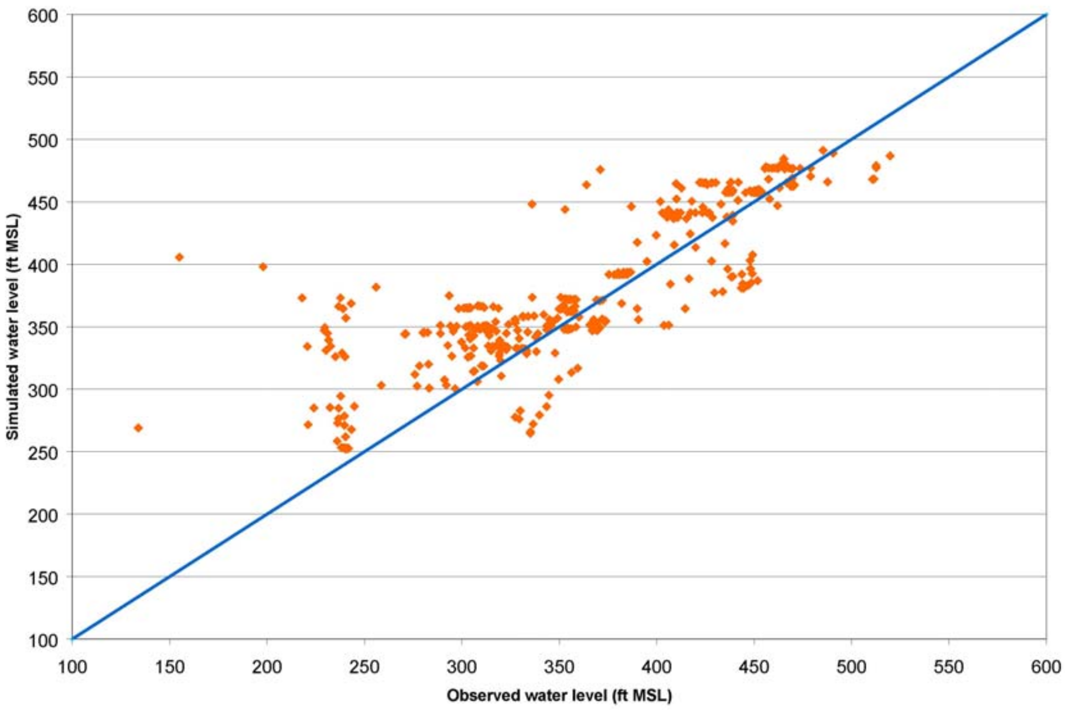


Figure 9.2.1 Simulated versus observed heads during the transient calibration period

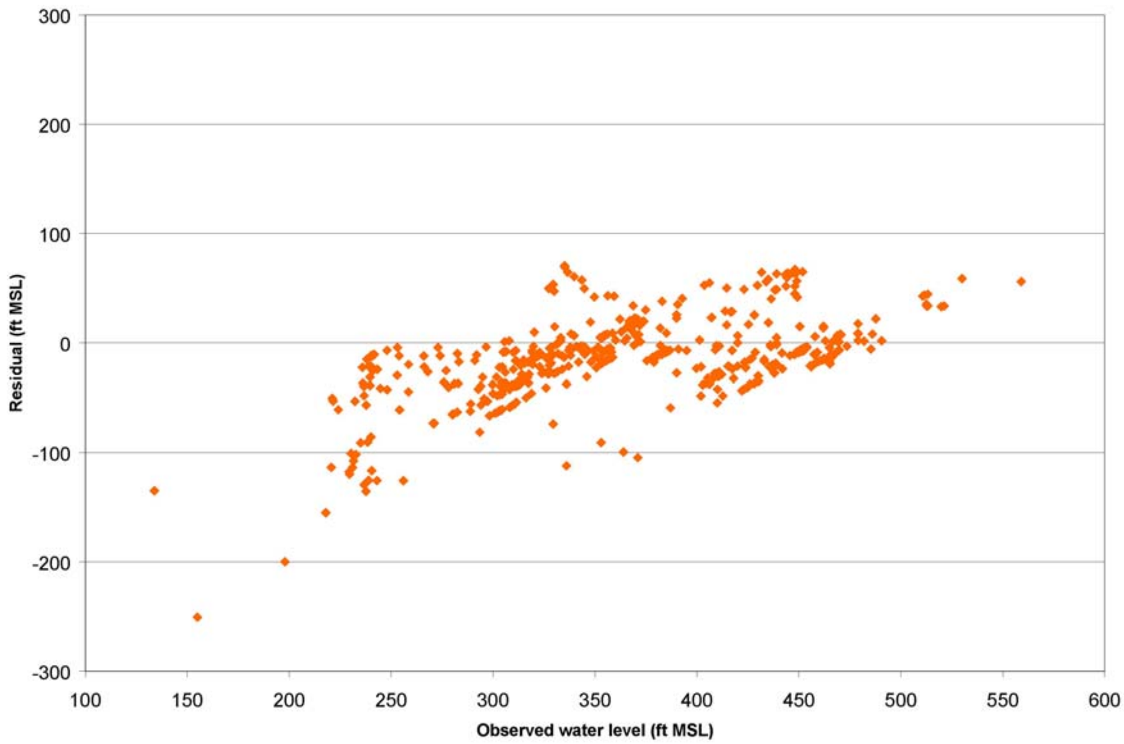


Figure 9.2.2 Residuals versus observed heads during the transient calibration period

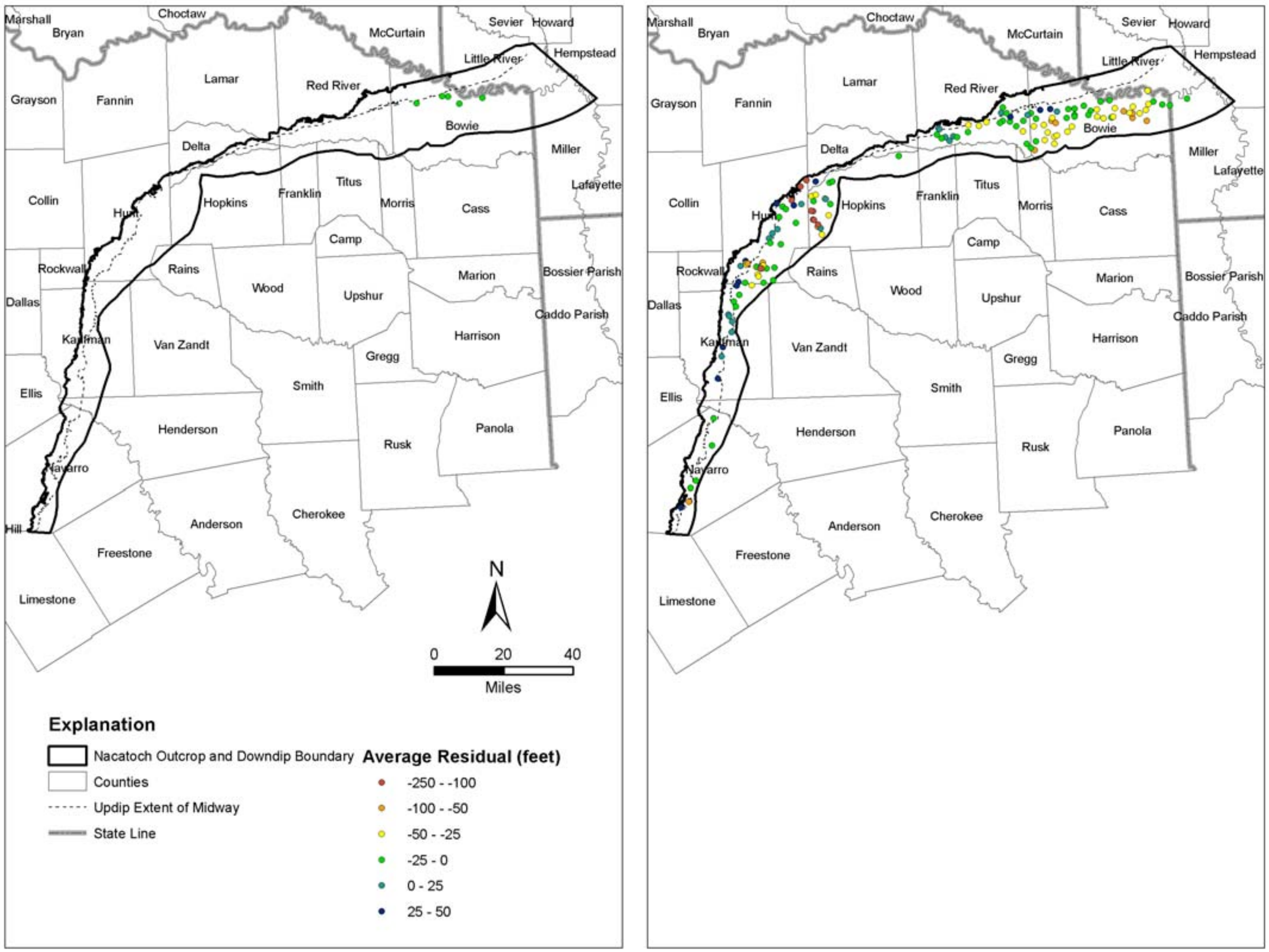


Figure 9.2.3 Average residuals for the calibrated transient simulation (1980-1997) in layer 1 and layer 2

9.2.2 Hydraulic Heads

Figure 9.2.4 shows the simulated hydraulic heads in layer 1 in 1990 and 1997. No residuals are shown in this figure because there are no calibration targets in layer 1 for this time period. Figure 9.2.5 shows the simulated hydraulic heads and available residuals in layer 2 in 1990 and 1997. In general, the hydraulic head maps show similar trends as discussed in the conceptual model report.

Figure 9.2.6 through Figure 9.2.8 show simulated and observed hydrographs for selected wells in different areas of the model. In general, there is an agreement between the observed and simulated water levels, but more importantly, the simulated trends are very similar to observed trends.

Figures 9.2.9 and 9.2.10 show the simulated water level declines in layer 1 and 2 respectively between 1980 and 1997. The water level changes in the Nacatoch Aquifer are consistent with the observed regional changes.

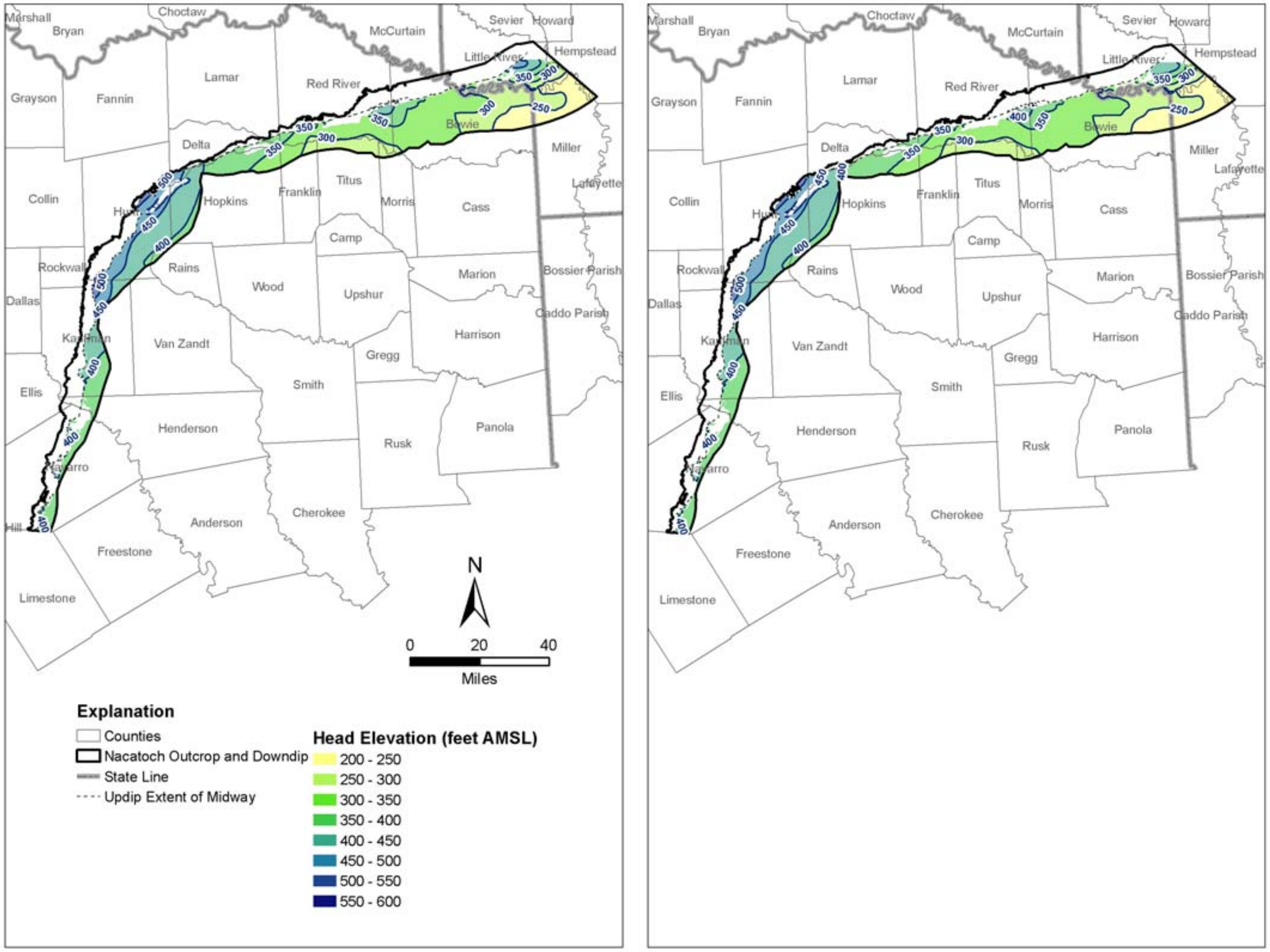


Figure 9.2.4 Simulated hydraulic heads in layer 1 in 1990 and 1997

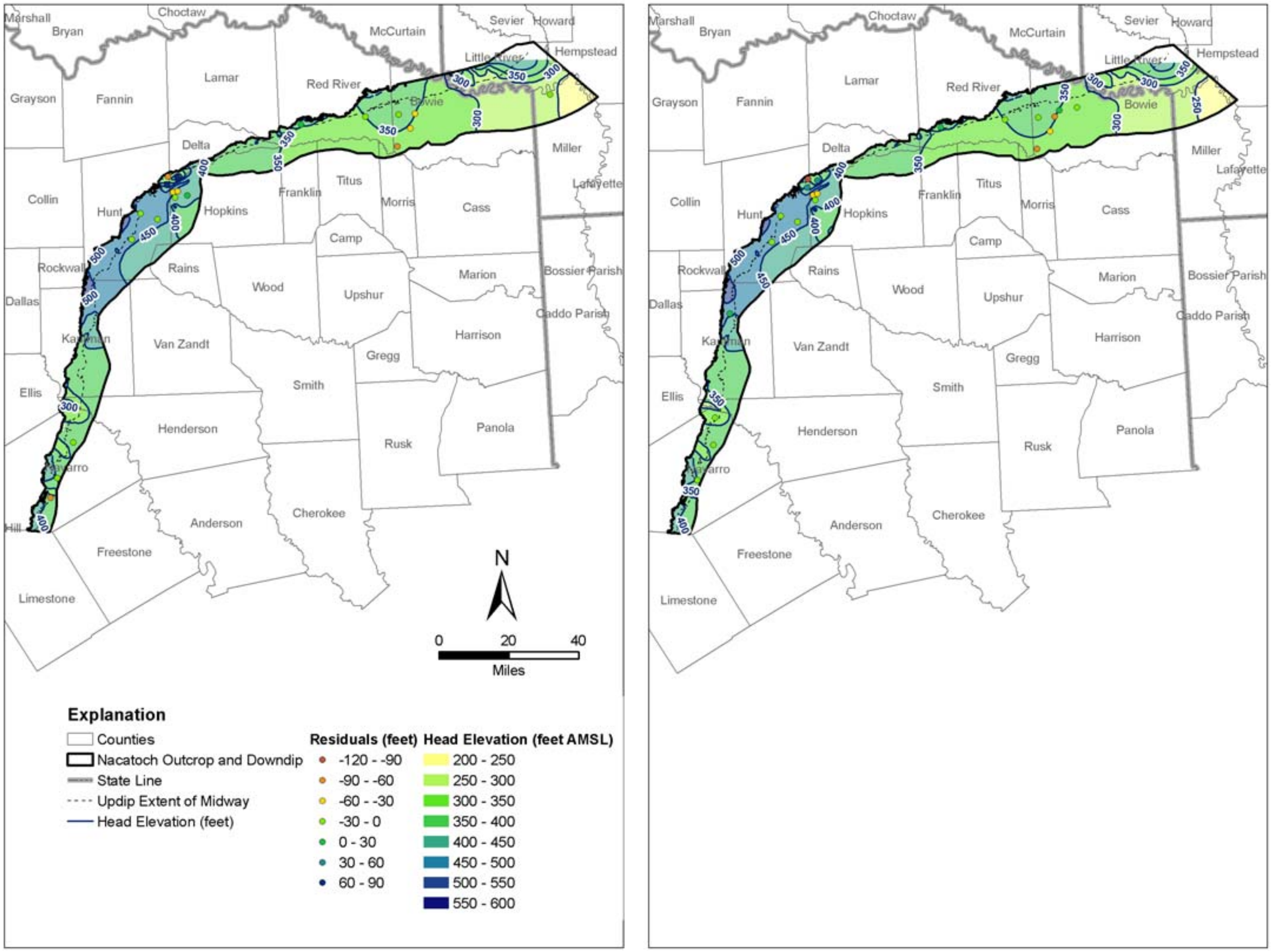


Figure 9.2.5 Simulated hydraulic heads and residuals in layer 2 in 1990 and 1997

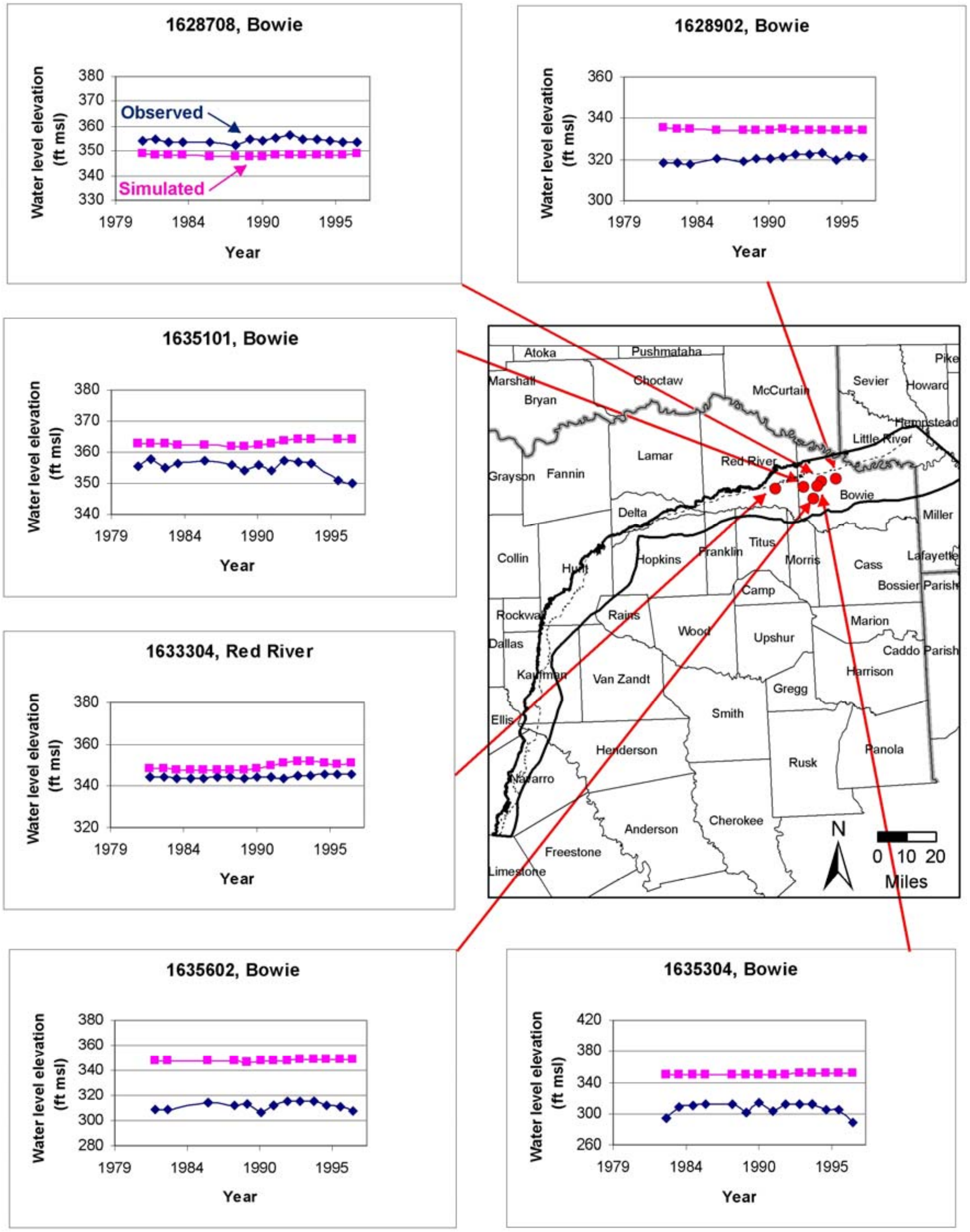


Figure 9.2.6 Simulated and observed hydrographs between 1980 to 1997 (area 1)

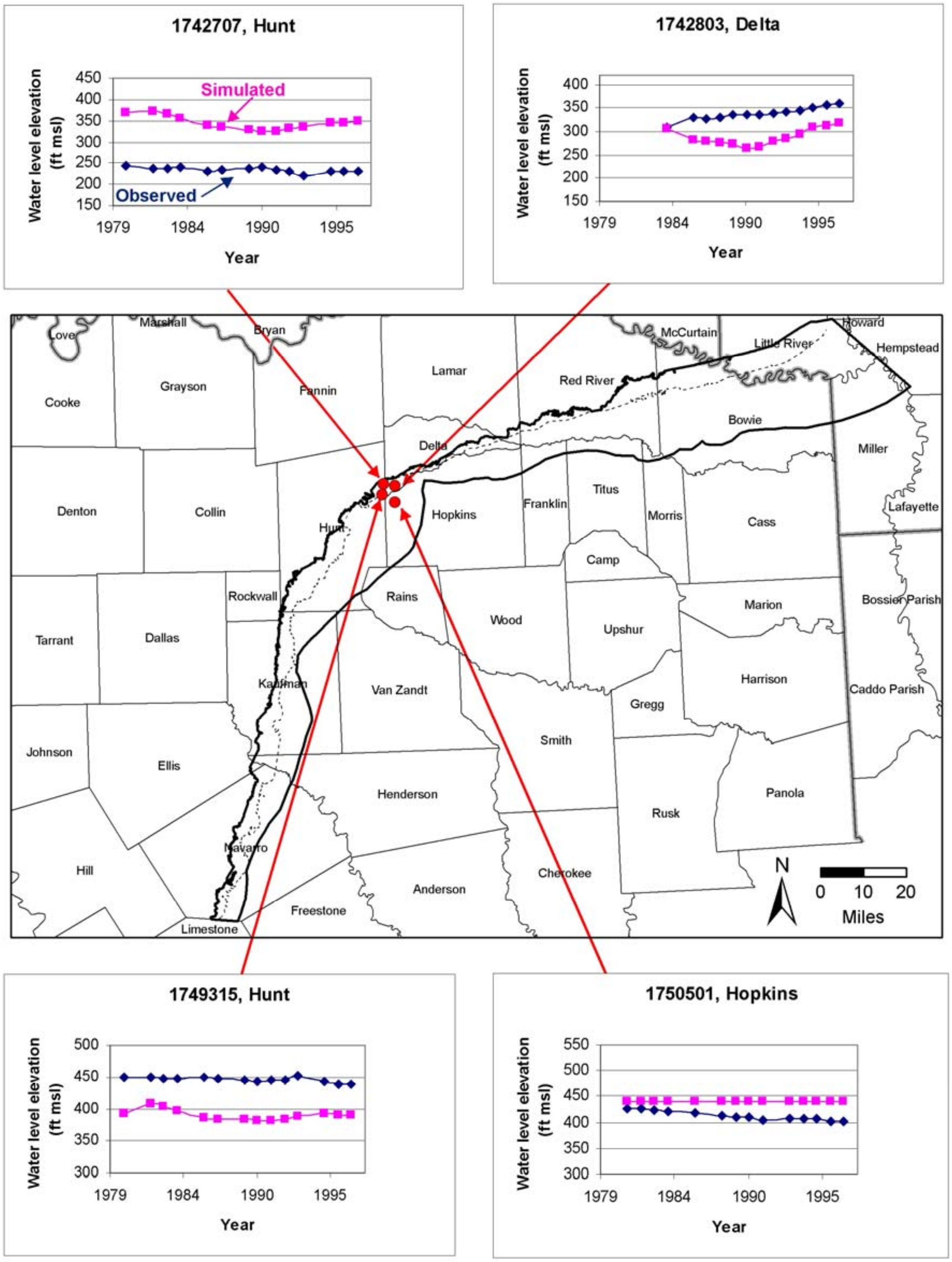


Figure 9.2.7 Simulated and observed hydrographs between 1980 to 1997 (area 2)

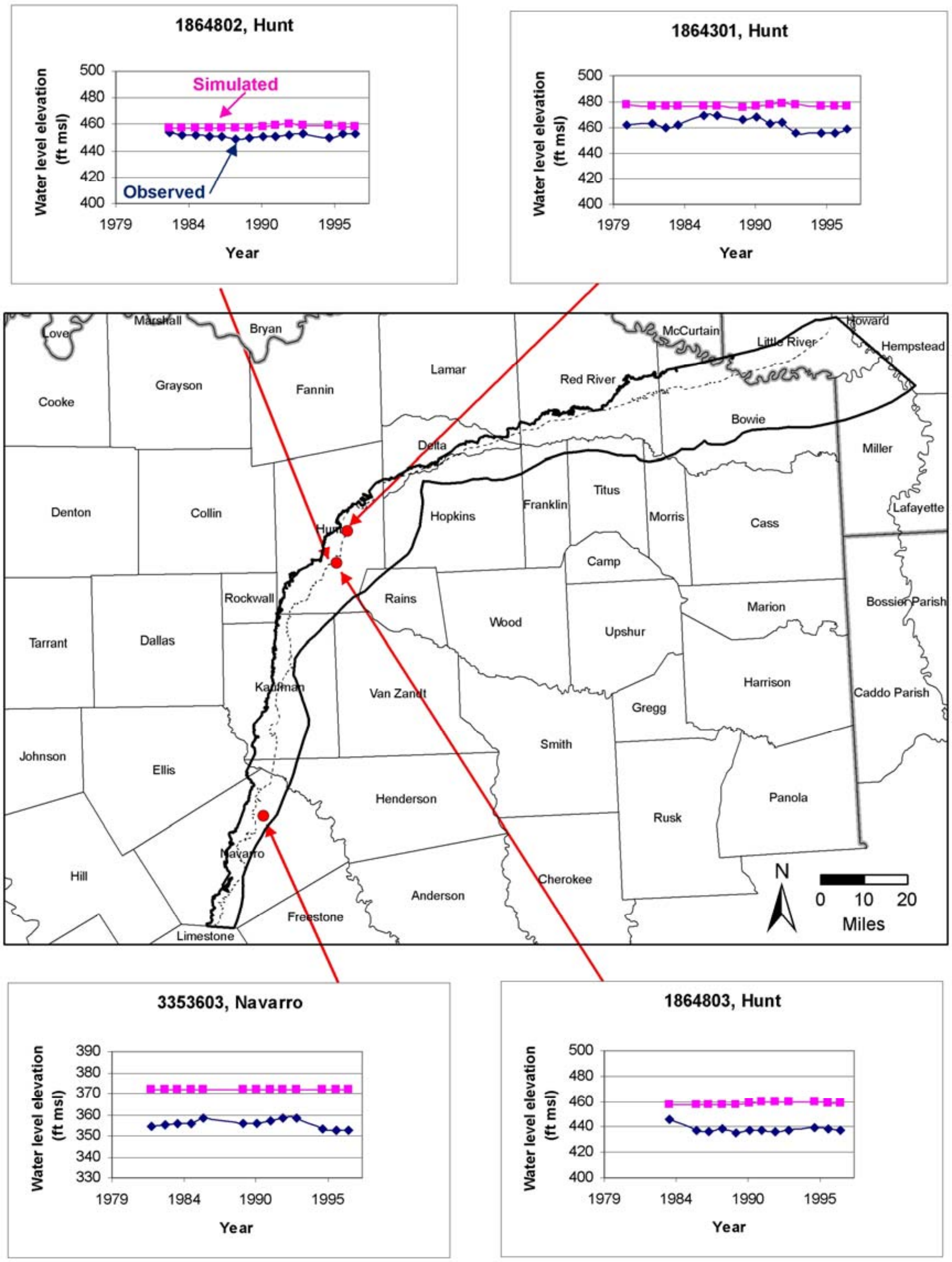


Figure 9.2.8 Simulated and observed hydrographs between 1980 to 1997 (area 3)

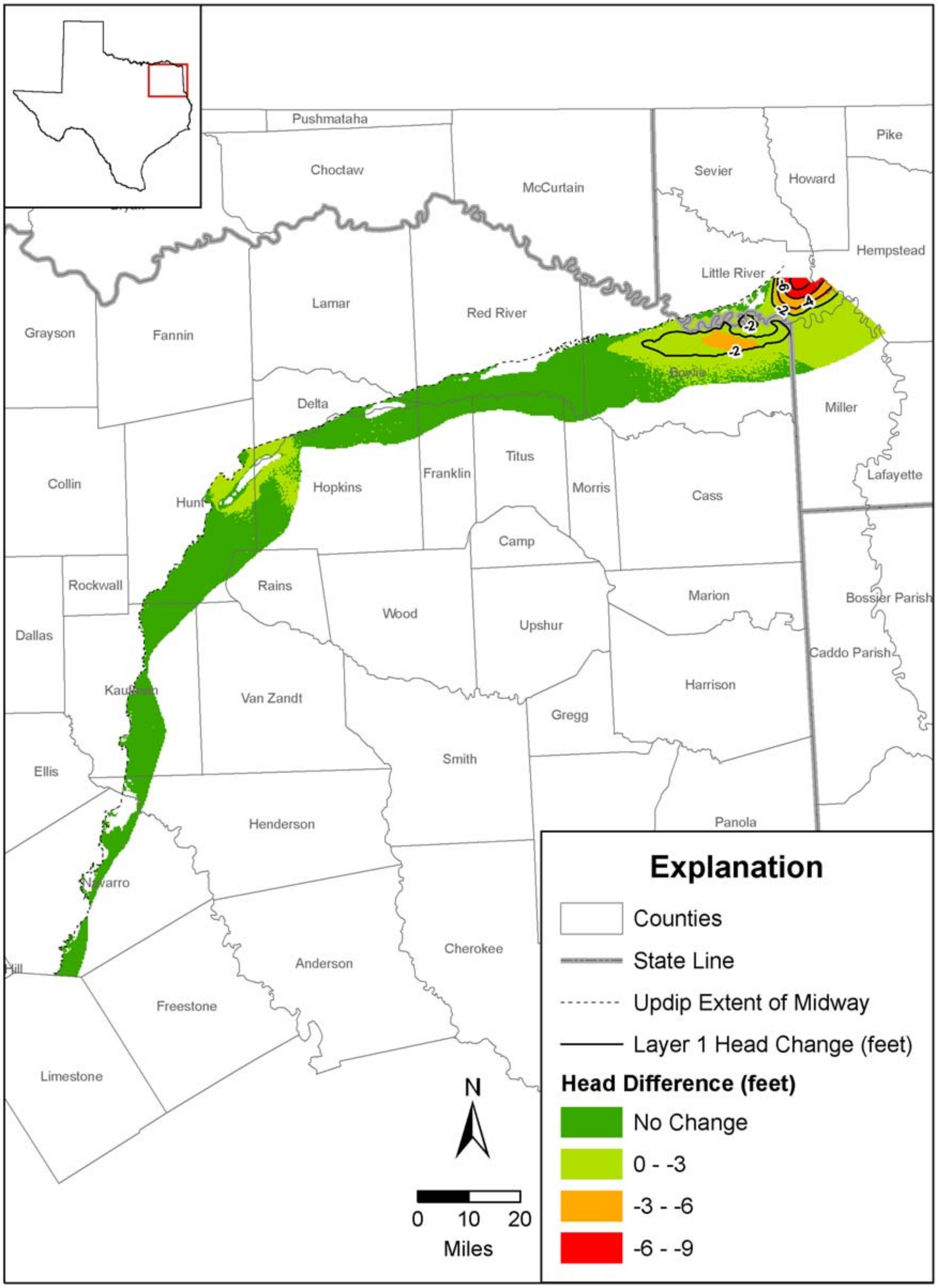


Figure 9.2.9 Change in water levels between 1980 and 1997 in layer 1

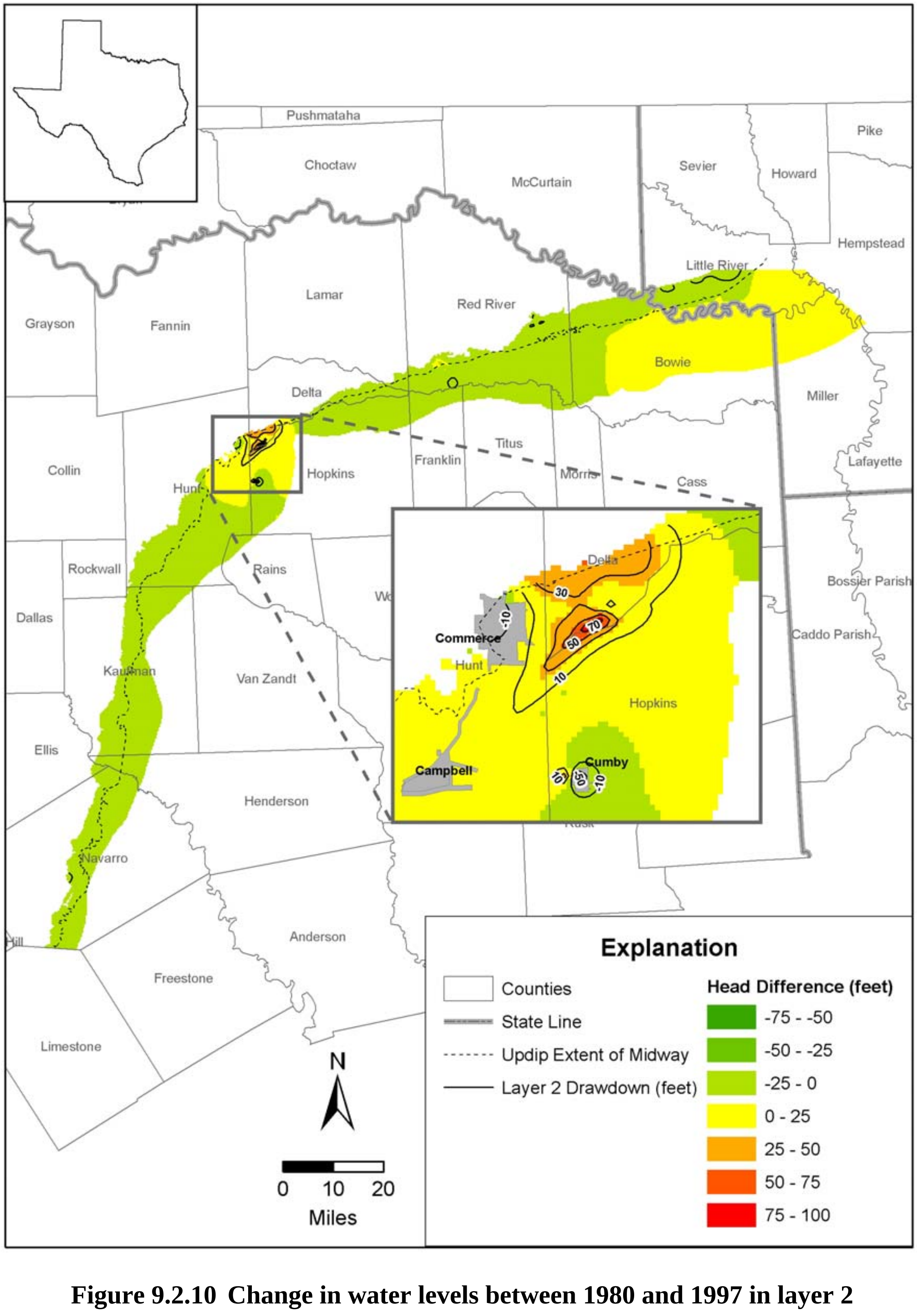


Figure 9.2.10 Change in water levels between 1980 and 1997 in layer 2

9.2.3 Water Budget

Figures 9.2.11 and 9.2.12 provide a graphical summary of the water budget components for layers 1 and 2, respectively, during the transient calibration period. Table 9.2.2 is the summary of water budget for 1990 and 1997. The water budget numbers were obtained by using USGS Zone Budget program. The major changes in the layer 1 flow components are cross-formational flow and recharge.

Layer 2 flow components show some temporal variation due to changes in recharge. The change in recharge on a yearly basis is mimicked by a corresponding change in aquifer storage due to increasing water levels. During years when recharge increases from the previous year, there is a corresponding increase in storage (shown on the graph as a decrease in storage outflow). ET also increases when recharge is high. Appendix A contains a summary of the 1997 water budget for each county in Texas.

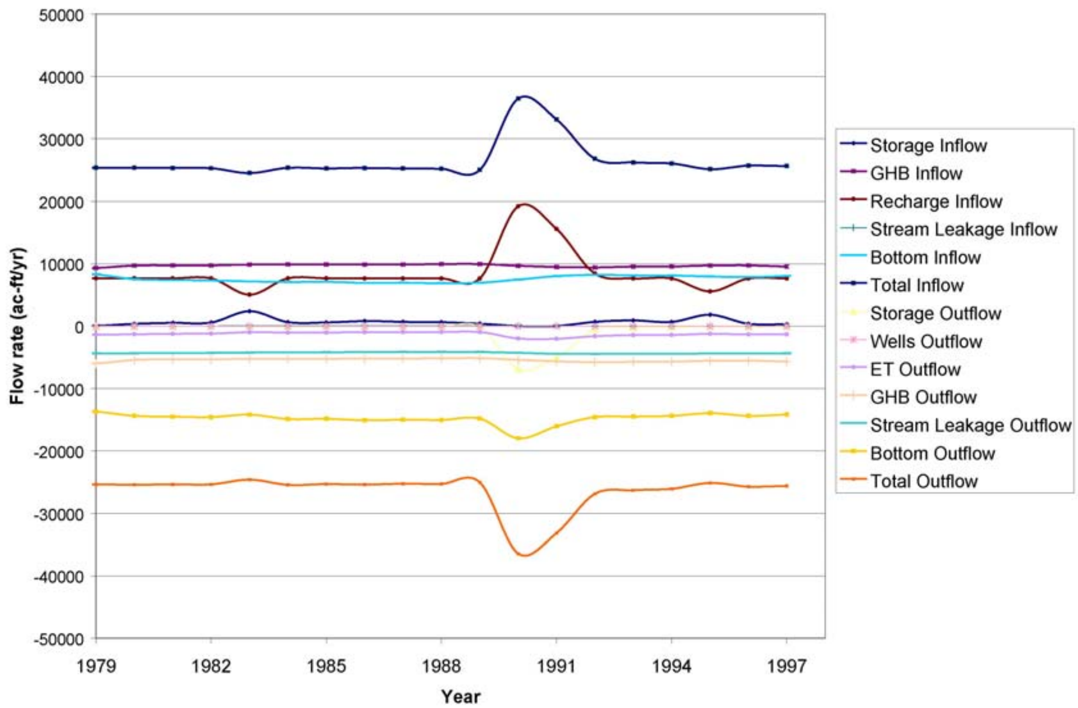


Figure 9.2.11 Water budget components between 1980 and 1997 for layer 1

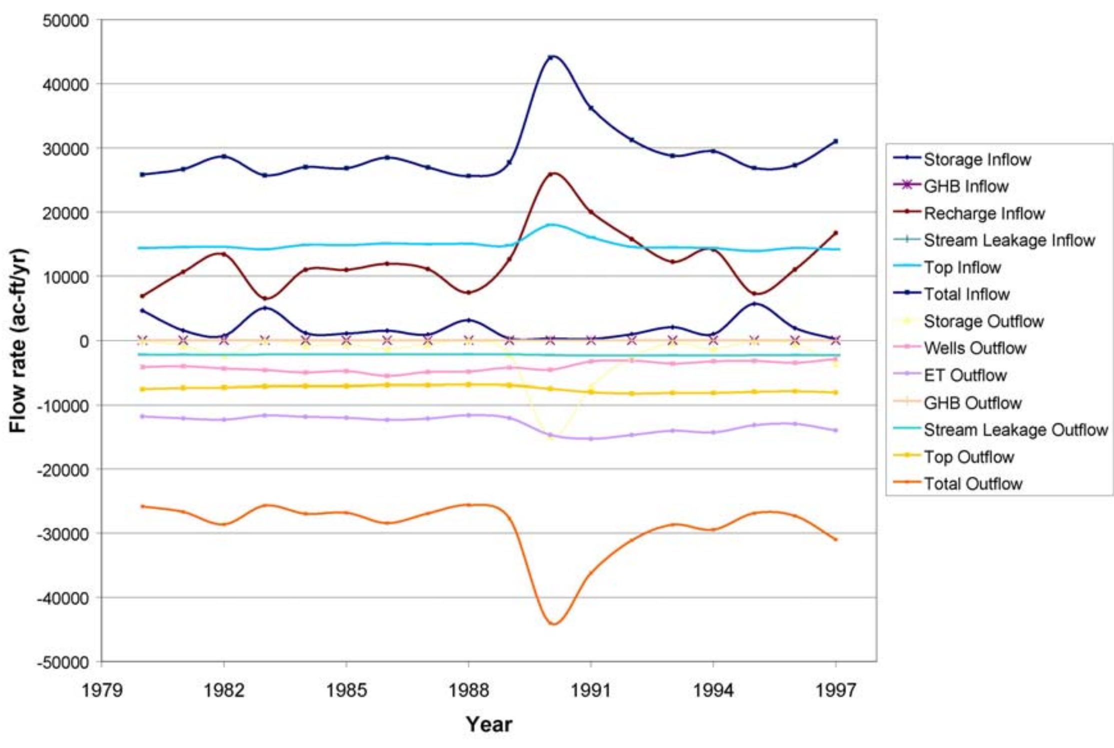


Figure 9.2.12 Water budget components between 1980 and 1997 for layer 2

Table 9.2.2 Water budget for 1990 and 1997 calibration periods

		Layer	Top	Bottom	ET	Stream	GHBs	Recharge	Storage
1990	**IN**	1	0	6,850	0	44	9,525	18,227	38
		2	17,876	0	0	9	0	26,741	265
		Sum	17,876	6,850	0	53	9,525	44,968	303
	OUT	1	0	17,876	821	3,973	5,339	0	6,920
		2	6,850	0	16,332	2,301	0	0	14,618
		Sum	6,850	17,876	17,153	6,274	5,339	0	21,538
1997	IN	**1**	0	7,307	0	44	9,403	7,329	327
		2	14,276	0	0	10	0	16,950	151
		Sum	14,276	7,307	0	54	9,403	24,279	478
	OUT	**1**	0	14,276	577	4,032	5,590	0	107
		2	7,307	0	15,136	2,322	0	0	3,410
		Sum	7,307	14,276	15,713	6,354	5,590	0	3,517

Note: Units are in ac-ft/yr. A positive number indicates water entering the aquifer system or layer while a negative number indicates water leaving the aquifer system or layer.

9.3 Sensitivity Analysis

A sensitivity analysis was performed on the calibrated transient model to provide a summary of the sensitivity of the model to changes in individual input parameters. For this analysis, model parameters were globally adjusted from their calibrated values and the results of average head change in each layer were calculated. As in the steady-state sensitivity evaluation, the model parameters were adjusted +/- 10% and +/- 50% from their calibrated value. This sensitivity analysis helps to identify the hydrologic parameters which have the most influence on the hydrologic system being modeled and can help assess which parameters should be better determined in future field studies in order to lower the model uncertainty. A summary of the transient sensitivity analysis is provided below.

For the transient analysis, the sensitivity of nine parameters was evaluated. The nine parameters are:

1. Horizontal hydraulic conductivity (Kx)
2. Vertical hydraulic conductivity (Kz)
3. Recharge (RCH)
4. GHB head (GHBh)
5. GHB conductance (GHBc)
6. Storativity – confined (Ss)
7. Specific yield – unconfined (Sy)
8. Stream conductance (Str)
9. Pumping (P)

In general, there are similarities and differences between the results of the steady-state and the transient sensitivity analysis. As shown in Figure 9.3.1, the most sensitive positively correlated parameter is GHB head. Again, large changes in GHB heads were not included in the graph as the model results may not be realistic. The parameter which is positively correlated to a lesser degree is recharge. Of the two storage properties assessed herein, specific yield has more influence on average head than does storativity. Storativity and GHB conductance are not very sensitive.

Doubling the pumping amount would reduce heads about 10 feet in Nacatoch Aquifer (Figure 9.3.2). While horizontal hydraulic conductivity is negatively correlated to heads in layer 1, it is positively correlated to heads in layer 2. Sensitivity to hydraulic conductivity for both layers is summarized in Figure 9.3.3. Recharge, on the other hand, is positively correlated to heads in both layers (Figure 9.3.4). Figure 9.3.5 shows the sensitivity of water level to global changes in horizontal hydraulic conductivity. In most cases, the hydrograph did not change very much.

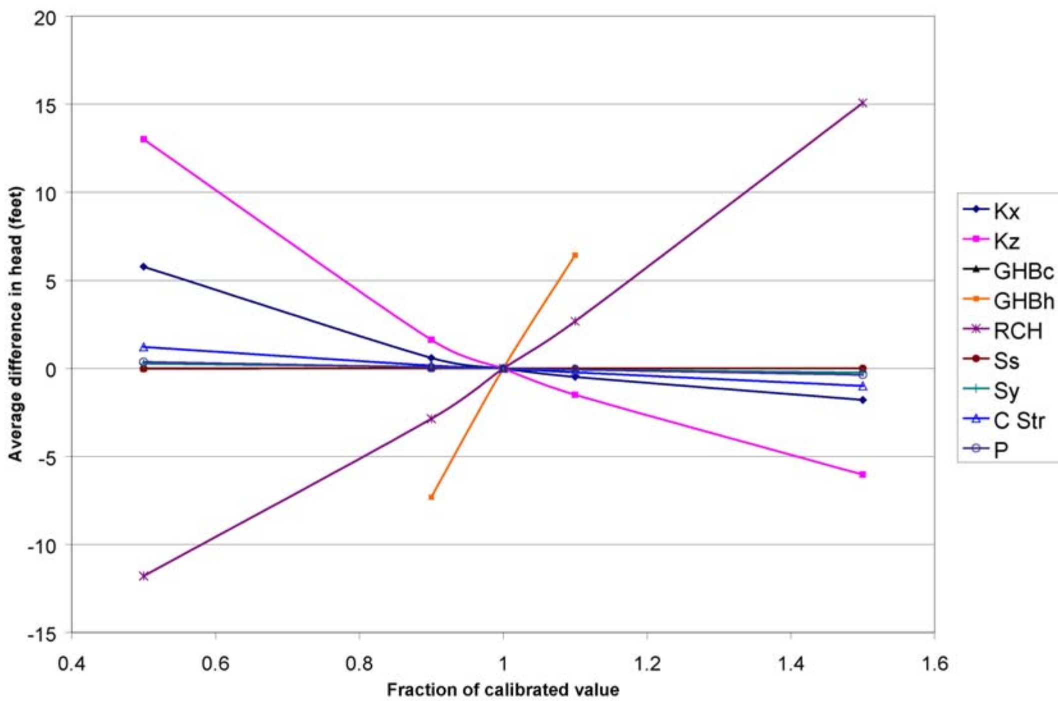


Figure 9.3.1 Transient sensitivity results for layer 1

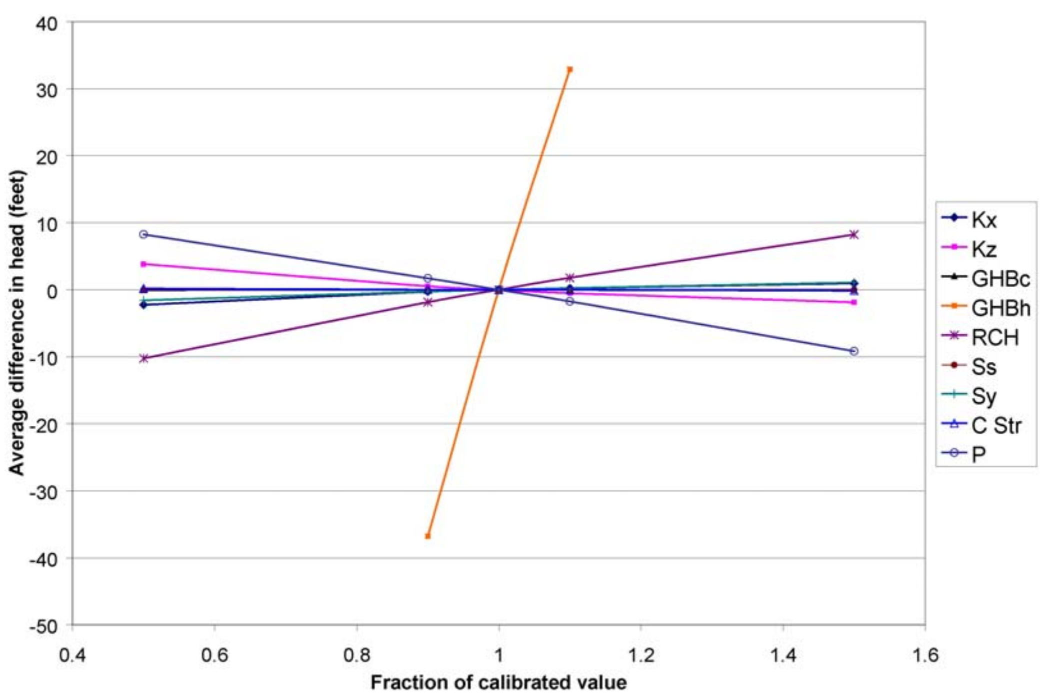


Figure 9.3.2 Transient sensitivity results for layer 2

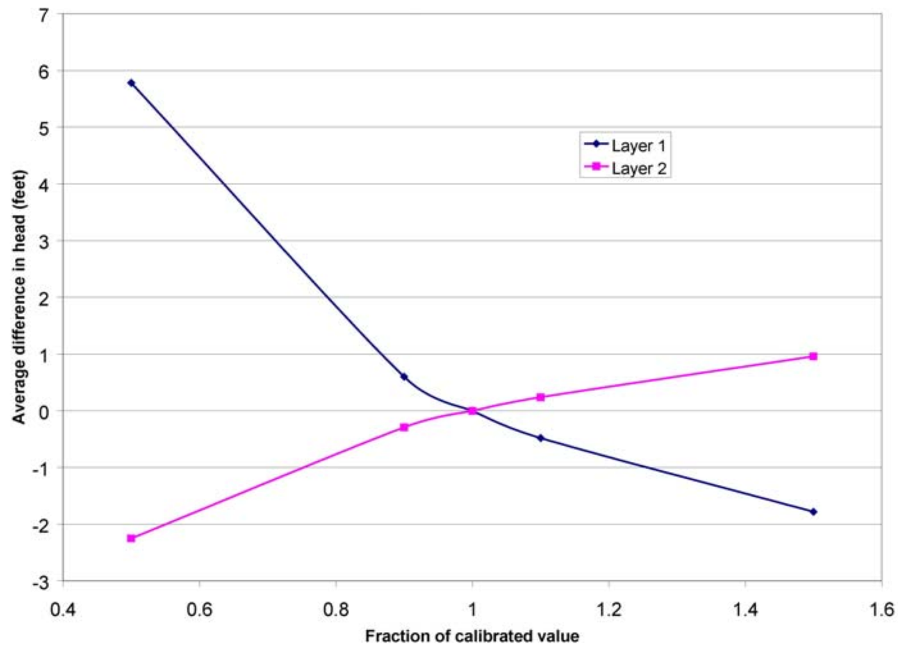


Figure 9.3.3 Transient sensitivity results by layer where horizontal hydraulic conductivity is varied

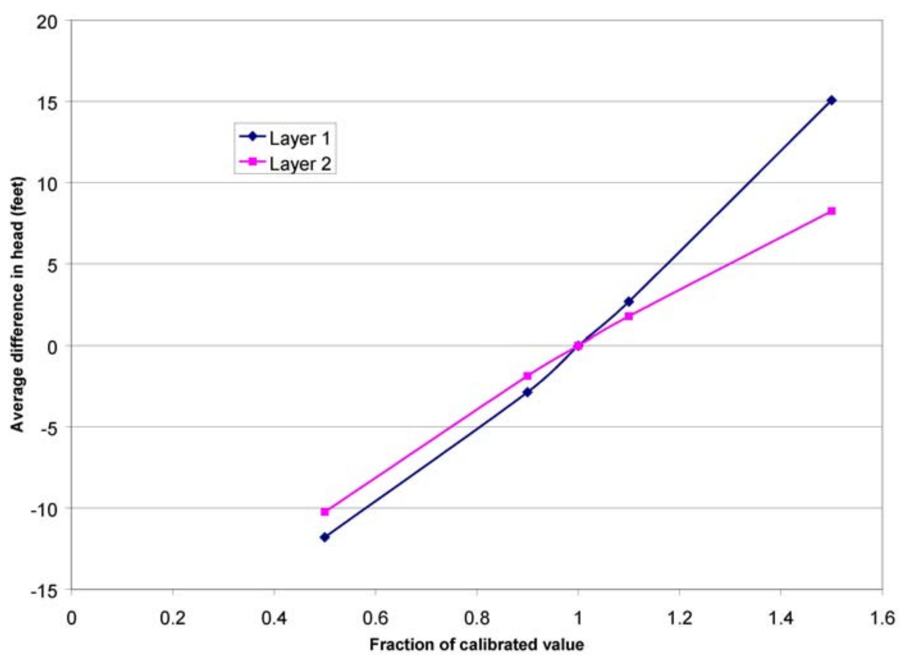


Figure 9.3.4 Transient sensitivity by layer where recharge is varied

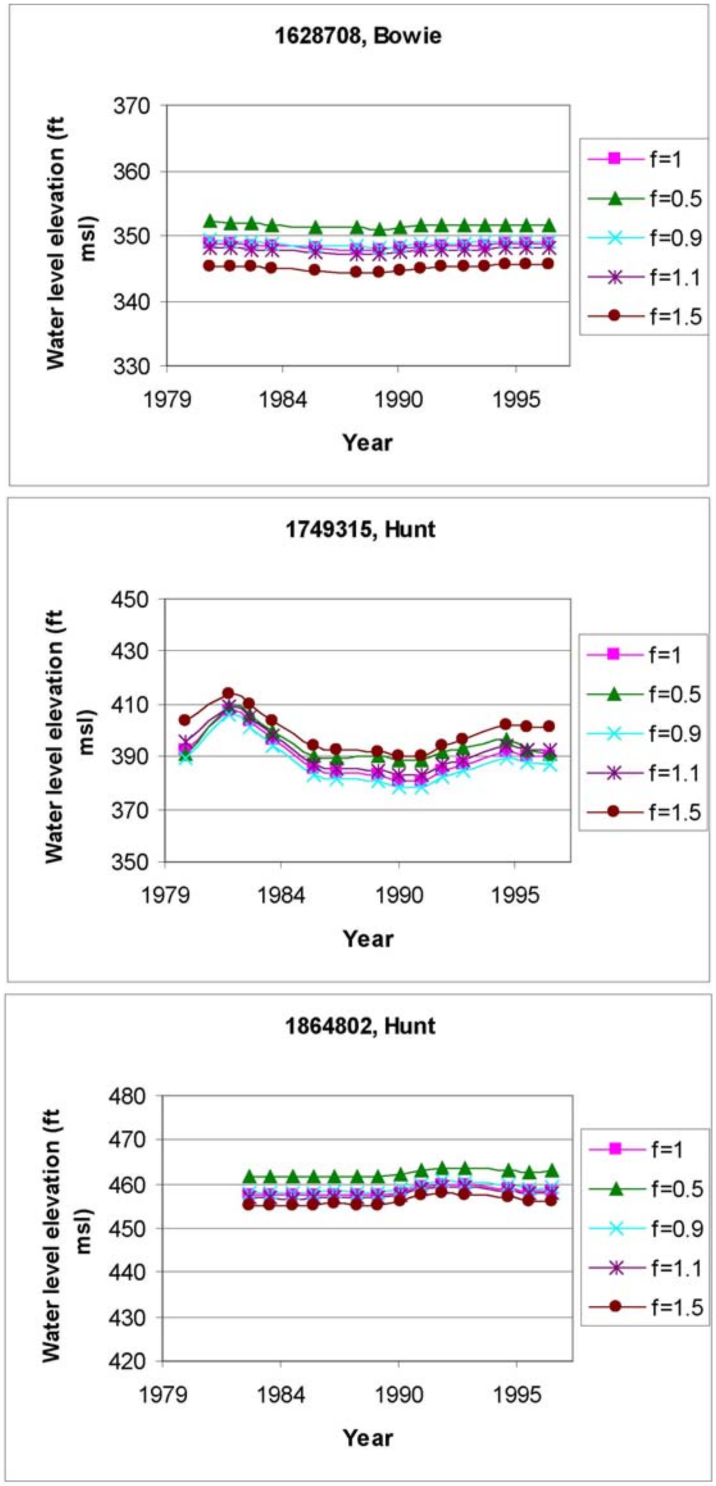


Figure 9.3.5 Transient sensitivity hydrographs where horizontal hydraulic conductivity is varied

10.0 LIMITATIONS OF THE MODEL

A groundwater model simulates aquifer dynamics and responses to hydrologic stresses such as groundwater withdrawals and changes in recharge conditions. The accuracy to which a model can make these predictions is directly related to the reliability of aquifer data that are input into the model.

The Nacatoch aquifer has been used in some regions but not others. In the regions where the aquifer has been used, some groundwater data was documented. This provides valuable information for model calibration. However, in areas where it has not been used significantly, only scarce data is available. This lack of data presents challenges when developing a groundwater flow model, even on a regional scale. Some examples of data shortages include the lack of:

- sufficient well completion data for a stratigraphy assessment,
- sufficient long-term water-level trends in different areas,
- aquifer transmissivity and storativity data,
- location and extent of fracture zones and associated hydraulic characteristics, and
- structural controls and other factors which impact stream-aquifer interaction.

The flow system in the study area contains several complexities that have been simplified for modeling purposes. The Nacatoch Sand was represented by a single model layer in the conceptual and numerical models. In reality, the aquifer consists of many different zones that are hydraulically connected in varying degrees.

Hydrologic parameters and stresses are averaged spatially to the model grid resolution. In some cases, this representation limits the accuracy of small-scale hydrologic phenomenon. Model boundaries have been simplified as well. The concept of a no-flow boundary in the downdip is only valid if no significant stress is close to it. Recharge and evapotranspiration estimates, while based on available information, are still uncertain.

The Nacatoch Aquifer GAM was not designed to be used for estimation of individual well yields, and caution should be exercised when using this model to evaluate local well fields. Much more detailed information and in some cases redefined boundary conditions may be necessary to obtain realistic results for this level of evaluation.

Surface water-groundwater interaction has been included in this model in a very general manner. Not much information is available to constrain simulated flux between the aquifer and streams. Therefore, it is not appropriate to use the model to evaluate specific impacts of pumpage on individual streams.

11.0 FUTURE IMPROVEMENTS

In general, the structure data obtained during this modeling process seems reasonably adequate for constructing a regional model. However, refinement of the structural data in the areas of extensive faulting and deformation would likely improve the accuracy of the simulations. Additional data about the extent and characteristics of the fault zones, especially those close to the pumping center, would make further refinement possible and would improve the accuracy of the simulations.

Groundwater in the Nacatoch Aquifer has been used in some regions but not others. Coverage of basic groundwater data (water levels, water chemistry and pumping tests) in regions where it is not used may be useful to improve calibration. Continued collection of basic groundwater data in regions where it is used would help refine the model.

The sensitivity analyses indicated the model is sensitive to recharge flux. Estimates of annual recharge were based on yearly rainfall. The approach is empirical but might be the most practical for this modeling effort. In some cases, a relatively dry year may have a couple of relatively wet periods when recharge is significant and perhaps even higher than a relatively wetter year. On the other hand, large storm events may occur in some years that increase the total yearly precipitation above average, but most of the rainfall may run off. The equation developed in this modeling process cannot capture such variations. Further recharge study, including frequency analysis of storm events and corresponding groundwater responses would contribute to model improvement.

The distribution of historical pumping has a significant impact on model calibration. The pumpamatic procedure developed by the TWDB has provided a consistent approach for pumping allocation. However, some records may not be reliable and some information may be missing. Continued efforts to improve water use survey data will help bridge the gap in historical pumping data.

12.0 CONCLUSIONS

A three-dimensional groundwater model was developed for the Nacatoch Aquifer according to a methodology prescribed by the TWDB. This modeling approach was consistent with TWDB GAM protocol and includes: (1) the development of a conceptual model of groundwater flow in the aquifer, (2) model design, (3) model calibration, (4) sensitivity analysis, and (5) documentation of the model.

The model is regional in scale, and was developed with the MODFLOW-2000 flow code. The conceptual model developed for the flow model divides the aquifer system into two layers. Layer 1 represents the Midway, and in areas near the Red River, layer 1 represents the alluvium associated with the Red River. Layer 2 represents the Nacatoch Aquifer. The conceptual model was based on data compiled from many sources and included a detailed analysis of recharge and evapotranspiration for the model area. Available hydraulic conductivity, aquifer storage properties, and water level measurements were assimilated for use in developing a representative and defendable model.

The calibrated steady-state model reproduces the available water level measurements and flow directions relatively well. Sensitivity analysis indicates that the most sensitive parameters in the model are boundary heads and recharge. Calibration of the transient model from 1980 through 1997 incorporated historical pumping and variable recharge. The model is capable of reproducing aquifer heads reasonably well as indicated by estimated head target errors. In addition, the Nacatoch Aquifer GAM can be refined as more information becomes available.

Analyses of the model results indicate that groundwater levels in the Nacatoch Aquifer are more sensitive to aquifer boundary conditions than to aquifer hydraulic properties for the entire model area. The transient model provides a well-documented framework for evaluating groundwater availability at the regional scale. In addition, the model can be modified to serve as a predictive tool for estimating future aquifer conditions based on changes in pumping, recharge or other variables.

13.0 ACKNOWLEDGMENTS

The successful completion of a major modeling project, such as this Nacatoch Aquifer GAM, requires the cumulative knowledge, assistance, and backing of many individuals and groups outside the modeling team itself. We wish to thank the Texas Water Development Board for its forward thinking in developing and funding the statewide aquifer GAM program. In addition, we thank the TWDB staff for their guidance and assistance in completing the project, especially the project manager, Cindy Ridgeway.

Comments received from the TWDB and stakeholders on the Draft Conceptual Model Report and the Draft Final Report can be found in Appendix B. Responses to each comment are also included in Appendix B.

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APPENDIX A

WATER BUDGETS BY COUNTY

Table A-1. Steady state water budget

County		Layer	Lateral	Top	Bottom	Recharge	ET	GHB	Stream
Bowie	IN	***1***	103	0	1292	4151	0	127	1
		2	1103	3189	0	1590	0	0	1
		All	1206	3189	1292	5741	0	127	2
	OUT	***1***	317	0	3189	0	460	1350	352
		2	2396	1292	0	0	2014	0	183
		All	2713	1292	3189	0	2474	1350	535
Red River	IN	***1***	2	0	1133	0	0	1206	0
		2	132	1169	0	1659	0	0	1
		All	134	1169	1133	1659	0	1206	1
	OUT	***1***	11	0	1169	0	0	1128	0
		2	781	1133	0	0	1061	0	24
		All	792	1133	1169	0	1061	1128	24
Morris	IN	***1***	3	0	25	0	0	0	0
		2	94	0	0	0	0	0	0
		All	97	0	25	0	0	0	0
	OUT	***1***	1	0	0	0	0	27	0
		2	69	25	0	0	0	0	0
		All	70	25	0	0	0	27	0
Titus	IN	***1***	6	0	160	0	0	0	0
		2	201	0	0	0	0	0	0
		All	207	0	160	0	0	0	0
	OUT	***1***	0	0	0	0	0	164	0
		2	42	160	0	0	0	0	0
		All	42	160	0	0	0	164	0
Franklin	IN	***1***	4	0	88	0	0	0	0
		2	104	0	0	0	0	0	0
		All	108	0	88	0	0	0	0
	OUT	***1***	0	0	0	0	0	90	0
		2	17	88	0	0	0	0	0
		All	17	88	0	0	0	90	0
Lamar	IN	***1***	0	0	0	0	0	155	0
		2	51	155	0	63	0	0	0
		All	51	155	0	63	0	155	0
	OUT	***1***	0	0	155	0	0	0	0
		2	78	0	0	0	182	0	9
		All	78	0	155	0	182	0	9
Delta	IN	***1***	1	0	9	0	0	386	0
		2	290	384	0	424	0	0	0
		All	291	384	9	424	0	386	0
	OUT	***1***	2	0	384	0	0	9	0
		2	296	9	0	0	656	0	136
		All	298	9	384	0	656	9	136

County		Layer	Lateral	Top	Bottom	Recharge	ET	GHB	Stream
Hopkins	IN	***1***	4	0	277	0	0	193	0
		2	342	201	0	19	0	0	0
		All	346	201	277	19	0	193	0
	OUT	***1***	2	0	201	0	0	271	0
		2	236	277	0	0	15	0	21
		All	238	277	201	0	15	271	21
Hunt	IN	***1***	0	0	2256	0	0	1968	0
		2	539	1949	0	2614	0	0	1
		All	539	1949	2256	2614	0	1968	1
	OUT	***1***	4	0	1949	0	0	2249	0
		2	252	2256	0	0	2429	0	179
		All	256	2256	1949	0	2429	2249	179
Rains	IN	***1***	1	0	70	0	0	0	0
		2	128	0	0	0	0	0	0
		All	129	0	70	0	0	0	0
	OUT	***1***	0	0	0	0	0	71	0
		2	58	70	0	0	0	0	0
		All	58	70	0	0	0	71	0
Kaufman	IN	***1***	1	0	145	0	0	2079	0
		2	21	2036	0	1754	0	0	1
		All	22	2036	145	1754	0	2079	1
	OUT	***1***	0	0	2036	0	0	146	0
		2	953	145	0	0	2456	0	296
		All	953	145	2036	0	2456	146	296
Henderson	IN	***1***	0	0	0	0	0	777	0
		2	716	776	0	65	0	0	0
		All	716	776	0	65	0	777	0
	OUT	***1***	0	0	776	0	0	0	0
		2	309	0	0	0	773	0	476
		All	309	0	776	0	773	0	476
Ellis	IN	***1***	0	0	0	0	0	0	0
		2	52	0	0	21	0	0	0
		All	52	0	0	21	0	0	0
	OUT	***1***	0	0	0	0	0	0	0
		2	57	0	0	0	0	0	16
		All	57	0	0	0	0	0	16
Navarro	IN	***1***	0	0	356	0	0	2071	0
		2	300	2030	0	1126	0	0	1
		All	300	2030	356	1126	0	2071	1
	OUT	***1***	0	0	2030	0	0	367	0
		2	229	356	0	0	2731	0	166
		All	229	356	2030	0	2731	367	166
Outside Texas	IN	***1***	316	0	1939	3193	0	0	43
		2	2340	1402	0	1098	0	0	0

County		Layer	Lateral	Top	Bottom	Recharge	ET	GHB	Stream
		All	2656	1402	1939	4291	0	0	43
	OUT	***1***	103	0	1402	0	139	171	3682
		2	633	1939	0	0	1472	0	797
		All	736	1939	1402	0	1611	171	4479

Table 2. Water budget for 1997 (end of calibration)

County		Layer	Lateral	Top	Bot	RCH	ET	GHB	STR	Wells	Storage
Bowie	IN	***1***	100	0	1252	4136	0	120	1	0	285
		2	1229	3432	0	2587	0	0	1	0	15
		All	1329	3432	1252	6723	0	120	2	0	300
	OUT	***1***	310	0	3432	0	409	1303	346	0	83
		2	2383	1252	0	0	2304	0	195	571	559
		All	2693	1252	3432	0	2713	1303	541	571	642
Red River	IN	***1***	2	0	1024	0	0	1177	0	0	0
		2	147	1204	0	2697	0	0	2	0	0
		All	149	1204	1024	2697	0	1177	2	0	0
	OUT	***1***	11	0	1204	0	0	1018	0	0	0
		2	852	1024	0	0	1113	0	25	480	482
		All	863	1024	1204	0	1113	1018	25	480	482
Morris	IN	***1***	3	0	25	0	0	0	0	0	0
		2	91	0	0	0	0	0	0	0	0
		All	94	0	25	0	0	0	0	0	0
	OUT	***1***	1	0	0	0	0	26	0	0	0
		2	66	25	0	0	0	0	0	0	0
		All	67	25	0	0	0	26	0	0	0
Titus	IN	***1***	6	0	158	0	0	0	0	0	0
		2	213	0	0	0	0	0	0	0	0
		All	219	0	158	0	0	0	0	0	0
	OUT	***1***	0	0	0	0	0	163	0	0	0
		2	50	158	0	0	0	0	0	6	0
		All	50	158	0	0	0	163	0	6	0
Franklin	IN	***1***	4	0	82	0	0	0	0	0	0
		2	104	0	0	0	0	0	0	0	0
		All	108	0	82	0	0	0	0	0	0
	OUT	***1***	0	0	0	0	0	84	0	0	0
		2	17	82	0	0	0	0	0	4	0
		All	17	82	0	0	0	84	0	4	0
Lamar	IN	***1***	0	0	0	0	0	151	0	0	0
		2	55	151	0	98	0	0	0	0	0
		All	55	151	0	98	0	151	0	0	0
	OUT	***1***	0	0	151	0	0	0	0	0	0
		2	88	0	0	0	195	0	9	1	11
		All	88	0	151	0	195	0	9	1	11
Delta	IN	***1***	1	0	5	0	0	617	0	0	0
		2	391	620	0	586	0	0	2	0	3
		All	392	620	5	586	0	617	2	0	3
	OUT	***1***	2	0	620	0	0	4	0	0	0
		2	311	5	0	0	608	0	108	435	129
		All	313	5	620	0	608	4	108	435	129

County		Layer	Lateral	Top	Bot	RCH	ET	GHB	STR	Wells	Storage
Hopkins	IN	***1***	4	0	199	0	0	488	0	0	0
		2	408	477	0	25	0	0	0	0	28
		All	412	477	199	25	0	488	0	0	28
	OUT	***1***	2	0	477	0	0	198	0	0	0
		2	308	199	0	0	16	0	21	391	6
		All	310	199	477	0	16	198	21	391	6
Hunt	IN	***1***	0	0	2044	0	0	2187	0	0	0
		2	560	2219	0	4077	0	0	2	0	17
		All	560	2219	2044	4077	0	2187	2	0	17
	OUT	***1***	4	0	2219	0	0	2037	0	0	0
		2	330	2044	0	0	2642	0	150	874	765
		All	334	2044	2219	0	2642	2037	150	874	765
Rains	IN	***1***	1	0	67	0	0	0	0	0	0
		2	124	0	0	0	0	0	0	0	0
		All	125	0	67	0	0	0	0	0	0
	OUT	***1***	0	0	0	0	0	68	0	0	0
		2	48	67	0	0	0	0	0	9	0
		All	48	67	0	0	0	68	0	9	0
Kaufman	IN	***1***	0	0	149	0	0	1982	0	0	0
		2	26	2021	0	2912	0	0	1	0	1
		All	26	2021	149	2912	0	1982	1	0	1
	OUT	***1***	0	0	2021	0	0	151	0	0	0
		2	1003	149	0	0	2813	0	302	75	569
		All	1003	149	2021	0	2813	151	302	75	569
Henderson	IN	***1***	0	0	0	0	0	784	0	0	0
		2	752	786	0	120	0	0	0	0	0
		All	752	786	0	120	0	784	0	0	0
	OUT	***1***	0	0	786	0	0	0	0	0	0
		2	299	0	0	0	794	0	486	54	23
		All	299	0	786	0	794	0	486	54	23
Ellis	IN	***1***	0	0	0	0	0	0	0	0	0
		2	56	0	0	38	0	0	0	0	0
		All	56	0	0	38	0	0	0	0	0
	OUT	***1***	0	0	0	0	0	0	0	0	0
		2	64	0	0	0	0	0	18	0	12
		All	64	0	0	0	0	0	18	0	12
Navarro	IN	***1***	0	0	367	0	0	1899	0	0	0
		2	290	1983	0	2253	0	0	1	0	0
		All	290	1983	367	2253	0	1899	1	0	0
	OUT	***1***	0	0	1983	0	0	371	0	0	0
		2	241	367	0	0	2951	0	171	11	695
		All	241	367	1983	0	2951	371	171	11	695
Outside Texas	IN	***1***	309	0	1938	3193	0	0	44	0	42
		2	2327	1383	0	1547	0	0	0	0	87

County		Layer	Lateral	Top	Bot	RCH	ET	GHB	STR	Wells	Storage
		All	2636	1383	1938	4740	0	0	44	0	129
	OUT	***1***	100	0	1383	0	167	165	3687	0	23
		2	704	1938	0	0	1701	0	837	16	158
		All	804	1938	1383	0	1868	165	4524	16	181

- All values recorded in acre feet per year
- OutTX – study area that is outside the State of Texas

Explanation of Water Budget Components

- Lateral – Water that flows into and out of the specific area from the west, east, north and south side of that area.
- Top or Bot – Water that flows into and out of the specific area from the top or the bottom boundary.
- Recharge – Areally distributed recharge due to precipitation.
- ET – Water that flows out of the aquifer due to evaporation and transpiration. This component of the budget will always be shown as outflow.
- GHB – General head boundary. Used in the model to simulate the flow into and out of the Nacatoch Sands.
- STR – Water exchange between streams and the aquifer. Water that flows into the aquifer is shown as inflow.
- Wells – Pumping
- Storage – Change in aquifer storage

APPENDIX B

RESPONSE TO TWDB COMMENTS ON CONCEPTUAL MODEL AND SOURCE DATA

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Appendix B

Response To TWDB Comments

This appendix contains responses to all the comments received from the TWDB on the conceptual model report.

1.0 RESPONSE TO CONCEPTUAL MODEL COMMENTS

1.1 TWDB Conceptual Model Report Comments

Comment: All Figures: Many figures include the "Geologic Outcrop Units" as a reference rather than a study area outline. Since the text refers to the study area, please update all applicable figures and figure legends throughout the report with a study area outline instead of using geologic outcrop units so figures and text are in agreement.

Response: *Study area outline added to figures as requested.*

Comment: All Figures: Please revise figures for consistency, as applicable. We suggest including county name labels in all figures with county boundaries and using the same study and/or model outline when referencing the study/model area.

Response: *County labels and/or model outline added to figures as reference as requested.*

Comment: All Figures: Please check all figures to ensure that all landmark or reference referred to in the text is included in the figure. This is a problem throughout the report. For example, if the text refers to the City of Commerce (page 2-1) then make sure the referenced figure (in this case Figure 2.1.1) includes the City of Commerce on it.

Response: *Figures checked and modified if necessary.*

Comment: Cover and 1st Page: Per contract, Exhibit B, Attachment 1, Section 4.4.3 Report Deliverables, last paragraph: Each report shall have an authorship list of persons responsible for the studies: firm or agency names as authors will not be acceptable.

Response: *Corrected as requested.*

Comment: General: Please consistently use "and others" instead of "et al" when citing multiple authors.

Response: *Corrected as requested.*

Comment: General: Please make the terminology consistent throughout the report with respect to "project area," "model area," or "study area." This is especially problematic when coupled with the varying outlines of the "model area" or "study area" in the figures, as discussed above.

Response: *Boundaries clarified in text and figures.*

Comment: Page 1-1, Paragraph 2: Please insert mg/l after 3,000 and include the Mexia-Talco fault zone as a consideration for delineation of the model boundary.

Response: *Corrected as requested.*

Comment: Page 1-1, Paragraph 4: Please eliminate or explain predictive simulations referenced on page 1-1 as this is outside the scope of work.

Response: *Text corrected as requested.*

Comment: Page 2-1, General: Section 2 numbering is incorrect. Please follow report numbering specified in Section 4.4.1 of Attachment B of the contract.

Response: *Section 4.4.1 of Attachment B states minimum required sections in GAM report, therefore Section 2.1 changed to "Location" and left as is.*

Comment: Page 2-1, Paragraph 1: Please include the City of Commerce on Figure 2.1.1 as it is referenced in the text.

Response: *Corrected as requested.*

Comment: Page 2-1, Paragraph 1: Please note that the model area include the alluvium and terrace deposits in addition to the Nacatoch Sand.

Response: *Text updated as requested.*

Comment: Page 2-3, Figure 2.1.2: Please include Chambers and Richland Creeks as they are mentioned in the text.

Response: *Figure labels added as requested.*

Comment: Page 2-1, Paragraph 2: Paragraph describes extent of silt and floodplain deposits in the area but map shows alluvium and terrace deposits. Please clarify.

Response: *Clarified in text.*

Comment: Page 2-1, Paragraph 3: Figure 2.1.4 shows five minor aquifers, not four as described in the text. Please correct the text to include the Nacatoch.

Response: *Corrected as requested.*

Comment: Page 2-1, Paragraph 3: Please clarify the second sentence. Suggest relating the other major and minor aquifers in the area to the Nacatoch Aquifer.

Response: *Text modified as requested.*

Comment: Page 2-1, Paragraph 4: The downdip limit of the Nacatoch is not shown in Figure 2.1.7, as is implied in this sentence. Please clarify either text or figure as needed.

Response: *Corrected as requested.*

Comment: Page 2-1, Paragraph 5: The study area in Figure 2.1.4 is not bounded by the aquifer extent only in the southwest, and the Red River is not a study area boundary as defined in this project. Also, the "Study Area" boundary as shown in figures does not coincide with the Nacatoch outcrop at all. Please adjust the text or figure as needed so they agree. Also please reword caption for Figure 2.1.4 since the Blossom Aquifer does not yet have a model.

Response: *Text and figure caption modified to reflect figure.*

Comment: Page 2-1, Paragraph 5: Please rewrite "The lower model surface boundary …the upper model surface boundary…" so it agrees with Table 2.3.1, which indicates the Nacatoch is bounded by the Neylandville (Lower Navarro) Formation below and the Kemp Clay (Upper Navarro Marl) above. Per Table 2.3.1, the bottom surface of the model is not defined by the Midway-Wilcox geologic contact. Please clarify and correct as needed.

Response: *Text corrected.*

Comment: Page 2-6, Figure 2.1.5: Please correct label in Figure 2.1.5 for North East Texas regional planning group by adding a space in Northeast.

Response: *Corrected as requested.*

Comment: Page 2-9, Paragraph 4: Text indicates elevations from 230 to 640 feet; however, Figure 2.2.3 shows a range of 141 to 1106. Portions of Delta and Hunt County are stated in text to be as high as 640 feet, but figure would appear to indicate elevations of over 1,000 feet. Please clarify and adjust as needed.

Response: *Figure adjusted. Text is correct.*

Comment: Page 2-9: Section 2.2 describes spatial variability of precipitation however per contract Exhibit B, Attachment 1, Section 3.3.1, Physiography and Climate, bullets: this section should include descriptions and maps of spatial and temporal variability of precipitation. Please update section with temporal variability (during the year – i.e. monthly variations) of precipitation to assist with possible future enhancements to the model.

Response: *Temporal variability of precipitation noted in Figure 2.2.7.*

Comment: Page 2-10, Paragraph 2: Please make the figure and text consistent. There are not 22 gages within the outcrop area of the active model region, and the "active model region" is not shown in the above figure. According to Figure 2.2.5 there are only 4 to 6 within the outcrop area. In addition, the active model region and active model domain have not been defined as yet but being discussed in this paragraph.

Response: *Text corrected, study and model area defined more clearly.*

Comment: Page 2-10, Paragraph 4: states net pan evaporation in the study area ranges from 43.35 to 58.15 inches per year; however, Figure 2.2.8 shows a range of 38.34 to 58.15 inches per year. Please adjust this statement so text and figure agree or state "study area in Texas" or "over the exposed portions of the aquifer."

Response: *Text corrected.*

Comment: Page 2-10, Paragraph 4: states Navarro County is in the southeast portion of the study area, please update to southwest portion of the study area.

Response: *Corrected as requested.*

Comment: Page 2-10, Paragraph 5: Please clarify why downdip migration would have an impact on the significance of groundwater ET in the outcrop portion of the aquifer. ET could potentially be important in the Nacatoch sand due to lower depth to water table and not lack of downdip migration of groundwater.

Response: *Text clarified.*

Comment: Page 2-10, Paragraph 4-5: Section 2.2 describes spatial variability of evaporation however per contract Exhibit B, Attachment 1, Section 3.3.1, Physiography and Climate, bullets: this section should include descriptions and maps of spatial and temporal variability of evaporation. Please update section with temporal variability of evaporation to assist with possible future enhancements to the model.

Response: *Figure 2.2.9 added with temporal evaporation.*

Comment: Page 2-11, Figure 2.2.1: Please correct spelling of Blackland Prairie in legend. Please verify source reference, which is not included in References section, unable to locate this information on Texas Parks and Wildlife website, however did locate data on Bureau of Economic Geology website.

Response: *Corrected as requested.*

Comment: Page 2-13, Figure 2.2.3: Please also show river basins on this map as comparison was made to elevations in river basins in the text on page 2-9. If river basin outlines are not added, then the text should be clarified to note which counties these river basins are located in.

Response: *River basin labels added as requested.*

Comment: Page 2-13, Figure 2.2.3: Outline of modified study area not listed in legend. Also previous figures used a more generalized study area boundary. Please select one study area outline and use consistently or clarify difference in legend or caption.

Response: *Legend updated.*

Comment: Page 2-17, Figure 2.2.7: Please clarify what the red outline is in this figure. It does not match either the geologic outcrop or study area as previously shown in report.

Response: *Figure and text updated.*

Comment: Page 2-18, Figure 2.2.8: Please clarify what the red outline is in this figure. It is not on the legend and does not match either the geologic outcrop or study area as previously shown in report. It doesn't match previous figure's red outline either.

Response: *Figure updated.*

Comment: Page 2-19, Paragraph 3: 1st, 2nd, 3rd paragraph: References Sellards, 1932. Please update Reference section with this citation. Note: Sellards, 1932 is also cited on page 2-34

Response: *References in text updated.*

Comment: Page 2-20, Paragraph 1: Please make nomenclature consistent, for example, Lower Navarro Formation is cited in Table 2.3.1, Lower Navarro Clay is cited in text.

Response: *Text clarified.*

Comment: Page 2-20, Paragraph 1: This references Mexico-Talco fault zone, please update to Mexia-Talco fault zone.

Response: *Text corrected.*

Comment: Page 2-20, Paragraph 2: The Navarro Group has four units not three as per table 2.3.1. Please clarify and adjust as needed.

Response: *Corrected as requested.*

Comment: Page 2-20, Paragraph 2-3: The City of Greenville is not shown on any figure. Please ensure that landmarks used in the text are shown in the appropriate figures.

Response: *Figure showing Greenville reference in paragraph.*

Comment: Page 2-20, Paragraph 3: Although the text states that on the GAT the units are undivided east of Greenville, there is no "undivided Navarro Group" in the figure. Please clarify and adjust as needed.

Response: *GAT sheets were modified for this modeling project and the modification is shown in the figure, not original undivided units. Text has been clarified.*

Comment: Page 2-21, Paragraph 4: How did Knight use five test holes from Ashworth (1988) in his study dated 1984? Please clarify.

Response: *Text has been clarified.*

Comment: Page 2-24, Figure 2.3.2: the only thing that is referenced in this figure is the source, GAT. If this figure does not show what the GAT shows (as noted in previous comment), then a note in the figure or the figure title as to what was done is needed. The figures should stand on their own.

Response: *Figure caption modified.*

Comment: Page 2-26, Paragraph 2.3.4: Is this how the figure was presented in McGowen and Lopez? It seems odd that the deposits are broken out in generalized source descriptions like "Deltaic" and "Outer Shelf" for most areas, but with a specific formation name for the Nacatoch. Please clarify.

Response: *Figure notes modification from McGowen and Lopez.*

Comment: Page 2-27, Figure 2.3.5: Please label counties, please insert Pittsburg syncline as referred to in text (pg. 2-21), and please insert year for reference in the caption.

Response: *Figure 2.3.5 corrected as requested. Pittsburg Syncline is noted in Figure 2.3.1.*

Comment: Page 2-28, Figure 2.3.6: Terrace deposits were shown on various maps but have not been discussed in the text. Please include a discussion in the text.

Response: *Alluvium and terrace deposits in the outcrop area are discussed on page 2-2, paragraph 2.*

Comment: Figure 2.3.7/ page 2-29: Cross section in figure 2.3.6 indicates interpretation for A-A' begins in Navarro, crosses through Henderson before entering Kaufman County. Figure 2.3.7 suggests A-A' does not include Henderson County. Please adjust figures so they agree.

Response: *Figure modified to include missing county boundaries*

Comment: Figure 2.3.7/ page 2-29: It would help if the bottom of what is being called the Nacatoch Sand were indicated on this figure. Please add this if possible.

Response: *Text modified to indicate the bottom of the Nacatoch is assumed to be the bottom of the lowest sand package in this cross-section.*

Comment: Paragraph 5/ page 3-2: This references Mexico-Talco Fault Zone, please adjust to read Mexia-Talco Fault Zone.

Response: *Text corrected.*

Comment: Page 3-2: Please include a discussion of previous modeling efforts in the study area. If no previous modeling efforts exist, please mention this in the text.

Response: *Section 3.2 added noting no previous modeling efforts found in this area.*

Comment: Paragraph 1/ page 4-1: Please expand this discussion significantly. This is an appropriate place to detail the hydrostratigraphy of the aquifer beyond what was mentioned in Section 2.3.2. Per Exhibit B, Attachment 1, Section 3.1.3, the hydrostratigraphy for the study area shall be presented and discussed. The discussion shall include a detailed hydrostratigraphic chart and information on the rationale for the hydrostratigraphic units. Please update this section to include this required information.

Response: *Additional discussion added as requested.*

Comment: Paragraph 1/ page 4-1: Section 4.1 references Mexico-Talco Fault Zone, please adjust to read Mexia-Talco Fault Zone.

Response: *Text corrected.*

Comment: Page 4-1: Suggest inserting paragraph before section 4.1 to introduce Hydrologic Setting and the subsections to follow.

Response: *Introductory paragraph added.*

Comment: Paragraph 3/ page 4-2: Please clarify "Figures 5 and 6 of Ashworth (1988)". Suggest updating text to simply say that maps of top and bottom elevations were digitized and not suggest that the reader should know what Figures 5 and 6 in Ashworth (1988) are or go look these up.

Response: *Text clarified.*

Comment: Paragraph 2/ page 4-3: The text states, "The second surface developed was the thickness of the Nacatoch". Please clarify how the thickness was developed prior to developing the top elevation. The previous text suggests the top of Nacatoch was included in your process (Step 1 was digitizing Figures 5 and 6, and Figure 5 was the top). Please expand this discussion to explain how the alluvium was separated and delineated from the Nacatoch Sand.

Response: *Text in this section clarified to better understand process of structure construction.*

Comment: Figure 4.2.1/ page 4-4: Please clarify the caption. Unclear if this figure represents the base of the Nacatoch Sand, the conceptual base of the model, or both. The same concept applies to the captions for figures 4.2.2 and 4.2.3.

Response: *Captions for all structural figures clarified to note they are estimations for conceptual model.*

Comment: Page 4-4: Please clarify on why there is a downdip model extent included. An extent of the model has not been proposed at this point.

Response: *Text and figures have been updated to propose the downdip extent of the Nacatoch in Figure 2.3.2 so no change necessary.*

Comment: Page 4-5, Figure 4.2.2: Please extend thickness in the downdip to match downdip outlines of figures 4.2.1, 4.2.3, and 4.2.4 or clarify why 4.2.2 has a different outline.

Response: *Figure extent updated.*

Comment: Page 4-7, Figure 4.2.4: Terrace deposits and alluvium outcrop are the same color family used for the contouring and therefore makes it difficult to determine if the thickness of the alluvium in outcrop is 20-100 feet and the terrace deposits are 800-900 feet or not included. Please clarify in text and possibly use another grade of colors in figure, or reconsider using geologic outcrop units as a substitute for study area outline. The structure figures (4.2.1 to 4.2.4) suggests the alluvium and terrace deposits are included in the Nacatoch, however text and Table 2.3.1 suggest they are separate, please clarify.

Response: *Figure modified.*

Comment: Page 4-10, Paragraph 1: Suggest rewording since it may be misleading to say that the data "ranged" from 24 to 17 feet when there really are only two data points in your data set.

Response: *Text clarified.*

Comment: Page 4-11, Paragraph 2: Figure reference should be 4.3.4

Response: *Text corrected.*

Comment: Page 4-11, Paragraph 2: Regarding the statement "one can immediately see a close conformance with topography." Please clarify, reword sentence, or delete this reference since the text suggests the map was developed by subtracting land surface elevation from the y-intercept of 18.8 feet and would therefore intuitively mimic topography.

Response: *Text deleted.*

Comment: Page 4-12, Figure 4.3.7: The second (upper) drawdown cone cannot be easily seen on the figure. The contours make it impossible to see the coloring and this cone is easily missed. Suggest blowup of area of interest.

Response: *Figure modified.*

Comment: Page 4-12, Paragraph 2: Please expand sentence starting "The other significant water use" as it appears disjointed from the previous sentences. Possibly suggest stating other significant water use in the study area includes irrigation…

Response: *Text clarified.*

Comment: Page 4-17, Figure 4.3.1: Please be consistent with figures. Counties are not labeled on this one and in this figure the red outline is titles "Water Level Area Boundary," which is a new description for these outline.

Response: *Figure and legend updated.*

Comment: Page 4-19, Figure 4.3.3: Please correct the legend. There are only four labels in the legend for 7 points and a line.

Response: *Figure updated in report.*

Comment: Page 4-20, Figure 4.3.4: Suggest replacing "…Regression with validation crossplots" with "… based on the regression between land surface elevation and water level elevation" to more clearly convey the point.

Response: *Figure caption modified as requested.*

Comment: Page 4-21, Figure 4.3.5: The color selection for shading the water levels in this figure and 4.3.6, 4.3.8, and 4.3.9 make it very difficult to see the contours. Please select either a new color scheme for the fill or a different color for the contours.

Response: *Contours modified in figures.*

Comment: Page 4-23, Figure 4.3.7: The upper cone of depression is virtually impossible to discern in this figure. If there is a localized area of interest in a figure, in this case the area with two drawndown cones, suggest providing a blowup of that area in a box in the figure.

Response: *Figure modified to include blowup of area of interest.*

Comment: Page 4-23, Figure 4.3.7: Text refers to drawdown cones in Hunt/Delta and Hunt/Hopkins counties; however, counties are not labeled on this figure. Please update figure with county labels.

Response: *Corrected as requested.*

Comment: Page 4-23, Figure 4.3.7: Technically, drawdowns should be positive numbers. Please either change the values or change the legend to read "Water Level Change (ft)"

Response: *Values changed to reflect positive drawdown values.*

Comment: Page 4-26, Figure 4.3.10: Please label counties on all figures, especially if the text refers to specific counties by name.

Response: *Counties labeled as requested.*

Comment: Page 4-27, Figure 4.3.11: Please label counties on all figures, especially if the text refers to specific counties by name.

Response: *Significant counties labeled as requested.*

Comment: Page 4-29, Paragraph 3: Please elaborate further on this sentence. Unclear on why it is only where the water table is "sloping away" where it is considered recharge. It would seem that if water reached the water table in an area where it isn't "sloping away," the water reaching the water table help create a gradient.

Response: *Text updated to clarify content.*

Comment: Page 4-29: Please include a discussion of the concept of "rejected recharge," as required per Exhibit B, Attachment 1, Section 3.1.6

Response: *Added sentence to indicate that surficial discharge is sometimes called "rejected recharge". In previous GAMs, the phrase "rejected recharge" has been unpopular with stakeholders (to some it implies an unexploited resource) so we since typically offered these concepts in terms of shallow surficial discharge components.*

Comment: Page 4-30, Paragraph 3: Please elaborate further on the role that groundwater ET might play in the discharge of shallow recharge, and whether the assumption that most of the shallow recharge discharges through baseflow is valid. Groundwater ET would seem to potentially play a major role in the discharge of shallow recharge, especially because this would be primarily occurring in riparian zones where the groundwater ET is higher, yet somewhat downplayed. The text says that the baseflow estimates are therefore considered a minimum, but if groundwater ET is significant, these shallow recharge estimates could be significantly more than that. And while the text indicates that the baseflow estimate is a minimum, it then goes on to say that the area-weighted shallow recharge is 0.5 inches per year. Please clarify/explain as needed.

Response: *We corrected the "is" to "is a minimum of". We have no measurements (or secondary estimates) of groundwater ET in the region, so its contribution to discharge is difficult to quantify. We added some discussion to the relevant section about possible ranges and how this could be handled during calibration. We also added a pointer to our discussion of ET conceptualization in a following section.*

Comment: Page 4-30, Paragraph 5: Please either show or define the referenced subwatersheds or at a minimum a description might be sufficient.

Response: *Section 4.4.2 notes details on baseflow analysis are discussed in section 4.7.1, Figure 4.7.4 located subwatersheds.*

Comment: Page 4-30: Section 4.4.3, beginning on page 4-30: suggests a relationship on how recharge would vary temporally. Per contract Exhibit B, Attachment 1, Section

3.1.6 Recharge, states the effects of seasonal variations shall be examined and discussed. Please expand the Recharge Section to include a discussion to determine if seasonal variability is a significant factor. If so, future model enhancements may include re-examining the length of stress periods.

Response: *Because the stress periods are annual, in-year seasonal variations are not emphasized in the analysis. Little correlation was found between precipitation events and baseflow (the indicator of shallow recharge) on timescales smaller than one-year. Words to this effect were added to the report.*

Comment: Page 4-31: Please include a discussion on why the role of bank storage is not considered in the analysis of baseflow.

Response: *In typically gaining streams, bank storage affects the timing rather than the magnitude of baseflow. Because we were analyzing baseflow over long-term (i.e. annual) averaging windows, bank storage should have a minimal effect. We added a sentence with this explanation.*

Comment: Page 4-32, Paragraph 2: Please clarify statement concerning the relationship that in low precipitation years recharge is mostly deep. This is counterintuitive. In years of low precipitation, typically the plants, soil, and runoff predominant and precipitation rarely makes it past the local system. As precipitation increases then water lost to the local system reaches a saturation point and deep recharge is typically included.

Response: *The comment appears to confuse percolation with recharge. During low precipitation years, less water percolates deep through the vadose zone. This means less water reaching the water table, and muted recharge events. Shallow recharge is driven by local gradients; these local gradients would be affected more dramatically by these muted recharge events than the regional gradients that drive deep recharge.*

Comment: Page 4-32, Paragraph 3: Suggest adding ‘steady-state’ to reference to predevelopment model since without this modifier the sentence suggests that in predevelopment times precipitation and recharge do not vary temporally.

Response: *Text modified.*

Comment: Page 33, Paragraph 5: Most of the Red River on the Texas border cannot be seen in Figure 4.4.8 because the state border is so wide it obliterates the underlying K sat feature. Please revise Figure 4.4.8 to show the feature being highlighted in the text.

Response: *Figure modified for clarity as requested.*

Comment: Page 4-38: Please indicate in the figure title or in the figure itself that this is not a defined distribution of recharge but rather simply a plot of a relationship between average precipitation and estimated recharge that was used to estimate recharge for this project. The figure title implies that this is average recharge.

Response: *Figure caption clarified.*

Comment: Page 4-40, Figure 4.4.7: What is topographic multiplier? Please explain in the text or in the caption.

Response: *Figure label modified to reference "topographic indicator" addressed in the text.*

Comment: Page 4-40, Figure 4.4.7: Please correct reference in figure. It is misspelled and not included in references.

Response: *Corrected as requested.*

Comment: Page 4-40, Figure 4.4.7: Please be sure that filled-in shapefiles like the topography are not the top layer, which overlies county boundaries in the figure. Please update figure to show county boundaries.

Response: *Figure updated as requested.*

Comment: Page 4-41, Figure 4.4.8: Why do certain cities seem to be colored in the higher end of K sat? For example, Dallas, Paris, Sherman, and Greenville (among others) all appear in the figure in brown. Is this because of the color used for cities is the same as K sat, or is there something in these areas that causes higher K sat? Please elaborate or adjust figure appropriately to distinguish cities from K sat.

Response: *Figure modified as requested (cities boundaries clarified).*

Comment: Page 4-42, Paragraph 1: The "Rivers, Streams, Springs, and Lakes" section does not address streams and springs. Per contract Exhibit B, Attachment 1, Section 3.1.7, the primary streams and springs in the study area shall be identified and described along with historical flows; rivers and streams with gains and losses shall be identified and quantified, if possible; any specific or general information on streambed conductance shall also be addressed; and any other information needed for the MODFLOW packages shall be estimated and discussed. Please update this section with missing surface water/springs information or cross-reference as needed.

Response: *In the draft report, river/stream and spring information was given in the "Aquifer Discharge" section, where we feel they belong. However, to comply with the specified outline, introductory river/stream and spring descriptions were moved* *forward to Section 4.5. Discharge information remains in Section 4.7. Text has been added to address this.*

Comment: Page 4-42, Paragraph 1: Please elaborate further on the contention that reservoir recharge would only be shallow and therefore would not contribute to deep recharge. It is our understanding that since reservoirs are constructed in topographic lows, they are generally adding potentially hundreds of feet of head on top of the topographic lows, which typically influences groundwater beyond just shallow systems.

Response: *Because reservoirs are constructed in topographic lows, in regions where precipitation is significant and surface water bodies are typically gaining, the areas surrounding reservoirs would be conceptualized as mainly groundwater discharge areas.*

Comment: Page 4-44, Figure 4.5.2: Why is the only lake on the Nacatoch outcrop (Cooper-Chapman) not included in the ones showing a hydrograph? Please include this reservoir hydrograph if available, as well as more discussion on this feature.

Response: *Figure updated to include Cooper-Chapman hydrograph.*

Comment: Page 4-45: Please be consistent with page formatting (line spacing on this page)

Response: *Corrected as requested.*

Comment: Page 4-45, Paragraph 2: Correct “estmted.” Please spell check the document prior to submitting.

Response: *Corrected as requested.*

Comment: Page 4-45, Paragraph 2: Please comment on the relationship used to estimate T from Sc. The relationship shown in Figure 4.6.2 does not look very good based on the available data. One approach would be to use a bigger set of data to make this estimate (i.e. include other similar aquifers in the region to help develop a more solid relationship.)

Response: *Text added to discuss relationship further.*

Comment: Page 4-45, Paragraph 2: Please provide more detail in this section. How were net sand thicknesses determined? Driller’s logs? Is net sand thickness the same as aquifer thickness in this paragraph? If so, how valid is the assumption that screened interval thickness is equivalent to aquifer thickness? Were logs examined to verify this assumption? Please detail.

Response: *See figure 2.3.5 for net sand thickness. The net sand thickness is not the same as the aquifer thickness. The screened interval thickness generally differs from* *aquifer thickness. But to estimate hydraulic conductivity, it is the best information available. No logs were used.*

Comment: Page 4-47, Both Figures: Please correct these figures. Upper figure has different font size and a black box for the y-axis label. Please work to ensure consistency in figures.

Response: *Corrected as requested.*

Comment: Page 4-48, Paragraph 1: As noted in a previous comment, restricting yourself to only wells in this area may hinder estimation of aquifer properties. Can other alluvial aquifer wells in the region/state be used to help develop the relationship? As above, please comment on other details of this analysis. This is a very important section for the development of the model and it does not to have been covered in the detail that it could have been to develop the best estimates.

Response: *The estimated aquifer properties for this project are within the typical range of estimates from other region.*

Comment: Page 4-49, Paragraph 1: Can estimates of storage used in other GAMs in the region be referenced? Are they appropriate? Data from other similar aquifers in this region might be of some help given the complete lack of data in this aquifer, and are probably as good or better than just generically referring to Freeze and Cherry. Please clarify and update section as needed.

Response: *The storage properties are also comparable to other GAM estimates. The storage properties are treated as calibration parameters and are not very sensitive.*

Comment: Page 4-50, Figure 4.6.5: Please fix label in legend. This is not "hydraulic properties (ft/day)" but "hydraulic conductivity (ft/day)." Also, the table indicates a maximum of 56, and the legend includes a symbol for 46-60, yet none of these show up on the figure. If the symbol is overlain by another symbol, suggest zooming the figure to the only area where you have data.

Response: *Figure corrected as requested.*

Comment: Page 4-51, Paragraph 2: The last sentence states streams tend to flow year round; however, hydrographs in Figure 4.7.2 appear to show annual periods of no-flow in late summer, early fall. Please clarify so figures and text agree.

Response: *Text clarified.*

Comment: Page 4-51, Paragraph 3: After runoff, bank storage discharge may also contribute (potentially significantly) to natural surface-water flow, yet this is not mentioned. Please include a discussion on bank storage and why it was not considered in the analysis.

Response: *This is a regional groundwater model with annual stress periods. In gaining streams, bank storage typically affects the short-term timing, rather than the magnitude of baseflow, therefore it is not considered in the analysis. A note to this effect was added to the report.*

Comment: Page 4-51: Much of this section was supposed to be primarily in Section 4.5, in this section it would be better to refer back to Section 4.5 and detail the discharge components of this. Please move this to the correct location in the document.

Response: *As noted in the comment for 4-42 (1), introductory river/stream and spring information was moved to section 4.5, while the discharge analyses were kept in section 4.7.*

Comment: Page 4-51: There is no discussion on parameters needed for the MODFLOW Stream package, including elevations, stages, channel parameters, etc. Please include in the discussion.

Response: *MODFLOW specific parameters are typically discussed in the modeling section of the final report, not in the site conceptualization report. No changes were made.*

Comment: Page 4-52, Paragraph 2: Table 4.6 is referenced, which is not included in the report. Please clarify reference.

Response: *Table reference corrected.*

Comment: Page 4-52: The use/non-use of HYSEP for baseflow estimates must be discussed. If an alternate method was chosen, a discussion must be given as to why this was chosen over the method that was stated would be used in the team's SOQ.

Response: *BFI is a similar baseflow separation tool to HYSEP. Both codes are routinely used in the industry. In our opinion, BFI provides a more convenient interface for data processing. Text has been added clarifying reason for use.*

Comment: Page 4-53, Figure 4.7.1: Please revise this figure. Why are so many streams included? This makes the figure much harder to use, and it will not print well in Black-and-White. Also, the text refers to individual streams and rivers, yet none are labeled in the figure. Why are all of these extra gages included? Many are irrelevant to the discussion and study area and just make it harder to find the ones that are relevant.

Response: *Figure has been modified and labels added.*

Comment: Page 4-54: Please correct y-axis labels in all hydrographs and include units for flow. Also would suggest removing decimals from y-axis for stream gage 7343200.

Response: *Figure updated.*

Comment: Page 4-57, Paragraph 1: Heitmuller and Franklin (2003) is referenced, please update the Reference section or adjust citation to match references listed in the Reference Section.

Response: *References in text changed to Heitmuller and Reece (2003)*

Comment: Page 4-57, Table 4.7.2: Table 4.7.2 uses LPS, GPM, CFS, and NR abbreviations. Please either spell out or footnote what the abbreviations represent.

Response: *Table updated and labels clarified.*

Comment: Page 4-57, Paragraph 2: Figure 4.7.5 shows far more than 35 springs in the study area. Please elaborate and explain how they relate to the Nacatoch Aquifer.

Response: *Figure and text updated.*

Comment: Page 4-58: Table 4.7.2 and Figure 4.7.5 supposedly show the same data, they are both titled "Documented Springs." However, there are far more points in the figure than are included in the table. Please clarify.

Response: *Figure and text updated.*

Comment: Page 4-60, Paragraph 6: Figure 4.7.6 shows the values increasing from east to west. Please correct the text.

Response: *Corrected as requested.*

Comment: Page 4-67, Paragraph 2: Figure 4.7.11 shows only faults, yet the text states that it shows flow "evidenced by freshwater in the subcrop." Please include additional detail in the figure or clarify the text.

Response: *Figure has been updated to make the point clearer and text clarified.*

Comment: Page 4-67, Paragraph 2: Subsection Cross-formational flow, 2^{nd} paragraph, 1^{st} sentence. Please re-word as sentence structure appears corrupted.

Response: *Paragraph text clarified.*

Comment: Page 4-67, Paragraph 2: Please rewrite the entire latter half of this paragraph to clarify/explain a little better, it is hard to understand. The sentence reads "East of the center of Red River County there is a lack of faulting in the outcrop." On Figure 4.7.11 there appears to be no faulting in the outcrop in Red River County at all. The next sentence is hard to understand as well.

Response: *Paragraph text clarified.*

Comment: Page 4-67: Cross-formational flow is only discussed here in reference to the impact of faults on downdip flow. This would be a good place to discuss other aspects of cross-formational flow, such as leakage/vertical K estimates and how they might be derived or estimated. Or at least reference where they are discussed elsewhere in this document. Please include this discussion.

Response: *The discussion has been expended as suggested including reference to potential vertical properties in Section 4.6.*

Comment: Page 4-68, Figure 4.7.11: Figure 4.7.11 appears a duplicate of Figure 2.3.11. Suggest deleting Figure 4.7.11 and referencing Figure 2.3.11 in the text on page 4-67.

Response: *Nacatoch downdip boundary added showing correlation with fault zone and indicating approximate lower limit of freshwater.*

Comment: Page 4-72, Table 4.7.4: Please indicate in these tables that these are "estimated" rates of groundwater withdrawals.

Response: *Corrected as requested.*

Comment: Page 4-75, Figure 4.7.12: Please provide data for the entire "model boundary" area, as defined by the red line in the figure. Are US census data not available for areas outside Texas?

Response: *Figure updated.*

Comment: Page 4-84: Please clarify why SAR, which relates to irrigation water quality, was picked as the only constituent of concern to show in a figure and discuss separately in this report. As discussed earlier in the report, very little irrigation has occurred in this region, and based on Figure 4.7.14 there is none going on now.

Response: *SAR is added as general data for public use of possible future irrigation. It is also the parameter with more information available.*

Comment: Page 4-85, Figure 4.8.1: Please stay consistent with classifications of TDS that match what the TWDB uses and are also used in the text (i.e. moderately saline = 3,000 – 10,000; saline = 10,000+)

Response: *Figure modified as requested.*

Comment: Page 4-85, Figure 4.8.1: If, on figures like this, the Nacatoch outcrop is desired, we suggest merging it into one color and in the legend simply stating "Nacatoch Outcrop," rather than having units broken out. The discussion in the text does not focus on the individual units.

Response: *Figure modified as requested.*

Comment: Page 5-1, Paragraph 4: Figure 5.2.1 and the text on the previous page imply that only the river alluvium is Layer 1. Aren't the Midway and all younger strata also going to be modeled as Layer 1? Please clarify.

Response: *Text clarified.*

Comment: Page 5-2, Figure 5.2.1: Suggest adding arrow for recharge to alluvium so figures agree with the text. Also defining discharge or expanding discharge to account for ET, pumpage, and/or springs.

Response: *Text and figure modified to show proper recharge/discharge relationships in conceptual model.*

Comment: Page 6-1: Suggest using periods to separate authors' initials for all references. All references with 'et al' should be corrected to list other authors—please see Baker, Parker, and Scanlon.

Response: *Corrected as requested.*

Comment: Page 6-5: Reference for National Climatic Data Center (2003) appears incomplete. Please update.

Response: *Reference updated.*

1.2 TWDB Source Data Comments

Comment: NCDC_Stations_ppt: No values provided for any point feature classes or tables. Please provide precipitation values as attribute field data table with appropriate link/join attribute field.

Response: *Feature is intended for locating stations only, no data available.*

Comment: AvgTemp: Polygon feature class has no source listed in metadata. Please provide information regarding how polygon feature classes were developed or direct source of polygon feature class data.

Response: *Metadata updated.*

Comment: Pet_final: Raster data has insufficient source metadata information. Please provide information regarding how grids were developed or direct source of gridded data.

Comment: BotNac_DataPts: No values or other attributes except lat and lon. Please provide elevation values as attribute field or data table with appropriate link/join attribute field.

Response: *Attributes and metadata updated.*

Comment: TopNac_DataPts: No values or other attributes except lat and lon. Please provide elevation values as attribute field or data table with appropriate link/join attribute field.

Response: *Attributes and metadata updated.*

Comment: GEOL_StudyArea: No key attributes(s) to link to GEOL_Nacatoch table attributes. Please provide appropriate link/join attribute field(s).

Response: *Attributes updated to include "rockunit_cd" as link/join field.*

Comment: GEOL_NacOutcrop: No key attributes(s) to link to GEOL_Nacatoch table attributes. Please provide appropriate link/join attribute field(s).

Response: *Atributes updated to include "rockunit_cd" as link/join field.*

Comment: GEOL_Nacatoch: Table attributes cannot be linked to GEOL_StudyArea or GEOL_NacOutcrop polygon feature classes. Please provide appropriate link/join key attribute fields.

Response: *Atributes updated to include "rockunit_cd" as link/join field.*

Comment: GeologyGrids: Insufficient metadata information for how the grids within this raster catalog were developed or obtained. Please provide information regarding how grids were developed or direct source of gridded data.

Response: *Supplementary Information in metadata updated to reference contour feature metadata, which includes how rasters interpolated to create contours were developed.*

Comment: CrossSections: Geologic cross sections (raster, line, or polygon) used in Figures 2.3.7 – 2.3.10 were not provided for this line feature class. Suggest scanning as raster image and/or digitizing into polygon or line feature class and store under **Geology** feature dataset.

Response: *Feature showing location of cross-sections added to **Geology** feature dataset and raster images scanned and added to **Geology** raster catalog.*

Comment: Figure 2.3.1: (Major tectonic and structural features) has no GIS data associated with it. Suggest scanning as raster image and/or digitizing into polygon or line feature class and store under **Geology** feature dataset.

Response: *Figure scanned as raster image and added to **Geology** raster catalog.*

Comment: Figure 2.3.4: (Nacatoch facies distribution) has no GIS data associated with it. Suggest scanning as raster image and/or digitizing into polygon or line feature class and store under **Geology** feature dataset.

Response: *Figure scanned as raster image and added to **Geology** raster catalog.*

Comment: Figures 2.3.11 and 4.7.11: (Mexia-Talco fault zone with major grabens) has no GIS data associated with it. Suggest scanning as raster image and/or digitizing into polygon or line feature class and store under **Geology** feature dataset.

Response: *Feature class added to **Geology** feature dataset.*

Comment: Figures 4.2.1, 4.2.2, and 4.2.3: Have no GIS data associated with downdip model extent. Please provide polygon or line feature class and store under **Geology** feature dataset.

Response: *Line feature added to **Geology** feature dataset and named "Nacatoch_Downdip_Extent"*

Comment: GeomorphologyDEM: No DEM raster provided as used in Figure 2.2.3 (raster catalog is blank). Please provide DEM raster data.

Response: *Raster catalog updated with DEM named "topo_county".*

Comment: Figures 4.4.2, 4.4.3, 4.4.4, and 4.4.5: Have no data tables associated with them. Please provide time series data for baseflow and precipitation used in these figures.

Response: *Added tables to Source Geodatabase named "RECH_precip_vs_baseflow", "RECH_Freq_Histograms_BF-precip", and "RECH_Rech_vs_precip"*

Comment: Figures 4.5.2 and 4.7.1: Have no GIS data associated with streams. Please provide line feature class and store under **SurfaceHydro** feature dataset.

Response: *Stream feature class modified for both figures, added to* ***SurfaceHydro*** *feature dataset and named "Streams_EPA_RF1_RiverReach"*

Comment: StrmGage_NacOutcrp: No time series data table provided for these stream gage data location associated with Figure 4.7.2 and 4.7.3. Please provide time series data for these stream gage locations.

Response: *Table added with selected stream hydrographs named "SURHYD_Streamflow_hydr"*

Comment: TX_Reservoirs: No time series data table provided for these reservoir data location associated with Figure 4.5.2. Please provide time series data for these reservoir locations.

Response: *Table added with selected stream hydrographs named "SURHYD_Reservoir_Levels"*

Comment: topo_county: Raster image is corrupt. Please provide working raster.

Response: *Raster catalog updated with working raster for "topo_county".*

Comment: recharge: Raster image is corrupt. Please provide working raster.

Response: *Raster catalog updated with working raster named "nac_recharge".*

Comment: Figure 4.4.6: Has no GIS data associated with average recharge. Please provide raster or polygon/line feature class and store under **Recharge** feature dataset.

Response: *Raster catalog updated with working raster named "nac_recharge".*

Comment: Figure 4.4.8: Has no GIS data associated with the estimate of soil saturated conductivity. Please provide raster or polygon feature class and store under **Soils** feature dataset.

Response: *Raster catalog updated with working raster named "ksat_fpd".*

2.0 RESPONSE TO DRAFT FINAL COMMENTS

2.1 General Comments

Comment: Please spell out all abbreviations in the text.

Response: *Text updated.*

Comment: Please clearly and consistently use “Nacatoch Sand” or “Nacatoch Aquifer”.

Response: *Used “Nacatoch Sand” when describe structure formation and “Nacatoch Aquifer”as a general term to refer to the aquifer.*

Comment: Please change “et al.” to “and others” where it appears in the text.

Response: *Text updated.*

2.2 Specific Comments

Comment: List of Tables, page iv: Table 9.2.2 is referenced on incorrect page. Please revise.

Response: *Text revised.*

Comment: List of Figures, pages vii-viii: Figures 9.2.1-9.3.5 are referenced on the incorrect pages. Please revise. .

Response: *Text revised.*

Comment: Page ix, Executive Summary: Please provide an executive summary per contract Exhibit B, Attachment 1, Section 4.4.1.

Response: *Summary added.*

Comment: Page 2-1, paragraph 1: Text states aquifer extends into Louisiana and refers to Figure 2.1.1; however, figure does not reflect this. For consistency, please revise or clarify in text and/or figure.

Response: *Aquifer does not extend into Louisiana. Text revised.*

Comment: Page 2-1 (continued on 2-2), paragraph 3: Please clarify that the Blossom and Woodbine Formations underlie the Nacatoch Aquifer; however, the Blossom and Woodbine aquifers do not.

Response: *Text revised for clarity.*

Comment: Page 2-5, Figure 2.1.3, Please include the outline of the Nacatoch Aquifer (and add to legend) so the proximity of the major aquifers in the study area to the Nacatoch Aquifer is clear

Response: *Figure updated to include TWDB Nacatoch Aquifer outline.*

Comment: Page 2-7, Figure 2.1.5: Please add a symbol in the Explanation for this figure that indicates the Nacatoch Outcrop per contract Exhibit B, Attachment 3, Section 2.2.2.

Response: *Figure updated*

Comment: Page 2-10, Section 2.2, Paragraph 3: The text lists the Texas Parks and Wildlife Department (TPWD) as the source of the ecological region information, but Figure 2.2.2 (page 2-15) suggests the "US Environmental Protection Agency, 2004" is the source. Please verify the correct source of this information and update the text or figure as appropriate.

Response: *Text modified. The correct source is EPA.*

Comment: Page 2-10, Section 2.2, Paragraph 4: The description of the ground surface elevation range is uncertain. The symbology in Figure 2.2.3 (page 2-16) suggests that the elevation ranges from less than 701 feet above sea level to greater than 200 feet above sea level. Please update the description in the text to indicate a clear elevation range for the subject counties/regions.

Response: *Text updated to reflect figure.*

Comment: Page 2-11, paragraph 1: Refers to Figure 2.2.4 for air temperature information. Please update figure to reflect this information.

Response: *Correct figure inserted into document.*

Comment: Page 2-11, paragraph 3: Please revise the first sentence to reflect that there are more than five stations on the in the study area shown in Figure 2.2.4.

Response: *There are only five in the outcrop area, it seems this is confusing "outcrop area" with "study area."*

Comment: Page 2-11, paragraph 4: Please add reference to Figure 2.2.6 to the first sentence.

Response: *Text updated.*

Comment: Page 2-12, paragraph 1: Please change "…shows annual precipitation…" to "…shows average monthly precipitation…".

Response: *Text modified.*

Comment: Page 2-12, paragraph 2: Please indicate the 'water budget' referred to in this paragraph is not the same as the model water budget later in the text.

Response: *Text modified.*

Comment: Page 2-12, first sentence: "In the northern half of the study area, precipitation also increases with proximity to the coast." Please revise to exclude reference to the coast since this is not shown in the figures or delete this sentence.

Response: *Sentence deleted.*

Comment: Page 2-14, Figure 2.2.1: This figure is inconsistent with the data (NaturalRegions feature class). Please revise.

Response: *Figure refers to Physiography feature in Geomorphology feature dataset in the source geodatabase.*

Comment: Page 2-15, Figure 2.2.2: The source for this figure is inconsistent with the text (page 2-10, paragraph 3). Please revise.

Response: *Text revised.*

Comment: Page 2-16, Figure 2.2.3: This figure is referenced in the text with county names; however, county labels are hardly legible. Please add masking to labels.

Response: *Figure revised.*

Comment: Page 2-17, Figure 2.2.4: Please provide the correct figure of the average annual air temperature as per contract Exhibit B, Attachment 1, Section 4.4.2, page 20 of 26. Please revise this figure.

Response: *Figure revised.*

Comment: Page 2-18, Figure 2.2.5: Since you have no data for the weather stations, it is misleading to indicate they contributed to your analysis.

Response: *The weather stations layer is used for Figure 2.2.5 to show where the NCDC stations are located. We did not actually download data for all of these stations. The time series precipitation data that was actually used was submitted where appropriate, e.g. for Figures 4.4.2-4.4.4.*

Comment: Page 2-20, Figure 2.2.7: Please add average annual precipitation for each station as indicated in the text.

Response: *Change title to "Monthly."*

Comment: Page 2-22, Figure 2.2.9: Please indicate the source of the data. Revise the figure to replace number 1 through 12 with the month (see Figure 2.2.7).

Response: *Source indicated in text and figure revised.*

Comment: Page 2-24, Section 2.3.2, Paragraph 1 and Paragraph 3 (page 2-25): The text refers to the "Neylandville Marl" unit, but Table 2.3.1 (page 2-25) and Figure 2.3.3 (page 2-31) use the term "Neylandville Formation" to describe the unit. Please revise the text or figures so the designation is consistent throughout the document.

Response: *Text revised to "Formation" for consistency.*

Comment: Page 2-27, Section 2.3.2, Paragraph 1: The text refers to Figures 2.3.8 through 2.3.11 for illustrations of the geologic cross sections. However, these illustrations are not labeled with figure or page numbers, and the page margins are less than one inch as per contract Exhibit B, Attachment 3, Section 2.2.1.

Response: *Figures revised and captions added.*

Comment: Page 2-27, paragraph 2: Please change "…Bowie and Cass Counties…" to "…Bowie County…".

Response: *Text revised to exclude Cass Co. and include Miller Co. in AR.*

Comment: Page 2-29, Figure 2.3.1: Please list the source of this information in the figure as per contract Exhibit B, Attachment 3, Section 2.2.3.

Response: *Source added to figure.*

Comment: Page 2-35, Figure 2.3.7: This figure indicates that the geologic cross section F-F' begins in Delta County and ends in Hopkins County. However, the illustration for cross section F-F' on the unnumbered page preceding page 2-40 does not show both counties. Please revise Figure 2.3.7, or the illustration for cross section F-F' to show the county boundary, as necessary.

Response: *Figure updated to show inclusion of both counties.*

Comment: Figures 2.3.8 through 2.3.11: These figures do not have captions, and pages do not have numbers. Please revise.

Response: *Figure captions and page numbers added.*

Comment: Page 3-3, paragraph 3: Please change "TWDB Report 305" to "Ashworth, 1988"

Response: *Text revised.*

Comment: Page 4-1, Section 4.1, Paragraph 1: The use of the term "Neylandville Marl" is inconsistent with the referenced Table 2.3.1 (page2-25) and Figure 2.3.3 (page 2-31), which use the term "Neylandville Formation" to describe the unit. Please revise the text so the designation is consistent throughout the document.

Response: *Text revised for consistency.*

Comment: Page 4-8 (Figure 4.2.3), Page 4-9 (Figure 4.2.4), Page 4-27 (Figure 4.3.5), Page 4-30 (Figure 4.3.8), Page 4-31 (Figure 4.3.9), and Page 4-82 (Figure 4.7.9): Please fix figure borders.

Response: *Figures revised.*

Comment: Page 4-27 (Figure 4.3.5), Page 4-28 (Figure 4.3.6), Page 4-30 (Figure 4.3.8), and Page 4-31 (Figure 4.3.9): These figures are unreadable in black and white. Please revise color scheme or classification per contract Exhibit B, Attachment 3, Section 2.2.

Response: *Figures' color scheme revised.*

Comment: Page 4-29, Figure 4.3.7: Please adjust legend and caption to reflect water level differences instead of just drawdown. The legend currently only suggests positive values for both drawdown and recovery.

Response: *Figure legend and caption updated.*

Comment: Page 4-36, Section 4.4.1, Paragraph 2: It appears that the referenced subject is missing from the second sentence, "The values in [?] represent estimates...". Please update the text as appropriate.

Response: *Text revised.*

Comment: Page 4-37, paragraph 4: Please provide a reference for the PRISM data.

Response: *Reference added in text.*

Comment: Page 4-38, Table 4.4.1: Please include the caption and header row for the portion of this split table that is on page 4-39, or place the entire table on one page as per contract Exhibit B, Attachment 3, Section 2.3.

Response: *Table updated to include caption on every page.*

Comment: Page 4-40, paragraph 2: Text states that some percentage of the pumped water for irrigation makes its way back as shallow recharge. Please explain and cite a reference to substantiate this statement.

Response: *In text, "In general, current good agricultural management practices for most crops include balancing irrigation application with plant evapotranspiration requirements (e.g., Allen et al., 1998)."*

Comment: Page 4-42, Section 4.4.6, Paragraph 3: In the discussion about the increase in Ksat, the implied boundary between the Midway outcrop and the Carrizo-Wilcox formation is not indicated in the referenced Figure 4.4.8 (page 4-49). In addition, the Midway outcrop and the Carrizo-Wilcox formation are not indicated in the referenced figure. Please provide clarification to the text and/or figure that better defines were these boundaries are located.

Response: *Text revised for clarification.*

Comment: Page 4-42, Figure 4.4.1: Please fix spelling of precipitation in caption.

Response: *Text revised.*

Comment: Page 4-50, Section 4.5, Paragraph 3: The text states that there are "8 significant reservoirs in the active model boundary," but Figure 4.5.3 (page 4-54) labels more than eight reservoirs and lakes in the model area, and it is not clear if the active model boundary coincides with any of the symbology on the map. In addition, the Midway outcrop is referenced in the text, but it is not indicated in the symbology of Figure 4.5.3. In a related matter, Table 4.5.1 (page 4-51) lists Reservoir Numbers 1-9, with 4 being omitted. It is unclear whether these should be renumbered in the range 1-8, or if the numbers coincide with something else.

Please review these areas of the report, and provide the necessary revisions and clarification.

Response: *Figure labels in 4.5.3 revised and limited to significant reservoirs and text revised to clarify location of Midway outcrop. Table 4.5.1 numbering corrected.*

Comment: Page 4-65, Table 4.7.1: Drainage area in this table does not match the values from the 'SubWatershed' feature class in the source data. Please update table analysis to agree with source data.

Response: *Table reports total drainage area, not subwatershed drainage area. Text and Table revised for clarification.*

Comment: Page 4-70, Table 4.7.2: There is a number for footnote 5 in the header row, but there is no explanation for it provided at the end of the table. In addition, the table number and description should be carried to the second page since the table is split between pages. Please provide the additional information as per contract Exhibit B, Attachment 3, Section 2.3. Please check the USGS (2003) citation against the USGS (2004) reference in the list of references.

Response: *Table caption added, footnotes corrected, USGS (2003) reference added in References section.*

Comment: Page 4-73, Section 4.7.1 (Evapotranspiration), last paragraph on page: Since a comparison is being made in the text between Figure 4.7.7 (page 4-78) and Figure 4.7.8 (page 4-79), it would be much easier to make this assessment if the two figures were on the same page. In addition, the y-axis scales of the two figures should have the same range, and the units should be provided for the y-axis.

Response: *Merged into one graph (Figure 4.7.7).*

Comment: Page 4-73, paragraph 4: Please add references for the datasets.

Response: *The datasets are example subsets from the TX-GAP referenced in the previous paragraph.*

Comment: Page 4-74, paragraph 2: Please clarify if Scanlon (2005) should be Scanlon and others (2005). Please correct or add citation to the list of references.

Response: *Text corrected.*

Comment: Page 4-74, Table 4.7.3: Please add reference for source of data.

Response: *Scanlon (2005) is given as the reference for the table.*

Comment: Page 4-75 (Figure 4.7.4) and Page 4-76 (Figure 4.7.5): Please provide the datasets used for these figures.

Response: *Figure 4.7.4 - Source geodatabase, raster catalog ClimatePRISM/pet_final.*
Figure 4.7.5 - Source geodatabase table CLIM_Yr_ET

Comment: Page 4-76, Figure 4.7.5: Please add reference for source of data. Please revise the scale of the graph so the bars do not project beyond the limit of the y-axis, and include units.

Response: *The ET estimates were calculated using the Hargreaves method, as stated in the text. Units are inches per year.*

Comment: Page 4-77, Figure 4.7.6: Please revise the study area extent in the locator map. Please correct spelling of Temperate in legend for Broad-leaved Evergreen Woodland.

Response: *Figure and text corrected.*

Comment: Page 4-78, Figure 4.7.7: Please add reference for source of data and please expand caption to state frequency based on what parameter(s)?

Response: *Frequency is a count of the raster cells in the GAP vegetation coverage, which are 295 ft square. Caption revised for clarity.*

Comment: Page 4-79, Figure 4.7.8: Please add reference for source of data and please expand caption to state frequency based on what parameter(s)?

Response: *Figure merged with Figure 4.7.7.*

Comment: Page 4-83, Section 4.7.2: Please add a map showing the spatial distribution of pumpage for a specific period of time, for example 1997.

Response: *Figure 4.7.9 added showing pumping distribution in 1997.*

Comment: Page 4-83, paragraph 3: Replace "depth below mean sea level" with either "depth below land surface" or "elevation above mean sea level."

Response: *Replaced with "depth below land surface."*

Comment: Page 4-84, paragraph 2: Please expand this section to discuss the overlap with the subcrop of the Trinity Aquifer.

Response: *Overlap with the Trinity aquifer not applicable to this model.*

Comment: Tables 4.7.4 and 4.7.5, Figures 4.7.11 to 4.7.18: Please data associated with these tables and figures in pumpage geodatabase.

Response: *Pumpage Geodatabase tables – GAM_PUMPAGE_tables. Tables labeled according to report table/figure number.*

Comment: Page 4-101, Figure 4.8.1: There does not appear to be any data shown on the map in the greater than 10,000 mg/L range unless it is hidden under other data points. Please revise the symbology to eliminate the "> 10,000" level if there is not data to support this division.

Response: *Text updated to clarify no "very saline" (>10,000 TDS) water in the area.*

Comment: Page 4-106, Figure 4.8.4: Please change the color symbol for the “3,000 – 5,000 mg/L” division for TDS so it is not the same as any of the colors used for the Geologic Outcrop Units symbols.

Response: *Figure symbology revised for clarity.*

Comment: Page 5-3, Figure 5.2.1: Please add General Head Boundaries to this figure, more clear indicate extent of Layer 1 in bottom figure.

Response: *Figure revised for clarity.*

Comment: Page 6-1, paragraph 2: Please add the reference for MODFLOW 2000 to the list of MODFLOW references.

Response: *References added.*

Comment: Page 6-1, paragraph 3: Please specify which version of Groundwater Vistas and Windows XP (Professional, home, …) was used.

Response: *Text updated.*

Comment: Page 6-1, paragraph 4: Please move to section 6.2.

Response: *Text revised as suggested.*

Comment: Page 6-2, paragraph 3: Please change “fault” to “Fault Zone”.

Response: *Text revised as suggested.*

Comment: Page 6-4, Figure 6.2.1: The northernmost part of the aquifer extends beyond grid. Please point this out in the text and briefly discuss. Please fix figure borders.

Response: *The model grid extends into Arkansas to a sufficient distance so that pumping near the Red River in Texas would not be greatly affected by boundary conditions. The grid does not extend to the full extent of the Nacatoch sand in Arkansas because it was not necessary for the Texas model.*

Comment: Page 6-5, Figure 6.2.2: Please move the State Line up in priority in the list of layers so that it overlays the Boundary Conditions symbols.

Response: *Figures updated.*

Comment: Page 6-6, Figure 6.2.3: It is unclear from the figure if there is series of grid cells associated with this layer or if there should be a layer of grid cells. Please provide clarification or adjust the symbology if necessary.

Response: *Active grid cells without specified boundary condition within the model extent are labeled as white/clear as in Figure 6.2.2.*

Comment: Page 6-7, Section 6.3: Please discuss parameters such as the solver and convergence criteria used in the model.

Response: *Text added to Section 6.1.*

Comment: Page 7-2, paragraph 3: Please specify the steady-state time period.

Response: *Text added.*

Comment: Page 7-2, paragraph 3: Text states you added a “short” transient period prior to 1980. Please revise text to reflect the time period listed on page 9-1.

Response: *Text revised for clarity.*

Comment: Page 7-4, paragraph 5: Please change “… but hard …” to “… but are hard …”.

Response: *Text revised as suggested.*

Comment: Page 8-1, paragraph 2: Please explicitly state that Layer 1 is not calibrated and justify.

Response: *Layer 1 was not calibrated because no target data available. Text added.*

Comment: Page 8-3, paragraph 2: Please specify that the lower hydraulic conductivity is in Layer 2.

Response: *Text added.*

Comment: Page 8-9 (Figure 8.1.5) and Page 8-11 (Figure 8.1.7): Please revise the data and the figure to show positive numbers for consistency.

Response: *Figures updated for consistency.*

Comment: Page 8-12, paragraph 1: Please provide details and justification for the general head boundaries. This should include figures showing the distribution of GHB heads and conductance, as well as, the source of head data.

Response: *GHBs were used in layer 1 to allow a small amount of groundwater to move into and out of the Midway, which is consistent with the conceptual model. More figures have been included.*

Comment: Page 8-12, paragraph 4: Please change “10,000 days” to “100,000 days”.

Response: *Text revised as suggested.*

Comment: Page 8-16, Figure 8.2.3: Please use a color scale for the residuals that makes it easier distinguish the positive and negative magnitudes of residuals and does not conflict with the simulated heads (see Figure 9.2.3).

Response: *Figure revised.*

Comment: Page 8-17, paragraph 1: Please indicate the methodology used to calculate the water budget.

Response: *Text added.*

Comment: Page 8-27, Table 8.2.2 and Page 9-21, Table 9.2.2: Please use a consistent format for the water budget.

Response: *Table revised for consistency.*

Comment: Page 8-20, Figure 8.3.1: Please spell out the parameters in the legend.

Response: *Parameters spelled out in the text.*

Comment: Page 9-1, paragraph 2: The model has 21 stress periods. There is no apparent buildup period between the predevelopment period and the historic transient period. Please discuss no buildup period was factored into the model.

Response: *The model has a buildup period, which is two years, between the predevelopment and historical transient period.*

Comment: Page 9-7, Section 9.2.1, Paragraph 1: The values described in the text do not reflect what is listed in Table 9.2.1 (page 9-8). Please verify which section is correct and update the other as necessary.

Response: *Text updated to reflect values in table.*

Comment: Page 9-7, paragraph 2: Please revise the text to reflect Table 9.2.1 or vise versa.

Response: *Text updated to reflect values in table.*

Comment: Page 9-10, Figure 9.2.3: Please specify the time period (transient calibration period, 1980, …).

Response: *Caption updated.*

Comment: Page 9-12, Figure 9.2.4: Please add the residuals to the maps.

Response: *No residuals in layer 1, figure caption and text revised to reflect such.*

Comment: Page 9-24, Figures 9.3.1 and 9.3.2: Please spell out the parameters in the legend.

Response: *Parameters spelled out in the text.*

Comment: Page 10-1, paragraph 1: The Midway and alluvium are not calibrated. Please delete "… and the Midway and alluvium and terrace deposit."

Response: *Deleted as suggested.*

Comment: Page 10-1, paragraph 2: Please delete the first sentence.

Response: *The first sentence deleted as suggested.*

Comment: Page 12-1, paragraph 2: Please change "Nacatoch sand aquifer" to "Nacatoch Aquifer".

Response: *Text revised as suggested.*

Comment: References beginning page 14-1: Please add Heitmuller and Reece (2003) to the list of references.

Response: *Reference added.*

Comment: References beginning page 14-1: Please add Kelley and other (2004) reference to the list of references.

Response: *Reference added.*

Comment: References beginning page 14-1: Please add the Freeze (1971) reference to the list of references.

Response: *Reference added.*

Comment: References beginning page 14-1: Please add the Freeze and Cherry (1979) reference to the list of references.

Response: *Reference added.*

Comment: References beginning page 14-1: In the list of references, please ensure that each initial is followed by a period.

Response: *Reference added.*

Comment: References beginning page 14-1: Please add the Anderson and Woessner (1992) reference to the list of references.

Response: *Reference added.*

Comment: References beginning page 14-1: Please add the Hill and others (2000) reference to the list of references.

Response: *Reference added.*

Comment: References beginning page 14-1: Please add the following citations to the list of references: McDonald and Harbaugh, 1988; Harbaugh and McDonald, 1988; 1996; Rumbaugh and Rumbaugh, 2007.

Response: *Reference added.*

Comment: References beginning page 14-1: Please revise the list of references deleting all of the references not cited in the text.

Response: *Reference revised.*

Comment: References beginning page 14-1: Please differentiate among the three TWDB (2007) references.

Response: *Reference revised.*

Comment: References beginning page 14-1: Please change “Roemer, …” to “Roemer, F., …”.

Response: *Reference revised.*

Comment: References beginning page 14-1: Please change “Brune, Gunnar, …” to “Brune, G., …”.

Response: *Reference revised.*

2.3 Appendix A

Responses to comments from the conceptual report. The following comments have not been completely addressed in the draft final report. Please address these comments in the final report:

Comment: ClimatePRISM raster catalog: Please include measurement units in the metadata.

Response: *Measurements included*

Comment: Figure 2.3.2 shows fault dip direction; however, this information is not available in the 'MexTalco_Faultzn'. Please revise either the figure or the attribute to table.

Response: *Faults are digitized and symbolized by BEG to reflect the nature of the fault. See metadata.*

Comment: Figure 2.3.5 (Nacatoch facies distribution) still has no GIS data associated with it. Please georeference and digitize the features present in this figure. Also, it seems that the facies distribution does not cover the study area entirely. Please explain.

Response: *Map converted to raster format and added to "GeologyGrids" raster catalog as "Fig235.jpg" but not drawn to scale so cannot be georeferenced.*

Comment: Original comment: *"Figures 4.4.2, 4.4.3, 4.4.4, and 4.4.5: Have no data tables associated with them. Please provide time series data for baseflow and precipitation used in these figures."* You did not respond to this comment. Please respond appropriately and include requested data.

Response: *Figure 4.4.2 – added in table "RECH_Freq_BF_precip"*
Figure 4.4.3 and 4.4.4 – added in table "RECH_precip_vs_baseflow"
Figure 4.4.5 – added in table "RECH_Rech_vs_precip"

Comment: Original comment: *"StrmGage_NacOutcrp: No time series data table provided for these stream gage data location associated with Figure 4.7.2 and 4.7.3. Please provide time series data for these stream gage locations."* This comment was incompletely addressed. Please include time series data for baseflow and runoff shown in table 4.7.3.

Response: *Figure 4.7.2 data added in table "SURHYD_BF_separation"*

2.4 Suggestions

Comment: Page 1-2, paragraph 1: Please change “created” to “constructed”.

Response: *Text revised as suggested.*

Comment: Page 2-11, paragraph 2: Please capitalize “data center” as it is part of the institution’s name (NCDC).

Response: *Text revised as suggested.*

Comment: Page 2-12, paragraph 2: Please end third sentence with a period.

Response: *Text revised as suggested.*

Comment: Page 2-12, paragraph 2: Please change “northern most” to “northernmost”.

Response: *Text revised as suggested.*

Comment: Page 2-23, paragraph 1: Please change “…land construction followed by inland sea invasion…” to “…sea-level fluctuations…”, and “…epicontinental sea invasions…” to “…sea-level rises…”.

Response: *Text revised as suggested.*

Comment: Page 2-24, paragraph 4: Please change “Neylandville Marl” to “Neylandville Formation” to be consistent with Table 2.3.1 and Figure 2.3.3.

Response: *Text revised as suggested.*

Comment: Page 4-1, paragraph 2: Please change “Neylandville Marl” to “Neylandville Formation” to be consistent with Table 2.3.1 and Figure 2.3.3.

Response: *Text revised as suggested.*

Comment: Page 4-1, paragraph 3: Definition of model layers should be made in Chapter 5. Please delete this paragraph or revise to remove references to model layers.

Response: *Text revised as suggested.*

Comment: Page 4-26, Figure 4.3.4: Please rephrase the caption for clarity to state estimated pre-development water-level elevation contours [for the] the Nacatoch Aquifer based on relationship of land surface to estimated water levels.

Response: *Text revised as suggested.*

Comment: Page 4-39, paragraph 1: Suggest deleting the word “significant” when discussing variation of coefficients ranging from 0.4 to 0.6.

Response: *Text revised as suggested.*

Comment: Page 4-80, paragraph 1: Please change “discharge” to “inflow and outflow” and “…from the Nacatoch aquifer” to “…between the Nacatoch Aquifer and over- or underlying aquifers”

Response: *Text revised as suggested.*

Comment: Table 8.1.1: Please replace “e” with “$\times 10^{x}$”

Response: *Text revised as suggested.*

Comment: Figure 9.2.4: Please make the maps larger so the data will be seen by the reader.

Response: *Figure are not changed under discretion of contributor.*

Comment: Figures 9.2.11 and 9.2.12: Please use a larger font in the legend.

Response: *Figures are not changed under discretion of contributor.*

2.5 Model Comments

Comment: In the MODFLOW Options menu, the Continue *MODFLOW Simulation Even if Convergence Not Achieved* option is activated. This is not acceptable because each stress periods must converge, failure to do so could produce erroneous model results.

Response: *Issue addressed by choosing an alternative solver.*

Comment: Without the failure to converge override model does not converge in the first time step of the first stress period. Please correct this.

Response: *Issue addressed by choosing an alternative solver.*

2.6 Pumpage Comments

Comment: Draft deliverable did not include the pumpage geodatabase (pumpamatic) unable to provide comments at this time. Per contract Exhibit B, Attachment 2, Section 1.1.2 this is a required deliverable.

Response: *Pumpage Geodatabase included in deliverables.*

2.7 Source Geodatabase Comments

Comment: General Metadata comment: Most of the metadata suffers from broken hyperlinks in the Attributes section. Please use the ArcCatalog metadata editor to edit metadata and repair broken hyperlinks. The Attributes section is important because it tells a user what all your abbreviated field names mean. Where applicable please make sure fields have brief description and measurement units.

Response: *Metadata has been updated to include attribute descriptions.*

Comment: **Climate Series:** NCDC_Stations_ppt - No values provided for any point feature classes or tables. Please provide precipitation values as attribute field or data table with appropriate link/join attribute field.

Response: *This layer is used for Figure 2.2.5, to show where the stations are located. We did not actually download data for all of these stations. The time series precipitation data that was actually used was submitted where appropriate, e.g. for Figures 4.4.2-4.4.4.*

Comment: **Climate Series:** AvgTemp - polygon feature class has no source listed in metadata. Please provide information regarding how polygon feature classes were developed or direct source of polygon feature class data.

Response: *We are assuming this comment directed to the polygon feature class "Avg_Ann_Temp". The supplementary information in the metadata reports that the polygons were "digitized from Griffish and Orton 1968" and provides a URL to the picture source. We added this information to the "lineage" section.*

Comment: **Climate Series:** Pet_final - Raster data has insufficient source metadata information. Please provide information regarding how grids were developed or direct source of gridded data.

Response: *The supplementary information in the metadata reports that the "pet_final" coverage is from Borrelli et al. (1998). The raster dataset was provided as is. Raster was simply clipped to the model region. This information was added to the metadata.*

Comment: **Geology Series:** BotNac_DataPts - No values or other attributes except lat and lon. Please provide elevation values as attribute field or data table with appropriate link/join attribute field.

Response: *Elev_Base field added.*

Comment: **Geology Series:** TopNac_DataPts - No values or other attributes except lat and lon. Please provide elevation values as attribute field or data table with appropriate link/join attribute field.

Response: *Elev_Top field added.*

Comment: **Geology Series:** GEOL_StudyArea - No key attribute(s) to link to GEOL_Nacatoch table attributes. Please provide appropriate link/join attribute field(s).

Response: *Key attribute is Rockunit_cd.*

Comment: **Geology Series:** GEOL_NacOutcrop - No key attribute(s) to link to GEOL_Nacatoch table attributes. Please provide appropriate link/join attribute field(s).

Response: *Key attribute is Rockunit_cd.*

Comment: **Geology Series:** GEOL_Nacatoch - Table attributes cannot be linked to GEOL_StudyArea or GEOL_NacOutcrop polygon feature classes. Please provide appropriate link/join key attribute fields.

Response: *Key attribute is Rockunit_cd.*

Comment: **Geology Series:** GeologyGrids - Insufficient metadata information for how the grids within this raster catalog were developed or obtained. Please provide information regarding how grids were developed or direct source of gridded data.

Response: *Metadata added.*

Comment: CrossSections - Geologic cross sections (raster, line, or polygon) used in Figures 3.2.7 to 3.2.10 were not provided for this line feature class. Suggest scanning as raster image and/or digitizing into polygon or line feature class and store under **Geology** feature dataset.

Response: *Assuming this comment refers to Figures 2.3.8 through 2.3.11, the original maps digitized were scanned as raster images and added to the source geodatabase in the "GeologyGrids" raster catalog.*

Comment: Figure 2.3.1 (Major tectonic and structural features) has no GIS data associated with it. Suggest scanning as raster image and/or digitizing into polygon or line feature class and store under **Geology** feature dataset.

Response: *Scanned and georeferenced Figure 2.3.1 and added to "GeologyGrids" raster catalog as "Fig231.jpg".*

Comment: Figure 2.3.4 (Nacatoch facies distribution) has no GIS data associated with it. Suggest scanning as raster image and/or digitizing into polygon or line feature class and store under **Geology** feature dataset.

Response: *Now Figure 2.3.5 in report, map converted to raster format and added to "GeologyGrids" raster catalog as "Fig235.jpg" but not drawn to scale so cannot be georeferenced.*

Comment: Figures 2.3.11 and 4.7.11 (Mexia-Talco fault zone with major grabens) has no GIS data associated with it. Suggest scanning as raster image and/or digitizing into polygon or line feature class and store under **Geology** feature dataset.

Response: *Now figures 2.3.2 and 4.7.8, fault and graben features included in source geodatabase as "MexTalco_Faultzn" and "Fault_Graben.s"*

Comment: Figures 4.2.1, 4.2.2, and 4.2.3 have no GIS data associated with downdip model extent. Please provide polygon or line feature class and store under **Geology** feature dataset.

Response: *Feature included in source geodatabase as "BOUND_Nac_Downdip."*

Comment: **Geomorphology:** GeomorphologyDEM - No DEM raster provided as used in figure 2.2.3 (raster catalog is blank). Please provide DEM raster data.

Response: *DEM provided in GeomorphologyDEM raster dataset as "topo_county"*

Comment: **SubSurfaceHydro:** SubSurfaceHydroWaterLevels – The extent of these grids does not completely overlap (northeastern part) with the Model_WL_area polygon feature class. Suggest revising model water level area polygon or the water level grids.

Response: *Raster datasets clipped to model extent.*

Comment: **SubSurfaceHydro:** 1989wls_c - This raster name does not correspond to Figure 4.3.8 (Water-level elevations for the Nacatoch aquifer in 1990). Suggest correcting either data set or figure.

Response: *Year corrected to read 1990.*

Comment: **SubSurfaceHydro:** WELLS_Nac_obs - No time series table data provided for these transient water-level data locations associated with Figures 4.3.11 and 4.3.12. Please provide time series data for these observation well locations.

Response: *Table added to source geodatabase called "SUBHYD_Well_Hydros."*

Comment: **SurfaceHydro:** Figures 4.4.2, 4.4.3, 4.4.4, and 4.4.5 have no data tables associated to them. Please provide time series data for baseflow and precipitation used in these figures.

Response: *Figure 4.4.2 – added in table "RECH_Freq_BF_precip"*
Figure 4.4.3 and 4.4.4 – added in table "RECH_precip_vs_baseflow"
Figure 4.4.5 – added in table "RECH_Rech_vs_precip"

Comment: Figures 4.5.2 and 4.7.1 have no GIS data associated with streams. Please provide line feature class and store under **SurfaceHydro** feature dataset.

Response: *Feature included in source geodatabase as "Streams_EPA_RF1_RiverReach."*

Comment: StrmGage_NacOutcrp - No time series data table provided for these stream gage data locations associated with Figure 4.7.2 and 4.7.3. Please provide time series data for these stream gage locations.

Response: *Time-series data for these gages were provided as the data for Figures 4.4.3 and 4.4.4.*

Comment: TX_Reservoirs - No time series data table provided for these reservoir data locations associated with Figure 4.5.2. Please provide time series data for these reservoir locations.

Response: *Table added to source geodatabase called "SURHYD_Reservior_Levels."*

Comment: **Recharge:** topo_county - Raster image is corrupt. Please provide working raster.

Response: *Issue resolved.*

Comment: **Recharge:** recharge - Raster image is corrupt. Please provide working raster.

Response: *Issue resolved.*

Comment: Figures 4.4.6 has no GIS data associated with average recharge. Please provide raster or polygon/line feature class and store under **Recharge** feature dataset.

Response: *Raster included in "RechargeGrids" raster catalog as "nac_recharge."*

Comment: **Soils:** Figures 4.4.8 has no GIS data associated with estimate of soil saturated conductivity. Please provide raster or polygon feature class and store under **Soils** feature dataset.

Response: *Raster included in "SoilGrids" raster catalog as "ksat_fpd."*

Comment: 'PanEvap' feature class: Please include measurement units in the metadata.

Response: *Measurement units added to attributes descriptions as suggested.*

Comment: 'ClimatePRISM' raster catalog: Please include measurement units in the metadata.

Response: *Measurement units added to attributes descriptions as suggested.*

Comment: 'CONT_NacThk' feature class: Please specify the contour interval in the metadata.

Response: *Metadata revised.*

Comment: 'CONT_NetSandThk' feature class: Please specify the contour interval in the metadata.

Response: *Metadata revised.*

Comment: 'GeologyGrids' raster catalog: Please include measurement units in the metadata.

Response: *Measurement units added to attributes descriptions as suggested.*

Comment: 'GeomorphologyDEM' raster catalog: Please include measurement units in the metadata and add the equivalent of 30m resolution in feet.

Response: *Measurement units added to attributes descriptions as suggested.*

Comment: 'Head_1980_Lay1' feature class: Please provide metadata.

Response: *Metadata added.*

Comment: 'Head_1980_Lay1_cont' feature class: Please provide metadata.

Response: *Metadata added.*

Comment: 'Head_1980_Lay2' feature class: Please provide metadata.

Response: *Metadata added.*

Comment: 'Head_1980_Lay2_cont' feature class: Please provide metadata.

Response: *Metadata added.*

Comment: 'Head_1990_Lay1' feature class: Please include measurement units in the metadata.

Response: *Measurement units added to attributes descriptions as suggested.*

Comment: 'Head_1990_Lay1_cont' feature class: Please revise contour description in the metadata to match data from the table.

Response: *Metadata revised.*

Comment: 'Head_1990_Lay2' feature class: Please revise metadata to reflect the data and include measurement units. This feature class does not contain contours.

Response: *Measurement units added to attributes descriptions as suggested.*

Comment: 'Head_1997_Lay1' feature class: Please revise metadata to reflect the data and include measurement units. This feature class does not contain contours.

Response: *Measurement units added to attributes descriptions as suggested.*

Comment: 'Head_1997_Lay1_cont' feature class: Please revise contour description in the metadata to match data from the table.

Response: *Metadata revised.*

Comment: 'Head_1997_Lay2' feature class: Please revise metadata to reflect the data and include measurement units. This feature class does not contain contours.

Response: *Measurement units added to attributes descriptions as suggested.*

Comment: 'Head_SS_Lay1_cont' feature class: Please revise contour description in the metadata to match data from the table.

Response: *Metadata revised.*

Comment: 'SS_Target_Residuals' feature class: Please include measurement units in the metadata.

Response: *Measurement units added to attributes descriptions as suggested.*

Comment: 'SS_Target_Lay1' feature class: Please include measurement units in the metadata.

Response: *Measurement units added to attributes descriptions as suggested.*

Comment: 'SS_Target_Lay2' feature class: Please include measurement units in the metadata.

Response: *Measurement units added to attributes descriptions as suggested.*

Comment: 'TR_Target_Avg_Residuals_Lay1' feature class: Please include measurement units in the metadata.

Response: *Measurement units added to attributes descriptions as suggested.*

Comment: 'TR_Target_Avg_Residuals_Lay2' feature class: Please include measurement units in the metadata.

Response: *Measurement units added to attributes descriptions as suggested.*

Comment: 'TR_Target_Residuals_1990' feature class: Please include measurement units in the metadata.

Response: *Measurement units added to attributes descriptions as suggested.*

Comment: 'RechargeGrids' raster catalog: Please include measurement units in the metadata.

Response: *Measurement units added to attributes descriptions as suggested.*

Comment: 'CONT_1980WL' feature class: Please specify the contour interval in the metadata.

Response: *Metadata revised.*

Comment: 'CONT_1989WL' feature class: Please specify the contour interval in the metadata.

Response: *Metadata revised.*

Comment: 'CONT_1997WL' feature class: Please specify the contour interval in the metadata.

Response: *Metadata revised.*

Comment: 'CONT_PreDevWL' feature class: Please specify the contour interval in the metadata.

Response: *Metadata revised.*

Comment: 'CONT_PreDto1980Drawdn' feature class: Please specify the contour interval in the metadata.

Response: *Metadata revised.*

Comment: ‘WELLS_WaterLevels_1980’ feature class: Please include measurement units in the metadata.

Response: *Measurement units added to attributes descriptions as suggested.*

Comment: ‘WELLS_WaterLevels_1989’ feature class: Please include measurement units in the metadata.

Response: *Measurement units added to attributes descriptions as suggested.*

Comment: ‘WELLS_WaterLevels_Outcrop’ feature class: Please include measurement units in the metadata.

Response: *Measurement units added to attributes descriptions as suggested.*

Comment: ‘WELLS_WaterLevels_PreD’ feature class: Please include measurement units in the metadata.

Response: *Measurement units added to attributes descriptions as suggested.*

Comment: ‘SubSurfaceHydroWaterLevels’ raster catalog: Please include measurement units in the metadata.

Response: *Measurement units added to attributes descriptions as suggested.*

Comment: ‘StrmGage_NacOutcrop’ feature class: Please include measurement units in the metadata.

Response: *Measurement units added to attributes descriptions as suggested.*