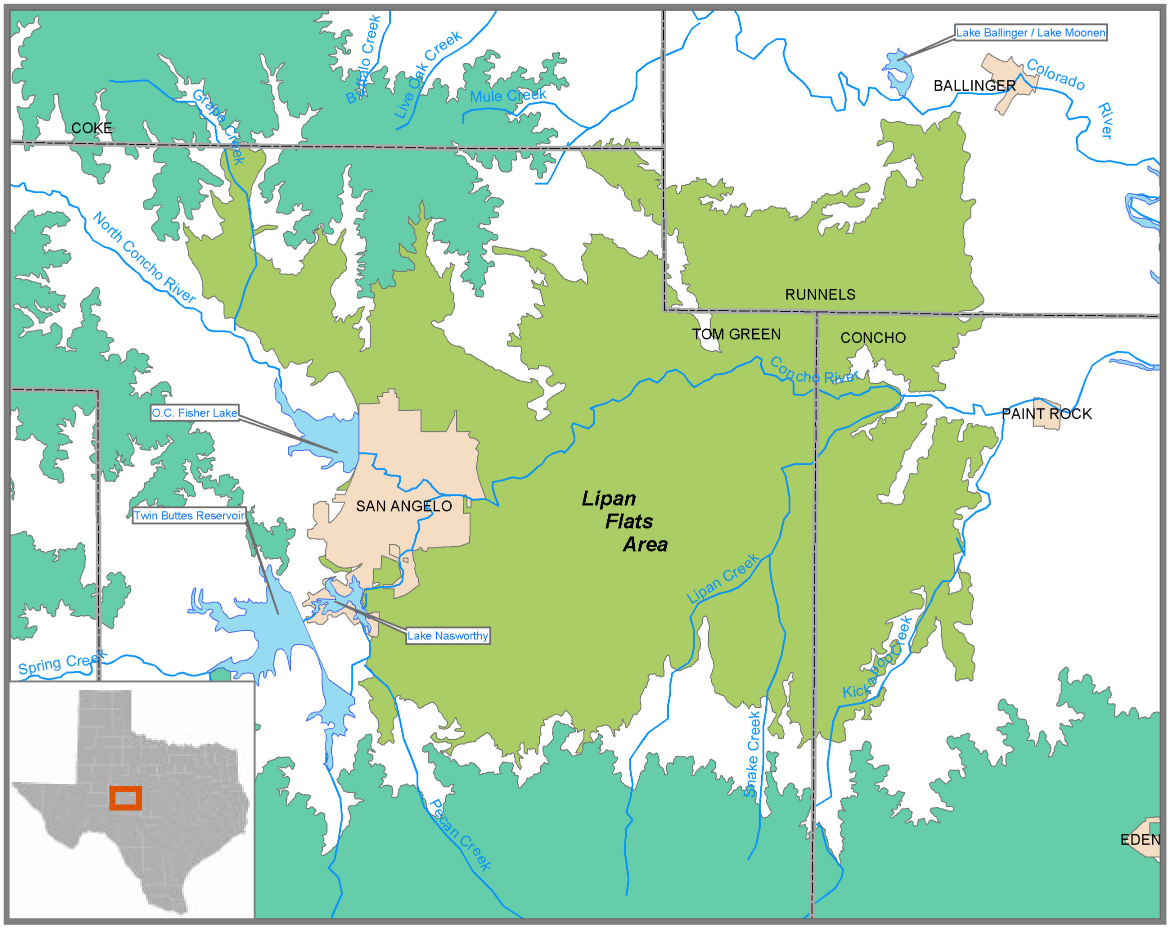
Groundwater Availability Model for the Lipan Aquifer in Texas



Prepared for:

Texas Water Development Board

By:

James A. Beach, Stuart Burton, and Barry Kolarik

June 2004

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Abstract

The Lipan aquifer in central-west Texas is an important source of water for irrigation, livestock, and rural domestic supply and has been used in this capacity for over 80 years. In recent years, increased demand in conjunction with drought conditions have increased the need to better understand the aquifer and to develop quantitative tools to support all stakeholders in planning the future of the aquifer.

A groundwater model was developed for the Lipan aquifer as a tool to evaluate groundwater availability and water level responses due to projected pumping under normal and drought conditions. The conceptual model was based on data compiled from many sources and included a detailed analysis of the hydrogeologic data for the model area. Available information regarding aquifer hydraulic and storage properties, pumping information, and water level measurements were assimilated for use in developing a representative model. The MODFLOW flow code was used to develop the regional groundwater flow model. The model was successfully calibrated to steady-state conditions in 1980 and transient conditions between 1980 and 1999. The model simulates water level responses in the Lipan aquifer relatively well. The most sensitive model parameters are hydraulic conductivity and recharge.

The model was used to assess aquifer response from 2000 to 2050 based on water demand projections contained in the 2002 State Water Plan for Texas. Model results indicate that some of the adopted water management strategies may cause continued water level declines in the Lipan aquifer over the 50-year simulation period.

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1.0 INTRODUCTION

The Lipan aquifer is classified as a minor aquifer by the TWDB (Ashworth and Hopkins, 1995) and covers parts of four counties in west-central Texas. The Lipan aquifer, as well as adjacent water-bearing formations, was evaluated to establish a conceptual model for the flow system and a groundwater availability model (GAM) for the aquifer. The major goal of the GAM is provide a scientific, quantitative tool to evaluate impacts of pumping and drought in the study area and to assist in regional water planning efforts and aquifer management decisions. The Lipan aquifer GAM provides a MODFLOW model of the aquifers that can be used to help assess groundwater availability. The GAM process was designed to incorporate all pertinent information about the aquifer and provided the stakeholders an opportunity to comment on the model development. The result is a standardized, thoroughly documented, and publicly available numerical groundwater flow model. The Lipan GAM will be one of the primary tools to evaluate water management strategies and the availability of groundwater in the regional water planning areas (RWPA) and groundwater conservation districts in the study area.

The Lipan aquifer comprises saturated alluvial deposits and the up dip portions of the underlying Permian age limestones, dolomites, and shales that are hydrologically continuous with the alluvium. The underlying Permian units extend beyond the boundaries of the alluvium and form a more extensive aquifer to the east and north of the alluvium. Groundwater in the Lipan aquifer naturally discharges to the Concho River and by evapotranspiration in areas where the water table is at or near land surface. The aquifer contains fresh to slightly saline water.

The Lipan aquifer provides water to support much of the farming industry in the area. A small amount of groundwater is used for livestock, municipal and rural domestic supply, and manufacturing. The heaviest groundwater usage from the aquifer has been in the Lipan Flats agricultural area of eastern Tom Green and western Concho Counties. In the 1950’s, row irrigation began in the area and increased moderately until the mid to late 1980’s. In the late 1980’s, pivot irrigation systems came into use and groundwater pumping for irrigation increased from about 20,000 to over 70,000 acre-feet per year by the late 1990's.

Historical well records show a dramatic increase in the number of irrigation wells in the Lipan aquifer during the 1990's. The number of irrigation wells increased from approximately 200 in 1990 to over 1,000 wells by the year 2000. However, since 1998, water levels have decreased significantly in some areas so that pumps in irrigation wells cannot be run through the entire irrigation season. Wells in other areas continue to produce through the irrigation season, but at a reduced pumping rate. During the 1990's, water level declines of up to 100 feet were observed in the Lipan aquifer. Base flow in local creeks and the Concho River may be impacted by heavy groundwater withdrawals and drought.

The Lipan GAM conceptual model incorporates all the pertinent geologic and hydrologic information that is available for the study area. These data are used to develop a computer model of the aquifer. The Lipan GAM computer model provides predictions of water level changes in the aquifer through 2050 based on data from the 2002 State Water Plan during average recharge and drought-of-record recharge conditions. Because these predictive simulations were based on the 2002 State Water Plan projected demands, this model provides a tool to investigate the viability of current groundwater management strategies. This insight is important to those dependent on the Lipan aquifer for water supply.

2.0 STUDY AREA

2.1 General Description

The Lipan GAM study area (Figure 2.1.1) is located in central Texas near San Angelo in an area known as the Lipan Flats. The study area almost completely encompasses Tom Green County with small areas overlapping into Concho, Runnels, Irion, and Coke counties and is completely with in the Colorado River basin (Figure 2.1.2). The TWDB designated the Lipan as a minor aquifer system due to its importance to the local economy. The TWDB's delineation of the Lipan aquifer, shown in Figure 2.1.3, is based on the lateral extent of Quaternary alluvial deposits in the study area as well as the extent of the historical irrigation in the area (Ashworth and Hopkins, 1995).

The study area lies completely within Regional Water Planning Area F, as shown in Figure 2.1.4. There are three water conservation districts (WCD) in the study area. A large portion of the study area lies in the Lipan-Kickapoo WCD (LKWCD) with small parts in the Irion County WCD and Coke County Underground WCD. Figure 2.1.5 shows the conservation districts in the study area.

The model boundaries extend beyond the mapped extent of the Lipan aquifer in order to minimize boundary condition effects on the model results. The southern boundary is positioned to coincide with a groundwater divide, which was based on historical groundwater levels in the Edwards-Trinity (Plateau) aquifer to the south (Bush et. al., 1993). The western boundary coincides with the 2,100-foot water level contour from Bush et. al (1993) and the northern boundary is located along the surface water divide between the Colorado and Concho Rivers. The eastern boundary is located at the eastern extent of the Lipan aquifer and will be specified as a general head boundary and based on Bush et. al. (1993) water levels at the eastern edge of the model domain.

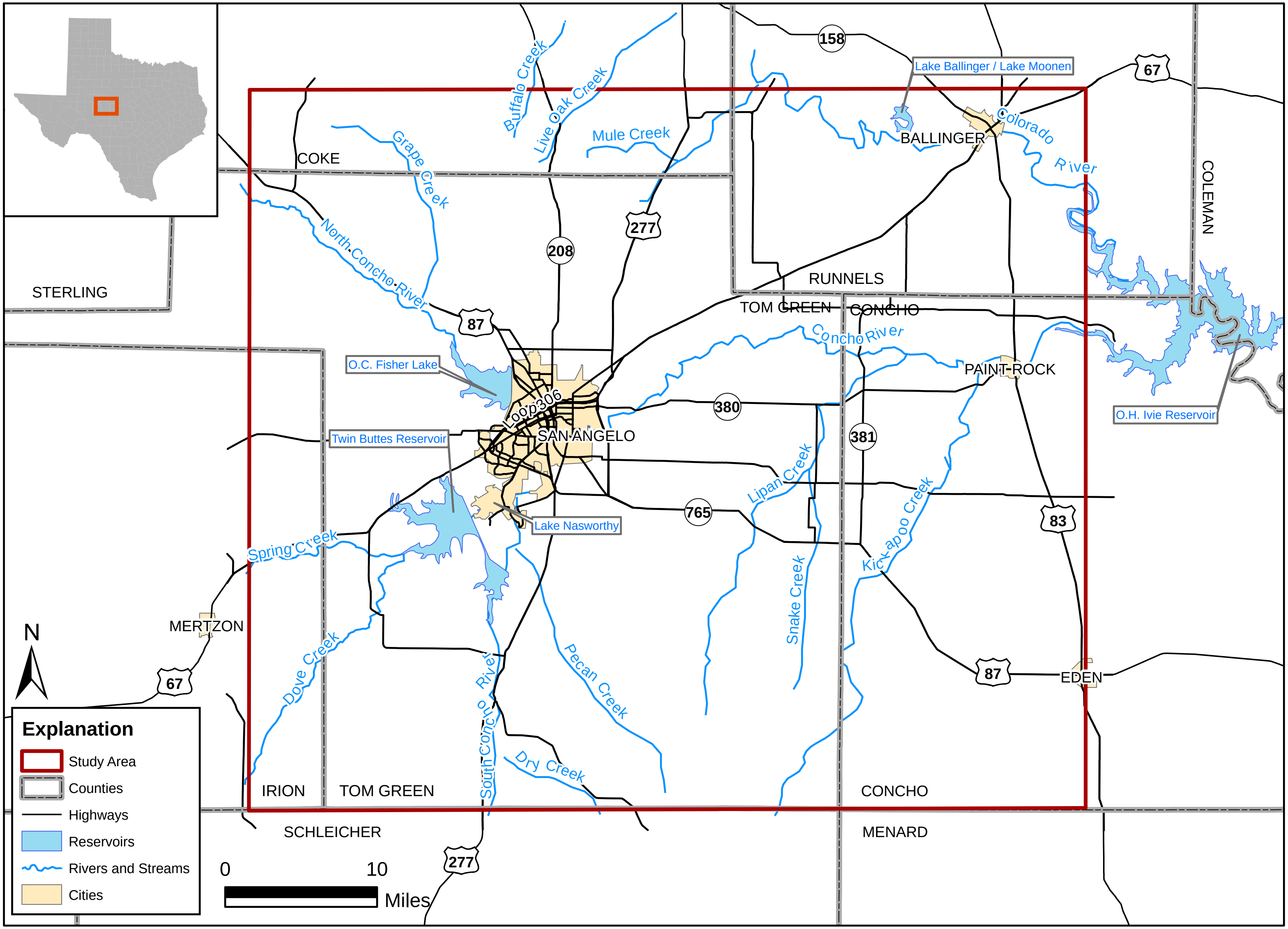


Figure 2.1.1 - Location of the Study Area

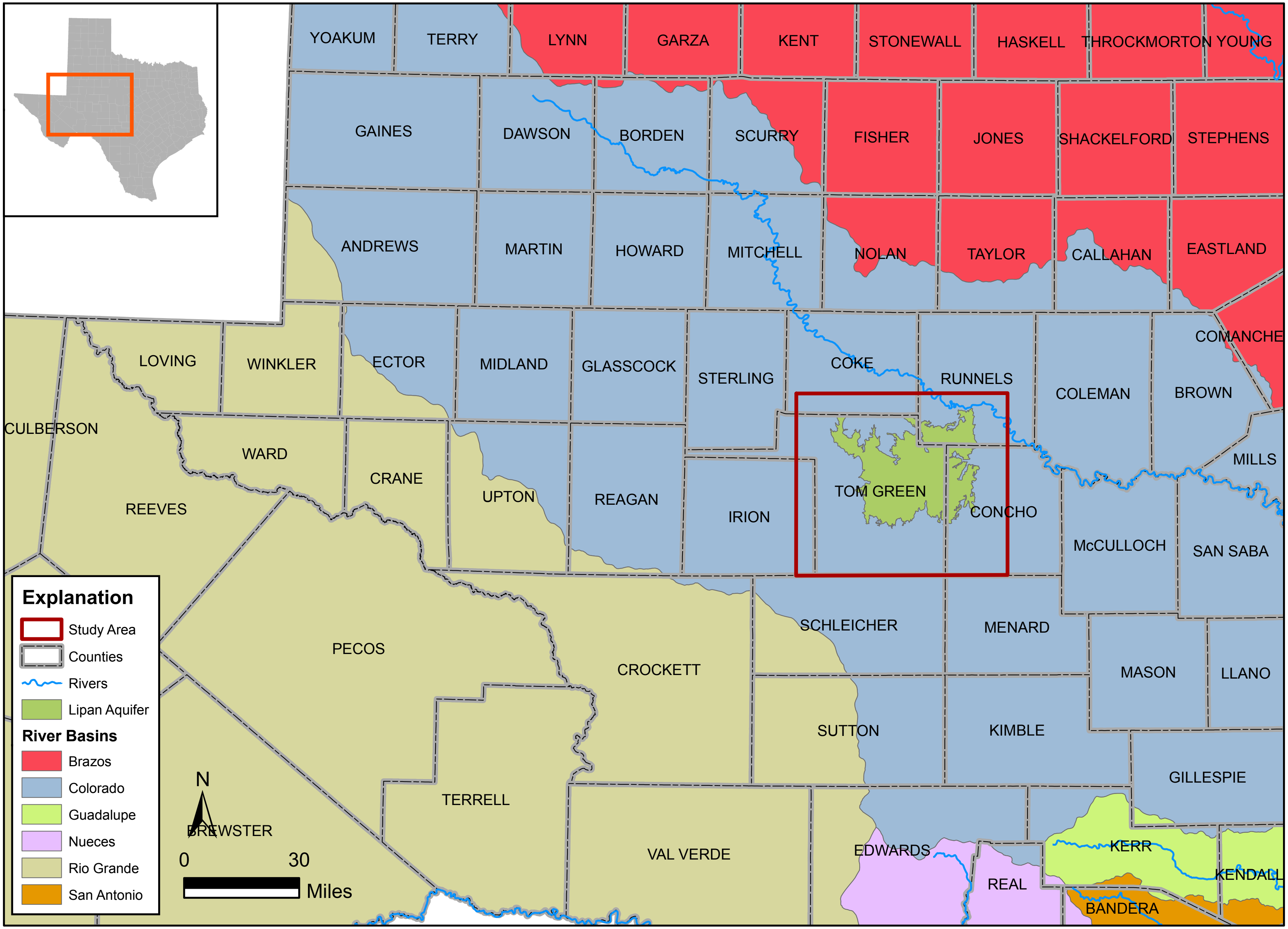


Figure 2.1.2 - River Basins

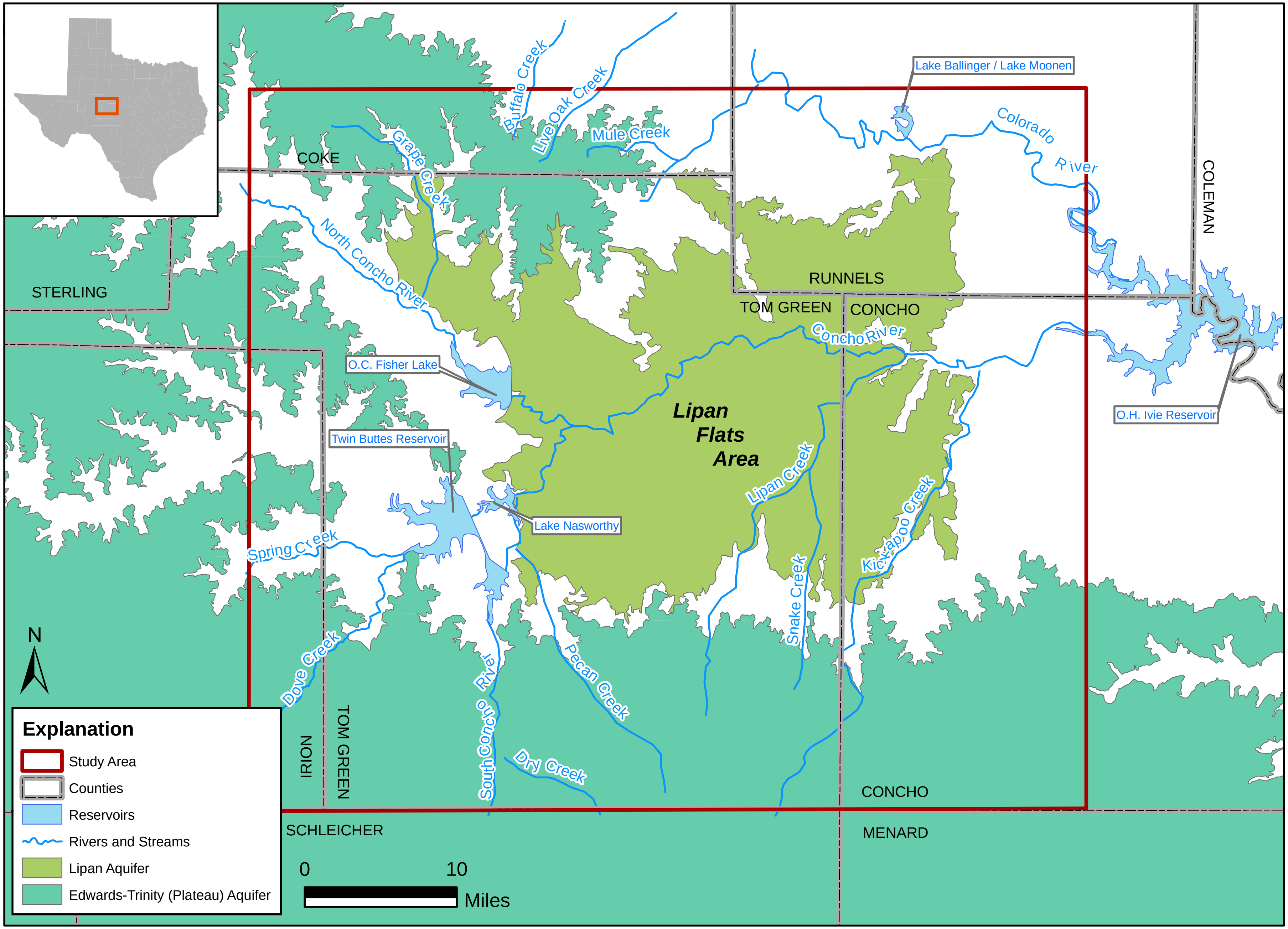


Figure 2.1.3 - TWDB Designated Aquifers

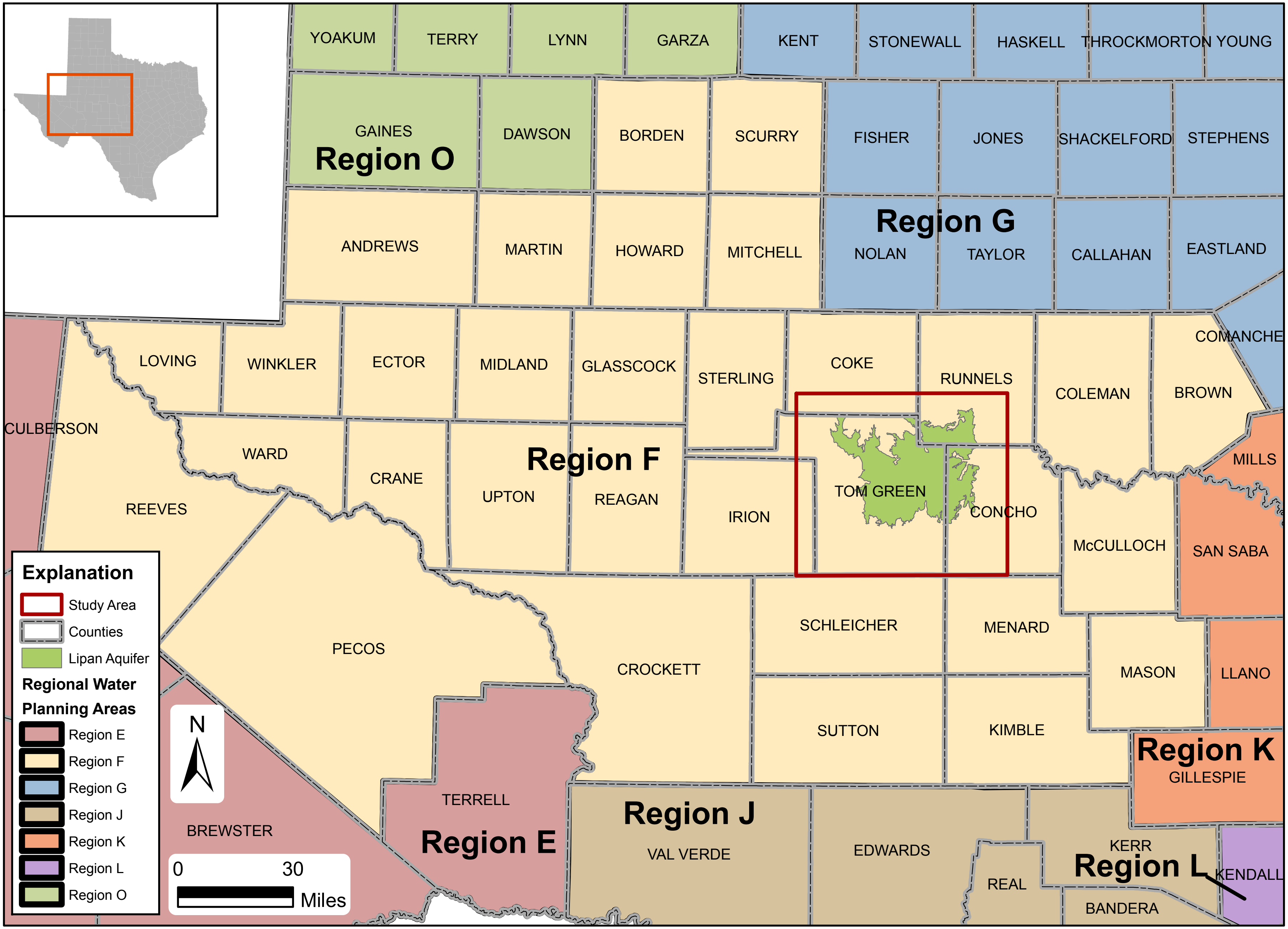
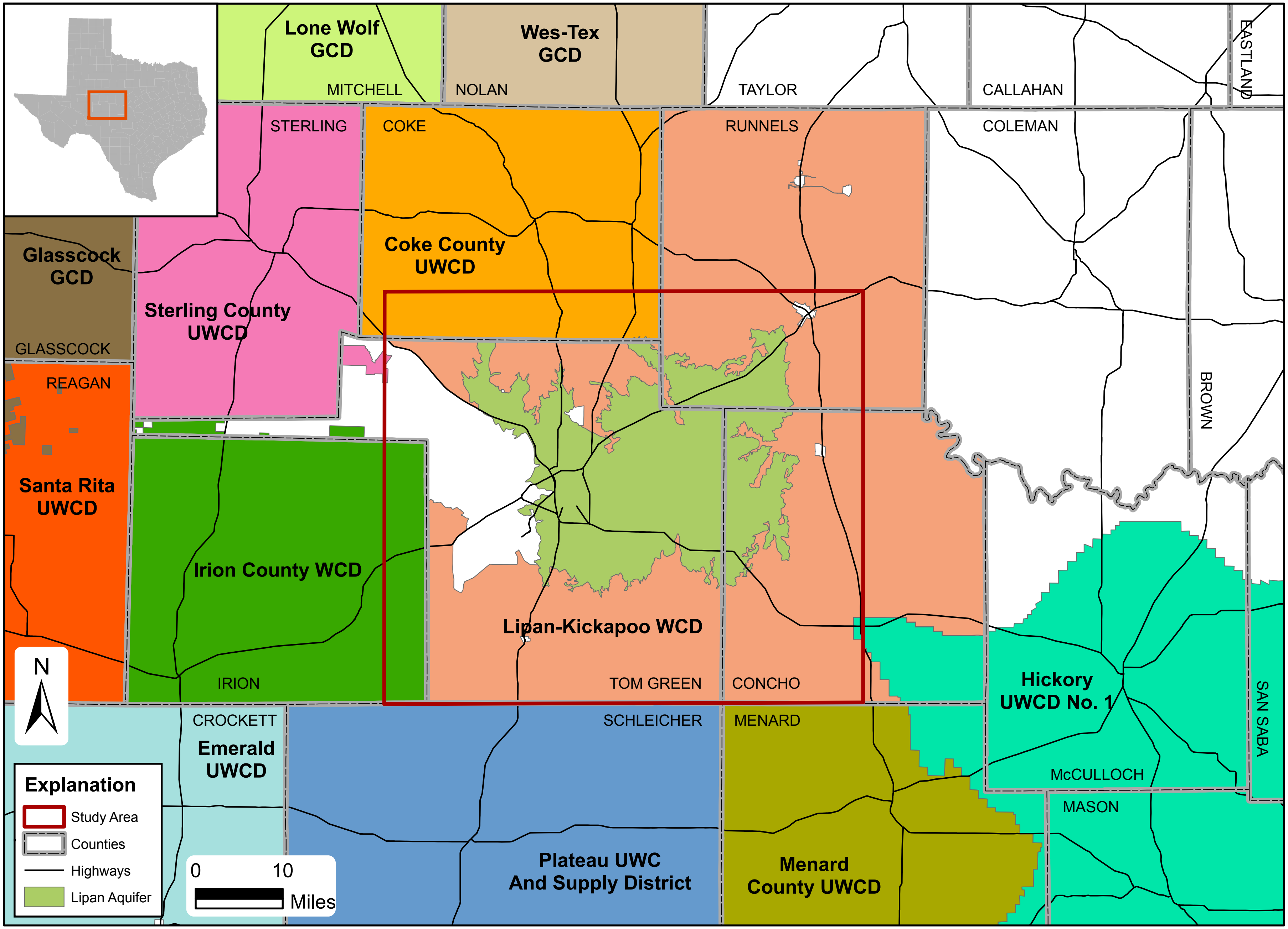


Figure 2.1.4 - Regional Water Planning Areas in the Area



WCD = Water Conservation District
GCD = Groundwater Conservation District
UWCD = Underground Water Conservation District
UWD = Underground Water District
UWC = Underground Water Conservation

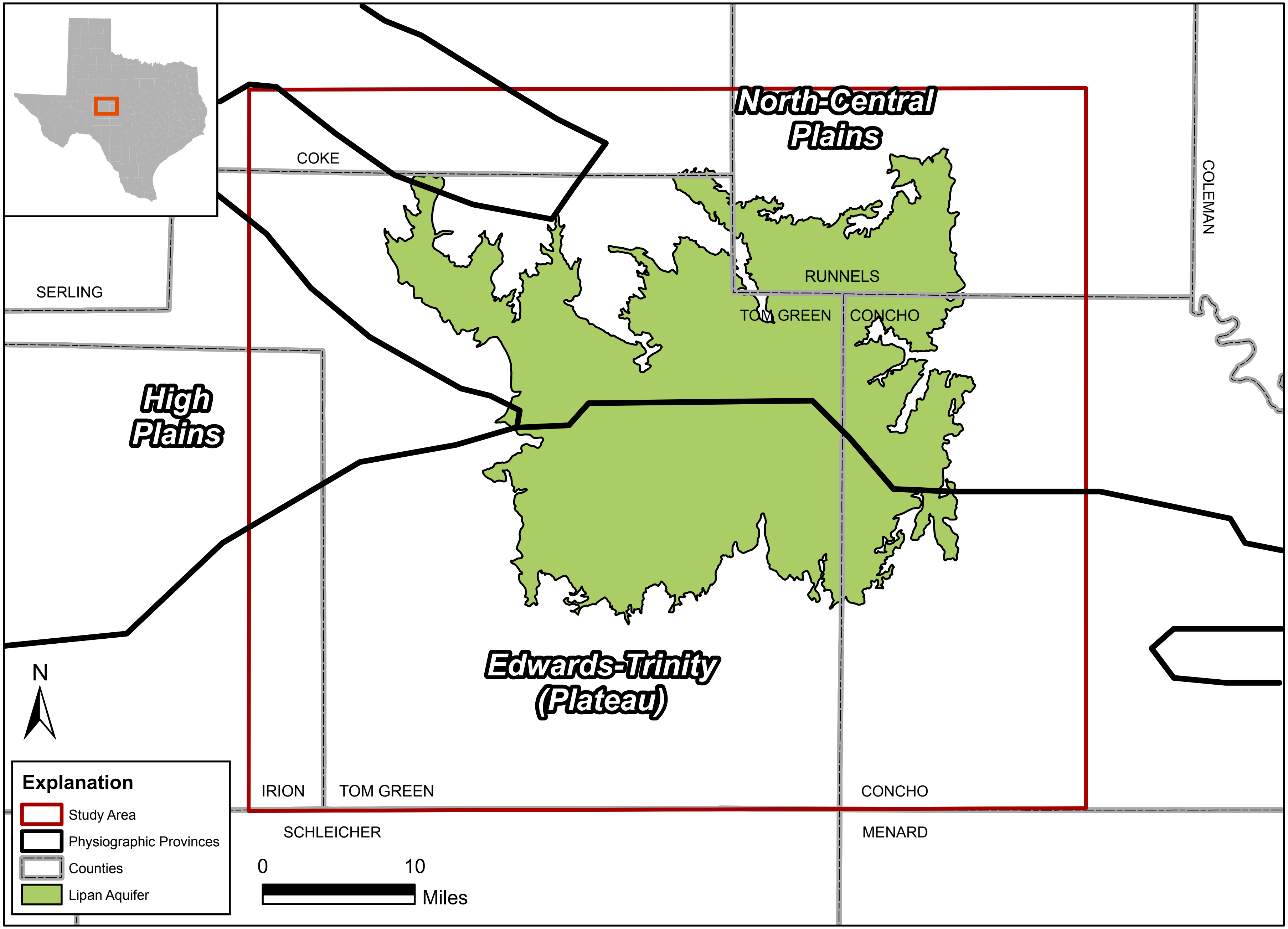
Figure 2.1.5 - Goundwater Conservation Districts in the Area

2.2 Physiography and Climate

The study area lies partially in the North-Central Texas Plains, Southern High Plains and partially in the Edwards Plateau province of Texas (BEG, 1996), as shown in Figure 2.2.1. Prairie lands dissected by meandering rivers are common in parts of the Northern-Central province, which occurs in the northern portion of the study area. In areas of harder bedrock, gently rolling hills and steep ravines are prevalent. The Edwards Plateau province, which occurs in the southern portion of the study area, is dominated by a hard cretaceous limestone caprock. The relatively flat plateau is sculpted by fault escarpments and stream entrenchment. Meandering streams and rivers transverse the study area and, in areas of harder bedrock, can form deeply incised channels. The Edwards Plateau province portion of the study area is characterized by hard Cretaceous limestones deeply entrenched by streams and rivers. A small portion of the Southern High Plains province occurs in the far western area of the study area. This province is characterized by the westerly dipping Permian bedrock, overlain by flat eolian silts and sands.

Ground surface elevations vary across the study area from about 1,500 feet above mean sea level (AMSL) in the east to about 2,500 feet in the west and north (Figure 2.2.2). The Lipan Flats, a broad, flat plain dominated by farmland, lies in the center of the study area. Gently sloping hills, entrenched by seasonal spring fed streams, rise up from the Lipan Flats to the north, west and south. Mesquite, juniper and ash shrubs and brush make up a large portion of the vegetation in the rangeland areas. Riparian areas dot the area immediately adjacent to the Concho River.

The study area is characterized by hot, dry summers and moderate winters. There is generally more precipitation in the spring and fall, however summertime thunderstorms can produce locally large amounts of rainfall in a short amount of time. The average high temperature is 78.1 and the average low is 51.6 degrees Fahrenheit. San Angelo, the largest population center in the study area, has an average annual rainfall of 20.5 inches. From 1960 through 1996, average precipitation was 22.1 inches per year in the study area (TWDB website). On the eastern side of the study area, the precipitation averages about 25 inches per year and decreases to around 20 inches per year on the western side of the



Modified Slightly after BEG

Figure 2.2.1 - Physiographic Provinces in the Study Area

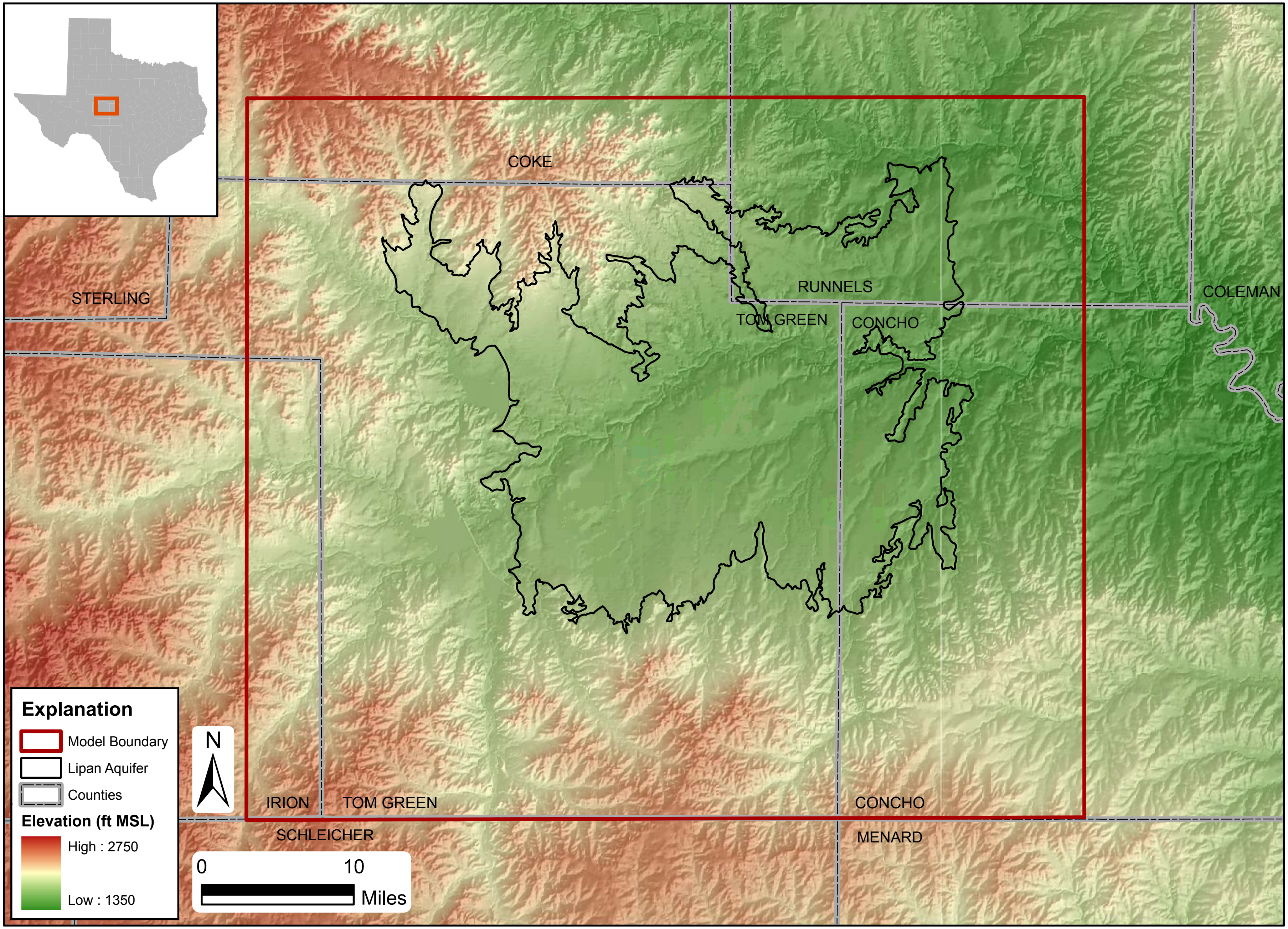


Figure 2.2.2 - Land Surface Elevation

study area. Figure 2.2.3 shows a comparison of precipitation contours developed from long-term average data (TWDB website) and data obtained from the National Weather Service (NWS) for this study. Although there are slight variations in the contours, they show good agreement throughout the study area. Figure 2.2.4 shows historical precipitation at five rain gages located in the study area. These data indicate that variation in annual precipitation across the study area is relatively small. Gaps in the annual precipitation charts indicate that data was incomplete for the corresponding year.

As is typical for arid and semi-arid locations, potential evaporation generally exceeds precipitation on a monthly and yearly basis, and is especially dissimilar in the summer months. Figure 2.2.5 shows the average annual net lake evaporation in the study area (65.3 in/yr), based on TWDB data.

In 2000, the LKWCD established a network of rain gages that is monitored by local residents who record daily precipitation in the LKWCD. At the end of 2002, the network consisted of 46 rain gages (Lange, 2003) as shown in Figure 2.2.6. These data were not be used for model calibration because the calibration and verification period go from 1980 through 1999. However, in the future, these data may be helpful in assessing recharge and historical irrigation demands.

The predominant soils in the study area are clays and sandy, silty clays, with some small areas of silty gravels and silty sands. These soils generally thicken towards the Concho River and thin near the edges of the Lipan Flats. Soil thickness range from 12 to 17 inches with localized areas of thinner and thicker deposits. Figure 2.2.7 shows the predominant soil types in the study area (USDA, 1994). A further discussion of soils appears in Section 4.4.

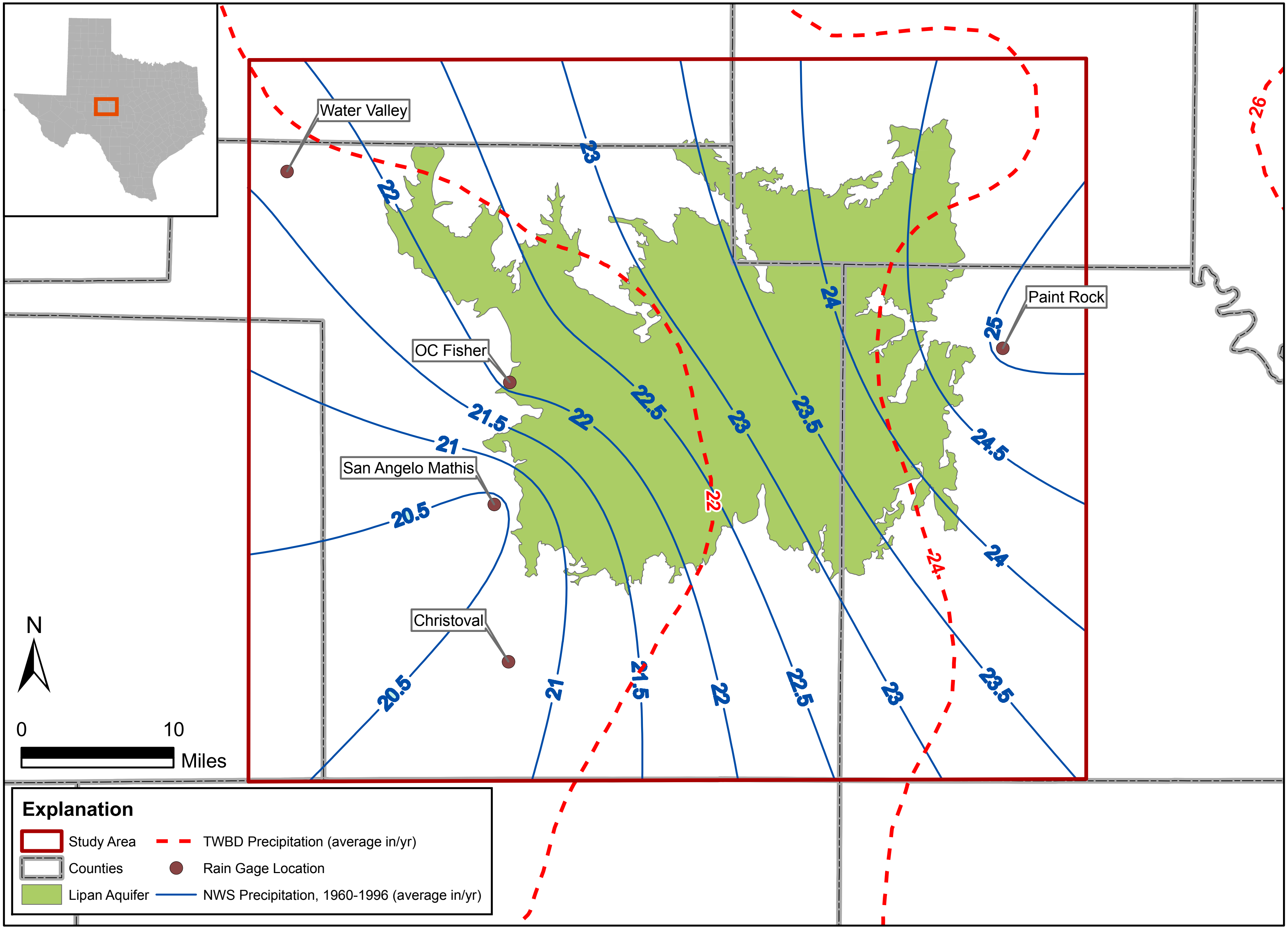
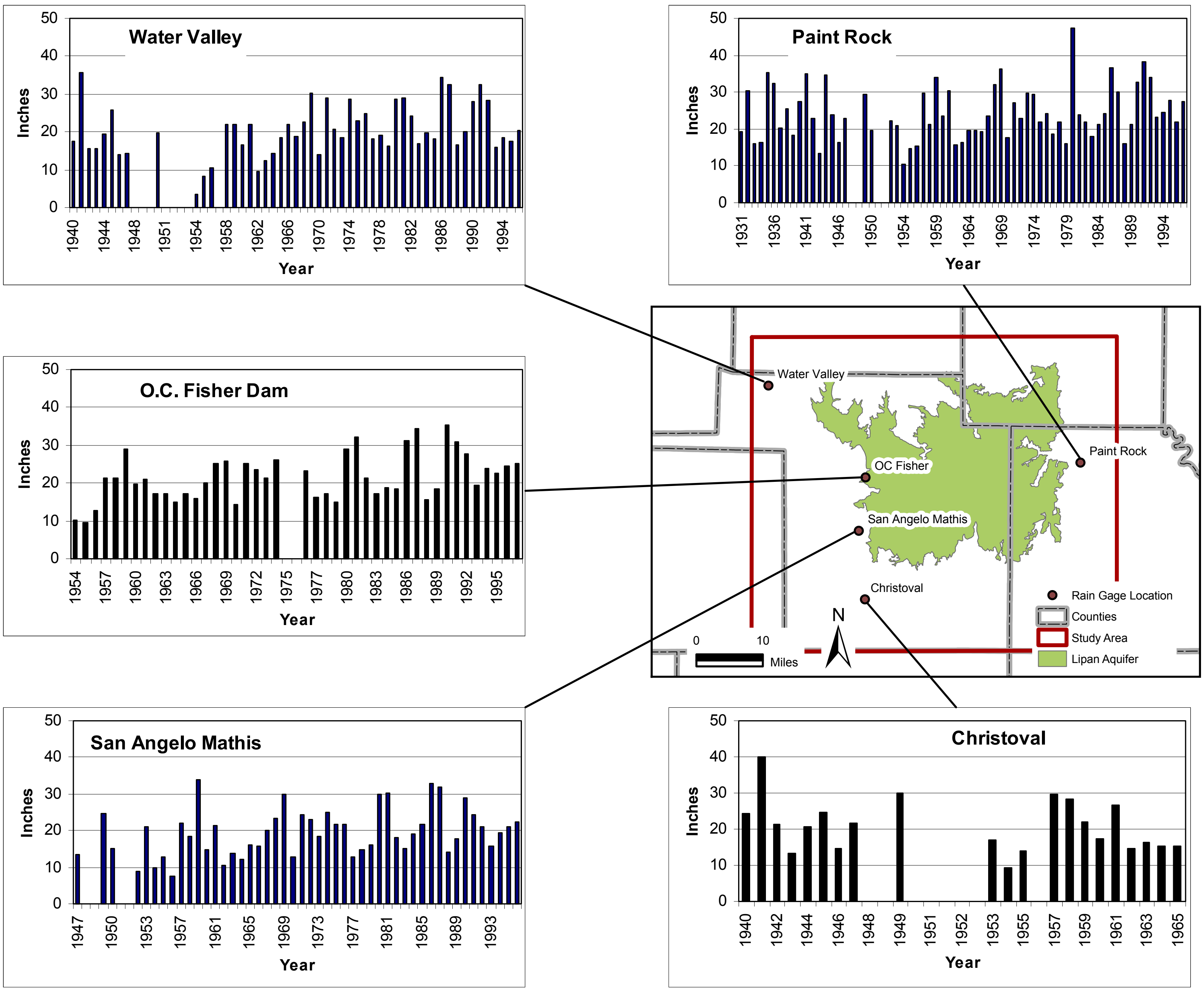


Figure 2.2.3 - Average Annual Precipitation



Note: Gaps in charts indicate incomplete data for that year.

Figure 2.2.4 - Historical Annual Precipitation

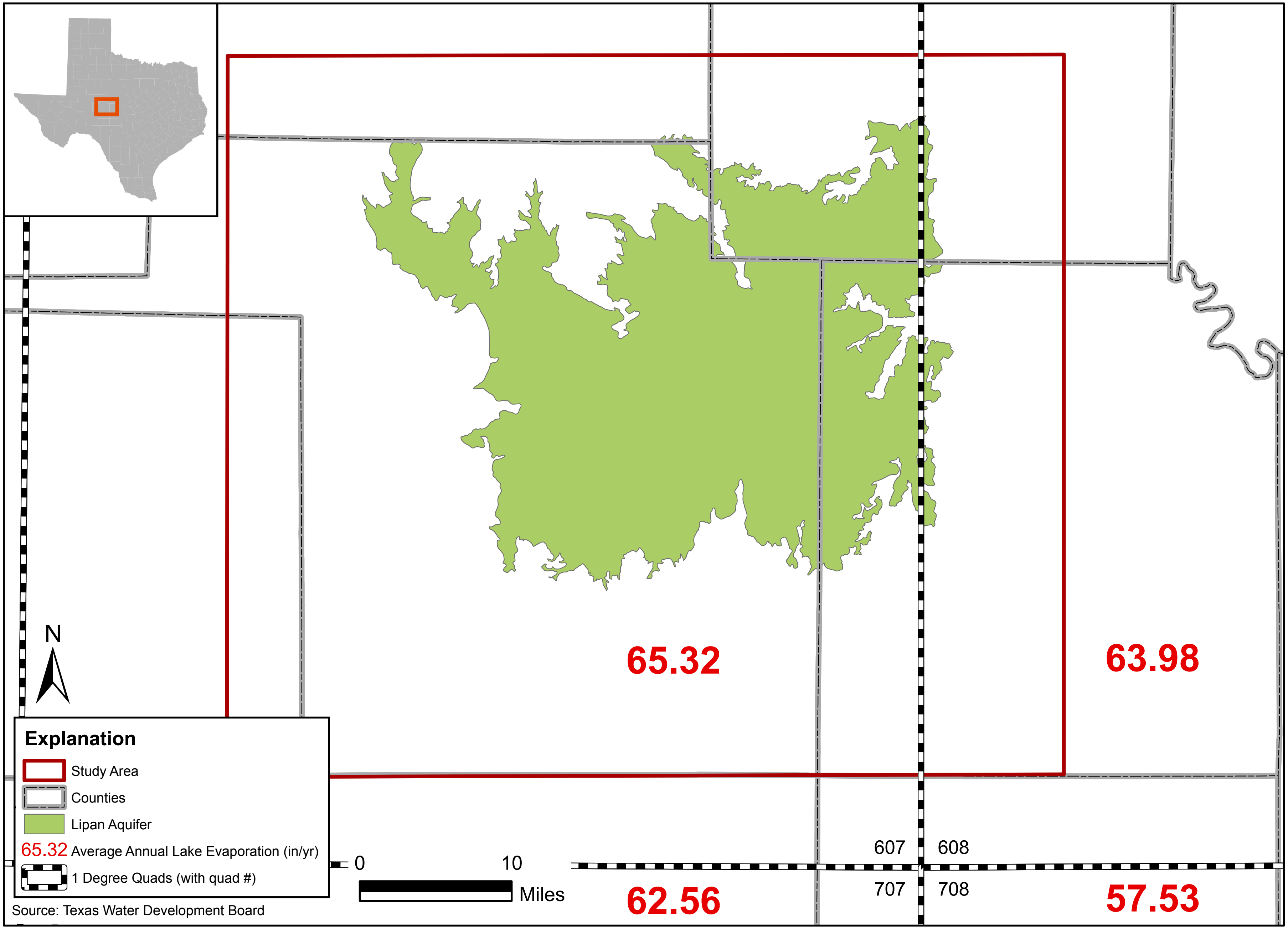


Figure 2.2.5 - Average Annual Net Lake Evaporation

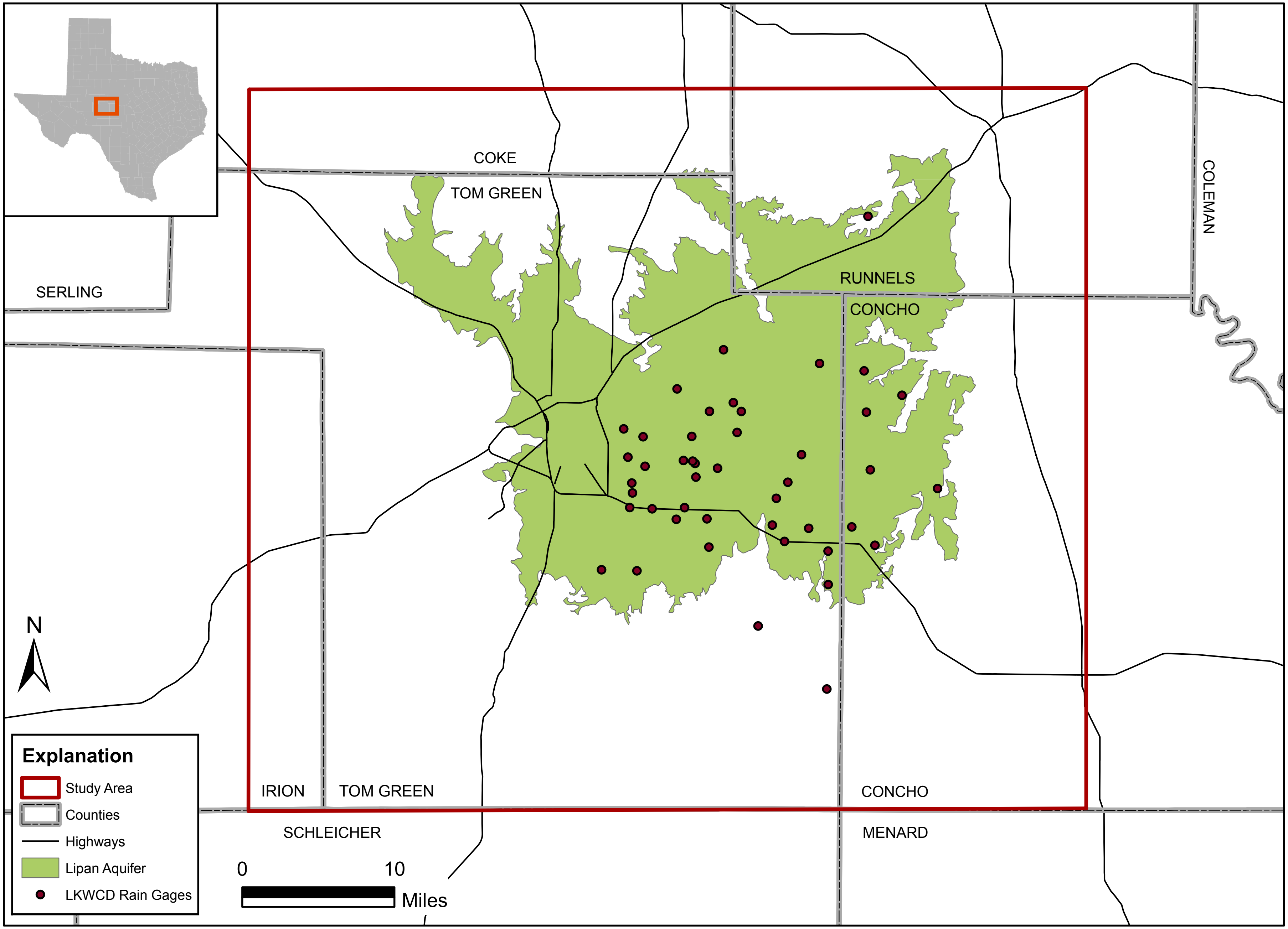
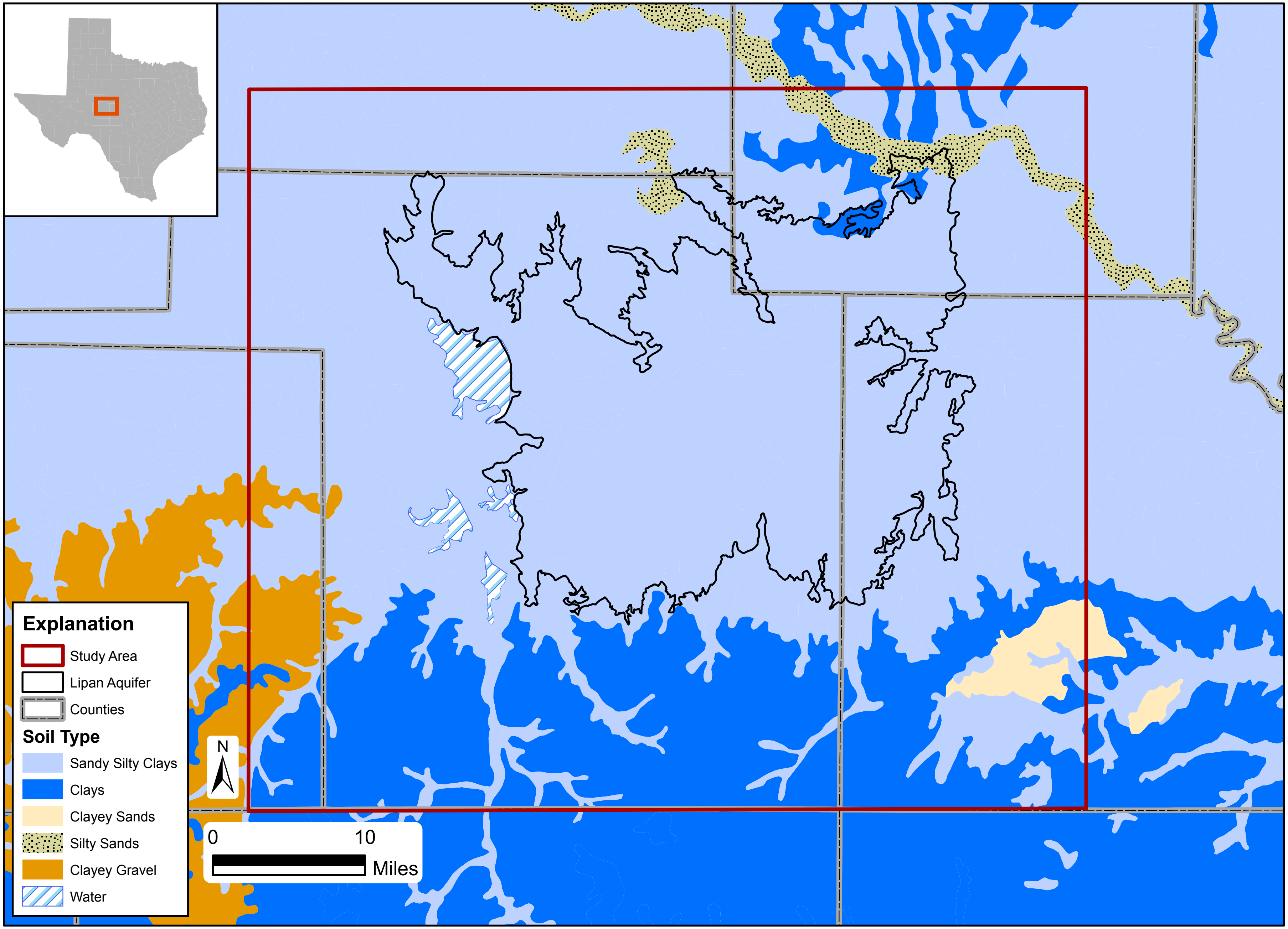


Figure 2.2.6 - Location of Lipan-Kickapoo WCD Rain Gages

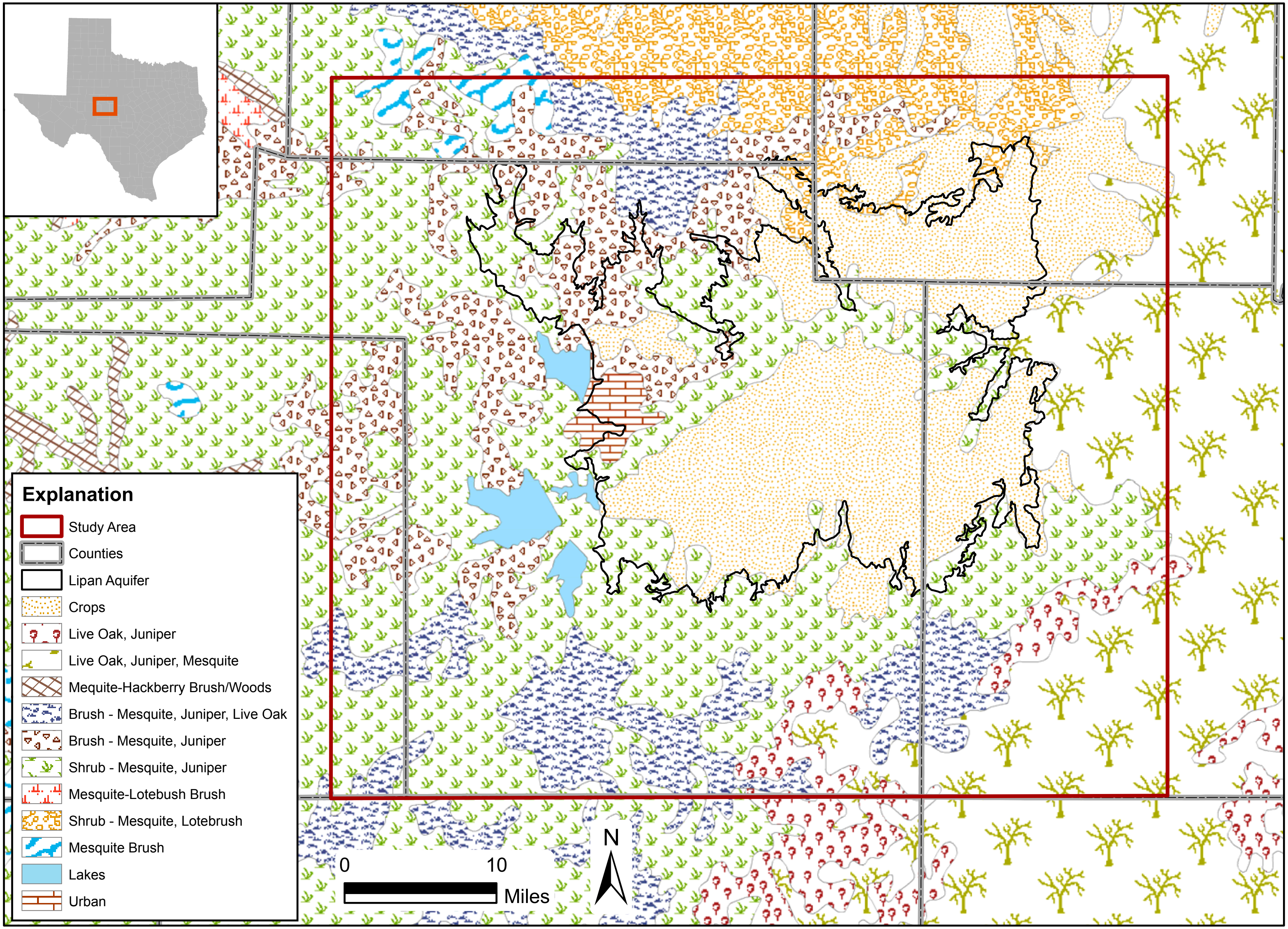


Source: STATSGO

Figure 2.2.7 - Predominant Soils in the Study Area

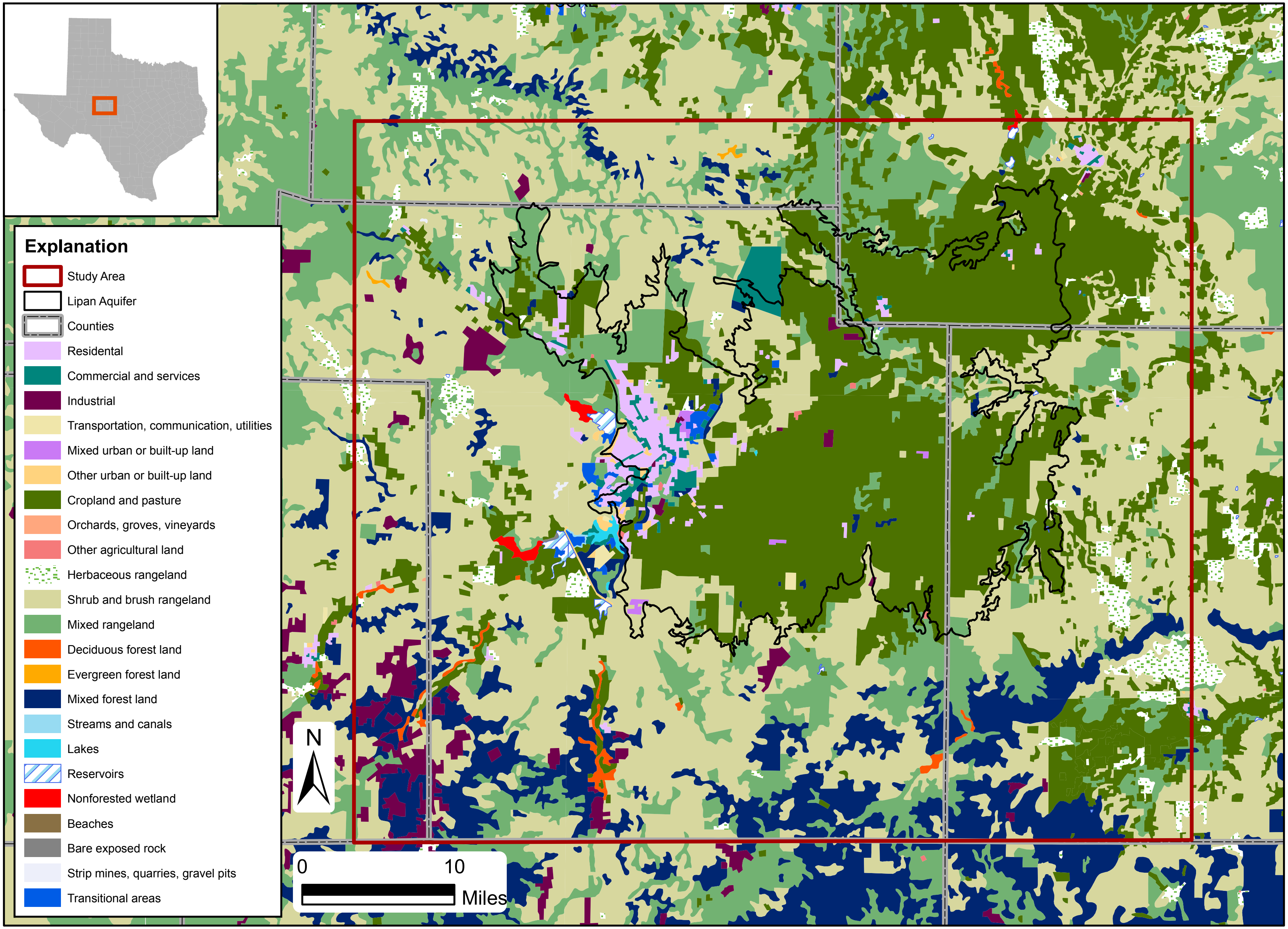
Cropland dominates the central portion of the study area, with gently rising hills of mesquite, juniper and live oak to the west, north and south, as shown in Figure 2.2.8, based on vegetation coverage by McMahan, et al., (1984). Cotton and grain sorghum are the main crops grown in the Lipan Flats (Lee, 1986). Riparian areas near the Concho River and its tributaries support salt cedars (*Tamarix sp*.), honey mesquite, and juniper (UCRA, 2000).

The Land use and land cover data (USGS, 1990) may be helpful for estimating areas of potential evapotranspiration directly from the water table. As shown Figure 2.2.9, a large portion of the Lipan aquifer is designated as cropland and pasture with the majority of the remaining land being a mix of brush and shrub rangeland and forest land. There are small areas on commercial, industrial, residential, and urban land designation in the study area, but these are mostly insignificant at the scale being studied.



Source: Texas Parks and Wildlife

Figure 2.2.8 - Vegetation in the Study Area



Source: U.S. Geological Survey

Figure 2.2.9 - Land Use and Land Cover in the Study Area

2.3 Geology

The Lipan aquifer is primarily comprised of quaternary aged alluvial deposits unconformably overlying Permian limestones and shales (Lee, 1986). Groundwater in the alluvial deposits and Permian limestones is hydraulically connected, and many wells in the area are completed in both units. An eroded paleo-surface on the Permian rocks forms the contact between the two units. This contact is an undulating erosional surface characterized by differential weathering of the Permian formations.

Figure 2.3.1 illustrates the general surface geology in the study area. A stratigraphic/hydrostratigraphic section of the major formations in the study area is shown in Figure 2.3.2.

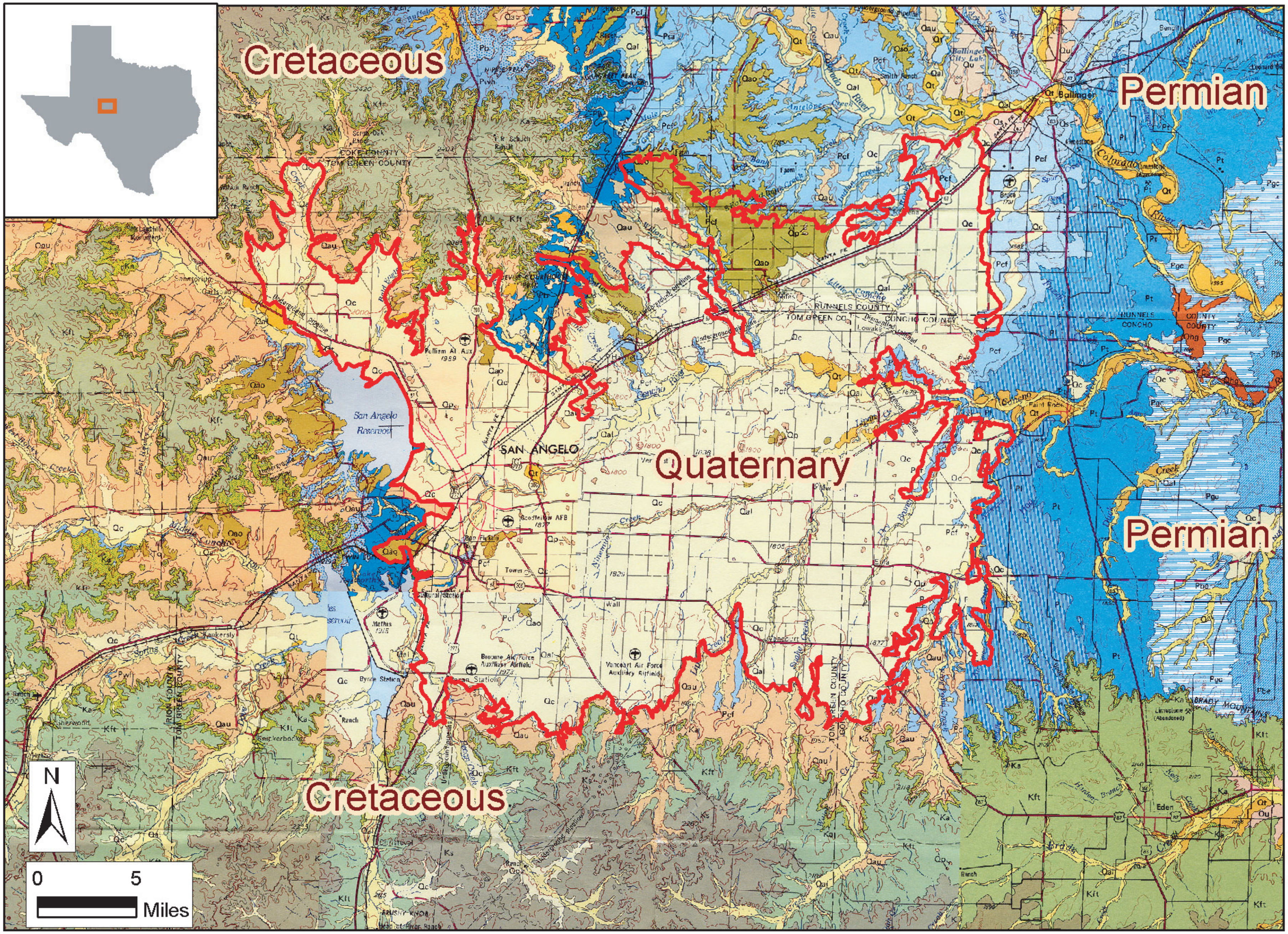
The surface geology in the Lipan Flats area is composed of Quaternary Leona Formation deposits. These deposits, which can be up to 125 feet thick, consist mostly of gravels and conglomerates cemented with sandy lime and layers of clay. However, according to a recent analysis of well driller's logs significantly less sand is found in the Leona formation than previously reported (UCRA, 2000). The Leona Formation generally fines upwards with conglomerates existing mainly in locations of thicker alluvium. Cross-sections reviewed for this study show the conglomerates at the base of the alluvium in locations where the alluvium is thicker (UCRA, 2000). The most abundant lithologic unit observed in the Leona Formation consists of consolidated alluvium and detritus. It mainly contains poorly sorted, rounded to sub-angular chert and limestone gravels. Fine to very fine sands occur in minor amounts (McWilliams,2000).

The Permian formations underlying the alluvium are predominantly limestones and shales of the Clear Fork Group. As shown in the cross-sections in Figure 2.3.3, these formations, which dip westward towards the Permian basin at about 50 feet/mile, include the Choza Formation, the Bullwagon Dolomite Member, the Vale Formation, the Standpipe Limestone Member, and the Arroyo Formation (after Lee, 1986).

Edwards-Trinity (Plateau) aquifer formations of Cretaceous age outcrop to the north, west, and south, and represent the lateral extent of the Lipan aquifer in those directions. To the east, the thinning and pinching out of the Leona Formation represents the eastern extent of the Lipan. Other noncontiguous Quaternary alluvium deposits exist in Runnels, Concho, and McCulloch Counties and have similar characteristics as the Leona Formation in the Lipan Flats of Tom Green County. The Cretaceous formations of the Edwards-Trinity (Plateau) aquifer consist mostly of massive limestones and unconsolidated to cemented gravels, sands and clays (Lee, 1986). Springs are found along the contact between the Cretaceous and Quaternary, which drain the Edwards-Trinity (Plateau) and add a small amount of water to the Leona Formation.

Age	Formation	Thickness	Hydrologic Unit	Description and Water-Bearing Characteristics
Quaternary	Leona Formation and Alluvium	0 - 125 feet	Leona Aquifer	Gravel and Stream Channel Deposits with conglomerate of Limestone cemented with sandy lime. Some layers of caliches and clay. Yields sufficient water for irrigation where thickness is suitable.
Permian Clear Fork Group	**San Angelo Sandstone**	250 feet	San Angelo Aquifer	Bright red sandstone with some clay and gypsum. Conglomerate at base. Yields small quantities of water.
	Choza Formation	625 feet	Choza Aquifer	Gray dolomitic limestone with clay and some silty clay layers. Yields small quantities of water.
	Bullwagon Dolomite	75 feet	Bullwagon Aquifer	Massive yellow to gray dolomitic limestone and green and red shale layers. Yields sufficient water for irrigation.
	Vale Formation	140 feet	Vale Aquifer	Shale at top. Rest is red sandy shale with thin streaks of green shale. Yields small quantities of water.
	Standpipe Limestone	15 feet	Standpipe Aquifer	Yellowish to light gray marly limestone. Yields small quantities of water.
	Arroyo Formation	60+ feet	Arroyo Aquifer	Alternating layers of shale and limestone. Yields small quantities of water from the limestone horizons.

Figure 2.3.1 Stratigraphic/hydrostratigraphic Section of the Lipan Aquifer (after Lee, 1986)



Source: BEG Geologic Atlas of Texas

Figure 2.3.2 - General Surface Geology the Study Area

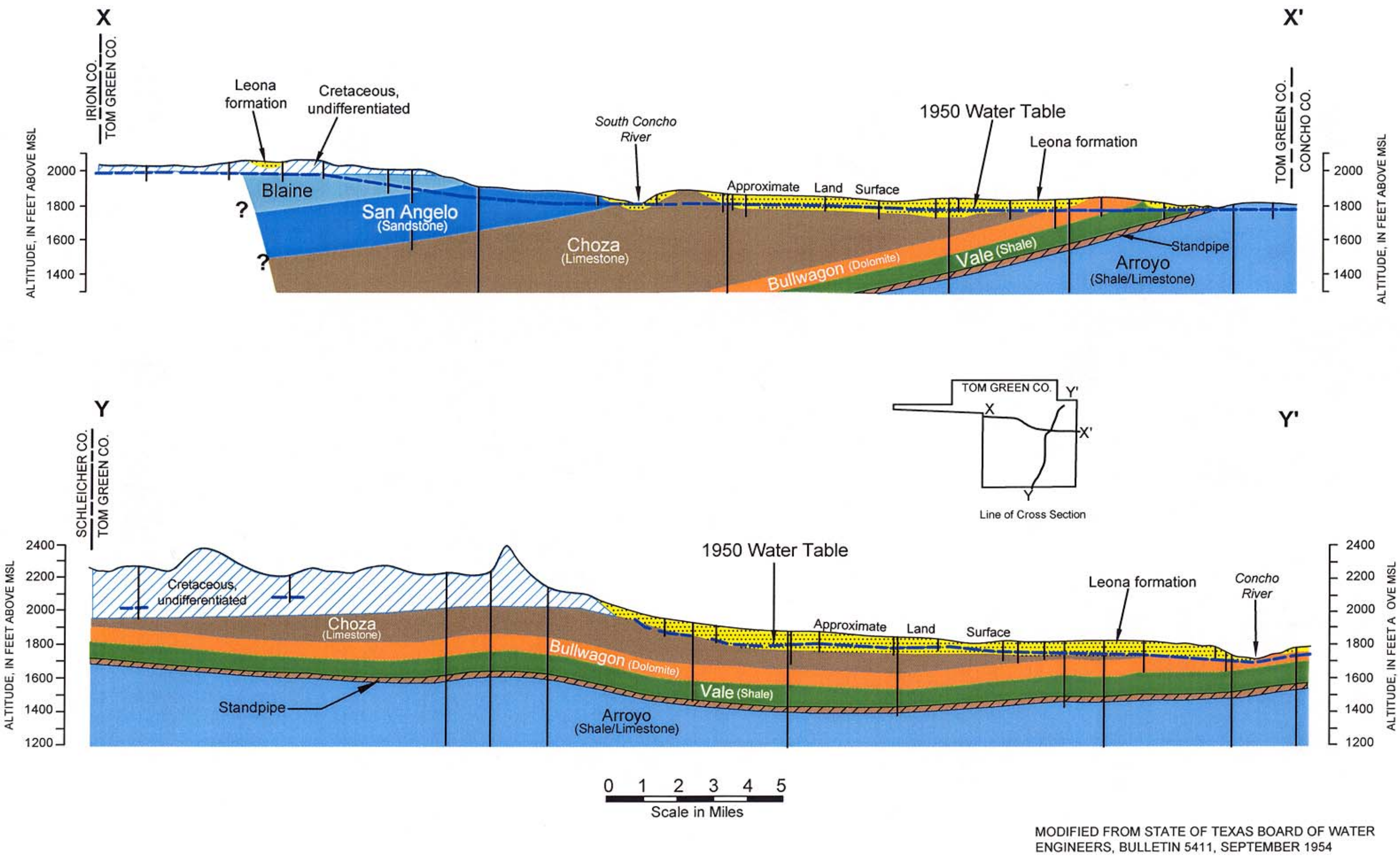


Figure 2.3.3 – Geologic Cross-sections of the Lipan Aquifer Study Area

3.0 PREVIOUS WORK

There is no existing published groundwater model of the Lipan aquifer, and there are few regional evaluations of the groundwater conditions in the study area. Beach and Standen (2000) presented the results of a preliminary groundwater model of the Lipan aquifer, however, no documentation was ever published.

In 1986, the USGS published a report on the occurrence of shallow groundwater in Tom Green County, Texas (Lee, 1986). In this report, there is mention of previous studies in the study area that contained inventories of existing wells. Willis (1954) described the geology of Tom Green County and provided an extensive inventory of existing wells and springs. A larger scale report on the groundwater resources in the Colorado River basin (Mount et al., 1967) briefly mentions the alluvial aquifer resources of the Lipan aquifer system.

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4.0 HYDROGEOLOGIC SETTING

4.1 Hydrostratigraphy

Delineation of the production capacity of wells in the Leona Formation exhibits an orientation that mimics the strike orientation of the Permian formations below. Higher production wells appear to correspond to Leona alluvial deposits overlying the Choza, Bullwagon and Vale formations. In these areas, there are thick alluvial deposits with conglomerates near the contact with the Permian. These Permian Formations, which outcrop to the east and north of the Lipan aquifer, produce potable to highly mineralized groundwater. The Bullwagon Dolomite Member usually produces water in sufficient quantities for irrigation. Other Permian formations in the Clear Fork Group yield smaller amounts of water from limestone layers.

The formations that comprise the Lipan aquifer are hydraulically connected and indistinguishable based on existing groundwater observations. Therefore, they are treated as one vertically contiguous unit through which the groundwater flows.

4.2 Structure

Groundwater flow in the Lipan aquifer does not appear to be structurally controlled. No vertical gradients have been observed in wells and water levels measured at different elevations within the aquifer do not appear to be influenced by the unconformity between the Quaternary Leona Formation and the Permian Clear Fork Group. Wells completed in the Leona and the Permian show that these two geologic units are indistinguishable from one another based on water levels.

Geophysical logs were used to estimate the location of the unconformity at the base of the alluvium, where a thin clay layer typically forms at a weathered limestone contact. A pronounced increase in gamma log activity was assumed to represent this clay layer. Of the 59 geophysical logs evaluated, the contact was reasonably evident on 48 logs, and the elevation of the base of the alluvium was estimated using these logs. Figure 4.2.1 shows the elevation of the base of the alluvium and the locations of the geophysical logs used for this evaluation.

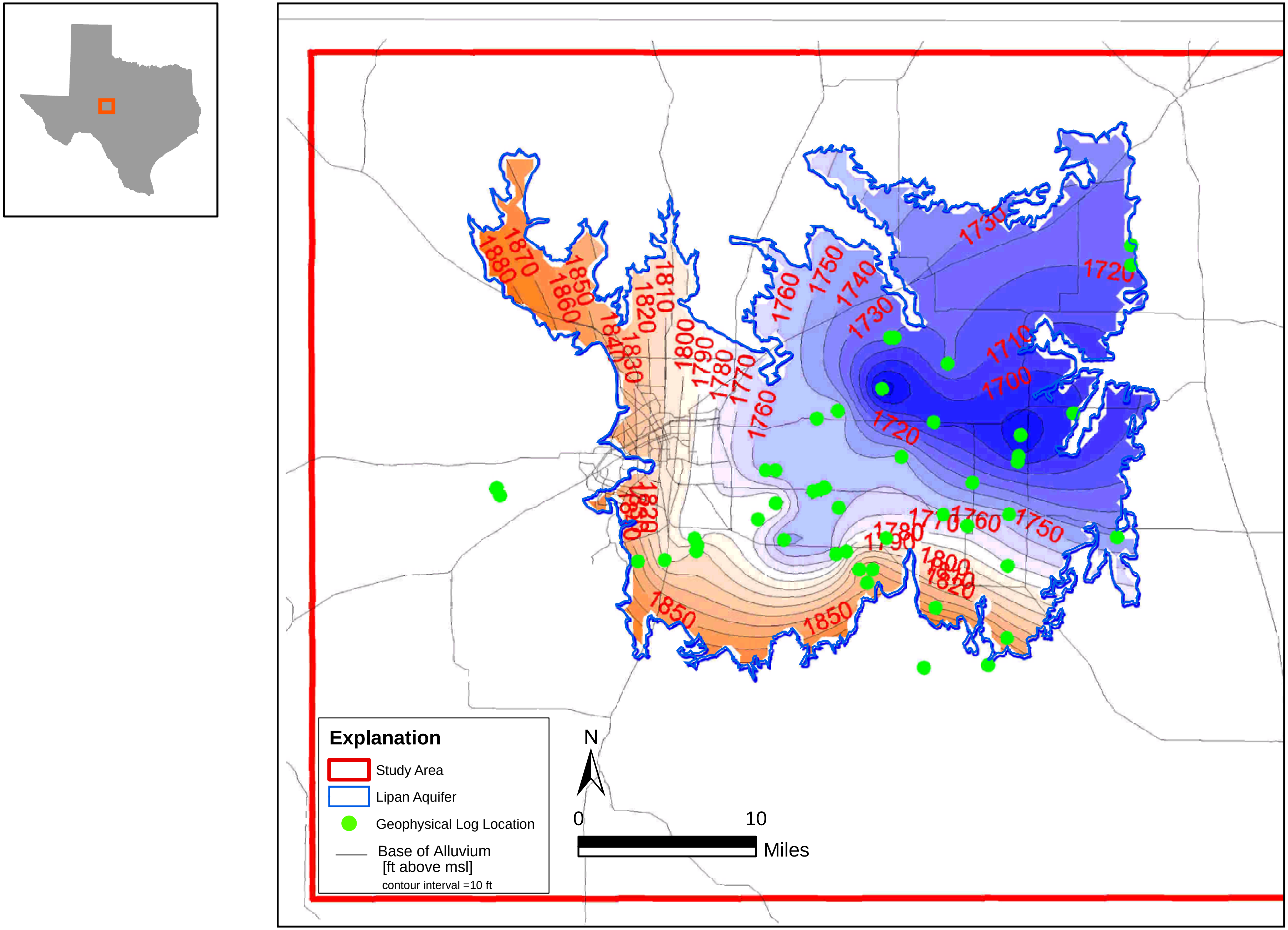


Figure 4.2.1 - Elevation of the Base of the Alluvium

The estimated thickness of the alluvium is shown in Figure 4.2.2. Based on this analysis, the alluvium thickness appears to vary from 0 to about 100 feet throughout the Lipan aquifer.

The depth of the Lipan aquifer is based on water quality and well production findings. Water quality generally deteriorates with depth and becomes increasingly saline. In addition, permeability of the aquifer decreases with depth greatly restricting flow. A total of 157 wells have reported total depths with the deepest being 300 feet. In order to minimize any adverse effects the bottom of the aquifer has on model results, the base of the aquifer was set at 400 feet below land surface.

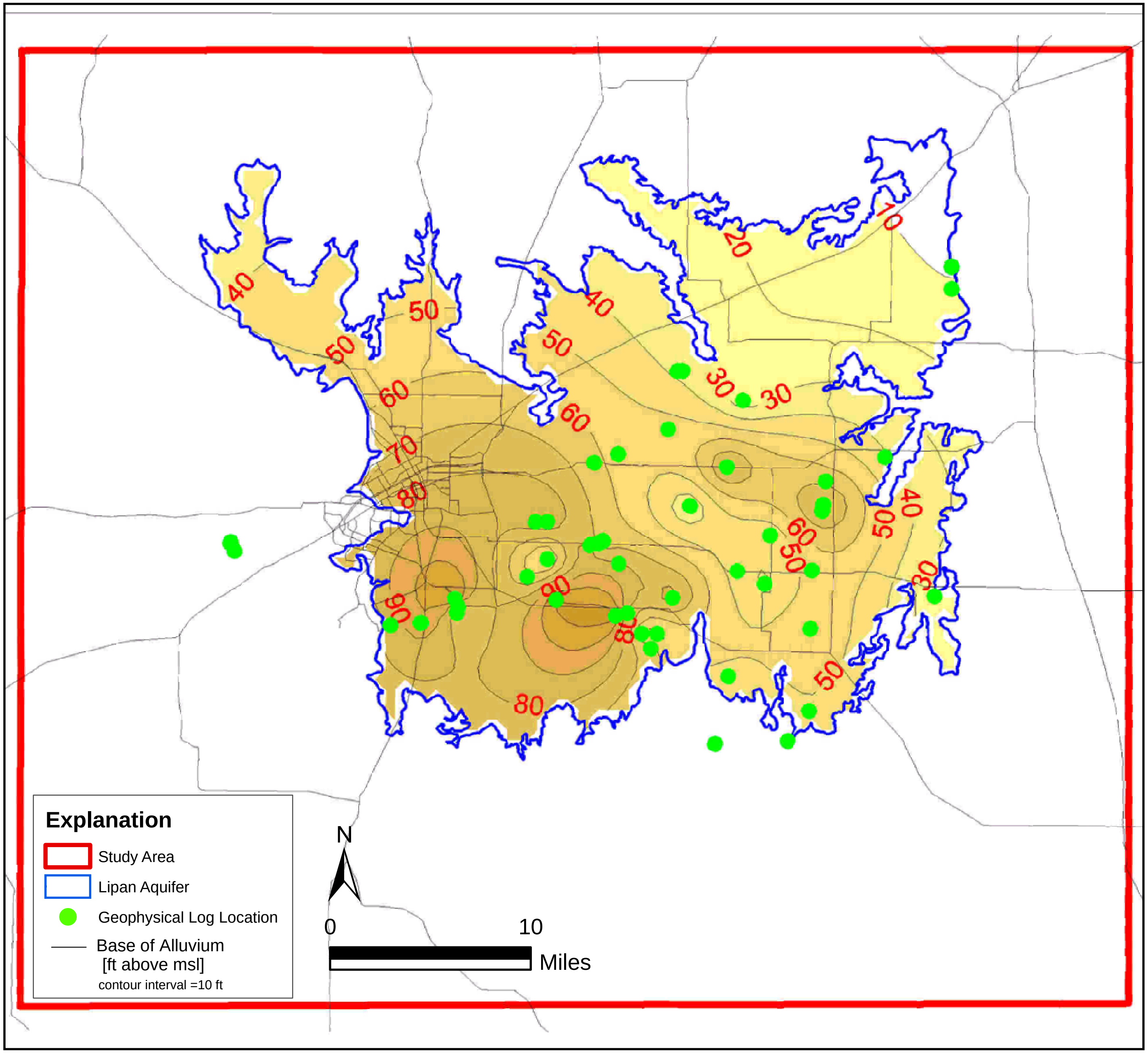


Figure 4.2.2 - Estimated Thickness of the Alluvium

4.3 Water Levels and Regional Groundwater Flow

Water level data for the Lipan aquifer were compiled using both the TWDB and LKWCD water level databases. These databases contained 1,236 unique water level measurements collected between 1906 and 2002. For many of these locations, the only reported water level is the water level estimated by the driller when the well was drilled and installed. There were 2,081 water level measurements reported at these locations. Of these water level measurements, only 133 occurred before 1980. Therefore, there is limited data available for predevelopment calibration.

4.3.1 Predevelopment Water Levels

Because water level data in the Lipan aquifer prior to 1980 is scarce, water levels in 1980 were chosen to represent predevelopment conditions. Bush et. al (1993) published a potentiometric map of the Edwards-Trinity (Plateau) aquifer, which lies to the south and west of the Lipan. On this map, which is based on data collected in the 1950's, water level contours at the edges of the Lipan aquifer are shown. Water levels on this map agree with water levels on the predevelopment water level map, except for areas with little or no data. Because the Lipan has good hydraulic connection to the Edwards-Trinity (Plateau) aquifer, water levels at the edge of the Lipan are congruent with water levels in the Edwards-Trinity (Plateau). These water levels were used to define water level boundary conditions to the south, west and north.

4.3.2 1980, 1990, and 2000 Water Levels

Water level data from a large sample of wells both inside and outside of the study area were used to create water level contour maps for 1980, 1990, and 2000. Using data outside of the study area allows for better interior contouring and minimizes data extrapolation. However, only contours within the study area are shown. Potentiometric maps for 1980 and 1990 are shown in Figures 4.3.1 and 4.3.2. A comparison of these two maps shows that water levels appear to remain unchanged, or rise slightly, between 1980 and 1990. When comparing these maps with the potentiometric map for 2000 (Figure 4.3.3), a general decrease in water levels is observed in the center of the Lipan Flats area. Water levels near the edges of the Lipan aquifer and in the Edwards-Trinity (Plateau) do not change significantly between 1980 and 2000.

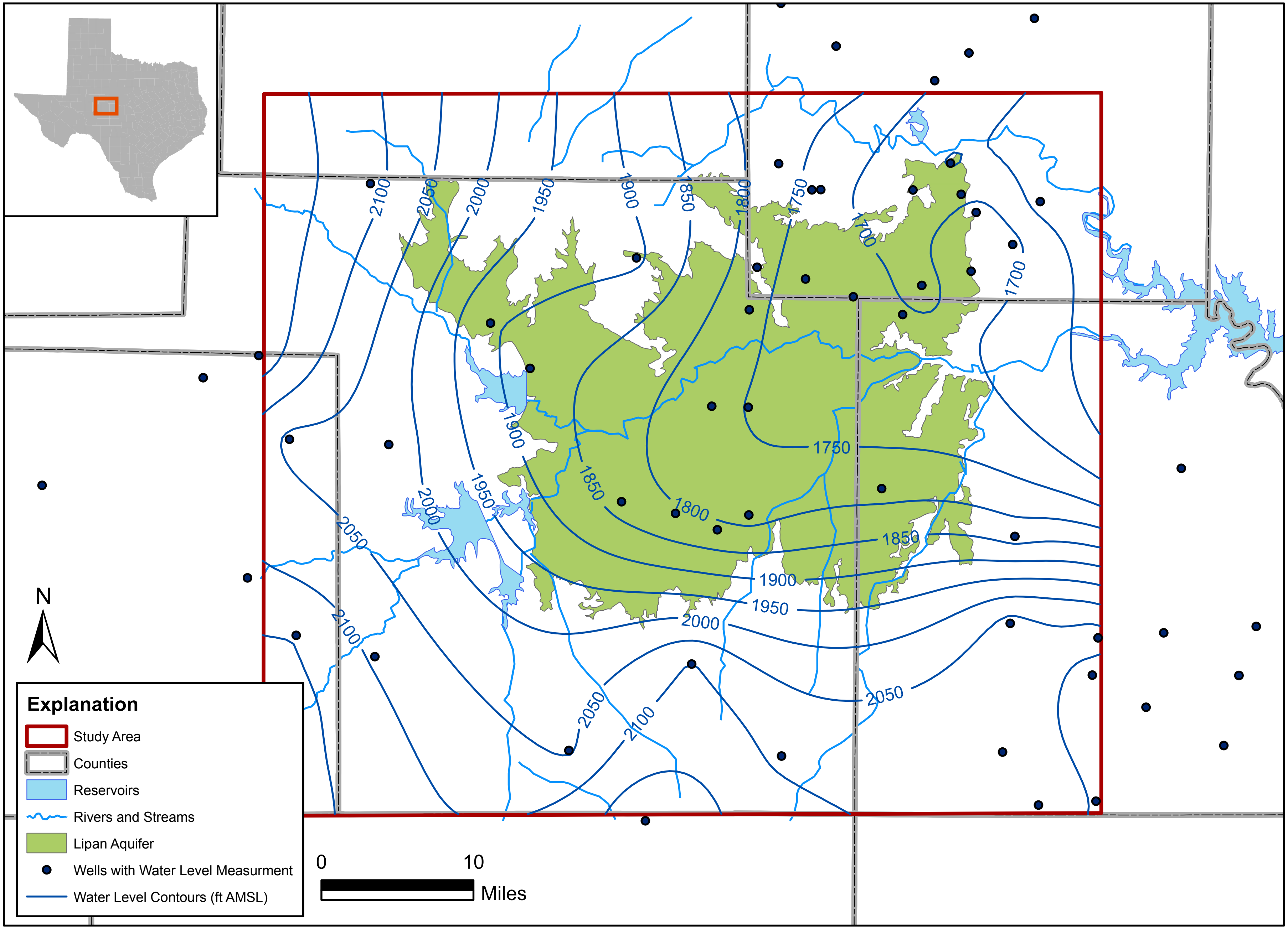


Figure 4.3.1 - Water Levels - 1980

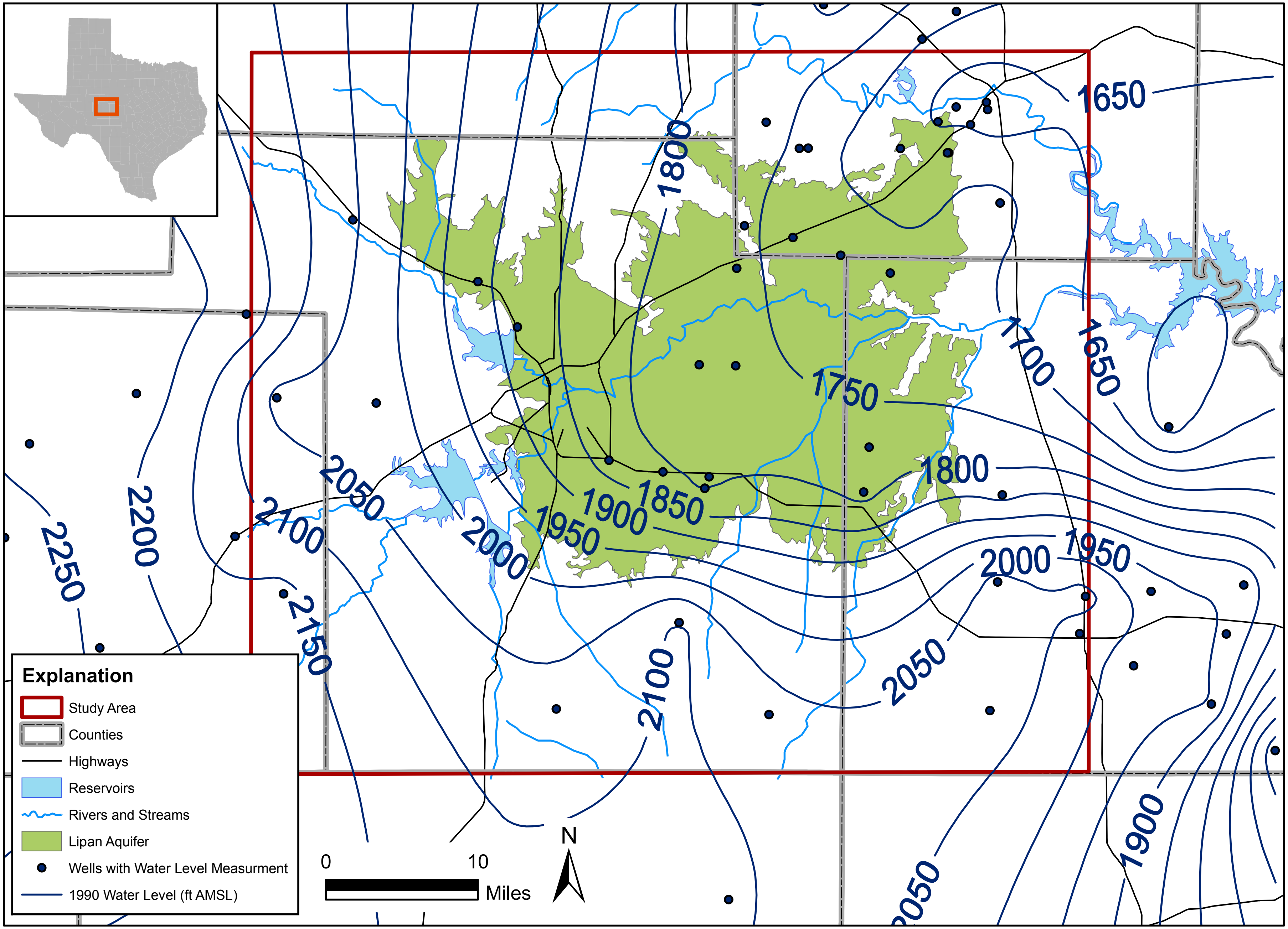


Figure 4.3.2 - Water Levels - 1990

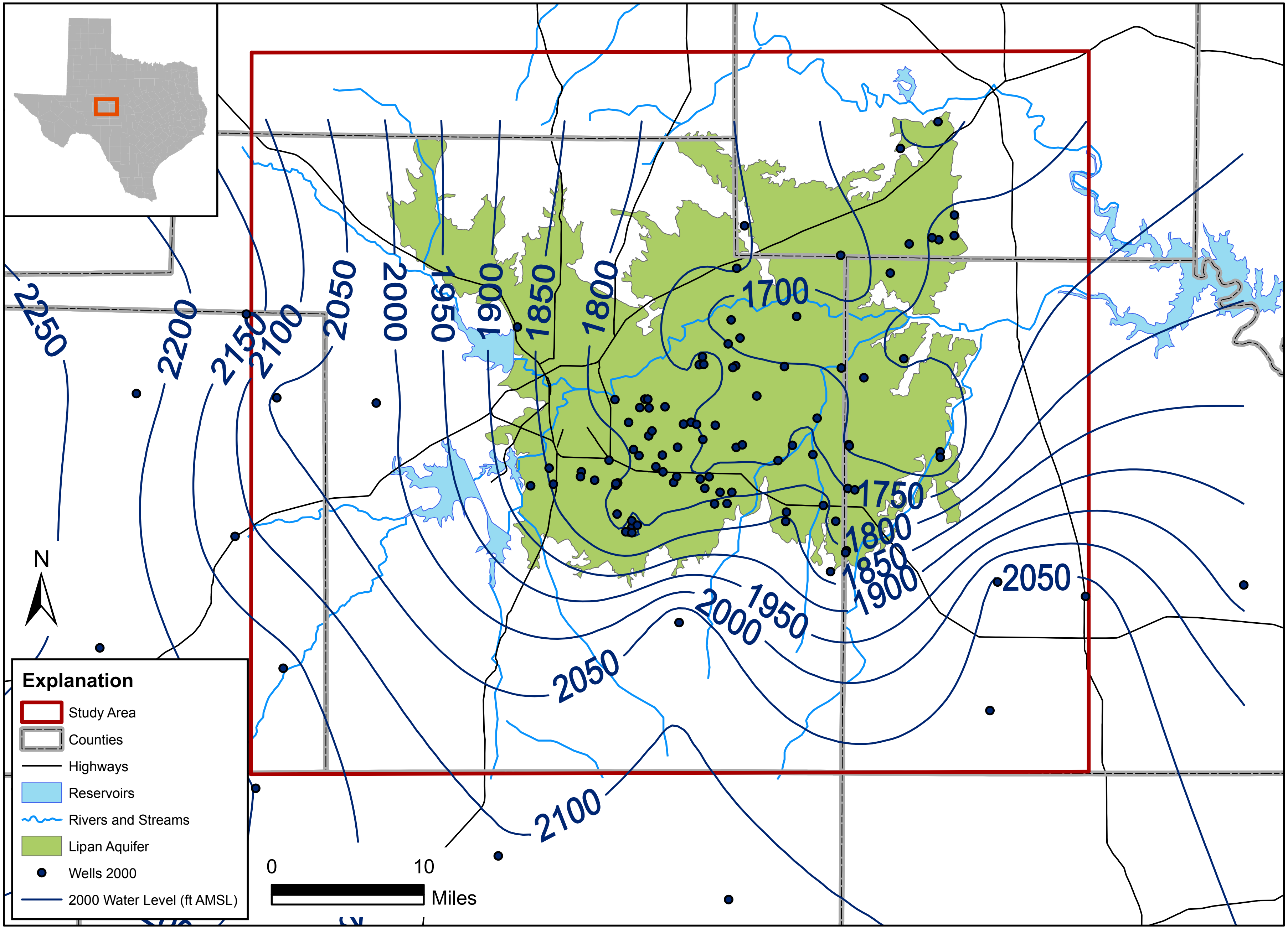


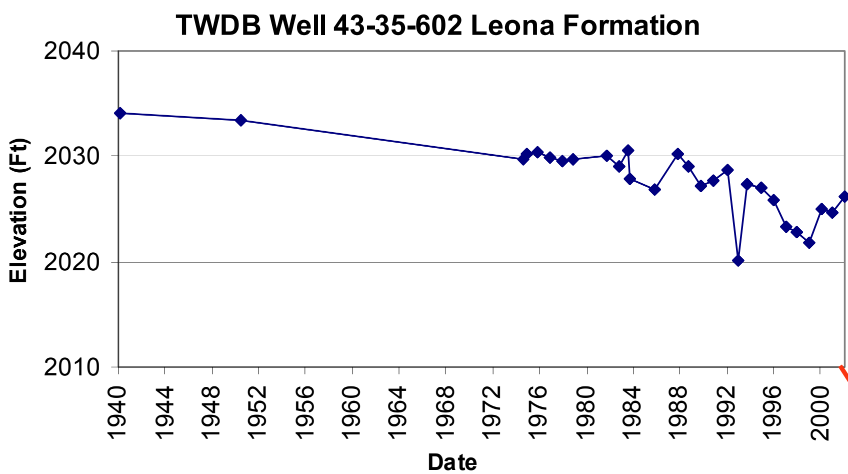
Figure 4.3.3 - Water Levels - 2000

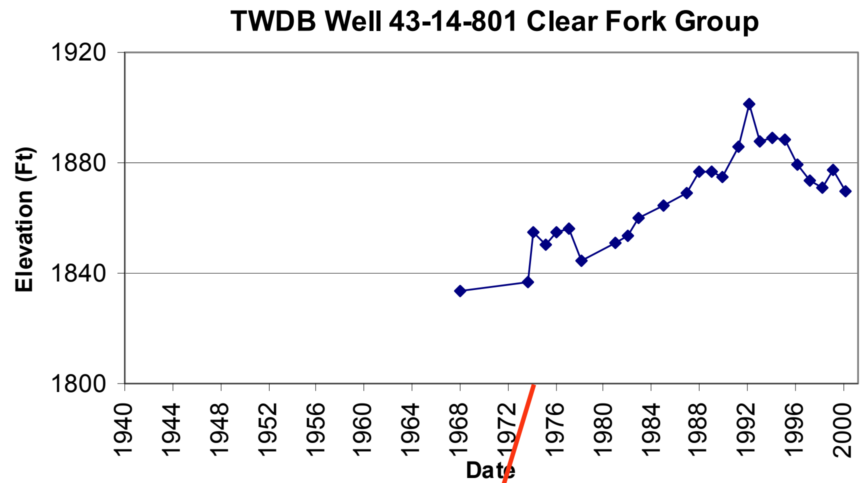
Hydrographs for wells in and near the Lipan aquifer were developed with data from 1940 to 2000, and are shown in Figures 4.3.4 through 4.3.7. The hydrographs in Figure 4.3.4 are for wells in the western portion of the study area and in locations distal from the Lipan aquifer. The hydrograph for well 43-61-706, an Edwards Formation well, displays typical karst aquifer responses and is not indicative of the typical response observed in Lipan aquifer water levels. However, this type of water level behavior may exist in Lipan wells, but there are currently no data collected at the same interval that data has been collected in well 43-61-706.

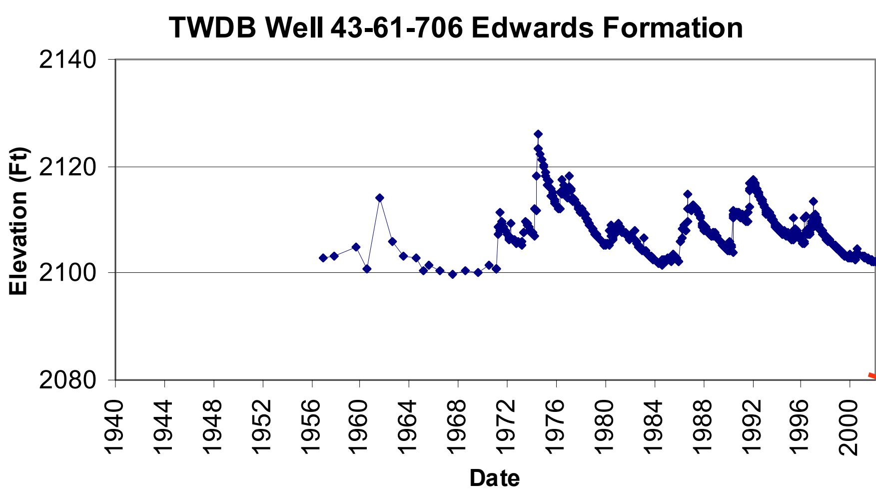
Figure 4.3.5 shows hydrographs for wells in the northwestern part of the Lipan aquifer. These wells also show water levels decreasing in the 1990's. Both of these wells are completed in the Leona Formation and indicate a flow direction to the southeast. The gradient between these two wells in the winter of 2002 is 0.002 ft/ft to the southeast.

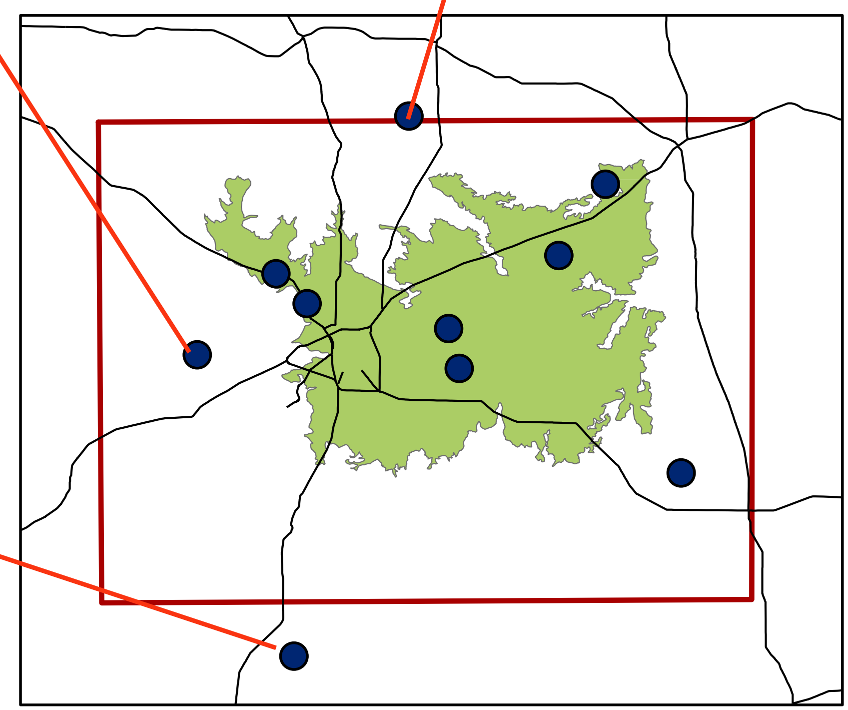
The hydrograph for Leona Formation well 43-38-301 is shown in Figure 4.3.6. This figure indicates a steady water level rise from 1940's to the mid-1970's, with declines during the 1950's drought of record. From the mid-1970 to mid-1980, water levels decreased slightly, and then about 1987,an increase of nearly 40 feet is observed over a two-year period. After this increase, water levels began a slow decline again. The second hydrograph shown here has a short period of record from the late-1940's to 1970. Although water levels in this hydrograph are not very useful for investigating recent flow conditions, a comparison to the hydrograph for well 43-38-301 indicates that both wells exhibit the same water level response between 1950 and 1970.

Hydrographs for three additional wells are shown in Figure 4.3.7. Two of these wells are located in the Lipan aquifer and the third is completed in the Edwards Formation to the south.









Note: vertical scales vary between hydrographs for readability.
Minimum value = 1800 ft (TWDB Well # 43- 14- 801]
Maximum value = 2140 ft (TWDB Well # 43- 61 -706]

Figure 4.3.4 - Well Hydrographs - West

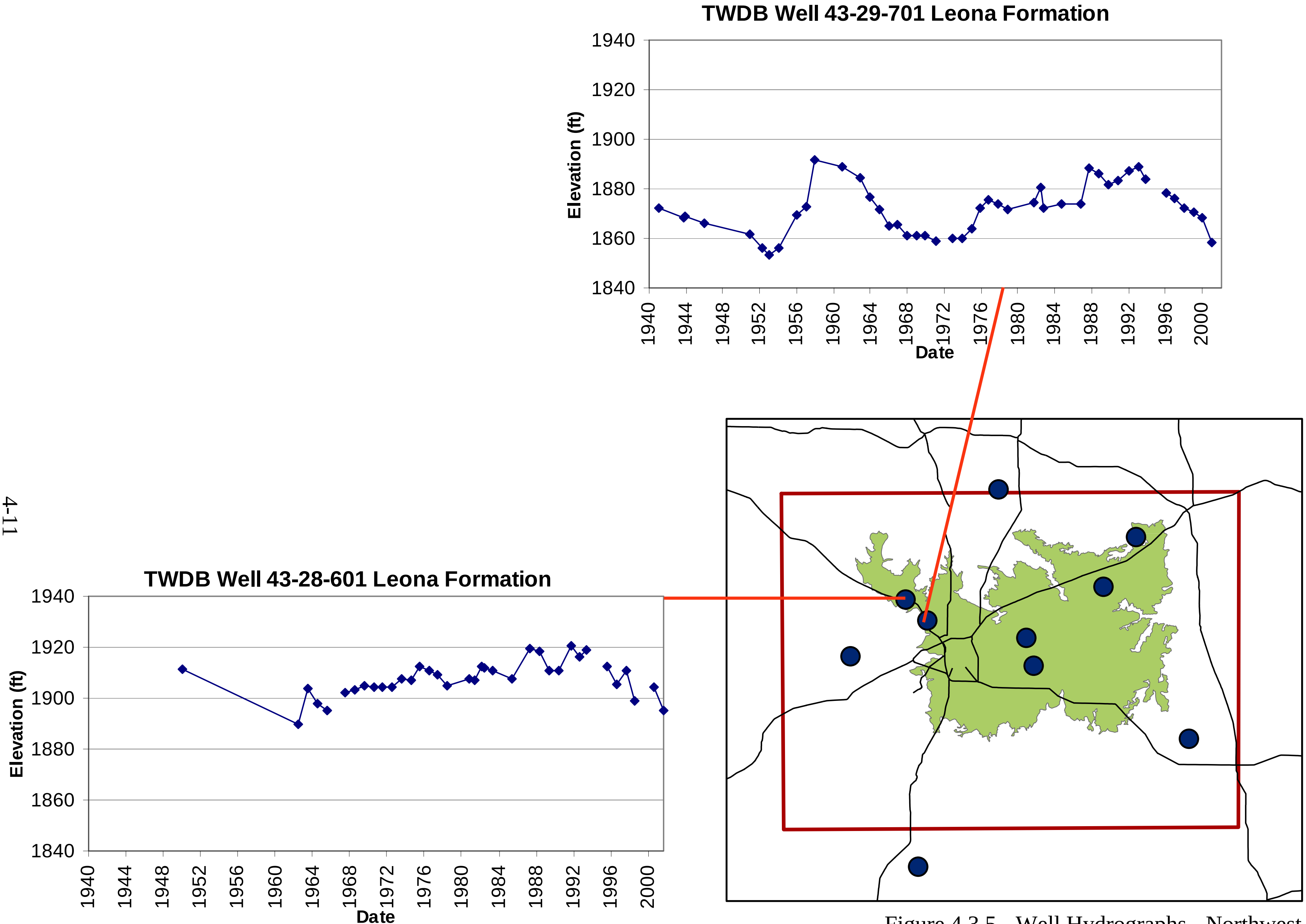


Figure 4.3.5 - Well Hydrographs - Northwest

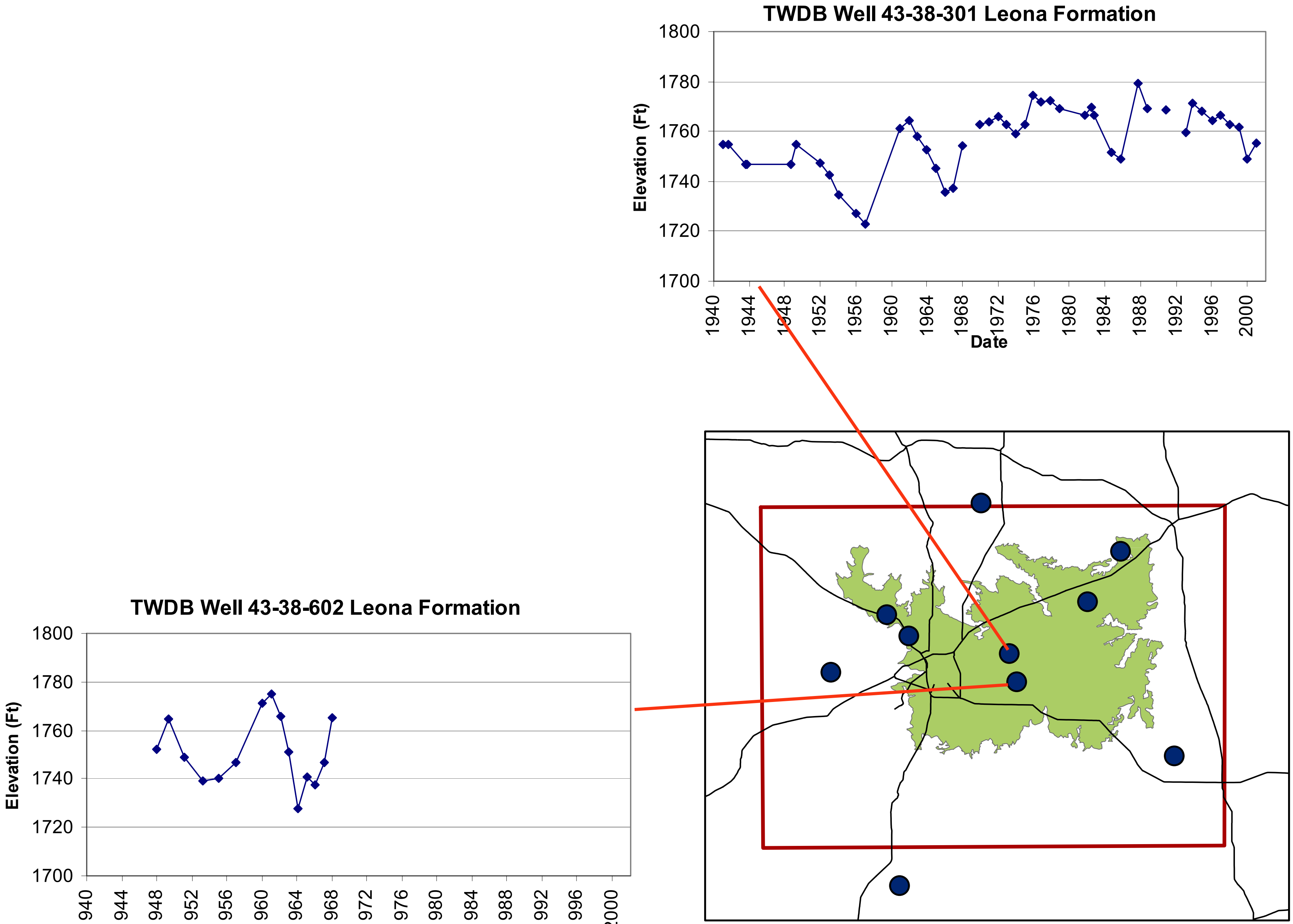
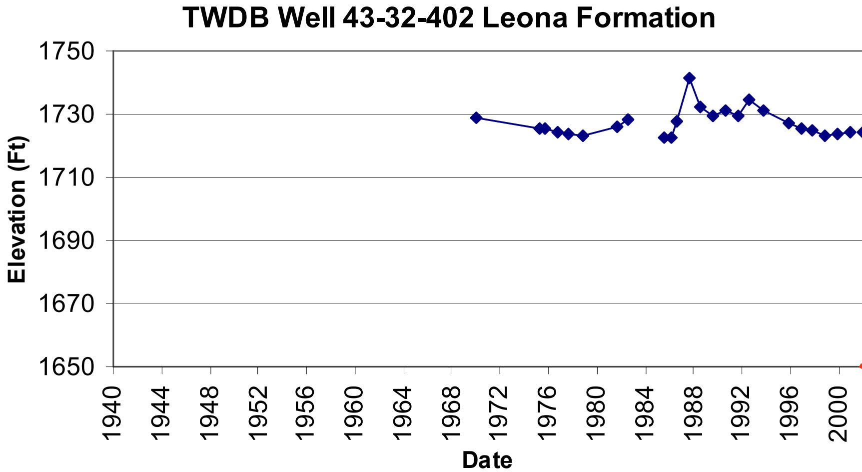
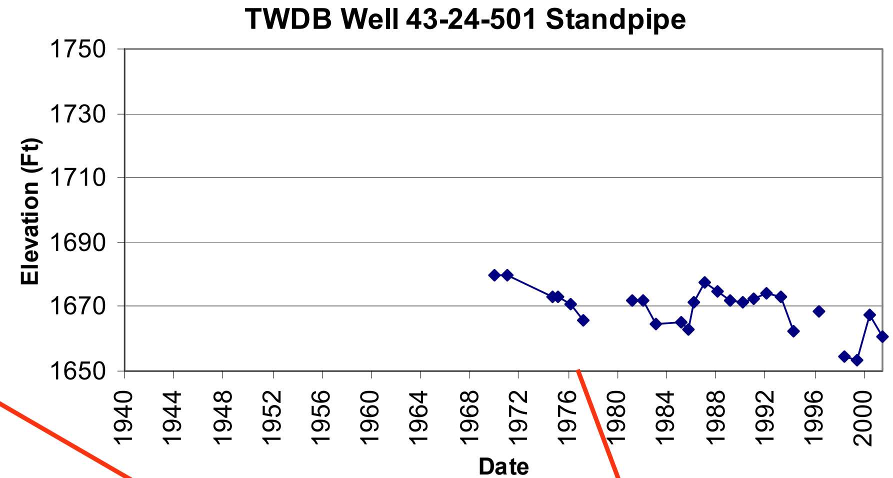
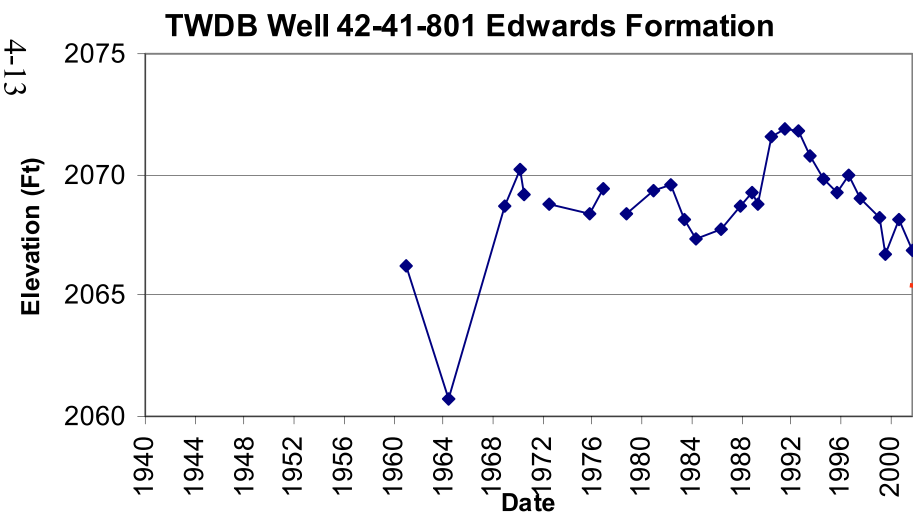
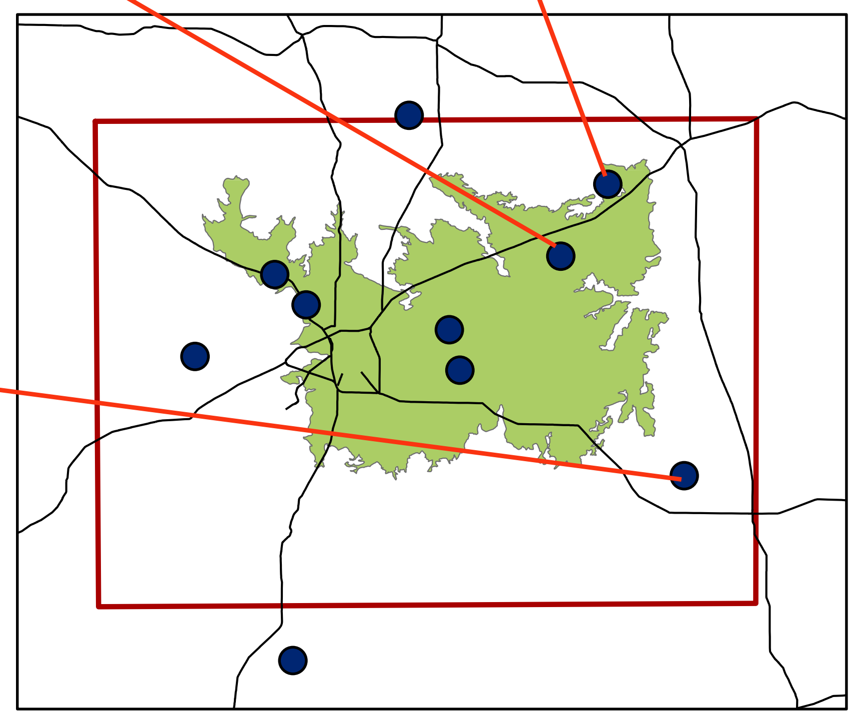


Figure 4.3.6 - Well Hydrographs - Central Lipan Flats









Note: vertical scales vary between hydrographs for readability.
Minimum value = 1650 ft (TWDB Wells # 43- 32- 402 & 43- 24 -501]
Maximum value = 2075 ft (TWDB Well # 42- 41 801]

Figure 4.3.7 - Well Hydrographs - East

4.3.3 Regional Groundwater Flow

The potentiometric surfaces indicate that groundwater generally flows laterally into the Lipan aquifer system from the water-bearing units located to the north, south and west. Groundwater flows out of the system to the east, as shown in Figure 4.3.8. Recharge mainly occurs in the uplands to the north, south and west. Water is removed or discharged from the Lipan aquifer naturally through seeps and springs, and evapotranspiration. When groundwater levels are relatively high, groundwater discharges from the aquifer to the Concho River and other streams. When groundwater levels are relatively low near the Concho River and streams, surface water may recharge the aquifer in local proximity to the stream.

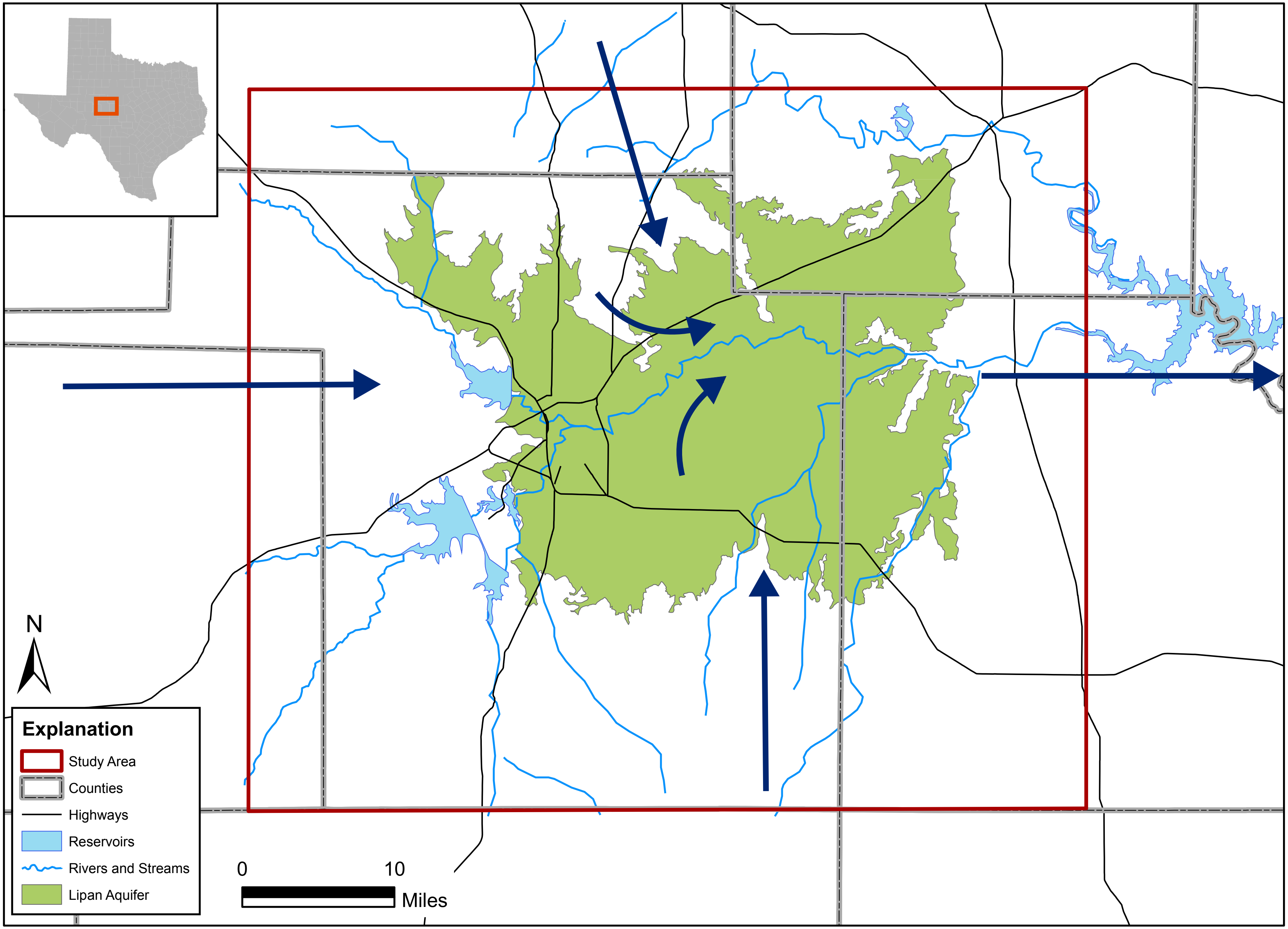


Figure 4.3.8 - Regional Groundwater Flow

4.4 Recharge

Recharge is an extremely important component of the hydrologic cycle. The primary sources of recharge to the Lipan aquifer are the infiltration of precipitation, lateral cross-formational flow from the Edwards-Trinity (Plateau) aquifer and other water-bearing formations, stream loss, and irrigation return flow. These four components comprise a net recharge amount that can vary both temporally and spatially, making it one of the more difficult model parameters to estimate. Further complicating this is the fact that recharge to the water table and evapotranspiration from the water table can partially or fully offset one another in some areas.

The infiltration of precipitation is controlled by many factors. The first factor is the amount of precipitation that occurs in the study area. Figure 2.2.3 shows the average annual precipitation from 1960 through 1995 at National Weather Service monitoring stations along with contours of precipitation based on data from the national weather service. Also depicted on this figure are the contours of annual total precipitation and the average annual value for the study area from the TWDB (http://hyper20.twdb.state.tx.us/Evaporation/evap.html). The average annual precipitation over the entire study area is approximately 22 inches and varies from about 20 inches in the west to 25 inches in the east.

Soil properties may also influence the ability of precipitation to recharge the groundwater. Figure 2.2.8 shows the predominant soil types in the study area. Estimating soil properties over large areas is difficult, especially in areas were topography, and vegetation and other factors cause significant variation in soil characteristics. For this study, soil properties were evaluated using the STATSGO database (USDA, 1994). The database provides a gross estimate of soil properties but is not geographically detailed. Sandy, silty clay soils cover the Lipan Flats and the northern portions of the study area and clay soils are dominant in the southern part of the study area. Soil permeabilities are shown on Figure 4.4.1. Most of the soils in the Lipan Flats area have permeabilities ranging between 2 and 3 centimeters per hour (cm/hr), with areas to the west and north having slightly higher rates. Soil thicknesses range from about 4 to greater than 17 centimeters (cm) in the study area. The Lipan Flats area contains soils 12 to 17 cm thick. Soil thicknesses in the study area are shown in Figure 4.4.2

Cross-formational inflow from the Edwards-Trinity (Plateau) aquifer and other water-bearing formations located north of the study area is also a source of recharge to the Lipan aquifer. While it is possible to estimate inflow directly from existing water level data, groundwater models may offer an improved method to refine inflow estimates because models are capable of considering all the components of the water budget simultaneously. Leakage from surface water features is another source of recharge to the aquifer. Streams and rivers lose water to the aquifer when groundwater levels drop below the base of the streambed. Conversely, when water levels are high, water from the aquifer discharges into streams and rivers. This surface water/groundwater interaction is discussed in more detail in Section 4.6.

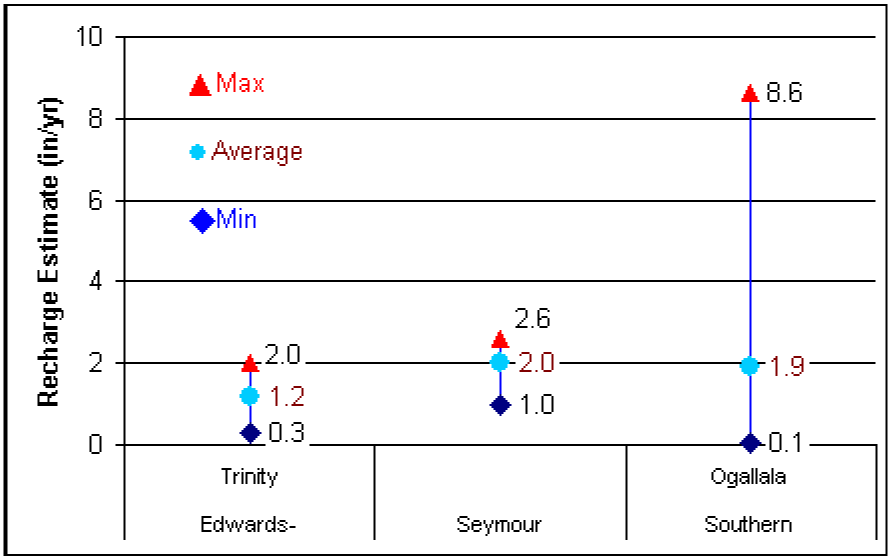
Irrigation return flow is water that is applied as irrigation but not taken up by the crops and returns to the aquifer, which may occur in the irrigated areas where row watering is used. For this study, it is assumed that return flow from pivot irrigation systems is insignificant. There is no reliable data available that identifies the distribution of row and pivot irrigation systems for the Lipan aquifer. Therefore, irrigation return flow will not be accounted for in the model directly. However, the calibration process will automatically offer an indirect way to account for this recharge because if required, the recharge to the model can be varied spatially.

Developing a direct estimate of recharge that accounts for all of these processes is difficult. Scanlon and others (2002) identify groundwater models as one method of estimating recharge. Therefore, an initial estimate of recharge for the groundwater model will be calculated by taking a percent of the average annual precipitation. Scanlon and others (2002) compiled recharge rate estimates for the major aquifers in Texas. However, no recharge estimates have ever been published for the Lipan aquifer. The estimates for the three closest major aquifers (the Edwards-Trinity (Plateau), Seymour, and Ogallala) are shown in Table 4.4.1. The average recharge estimates for these aquifers range from about 1.2 to 2 inches per year, or about 5 to 10 percent of average annual precipitation. Based on these estimates, an initial recharge estimate of 4% of average annual precipitation will be used, as shown in Figure 4.4.3. Based on this assumption, the initial estimate of recharge from precipitation for the Lipan aquifer ranges from about 0.8 to 0.96 inches per year. As discussed above, recharge from lateral inflow will also be included in the model.

Some water that recharges the aquifer may have a relatively small residence time in the aquifer for several reasons. This water is sometimes referred to as “rejected recharge”. Rejected recharge generally occurs when the water table is near land surface and recharge from precipitation moves to streams under natural gradients because it is not withdrawn by pumping. This type of recharge is referred to as rejected because if water was withdrawn from the aquifer at a higher rate by pumping, then this recharged water would add to the available groundwater from the aquifer instead of becoming streamflow. Very little, if any of this type of rejected recharge occurs in the Lipan aquifer. Structural features can also lead to rejected recharge. Structural control may cause flow to issue from the springs, however, this water generally flows a short distance and then re-enters the aquifer as stream-loss or recharge resulting in no net loss of recharge.

Table 4.4.1 Nearby Recharge Estimates

	Aquifer		
Recharge Rate (in/yr)	Edwards-Trinity	Seymour	Southern Ogallala
Min	0.30	1.00	0.05
Max	2.00	2.60	8.62
Average	1.18	2.02	1.92
Count	4	5	17



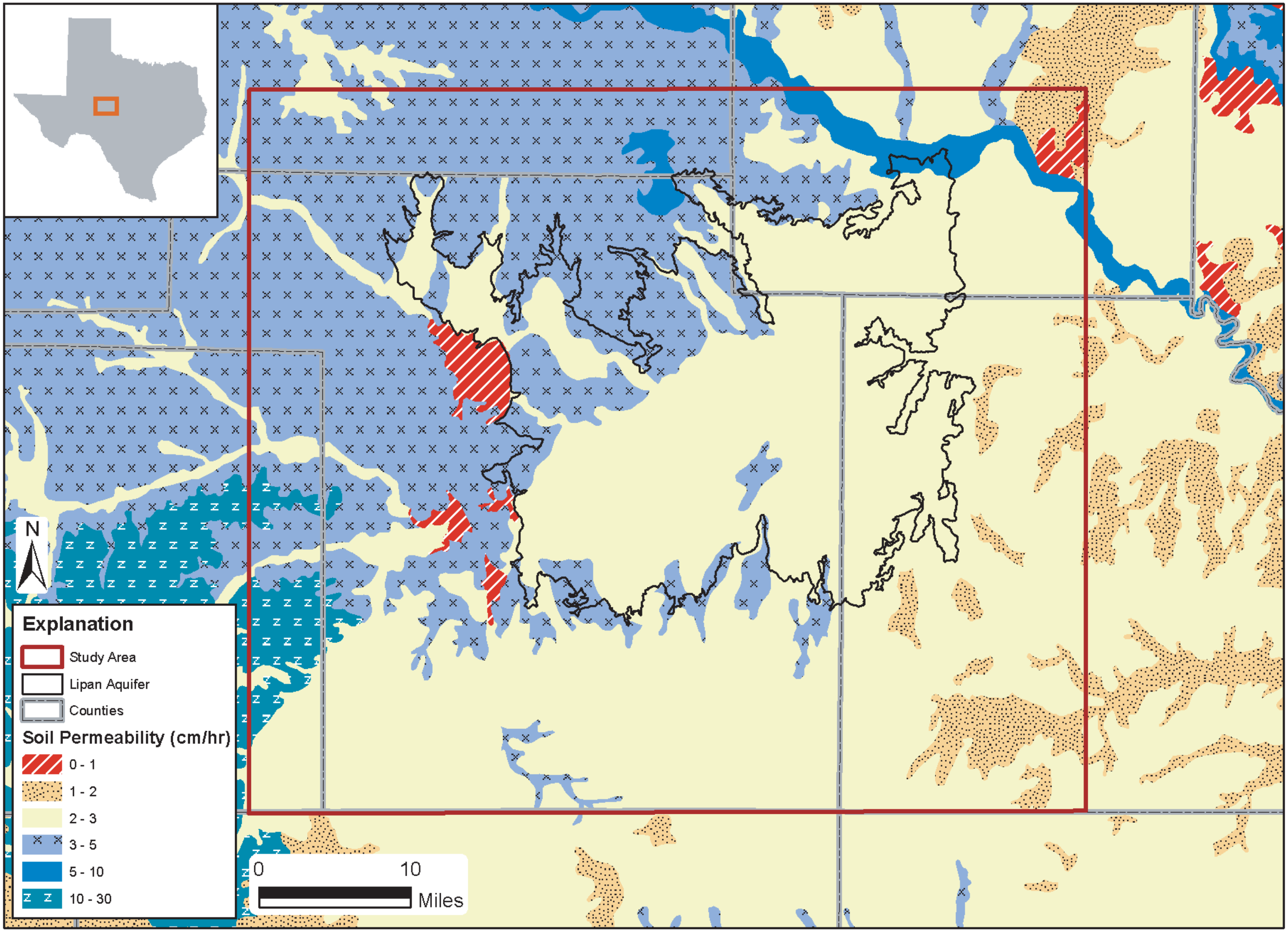


Figure 4.4.1 - Soil Permeability (source: USDA STATSGO 1994)

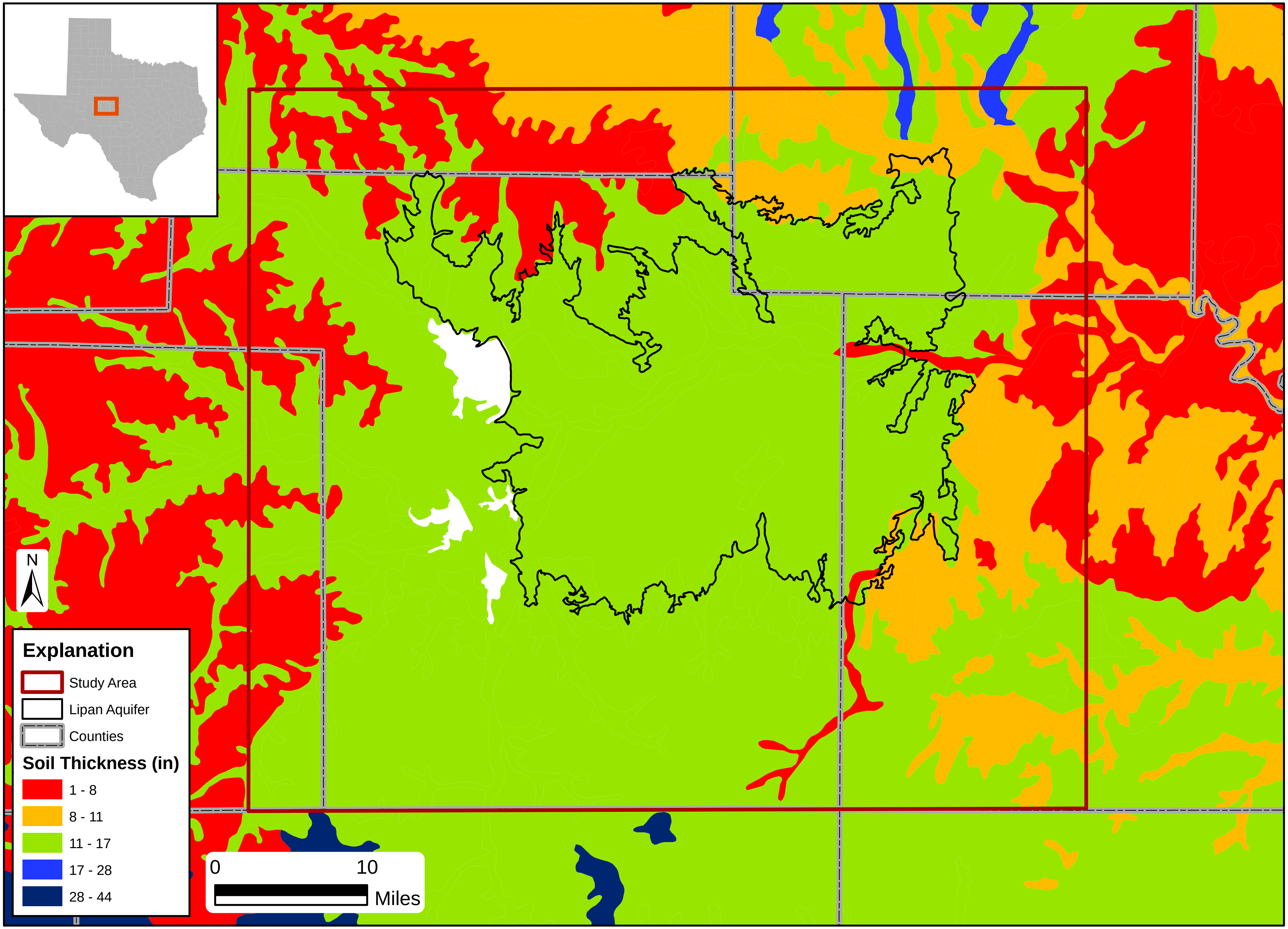


Figure 4.4.2 - Soil Thickness (source: USDA STATSGO 1994)

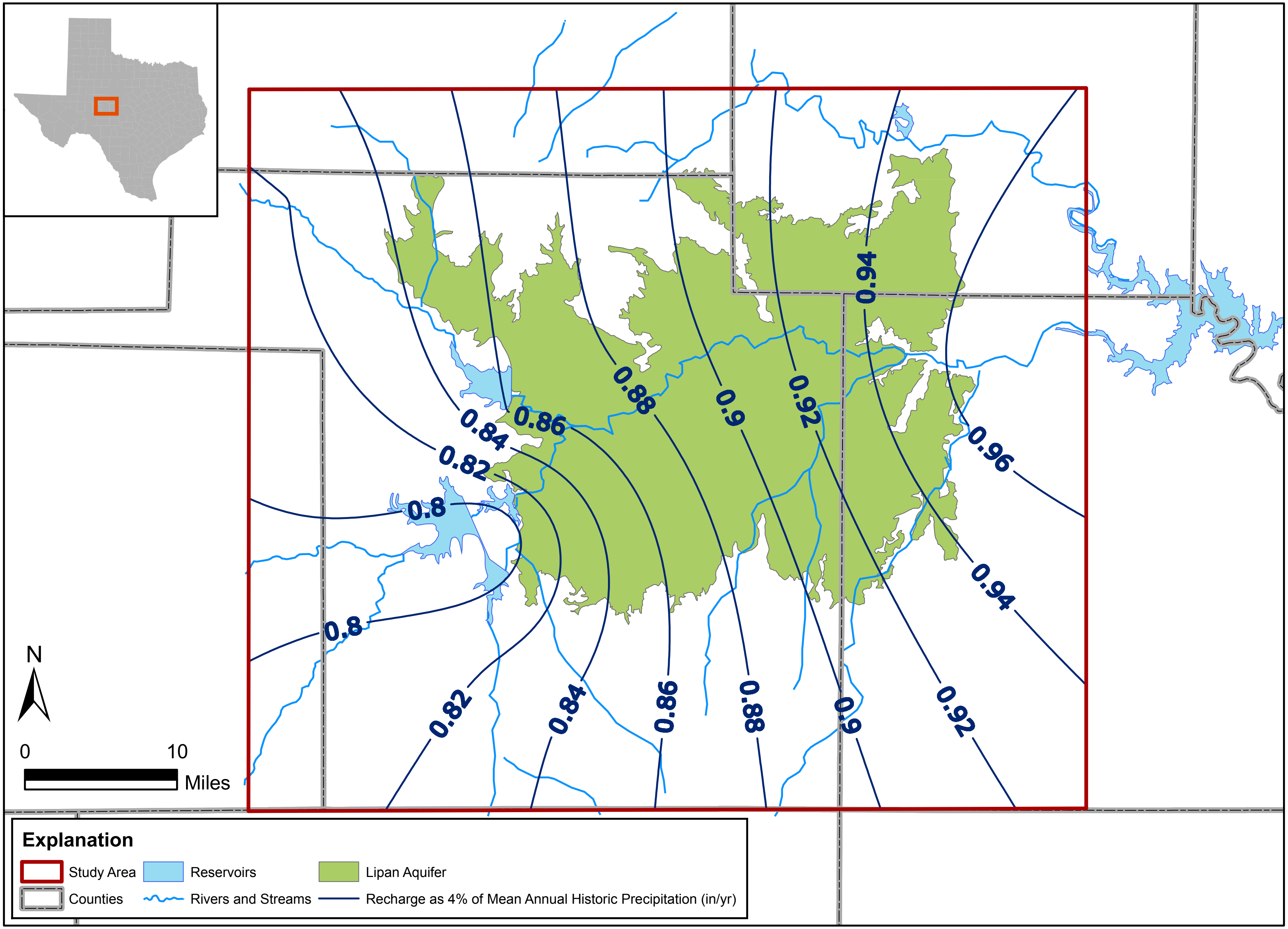


Figure 4.4.3 - Estimated Recharge based on 4% of Mean Annual Precipitation

4.5 Evapotranspiration

Evapotranspiration is the loss of groundwater due to evaporation and plant transpiration. Direct groundwater evaporation is only possible in areas where the water table is very close to or at the surface, and does not occur in the Lipan aquifer except potentially in riparian areas where the water table intersects the stream banks of streams and rivers. Transpiration of groundwater directly from the water table by plants can have a dramatic effect on the overall water budget. In areas there water table is near the surface or where there is a dense population of phreatophytic vegetation, a large amount of groundwater can be removed from the aquifer.

Generally, the effects of evaporation and transpiration are combined into one value referred to as evapotranspiration ET, because separating the effects of each of these is difficult. Because evapotranspiration will be driven by transpiration, locations of potential evapotranspiration are based on the presence of deep-rooted water-seeking plants, called phreatophytes. Several phreatophytes are found in the study area including mesquite, live oak, juniper, and crops. Table 4.5.1 lists parameters needed for incorporating evapotranspiration due to these plants into the model. Although mesquite has a relatively low evapotranspiration rate, it may be the dominant species due to its root depth. Although most evapotranspiration occurs in the unsaturated zone above the water table in the Lipan aquifer, the groundwater model only considers evapotranspiration directly from the water table. Therefore, the model will incorporate evapotranspiration in all areas where phreatophytes exist, but the evapotranspiration will only be active if the depth to water is less than the maximum root depth of the phreatophytes in that area.

Table 4.5.1 Evapotranspiration Values for Plants Commonly Found in the Study Area

Plant	Estimated Rate		Mean Maximum Root Depth[5] (Feet)
	Minimum (in/yr)	Maximum (in/yr)	
Crops [1]	30.8		6.9
Live Oak [2]	30.2		13 - 41
Juniper [3]	23.3	25	12.8
Mesquite [4]	8.8	25.4	39 - 46.9

1 ET Rates from Borelli et al., 1998.
2 ET Rates from Dolman, 1988
3 ET Rates from Dugas et al., 1998
4 ET Rates from Duell, 1990; Tromble, 1977; Ansley et al., 1998
5 Canadell and others, 1996

Salt cedar (Tamarix) is another plant that can have a large impact on groundwater availability in the study area. According to Hoddenbach (1987), a single large salt cedar plant can absorb 200 gallons of water a day, although evapotranspiration rates vary based on water availability, stand density, and weather conditions (Davenport et al. 1982). Salt cedars typically exist in riparian areas along the banks of rivers and streams. To account for these in the model, a slightly higher ET rate will be applied in riparian areas where salt cedar is known to exist.

4.6 Rivers, Streams, Reservoirs and Springs

4.6.1 Rivers and Streams

Although there are few surface water features in the study area, the interaction between surface water and groundwater is very important. The Concho River is a major discharge and recharge feature of the Lipan aquifer system. This river forms at the confluence of the Middle, North and South Concho Rivers in San Angelo and flows eastward towards the Colorado River. The Concho River is classified as a perennial river, and discharges into the O.H.Ivie reservoir at the extreme eastern edge of the study area. In recent times of drought, Concho River flow has ceased between San Angelo and Paint Rock.

There are five USGS stream gages in the study area with sufficient periods of record to be useful for the analysis of stream and river flows (Figure 4.6.1). Three of the gages are on tributaries of the Concho River and are located above the reservoirs. Two gages are on the Concho River, one at San Angelo and the other at Paint Rock, TX. These are described below.

Dove Creek was gaged from 1960 to 1995 at USGS stream gage #8130500 at Knickerbocker, TX. The mean monthly stream flow at this gage is shown in Figure 4.6.2. USGS stream gage #08131000, located on Spring Creek at Tankersly, TX, has a continuous period of record from 1960 through 1995. Mean monthly stream flow at this gage is shown in Figure 4.6.3. Figure 4.6.4 shows the mean monthly stream flow at USGS stream gage #08134000 on the North Concho River near Carlsbad, TX. Stream flows have been gaged at this location from 1924 through 2001.

The Concho River is gaged at two locations in the study area. With data from these two locations, the Concho River interaction with the aquifer was analyzed. The upstream gage, USGS stream gage #08136000 at San Angelo, has a period of record from 1915 to 2002. Downstream, the Concho River flows through USGS stream gage #08136500, located at Paint Rock. This gage also has a period of record from 1915 to 2002. Figure 4.6.5 shows the mean monthly stream flow for the Concho River at both of these gages.

Two gain-loss studies along the Concho River between San Angelo and Paint Rock have been documented (Slade et al., 2000). These studies were completed in 1918 and 1925, prior to impoundment of the reservoirs, and indicate that Concho River has received discharge from the Lipan aquifer along the river reach from San Angelo to Paint Rock. Figure 4.6.6 shows results of the USGS study for 1918. Positive values represent river gains from the aquifer. Results of the 1925 study are presented in Figure 4.6.7. The studies in 1918 and 1925 show a net gain of 5.4 and 5.2 cubic feet per sec (cfs), respectively. However, hydrologic and groundwater conditions before and during the studies are not known.

Dove Creek, Spring Creek and the South Concho River originate at springs near the outcrop of the Edwards-Trinity (Plateau) aquifer where it is in hydraulic connection with the Lipan aquifer. Dove Creek and Spring Creek flow into Twin Buttes Reservoir, and the South Concho River flows into Lake Nasworthy.

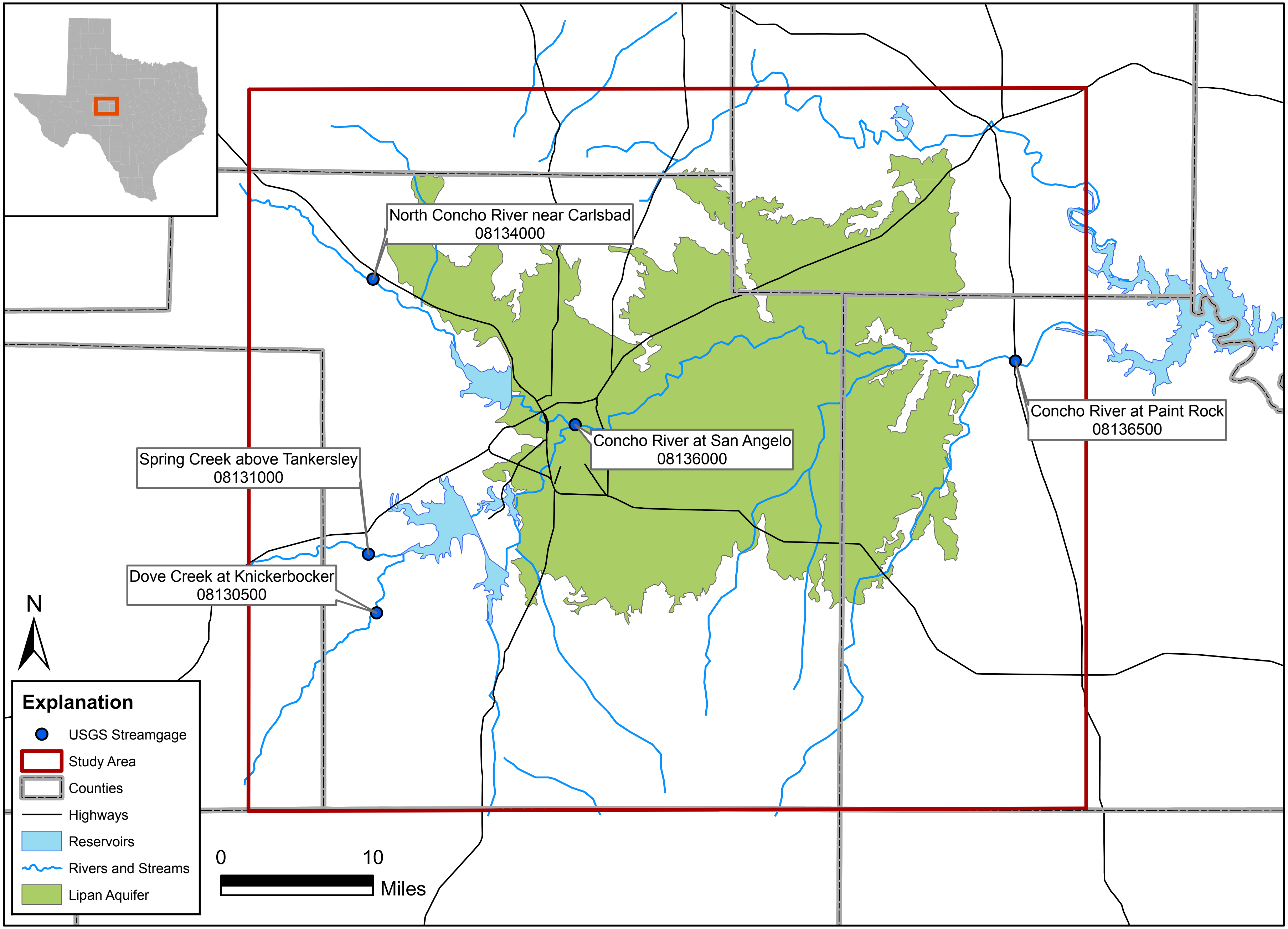


Figure 4.6.1 - Location of USGS Streamgages

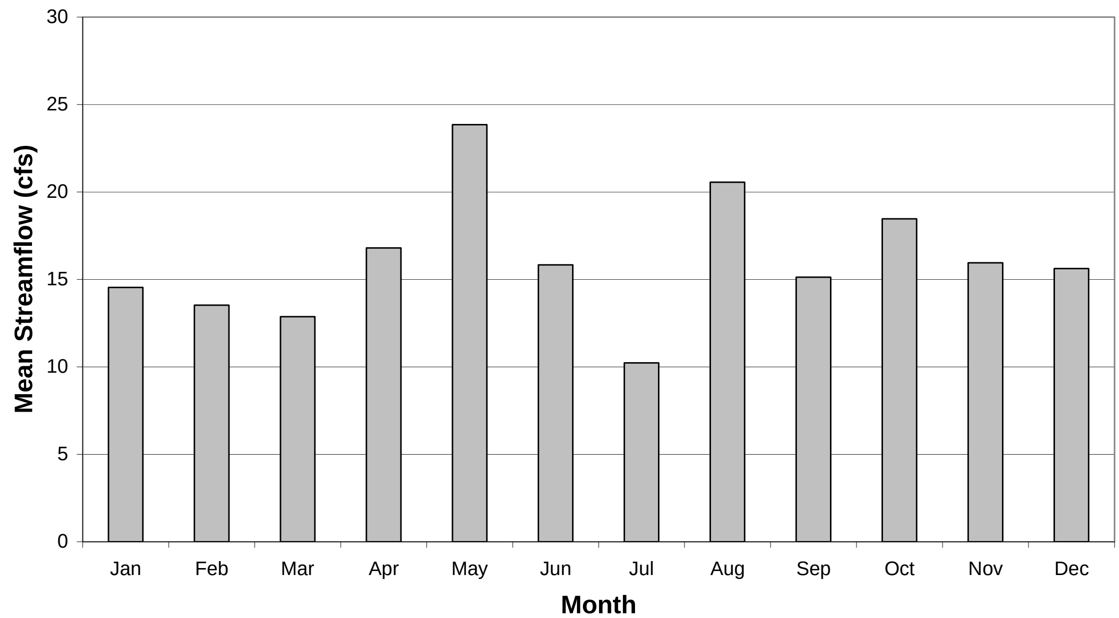


Figure 4.6.2 Mean Monthly Stream flow of Dove Creek at Knickerbocker, TX

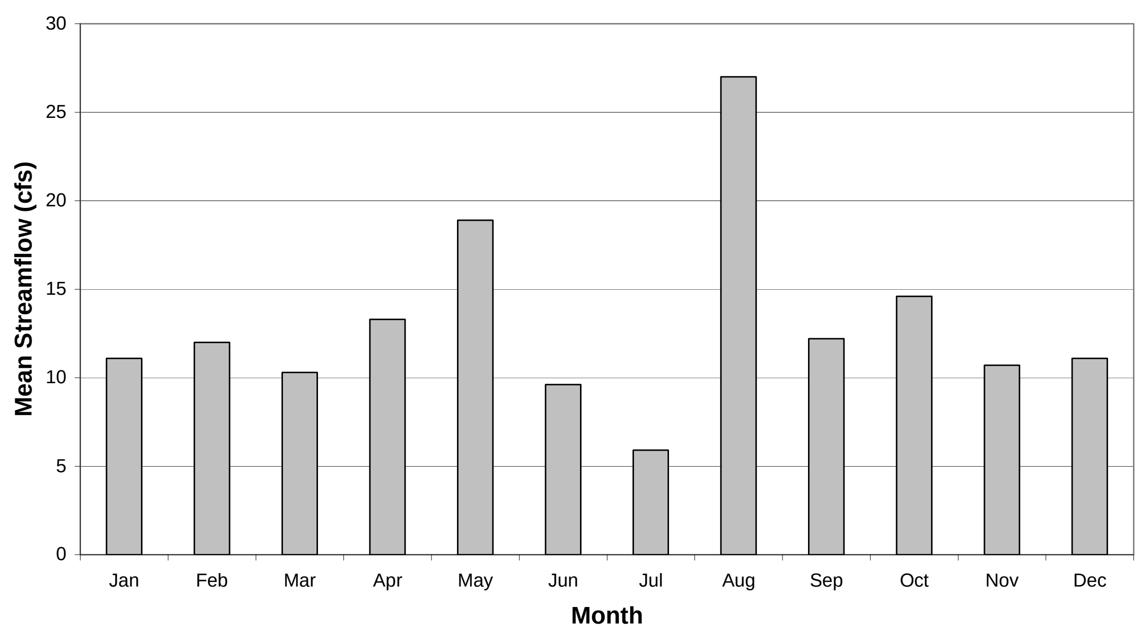


Figure 4.6.3 Mean Monthly Stream flow of Spring Creek at Tankersley, TX

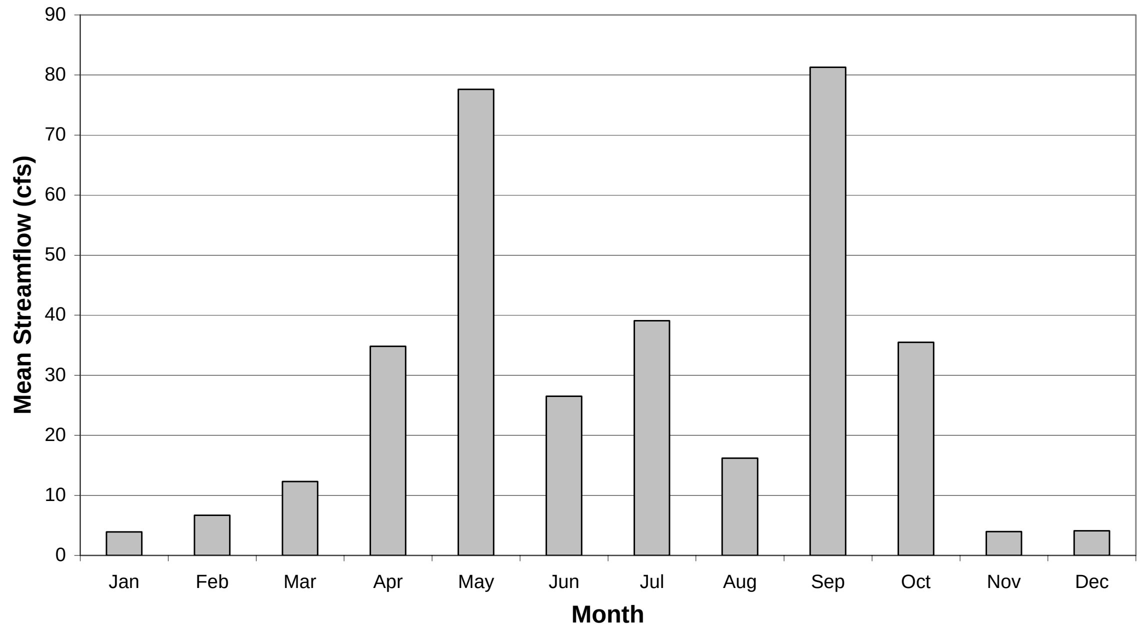


Figure 4.6.4 Mean Monthly Stream flow of the North Concho River near Carlsbad, TX

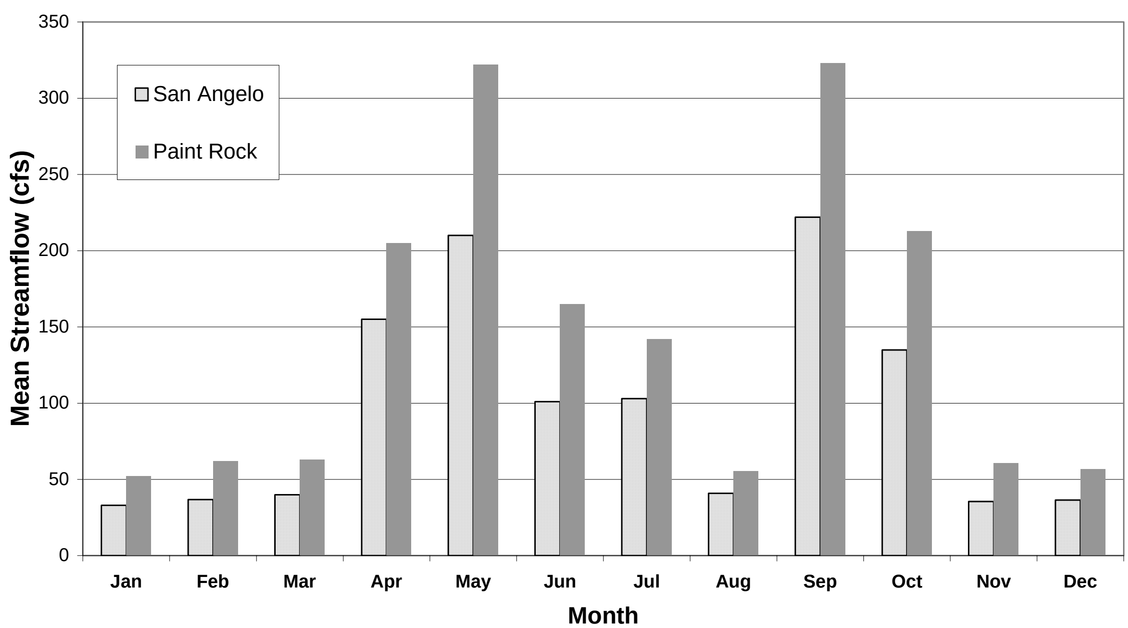


Figure 4.6.5 Mean Monthly Stream flow of the Concho River at San Angelo and Paint Rock, TX

4.6.2 Reservoirs and Lakes

There are three major reservoirs in the area. Lake Nasworthy, which was impounded in 1930, is a constant level reservoir held at 1,855 feet above mean sea level (MSL) with little or no fluctuation. Located at the confluence of the Middle and South Concho Rivers, it covers 1,598 acres and has a storage capacity of 12,230 acre-feet. A watershed area of 150 square miles drains into Lake Nasworthy. This relatively small watershed is due to the presence of Twin Buttes Reservoir just upstream on the Middle Concho River. Twin Buttes Reservoir was impounded in 1963 and has a conservation level of 1,940 feet MSL and a storage capacity of 186,200 acre-feet. A watershed area of 2,500 square miles feeds into the reservoir.

The other reservoir in the study area is O.C. Fisher, located on the North Concho River. This reservoir was impounded in 1952, has a storage capacity of 119,200 acre-feet, a conservation level of 1,908 feet MSL, and impounds a watershed area of 1,500 square miles. In recent times this reservoir has been nearly or completely dry. Data for these reservoirs were compiled from the San Angelo Website (sanangelotexas.org/citydepts/water.shtml), Texas Parks and Wildlife Department Website (www.tpwd.state.tx.us/fish/infish/regions/inpanhd.htm), and the Army Corp of Engineers Ft Worth district Reservoir control Office (www.swf-wc.usace.army.mil/reports/fish.htm).

These reservoirs will be modeled using a stage-dependent model boundary package. Reservoir water leaks into the underlying aquifer when the water level in the aquifer is lower to the stage level of the reservoir. If water levels in the aquifer are higher than the stage level of the reservoir, water will leak into the reservoir. Lakebed conductivity, along with difference in water levels between the aquifer and reservoir, determines the rate at which this leakage occurs.

4.6.3 Springs

There are several springs in the study area, but only few are large enough to be pertinent to the Lipan aquifer model. Many of the springs are located in small streams and creeks that are mostly dry. When these springs do flow, the water only flows a short distance before returning to the aquifer, resulting in no significant change to the water volume in the aquifer. A few of the springs flow from the contact between the Edwards-Trinity (Plateau) aquifer and the Lipan aquifer. These springs feed streams and rivers important to the groundwater system in the study area.

Figure 4.6.8 shows the springs incorporated in the current model. These springs are important because they allow water from the adjacent aquifer, the Edwards-Trinity (Plateau), to enter the Lipan aquifer study area.

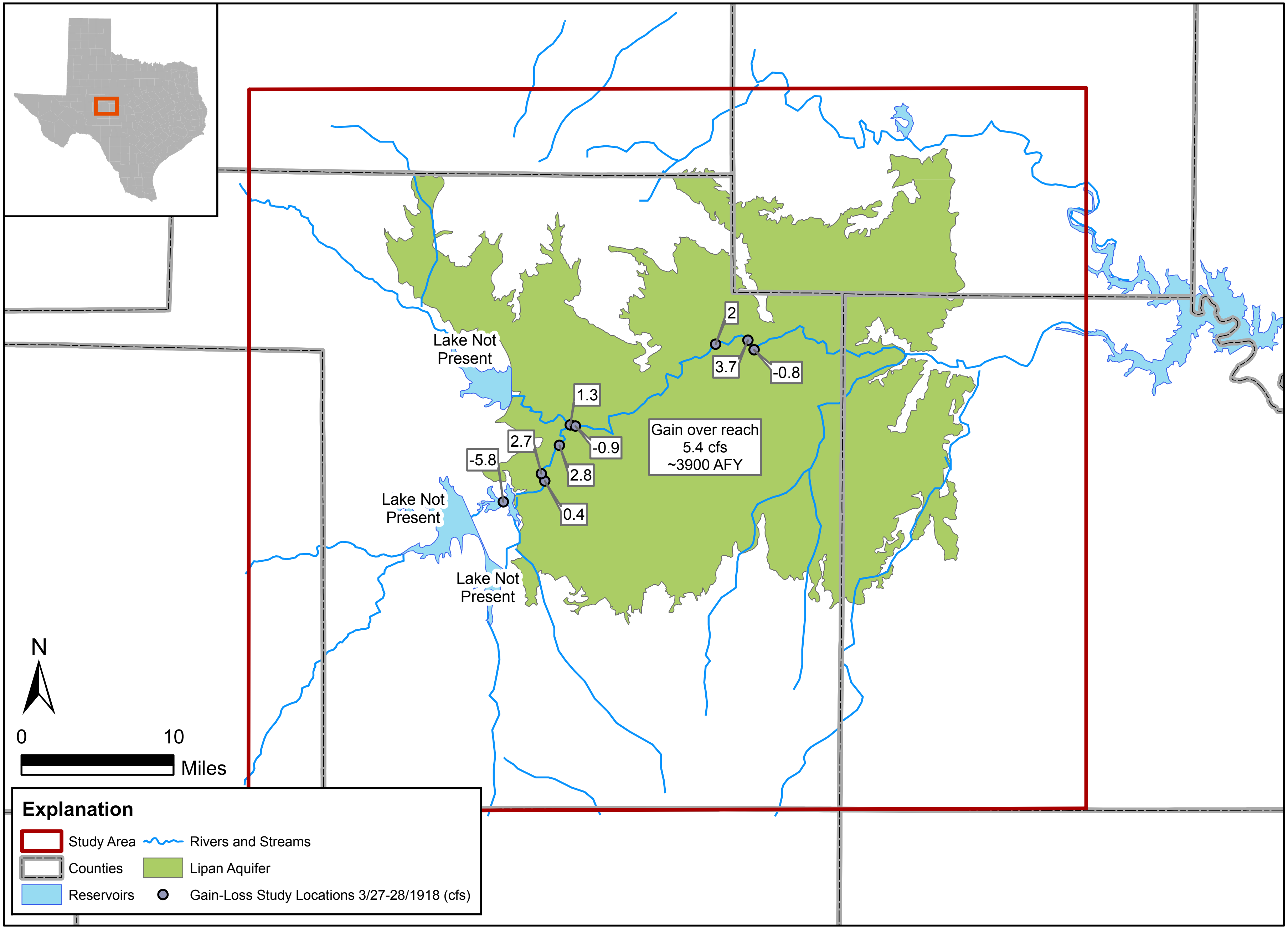


Figure 4.6.6 - USGS Gain-Loss Study in 1918

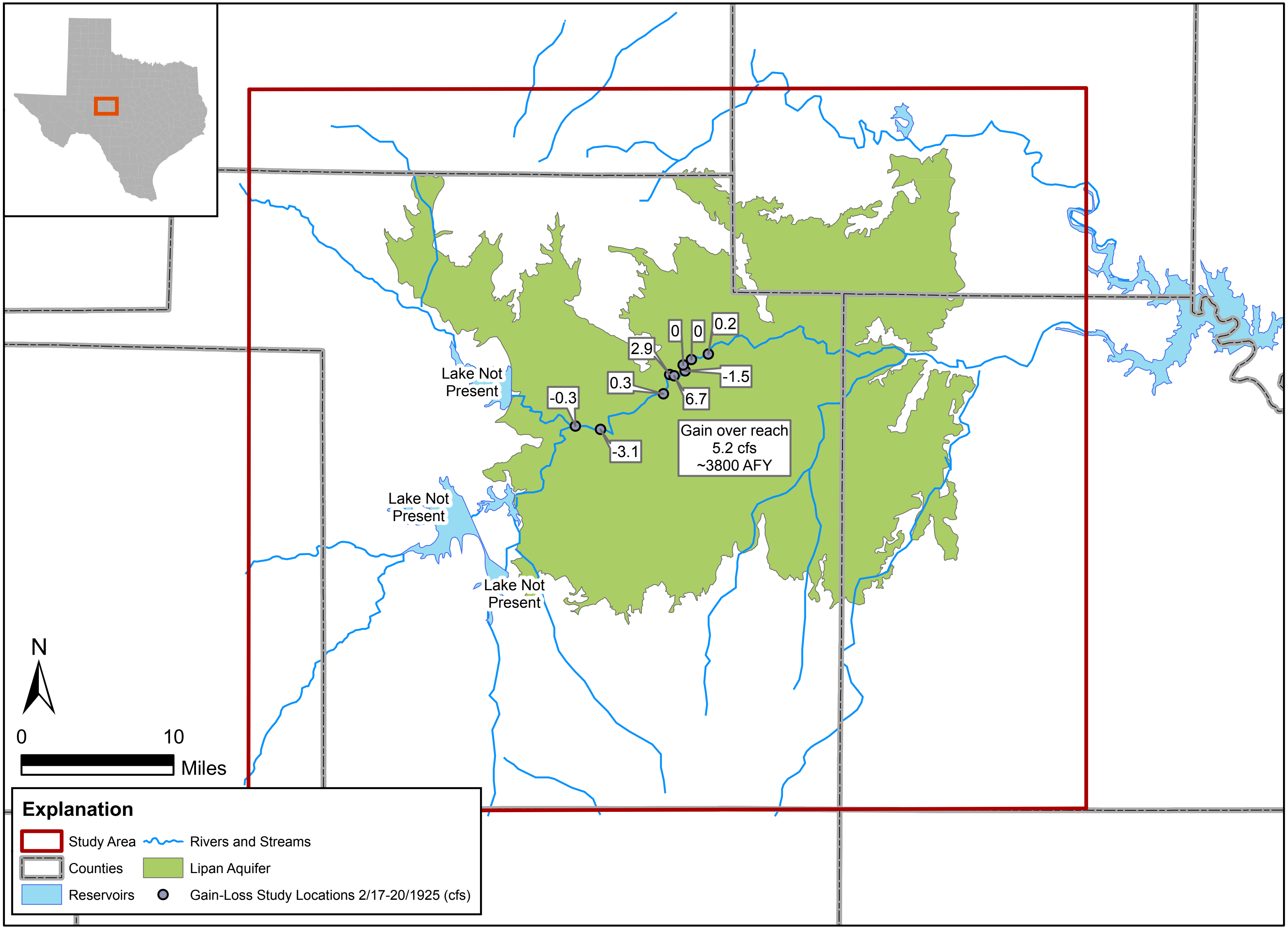


Figure 4.6.7 - USGS Gain-Loss Study in 1925

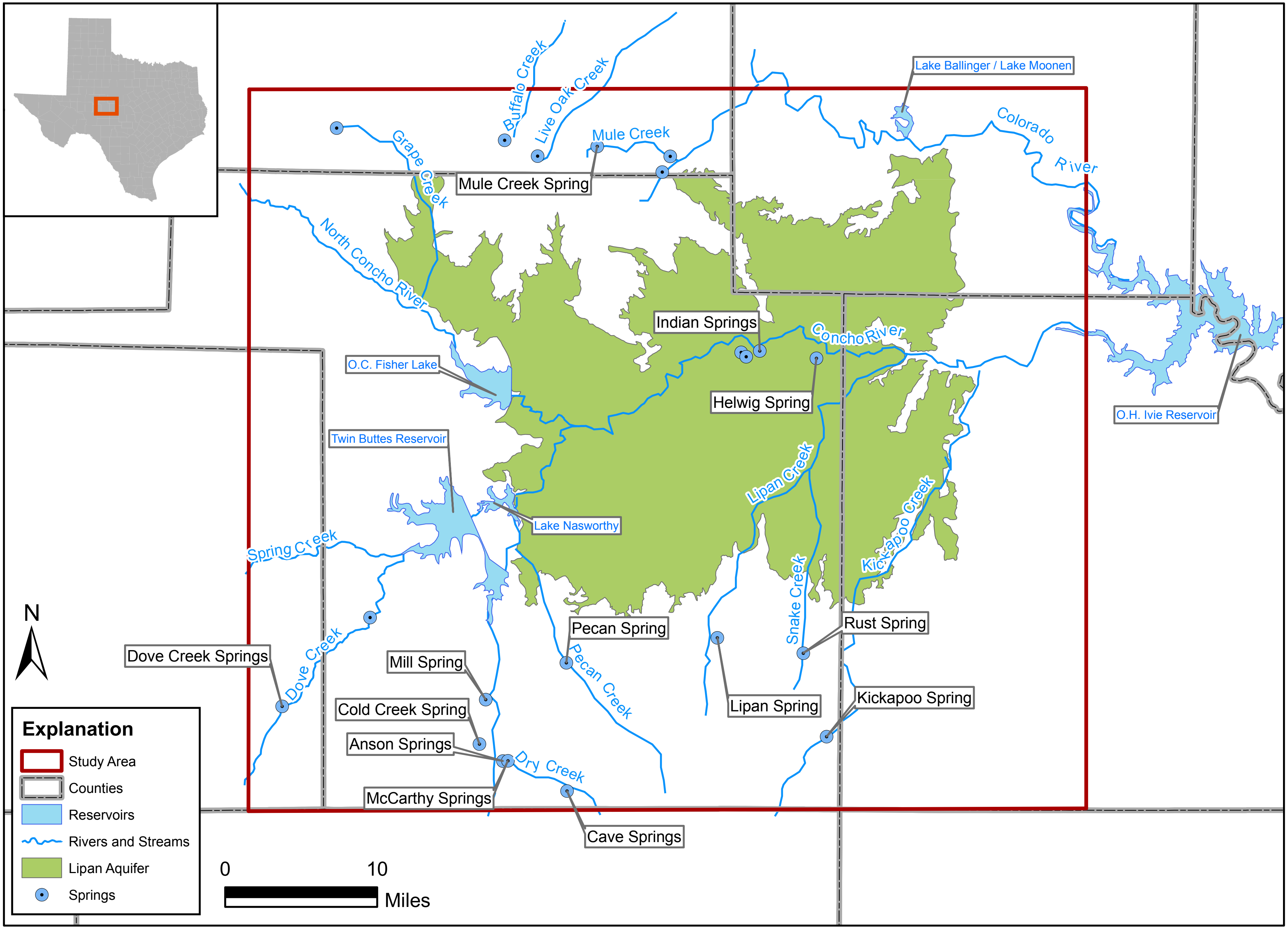


Figure 4.6.8 - Location of Springs in Study Area

4.7 Hydraulic Properties

4.7.1 Hydraulic Conductivity and Transmissivity

There is limited information on hydraulic properties in the Lipan aquifer. Usually, pumping tests are performed to evaluate aquifer properties. Results from only three tests could be located for the Lipan aquifer. Other tests may have been performed, but their results have not been published. These data indicate a large potential variation in the hydraulic conductivity of the aquifer over a relatively small distance. This finding is consistent with well production data, which can vary significantly over short distances. Because there are a limited number of hydraulic conductivity estimates for the Lipan aquifer, available production data was used to estimate hydraulic properties, as discussed below.

Air rotary drilling rigs are normally used to drill wells in the Lipan aquifer. Many times, after boreholes are drilled to total depth, drillers will perform a production capacity test on the borehole by "blowing" the well and estimating the flow rate. In the Lipan aquifer, there are over 1,300 wells where production capacity have been completed and reported. This production capacity data was used to estimate specific capacity values. Specific capacity is the ratio of the production rate in a well to the drawdown in a well during pumping. To estimate this ratio from the production test performed by blowing the well, it was assumed that the entire depth of the well is dewatered, and thus the drawdown in the well was equal to depth of the static water column in the well. The specific capacity is then estimated by dividing the amount of water produced during the test by the drawdown. This approach provides a relative magnitude of specific capacity throughout the aquifer, as shown in Figure 4.7.1. This figure indicates that there are areas of the Lipan aquifer that are more productive than others. The orientation of these high production zones is parallel to the strike of the geologic units and indicates that the underlying geology influences the permeability of the aquifer units. Statistical distributions of these calculated specific-capacity vales are shown in Figure 4.7.2. As expected, these histograms indicate that the specific capacity data is log normally distributed.

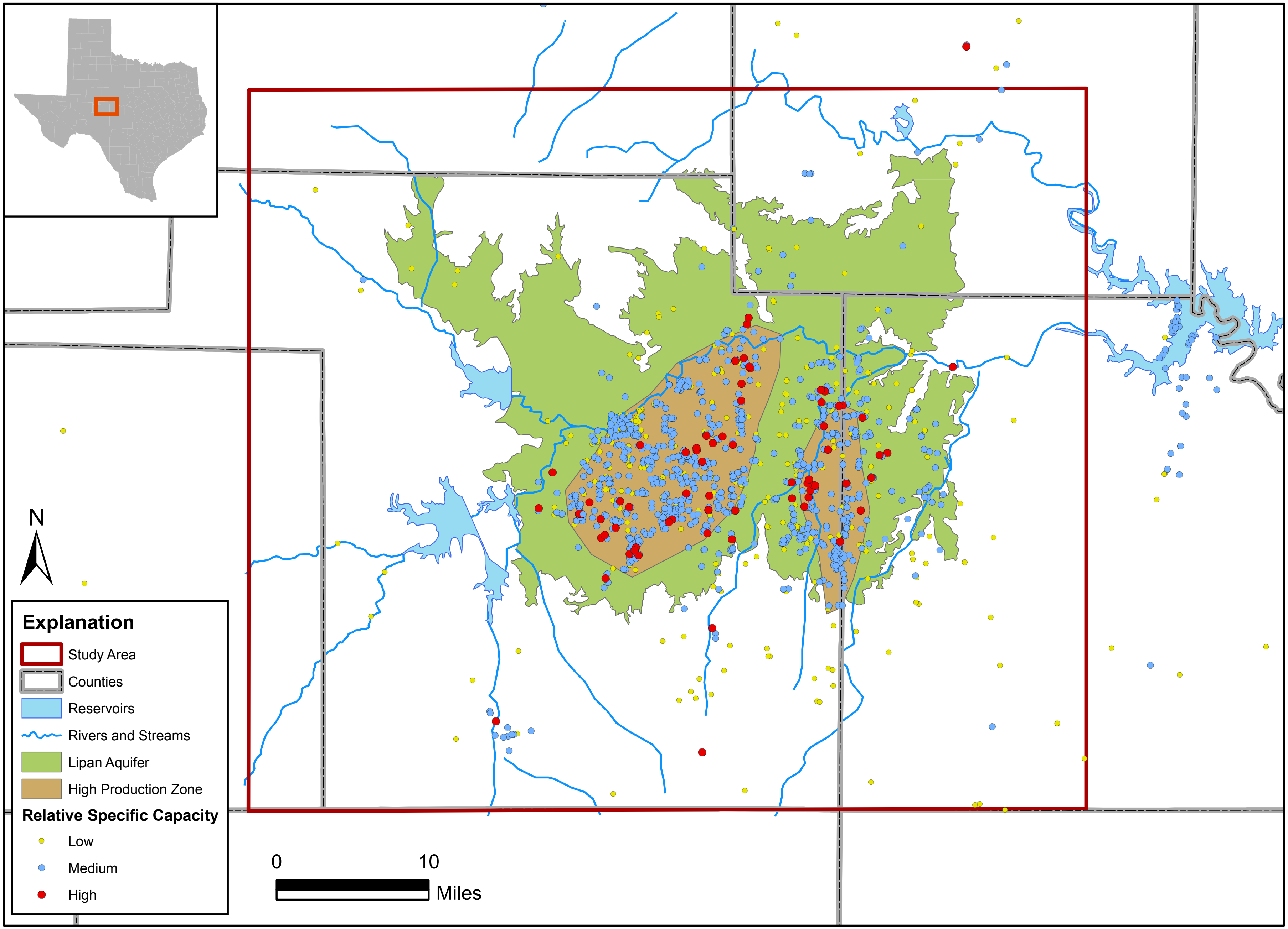


Figure 4.7.1 - Relative Magnitude of Specific Capacity

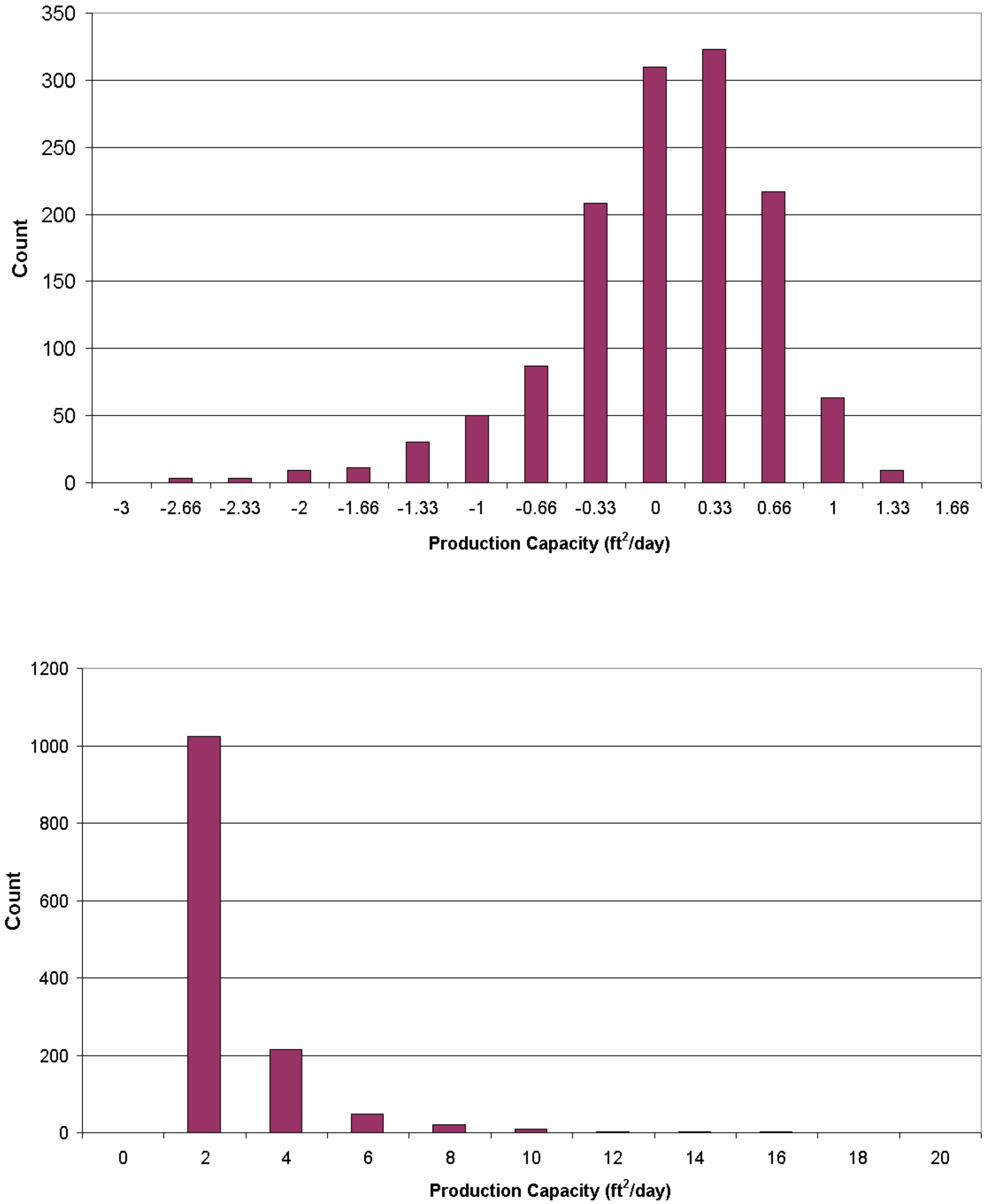


Figure 4.7.2 Distribution of specific-capacity values calculated from production capacity (ft^2/day) and the log distribution of these values.

Mace (2001) published a method for estimating transmissivity values from specific-capacity. Using this method, values of transmissivity were estimated for the 1,333 production capacity values. This resulted in transmissivity values ranging from 0.25 ft^2/d to over 4,400 ft^2/d with an average of 331 ft^2/d. The log of the average transmissivity is 2.2 and the geometric mean is 167 ft^2/d. These values are low for an alluvial aquifer consisting mainly of sands, clays and gravels. Assuming an average saturated thickness of 150 feet, the average hydraulic conductivity would be 2.2 ft/d and have a geometric mean of 1.1 ft/d. The methodology used to estimate the specific-capacity value from production capacity assumes complete drawdown of the aquifer to produce the amount of water observed. In most cases this is probably not accurate. However, there is no way to determine how much drawdown occurred in the wells. Therefore, these transmissivity values will be used to guide the spatial distribution of transmissivity and provide possible bounds on calibrated values. Figure 4.7.1 shows locations where transmissivity values were estimated from production capacity and a delineation of areas of higher production. Final values for transmissivity and hydraulic conductivity will be determined through calibration of the model.

4.7.2 Specific Yield

Specific yield is the volume of water released from aquifer storage due to declining water levels. This value is related to the effective porosity and lithology of the aquifer. Values for specific yield for alluvium aquifers generally range from 0.05 to 0.30 per foot of aquifer head decline. The specific yield of dolomite and limestone aquifers can vary greatly, is usually smaller than alluvium aquifers, and may range from 0.005 to 0.10. Specific yield is essentially the percentage of the total rock volume that can be drained.

Specific yield can be measured in the field through pumping tests. As noted above, pumping test data does not exist for the Lipan aquifer. For the tests that were performed, specific yield values were not reported. Specific yield values were estimated based on lithology and then adjusted during transient calibration.

4.8 Discharge

Groundwater discharge from the aquifer occurs through pumping, springs and seeps, and loss to surface water bodies. Evaporation and transpiration are also ways in which water is discharged from the aquifer. In predevelopment times, spring and seep discharge, along with evapotranspiration, were the dominant groundwater sinks. However, in post-development times, groundwater pumping far exceeds all other discharges. Table 4.8.1 lists the different types of pumping and the total pumping for 1997 in the Lipan aquifer.

Table 4.8.1 Distribution of Groundwater Pumping in 1997

Type of Pumping	Volume (acre-feet/year)	Percent of Total Volume
Irrigation	65,314	96.1 %
Livestock	24	0.0 %
Manufacturing	0.5	0.0 %
Rural Domestic	2,612	3.8 %
Total (1997)	67,949.5	100 %

TWDB divided groundwater pumping into seven water use categories, which are irrigation, municipal, rural domestic, manufacturing, power generation, livestock operations, and mining. Historical pumping estimates for 1980 through 1997 are available for all of these categories except power generation, which did not have any reported groundwater use during this time. For the 50 years from 2000 to 2050, estimated groundwater pumping requirements are based on Regional Water Planning Group and Water Conservation District estimates for these same seven categories. Estimated groundwater use for irrigation and livestock remain constant over the 50-year period at 36,362 AFY and 31 AFY, respectively. Rural domestic pumping fluctuates in response to projected population changes in the area. The total fluctuation over the 50-year simulation period is 1%. Estimated manufacturing pumping fluctuates 7% over the 50-years simulation.

Transient model calibration and verification included all documented pumping assigned to the model per TWDB Technical Memorandum 02-02 and supplemented with more detailed information from LKWCD and area locals. Transient calibration simulated the pumping from 1980 to 1989 and verification will simulate 1990 through 1999 conditions. Pumping was assigned on an annual basis for the 10 years simulations. Predictive simulations were developed to investigate groundwater availability for the next 50 years. TWDB supplied water demand projections based on data gathered from the RWPG and GCDs for each aquifer. For the Lipan aquifer, pumping generally remained constant over time with only minor fluctuation in response in projected population changes.

Total withdrawals in the model area, both historical and projected, are shown in Figure 4.8.1. Irrigation pumping dominates the groundwater usage, and rural domestic use accounts for most of the remaining pumping. This is consistent with the land use in the area as the Lipan flats area is mainly agricultural with very little manufacturing and industry.

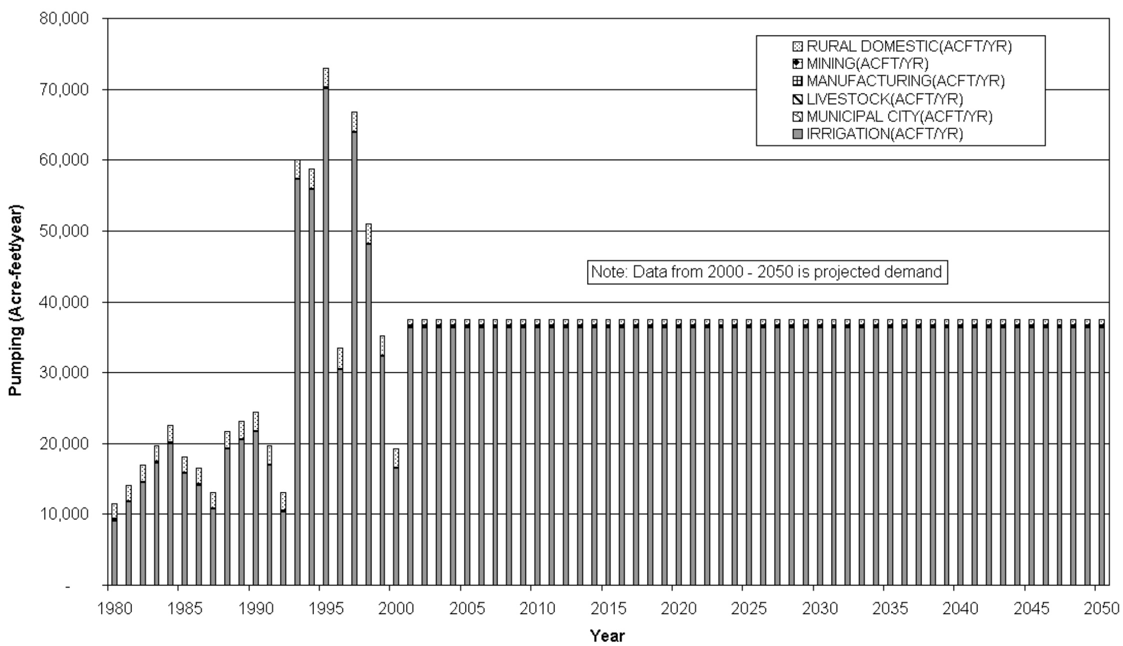


Figure 4.8.1 Total Groundwater Pumping 1980 – 2050

4.8.1 Irrigation Pumping

Prior to 1980, there were 133 reported irrigation wells in the Lipan aquifer (TWDB Database and LKWCD Database). TWDB reported that the total groundwater pumping in 1974 for Tom Green, Concho, and Runnels Counties was 14,902 acre-feet per year (AFY) of which 10,657 AFY was for irrigation. In 1977, these totals rose to 17,080 AFY total withdrawal with 14,050 AFY used for irrigation. In 1997, irrigation pumping from the Lipan aquifer totaled 65,000 AFY, according the TWDB. All other pumping in the Lipan aquifer for that year totaled just over 2,600 AFY. These data are illustrated in Figure 4.8.2.

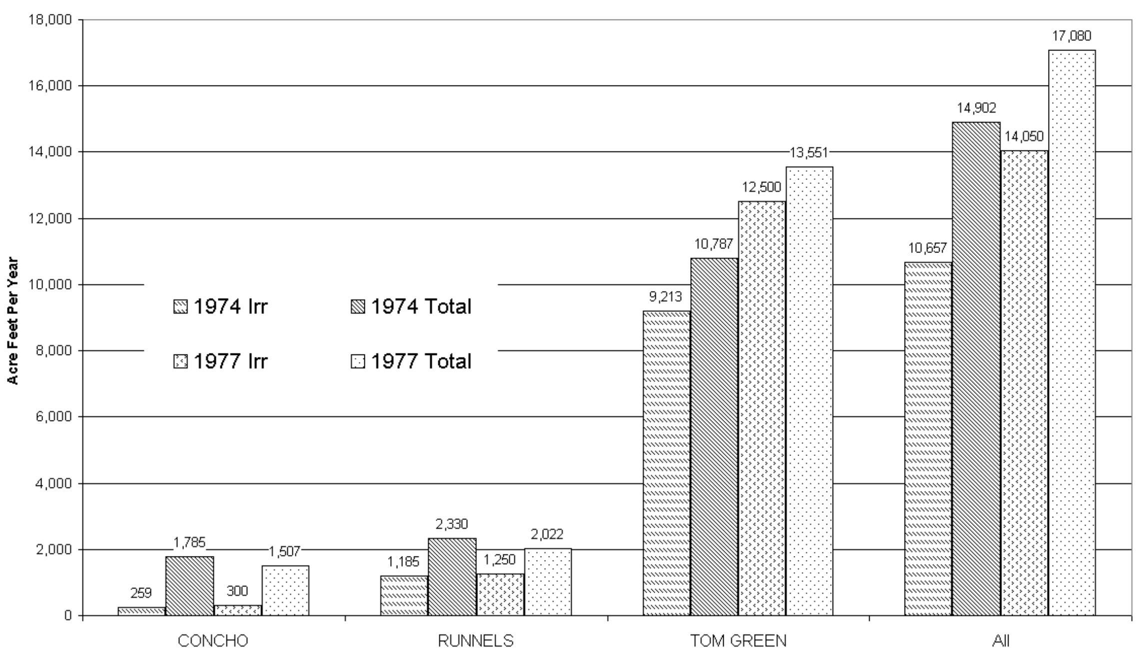


Figure 4.8.2 Summary of Pumping Prior to 1980

Very little data exists for the Lipan aquifer in predevelopment times. Because of this, 1980 was chosen for the steady-state calibration period. Therefore, it was necessary to incorporate irrigation pumping representative of pre-1980 values into the model. The 1974 and 1977 irrigation pumping data was reported county by county and may not be indicative to the actual amount pumped from the Lipan aquifer. Some pumping in the Lipan in Runnels and Concho counties occurs outside of the Lipan aquifer. However, very little data is available to indicate the location of the pumping within the county.

Two irrigation surveys were conducted for the TWDB, one in 1989 and the other in 1994. These surveys delineated the irrigated land areas and are shown in Figures 4.8.3 and 4.8.4. Prior to these studies, the USGS Land Use Land Cover data was used to determine areas of potential irrigation. However, this data does not delineate which cropland areas are irrigated and which are not. To compensate for this, the 1989 irrigation survey was used for spatial assignment of pumping prior to 1989.

Irrigation pumping in the Lipan aquifer for the period from 1980 to 1997 dramatically increased in the mid- to late 90’s. This is due mainly to the increasing popularity of pivot irrigation. Figure 4.8.5 shows the number of irrigation wells installed in the Lipan aquifer.

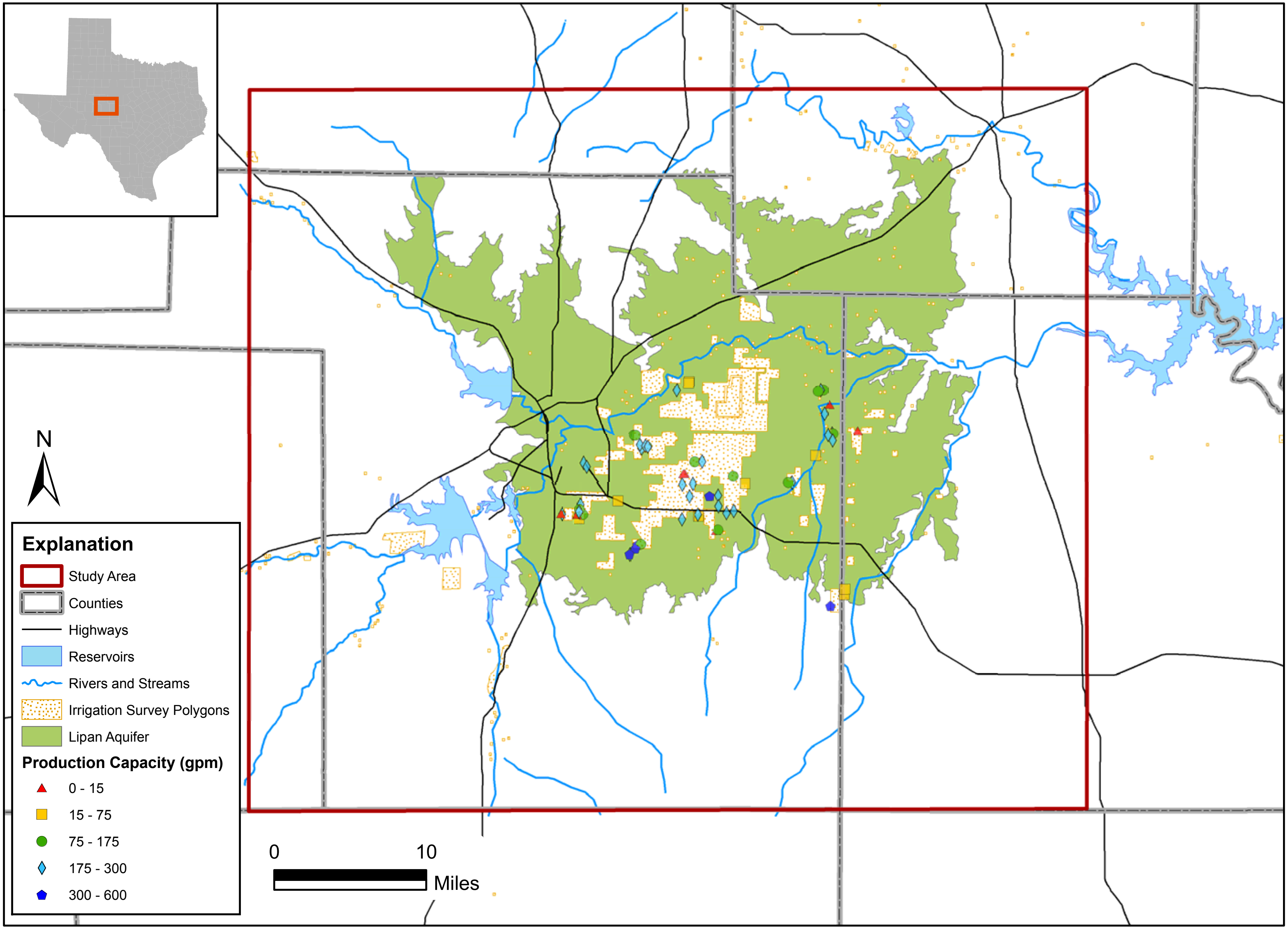


Figure 4.8.3 - TWDB Irrigation Survey Polygons for 1989

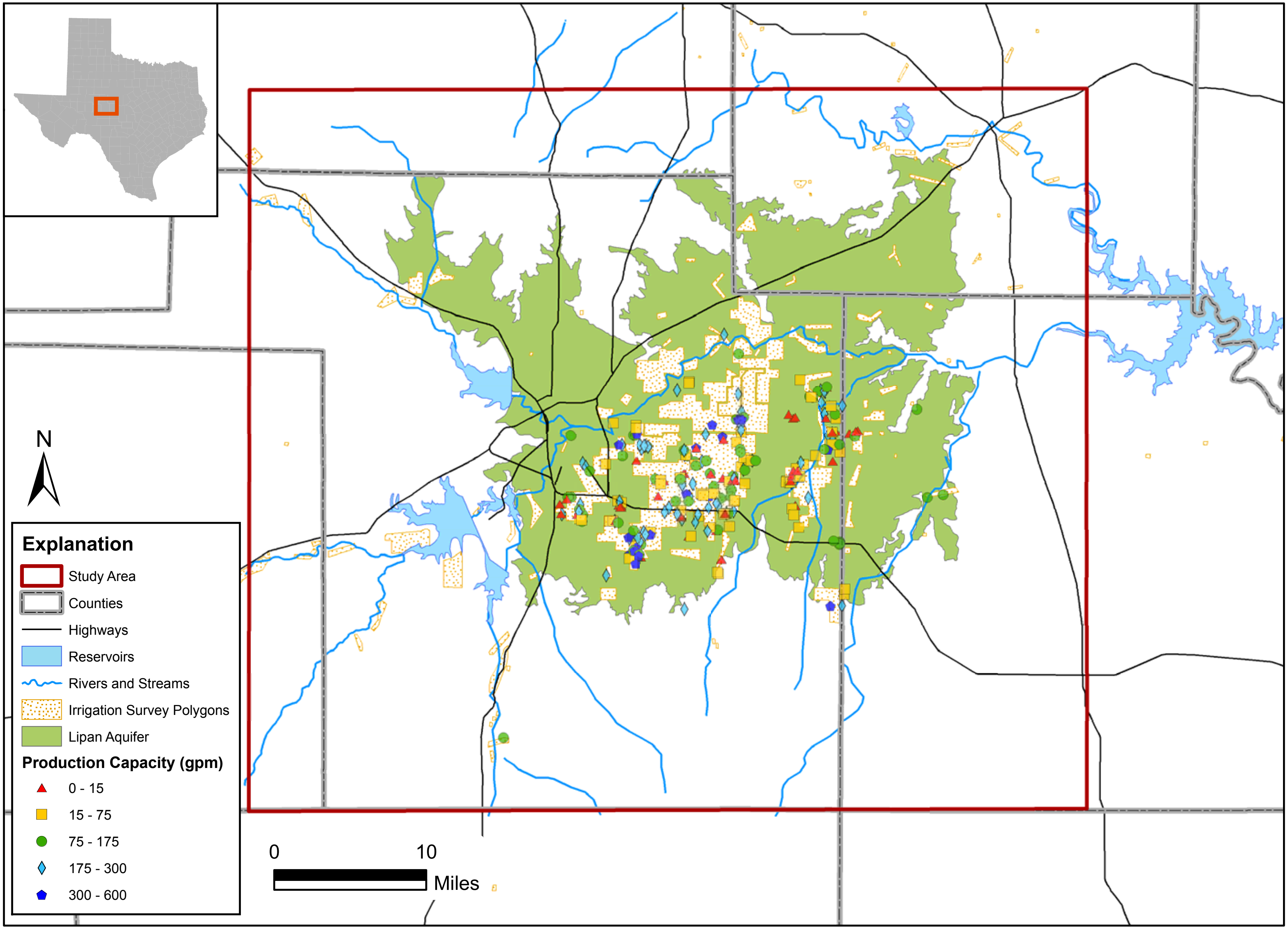


Figure 4.8.4 - TWDB Irrigation Survey Polygons for 1994

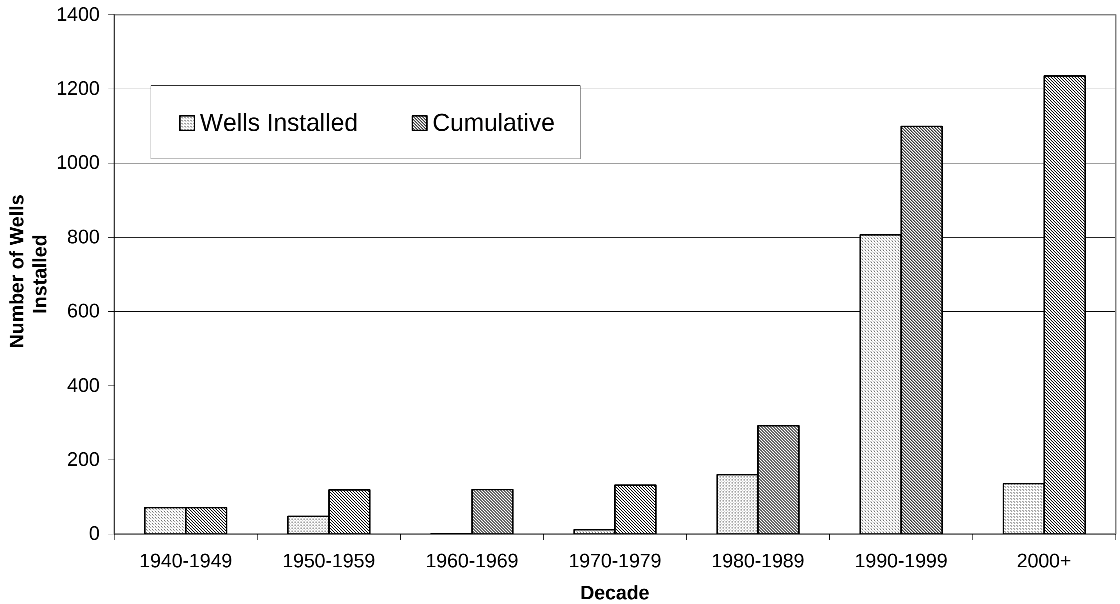


Figure 4.8.5 Irrigation wells installed in Lipan aquifer by decade.

Irrigation pumping is assigned by joining the model grid and the irrigation survey polygons in a GIS program. The current model grid has uniform cells that are a ½ mile on a side, creating cells that have an area of a ¼ square mile. When this grid overlies the irrigation survey polygons, some of the grid cells will be completely within polygons. Others will be partially inside polygons and partially outside. To determine the amount of irrigation pumping assigned to each cell that touches the irrigation polygons, the area and percent area that is inside the polygon must be calculated. Once this is done, the total pumping for a given year can be correctly distributed in the model.

Irrigation pumping was spatially distributed using the irrigation polygons for 1989 and 1994. The 1989 distribution was used to assign pumping for the steady-state calibration model and is shown in Figure 4.8.6. For pumping data in the 1990's, a more realistic approach was used. This method used the same method as before but assigned a weighting factor to scale the pumping based on production capacity. This results in areas where production capacity is high, receiving a higher percentage of pumping. The pumping distribution for the 1990's will be used for assigning the predictive simulation irrigation pumping.

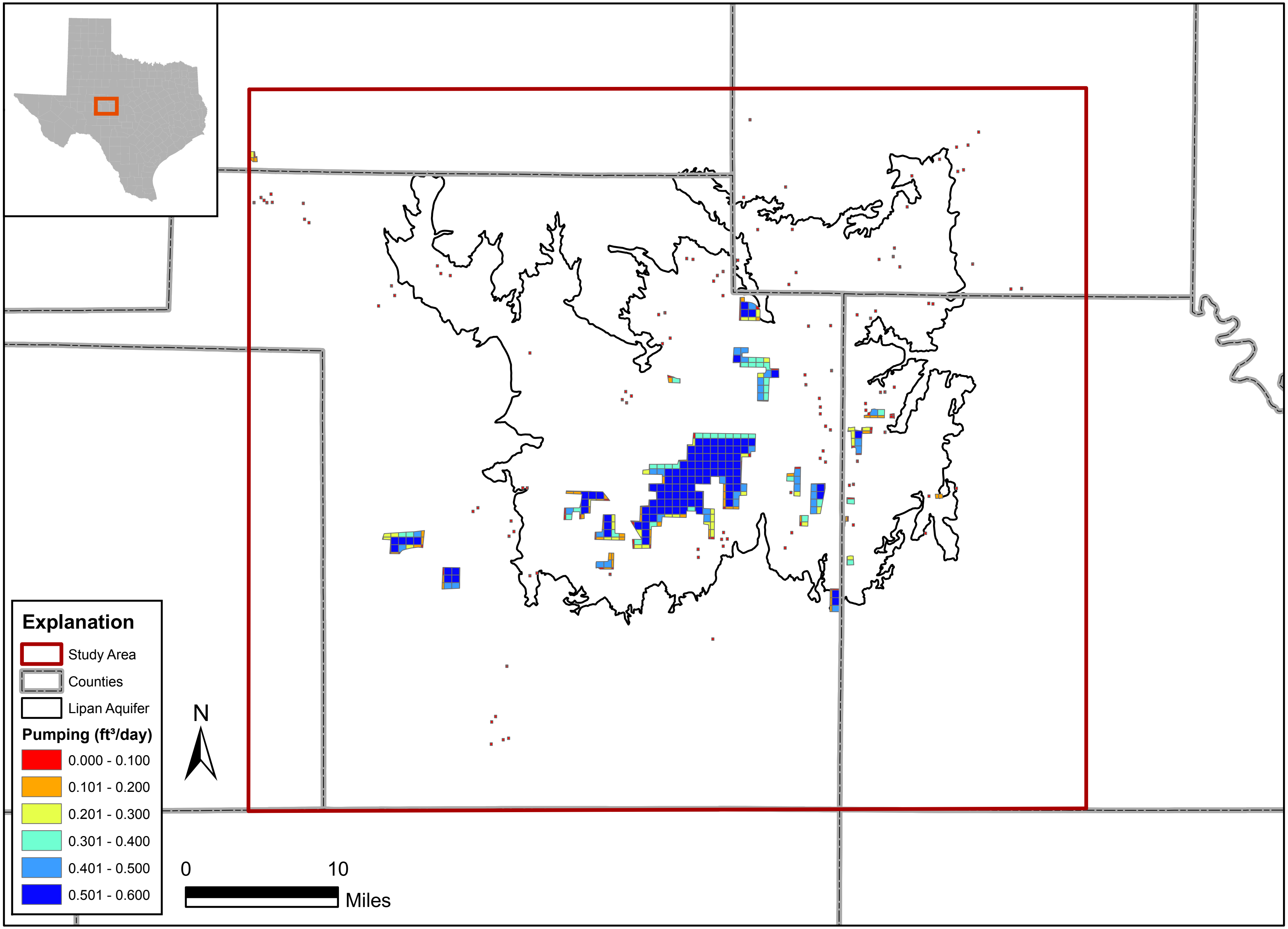
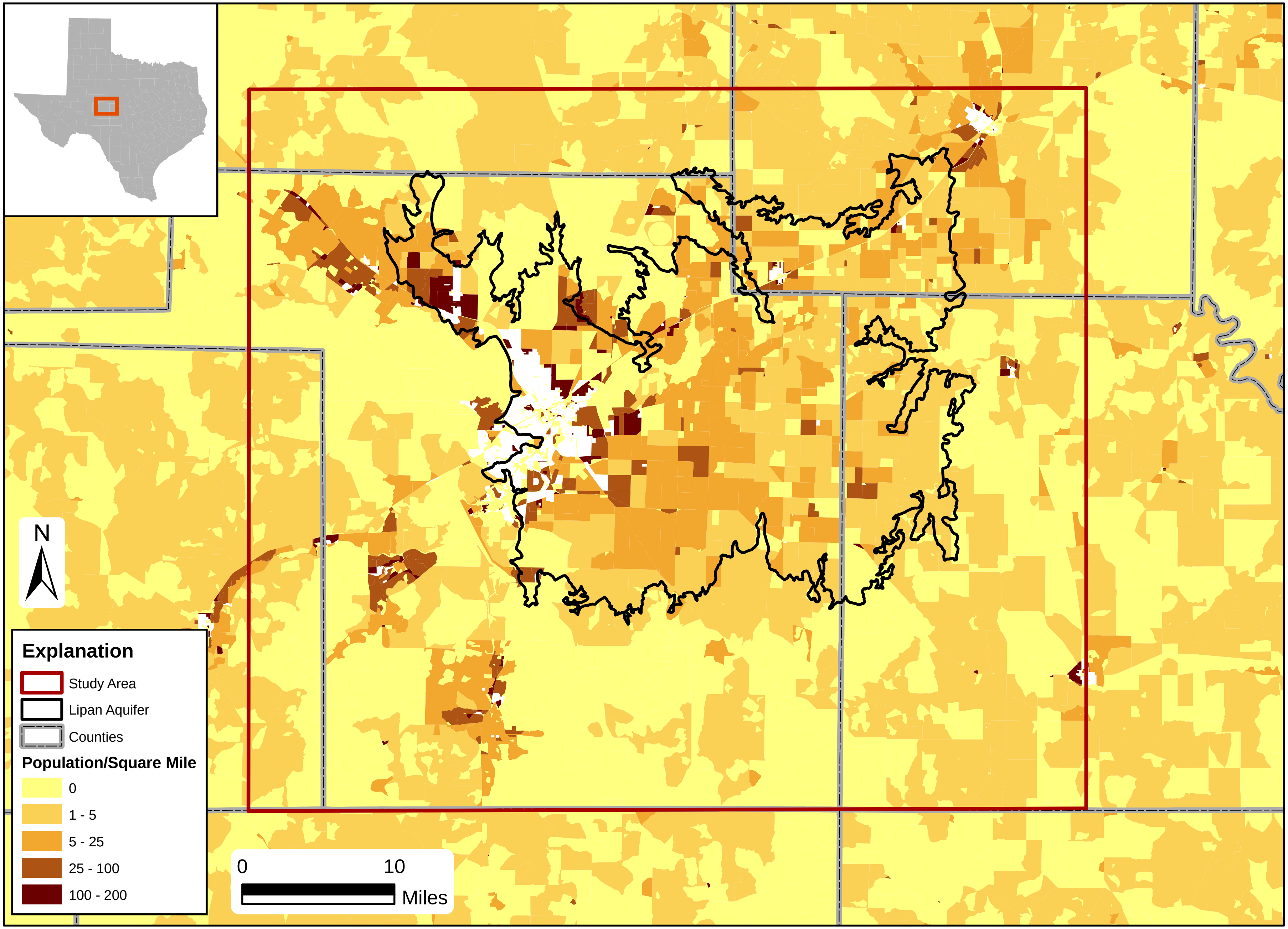


Figure 4.8.6 - Irrigation Pumping Distribution for Steady-State Model

4.8.2 Municipal, Industrial and Domestic Pumping

Municipal, industrial and domestic pumping accounts for less than five percent of the total pumping in 1997. San Angelo, the largest city in the study area does not use any groundwater. The second largest user of groundwater after irrigation is rural domestic pumping, accounting for almost four percent of the total pumping. Population is only predicted to increase one percent over the 50-year simulation period. The rural population density in 2000 is shown in Figure 4.8.7. Manufacturing is predicted to fluctuate seven percent over the simulation period. These changes in pumping will be incorporated into the model predictive simulations; however, the overall effects of the changes are very small compared to irrigation.



source: US Census 2000

Figure 4.8.7 - Rural Population Density in the Study Area in 2000

4.9 Water Quality

The quality of groundwater in the Lipan aquifers was evaluated to help determine if water quality should be considered in determining the boundaries of the model, and to help potential users of the model assess groundwater availability. Water-quality data was compiled from the TWDB groundwater database and the Texas Commission on Environmental Quality (TCEQ) public water-supply well database. For conceptual model evaluation purposes of groundwater flow, the main parameter of interest is total dissolved solids (TDS). Several other parameters may be of interest from an availability aspect, including nitrate.

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).

LBG-Guyton (2003) recently did a study analyzing the brackish groundwater throughout the state, including the Lipan aquifer. Much of the data used in this investigation is based on this work.

A total of 199 water sample data points were used for the analysis of groundwater quality in the Lipan aquifer. Figure 4.9.1 shows the distribution of fresh, slightly saline, moderate saline, and very saline analyses in the Lipan. As indicated in this figure, water quality is slightly saline throughout the Lipan, with fresh water only being found at a few locations at the aquifer margins.

In addition to an evaluation of TDS, several other common water quality parameters were evaluated. Nitrate was evaluated with respect to the primary drinking water standard of 10 mg/L. Nearly 85% of the samples contained nitrate concentrations above this standard, mostly in the outcrop area. However, it is important to note that reported nitrate values are difficult to evaluate without reviewing individual lab results to determine the form that the nitrate analyses are reported in. Parameters evaluated with respect to secondary drinking water standards include chloride (with a secondary standard of 300 mg/L), sulfate (300 mg/L), fluoride (with a primary standard of 4 mg/L and a secondary standard of 2 mg/L), and TDS (1,000 mg/L). TDS exceeded the secondary standard in nearly 83% of the available analyses, followed by chloride (75%), sulfate (45%), and fluoride (12% above the secondary standard and 1% above the primary standard).

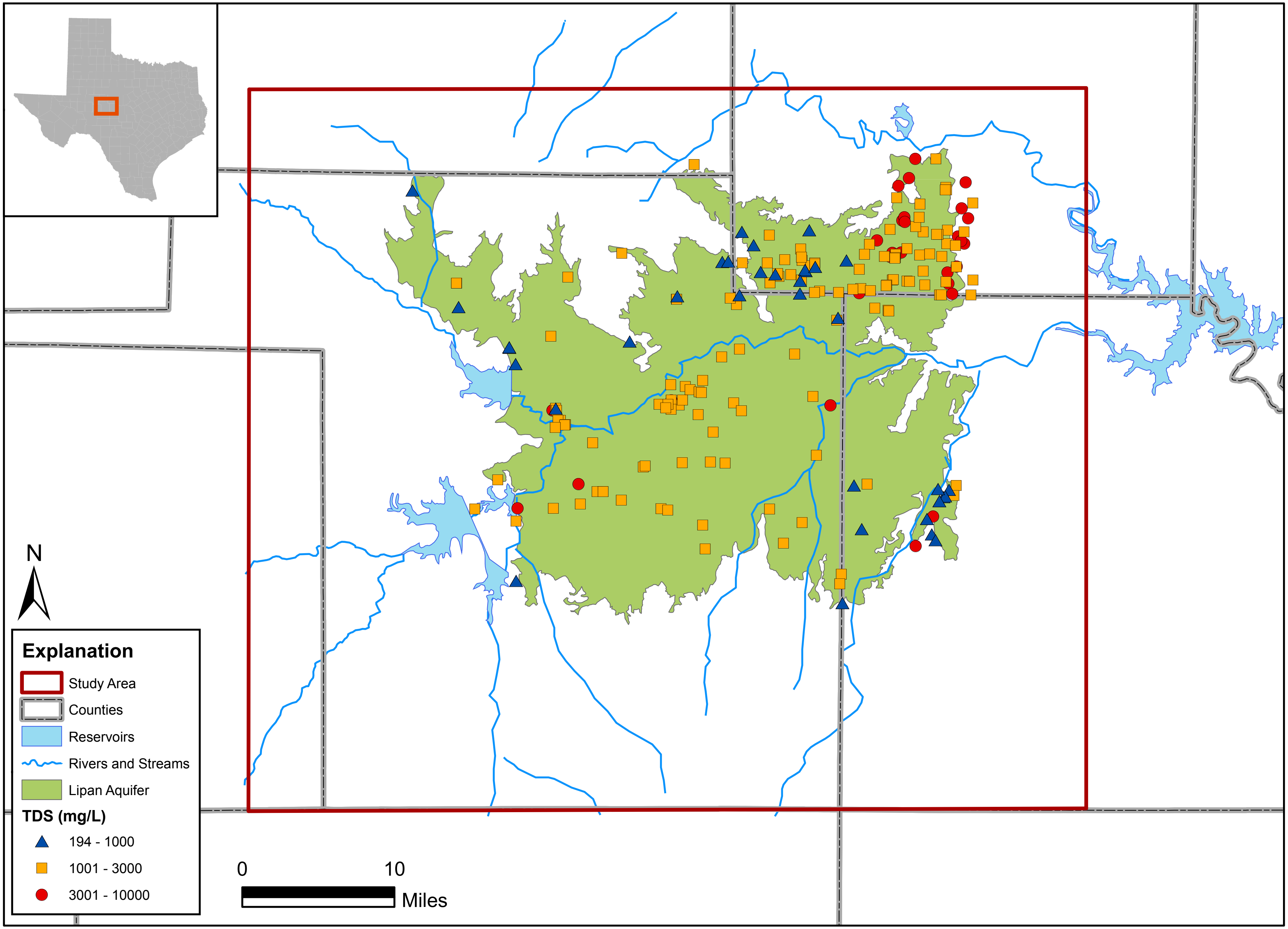


Figure 4.9.1 - Total Dissolved Solids in the Lipan Aquifer

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5.0 CONCEPTUAL GROUNDWATER FLOW MODEL

The Lipan GAM is one of a series of steps in developing a more comprehensive, quantitative understanding of the groundwater system for the Lipan aquifer. In Chapters 2 through 4 of this report, available data for the study area is presented and summarized. From these data, it is evident that there is much to learn about this aquifer system. However, the assimilated data provide a foundation for developing a quantitative understanding of the aquifers and a numerical model that can be improved as more data becomes available.

Anderson and Woessner (1992) describe a conceptual model as "a pictoral*(sic)* representation of the groundwater flow system, frequently in the form of a block diagram or a cross section". Conceptual models are used to describe the components of the groundwater flow system and their relationship to the overall flow regime in the aquifer. Several components have a major influence on the flow in the Lipan aquifer, including groundwater pumping and recharge, while others have a lesser impact on the flow system, including spring flow and evapotranspiration.

5.1 Lipan Aquifer Conceptual Model

Figure 5.1.1 shows the components of the conceptual flow model for the Lipan aquifer. The Lipan aquifer is represented by one hydrostratigraphic unit, which includes the Quaternary Leona Formation, the Permian Formations, and the Edwards-Trinity (Plateau) aquifer. A one-layer representation is used because the Leona Formation and Permian Formations act as a single hydraulic unit, and the Edwards-Trinity (Plateau) is hydraulically connected to this unit on the periphery of the model.

Water table conditions represent the top of the model. The base of the model is considered a no-flow boundary because the permeability of the Permian units decreases and the salinity increases with depth. Most groundwater containing less than 3,000 mg/L is located in wells shallower than 400 feet deep. The model boundary to the south is also specified as a no-flow boundary, corresponding to a groundwater divide observed in

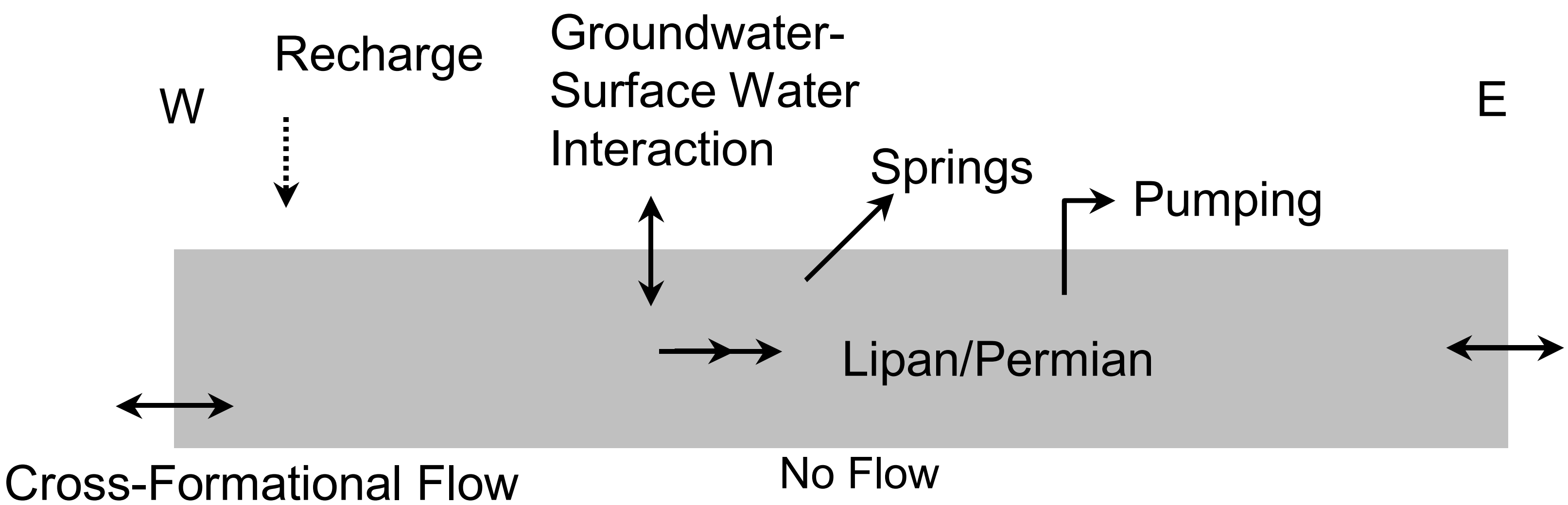

Figure 5.1.1 Conceptual Groundwater Flow Model for the Lipan Aquifer GAM

measured water levels. To the north, a no-flow boundary is used that corresponds to the drainage divide between the Colorado and Concho Rivers. Lateral inflow from the Edwards-Trinity (Plateau) and other water-bearing formations occurs on the western, southwestern, and northwestern boundaries of the study area and groundwater exits the eastern side of the study area.

Aquifer permeability, storage, and the spatial variability in these properties help control the movement of groundwater flows in the aquifer. The permeability distribution is based on well production capacity observations. Recharge and discharge are very important components of the water budget for the Lipan aquifer. Recharge is a function of both temporally and spatially distributed variables, but is difficult to measure directly on a regional basis with existing data. Recharge is a function of precipitation, soil type, geology, evapotranspiration, water levels and topography. Initially, the recharge will be assumed to be four percent of average precipitation, but was adjusted during model calibration.

Evapotranspiration is a major component of the hydrologic system and mainly impacts the water budget of the unsaturated zone (above the water table). Evapotranspiration functions to limit recharge to a small percentage of precipitation. In a few areas where the water table is close land surface, direct evapotranspiration from the water table may be a factor in the saturated zone water budget on a local scale. Groundwater evapotranspiration will be implemented in areas where mesquite and salt cedar is present and the water table is relatively close to land surface.

Under natural conditions, the Concho River serves as a regional sink for the Lipan aquifer. However, the outflow from the aquifer to the river has decreased due to increased irrigation pumping in the Lipan Flats area.

The Lipan conceptual model provides a regional perspective of the aquifer system dynamics. The conceptual model does not address each local scale hydrogeologic and groundwater detail in the study area for two main reasons. First, the data do not exist to quantitatively describe each detail. Second, while there have been great improvements in technology (computer hardware and software), it is generally still infeasible to develop numerical models that can account for both regional and very local scale phenomena with great certainty. One example in the Lipan study area is the precise simulation of water levels in local areas. The scale of the model and the data availability regarding the distribution of pumping precludes such detail. With time, the influence of both of these limitations may be decreased. However, because the TWDB GAM program is designed to assess regional groundwater availability, the nature and scale of the Lipan GAM is regional and may not be appropriate for evaluation of local scale issues.

6.0 MODEL DESIGN

Development of the actual ground-water flow model was based on the conceptual model that was developed in Section 2 through 4 above and described in Section 5. Developing the numerical model consisted of selecting the modeling code to be used, designing the model grid, assigning model stresses, hydraulic parameters and boundaries, and specifying model time parameters and solution criteria. This section describes all of the elements of the model design and how they were incorporated into the groundwater model.

6.1 Code and Processor

As specified by the TWDB, MODFLOW-96 (Harbaugh and McDonald, 1996), a multi-dimensional, finite-difference groundwater flow code, is the numerical modeling code used for the Lipan GAM. MODFLOW contains numerous packages that allow it to simulate all of the stresses and boundary conditions needed in this model. These include general head boundaries, streams and reservoirs, and drains, as well as the standard model stresses such as recharge and pumping.

Processing MODFLOW (PMWIN) Version 5.3.0 (Chiang and Kinzelbach, 2000), a MODFLOW pre- and post-processor, is used to facilitate construction of the numerical mode. PMWIN uses a graphical user interface, which allows for visual development of the model grid and assignment of model properties layer-by-layer. After completion of model construction, PMWIN translate all model data into the formats required by MODFLOW and checks the model files for errors. Results from simulations can be read by PMWIN and graphically investigated.

The model was run on a standard desktop PC using the Windows 2000 Professional operating system. The MODFLOW executable file used for the simulation was the one that was included with PMWIN with no modifications. Any modern personal computer should be capable of running the model

6.2 Layers and Grid

As described in Section 5 above, the Lipan aquifer is being modeled as a single-layer, which includes the Quaternary Leona Formation, the underlying Permian Formations, and Edwards-Trinity (Plateau) aquifer to the west, south, and north. The model grid was oriented so that the columns were aligned with due north and rows were east-west. A uniform grid spacing of one-half mile by one-half mile used as shown in Figure 6.2.1. The model contains a total of 101 rows and 121 columns for a total of 12,221 cells, of which 8,280 are active cells. The top of the model is land surface and the model is 400 feet thick.

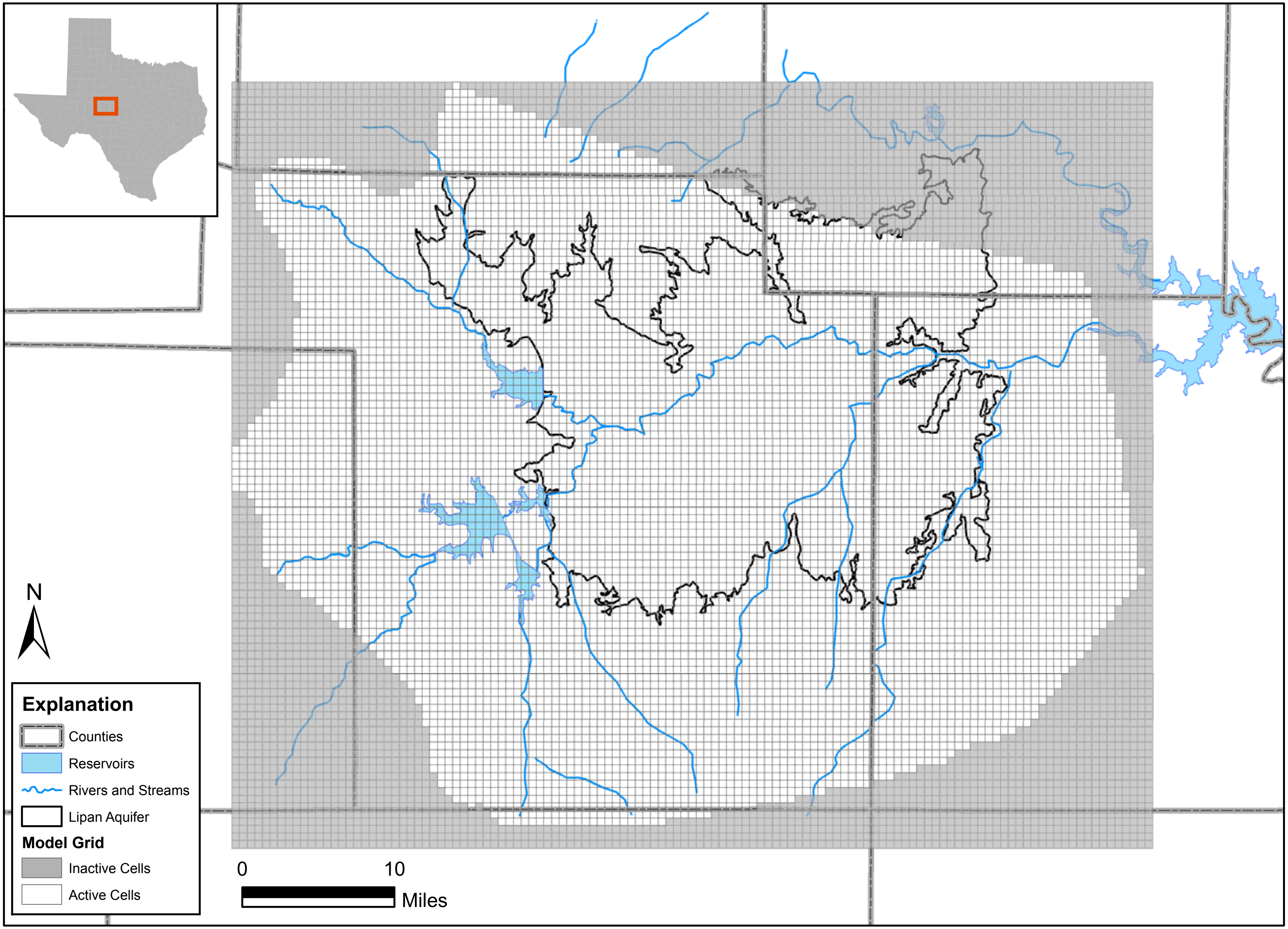

Figure 6.2.1 - Active and Inactive Model Grid Cells

6.3 Model Parameters

A numerical groundwater flow model is defined by many parameters that represent actual aquifer properties and stresses. These parameters include model boundary conditions, aquifer hydraulic properties, and natural and man-made stresses.

6.3.1 Boundary Conditions

A boundary condition is a constraint put on the groundwater model that characterizes the relationship between the aquifer being modeled and the environment outside the aquifer. Stresses applied to the model, such as recharge and pumping, are also boundary conditions. Boundary conditions are generally one of three types: specified head, specified flux, or a “mixed-type”, or head-dependent flux, boundary. Both specified flux and “mixed-type” boundaries are included in the Lipan model. Specified flux boundaries used in the model include zero flux (No Flow) lateral and vertical aquifer boundaries, recharge, and pumping. “Mixed-type” boundaries used in the model include streams, reservoirs, general-head aquifer boundaries, evapotranspiration, and drains.

6.3.1.1 Lateral and Vertical Aquifer Boundaries

Boundary conditions were specified for every physical model boundary in the Lipan groundwater model. Water table conditions represent the top of the model. The base of the model is modeled as a specified flux boundary with a flux of zero (No Flow). The model boundary to the south is also specified as a “No Flow” boundary, corresponding to a groundwater divide observed in measured water levels. To the north, a “No Flow” boundary is used that corresponds to the drainage divide between the Colorado and Concho Rivers. The eastern and western boundaries are general head boundaries with elevations based on water levels observed in 1981. Figure 6.3.1 shows the active and inactive cells in the Lipan model, as well as the boundary conditions represented in the model.

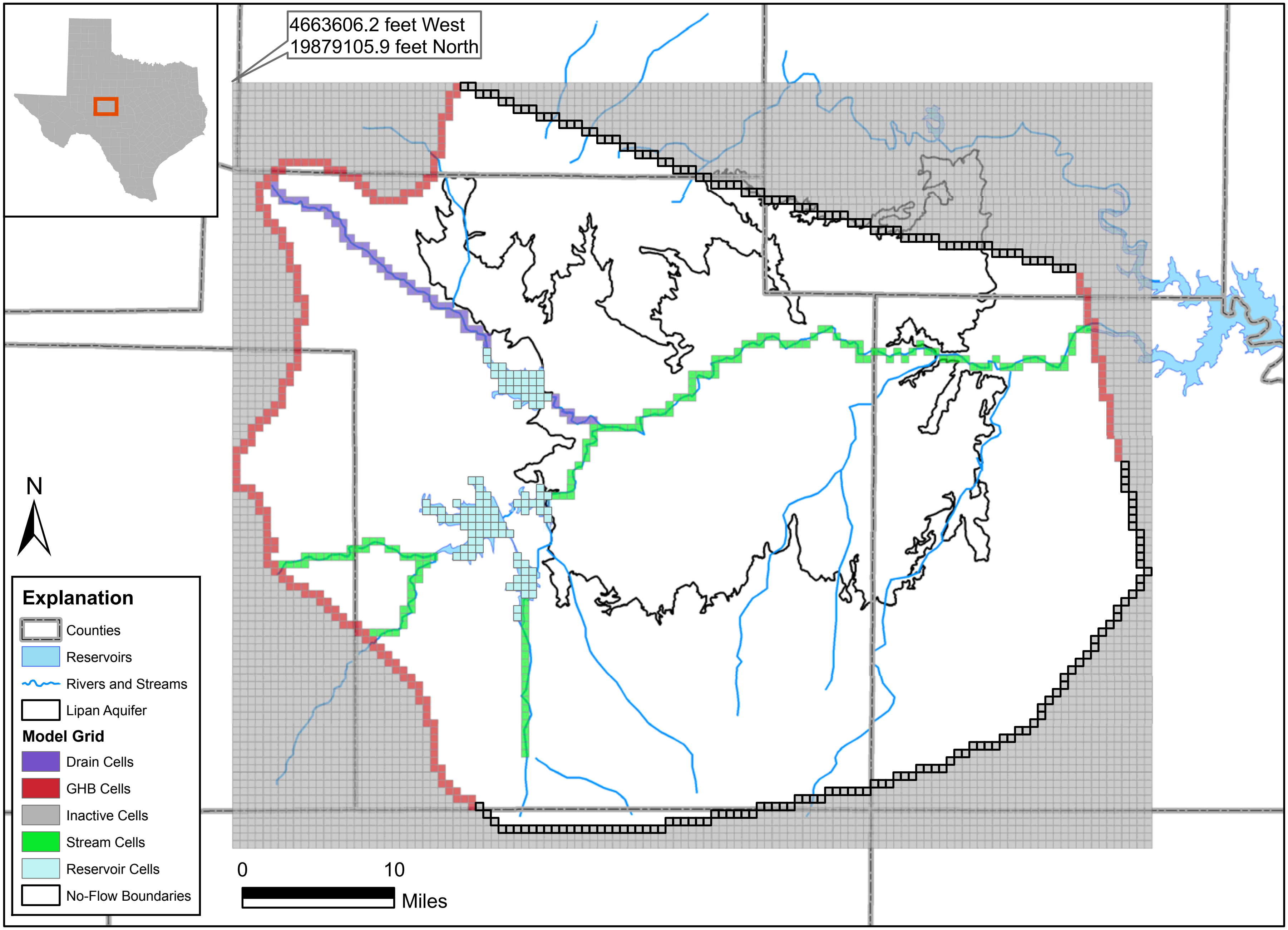

Figure 6.3.1 - Boundary Conditions

6.3.1.2 Streams

Streams, rivers, and springs were incorporated into the model using the MODFLOW stream-routing package. The stream-routing package allows for the appropriate interaction between the aquifer and streams in the study area, recharge via stream cells is allowed when aquifer levels are below the stream (losing conditions), and discharge from the aquifer to the stream is allowed when aquifer levels are above the stream (gaining conditions). This package also allows the streams to go dry if insufficient flow is present in the stream. Streams are defined with a network of segments and reaches, shown in Figure 6.3.2. A reach is the smallest component of a stream, and is located within a single cell. Segments are comprised of sets of reaches, without tributaries. The physical properties of the streambed dictate the ability of water to flow between the stream and the aquifer cell, and are described in the MODFLOW input file. Flow rates in the streams are defined for each stress period in the model for the most upstream segments in the model. Stream flows were based on historical data. Stream parameters are shown in Table 6.3.1.

Table 6.3.1 Stream Flow Parameters

Creek or River	Initial Flow (cfs)	Width (feet)	Bed Conductivity (feet/day)	Manning Roughness Coefficient
Concho River	36.55	20	1	0.05
South Concho River	8.42	5	1	0.05
Dove Creek	1.74	5	1	0.05
Spring Creek	1.49	5	1	0.05

Springs were also incorporated into the model using the stream-routing package. Historical spring flow was used as input to the most upper reach of the stream segment.

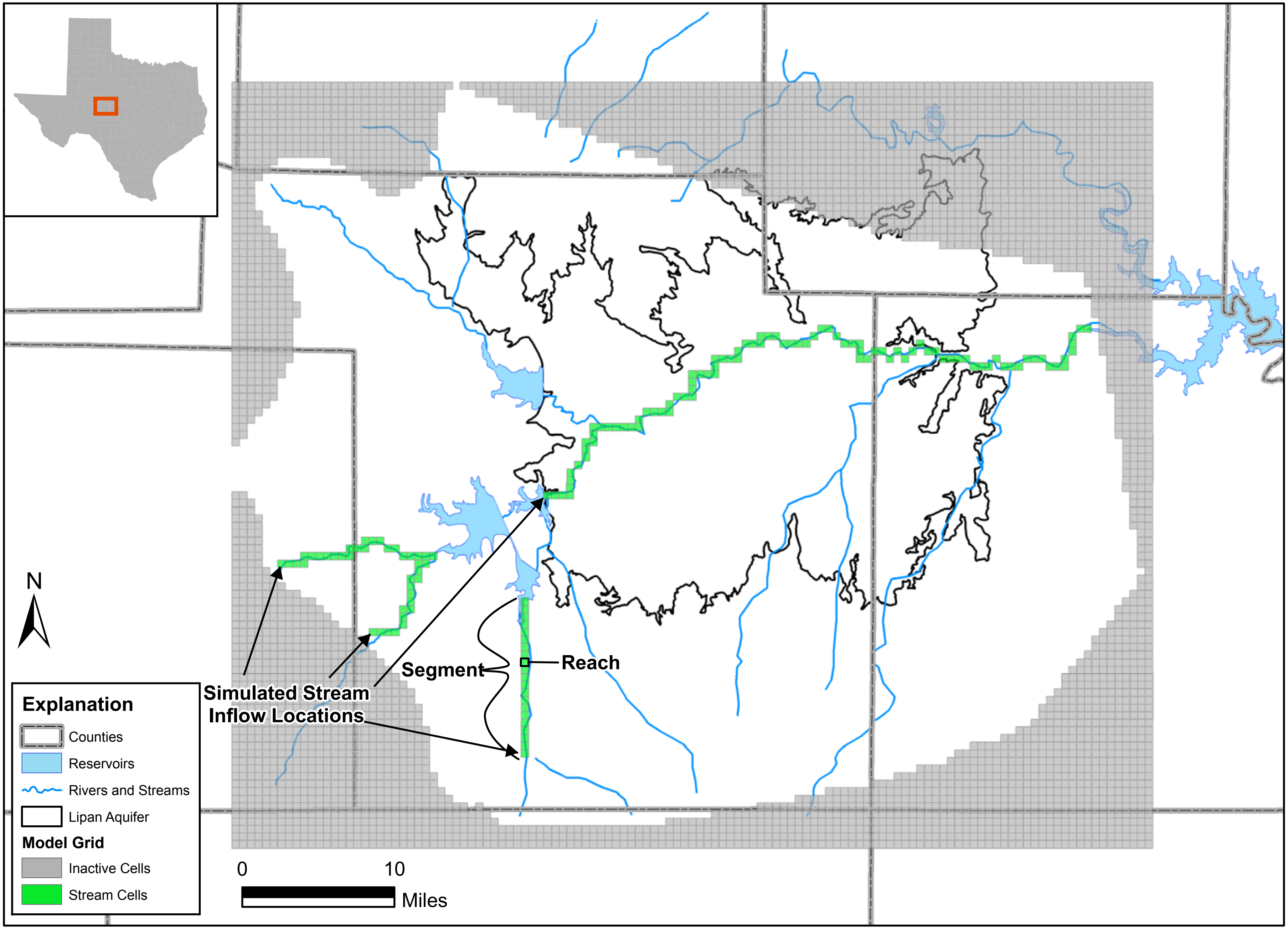

Figure 6.3.2 - Stream Segments and Reaches

6.3.1.3 Reservoirs

The MODFLOW reservoir package was used to include Twin Buttes and O.C. Fisher Reservoir And Lake Nasworthy in the groundwater model. The ability of water to move between the reservoir and the aquifer is dictated by a conductance term and the stage of the reservoir, which is defined in the reservoir input package. The conductance terms for the reservoirs were set to 0.01 foot per day with a bed thickness of 1 feet. Stages were held constant at the conservation level, as shown in Table 6.3.2.

Table 6.3.2 Summary of Reservoir Package Parameters

	Stage (feet)	Hydraulic Conductance (feet/day)
Twin Buttes	1940	0.01
O.C. Fisher	1908	0.01
Lake Nasworthy	1855	0.01

6.3.1.4 Recharge

Recharge was included in the Lipan model using the MODFLOW recharge package. This package allows a specified flux to be applied to cells in the top layer in the model. In the Lipan model, recharge is applied to all active cells in the model, except those corresponding to reservoirs. As discussed in Section 4.4, initial recharge estimates were based on a percent of precipitation. The initial distribution of recharge is shown in Figure 4.4.3.

Recharge was assigned to the model using GIS tools. A spatial distribution of the average precipitation for the period from 1980 to 2000 was developed using an inverse distance interpolation algorithm to assign a precipitation index to each active cell in the model. This index was then related to a table of precipitation for the model area. Precipitation was broken into zones with an interval of 2 inches. Recharge was then assigned to the model based on which precipitation zone corresponded to the cell.

6.3.1.5 Groundwater Pumping

Pumping was applied to the model to reflect actual reported amount for the Lipan aquifer as compiled by the TWDB. The TWDB memorandum 02-02 detailed the methodology used to assign pumping to the transient Lipan model. There are six categories of groundwater pumping used to develop pumping for the steady-state, transient and predictive models. These categories are: irrigation, livestock, rural domestic, manufacturing, mining, and municipal. Irrigation, rural domestic and livestock pumping are all distributed in the model based on spatial data described in the conceptual model. Manufacturing, mining and municipal pumping were all assigned as point values at the model cell closest to the actual well location. There was no pumping attributed the seventh TWDB pumping category, power, and therefore was not included in the model.

Irrigation pumping was applied using the TWDB supplied pumping amounts and the footprint of irrigated land supplied as a shapefile. There are two polygon shapefiles for irrigated land in the Lipan model area; one for 1989 and one for 1994.

The 1989 shapefile polygons were used for distribution of irrigation pumping for the transient calibration period, 1980 to 1989. Irrigation pumping was assigned using GIS tools to overly the irrigation polygons with the model grid. Using the area of each whole or partial model cell covered by the irrigation polygons, the percentage of irrigation pumping in a given cell was calculated. These factors were then multiplied by the total pumping for each year to create the irrigation distribution in the model for each year.

Irrigation pumping for the verification period, 1990 through 1999, was distributed in a similar way. However, based on observed production capacities of wells completed in the Lipan aquifer, as discussed in section 4.7.1, there are two areas of the aquifer that are more productive. Because of this, it as decided that a larger percentage of irrigation pumping should be attributed to cells that fell within these higher capacity areas. Initially two times more pumping was applied to areas in these zones than areas outside. This value was investigated during the transient calibration and was determined to be an appropriate number.

Rural domestic pumping was assigned in much the same was irrigation with the United States population Census shapefiles being used for the spatial distribution. For the transient calibration period, the 1990 Census was used, and the 2000 Census used for the verification period. In both cases, the distribution of rural domestic pumping was based on the census estimated population density in rural areas of the model. Rural areas were defined as all areas with concentrated populations less than 500 people. For the Lipan model, the only area excluded from the rural domestic pumping was San Angelo.

Distribution of rural domestic pumping was generated using GIS tools. The Census shapefiles were overlain with the model grid resulting in the population density of each grid cell. Then the estimated population of the county and total rural domestic pumping reported that year were used to develop a “pumping per person” value for each county for each year. Using these values and the population density of each cell, a value for rural domestic pumping was developed for each cell.

The distribution of livestock pumping was developed based on the USGS Land use land cover data presented in Section 2.1. All areas designated as cropland and pasture, or rangelands were assumed to be capable of being used for livestock. The TWDB provided values for livestock pumping on a yearly basis. To distribute the livestock pumping, the USGS land use land cover data was intersected with the model grid, and the total livestock pumping was equally distributed onto cells where livestock pumping could occur. In the Lipan aquifer, livestock pumping is only a small part of the overall groundwater usage.

Municipal, manufacturing and mining were all allocated based on data provided by the TWDB. This pumping was assigned as point values based on the known or presumed location of the wells. The total combined pumping for these categories was less than 1 percent of the total Lipan groundwater pumping.

6.3.1.6 Drains

The MODFLOW drain package was used to simulate the North Concho River. Drains were used in lieu of the stream-routing package because historically there has been little or no flow in this river. However, there is most likely underflow occurring in the vicinity of the river. The drains included in the model to represent any groundwater lost to the North Concho River were assigned an elevation coincident with land surface and a hydraulic conductance similar to the surrounding aquifer materials

6.3.1.7 Evapotranspiration

Water discharging from the Lipan aquifer due to evaporation and transpiration was removed from the model using the MODFLOW evapotranspiration package. Parameters for the evapotranspiration package were initially estimated based on the type of vegetation found in a particular area. The basic types of vegetation described include: mesquite, juniper, crops, and live oak. Mesquite was determined be dominant in term of evapotranspiration because of its deep extinction depth and high evapotranspiration rate. The evapotranspiration parameters based on these vegetation types are summarized in Table 6.3.3.

Table 6.3.3 Evapotranspiration Parameters

Vegetation Type	Extinction Depth (feet)	ET Rate (feet/day)
Crops	6.9	1.0×10^{-4}
Mesquite Shrub	47	7.5×10^{-4} to 2.25×10^{-3}
Mesquite Brush	47	3.0×10^{-3} to 3.9×10^{-3}

6.3.2 Aquifer Properties

The Lipan aquifer is characterized in MODFLOW using a variety of aquifer properties, including both physical properties, such as the top and bottom elevation of the aquifer, and hydraulic properties, such as the hydraulic conductivity and storage parameters of the aquifer. These properties are discussed in the section.

6.3.2.1 Hydraulic Conductivity

Based on the discussion of hydraulic properties in Section 4.7.1, an initial distribution of hydraulic conductivity was estimated. Because of the limited data available for the Lipan aquifer, large areas of the model were assigned the same value. This occurred in the west and northwest parts of the model as well as areas north of the Concho River.

Initial hydraulic conductivity values assigned to the model ranged from 4 to 20 feet per day. Observed well production, lithology and geomorphology were all used to guide this initial distribution.

6.3.2.2 Storage

Because the Lipan aquifer is an unconfined system, the only storage parameter in the model to be estimated was specific yield. Specific yield refers to the amount of water released from storage for a unit drop in head in the aquifer under transient conditions. Water may also enter storage when water levels are rebounding.

No measured values for specific yield exist for the Lipan aquifer. Initial values for the model were based on published values for aquifer materials similar to those in the Lipan aquifer. Also, estimates for specific yield were made based on observed responses in wells to pumping and recharge. Initially, specific yield was assigned 0.05 throughout the model. Specific yield was included as a calibration variable during transient calibration of the model.

7.0 MODELING APPROACH

Modeling of the Lipan aquifer was a three-part process. The first part was the calibration of the steady-state and transient models. For the Lipan model, this involved using a single model for both the steady-state and transient calibration. The transient model was then verified using different data than was used in the calibration. Verification helped determine the robustness of the calibrated model. Evaluating the sensitivity of the calibrated model was the second part of the modeling process. Finally, predictive simulations using the calibrated model were performed for various recharge scenarios outlined by the TWDB.

7.1 Calibration and Verification

7.1.1 Approach

Groundwater models are inherently non-unique. Non-uniqueness is the ability of a model to reproduce observed aquifer conditions using different suites of model parameters. To reduce the impact of non-uniqueness on model results, several approaches were used. Where possible, the model incorporated parameter values consistent with measured values. A long calibration period was used to incorporate a wide range of hydrologic conditions. The verification period used a different set of target data designed to test the robustness of the model calibration. Finally, to the degree possible, two different calibration performance measures (hydraulic heads and discharge rate) were used to reduce non-uniqueness in the model.

All available data assimilated in Section 4 developed were incorporated into the model. In areas where observed hydrologic data were not available, estimates were developed based on data compiled for other similar aquifers and data published for aquifer materials and settings similar to the Lipan aquifer.

Model parameters were held to within reasonable ranges based upon the available data and relevant literature. Adjustments 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 properties that have a good supporting database.

The model was calibrated for two hydrologic conditions, one representing steady-state conditions (corresponding to pre-development conditions) and one representing transient conditions (post-development). Because very little data exist for the Lipan aquifer before pumping started, a period with pumping occurring had to be used for the steady-state period. Because more data became available in the mid- to late-80's, a steady-state period corresponding to a time before 1/1/1980 was chosen for the steady-state period. The model was run for 10,000,000 days (27,380 years) using 1980 pumping, recharge and evapotranspiration data. At the end of this simulation, the model approximates steady-state conditions. Final heads for this steady-state model runs were used as initial heads for the transient calibration model.

After the model was calibrated to steady-state conditions, a transient calibration was conducted. The transient calibration period ran from 1981 to 1990. Once the transient model was calibrated, it was then verified. The transient verification period ran from 1991 through 1999. All stress periods during the calibration and verification period were one year in length due to the resolution of most of the pumping estimates in Lipan aquifer. The goal of the steady state predevelopment 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 occurred in the aquifers due to pumpage.

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). However, to address the issue of non-uniqueness, it is best to use as many types of calibration targets as possible. Therefore observed gains and losses along Concho River from San Angelo to Paint Rock were also used as calibration targets. Simulated heads were compared to measured water levels in wells through time (hydrographs) and head distribution maps.

Model calibration is judged by quantitatively analyzing the residuals, which are the differences between observed and model computed values at calibration target locations. Several statistical and graphical methods are typically used to assess the model calibration. These statistics and methods are described in detail in Anderson and

Woessner (1992). A mean error or mean residual that is positive indicates that the model has systematically underestimated heads, while a negative error indicates the opposite. It is possible to have a mean error near zero and still have considerable errors in the model (for example, errors of +50 and -50 give the same mean residual as +1 and -1). Thus, two additional measures are used to judge the model calibration- the mean absolute error (MAE) and root mean square of the errors (RMSE) (Anderson and Woessner, 1992). The mean absolute error is calculated by take the average of the absolute value of all of the errors or residuals, which quantifies the magnitude of the error in the model calibration. Finally, the RMSE is calculated by taking the square root of the average of the sum of the square residuals. The RMSE looks at the whole model and determines how well calibrated it is everywhere. A large RMSE indicates that a poorly calibrated model even if the other statistics are within reasonable limits.

7.1.3 Calibration Target Uncertainty

Groundwater elevation measurements have an inherent error component due to several factors, including instrument error, sampling scale limitations, and recording errors. It is important to define the level of plausible uncertainty in order to know when the model calibration is as good as warranted by the data, and to set goals in the context of the above statistical measures to avoid "over-calibrating" the model.

Uncertainty in water level measurements can be the result of many factors including, scale errors, measurement error, instrument error, and various types of averaging errors, both spatial and temporal. The calibration criteria for head is an RMS less than or equal to 10% of head variation within the aquifer being modeled. The head in the aquifers within the study area vary from approximately 1,700 to 2,100 feet, resulting in an acceptable RMS of approximately 40 feet. RMS can be compared to an estimate of the head target errors to determine what level of calibration the underlying head targets can support.

Groundwater models attempt to numerically represent the physical world. However, because of the large lateral dimensions of the model, the accurate simulation of local phenomena is not possible. In the Lipan aquifer model, each model cell is ½ mile by a ½ mile on a side with an area of ¼ square mile or 160 acres. Each model cell is assigned a single set of parameter values to describe the cell, including top and bottom elevations and many other parameters that are static for the duration of the simulation. Results from the model will include a single water level for each individual cell; even though it is probable that more than one well exists in each cell. However, all of the wells in a given cell will be assigned the same value for simulated head, even though the actual measured water level may be different due to changes in regional water levels and, completion differences, and proximity to pumping wells or other influences not explicitly modeled.

7.2 Sensitivity Analyses

A sensitivity analysis was performed on both the steady state and transient calibrated models to determine how changes in a calibrated parameter affect the results of the calibrated model. The sensitivity analysis was completed such that each of the hydraulic parameters or stresses were adjusted from their calibrated value by a small factor while all other hydraulic parameters were held at their calibrated value. 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.

7.3 Predictions

After the model was satisfactorily calibrated (i.e., the criteria for calibration and verification periods met predetermined objectives), the model was used to make predictive simulations to estimate aquifer response to future pumpage and recharge conditions. Six predictive simulations were completed. Pumping stresses for the predictive simulations were based on predicted groundwater demands between 2000 and 2050 developed by the Region F Planning Group and documented in the State Water Plan (TWDB, 2002).

The first predictive simulation incorporated average hydrologic conditions (i.e., recharge) from 2000 through 2050. The other predictive simulations were run from 2001 to 2010, 2020, 2030, 2040, and 2050 and incorporated the regional drought of record estimated recharge during the last seven years of each simulation. An additional five simulations were performed to assess the water level declines with different irrigation pumpage under average recharge conditions for 50 years.

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8.0 STEADY-STATE MODEL

This section details the calibration of the steady-state model for the Lipan aquifer and presents steady-state model results. This section also details the sensitivity of the steady-state model to steady-state model input parameters.

8.1 Calibration

The calibration of the steady state model involved adjusting a majority of the model input parameters in order to get a best fit with the calibration target data. The process of calibrating the Lipan aquifer model was an iterative process. The steady-state model was calibrated and the aquifer properties were then used in the transient calibration model and further adjustments were made. These adjusted model parameters were then used in the steady-state model to make sure it was still sufficiently calibrated. Calibration was achieved when the residuals of the heads; the difference between the measured head and the model simulated head at a given location, were reduced below a predetermined value. A combined steady-state / transient calibration model was developed during the calibration process to facilitate more efficient calibration simulations. This section describes the final steady state calibration results.

8.1.1 Calibration Targets

Water levels before development of the Lipan aquifer for use in the calibration of the steady-state model are uncommon, because wells installed in the region were typically pumped immediately. Therefore, only a total of 18 wells and water levels were considered acceptable for use in the steady-state model calibration. Figure 8.1.1 shows the locations of these wells.

Another calibration target used for the steady-state calibration was observed stream gains and losses on the Concho River between San Angelo and Paint Rock. Several model parameters, including recharge, evapotranspiration and hydraulic conductivity, in addition to the stream parameters, affect the stream interaction with the aquifer.

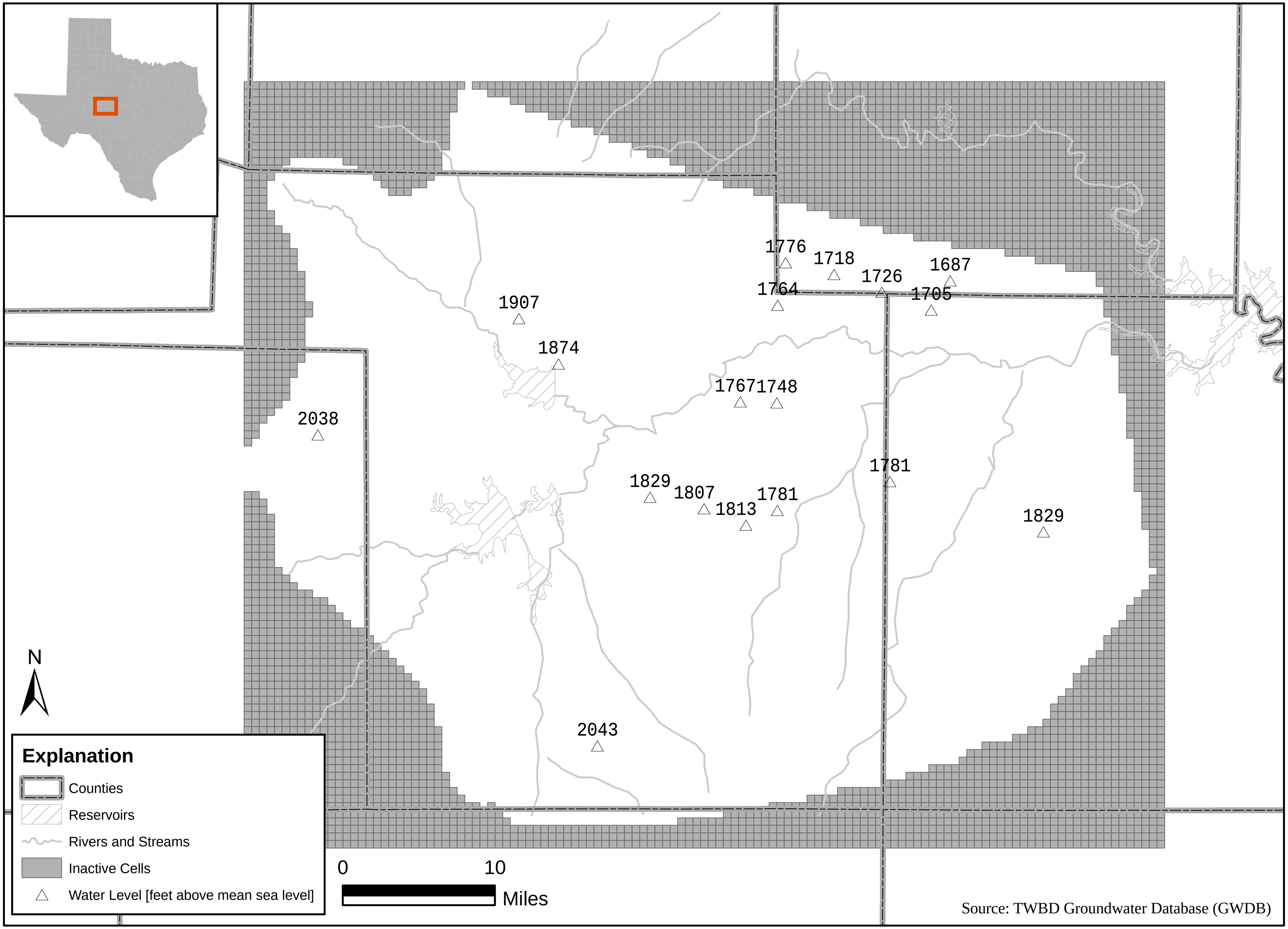

Figure 8.1.1 Steady-State Calibration Target Wells

8.1.2 Hydraulic Conductivity

As described in Section 4.7.1, an initial distribution of hydraulic conductivities was determined based on observed production capacities, lithology and geomorphology in the study area. Hydraulic conductivities were assigned to the model using a zone approach. Using zones allows for areas of the model that have the same hydraulic properties to be classified by a single zone number. During calibration, values corresponding a zone number can be changed and those changes will be reflected to all cells in the model indexed by that zone number.

There are four zones of hydraulic conductivity in the Lipan aquifer model. Two of these zones correspond to areas of higher production capacities observed in wells in the Lipan Flats area. The other two zones are used to represent the rest of the Lipan aquifer and the Edwards-Trinity (Plateau) aquifer that occurs at the periphery of the model to the south, west and north. The initial hydraulic conductivity assigned to each zone is shown in Table 8.1.1. Values in these zones were adjusted during calibration of the steady-state and transient models. During calibration, hydraulic conductivities in the low production zone of the Lipan aquifer varied from 3 to 5 ft/d and from 20 to 50 ft/d in the high production zones. Edwards-Trinity (Plateau) areas of the Lipan aquifer model varied from 5 to 20 ft/d. The final distribution of the hydraulic conductivity zones is shown in Figure 8.1.2. Final, calibrated hydraulic conductivities varied from 4 to 20 ft/d.

Table 8.1.1 Summary of Initial Hydraulic Conductivities in Lipan Model

Zone	Initial Hydraulic Conductivity (feet/day)
1	2.5
2	10
3 & 4	35

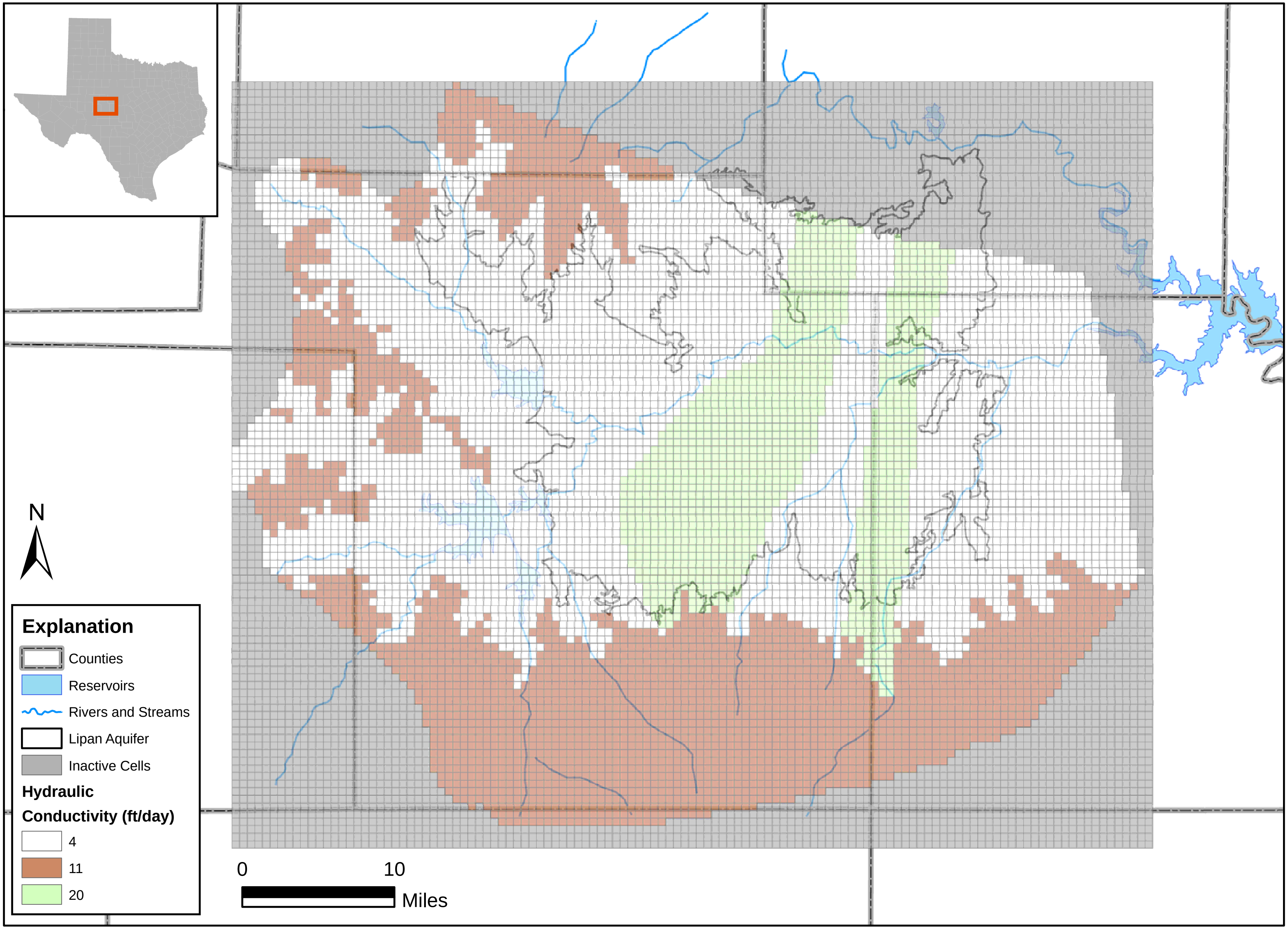

Figure 8.1.2 - Calibrated Hydraulic Conductivity Distribution

8.1.3 Recharge

Recharge to the model was based on precipitation. An initial estimate of 4% of annual average precipitation was used in the steady-state model. However, this recharge estimate was reduced during calibration because water levels in topographically low areas were above land surface. Also, simulated gains in the Concho River between San Angelo and Paint Rock were higher than observed. The final spatial distribution of calibrated recharge in the steady-state model is shown in Figure 8.1.3.

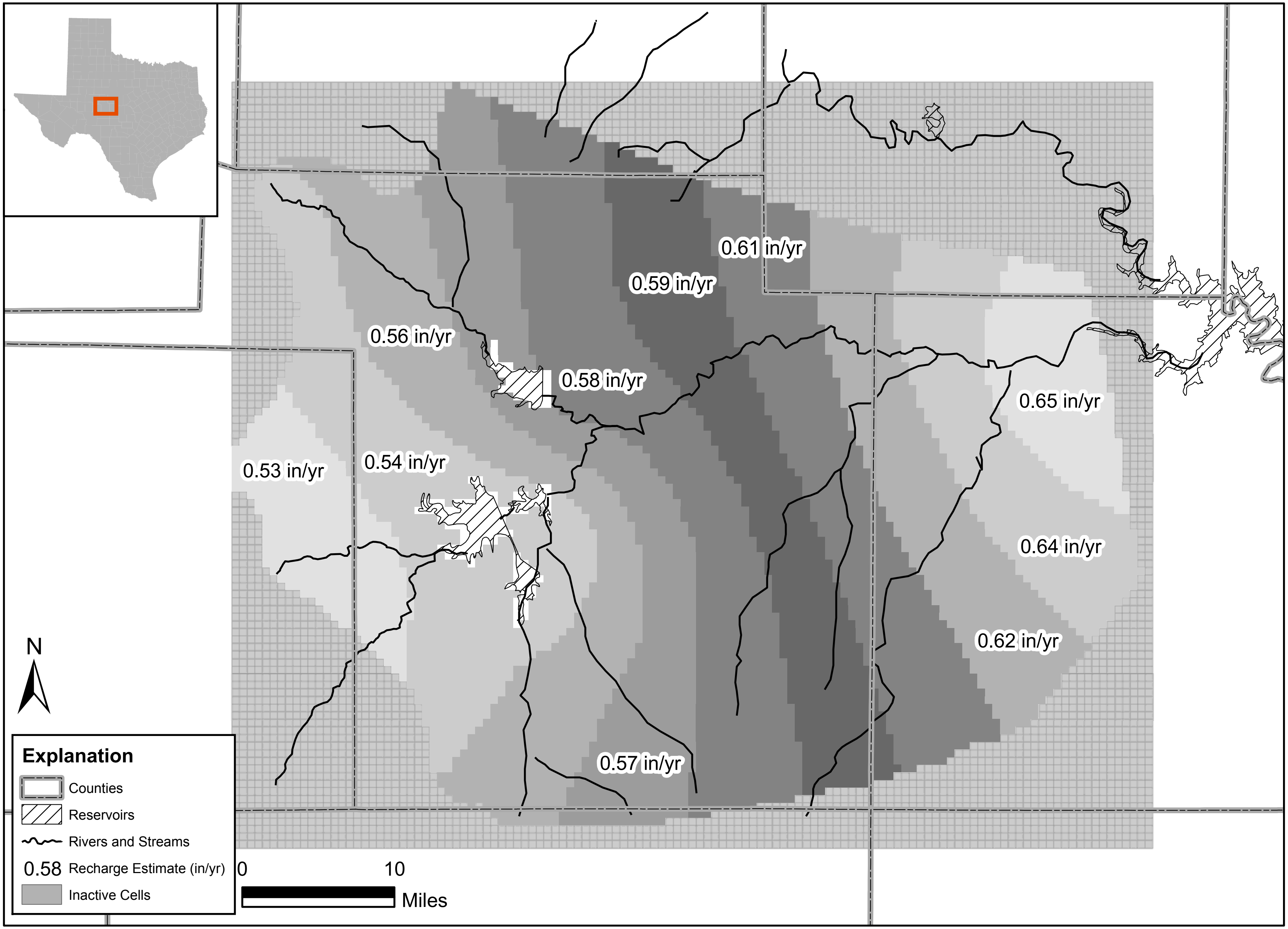

Figure 8.1.3 - Calibrated Recharge Distribution

8.1.4 Evapotranspiration

Evapotranspiration applied to the steady-state model was based on reported rooting depths and maximum transpiration rates of vegetation found in the model area. The final extinction depths and evapotranspiration rates used in the calibrated model are shown in Figure 8.1.4. Extinction depths were not varied from the initial distribution. Rates were varied from the initial distribution because simulated water levels in low areas near the rivers and streams were too high during calibration.

8.1.5 Streams

Rivers and streams that have been mostly perennial historically were explicitly included in the model using the MODFLOW streamflow routing package. These include the Concho and South Concho Rivers, and Dove and Spring creeks. Because the North Concho River has had no flow recent past, it was modeled using the MODFLOW drain package. Parameters used to model streams include: flow entering the stream from upstream, the stream stage, the streambed hydraulic conductance, and the width and slope of the stream channel, and the Manning's roughness coefficient of the streambed. Calibrated stream flow parameters are shown in Table 8.1.2.

Table 8.1.2 Stream-routing Parameters

Creek or River	Initial Flow (cfs)	Width (feet)	Bed Conductivity (feet/day)	Manning Roughness Coefficient (-)
Concho River	36.55	20	1	0.05
South Concho River	8.43	5	1	0.05
Dove Creek	1.74	5	1	0.05
Spring Creek	1.47	5	1	0.05

8.1.6 General Head Boundaries and Reservoirs

General head boundaries (GHB) were used for the western up-gradient and eastern down-gradient edges of the model area. The locations of GHB cells are shown in Figure 8.1.5. The western edge GHB cells are all assigned an elevation of 2,100-feet, based on published water levels in the Edwards-Trinity (Plateau) (Bush, *et al.* 1993). Elevations of GHB cells on the eastern edge of the model area were developed by extrapolation of observed water levels in the Lipan aquifer to the west and stream gage elevation at Paint Rock   The initial conductivities of the GHB cells were based on neighboring cell hydraulic conductivities and estimated flow properties beyond the edges of the model. Adjustments to these boundaries were made based on the magnitude of simulated gradients near the boundaries and total simulated inflows and outflow at the boundaries.

The MODFLOW reservoir package was used to model reservoirs/lakes in the model area, including Twin Buttes, OC Fisher and Lake Nasworthy. Reservoir cell properties include elevation of the reservoir bottom, thickness and hydraulic conductivity of the reservoir bed, and reservoir stage. Reservoir stage elevations were held at the published conservation levels due to lack of complete data records. To minimize the effects of this boundary, which has not been observed to have a significant influence on water levels, hydraulic properties of the reservoir bed material were set to very low values.   Figure 8.1.6 shows the locations of the three reservoirs and there conservation levels.

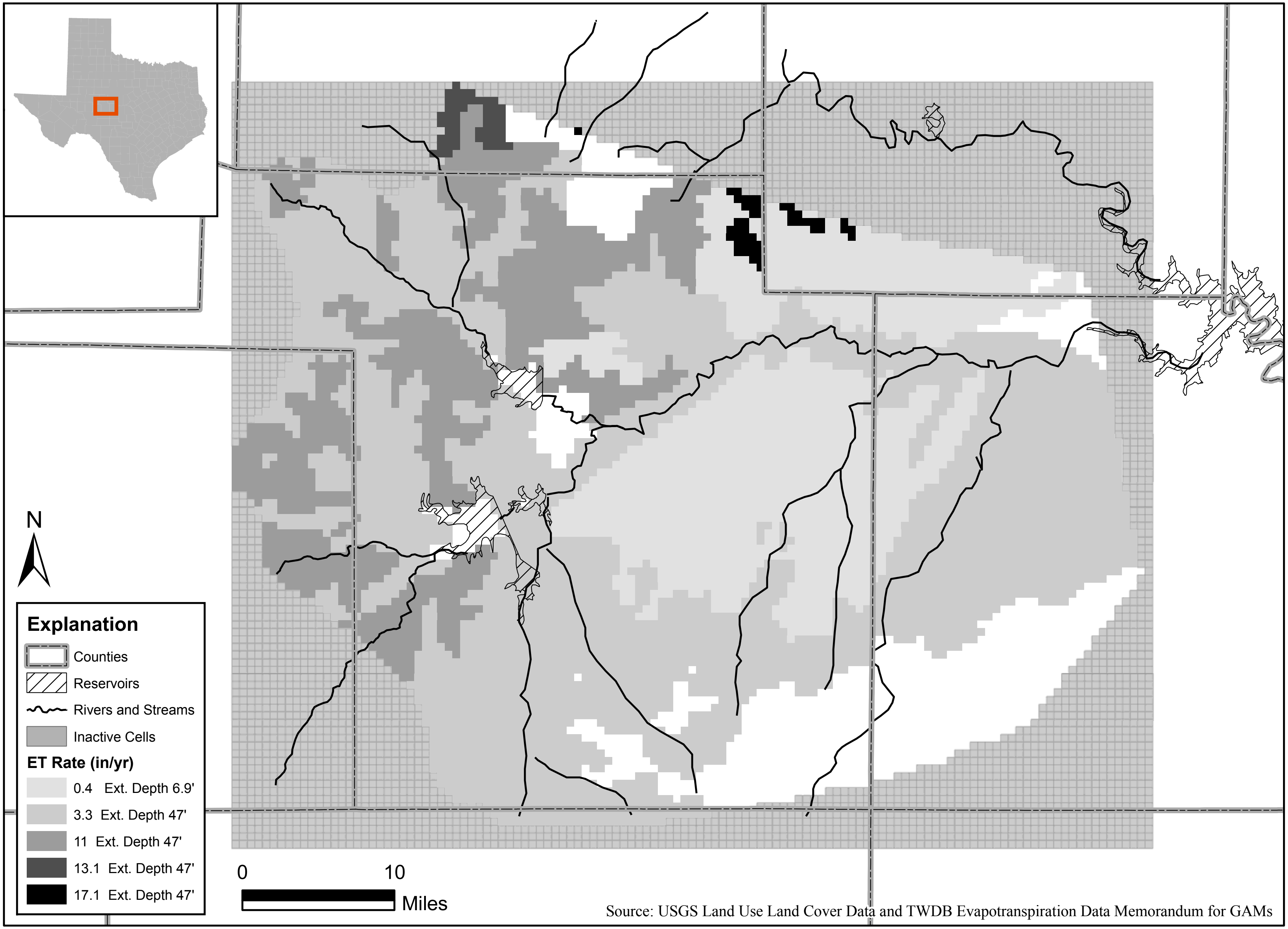

Figure 8.1.4 - Calibrated Evapotranspiration Rates and Extinction Depths

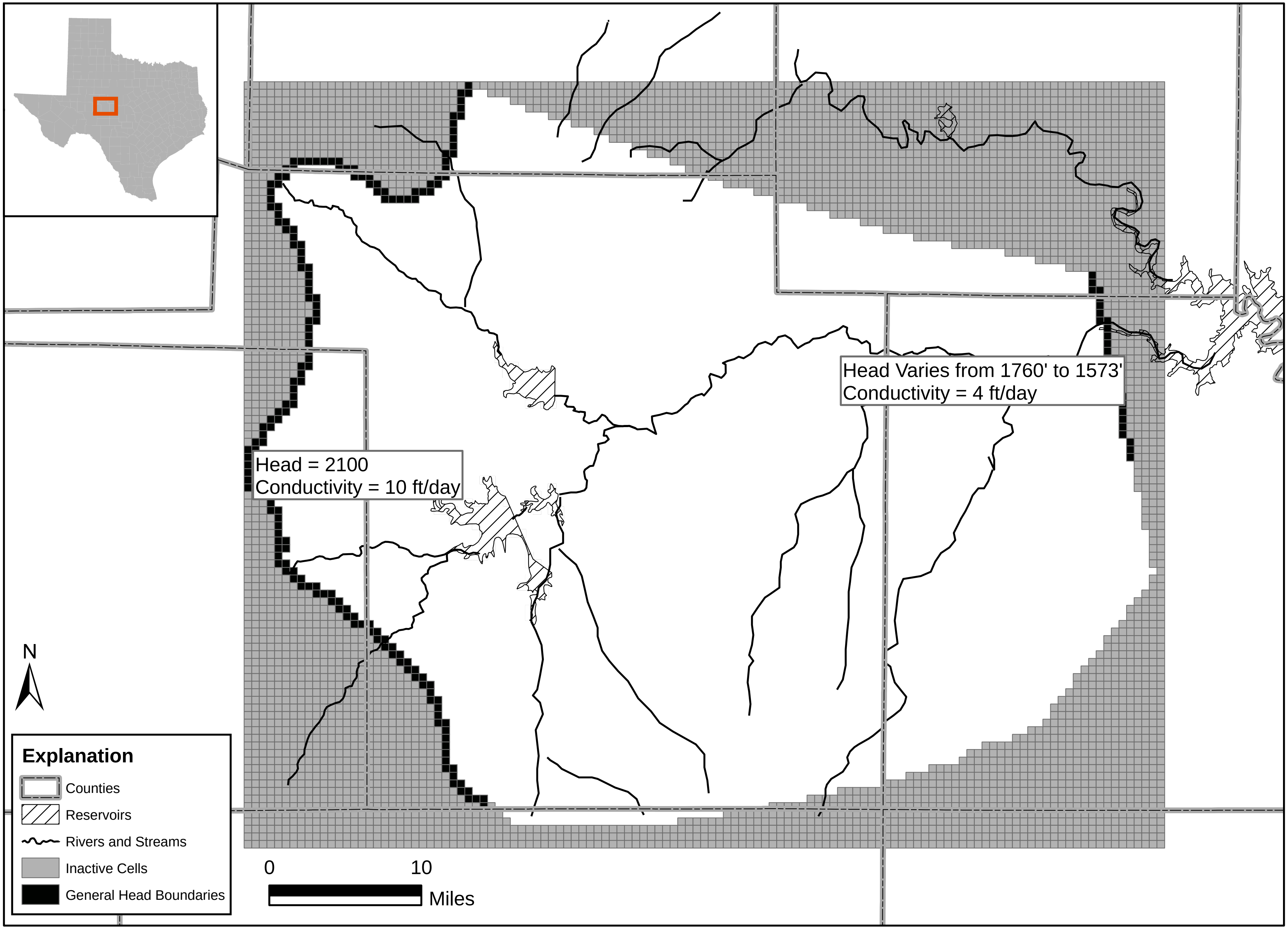

Figure 8.1.5 - Location of General Head Boundaries

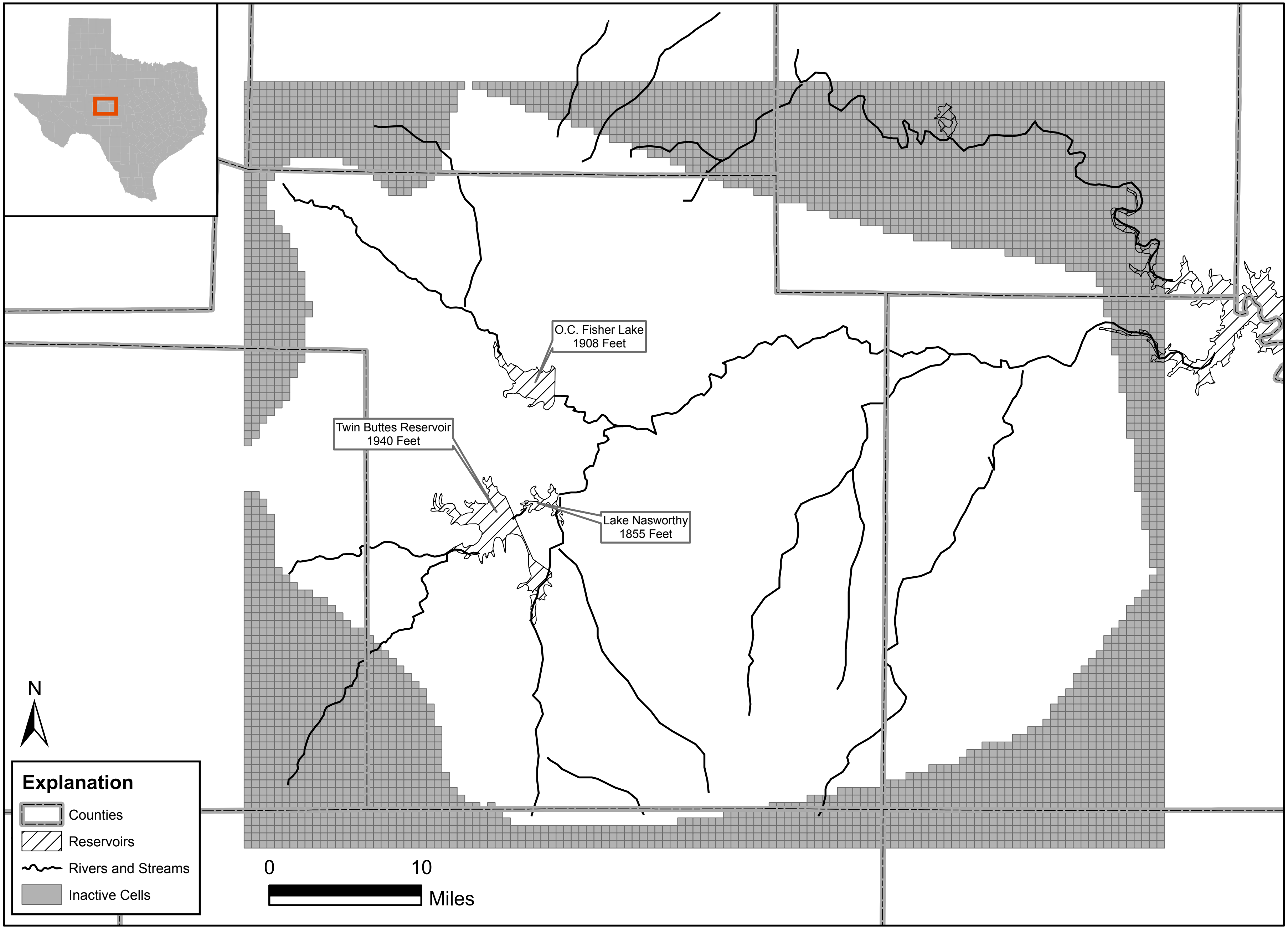

Figure 8.1.6 - Reserviors in Model with Stage Elevations

8.2 Pumping

Because the steady-state period chosen for the Lipan aquifer model was not pre-development but 1980, pumping occurring in 1980 needed to be incorporated into the model. All pumping in 1980 was included in the model and held constant during a 10,000,000 day long stress period to allow the model to approximate steady-state conditions. This approach was required by TWDB GAM protocol.

8.3 Calibration Results

The steady-state model was calibrated to water levels in 1980, which was defined as predevelopment conditions. This section describes calibration results of the steady-state portion of the model.

8.3.1 Hydraulic Heads

Figure 8.3.1 shows a map of the simulated hydraulic head results and residuals from the calibrated steady-state model. Observed heads in this figure differ from Figure 4.3.5 because these contours were created using only the calibration target data points. Calibration target data points were chosen because the observed heads in these wells did not indicate any increasing or decreasing trends. Residuals of less than zero indicate that the simulated head is higher than the measured head, and residuals of greater than zero indicate that the simulated head is lower than the measured head.

Figure 8.3.2 shows a scatter plot of simulated vs. observed hydraulic head for the steady state model calibration. This plot indicates that the calibrated model predicts lower heads higher and higher heads slightly lower. It also indicates that the model calibrates better to the higher water levels than the lower. This is logical because the higher water levels occur near the boundaries of the model where there is less pumping and more model boundary effects.

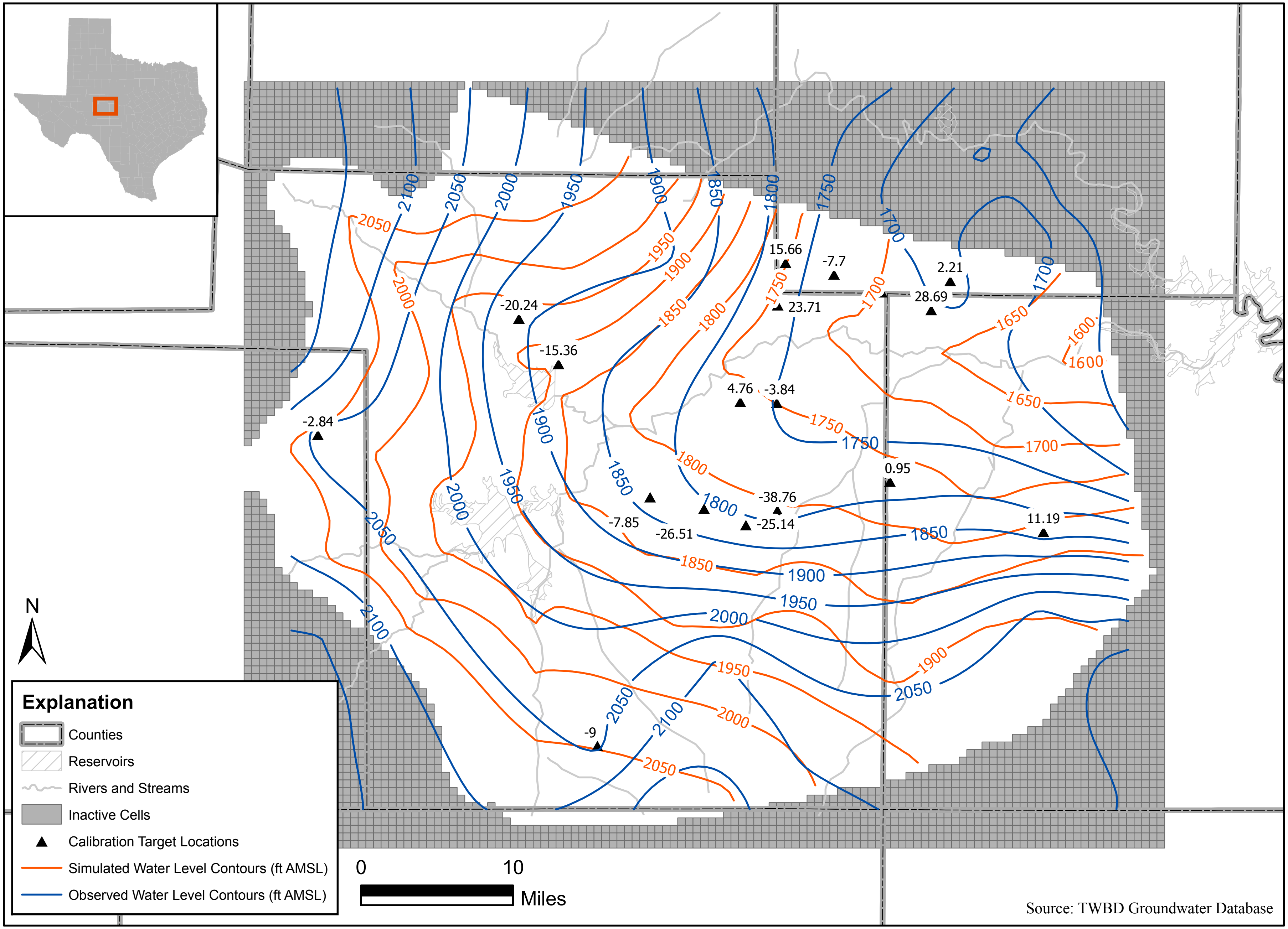

Figure 8.3.1 - Steady-State Simulated and Measured Heads with Posted Residuals

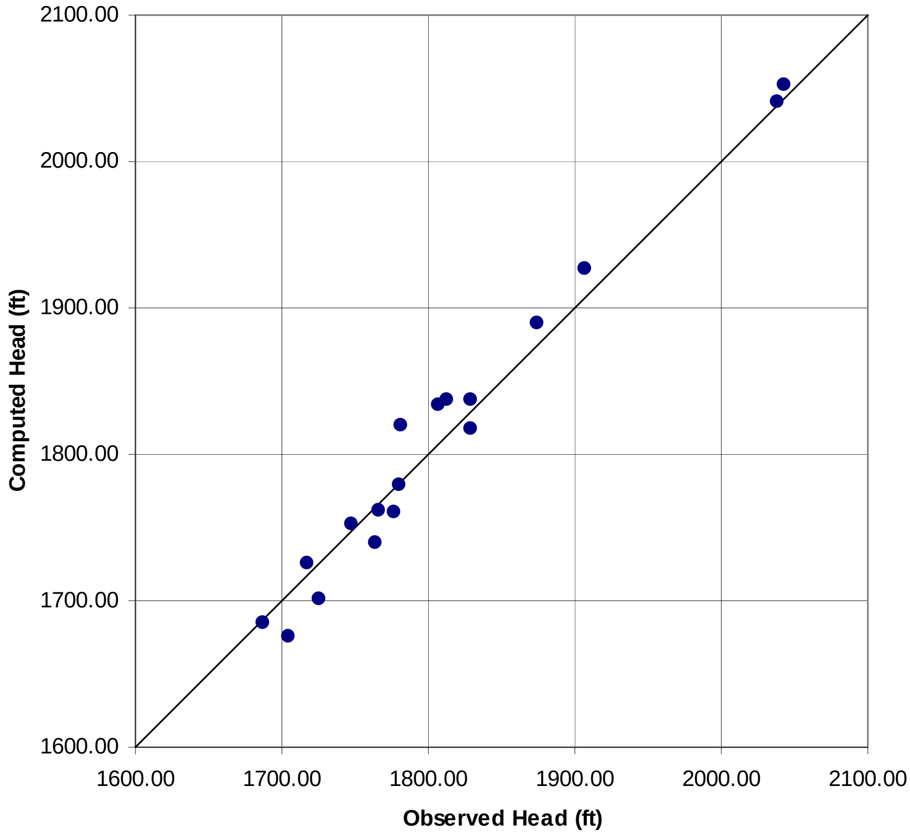

Figure 8.3.2 Scatter Plot of Steady-State Calibration

8.3.2 Streams

A summary of stream flow for the calibrated steady-state model is given in Table 8.3.1. The magnitude of the flow at both the San Angelo gage and the Paint Rock gage are much greater the observed flow at these gages. However, the amount of gain between San Angelo and the Paint Rock is comparable with the observed data. The error in the gain between these two gages is 8%.

Table 8.3.1 Stream Flow Gains and Losses in the Calibrated Model between San Angelo and Paint Rock

Gage Location	Average Minimum Flow (1979-1981) (CFS)	Computed (cfs)	Error (cfs)
San Angelo	8.2	1.5	6.7
Paint Rock	25.0	17.0	8.0
Gain (+) / Loss (-)	16.8	15.5	1.3

8.4 Water Budget

Table 8.4.1 gives a summary of the water budget at the end of the steady state model in terms of total volume as well as a percentage of total inflow and outflow. As indicated in this table, the model predicts that recharge is the dominant source of water to the Lipan aquifer. According to the calibration results, evapotranspiration accounts for more than 50% of the groundwater outflow in the steady-state model. For the steady-state calibration, well discharge was 10,245 acre-feet / year.

Table 8.4.1 Summary of Water Budget for the Steady-State Calibration Model

Component	Inflow (acre-feet/year)	Percent of Inflow	Outflow (acre-feet/year)	Percent of Outflow
Storage	0	0.0%	0	0.0%
GHBs	14,407	14.6%	4,478	4.4%
Recharge	63,311	64.2%		
ET			58,593	57.0%
Wells			10,678	10.3%
Drains			5,838	5.7%
Reservoirs	12,429	12.6%	3,600	3.5%
Streams	8,505	8.6%	19,694	19.1%
Total	98,652	100.0%	102,881	100.0%

Figure 8.4.1 shows a graph of all of the budget components for the steady state model. As this figure indicates, evapotranspiration is the dominant outflow component of the model and recharge is the dominant inflow. The total inflow and outflow quantities are virtually identical, resulting in a mass balance error of less than 0.01 %. Areas of active evapotranspiration in the steady-state model are shown in Figure 8.4.2.

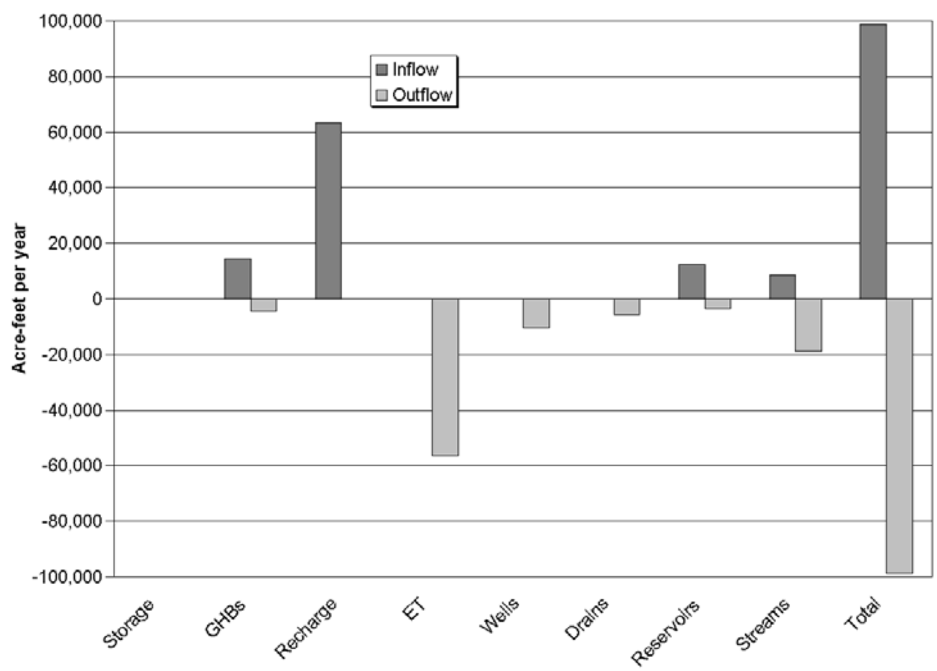

Figure 8.4.1 Summary of Water Budget for the Steady-State Calibration Model

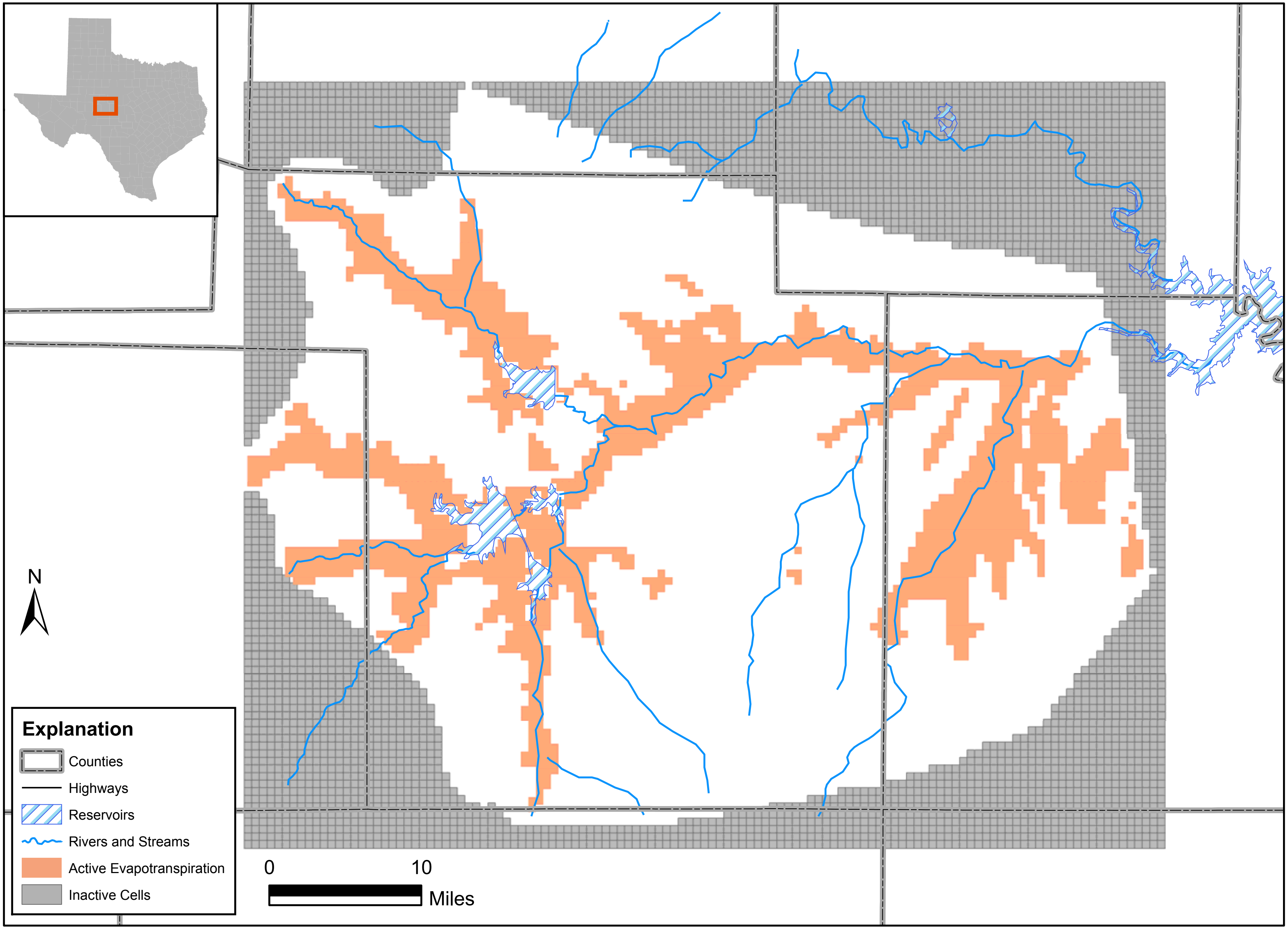

Figure 8.4.2 - Area of Active Evapotranspiration in the Steady-State Model

8.5 Calibration Statistics

The TWDB has several requirements for the calibration of the model that must be met. These include:

1) The difference between the total simulated inflow and the total simulated outflow (that is, the water balance) shall be less than one percent, and ideally less than 0.1 percent.

2) Root mean square error between measured hydraulic head and simulated hydraulic head shall be less than ten percent of the measured hydraulic head drop across the model area and better if possible. The error shall not be biased by areas with considerably more control points than other areas.

3) Final calibration results shall report the root mean square error, the mean absolute error, and the mean error.

Table 8.5.1 lists the calibration statistics for the steady-state calibration. As this table shows, the calibrated model meets the specified criteria the specified criteria for calibration. The mean error of -2.5 indicated a slight bias for the model to produce higher water levels globally.

Table 8.5.1 Calibration Statistics for the Steady-State Model

Number of Observations	18
Mean Error (feet)	-2.5
Standard Deviation Error (feet)	18.2
Sum of Squares Error (feet^2)	6,085
Mean Absolute Error (feet)	14.9
Min. Residual (feet)	-38.7
Max. Residual (feet)	28.6
Range of Observed Heads (feet)	355
RMSE (feet)	18.4
% RMSE / Range (%)	5.0

8.6 Sensitivity Analysis

A sensitivity analysis was performed on the calibrated steady-state model to provide a summary of the sensitivity of the model to changes in individual input parameters or groups of parameters. In the sensitivity analysis, the model parameters were globally adjusted from their calibrated values and the results of these changes on the water levels and fluxes in the model were recorded. The model parameters were adjusted +/- 10% and +/- 20% from their calibrated value. This analysis quantifies the uncertainty of the calibrated model to the uncertainty in the estimates of aquifer parameters, stresses, and boundary conditions, and offers insight into the non-uniqueness of the calibrated model. A sensitivity analysis also identifies which hydrologic parameters most influence the hydrologic system being modeled and can justify parameters that justify future study. A summary of the sensitivity analysis is given below.

Model parameters included in the sensitivity analysis of the steady-state calibration model include: hydraulic conductivity, recharge, evapotranspiration rate and extinction depth, and general head boundary conductance and well discharge. Figure 8.6.1 shows a graph of the steady-state model sensitivities to changes in these parameters. As seen in this graph, increasing hydraulic conductivity causes the average change in head across the model to be less. This indicates that model responses to stresses become less when higher hydraulic conductivities are used. Conversely, this graph shows that as recharge rates are increased, model responses to stresses are more muted. According to this graph, a change in general head boundary conductance has very little affect on the average head change in the model.

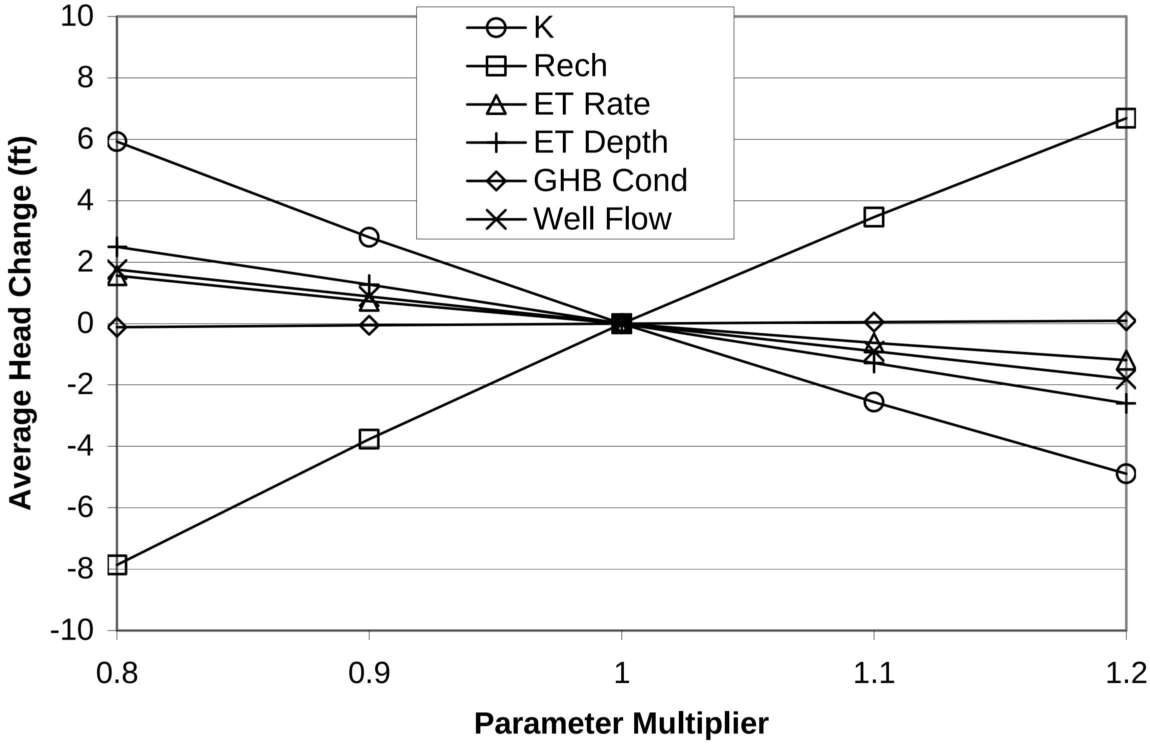

Figure 8.6.1 Result of Sensitivity Analysis of the Steady-State Model

9.0 TRANSIENT MODEL

This section describes the calibration and verification of the transient model for the Lipan aquifer and presents transient model results. As specified by the TWDB, the period from 1980 to 1999 was the focus of the transient portion of the modeling effort because of the greater certainty on historical pumping. The time period of 1980-1989 was used for the calibration phase of the model, and the time period of 1990-1999 was used for the verification phase of the model. This section also details the sensitivity analysis done on the transient model and the sensitivity of this model to various model input parameters.

9.1 Calibration

As discussed above in Section 8.2, many of the model input parameters in the steady state model are the same as in the transient model, and therefore a discussion of these input parameters will not be repeated here. One parameter that is not included in the steady-state model is specific yield. Several other input parameters were varied over time in the transient model including pumping and recharge. A detailed discussion of these parameters is included in this section.

9.1.1 Calibration Targets

Measured water levels in the Lipan aquifer between 1980 and 1999 were used in the calibration of the transient model. Figure 9.1.1 shows the locations of the wells with water levels that were used for the transient calibration. Thirty-three wells with water level measurements in the transient calibration and verification periods were considered acceptable for use in the transient model calibration.

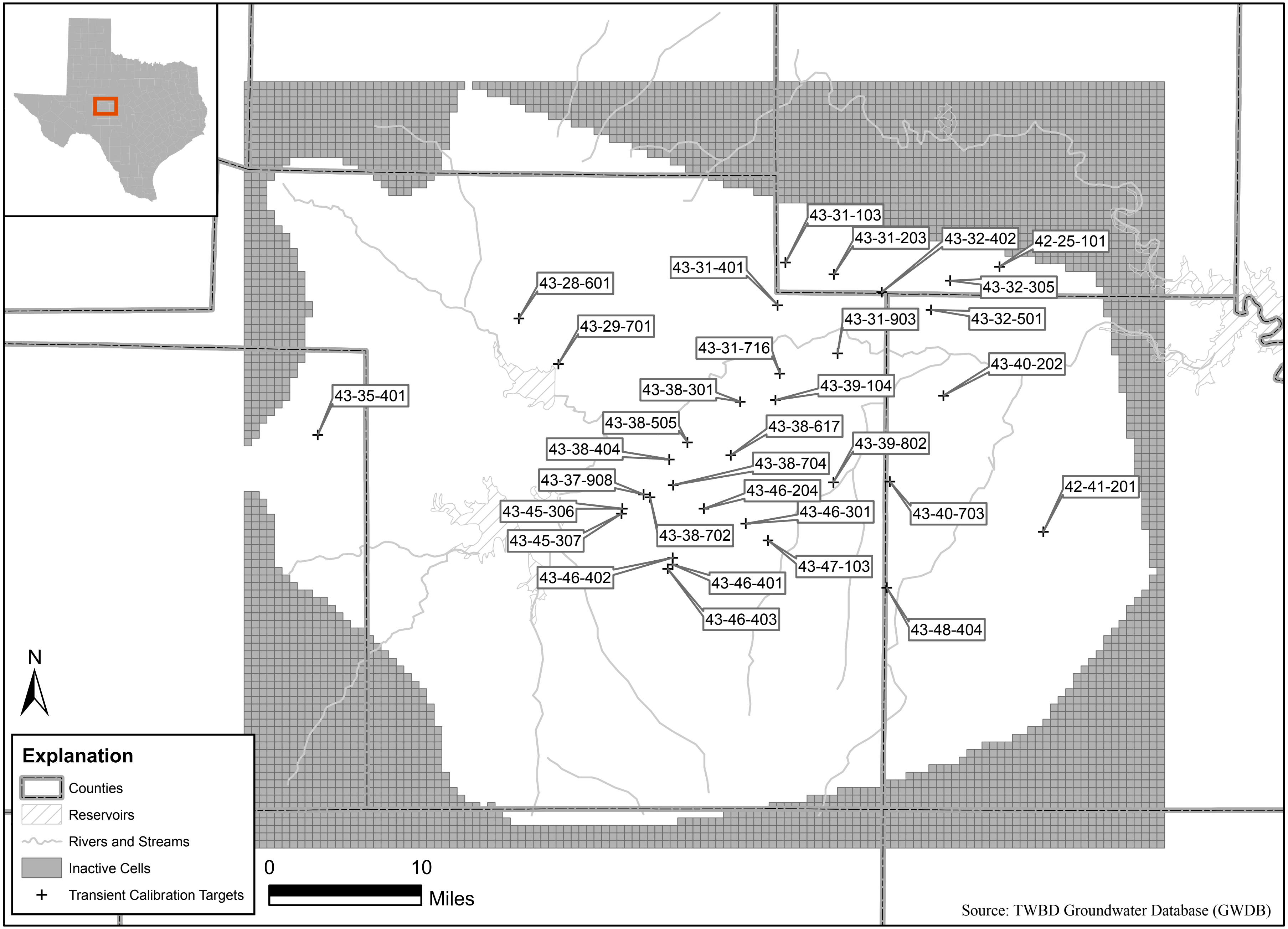

Figure 9.1.1 - Transient Calibration Target Locations

All of the wells used for transient calibration targets were completed in the Lipan aquifer. Some of them were completed in the Permian rocks of the Lipan with other completed in the alluvial portion. Water level responses to pumping varied spatially in the aquifer. Some of this is due to the completion of the well being measured and some due the wells proximity to pumping and physical boundaries such as rivers and creeks.

9.2 Specific Yield

Specific yield is an important part of a transient model. By definition, a steady-state model is a model where no change in aquifer storage occurs. By contrast, in a transient model, aquifer storage can have major effect on water levels and responses to groundwater pumping. In transient models, external model stresses, such as pumping, recharge, and other boundary conditions, can vary over time to represent conditions observed in the aquifer.

The final distribution of specific yield in the Lipan model is shown in Figure 9.2.1. A single storage value of 0.005 was used for the majority of the model, except for the two areas with higher hydraulic conductivity in the Lipan Flats area of the Model, which had a specific yield of 0.05.

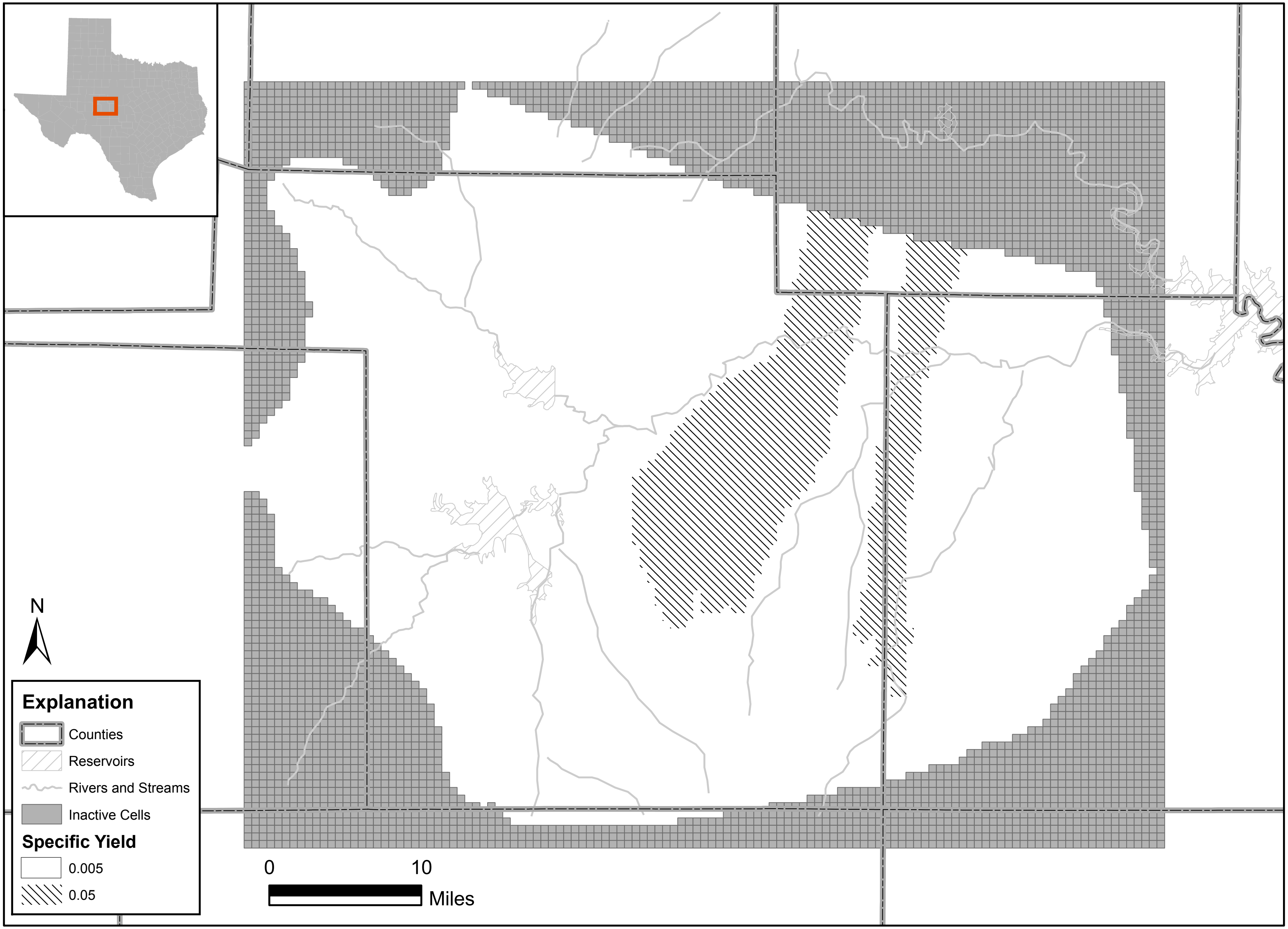

Figure 9.2.1 - Distribution of Calibrated Specific Yield

9.3 Recharge

Recharge to the transient calibration and verification model was varied over time based on a percentage of observed annual precipitation in the model area. Recharge rates were determined by creating a factor relating to the actual precipitation observed in a year to the average precipitation over the period from 1980 to 2000. This factor was multiplied to the average recharge used in the steady-state portion of the model on a year-by-year basis. Recharge factors for 1980 through 1999 are given in Table 9.3.1.

Table 9.3.1 Transient Recharge Multiplication Factors

Year	Recharge Multiplier
1980	1.20
1981	1.27
1982	1.00
1983	0.75
1984	0.90
1985	0.97
1986	1.51
1987	1.34
1988	0.72
1989	0.82
1990	1.32
1991	1.41
1992	1.17
1993	0.75
1994	0.95
1995	1.09
1996	0.78
1997	1.08
1998	0.66
1999	0.55

9.4 Calibration Results

As described in Section 8, the calibration of the transient model was iterative, and was coordinated with the calibration of the steady state model. The calibration was divided up into two periods, a calibration phase (1980-1989), and a verification phase (1990-1999). This section will describe the results of the calibration phase of the model and then detail how the model performed in the verification phase. The criteria for selecting transient calibration and verification targets was 1) wells completed in the Lipan aquifer, 2) wells had a good record of data for the calibration and verification time, and 3) the wells were spatially distributed to represent most of the active model domain. Contours of the target data are depicted in the calibration and verification figures. The contours in these figures differ from Figures 4.3.6 and 4.3.7 because only a select set of the overall water level data, specifically the target data, was used to develop these contours.

9.4.1 Calibration Phase

The time period of 1980 to 1989 was specified for the calibration of the groundwater model. During calibration, particular attention was paid to accurately representing water levels and fluxes during drought conditions and in areas with large drawdown. The range of water-level fluctuations in the observation wells was matched as closely as possible during the calibration period. The calibration and verification phases of the model were run and calibrated concurrently, and therefore any changes to the model input parameters made for the calibration portion of the simulation applied to the verification portion of the simulation.

9.4.1.1 Hydraulic Heads

Figure 9.4.1 shows the simulated and measured hydraulic heads in the Lipan aquifer at the end of 1989 with the residuals posted at the measured location. This map indicates that the flow directions, head elevations and gradients are all within general agreement. Residuals of less than zero indicate that the simulated head is higher than the measured head, and residuals of greater than zero indicate that the simulated head is lower than the measured head. As indicated in these figures heads in the Lipan

A plot of simulated versus observed heads is shown in Figure 9.4.2. This figure indicates that model results are match observed data fairly well. In some areas, heads appear to be significantly off, however, the overall gradient and flow direction of the observed and simulated heads match pretty well.

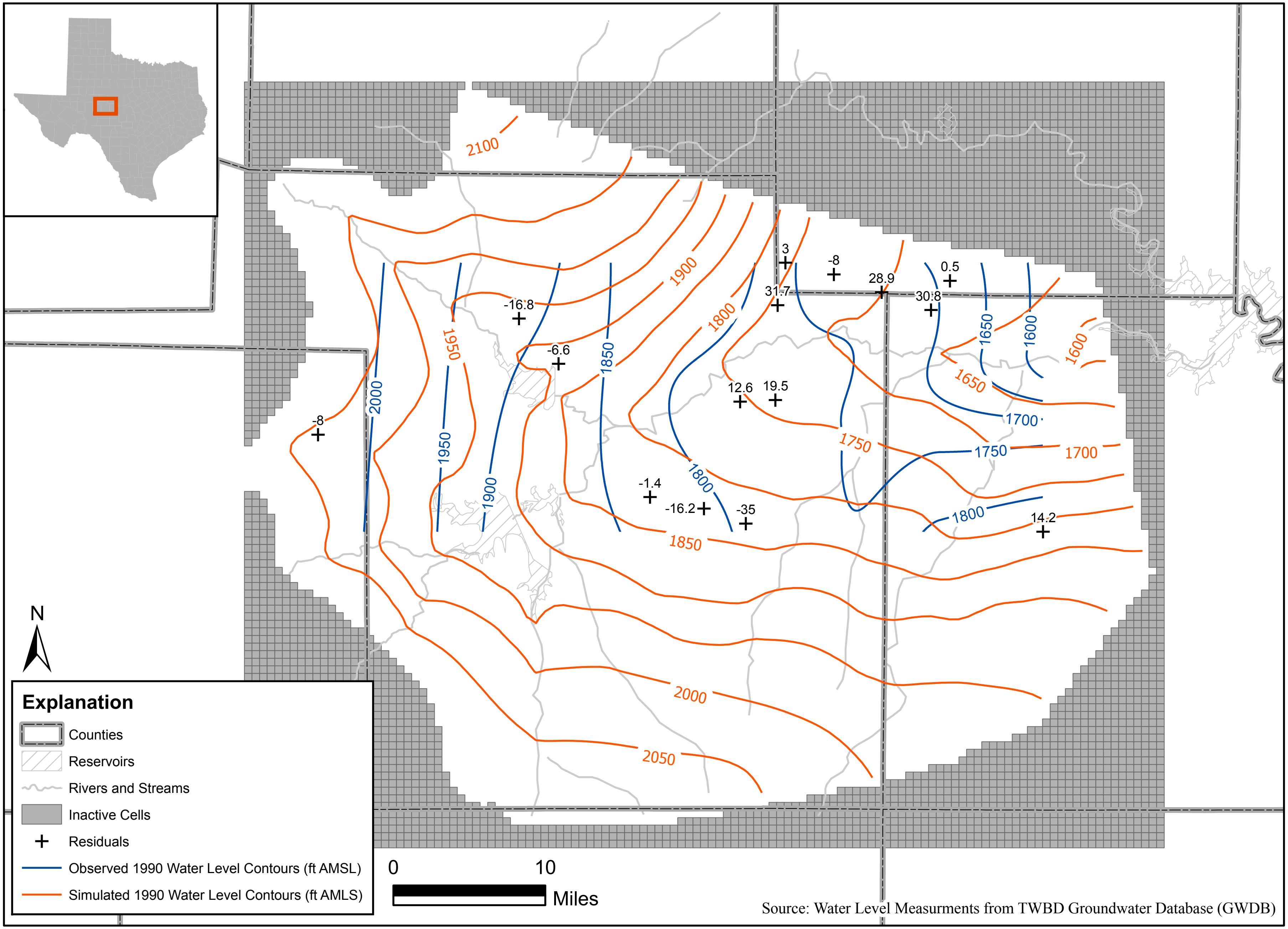

Figure 9.4.1 - Simulated and Observed Heads for Transient Calibration with Posted Residuals

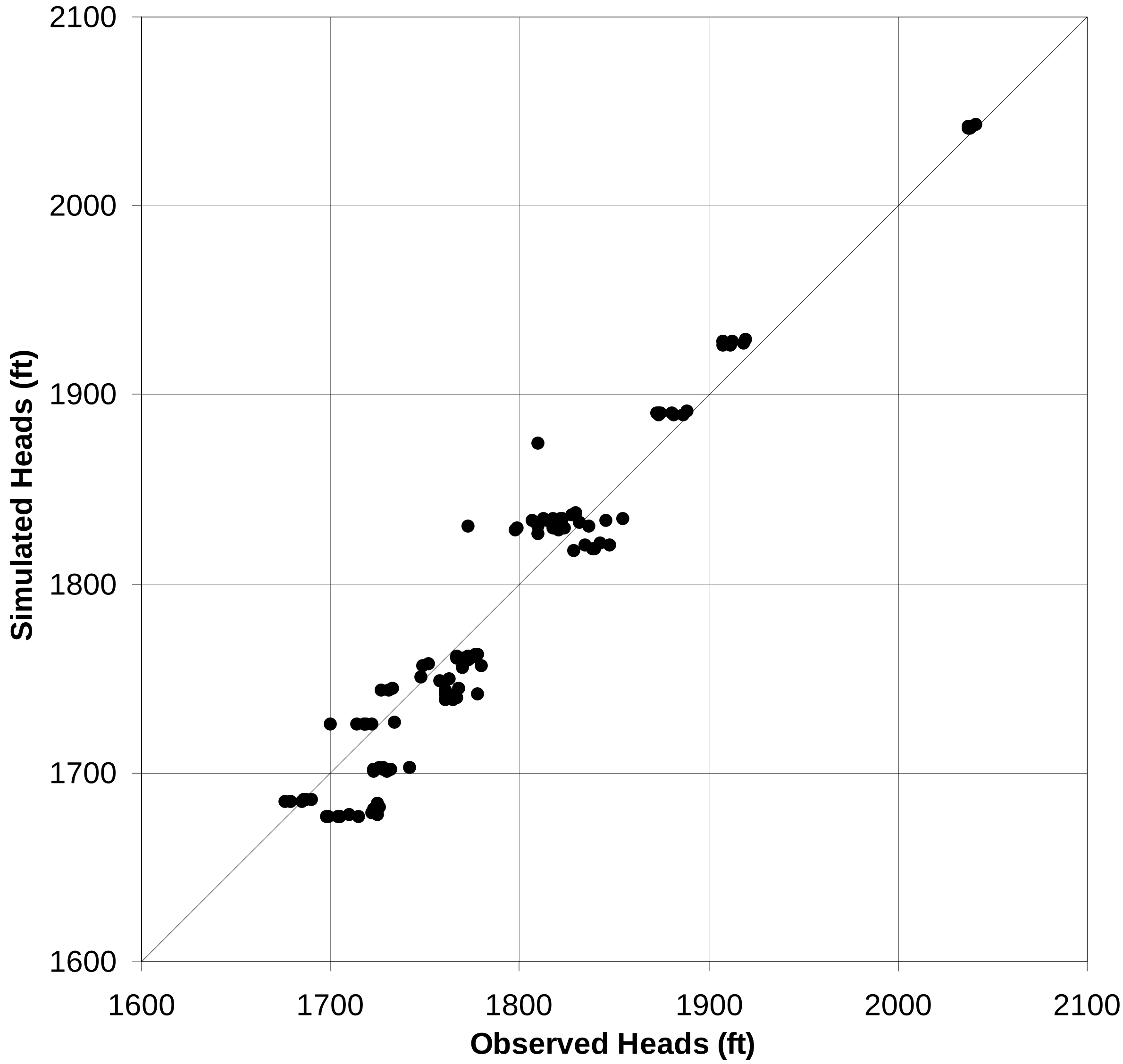

Figure 9.4.2 Observed versus Simulated Heads at the end of the Calibration Period

Table 9.4.1 lists the calibration statistics for the end of the calibration period. The mean residual of 4.68 indicates that the model predicts water level higher than measured however, the percent RMS error over the observed range in heads still meets the calibration criteria.

Table 9.4.1 Transient Calibration Statistics

Number of Observations	124
Mean Error (feet)	4.7
Mean Abs Error (feet)	17.5
Std Deviation of Error (feet)	20.9
Sum of Squares (feet^2)	56,416
Min Residual (feet)	-64.4
Max Residual (feet)	46.4
Range in Observed Head (feet)	365
RMSE (feet)	21.3
RMSE / range (%)	6.0

9.4.2 Verification Phase

The verification phase of the transient calibration modeling of the Lipan aquifer is designed to validate the calibration. Because there is much more water level data available for the verification time frame, from 1990 through 1999, verification of the model became an iterative process. In addition, groundwater pumping dramatically increased in nineties with the advent of new irrigation methods and decreasing precipitation.

When a suitable transient calibration was attained, the model was then run using data compiled for the 1990s including pumping and precipitation. Model results were then compared against measured data in the 1990s to determine the validity of the model. If simulated values in the verification did not match measured value, the model parameters were adjusted and the model was recalibrated. The model was considered calibrated when model statistics for both the eighties and the nineties met with the TWDB mandated calibration criteria.

9.4.2.1 Hydraulic Heads

Figure 9.4.3 shows the simulated and measured hydraulic heads in the Lipan aquifer at the end of the verification period, with model residuals posted. This figure indicates that the model is reproducing heads and gradients reasonably. In some areas, mostly in the Lipan Flats area, the model is predicting heads higher than observed. This would indicate that the hydraulic conductivity was too high allowing more water to move through the aquifer with less head change. However, decreasing the conductivity of the zones in which these wells are situated causes heads in other places in the model to become unreasonable.

A plot of simulated versus observed heads for the verification period is shown in Figure 9.4.4. This plot shows that the model is matching heads well globally with little or no bias high or low. At higher heads, the model is slightly biased high. Also, there is an area in the center of the graph that indicates that portions of the heads are higher than the observed heads. However, there is generally a good distribution of heads about the fit line (where observed = simulated). Table 9.4.2 shows the model statistics for the verification simulation.

Table 9.4.2 Transient Verification Statistics

Number of Observations	538
Mean Error (feet)	1.8
Mean Abs Error (feet)	16.6
Std Deviation of Error (feet)	21.9
Sum of Squares (feet^2)	259,905
Min Residual (feet)	-79.6
Max Residual (feet)	59.5
Range in Observed Head (feet)	369
RMSE (feet)	22.0
RMSE / Range (%)	6.0

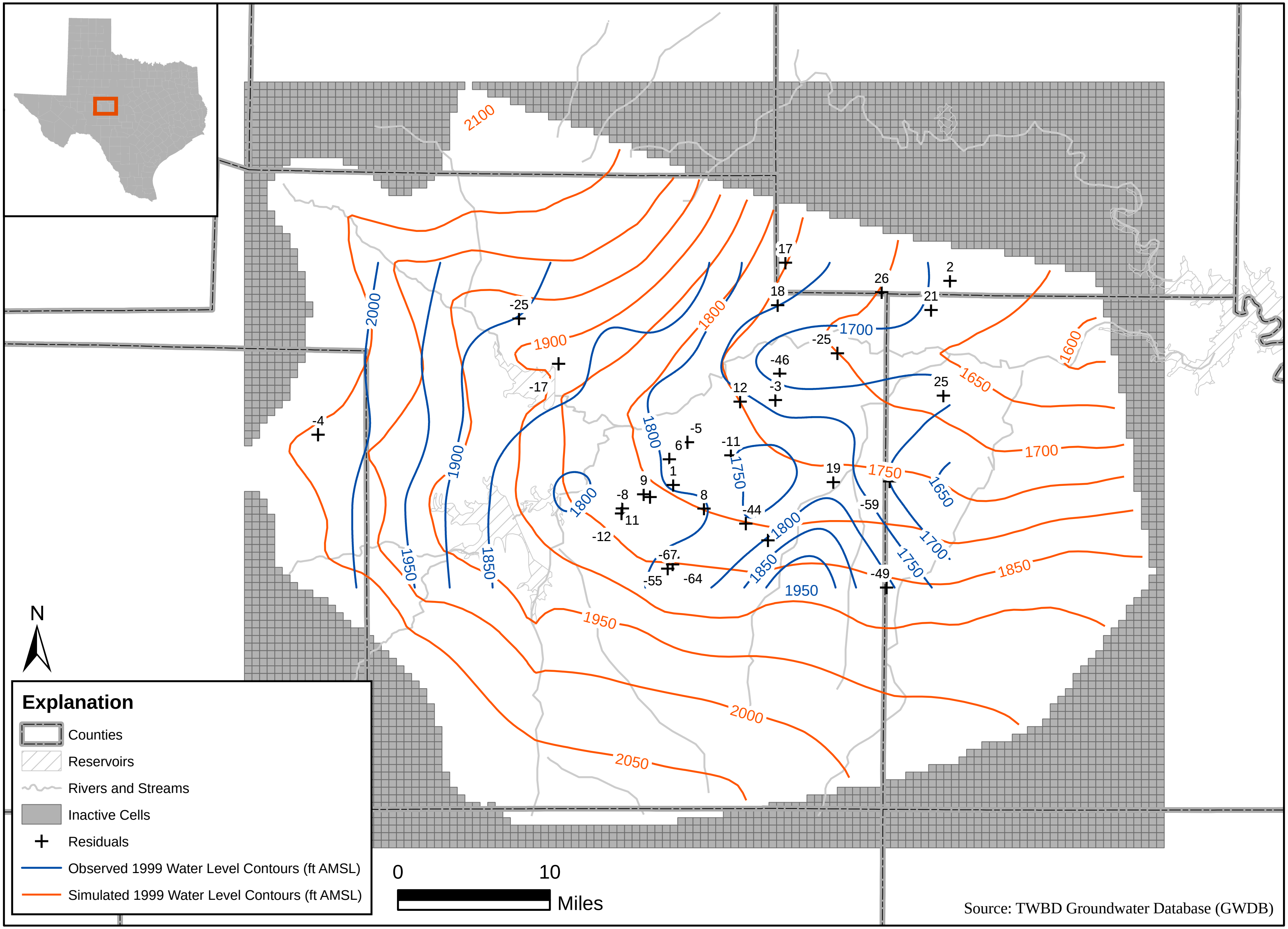

Figure 9.4.3 - Transient Verification Heads in 1999 with Posted Residuals

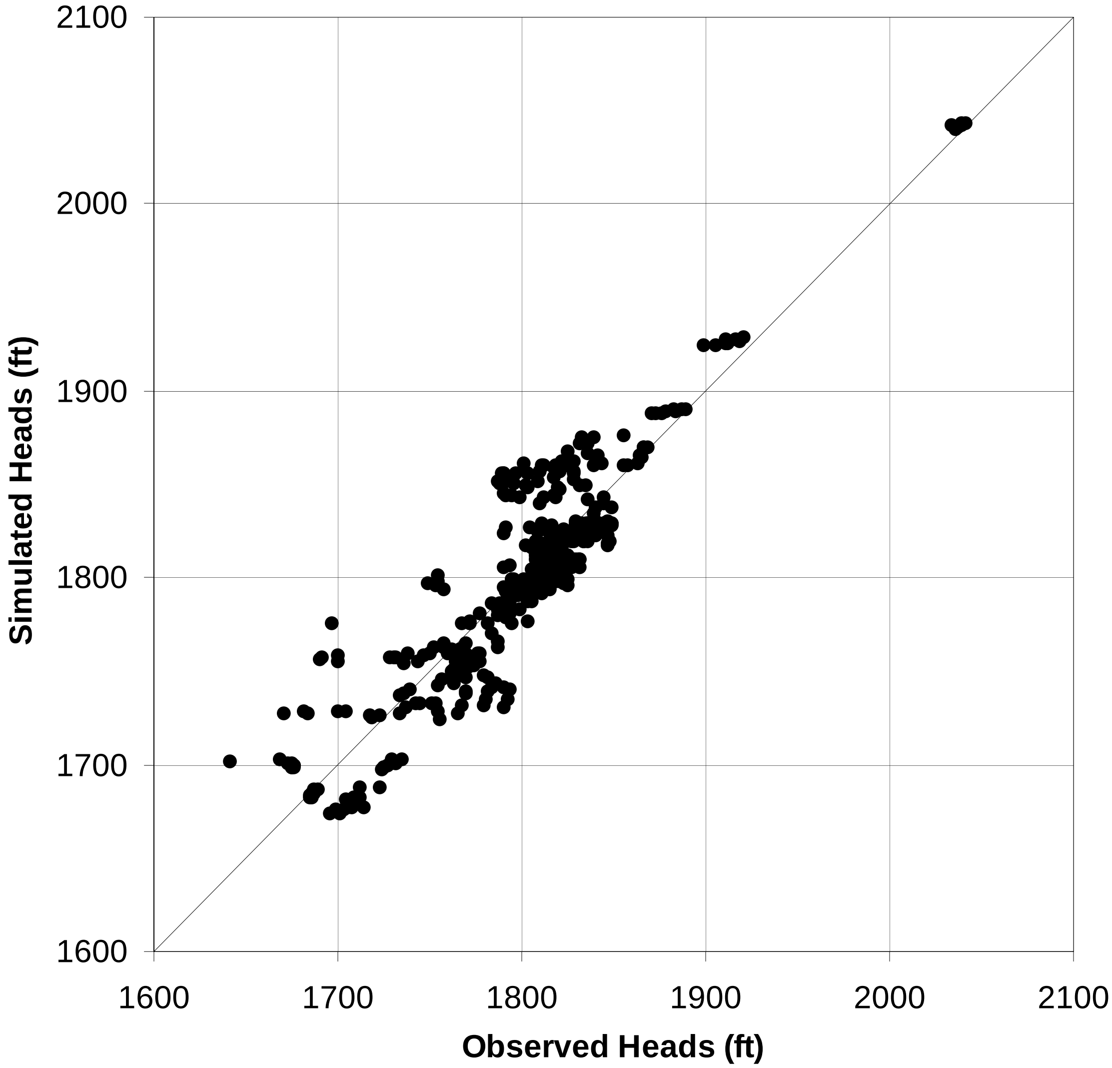

Figure 9.4.4 Simulated Versus Observed Data For The Verification Period

Figure 9.4.5 shows the change in hydraulic heads in the Lipan aquifer from steady-state to the end of the verification period (December 1999). This figure indicates drawdown in the model is occurring mainly in the Lipan Flats area, with a maximum drawdown of 39 feet. The majority of the irrigation pumping has historically occurred in this area. The Concho River appears to act as a barrier to the progression of drawdown to the north.

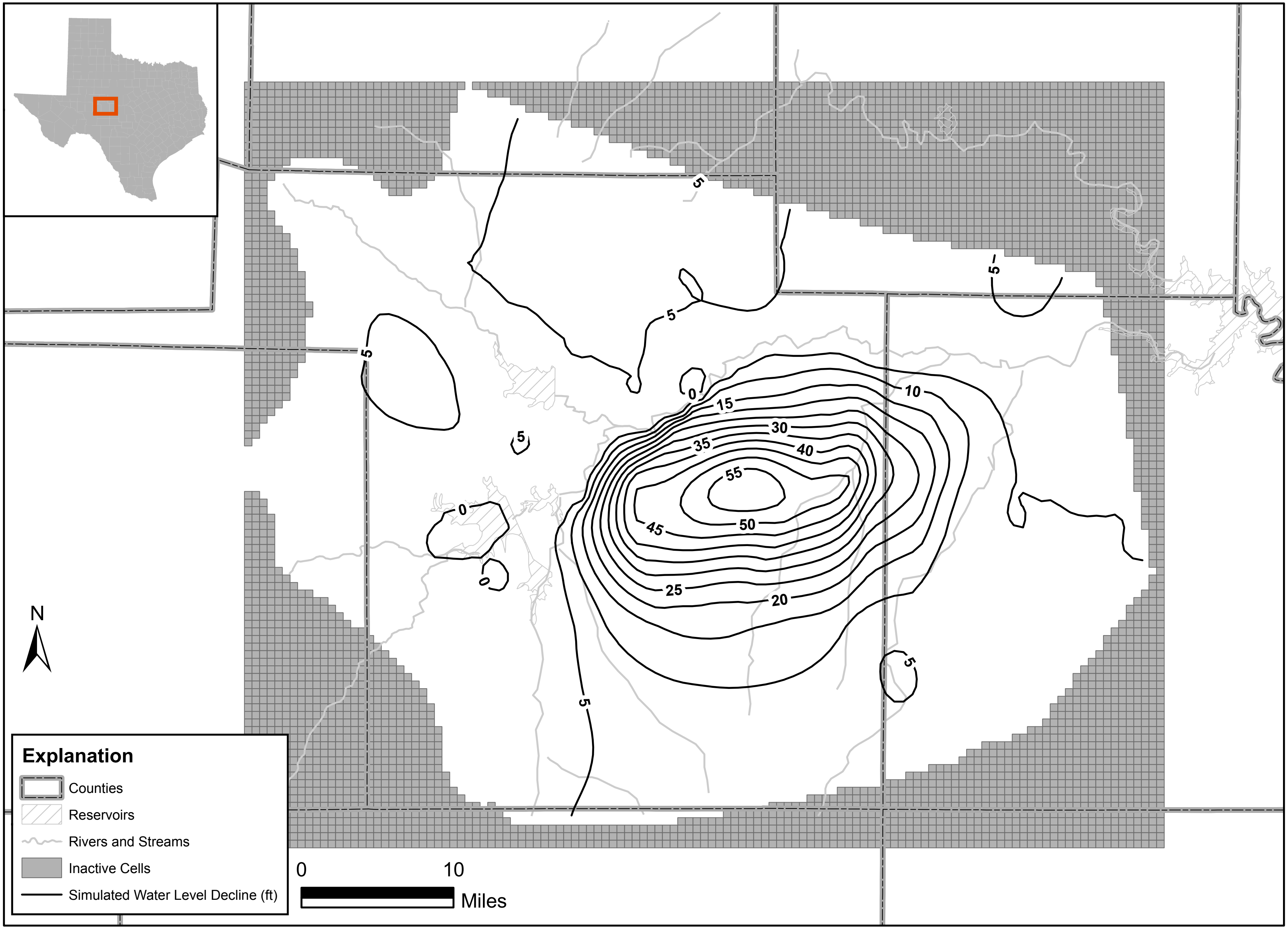

Figure 9.4.5 - Water Level Decline from Steady-State (1980) to the End of Verification (1999)

9.5 Hydrographs

Several hydrographs of observed and simulated heads in the Lipan aquifer during transient calibration and verification are shown in Figures 9.5.1, 9.5.2 and 9.5.3. Those hydrographs show that the transient calibration is fitting some well responses very well, while it not simulating other quite as well. This is partly because a numerical model is a simplification of actual hydrologic conditions. While overall model flow directions, head changes and gradients match pretty well, values at specific well location may not match that well. This does not indicate a poorly constructed or calibrated model as this model is not designed for accurate representation at the scale of individual wells.

In general, heads in the Lipan Flats area of the model seem to respond similarly to the observed heads in this area. Because most of the water produced from the Lipan aquifer comes from this area, matching head responses and water levels here is a priority. Also, heads near the edges of the modeled aquifer, or near model numerical boundaries, may be adversely affected. Wells distal from model boundaries were preferable to wells near the boundaries, however, due to the limited data available during calibration and verification, some of the wells near the boundaries were used.

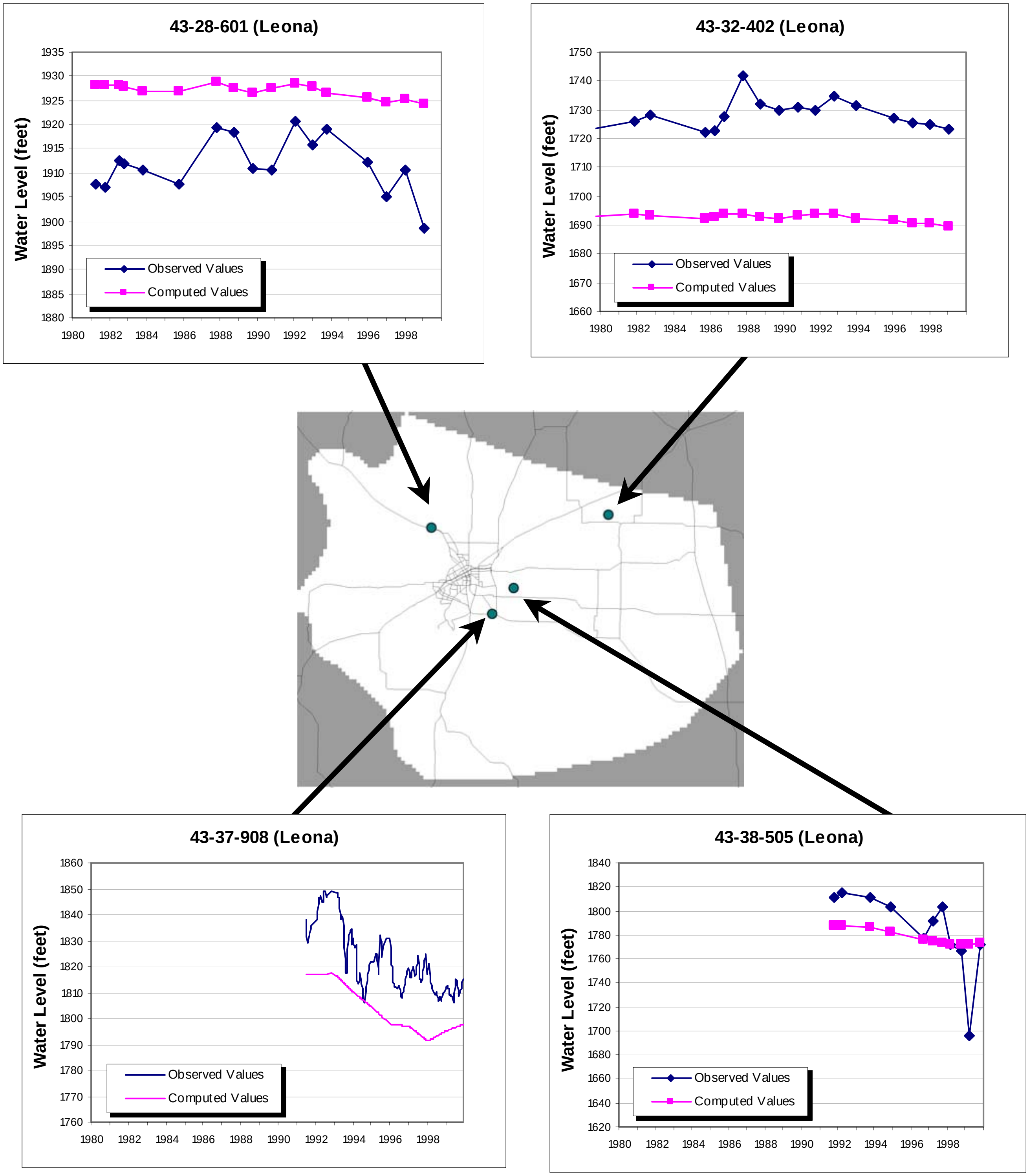

Figure 9.5.1 Selected Hydrographs in the Lipan Aquifer during Transient Calibration and Verification (1)

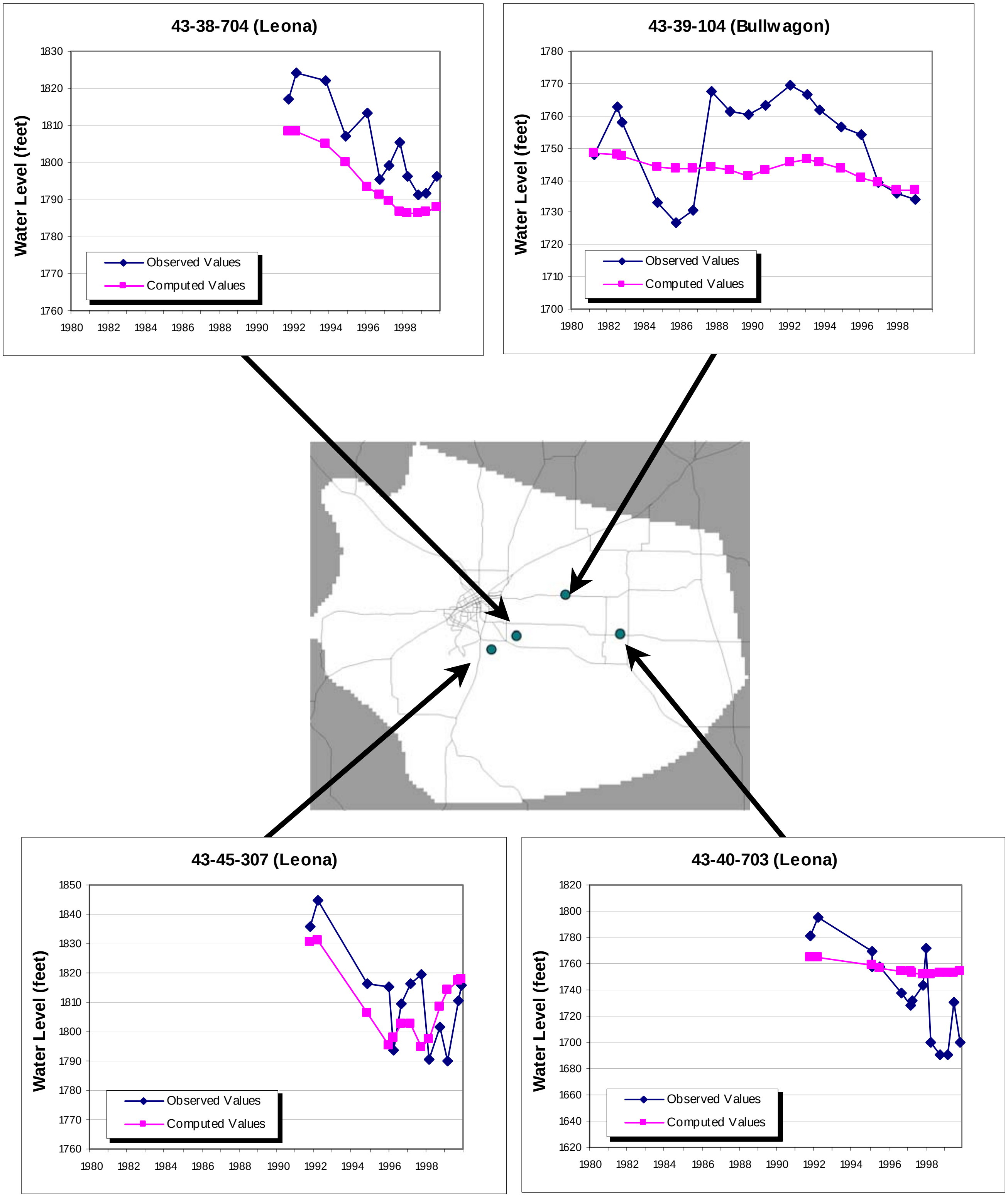

Figure 9.5.2 Selected Hydrographs Continued (2)

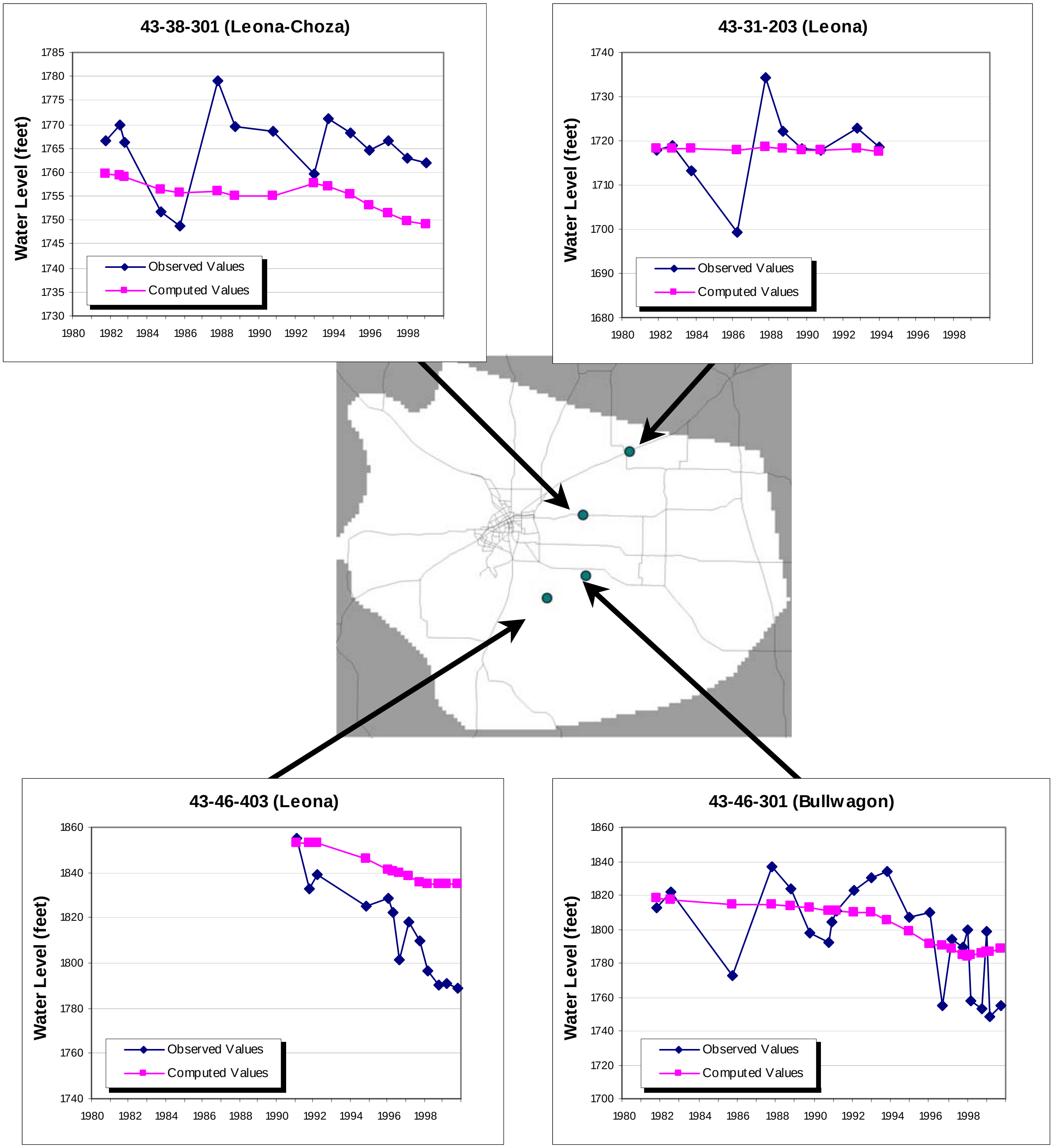

Figure 9.5.3 Selected Hydrographs Continued (3)

9.6 Water Budget for Calibration and Verification Model

Table 9.6.1 gives a summary of the water budget at the end of the calibration and verification period in terms of total volume as well as a percentage of total inflow and outflow. As indicated in this table, the overall mass balance error is lest than 0.01 percent indicating that a good model solution was achieved. A low mass balance error does not indicate a good model calibration, but it does mean that the model results are adequate be used in determination of the calibration.

The budget analysis indicates several facts about the transient calibration and verification model. Although the specific yield input values are relatively small, the storage component of the water balance is a significant amount. As was noted in the steady-state calibration model, recharge is the main inflow component of the model and ET is the largest outflow component.

Table 9.6.1 Water Budget at the End of Calibration / Verification in 1999

Component	Inflow (acre-feet/year)	Percent of Inflow	Outflow (acre-feet/year)	Percent of Outflow
Storage	13,065	14.7%	11,518	12.9%
GHBs	16,232	18.2%	3993	4.5%
Recharge	35,297	39.7%		
ET			49,060	55.1%
Wells			3,273	3.7%
Drains			4,560	5.1%
Reservoirs	12,835	14.4%	3,132	3.5%
Streams	11,577	13.0%	13,477	15.1%
Total	89006	100.0%	89,013	100.0%

Figure 9.6.1 shows a graph of all of the budget components for each year during the calibration and verification phase of the model. As seen in this figure, when pumping dramatically increased in the mid- to late-nineties, more water was released from storage and the water removed through ET declined due to declining water levels. Also contributing to the declining water levels is the reduced recharge due to the beginning of the drought as seen in this figure.

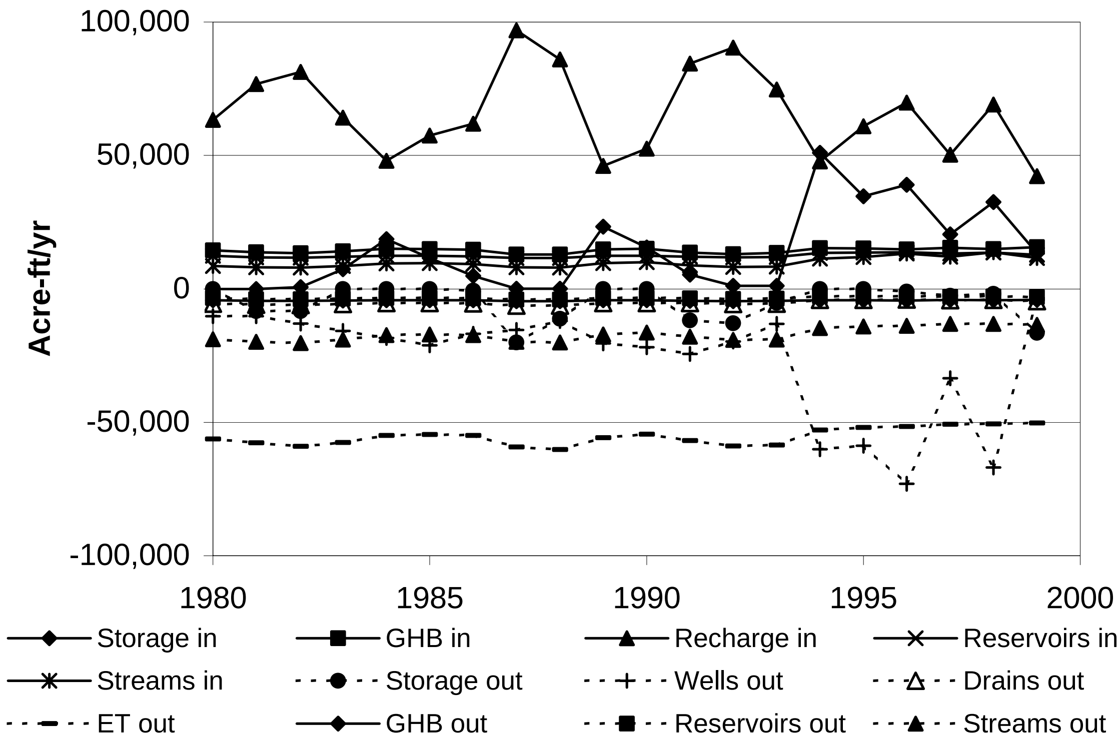

Figure 9.6.1 Water Balance for the Transient Calibration and Verification Model

9.7 Sensitivity Analysis

A sensitivity analysis was performed on the calibrated/verified transient model to provide a summary of the sensitivity of the model to changes in individual input parameters or groups of parameters. In the sensitivity analysis, the model parameters were globally adjusted from their calibrated values and the results of these changes on the water levels and fluxes in the model were recorded. The model parameters were adjusted +/- 10% and +/- 20% from their calibrated value. This analysis quantifies the uncertainty of the calibrated model to the uncertainty in the estimates of aquifer parameters, stresses, and boundary conditions, and offers insight into the non-uniqueness of the calibrated model. A sensitivity analysis also identifies which hydrologic parameters most influence the hydrologic system being modeled and can justify parameters that justify future study. A summary of the sensitivity analysis is given below.

For the transient model, all of parameters used in the steady-state sensitivity analysis were used, along with specific yield. These include: hydraulic conductivity, recharge rate, ET rate and extinction depth, general head boundary conductance, well pumping and specific yield. Figures 9.7.1, 9.7.2, and 9.7.3 show the results of the sensitivity analysis for ET extinction depth, hydraulic conductivity and recharge at four wells in the model area. These figures indicate that the transient model is most sensitive to recharge.

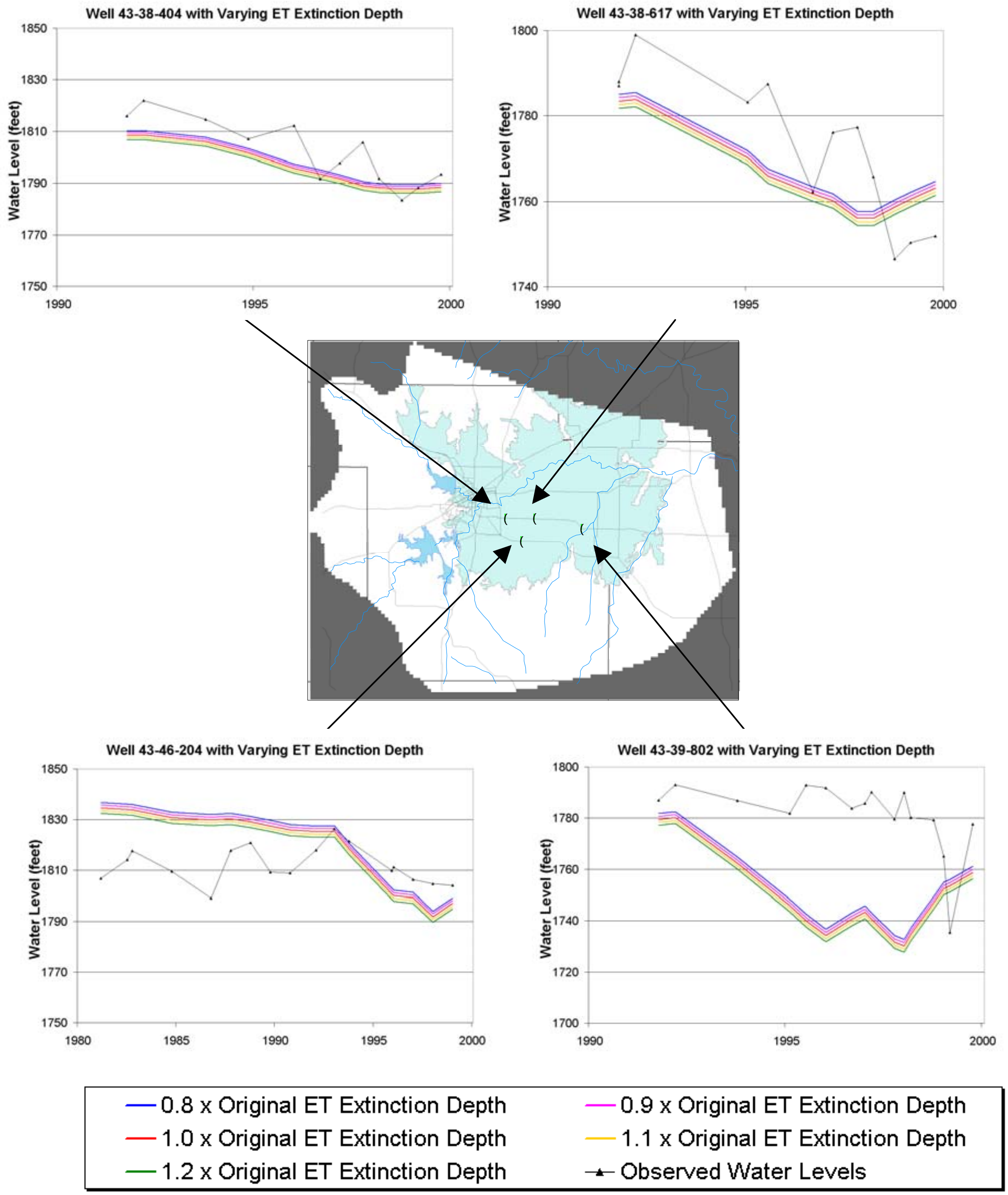

Figure 9.7.1 Transient Model Sensitivity to Changes in Evapotranspiration Extinction Depth

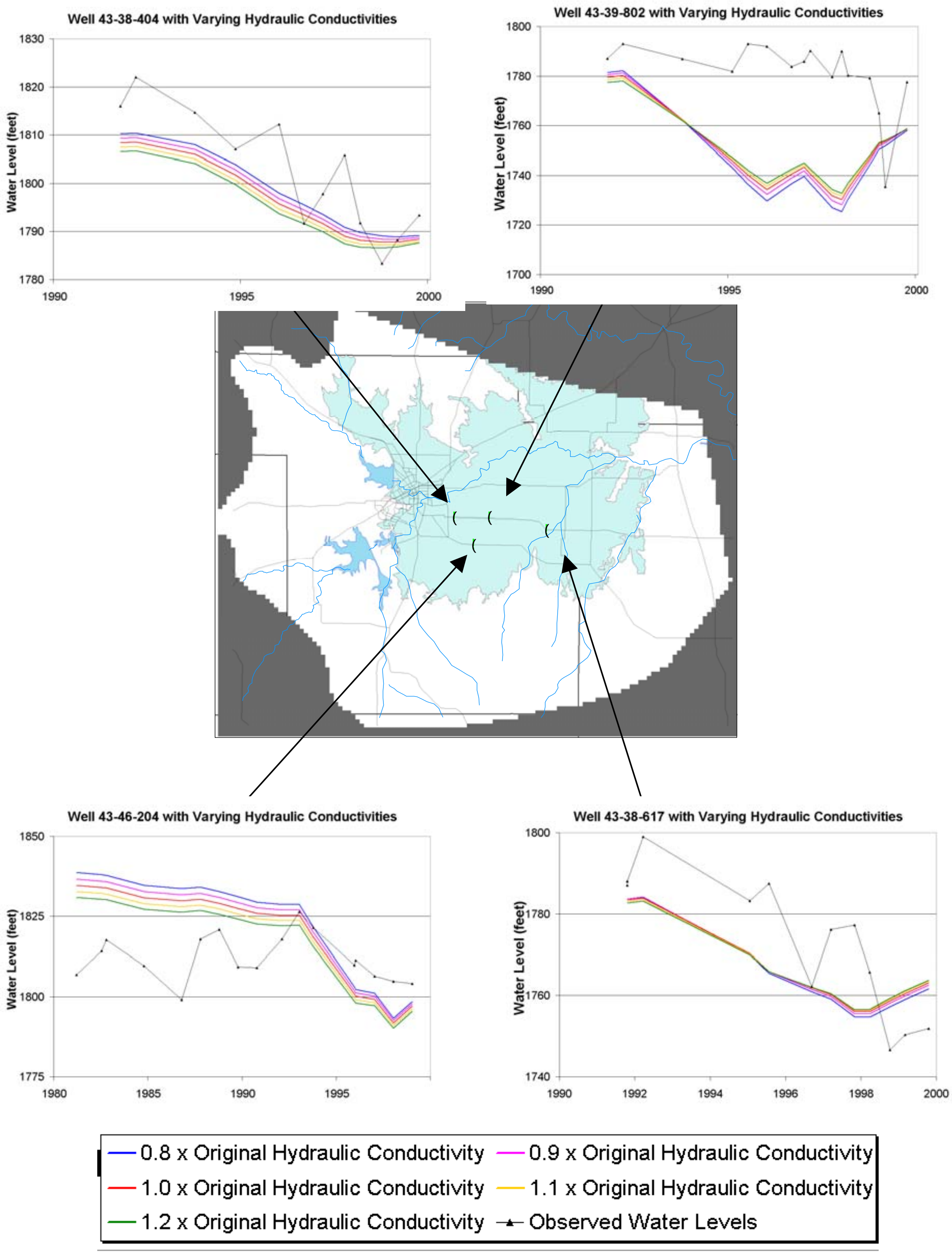

Figure 9.7.2 Transient Model Sensitivity to Changes Hydraulic Conductivity

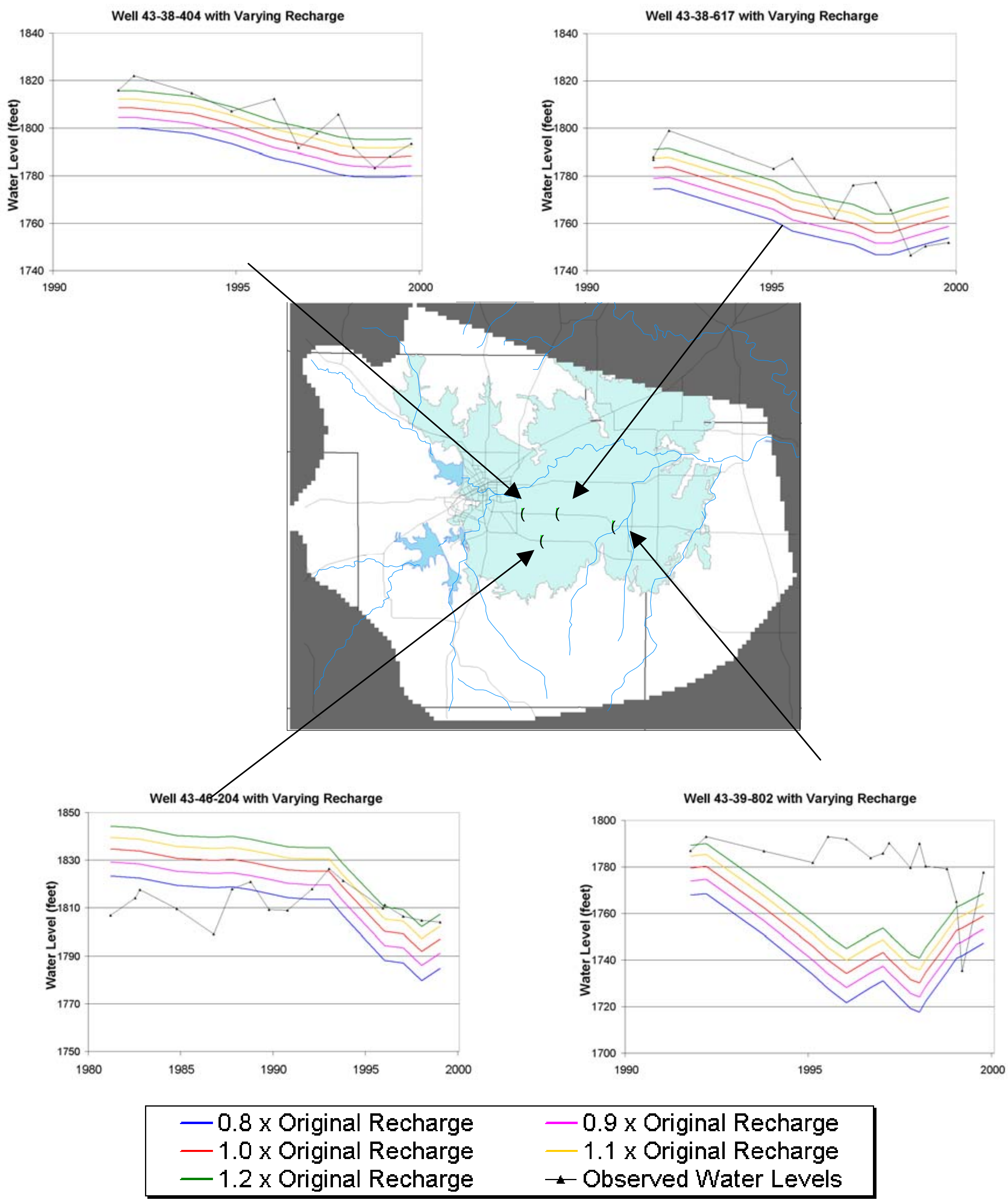

Figure 9.7.3 Transient Model Sensitivity to Changes in Recharge

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10.0 PREDICTIVE SIMULATIONS

The GAM was used to model the change in water levels and fluxes in the aquifer over a 50-year planning period (2000-2050) using water demand projections under average and drought-of-record (DOR) conditions. This section details the results of the predictive simulations.

Six predictive simulations were completed: (1) average recharge through 2050, (2) average recharge ending with the DOR in 2010, (3) average recharge ending with the DOR in 2020, (4) average recharge ending with the DOR in 2030, (5) average recharge ending with the DOR in 2040, and (6) average recharge ending with the DOR in 2050. During the predictive simulations, estimates of groundwater demand were based on projections developed by the Region F RWPG and documented in the 2002 State Water Plan for Texas (TWDB, 2002).

10.1 Drought of Record

Drought is a normal, recurring climatic event. It is conceptually defined by the National Drought Mitigation Center as a protracted period of deficient precipitation, usually over a season or more, resulting in a water shortage for some activity, group, or environmental sector. The TWDB GAM protocol specifies that the drought-of-record should be based on the past 100 years (or longest period of record) and should consider severity and duration. Drought is related directly to precipitation, which is the primary variable controlling recharge in the model region. Therefore, precipitation data were used to define the drought-of-record in the study area.

Long-term annual precipitation records were only available in the model area since the late 1930s and in multiple gages since 1940. Figure 10.1.1 shows the average annual precipitation for each of the four available gages with records that include at least part of the drought of the 1950s, and for the “Quad 607” rainfall data obtained by the TWDB. The slight upward shift in the “long term average” line in Figure 10.1.1 in 1960 is due to the difference in the average from 1940 to 2000 to the average for 1960 to 2000.

Inspection of the long-term precipitation chart indicates that the drought of the 1950s is the longest and most severe on record. The period of 1951 to 1956 averaged only 61% of normal precipitation for the region, and between 1954 and 1956, the region experienced only 52% of normal precipitation. Based on an average of all of the data, the six-year period from 1951 to 1956 contained the five lowest rainfall years during the period of record. Based on the TWDB "Quad 607" data, this six-year period contained the lowest three rainfall years and five of the lowest eight rainfall years for the period of record. In addition to this six-year period, 1950 had below-normal precipitation as well. Therefore the drought-of-record for the study area is considered the seven-year period from 1950 to 1956.

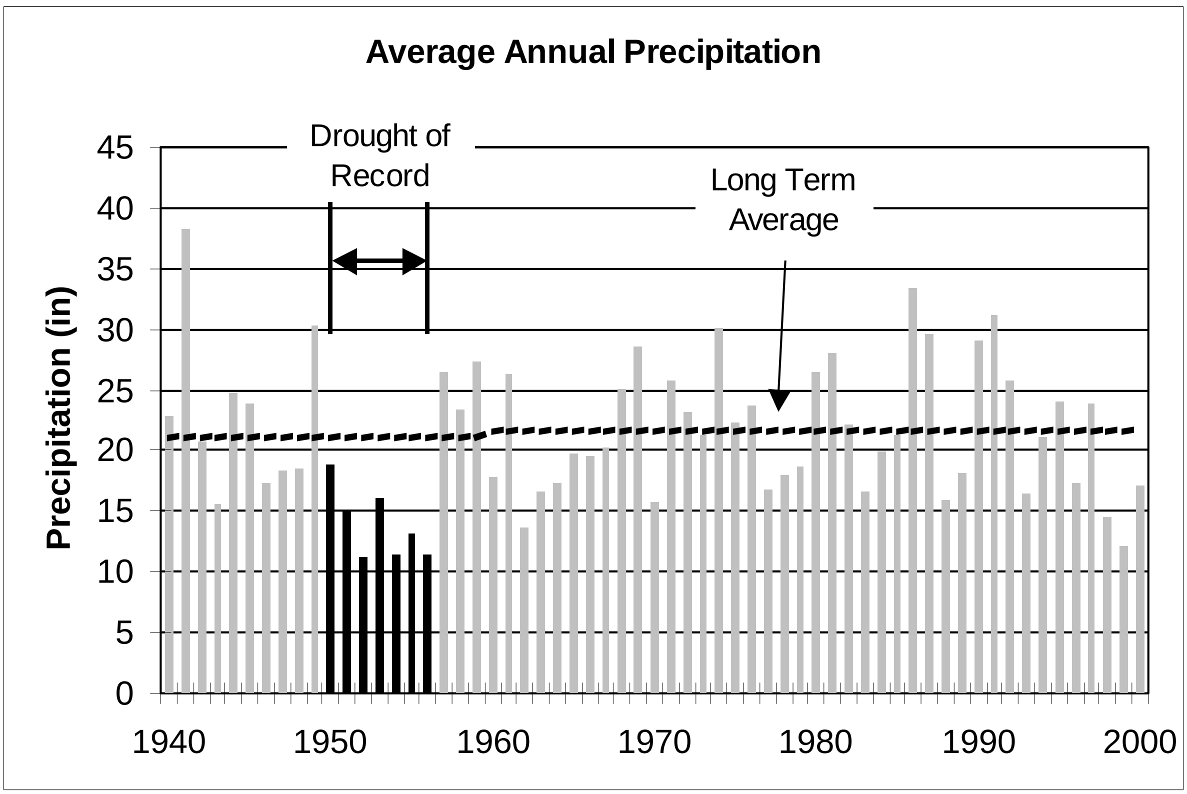

Figure 10.1.1 Drought of Record Analysis

10.2 Predictive Pumping Data Sets

Predictive pumping data was derived from Regional Water Planning Group data, which contained estimates for four of the six pumping categories. For the Lipan model area, only four of the seven TWDB pumping categories have projected pumping estimates. There was no estimated pumping for the other three categories. The four categories included containing pumping estimates are irrigation, rural domestic, livestock and manufacturing. Of these, only the method of assigning the manufacturing pumping was different than it was for the transient calibration model.

Manufacturing pumping from 1990 through 2000 averaged 10 acre-feet per year. However, for the predictive simulation, manufacturing pumping was estimated to be approximately 170 acre-feet per year. Because of the 17-fold increase in this category, it was assumed that this projected increase was meant to account for significant manufacturing growth in the area. For the transient model, manufacturing pumping was assigned as point value based on observed pumping. Assigning this predictive pumping to the cells used in the transient model was not appropriate. Therefore, for predictive simulations, manufacturing pumping was distributed to areas where the land use / land cover data indicated commercial or industrial space. Even though this pumping increased by more an order of magnitude from the transient calibration model to the predictive model, the percentage of total pumping attributed to manufacturing is still less than 0.5 percent of the total pumping.

10.3 Predictive Simulation Results

As described above, predictive simulations were run for the 50-year planning period using projected water demands from Region F that was included in the 2002 State Water Plan. Each of these predictive simulations is described below.

10.3.1 Average Conditions

The first 50-year predictive simulation uses average recharge conditions for the duration of the simulation. The average recharge used in these runs was based on the average precipitation in the period from 1960 to 2000. The slight upward shift in the "long term average" line in Figure 10.1.1 in 1960 is due to the difference in the average from 1940 to 2000 to the average for 1960 to 2000. Figures 10.3.1 through 10.3.5 show simulated water levels in the Lipan aquifer in 2010, 2020, 2030, 2040, and 2050, respectively, under average recharge conditions.

Figures 10.3.6 through 10.3.10 show water level declines in the Lipan aquifer in 2010, 2020, 2030, 2040, and 2050, respectively. These water level declines are calculated by subtracting the simulated water level in the future year from the simulated water levels in 2000. Water level declines over most of the model area are relatively small except in the Lipan Flats, where irrigation demand is the greatest. Water level decline in 2010 reached a maximum of over 50 feet in the center of the irrigation pumping. Water level decline continues to progress through time as seen in the subsequent figures. In 2050, the simulated water level decline is over 90 feet in the center of the Lipan Flats area.

Figures 10.3.11 through 10.3.15 show the simulated saturated thickness of the aquifer under average recharge conditions in 2010, 2020, 2030, 2040, and 2050, respectively. Saturated thickness is calculated by subtracting the water table elevation from the bottom of the aquifer. As discussed in Section 4.2, the aquifer bottom elevation is set at 400 feet below land surface. This was assumed the maximum depth at which usable water occurs. In many locations, the depth at which the water becomes unusable is shallower.

The hydrograph shown in Figure 10.3.16 shows the water level decline in the center of the Lipan Flats area. All of the well hydrographs in the model show very similar trends with the only difference being the proximity to the irrigation pumping. This figure indicates that while the rate of water level decline does decrease during the 50-year simulation period, water levels continue to decline. It should be noted that in areas where the aquifer is not as deep as assumed in the model, the model might overestimate the saturated thickness of the aquifer and the ground-water availability.

10.3.2 Drought-of-Record Conditions

Five different scenarios were run to simulate the impact of the drought of record. The predictive simulations included (1) average recharge ending with the DOR in 2010, (2) average recharge ending with the DOR in 2020, (3) average recharge ending with the

DOR in 2030, (4) average recharge ending with the DOR in 2040, and (5) average recharge ending with the DOR in 2050. These five simulations begin in 2000 and have durations of 10, 20, 30, 40, and 50 years, respectively.

Figures 10.3.17 and 10.3.18 show simulated water level and simulated water level decline in the Lipan aquifer in 2010 under drought of record conditions, respectively. These figures indicate that the seven-year simulated drought results in heads that are more than ten feet lower than under average recharge conditions. The area affected most by the drought is the area where the most pumping occurs; however, water levels across the aquifer drop due to decreased recharge. Figure 10.3.19 shows simulated saturated thickness of the aquifer in 2010 under drought of record conditions.

The remaining drought of record simulations results were very similar to the results for the 2010 drought of record simulation when compared to the average recharge simulations. Figures 10.3.20, 10.3.23, 10.3.26, and 10.3.29 show the simulated heads in the aquifer for the drought of record simulations. Figures 10.3.21, 10.3.24, 10.3.27, and 10.3.30 show the simulated water level declines for these same scenarios. Aquifer saturated thickness is shown in 10.3.22, 10.3.25, 10.3.28, and 10.3.31 for the same scenarios. These figures all show that, with the currently projected pumping, water levels will continue to decline until 2050.

Figure 10.3.32 shows the difference between water levels in 2010 under average recharge conditions and drought of record conditions. This figure shows that under drought of record conditions water levels in 2010 are a few feet lower in the area of largest water level declines than under average recharge conditions. Figure 10.3.33 shows similar results for the difference between the 50-year drought of record simulation and the 50-year average recharge simulation.

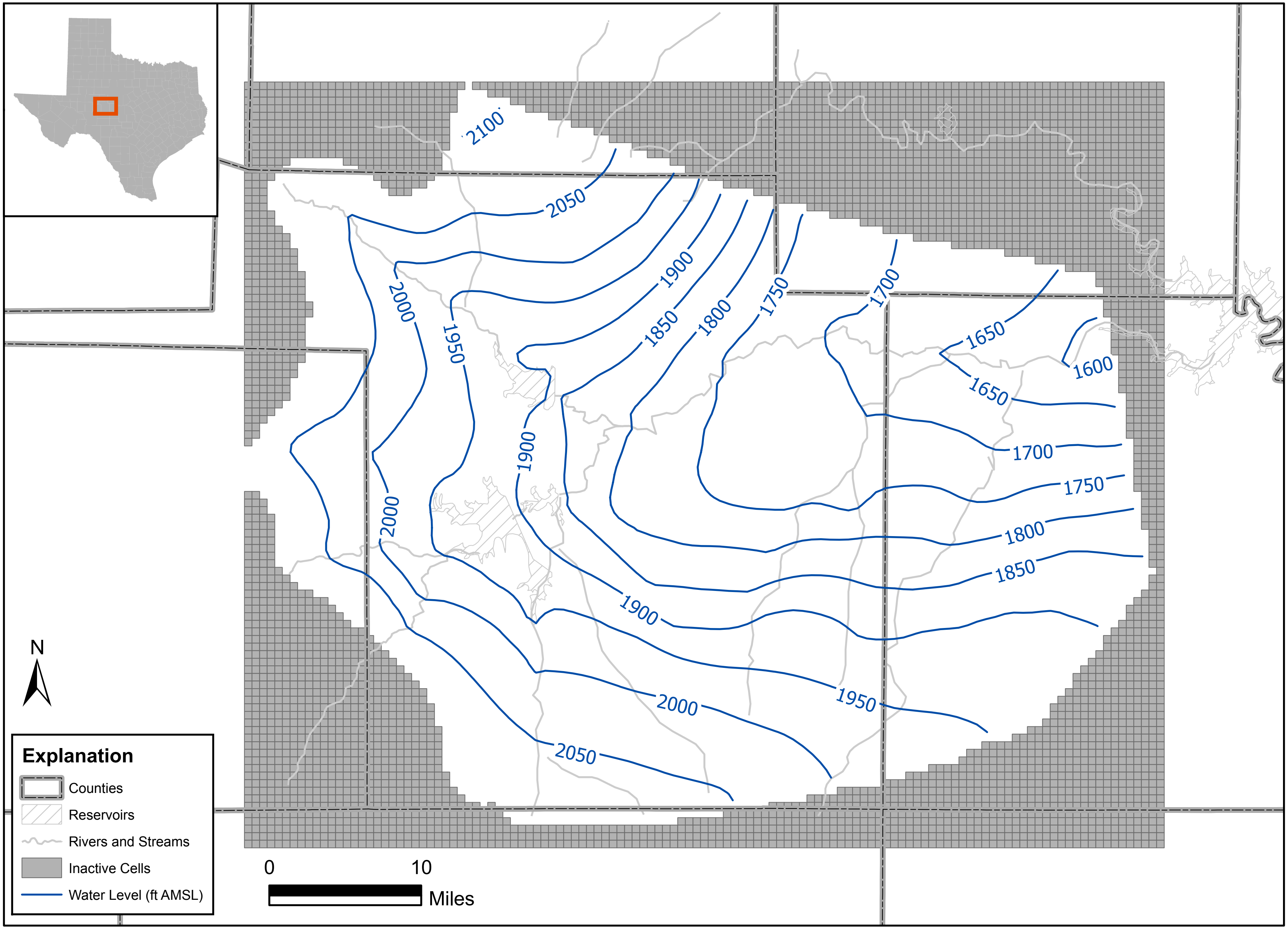

Figure 10.3.1 - Simulated Heads in 2010 - 50-Year Average Recharge Simulation

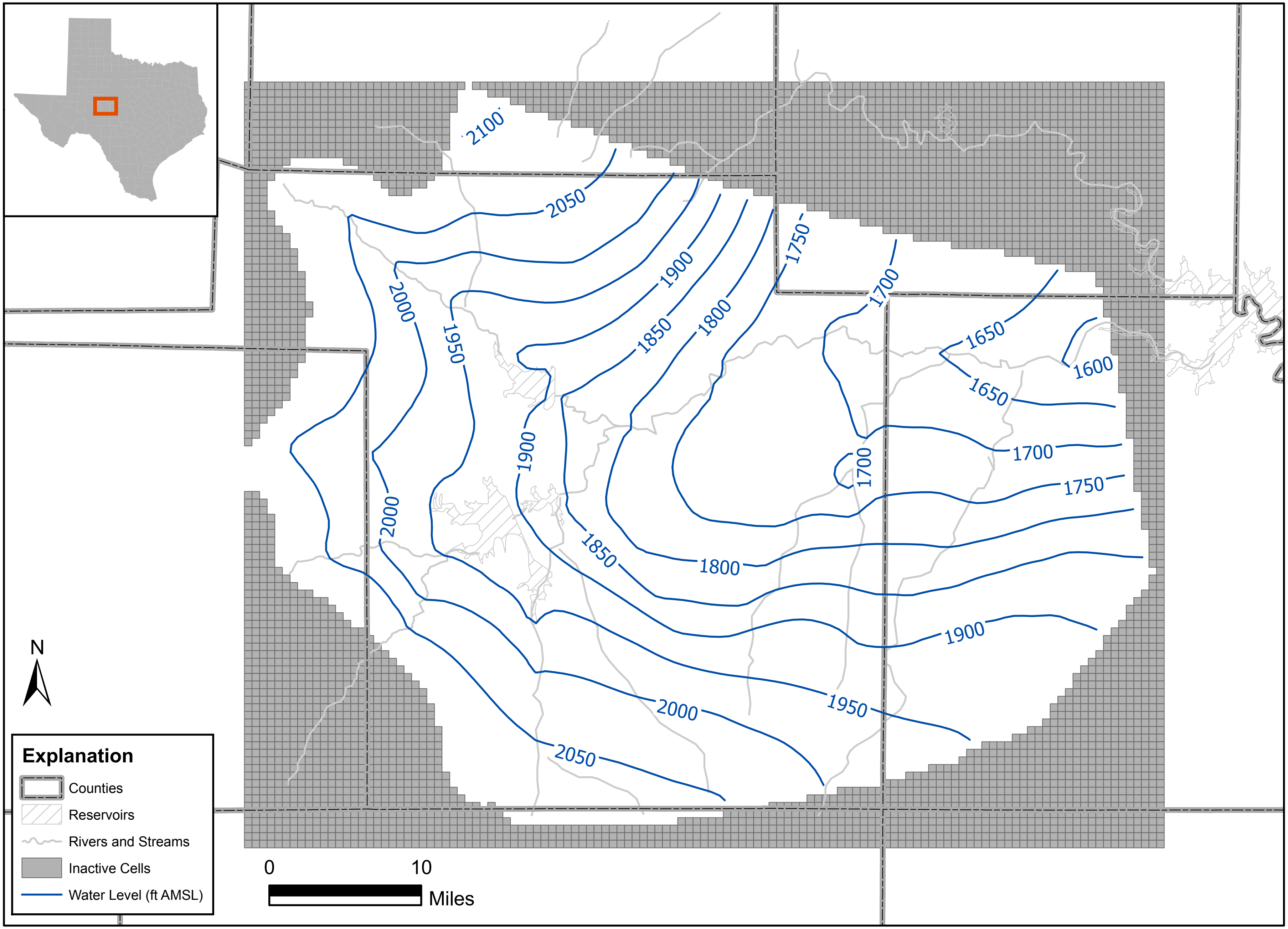

Figure 10.3.2 - Simulated Heads in 2020 - 50-Year Average Recharge Simulation

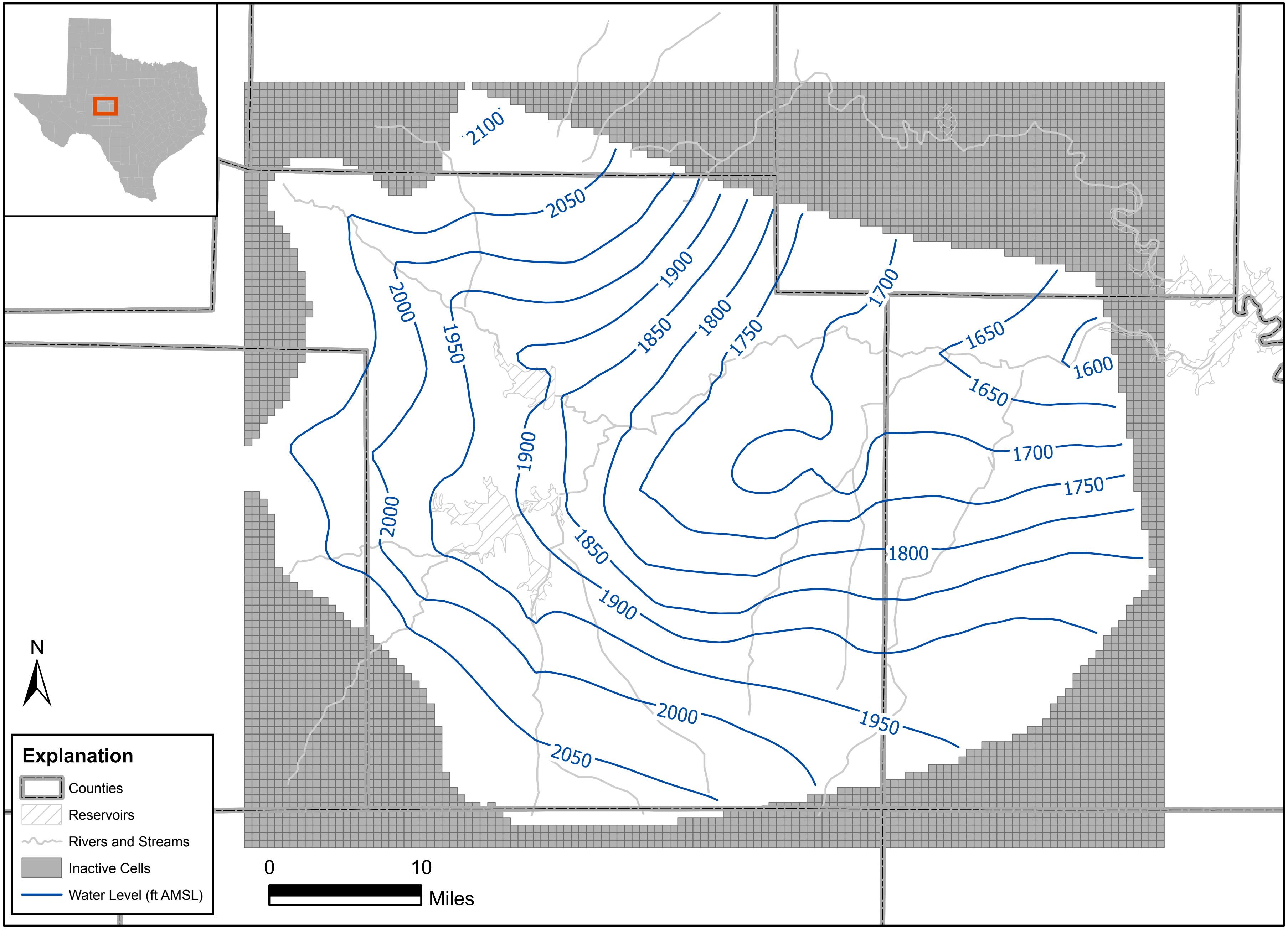

Figure 10.3.3 - Simulated Heads in 2030 - 50-Year Average Recharge Simulation

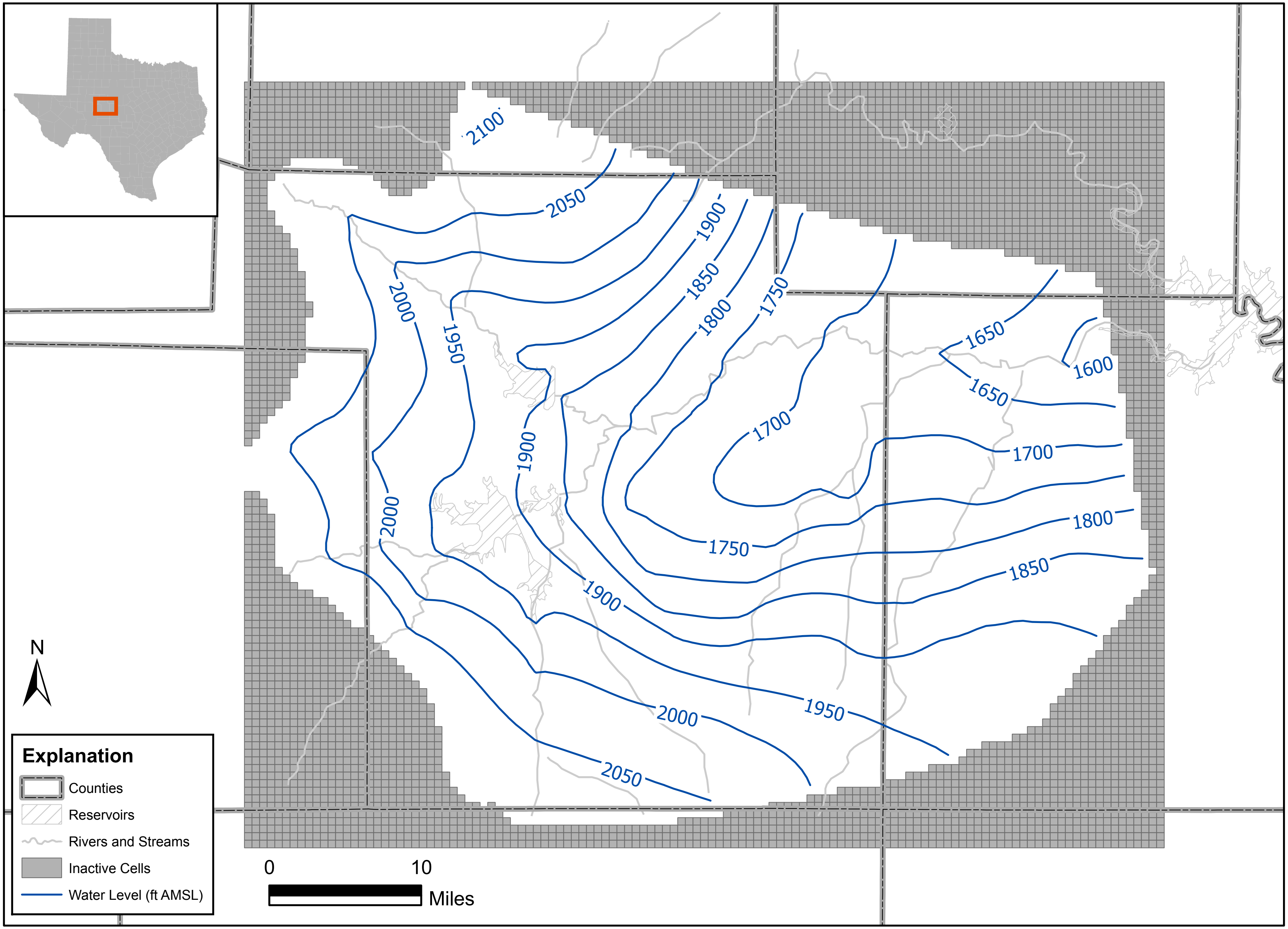

Figure 10.3.4 - Simulated Heads in 2040 - 50-Year Average Recharge Simulation

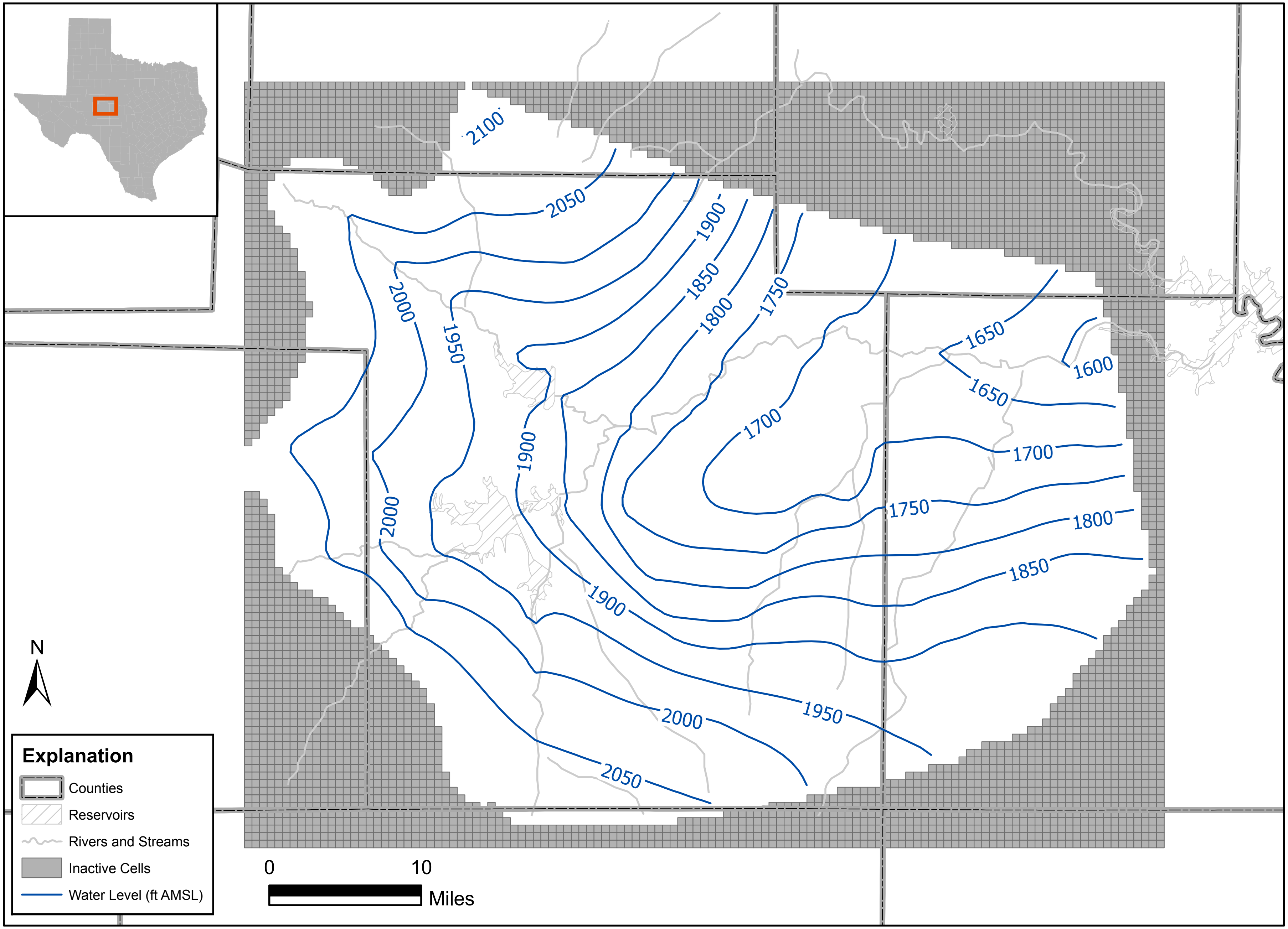

Figure 10.3.5 - Simulated Heads in 2050 - 50-Year Average Recharge Simulation

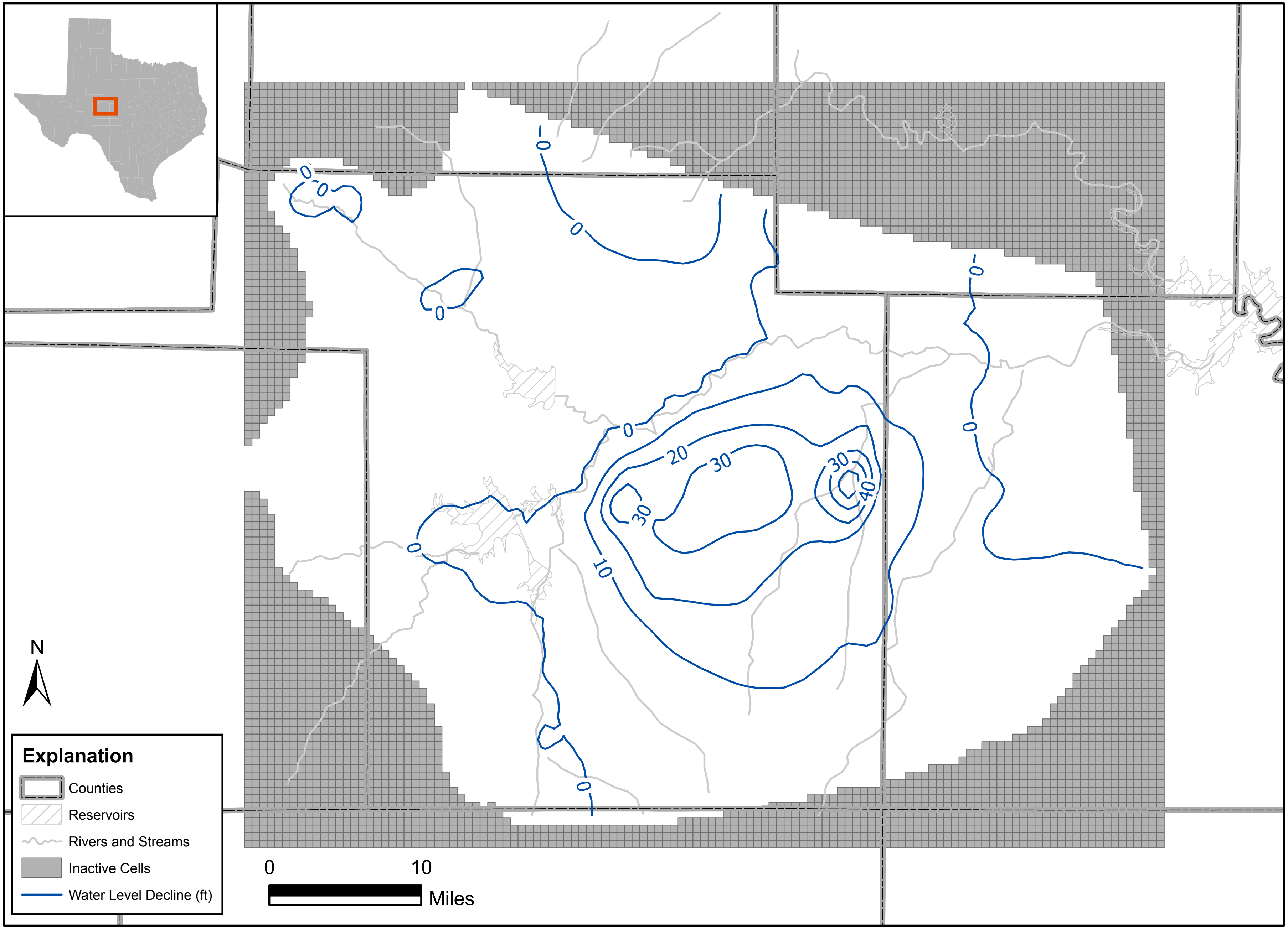

Figure 10.3.6 - Simulated Water Level Decline in 2010 - 50-Year Average Recharge Simulation

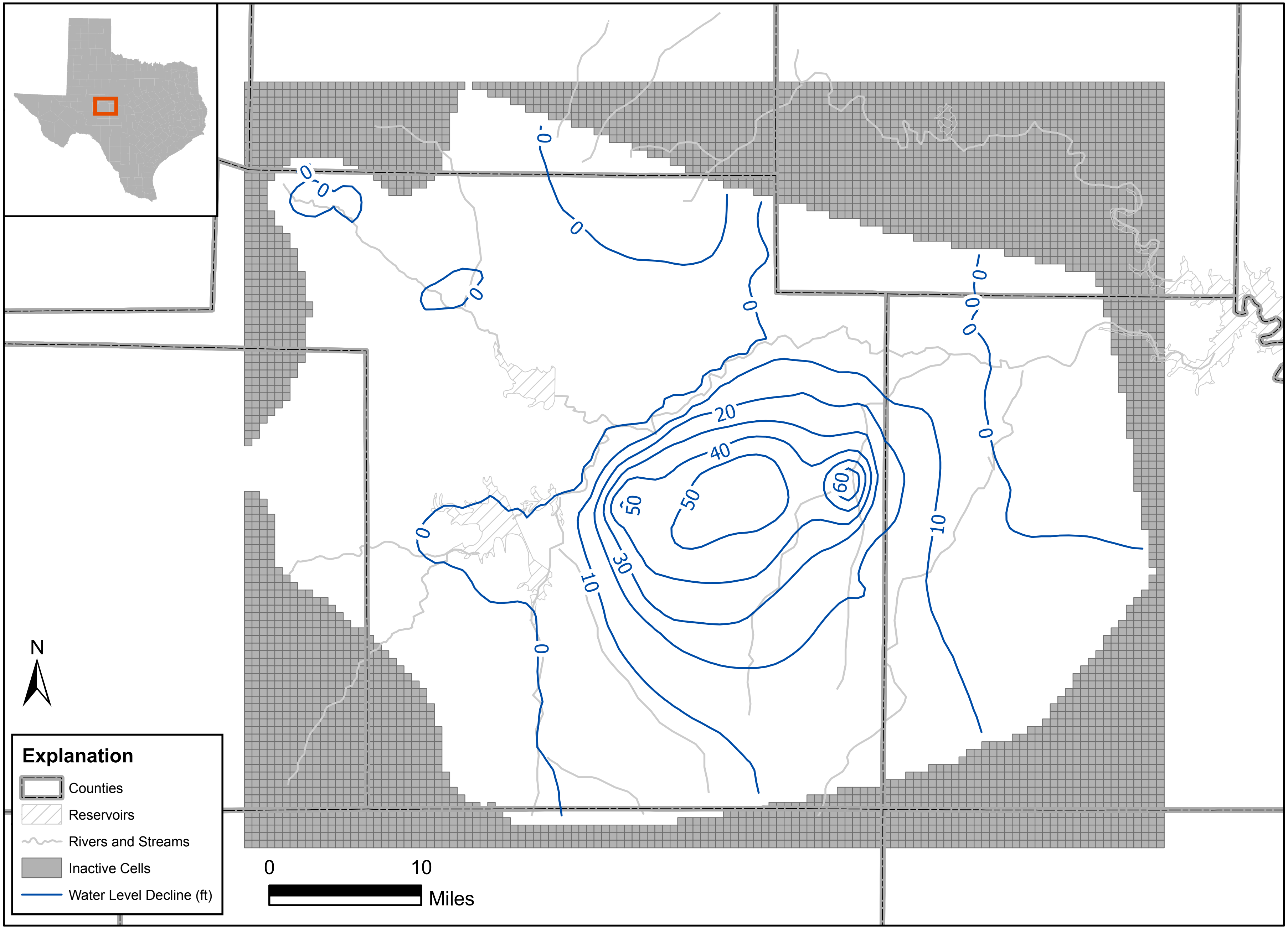

Figure 10.3.7 - Simulated Water Level Decline in 2020 - 50-Year Average Recharge Simulation

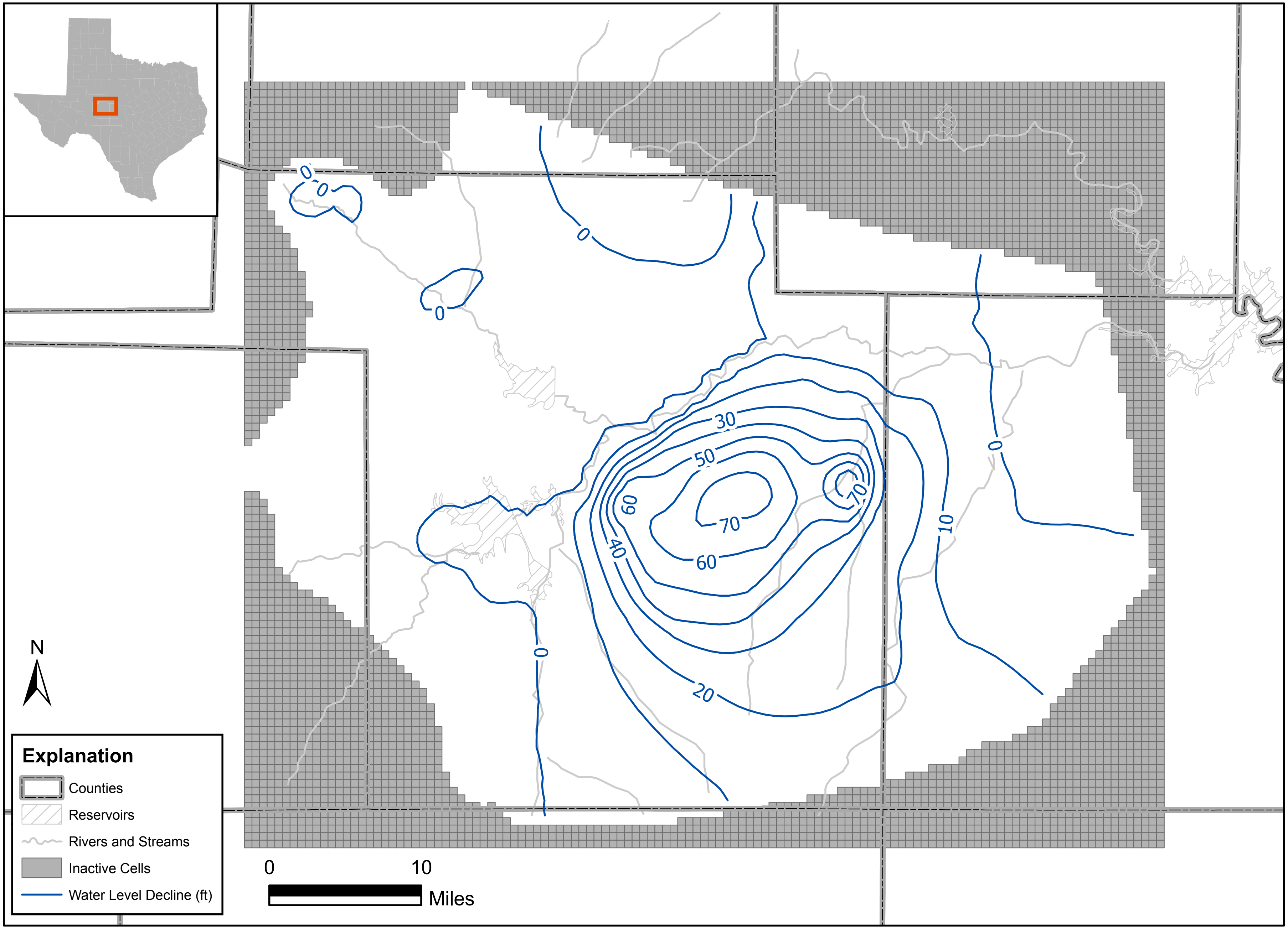

Figure 10.3.8 - Simulated Water Level Decline in 2030 - 50-Year Average Recharge Simulation

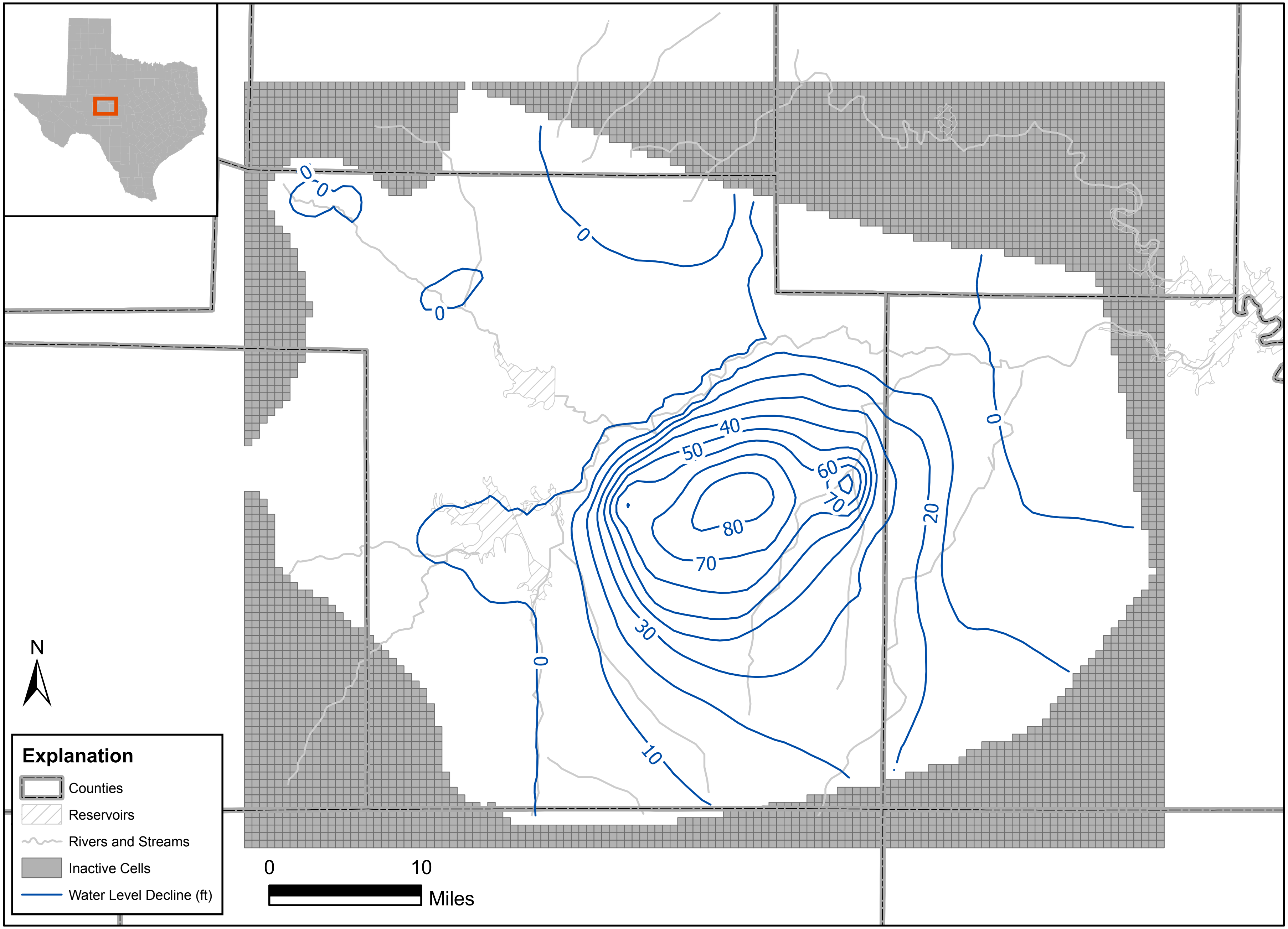

Figure 10.3.9 - Simulated Water Level Decline in 2040 - 50-Year Average Recharge Simulation

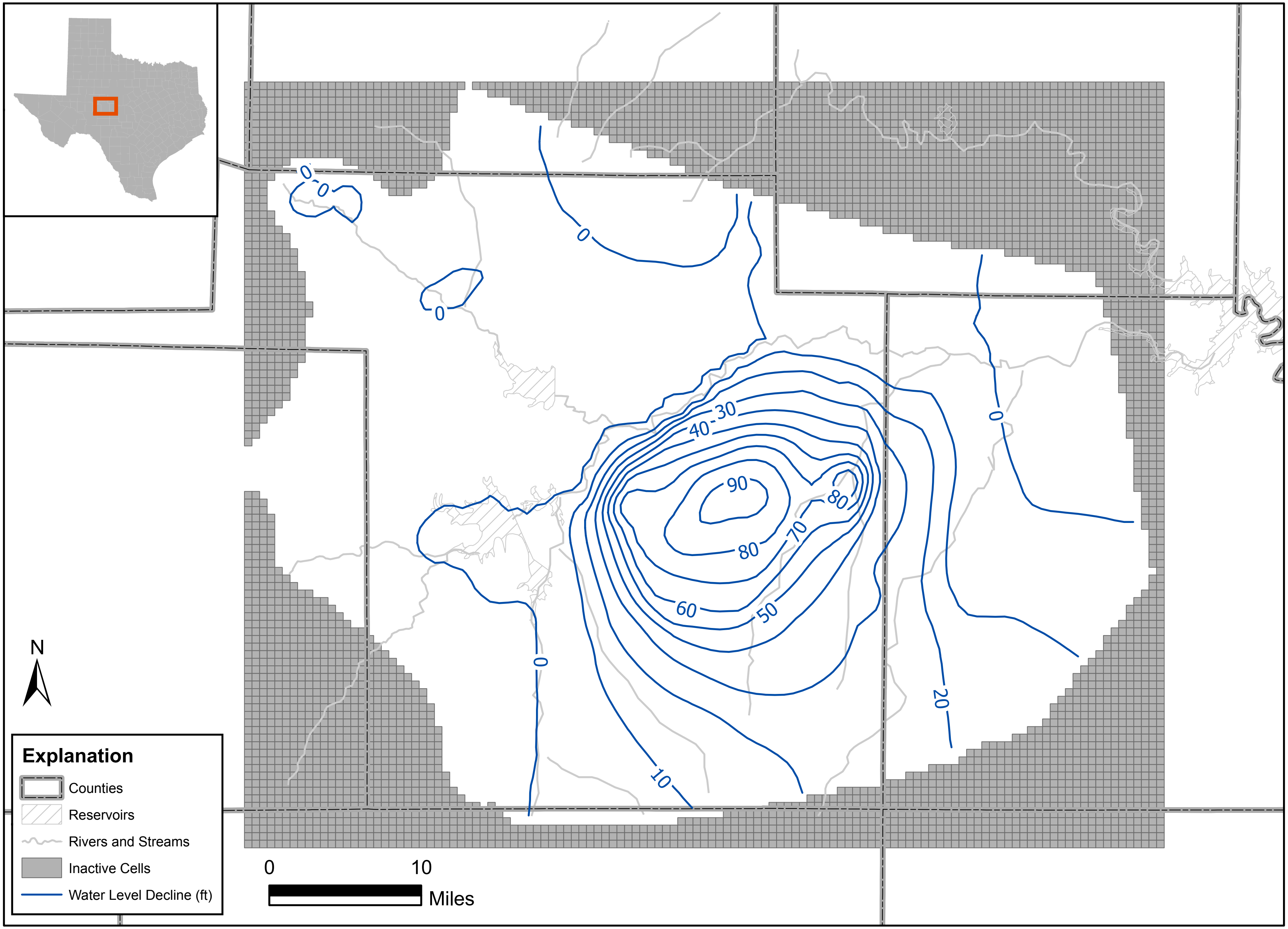

Figure 10.3.10 - Simulated Water Level Decline in 2050 - 50-Year Average Recharge Simulation

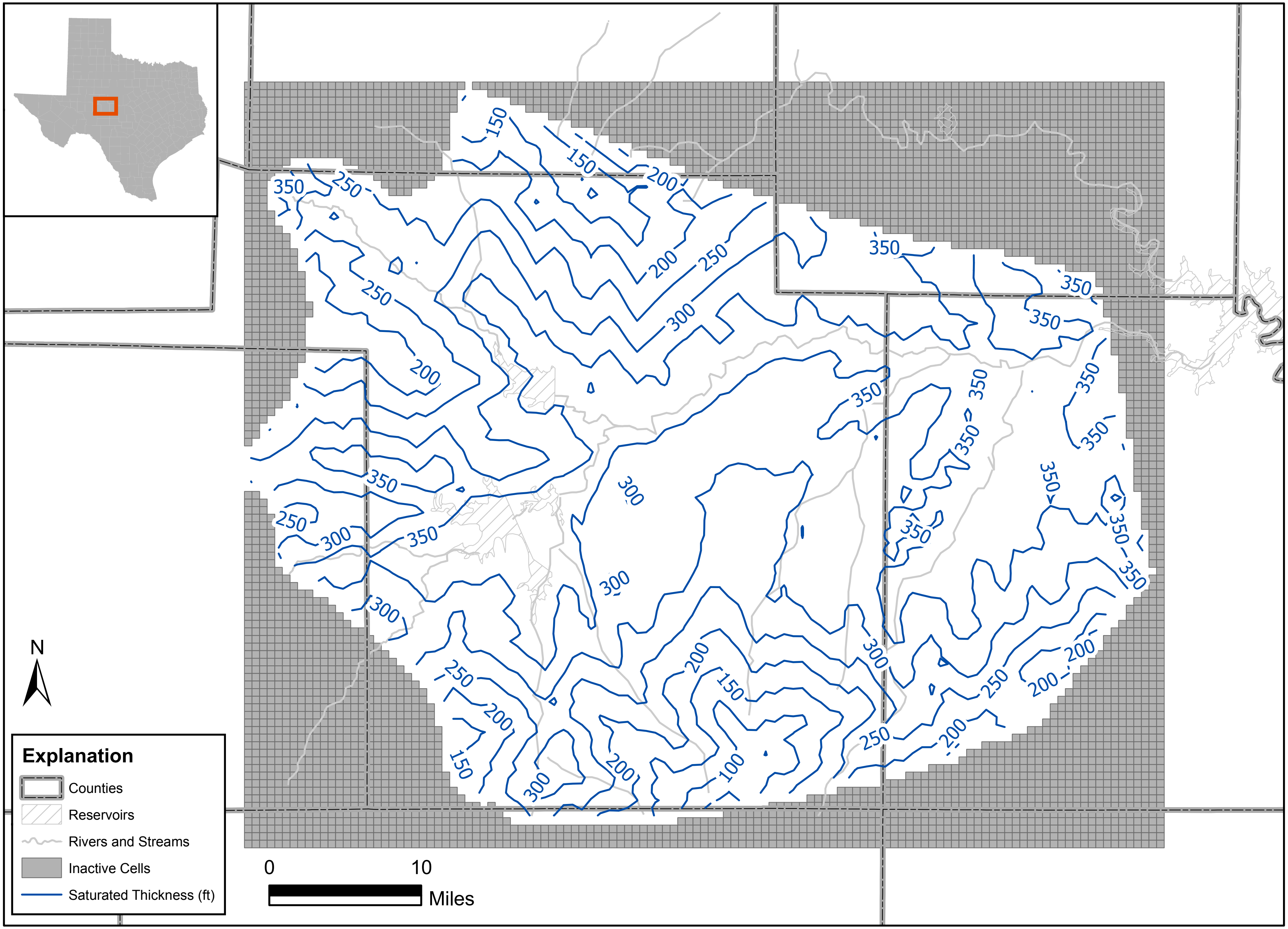

Figure 10.3.11 - Simulated Saturated Thickness in 2010 - 50-Year Average Recharge Simulation

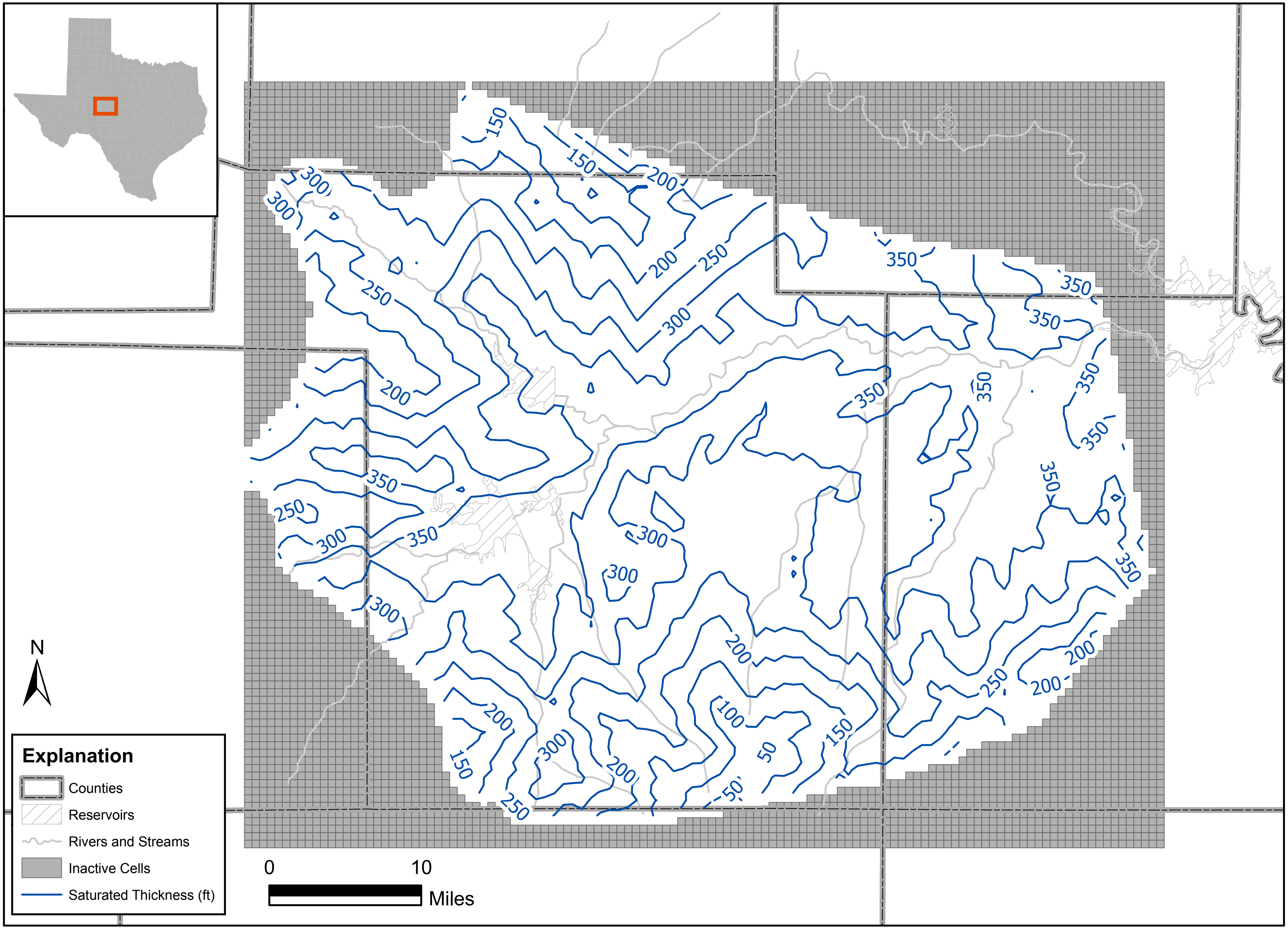

Figure 10.3.12 - Simulated Saturated Thickness in 2020 - 50-Year Average Recharge Simulation

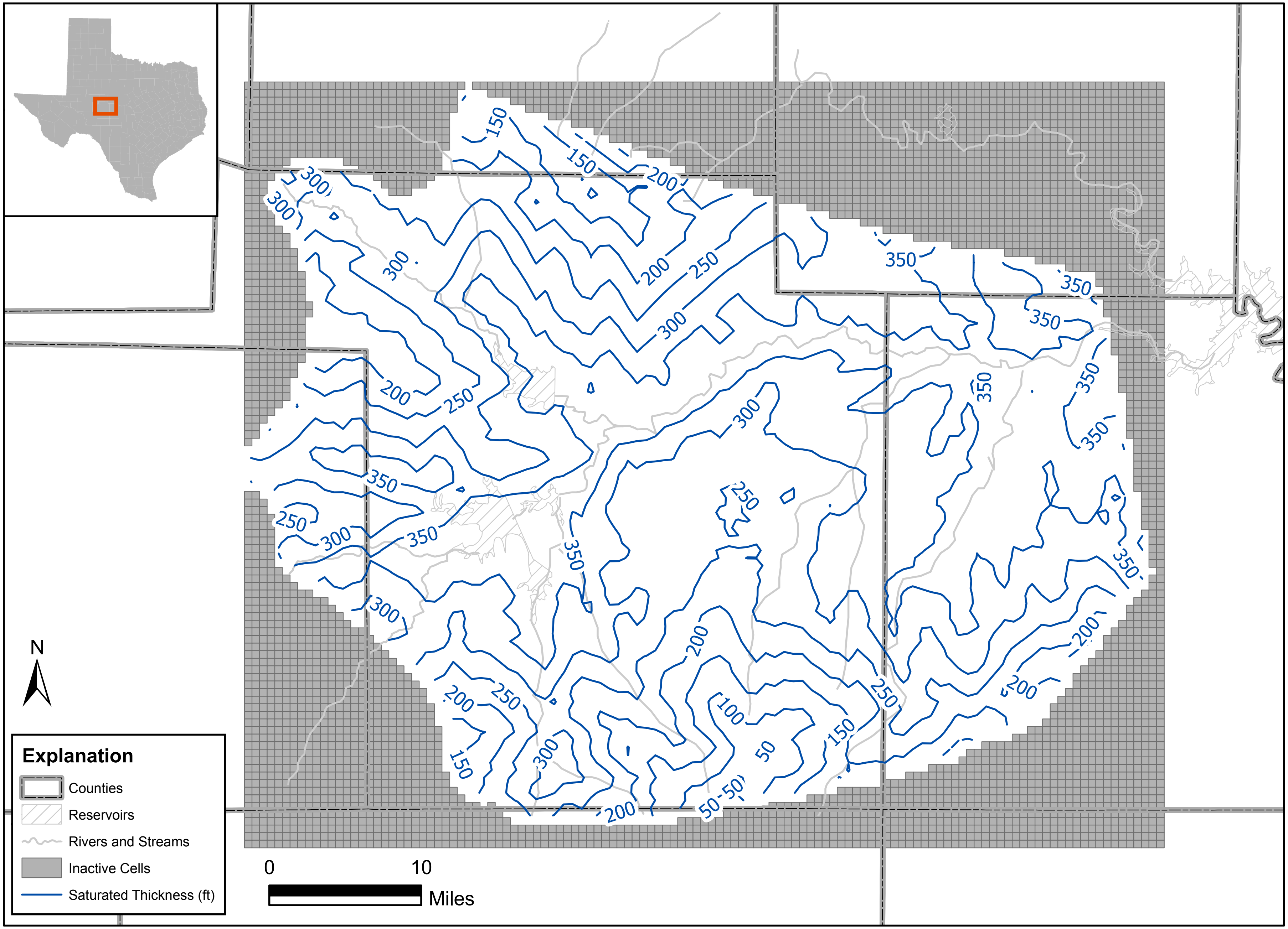

Figure 10.3.13 - Simulated Saturated Thickness in 2030 - 50-Year Average Recharge Simulation

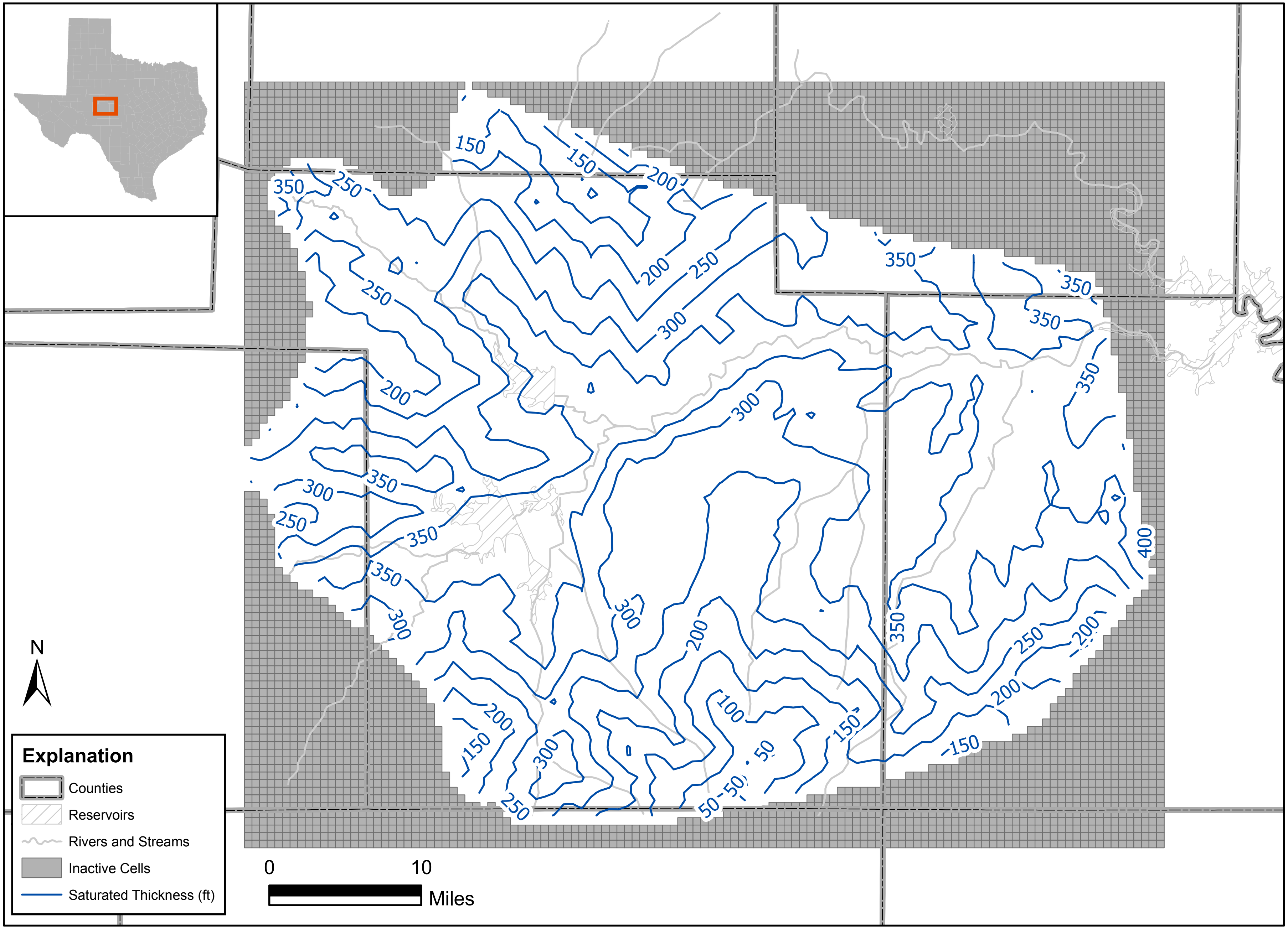

Figure 10.3.14 - Simulated Saturated Thickness in 2040 - 50-Year Average Recharge Simulation

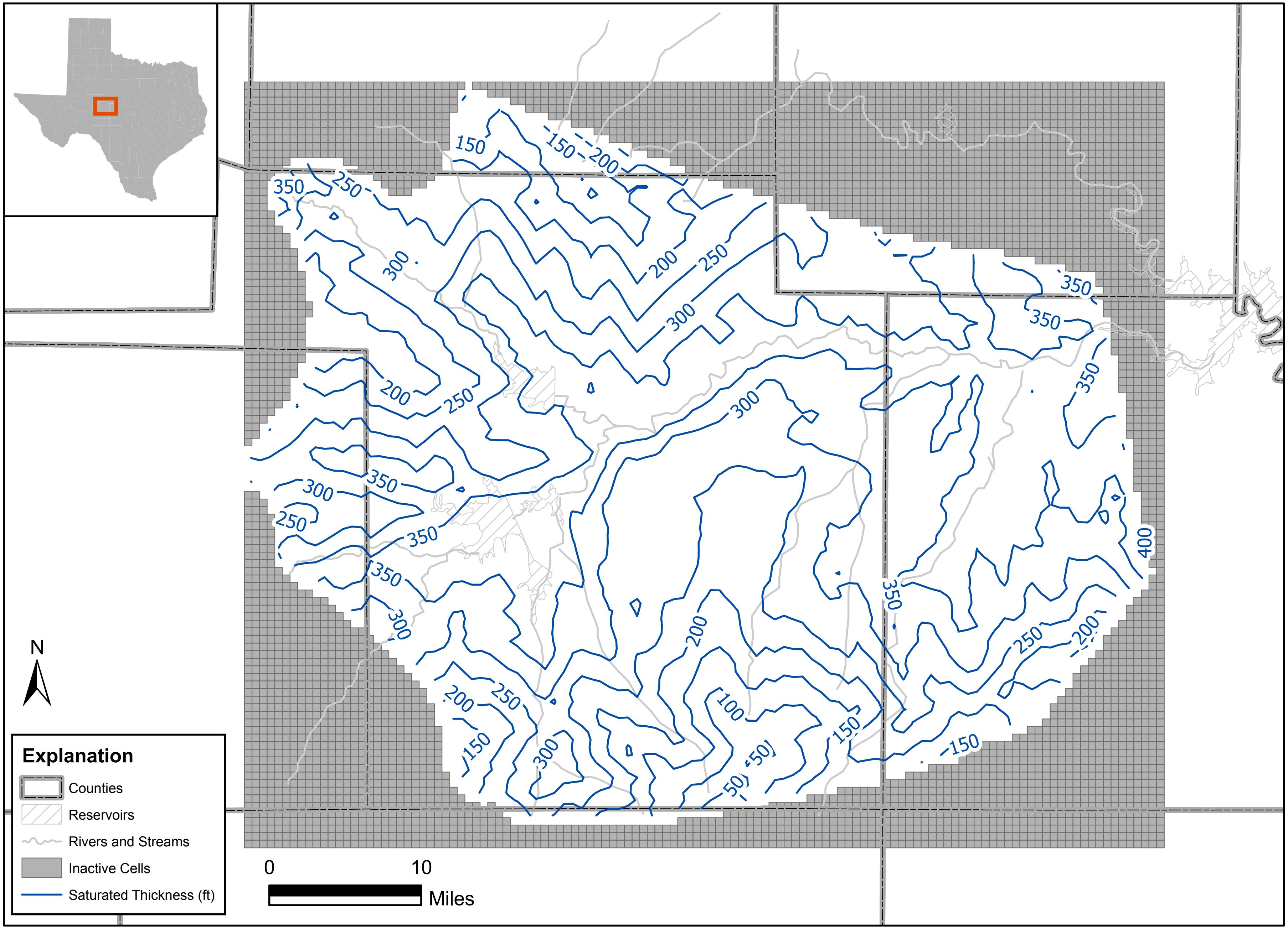

Figure 10.3.15 - Simulated Saturated Thickness in 2050 - 50-Year Average Recharge Simulation

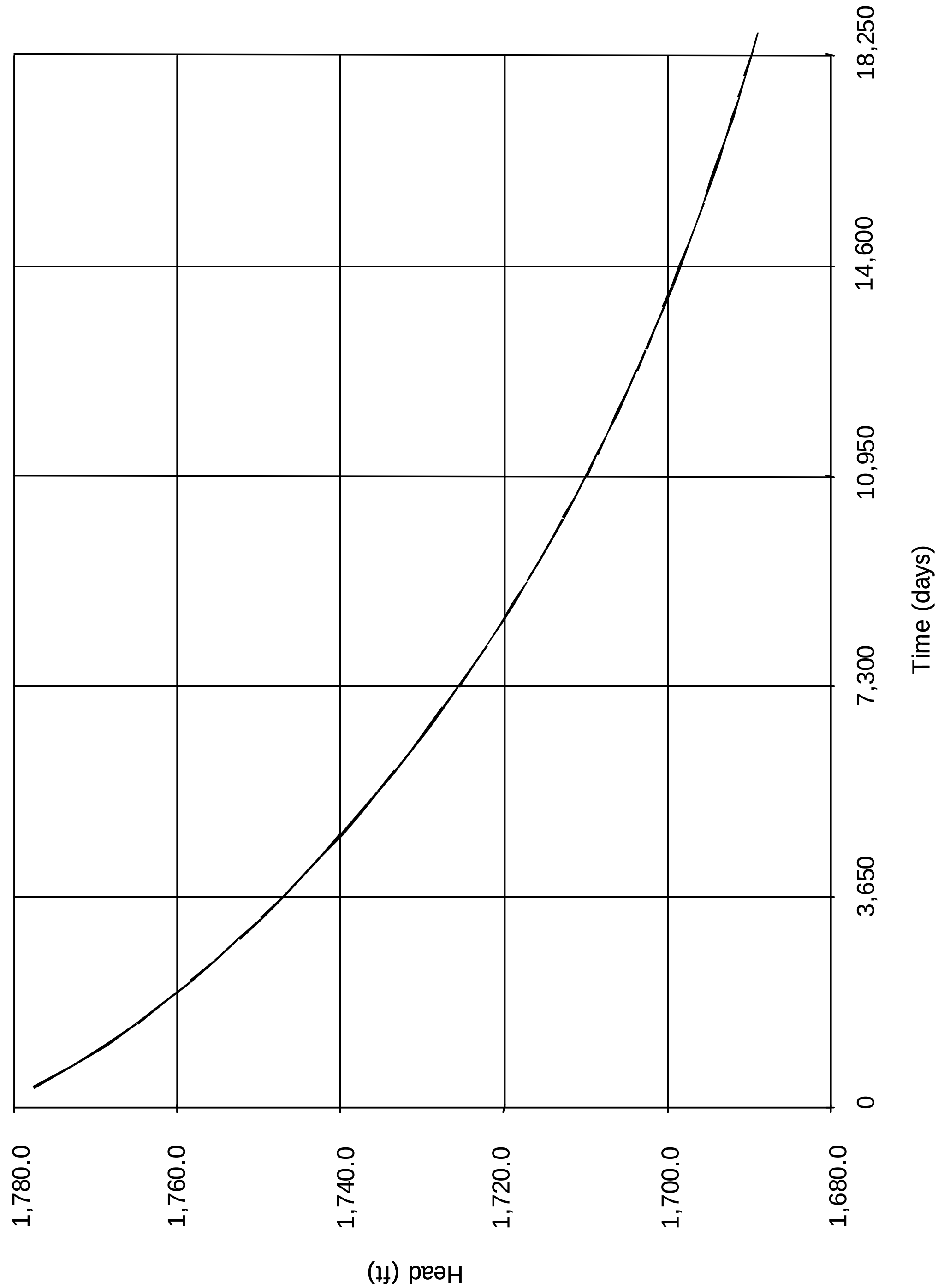

Figure 10.3.16 Simulated Water Level Decline in the Lipan Aquifer Model in 2050 with Average Recharge

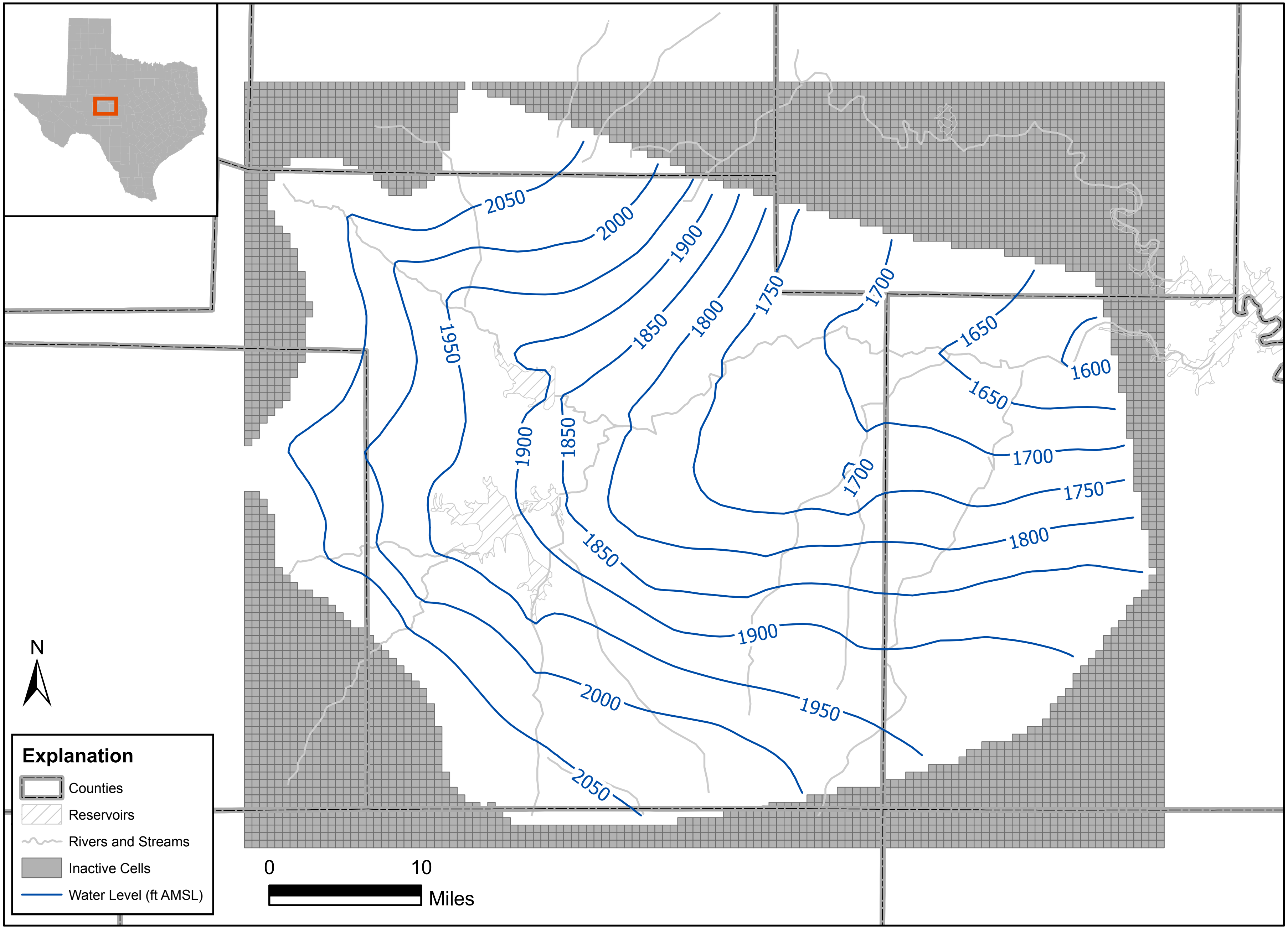

Figure 10.3.17 - Simulated Heads in 2010 - 10-Year Drought of Record Simulation

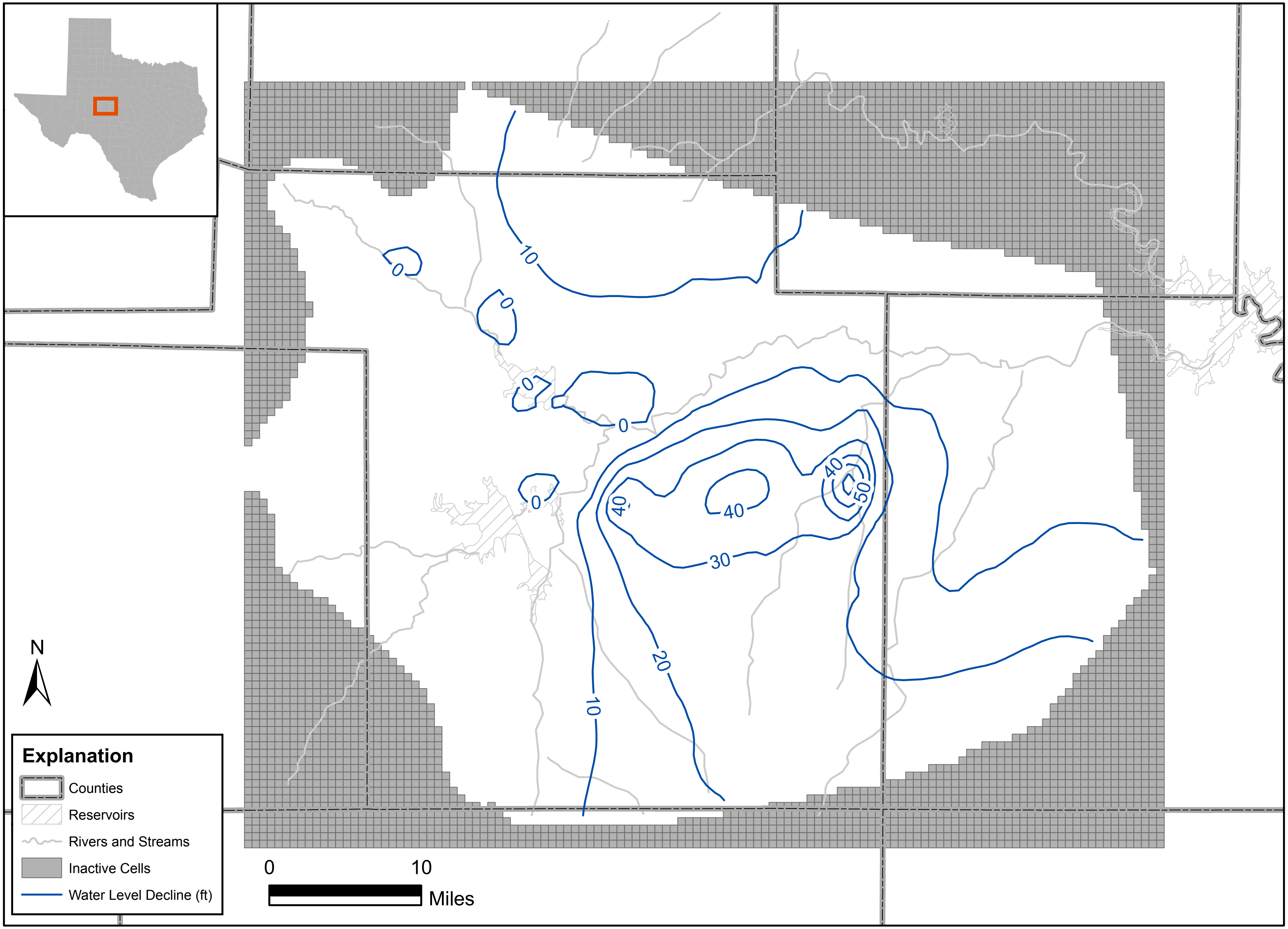

Figure 10.3.18 - Simulated Water Level Decline in 2010 - 10-Year Drought of Record Simulation

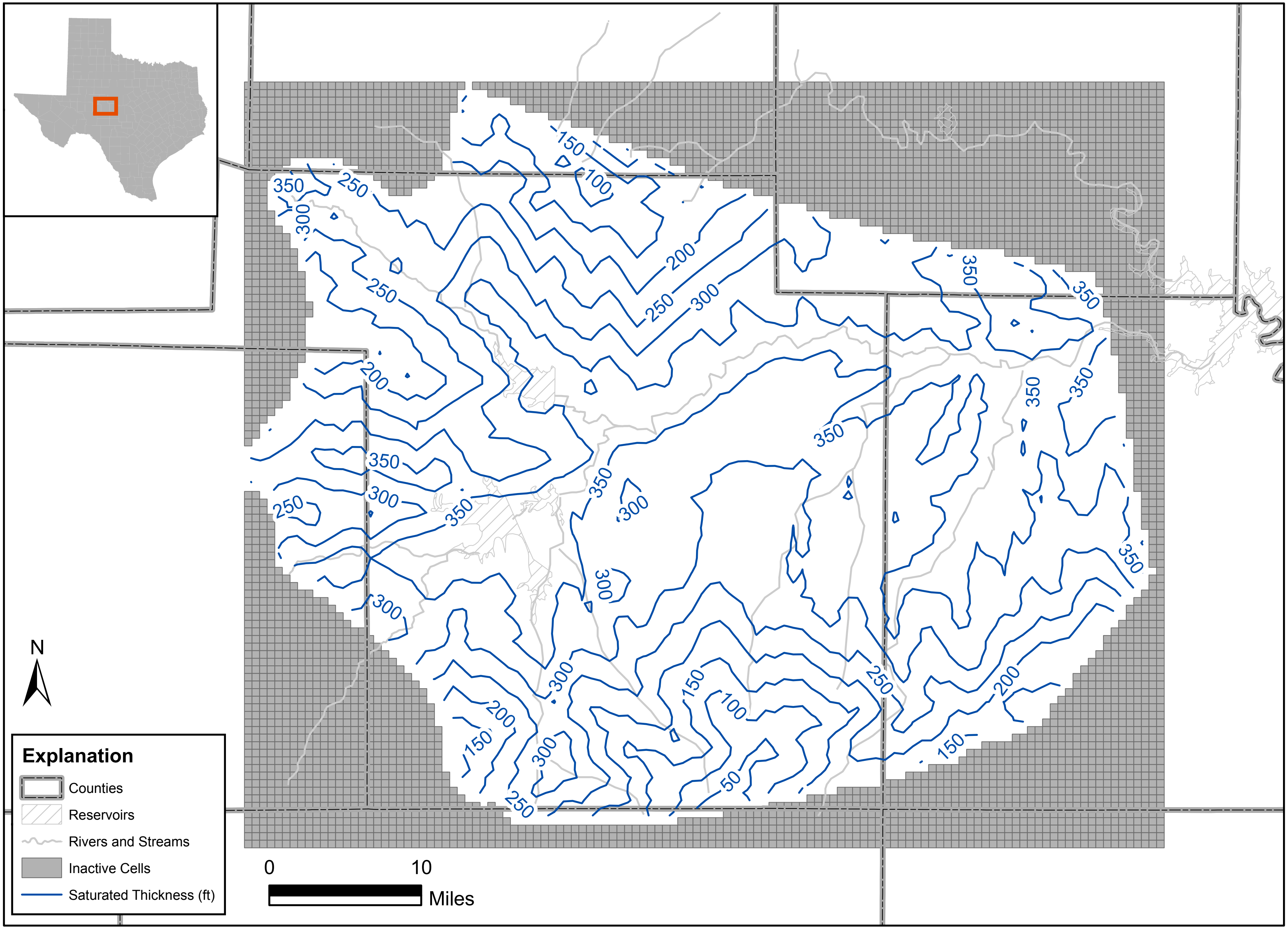

Figure 10.3.19 - Simulated Saturated Thickness in 2010 - 10-Year Drought of Record Simulation

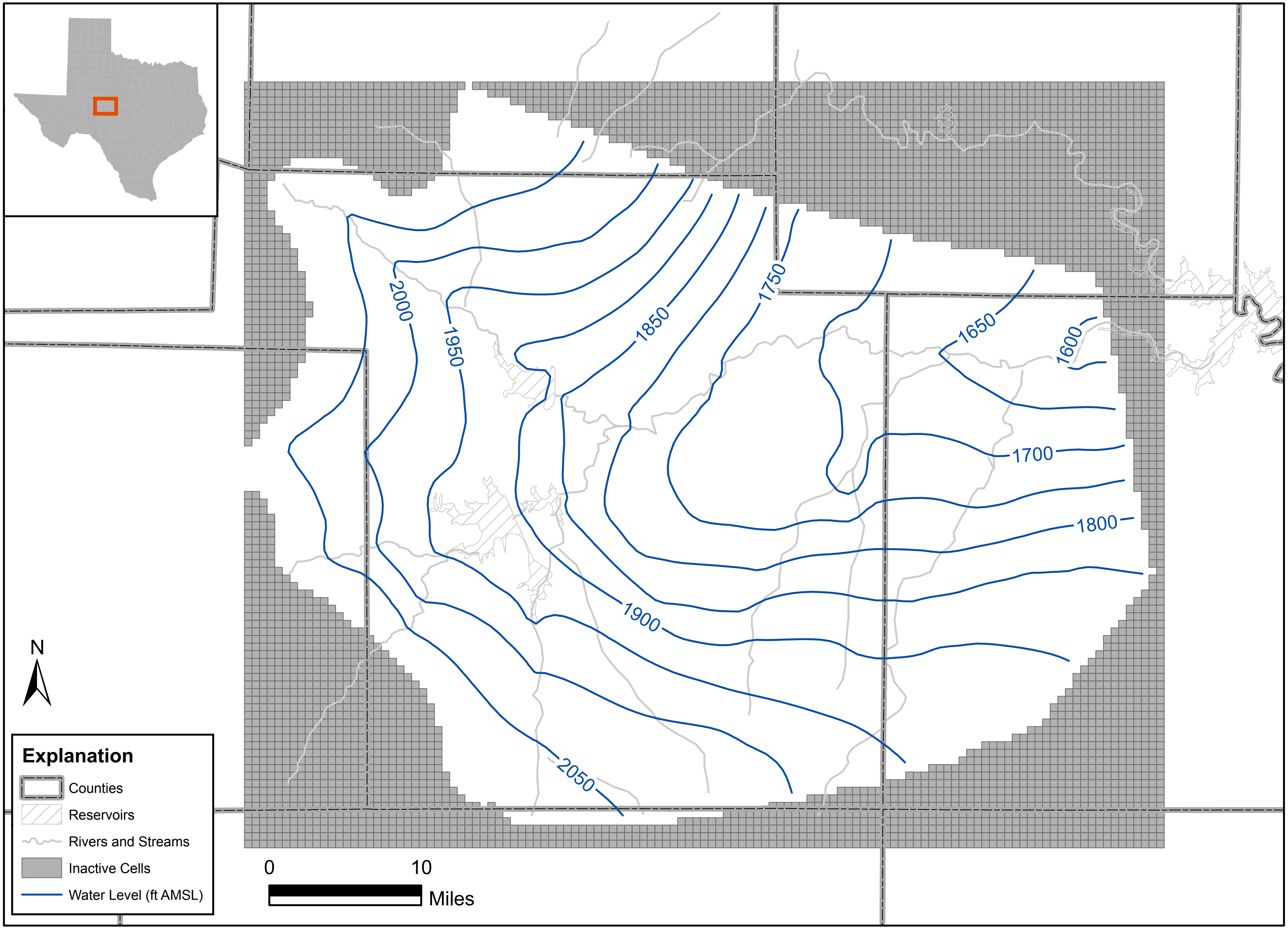

Figure 10.3.20 - Simulated Heads in 2020 - 20-Year Drought of Record Simulation

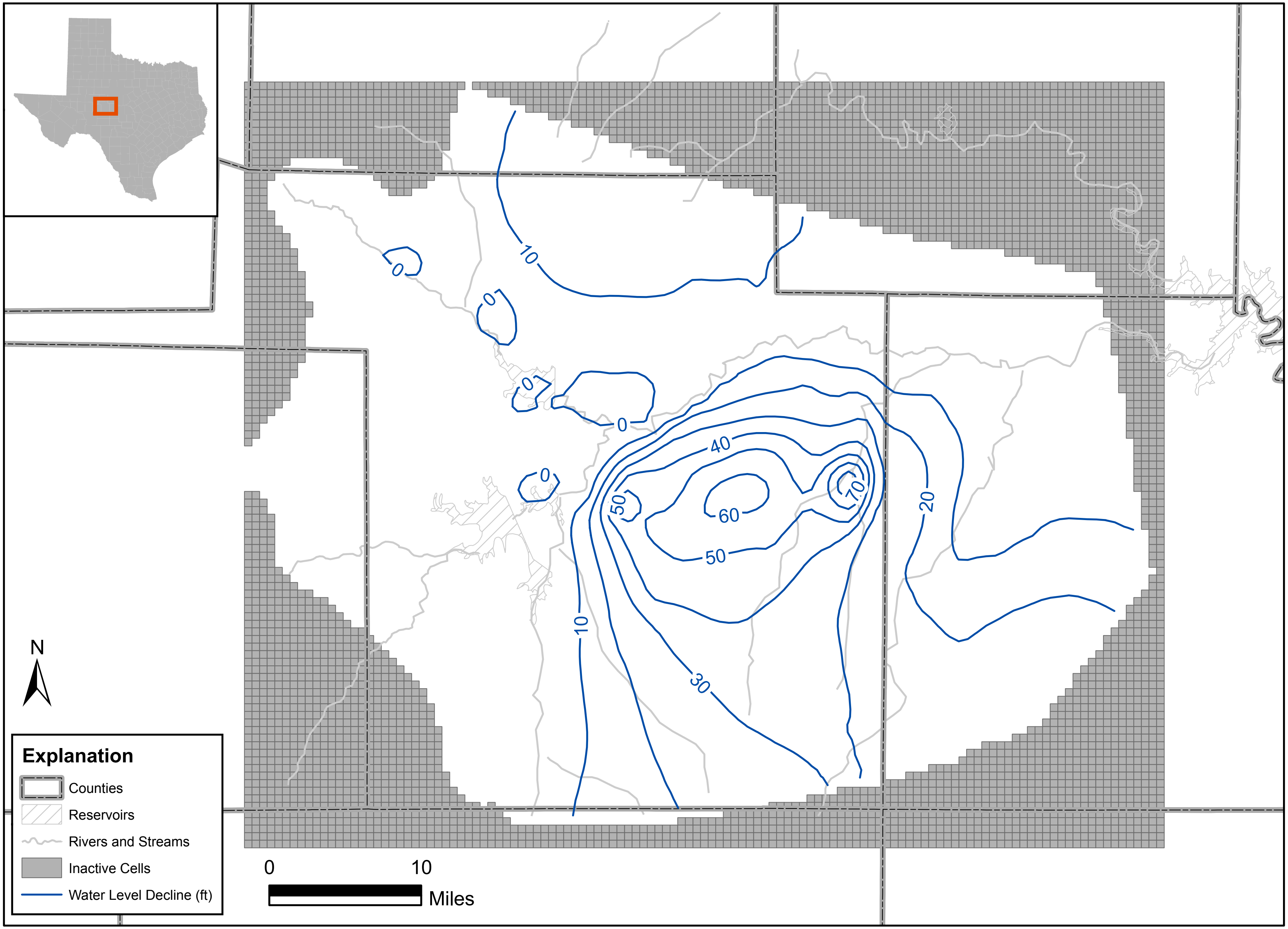

Figure 10.3.21 - Simulated Water Level Decline in 2020 - 20-Year Drought of Record Simulation

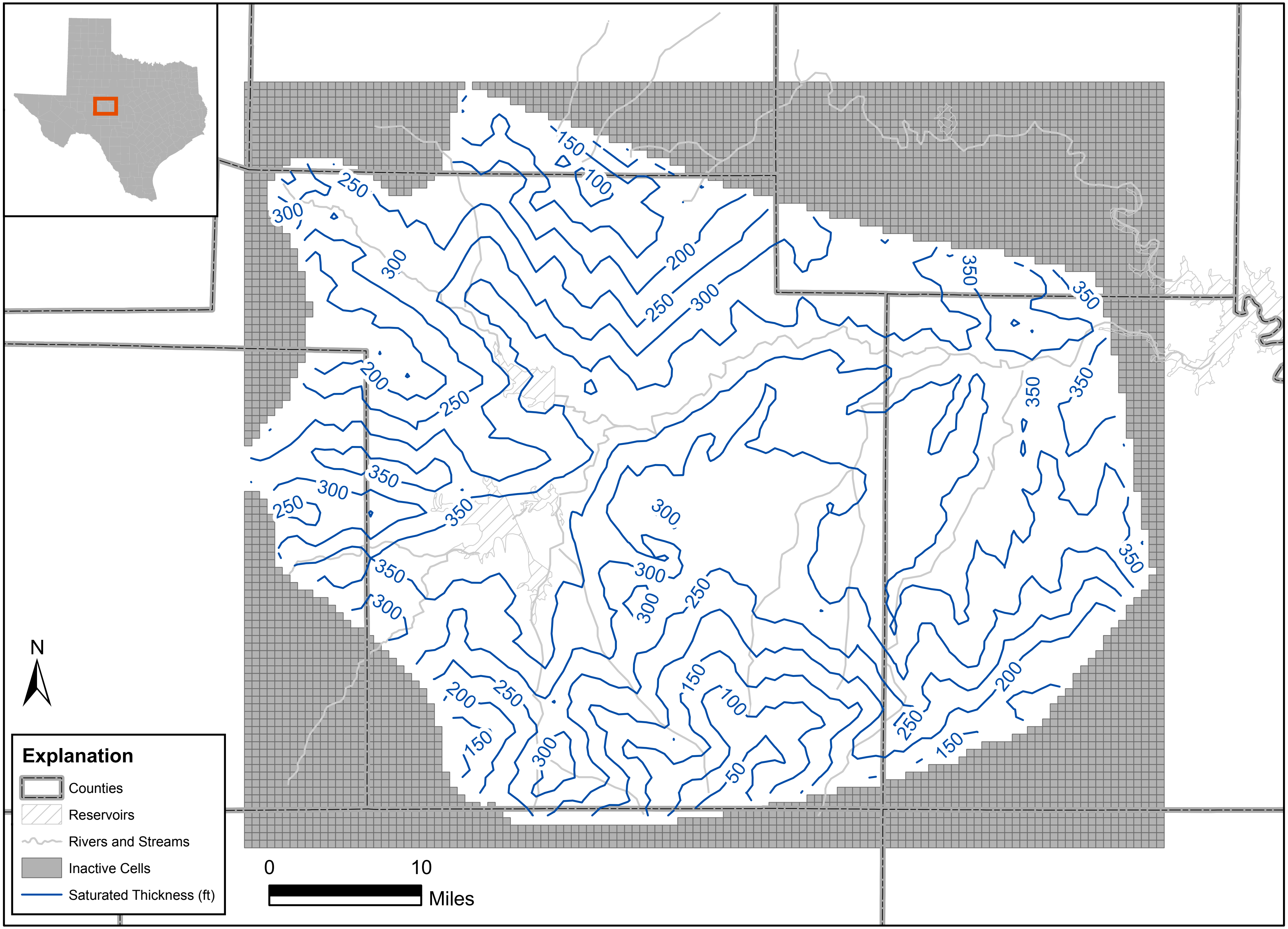

Figure 10.3.22 - Simulated Saturated Thickness in 2020 - 20-Year Drought of Record Simulation

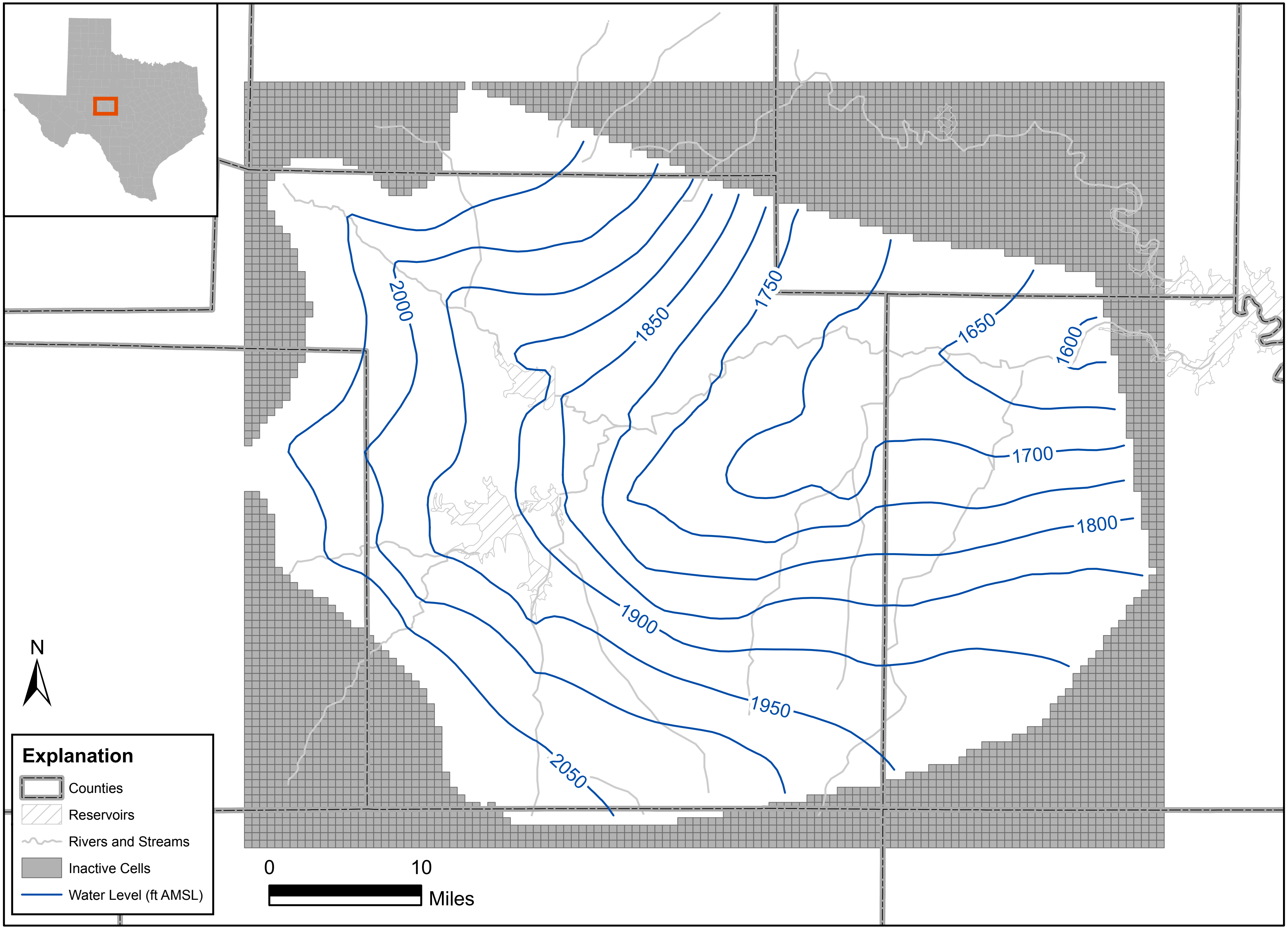

Figure 10.3.23 - Simulated Heads in 2030 - 30-Year Drought of Record Simulation

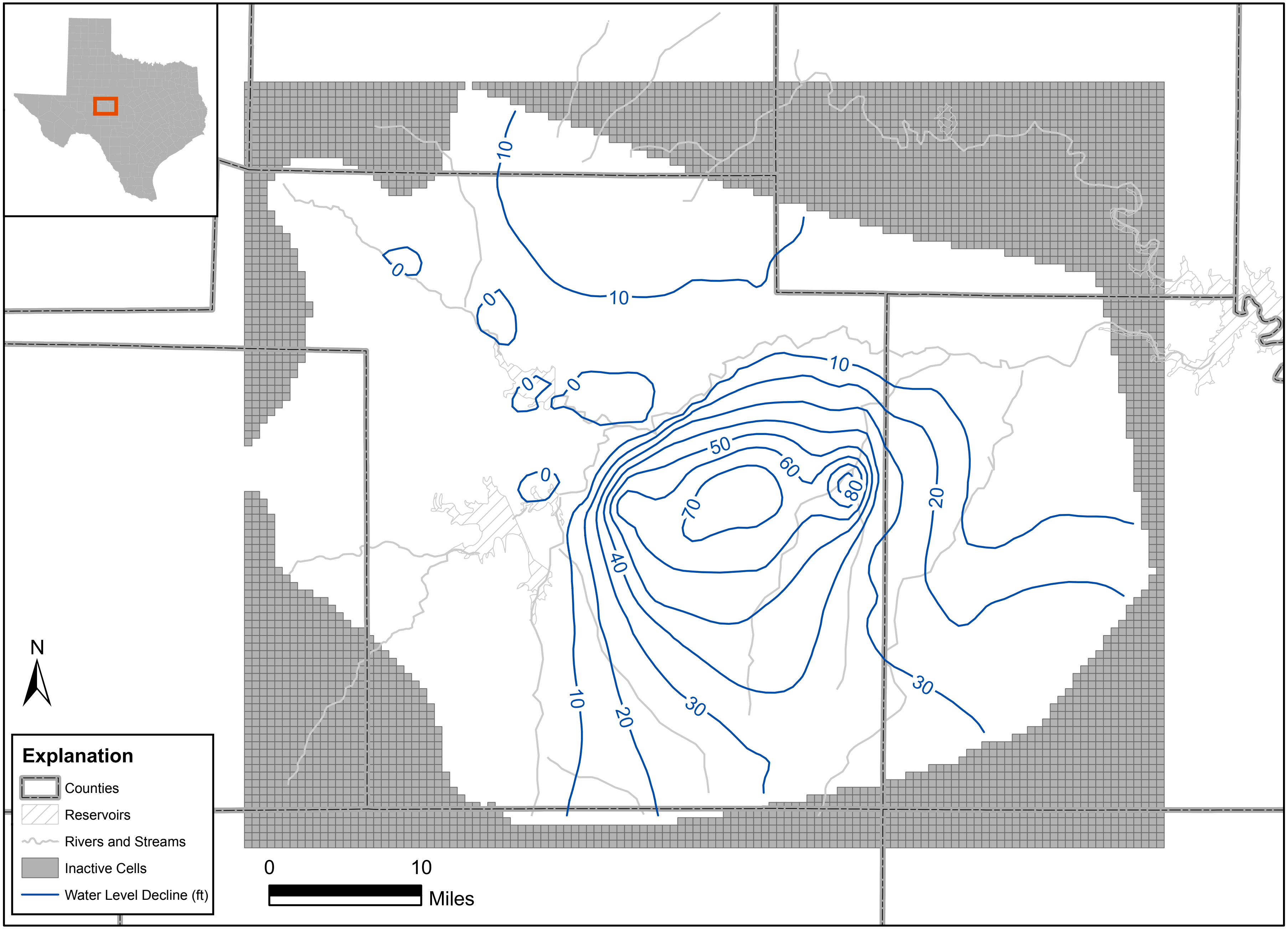

Figure 10.3.24 - Simulated Water Level Decline in 2030 - 30-Year Drought of Record Simulation

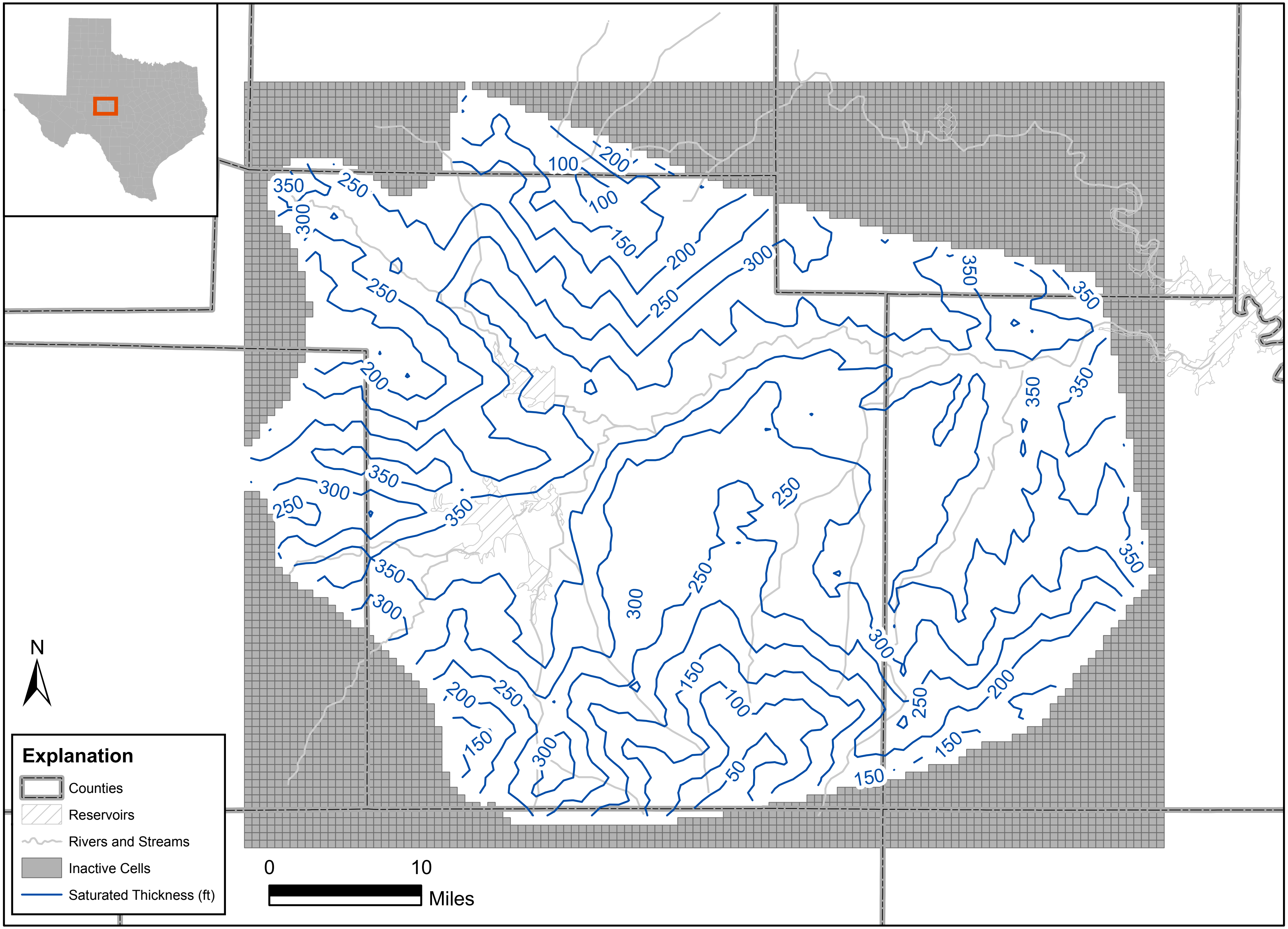

Figure 10.3.25 - Simulated Saturated Thickness in 2030 - 30-Year Drought of Record Simulation

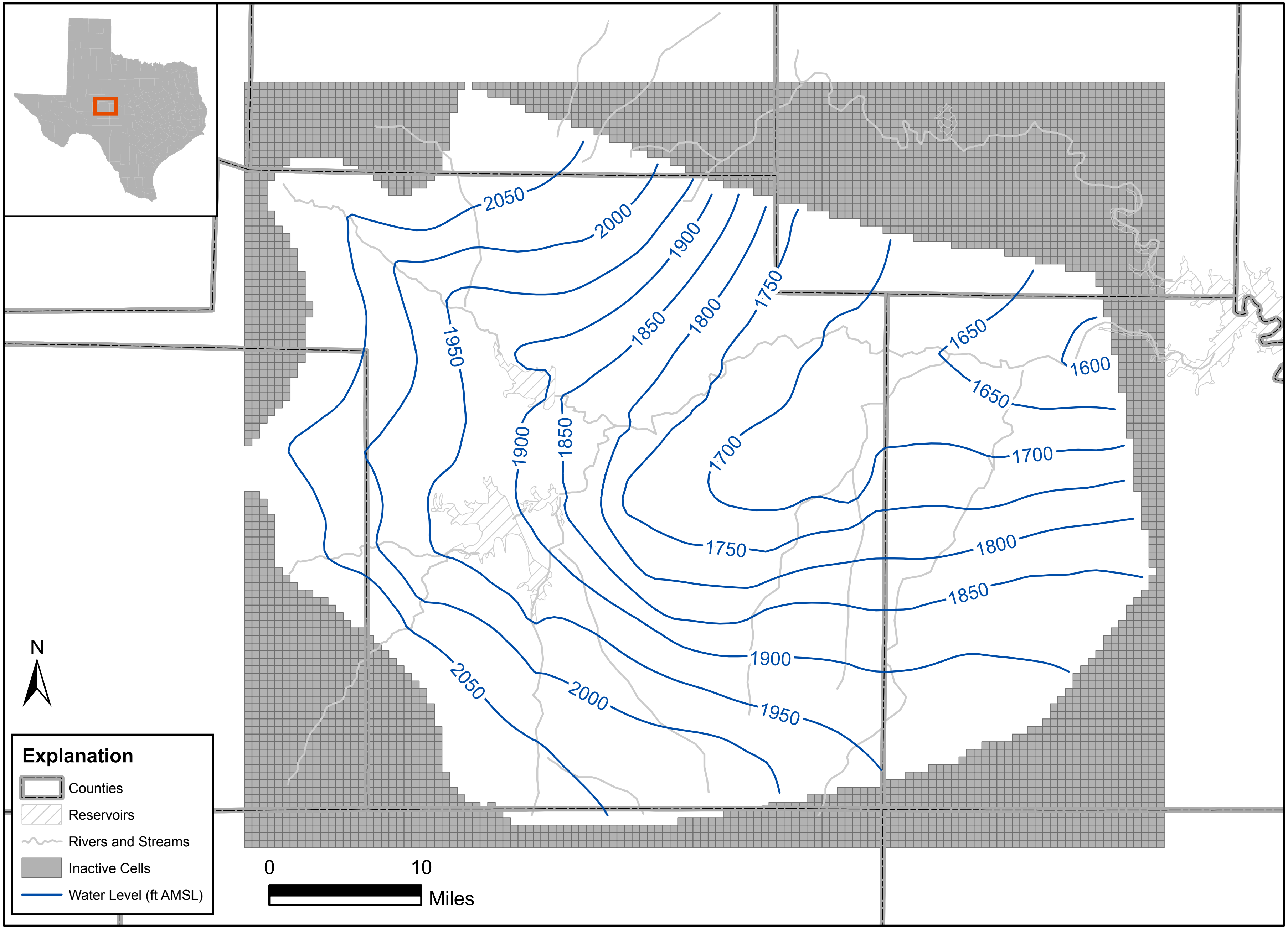

Figure 10.3.26 - Simulated Heads in 2040 - 40-Year Drought of Record Simulation

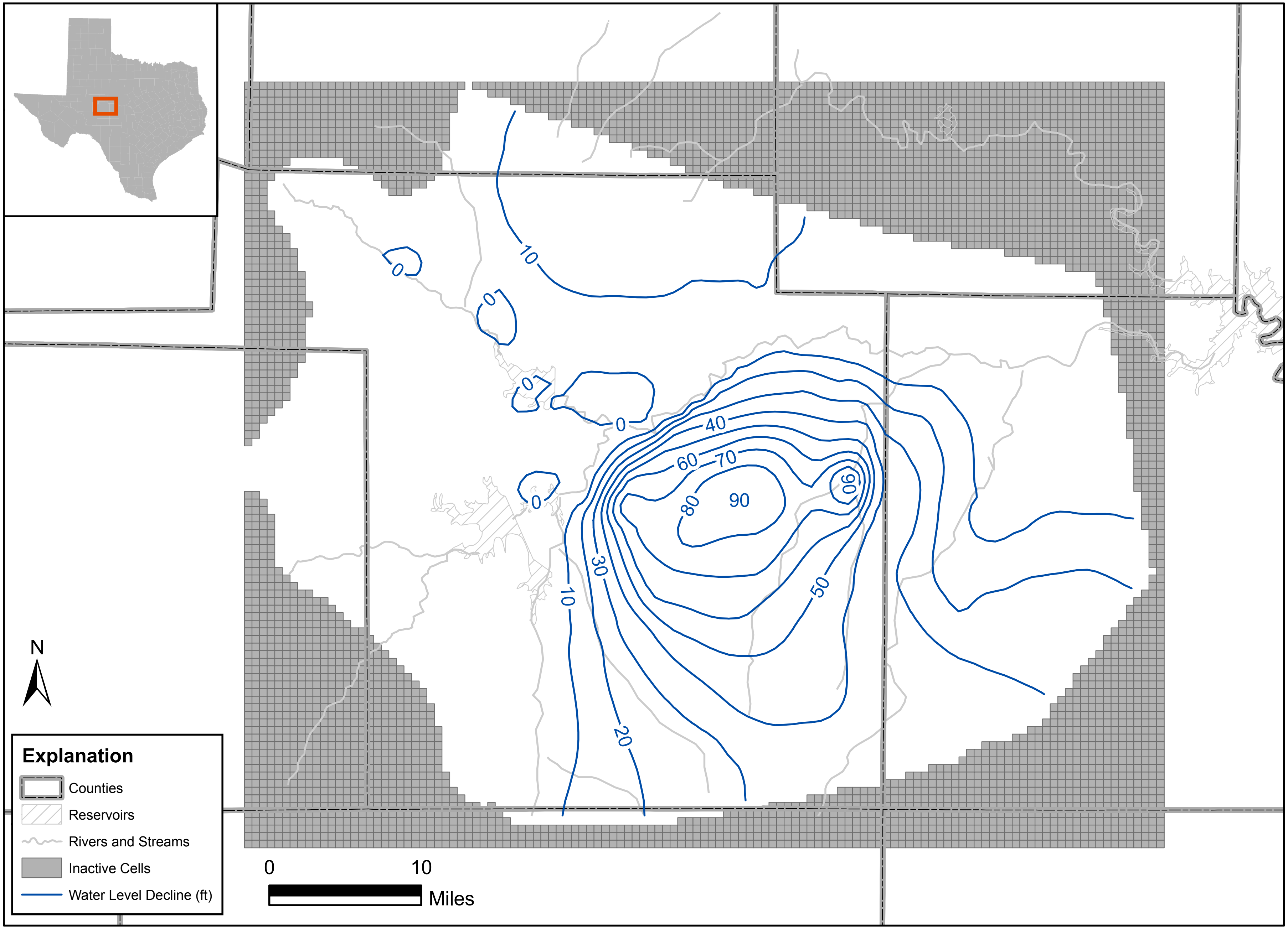

Figure 10.3.27 - Simulated Water Level Decline in 2040 - 40-Year Drought of Record Simulation

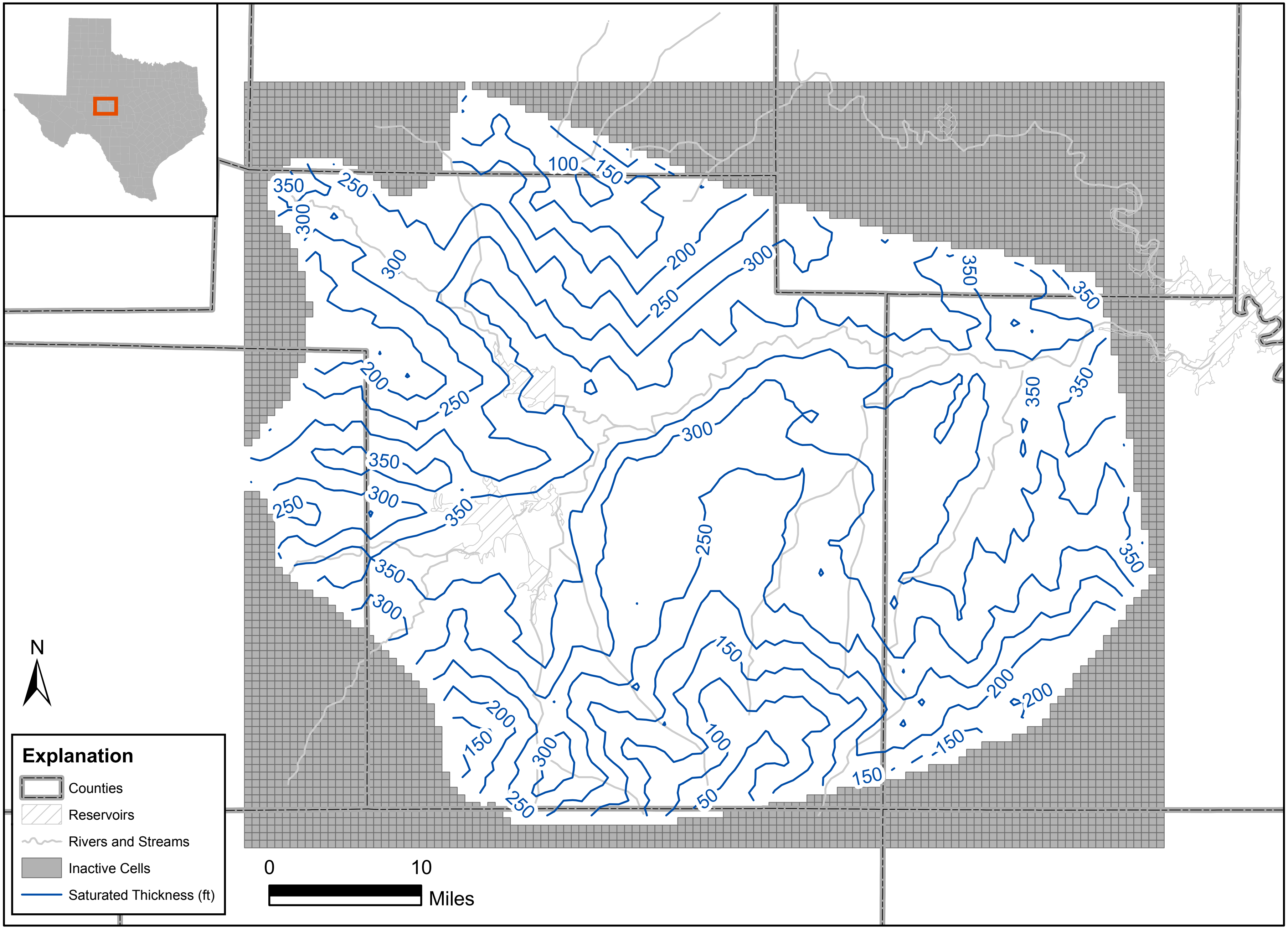

Figure 10.3.28 - Simulated Saturated Thickness in 2040 - 40-Year Drought of Record Simulation

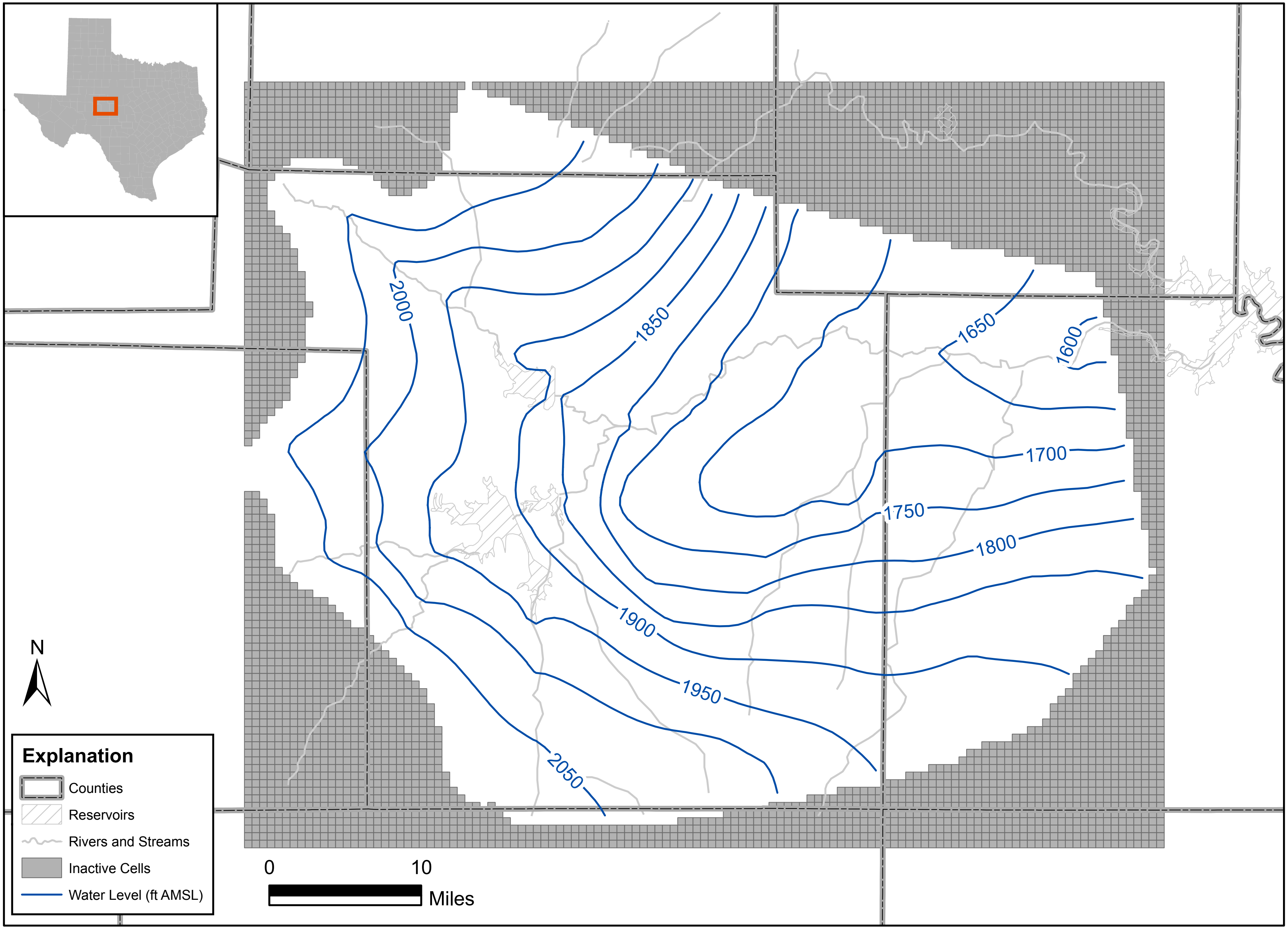

Figure 10.3.29 - Simulated Heads in 2050 - 50-Year Drought of Record Simulation

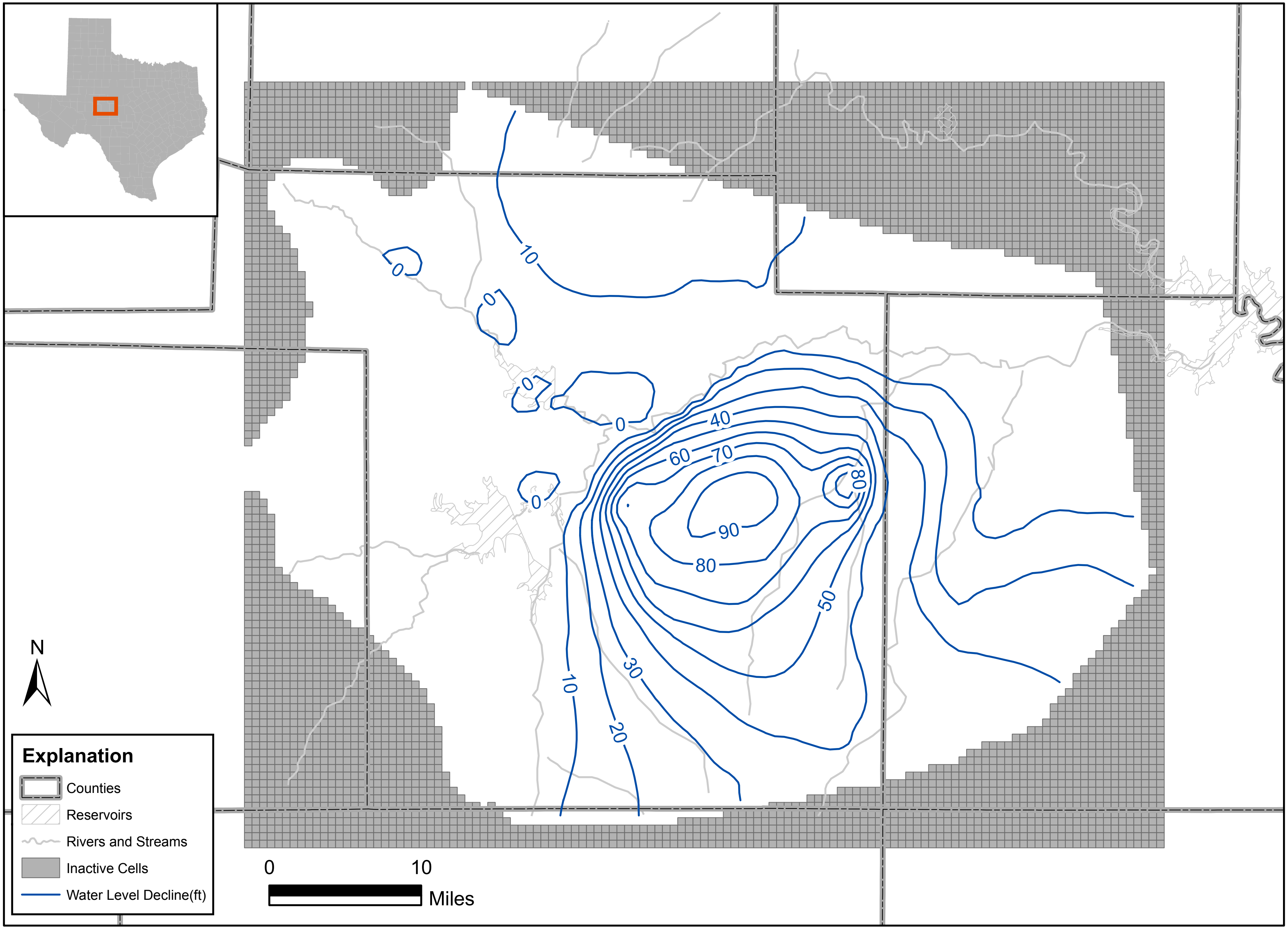

Figure 10.3.30 - Simulated Water Level Decline in 2050 - 50-Year Drought of Record Simulation

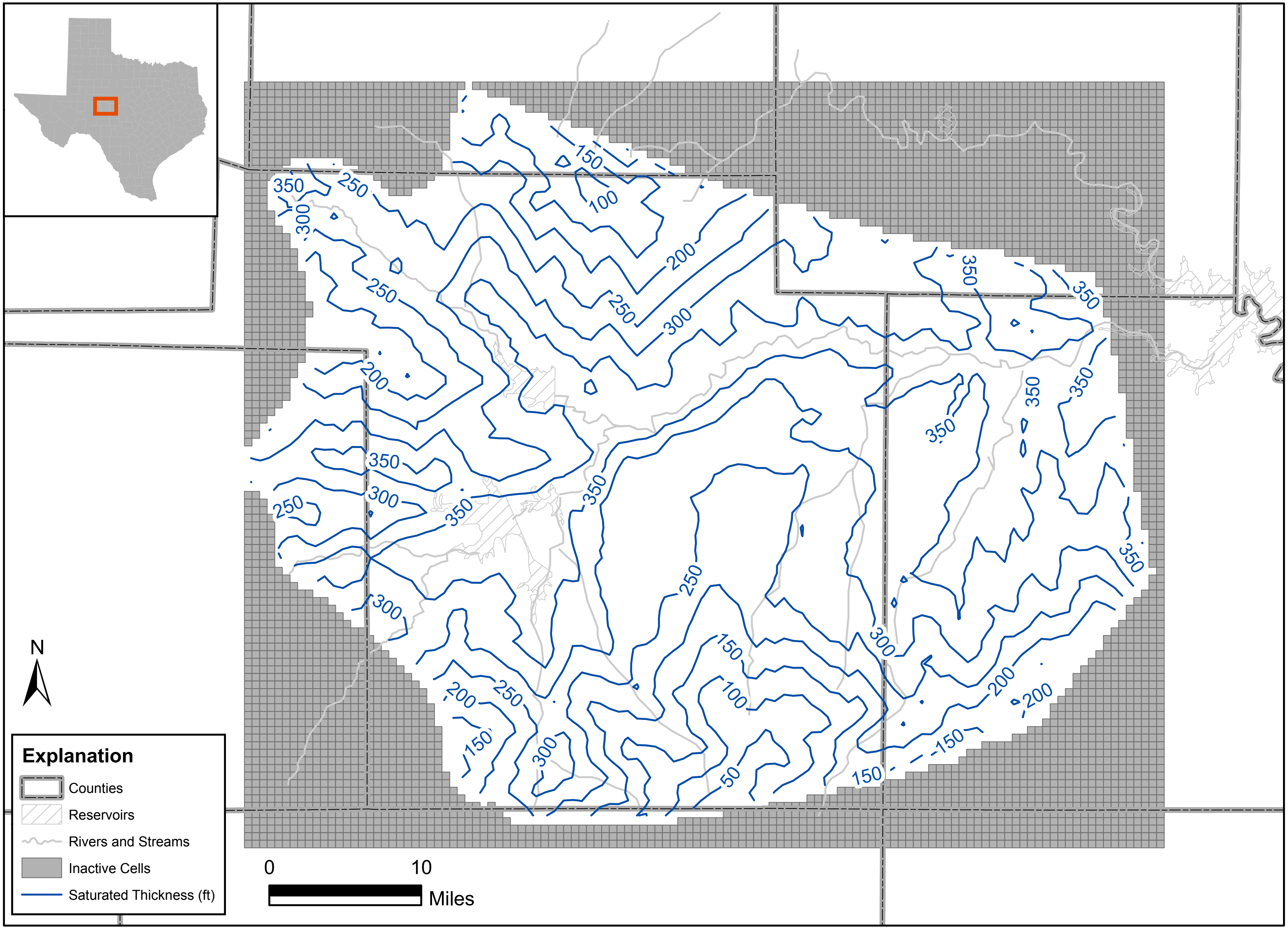

Figure 10.3.31 - Simulated Saturated Thickness in 2050 - 50-Year Drought of Record Simulation

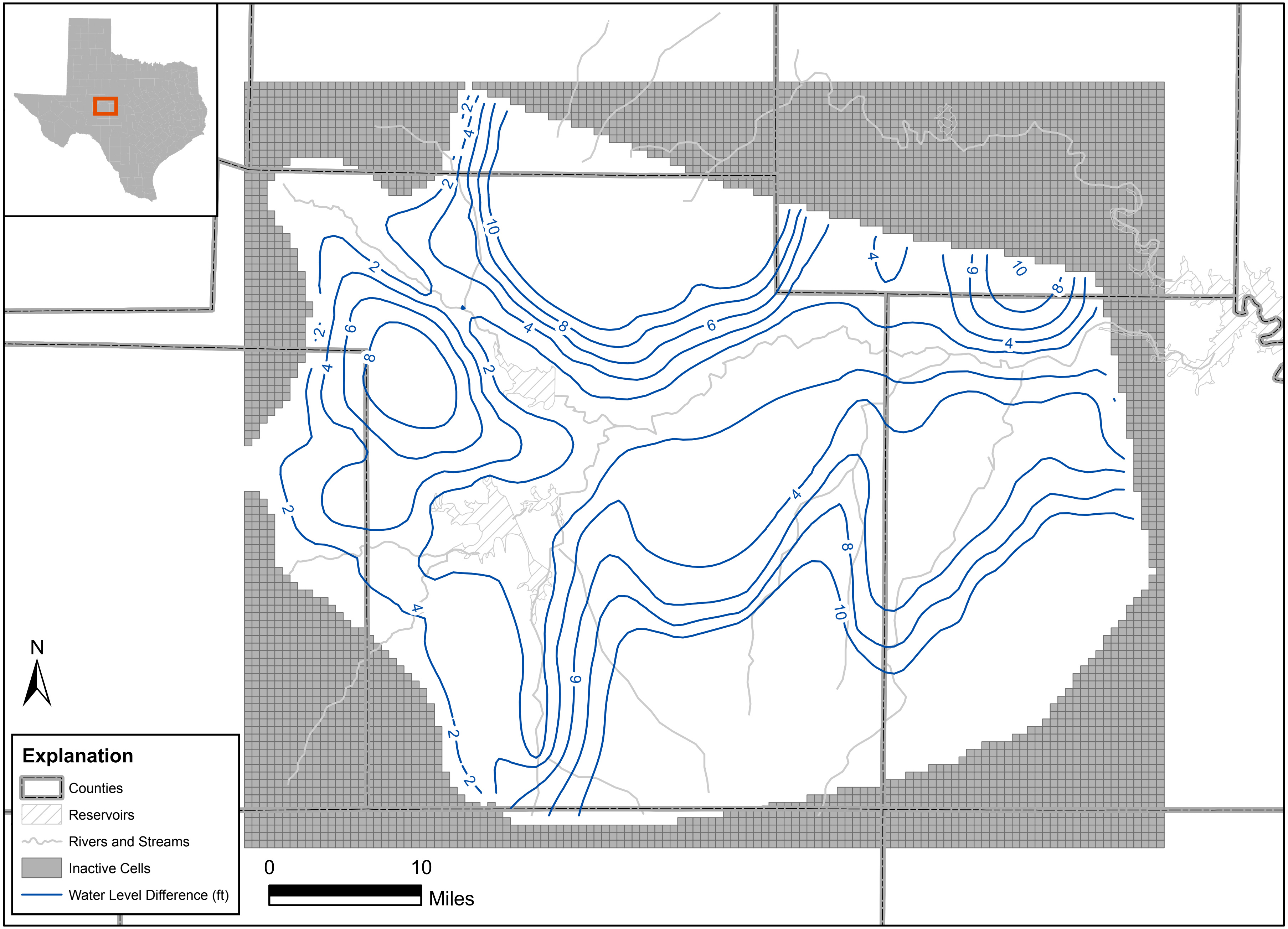

Figure 10.3.32 - Difference in Water Levels from 10-Year Drought of Record Simluation to 50-Year Average Recharge Simulation of 2010

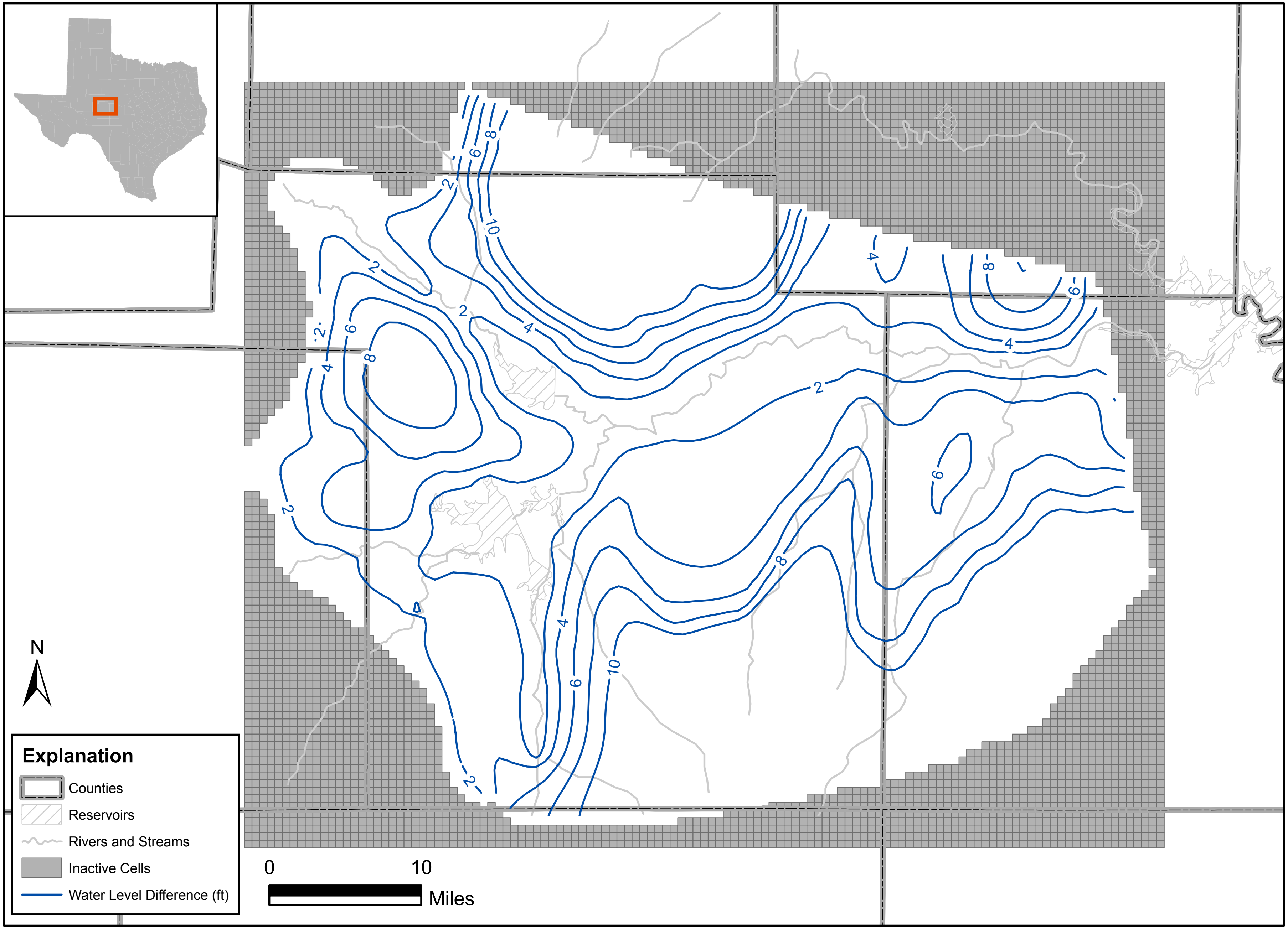

Figure 10.3.33 - Difference in Water Levels from 50-Year Drought of Record Simluation to 50-Year Average Recharge Simulation of 2050

10.4 Water Budget

This section presents a discussion of the 50-year drought of record water budget. Figure 10.4.1 shows a graph of all inflow and outflow components of the model for the 50-year drought of record simulation. This figure shows that much of the water pumped from the aquifer is coming from storage. Less water is available in storage as the heads drop due to pumping. In addition, as water levels drop, less water is lost to ET. When the drought of record begins in 2044, the drop in water levels migrates to the GHB boundary, causing a slight increase in flow through this boundary.

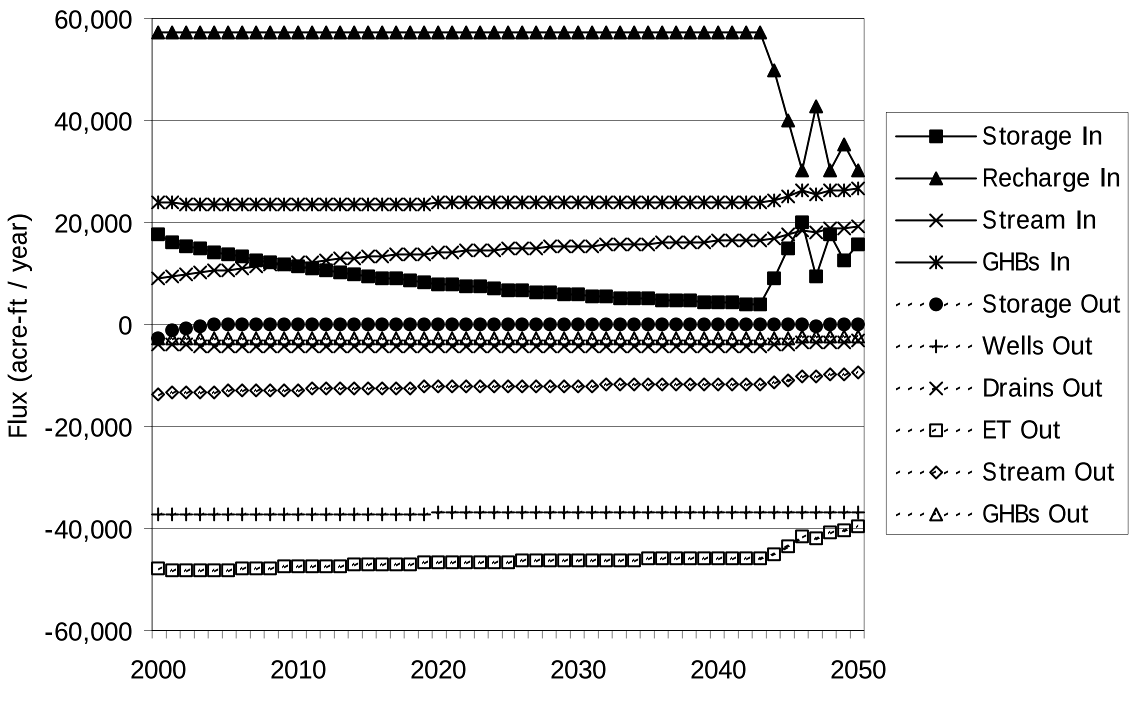

Figure 10.4.1 Water Budget for 50-year DOR Recharge Simulation

10.5 Water Level Declines in Irrigation Pumping Scenarios

Five addition scenarios were modeled to assess different long-term irrigation pumping in the Lipan aquifer. These five scenarios were all run for 50 years, from 2000 to 2050, with constant irrigation pumping for the duration. All other categories of pumping were the same as the predictive modeling discussed in Section 10.2. For these scenarios, irrigation pumping was held constant at a rate of 10,000 acre-ft/year in the first scenario, 20,000 acre-ft/year in the second, 30,000 acre-ft/year in the third, 40,000 acre-ft/year in the fourth, and 50,000 acre-ft/year in the fifth. The distribution of irrigation pumping remained the same in each scenario.

Figures 10.5.1 through 10.5.5 show the water level decline in the year 2050 for the five scenarios. Negative contours indicate an increase in water level. Each of these scenarios was started in 2000 with heads at the end of the transient verification period as the initial heads. For the 10,000 acre-ft/year scenario, shown in Figure 10.5.1, water levels rebound more than 25 feet in the Lipan Flats area. However, in the 20,000 acre-ft/year scenario shown in Figure 10.5.2, water levels decline more than 20 feet by 2050. Figures 10.5.3 – 10.5.5 show that as the constant irrigation pumping rate is increased from scenario to scenario, the water level decline in 2050 is more severe. In the 50,000 acre-ft/year simulation, water levels have dropped over 170 feet in 2050, which would effectively result in dewatering of the aquifer in some areas. These simulations indicate that, based on model results and the assumptions implemented here, average pumping of about 15,000 acre-feet per year would result in stable water levels in the Lipan Flats area. Obviously, the conclusion drawn from this assessment is very dependent on recharge estimates.

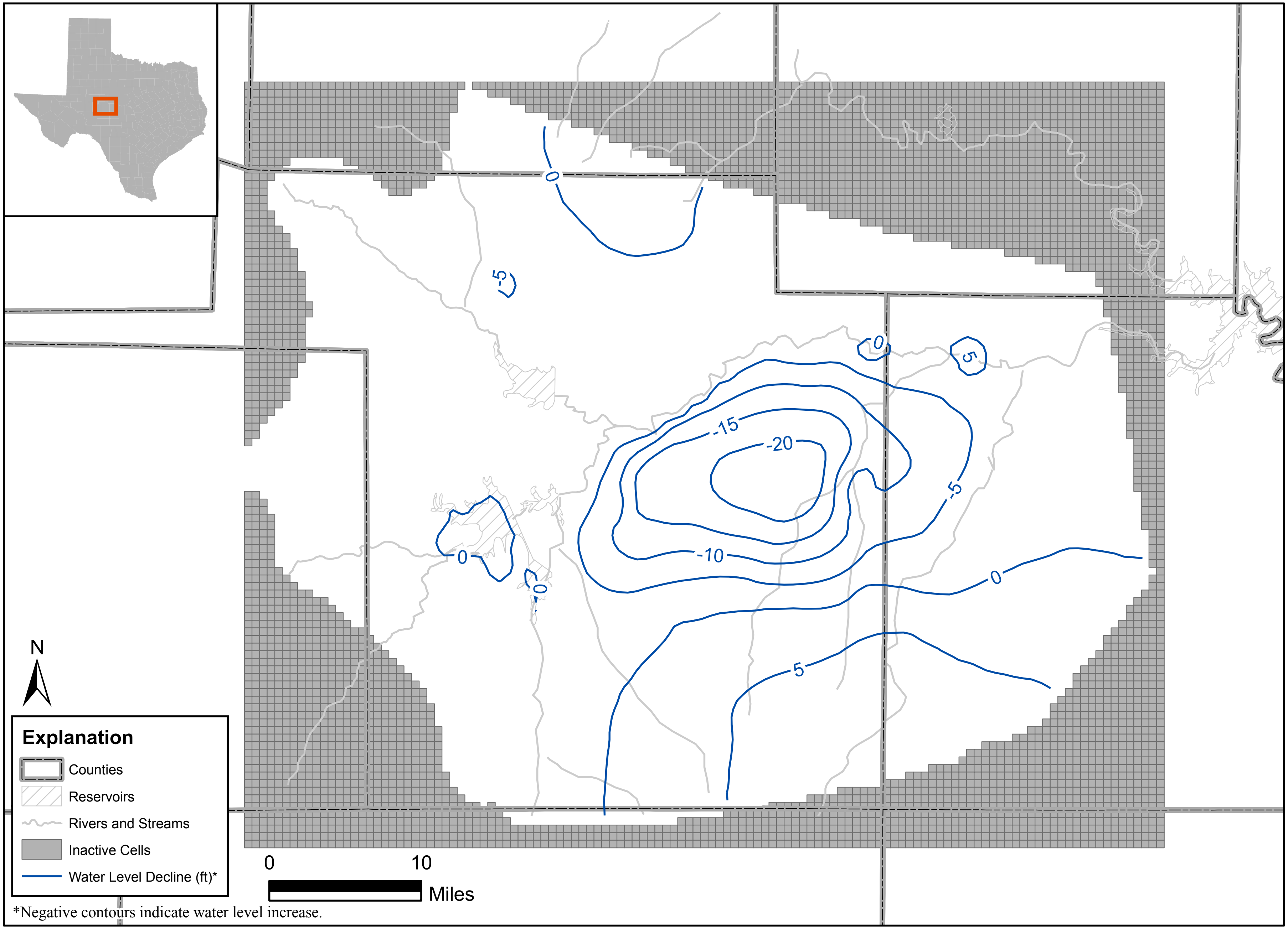

Figure 10.5.1 - Simulated Water Level Decline in 2050 with 10,000 Acre-ft/yr Irrigation Pumping in Tom Green County

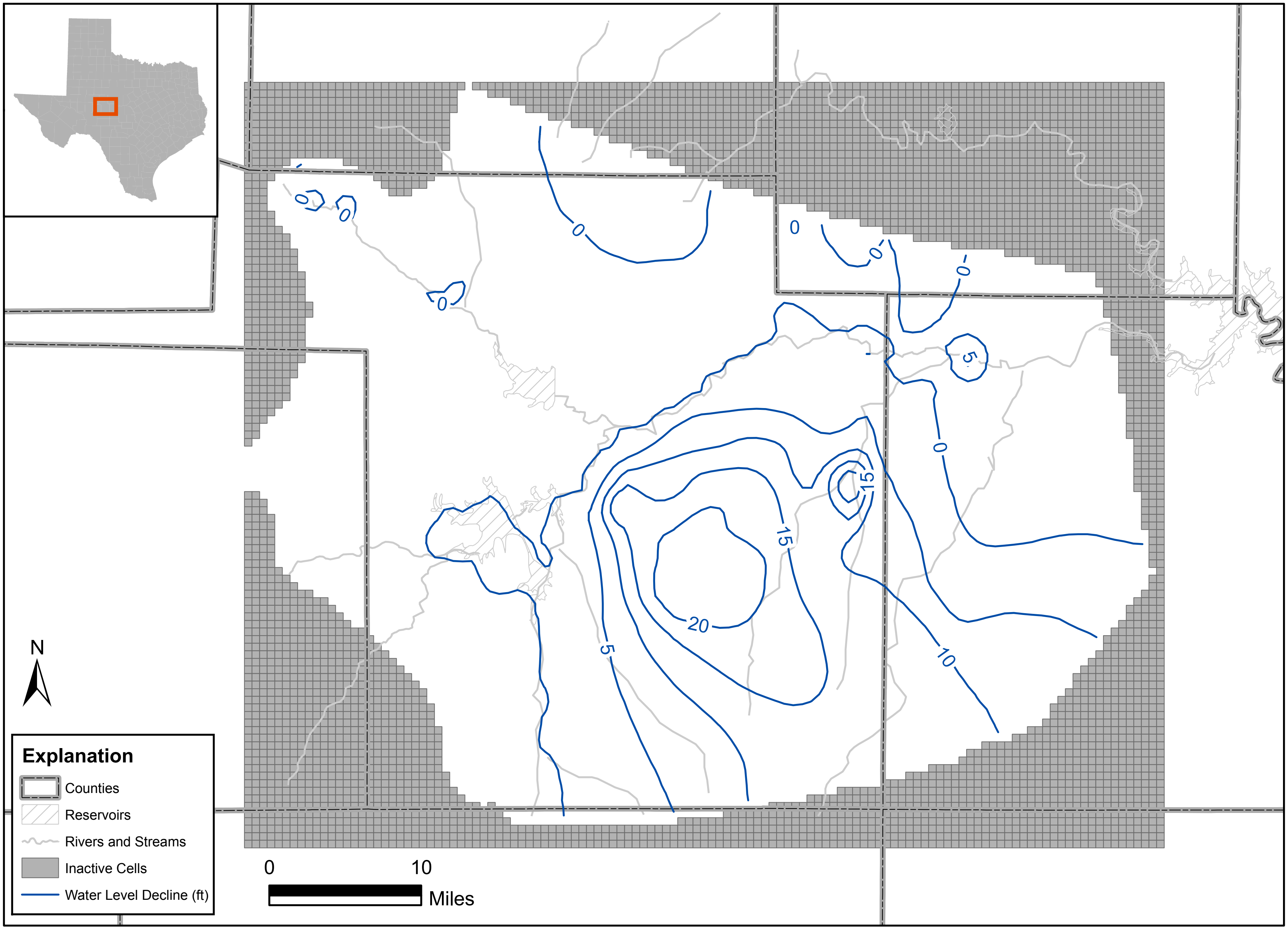

Figure 10.5.2 - Simulated Water Level Decline in 2050 with 20,000 Acre-ft/yr Irrigation Pumping in Tom Green County

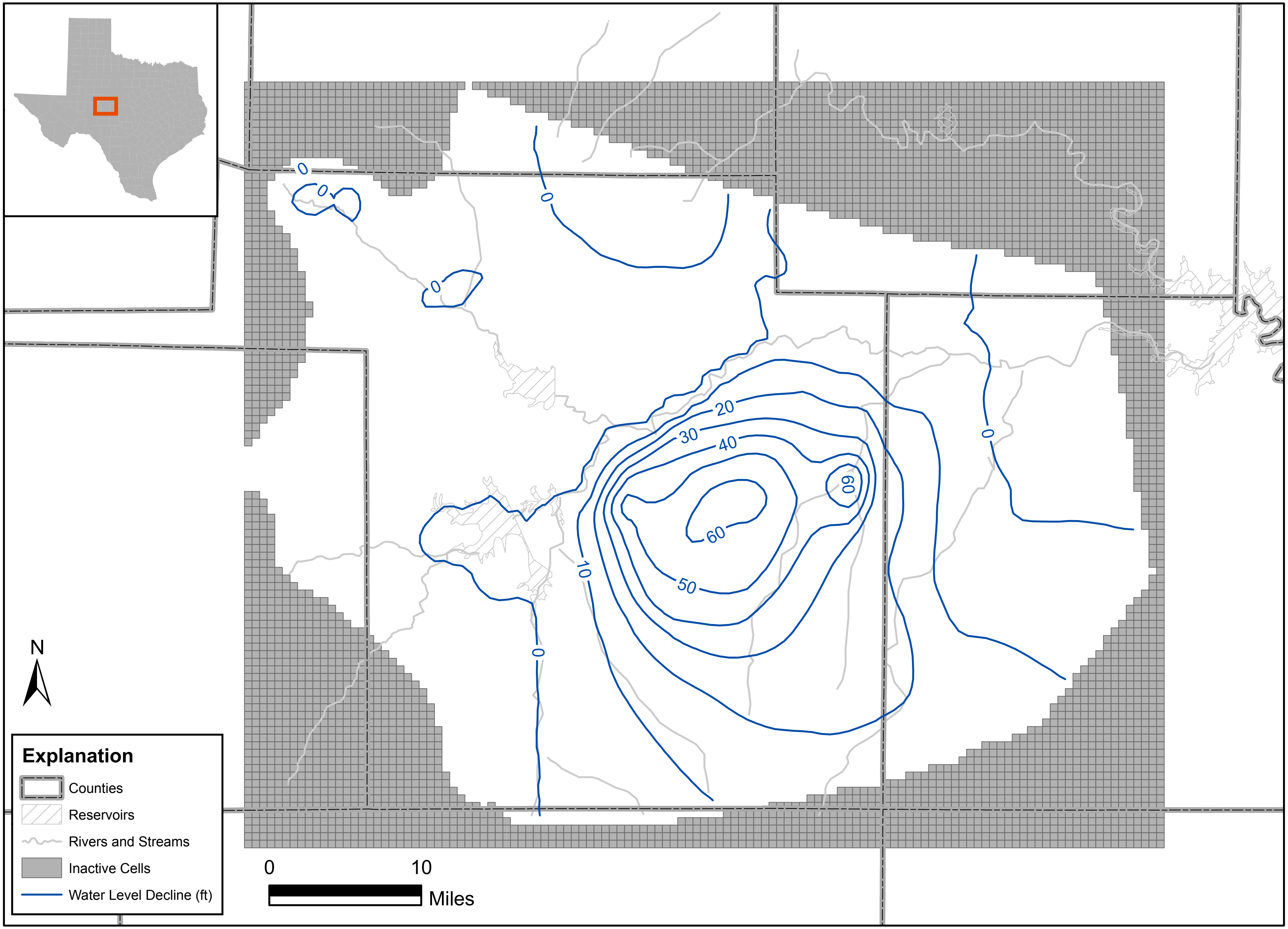

Figure 10.5.3 - Simulated Water Level Decline in 2050 with 30,000 Acre-ft/yr Irrigation Pumping in Tom Green County

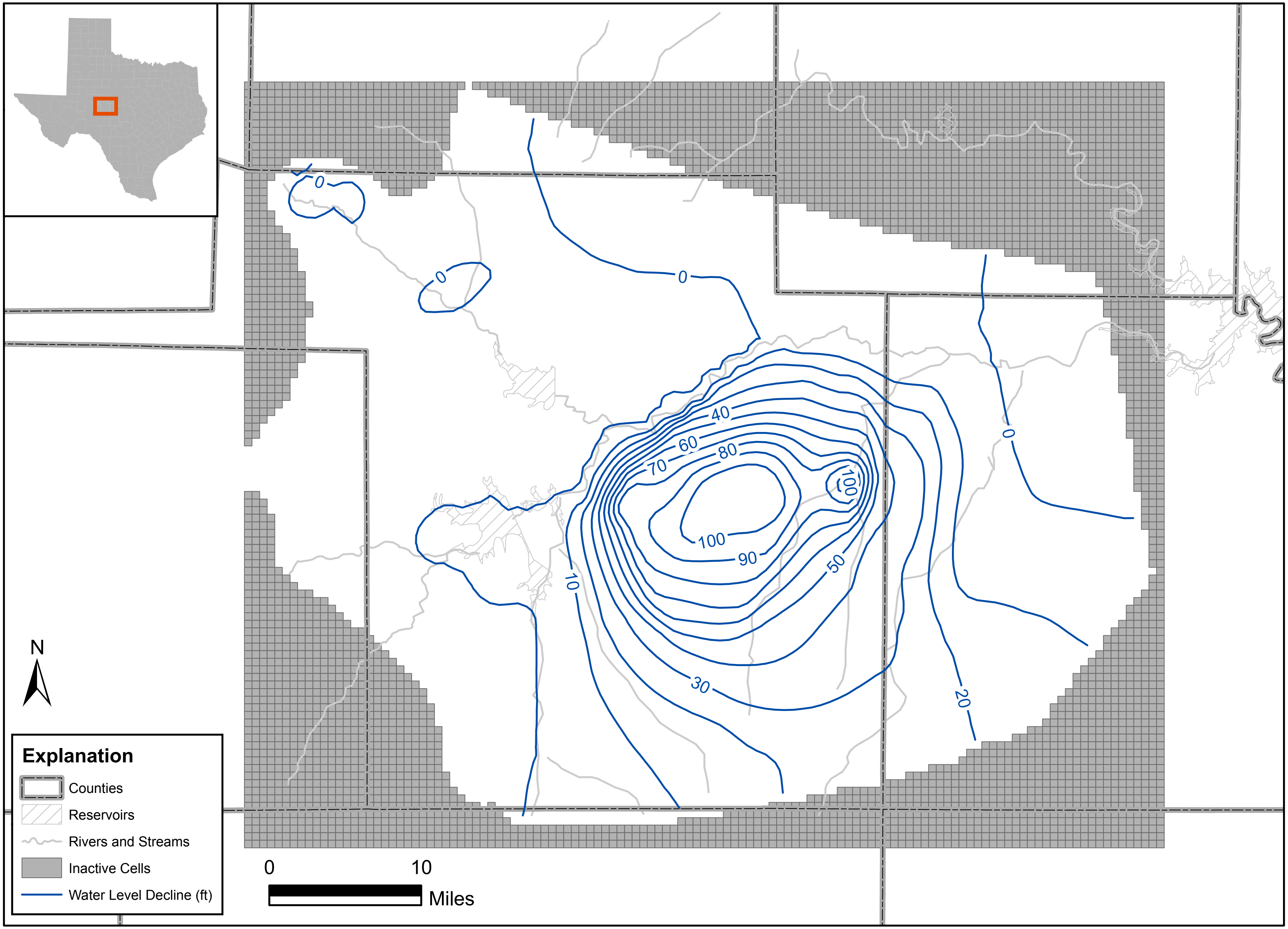

Figure 10.5.4 - Simulated Water Level Decline in 2050 with 40,000 Acre-ft/yr Irrigation Pumping in Tom Green County

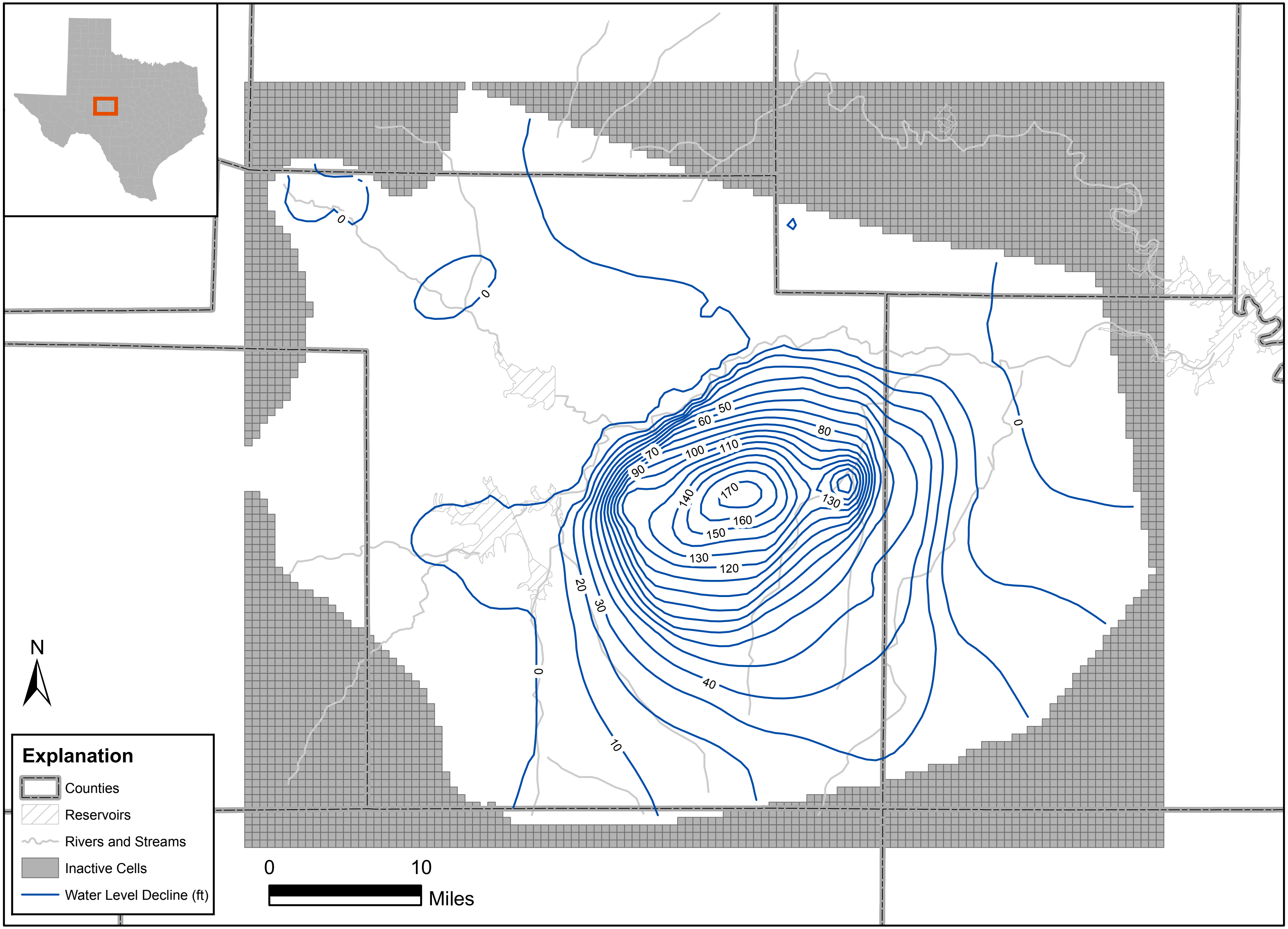

Figure 10.5.5 - Simulated Water Level Decline in 2050 with 50,000 Acre-ft/yr Irrigation Pumping in Tom Green County

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11.0 LIMITATIONS OF THE MODEL

A groundwater model is a tool to simulate aquifer responses to hydrologic stresses such as groundwater withdrawals and change in recharge conditions. However, the model will always be less complex than the natural system it is simulating, and as a result, every model has limitations. In addition, the accuracy of a model is dependent on the quantity, quality, and distribution of aquifer parameter information available. These limitations are discussed in the sections below.

11.1 Limitations of Supporting Data

The development of the Lipan GAM was limited by the quantity and quality of supporting data available for the aquifer. Many aquifer properties had little to no supporting data available in order to estimate these parameters. Water levels were sparse, especially prior to 1980, and water level measurements were not available prior to the aquifer "development" period.

Aquifer properties for the Lipan aquifer had to be estimated based on very limited data. As noted in Section 4, very little aquifer property data has been estimated from pumping test. Data limitations in the properties of the aquifer are obviously a significant limitation of the groundwater model.

Water level data, which were used as targets to evaluate the calibration of the model, were also limited. Because wells were installed in the aquifer to produce immediately, no water levels representing true "predevelopment" conditions exist, which is typical for aquifers throughout the state. Therefore, the steady state model had to be calibrated to water levels after pumping had begun.

Recharge is an important component in the overall water budget, and an important parameter in the groundwater model. Recharge was one of the parameters with significant sensitivity in both the steady state and transient models. Estimates of recharge vary significantly throughout the state and the region, and none are anything more than estimates. In other, similar, aquifers in the state, estimates of recharge vary widely, and therefore recharge cannot be uniquely determined or estimated. For the Lipan GAM, recharge was simply assumed equal to a percent of annual precipitation. A more detailed study of recharge in the area including determination of the mechanisms, preferred pathways, and limiting factors would decrease the uncertainty of this parameter in the model.

The lack of accurate pumping estimates from the Lipan aquifer is also a limitation in developing a well-calibrated model. Having a better understanding of the distribution of pumping would allow for better spatial allocation of pumping in the model.

11.2 Limiting Assumptions

Several assumptions were made during model development that produced inherent limitations to the accuracy of the model. These include the decision to use one layer to represent the Lipan aquifer and to use a constant thickness of 400 feet throughout. Although these assumptions are justified in light of the modeling objectives and data limitations, incorporating multiple layers within the model as better hydrogeologic data become available may produce a more robust model.

No-flow boundaries were used at the bottom of the aquifer as well as at the northern and southern boundaries of the model. The no-flow boundary condition at the base of the aquifer may unduly hinder groundwater flow from deeper regional systems.

Predictive runs were limited by the assumptions specified by the TWDB. Drought-of-record simulations used drought-of-record recharge, but did not use an increased amount of pumping to reflect production from the aquifer during drought-of-record conditions.

11.3 Limits for Model Applicability

MODFLOW is formulated to simulate flow in continuous porous media like sand and gravel aquifers. Flow in the Lipan aquifer occurs in fractures, karst conduits, and through the porous matrix. Simulating flow in such a complex system with MODFLOW offers significant limitations under some conditions. MODFLOW has been used successfully to simulate groundwater flow (i.e., regional heads, overall groundwater flow budgets, etc.) in karst and fractured flow systems. However, there are limits to the applications for the model.

The Lipan GAM is a regional model. This type of model is best suited to assess regional aquifer conditions, and for hydrologic conditions that are similar to available calibration data. This characteristic is an important limitation of the model and should be considered when drawing conclusions from the model.

The based of the Lipan aquifer was assumed to be 400 below ground surface. Most wells in the model area are less than 300 feet deep. A base of 400 feet below ground surface was selected because there is some water below 300 feet. However, in general, the quality and quantity of groundwater diminishes significantly below 300 feet. Because the saturated thickness maps are based on the base of aquifer assumption, the saturated thickness maps may overestimate availability in some cases. In most areas, actual well capacity would decrease significantly if the simulated saturated thickness drops below 100 feet. Therefore, the simulated saturated thickness of the aquifer should be used with this understanding when assessing the ground-water availability of the aquifer.

The Lipan model was developed using a grid scale of one-half mile by one-half mile. This means that the model is not capable of being used to make predictions or represent conditions in the aquifer at specific points, such as a specific well, or to evaluate water movement between two points located very close together, such as a leaky underground storage tank and a well located one-quarter of a mile away. Because the individual cells are one-half mile by one-half mile, the model is best suited to simulate regional responses and water balances. The response in a specific well to pumping from another well should not be simulated using the model.

The Lipan model does include streams with the MODFLOW stream-routing package. However, this is a very basic approach to coupling surface water to the aquifer, and is acceptable only for the purposes of groundwater modeling. The model should not be used as a surface water modeling tool.

The Lipan model was not developed and calibrated to address solute transport and water quality issues. Water quality is addressed in this report only as a preliminary assessment of the groundwater quality in the aquifer.

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12.0 FUTURE IMPROVEMENTS

The reliance on the Lipan aquifer model to predict future pumping and recharge scenarios means that the model should be improved and more data become available.

12.1 Supporting Data

Several types of data could be collected to better support the Lipan model, including additional aquifer testing, recharge studies, surface-water data, water level monitoring, and monitoring of pumping from wells.

One of the most glaring data limitations is the lack of available aquifer data based on aquifer testing. This data is important to the development of the model because the basic aquifer characteristics included in the model are based on these data. Additional aquifer testing would provide aquifer data that could be used in future updates to the Lipan model to help better define the characteristics of the Lipan aquifer.

Better estimates of recharge would reduce the model uncertainty significantly. Recharge studies could provide some solid data on the amount of recharge actually received by the aquifer under various conditions. The interaction between the Lipan aquifer and surface water should be investigated further. The influence of the reservoirs, if they have any, is not well understood at this time.

If the model is to be improved in the future, additional pumping data is critical. Actual pumping measurements should be made on at least some of the irrigation wells in the region to gain a better understanding of pumping trends.

12.2 Model Improvements

In addition to future model improvements based on the additional data recommended in Section 12.1 above, the model could be improved in several ways. Investigation of the interaction of the Lipan aquifer and the Edwards-Trinity (Plateau) aquifer would also be an improvement on the model. The model would also be improved by obtaining more recent surface/groundwater interaction information, as well as better estimates of evapotranspiration from the aquifer.

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13.0 CONCLUSIONS

A groundwater model was developed for the Lipan aquifer. The 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 and verification, (4) sensitivity analysis, (5) model prediction, and (6) documentation of the model. The groundwater availability model was developed to provide a scientific, quantitative tool to evaluate impacts of pumping and drought in the study area and to assist in regional water planning efforts and aquifer management decisions.

One purpose of this Lipan GAM is to provide predictions of groundwater availability through the year 2050 based on current groundwater demand projections during average and drought-of-record hydrologic conditions. The Lipan GAM integrates all of the available hydrogeologic data for the study area into the flow model that can be used as a tool for the assessment of water management strategies. Because the model and the supporting data is publicly available, it can be used by planners, Regional Water Planning Groups (RWPGs), Groundwater Conservation Districts (GCDs), and other entities to assess groundwater conditions under various scenarios.

The Lipan GAM is regional in scale, and was developed with the MODFLOW flow code. The conceptual model was based on data compiled from many sources and included a detailed evaluation of the hydrogeologic information available in the model area. Available hydraulic conductivity, aquifer storage properties, pumping information, 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 well. Sensitivity analysis indicates that the most sensitive parameters in the model are hydraulic conductivity and recharge. Calibration of the transient model from 1980 through 1999 incorporated historical pumping and variable recharge. In general, the transient simulated water levels exhibit the same trends as observed hydrographs.

The calibrated model was used to predict water level declines between 2000 and 2050 by incorporating projected groundwater demands developed by the Region F RWPG. Average and drought-of-record recharge conditions were simulated in the predictive simulations. Results from the predictive simulations indicate that currently proposed groundwater demands on the Lipan aquifer might result in continued water level declines in the future.

The Lipan GAM model is a valuable tool for evaluating proposed pumping and various drought conditions in the Lipan aquifer. Although the model can be used to simulate regional groundwater flow in the Lipan aquifer, it has limitations and is not applicable for some problems. However, the Lipan GAM does provide a well-documented tool for evaluating regional groundwater availability in the model area.

14.0 ACKNOWLEDGEMENTS

The successful completion of a major modeling project, such as this Lipan GAM, requires the cumulative knowledge, assistance, and backing of many individuals and groups outside the modeling team itself. The Lipan GAM Stakeholder Group provided vital input to the project. Comments provided by this group were critical in attaining a historical perspective on the groundwater response to the long-term use of local aquifers.

Special thanks are extended to the Lipan-Kickapoo Water Conservation District for their support and assistance in providing needed local well information and landowner contacts. In particular, Allan Lange is deserving of special appreciation for his personal interest in this project. Special thanks also to Scott McWilliams for providing help with understanding the correlation between the driller's logs and aquifer materials.

Finally, we wish to thank the Texas Water Development Board for its forward thinking in developing and funding the statewide aquifer GAM program. TWDB offered guidance and assistance in completing this Lipan GAM. Richard Smith (contract manager) and Cindy Ridgeway (program manager) are deserving of special thanks for their direct involvement.

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Appendix A

Responses to TWDB Comments

CONCEPTUAL DRAFT REPORT TECHNICAL/ADMINISTRATIVE COMMENTS:

1.0 INTRODUCTION

Comment: Section 1.0/page 1-2 to 1-3: The last paragraph states the predictive simulations will be based on the most recent groundwater demands. The data provided by TWDB was based on information from the 2002 State Water Plan. Please clarify. Region F most current demands for the next round of planning are still under review by TWDB staff.

Response: *Changed text to reflect source of water demand based on data in the 2002 State Water Plan.*

2.0 STUDY AREA

Comment: Figure 2-4/page 2-5: A more recent coverage of GCDs is available over the internet at http://www.twdb.state.tx.us/mapping/gisdata.html . Please update figure with the current coverage or please add a disclaimer stating the date coverage was developed per the metadata file.

Response: *Downloaded and used most recent.*

Comment: Section 2.1/pages 2-6 to 2-7, and 2-19: Please update references to figures in the text to include section i.e. Figure 2-5, Figure 2-11, Figure 2-16, etc. instead of Figure 5, Figure 6, etc. Also, in Figure 2-7, further explanation is needed.

Response: *Updated*

Comment: Per Exhibit B, Attachment 1, Section 3.1.1: The physiography and climate section shall also describe the river basins in the study area. Please update this section describing the river basins. Per Exhibit B, Attachment 1, Section 5.4 please include a map of the river basins in the study area.

Response: *Added map and discussion of river basin the study area.*

Comment: Per Exhibit B, Attachment 1, Section 5.4: Several plots of historical precipitation measured at rain gauges in study area shall be included. Figure 2-9 shows the average historical precipitation in the study area. Please clarify since the study area is comparatively small that when the individual rain gauge data is plotted no discernable differences between locations were observed.

Response: *Added plots of rainfall and discussed.*

4.0 HYDROGEOLOGIC SETTING

Comment: Base of the alluvium and alluvium thickness. The contractor used well logs (fig. 4-1, 4-2) to define the base of the alluvium but does not appear to have used the limit of the alluvium to constrain this information. The result is greater than zero thicknesses at the edges of the alluvium (fig. 4-3). The contractor needs to include edge information in their analysis of the alluvium.

Response: *The data used to create these figures is very sparse and does not reflect the extents of the aquifer as defined by the Texas Water Development Board*

Comment: The contractor needs to clip their water-level contours to reflect the limits of the actual data (fig. 4-4, 4-5, 4-6, 4-7).

Response: *Figure 4-4 removed. All other figures used data outside of the study area, however, the contours were clipped at the study area boundary. This is reflected in the text.*

Comment: Section 4.6/pages 4-25 to 4-37: Per Exhibit B, Attachment 1, Section 5.4 representative stream-flow hydrographs for the major streams in the study area shall be included with a map indicating gage locations, hydrographs of lake levels (if appropriate), and spring flow hydrographs with a map indicating spring locations. Please update this section with these figures, as data allows.

Response: *Updated*

Comment: Section 4.7.1/page 4-38: Second paragraph references figure 4-23 (which is the location of the springs in the study area). Please correct reference to figure. There are two figure 4-25's with the same caption. Please clarify if the first figure should be Figure 4-24 with the caption "Relative Magnitude of Specific Capacity" and update appropriately.

Response: *Corrected*

Comment: Section 4.7.1/page 4-39: First sentence references Figure 4-24. Please clarify if this should reference Figure 4-25, and update appropriately.

Response: *Updated*

Comment: Section 4.7.1/page 4-42: First sentence references Mace (2000). The reference section lists Mace 2001, please clarify the date of publication and update appropriately.

Response: *Updated*

Comment: Section 4.7.1/page 4-42: First paragraph references figure 4-23 (which is the location of the springs in the study area). Please correct reference to figure 4-24 and verify the first figure 4-25 should be re-labeled to Figure 4-24.

Response: *Corrected*

Comment: Section 4.8/page 4-44: Second paragraph discusses annual and monthly pumpage. Per contract amendment for fiscal year 2004, consultants were given the option not to develop monthly stress periods. If the consultant opts to model a three-year period with monthly stress periods during the calibration and verification runs surrounding a drought period then we suggest following the directions in Technical Memorandum 02-02 on how to develop the pumpage on a monthly basis. Please contact TWDB staff if additional information is needed.

Response: *Deleted because only yearly stress periods are used.*

Comment: Section 4.8.2/page 4-51: Per Exhibit B, Attachment 1, Section 5.4, please update this section with a map showing rural population densities.

Response: *Updated*

6.0 DRAFT REPORT - SECTION 6.0: REFERENCES

Comment: Missing reference for BEG, 1996 (page 2-6), NRCS, 1994 (page 4-18), and references listed for Table 4-2 (page 4-25),

Response: *Corrected*

<u>CONCEPTUAL DRAFT REPORT EDITORIAL COMMENTS:</u>

2.0 STUDY AREA

Comment: Figure 2-16/page 2-22: Under Description and Water-Bearing Characteristics please use lower case “L” for limestone in first description.

Response: *Changed*

4.0 HYDROGEOLOGIC SETTING

Comment: Section 4.2/page 4-2: Please update sentence," Figure 4-2 shows the elevation of the base of the alluvium and the locations of the geophysical [logs?] used for this evaluation".

Response: *Updated*

Comment: Section 4.3.3/page 4-8: Please correct first sentence from, "The potentiometric surfaces indicate that groundwater generally flow slaterally into the Lipan aquifer system from the water-bearing units located to the north, south, and west" to "The potentiometric surfaces indicate that groundwater generally flows laterally into the Lipan aquifer system from the water-bearing units located to the north, south, and west"

Response: *Corrected*

Comment: Figures 4-8 through 4-11: Suggest using same interval for vertical scale so comparisons may be made between hydrographs.

Response: *Same range is used on all graphs except one which is an Edwards graph.*

Comment: Section 4.8.1/page 4-45: Please update the fourth sentence with parenthesis around "Figure 4-26".

Response: *Changed in Final*

DRAFT REPORT- SECTION 6.0: REFERENCES

Comment: Please expand reference for Bush, Ardis, and Wynn (1993) to include first names or initials.

Response: *Expanded*

Comment: Please use a period after the date instead of a comma.

Response: *Corrected*

CONCEPTUAL DRAFT DATA SOURCE FILES COMMENTS:

Comment: Disk #1: Drive: Leon/grddata contains readme files, but no metadata files

Response: *Metadata files included*

Comment: Disk #1: Drive: Leon/modflow contains one readme file, other files to be completed.

Response: *All files included*

Comment: Disk #1: Drive: Leon/report contains Arcview figures and PDF figures for report.

Response: *Yes*

Comment: Disk #1: Drive: Leon/srcdata contains all data for the model but no metadata files.

Response: *Metadata added*

Comment: Disk #2: Drive: Leon for TWDB/grddata contains readme files, but no metadata files.

Response: *Metadata added*

Comment: Disk #2: Drive: Leon for TWDB/modflow contains one readme file, other files to be completed.

Response: *Completed*

Comment: Disk #2: Drive: Leon for TWDB/report contains Conceptual model report in PDF format and figures in PDF and Arcview.

Response: *See Final CD*

Comment: Disk #2: Drive: Leon for TWDB/srcdata contains Arcview files, needs metadata files and readme files to explain data sets.

Response: *See Final CD*

DRAFT FINAL REPORT TECHNICAL/ADMINISTRATIVE COMMENTS:

General Comments:

Comment: Line 7 of page 11, Exhibit B clearly states " Root mean square error between measured hydraulic head and simulated hydraulic head should be less than 10 percent of the maximum hydraulic head drop across the model area and better, if possible at the end of the calibration period and at the end of the verification period." Table 9.4.2 on page 9-14 of the draft final report indicates a root mean square error of almost 16 percent. This must be reduced to 10 percent or less before final acceptance of the report.

Response: *Data calculation error corrected.*

Comment: Pagination including formatting figures with page numbers and using a consistent system of referencing and labeling figures and tables will be necessary prior to final acceptance of the report. In your final report please include the review comments from the conceptual draft review with your responses, as well as your responses to the comments listed below.

Response: *Corrected*

Comment: Exhibit B, Attachment 1, Section 5.4, last paragraph states each report shall have an authorship list of persons responsible for the studies: firm or agency names as authors will not be acceptable. Please provide this information with the final report. In addition, with the new rules concerning geoscientists operating in the State of Texas working on state-related projects, please have the appropriate person or persons seal the final report using the guidance provided by the Texas Board of Professional Geoscientists (www.tbpg.state.tx.us).

Response: *Corrected*

ABSTRACT

Comment: Per Exhibit B, Attachment 1, Section 5.4 Final Report: the ‘Abstract’ shall be a brief summary of the modeling effort and discuss the modeling results. Please submit the final report with an abstract.

Response: *Abstract added*

TABLE OF CONTENTS

Comment: Figure 2.1.1 is listed in the List of Figures as appearing on page 2-1, please update to reference as page 2-8 in both the List of Figures and in the figure. The pages in the remainder of the section are not sequential. Please adjust the pages in the text and all references in the Table of Contents and List of Figures accordingly. Please add page numbers to all the figures in the report as discussed above.

Response: *Corrected*

Comment: Section 8.0 begins with page 8-6, please re-paginate section beginning with 8-1 and adjust all references in the Table of Contents, List of Figures, and List of Tables accordingly.

Response: *Corrected*

Comment: Section 9.0 is missing page 9-5 and Figures 9.7.2 and 9.7.3 appear on pages numbered as 9-1 and 9-2 in the back of the section, please re-paginate section. For example, Section 9.3 should begin on page 9-5 instead of 9-6. Please adjust pagination and update all references in the Table of Contents, List of Figures, and List of Tables accordingly.

Response: *Corrected*

Comment Section 10.0 begins with page 10-3, please re-paginate beginning with 10-1 and adjust all references in the Table of Contents, List of Figures, and List of Tables accordingly.

Response: *Corrected*

1.0 INTRODUCTION

Comment: Please adjust the spelling of Ground water to Groundwater in the first paragraph on page 1-2.

Response: *Changed*

Comment: Per previous comments from the Conceptual draft report, please reword final paragraph in Section 1.0. The pumpage for the predictive runs provided by TWDB was derived from data provided by the regional planning groups from the last round of planning and from data in the 2002 State Water Plan. The current demands from this round of planning were not used and would entail an additional model run.

Response: *Updated to reflect data source as 2002 State Water Plan*

Comment: Remove 's' from model on line 14, page 1-1.

Response: *"s" removed*

2.0 STUDY AREA

Comment: Please adjust legend for Edwards-Trinity Aquifer to Edwards-Trinity (Plateau) Aquifer in Figure 2.2.

Response: *Globally changes Edwards-Trinity to Edwards-Trinity (Plateau)*

Comment: Please adjust caption for 'Regional Water Planning Areas in the Area' from Figure 2.1 to 2.3.

Response: *Adjusted*

Comment: In section 2.1, please update the text references from Figure 2.15 to Figure 2.1.1, Figure 2.16 to Figure 2.1.2, Figure 2.1.7 to 2.1.3, Figure 7 to Figure 2.1.3, Figure 8 to Figure 2.1.4, Figure 2-13 to Figure 2.1.8, and Figure 2-14 to Figure 2.1.9 to agree with List of Figures and related captions. In section 2.2 please update the text references from Figure 2-15 to Figure 2.2.1, Figure 2-16 to Figure 2.2.2, and Figure 16 to Figure 2.2.3 to agree with List of Figures and related captions.

Response: *All graphics updated in format and layout.*

Comment: Using the physiographic map of Texas (http://www.lib.utexas.edu/geo/txphysio.jpg) , please clarify if the study lies within the North-Central Plains, Edwards Plateau and/or the Southern High Plains provinces and update discussion accordingly.

Response: *Updated*

Comment: Per previous comments from the Conceptual draft report: Exhibit B, Attachment 1, Section 3.1.1 states the physiography and climate section shall also describe the river basins in the study area. Please update section 2.1 with this information. In addition per Exhibit B, Attachment 1, Section 5.4, please include a map of the river basins in the study area and a map of the average annual net lake evaporation.

Response: *Included the discussions and figures.*

Comment: The captions for Figures 2.1.3 and 2.1.7 are unreadable. Please resize figures so caption appears above binding.

Response: *All figures resized to allow room for binding.*

Comment: Per Exhibit B, Attachment 1, section 5.4, units for annual precipitation shall be reported in inches per year (in/yr). Please adjust legend in Figure 2.1.3 to 'average in/yr'.

Response: *Adjusted*

Comment: Section 2.1 cites BEG, 1994; TWDB website and/or data; and personal communication with Allan Lange. Please update the Reference Section with the full citation for each of these. The references to TWDB website and/or TWDB data appear to reference multiple websites, publications, and/or possibly databases. Please clarify, please cite specific source information in more detail, please include full citation in the reference section, and please adjust references in the text as needed. In addition please include an appropriate specific reference for the National Weather Service information/data cited and the specific source for the monthly evaporation discussed on page 2-7 and Figure 2.1.5.

Response: *References updated*

Comment: Per Exhibit B, Attachment 1, Section 5.4, the figure captions should contain the appropriate source reference for the basemap and/or the included information. Please update **all** figures in the report and the reference section with this information, as needed and appropriate.

Response: *Done where data was available*

Comment: Figure 2.1.4 appears to have gaps in the annual precipitation data or years without precipitation. Please clarify and include an explanation in caption.

Response: *Added information in caption*

Comment: Figure 2.2.2 does not list the ‘Lipan aquifer’. Please state in caption how the Lipan aquifer relates to the Leona aquifer or the units in the stratigraphic column.

Response: *Added “Lipan Aquifer”*

Comment: Figure 2.2.3, please correct caption from, ’Geologic Cross-sections of *he* Lipan Aquifer’ to ’Geologic Cross-sections of *the* Lipan Aquifer Study Area’. Please label Lipan aquifer in the cross-sections or state in caption how the Lipan aquifer relates to the Leona aquifer or is delineated in the cross-sections.

Response: *Corrected*

Comment: Remove ‘study area’ on line 1, page 2-1.

Response: *Done*

Comment: Line 7 on page 2-6, Cretaceous is spelled with a capital ‘C’

Response: *Corrected*

Comment: Line 10, ‘sea’ level, page 2-6

Response: *Corrected*

Comment: Page 2-6, line 26 (three from the bottom), what happen to Figure 7 or whatever it should be?

Response: *Corrected*

Comment: Page 2-7, line 3, what happened to figure 8?

Response: *Corrected*

Comment: Figure 2.2.2, all 'Aquifer' entries should be changed to Formation or member, which ever is appropriate

Response: *Corrected*

4.0 HYDROLOGIC SETTING

Comment: Text on page 4-2 references Figures 4-1, 4-2, and 4-3. As noted above, please use a consistent numbering system for figures and reference the same system in the text , figure captions, and List of Figures. Based on the system used in the majority of figure captions and List of Figures, then both the text and captions need to be revised to 4.2.1, 4.2.2, and 4.2.3 since the figures are cited in section 4.2 of the report. Those figures referenced in section 4.3 would need to be renumbered to 4.3.1, 4.3.2, etc. Alternatively you may label all the figures according to the major chapter/section i.e. 4-1, 4-2, 4-3, etc. or 4.1, 4.2, 4.3, etc. and not reference the subsection. Please use one system consistently throughout the report. Please review all text references to figures and tables and make sure they agree with the figure and table captions.

Response: *Done*

Comment: As noted in conceptual draft report review, please correct the first sentence in section 4.3.3 to read, 'The potentiometric surfaces indicate that groundwater generally flows laterally into the Lipan aquifer system from the water-bearing units located to the north, south, and west'.

Response: *Done*

Comment: Exhibit B, Attachment 1, section 3.1.6, models must include the concept and effect of 'rejected recharge', please expand this section with a discussion of this.

Response: *Included*

Comment: Please include references cited in Table 4.5.1 in the Reference Section of the report.

Response: *Included*

Comment: The captions for Figures 4.4.2, 4.6.7, 4.7.1, and 4.8.2 are unreadable. Please resize figures so that full caption appears above binding.

Response: *Corrected*

Comment: Please update page 4-42 reference to Mace (2000) to agree with citation in Reference Section.

Response: *Corrected*

Comment: Section 4.8, please update text from Table 3 to Table 4.8.1 in first paragraph.

Response: *Corrected*

Comment: Section 4.8, second paragraph, states the TWDB estimated groundwater pumping requirements for the years 2000 to 2050. Please reword this sentence. TWDB provided guidance in Technical Memorandum 02-02 on the preferred method of applying the pumpage derived from the regional planning data to the groundwater availability models for the predictive model runs.

Response: *Corrected*

Comment: Section 4.8, third paragraph states monthly pumping rates will be developed by dividing total annual discharge into twelve equal divisions. As noted in the conceptual draft report review and per Technical Memorandum 02-02, this method was only encouraged for livestock. Irrigation was to be temporally distributed based on a method that considered rainfall, plant needs, and crop planting cycles. Monthly factors for the temporal distribution of irrigation were provided and accessible through the GAM web site. All other categories should be based on data provided.

Response: *Removed paragraph.*

Comment: Per Exhibit B, Attachment 1, Section 5.4, please include a bar chart of yearly total historical and predicted groundwater usage used in the model.

Response: *Added Figure 4.8.1*

Comment: Section 4.9, first paragraph, last sentence states additional parameters are presented in this section and will be fully detailed in the final report. Since this is the final report, please remove this sentence.

Response: *Corrected*

Comment: Page 4-19, line 6, Edwards-Trinity Plateau aquifer….

Response: *Globally changed Edwards-Trinity to Edwards-Trinity Plateau.*

Comment: Page 4-43, Table 4.8.1, Total contains too many decimal places

Response: *Fixed*

6.0 MODEL DESIGN

Comment: Please update the Reference Section with the Harbaugh and McDonald, 1996 and Chiang and Kinzelbach, 2000 reference information.

Response: *Updated.*

Comment: Please provide the PMWIN version used in section 6.1.

Response: *Version provided.*

Comment: The caption for Figure 6.3.1 is unreadable. Please resize figure so that full caption appears above binding. Also please show in legend and on figure the location of the southern, eastern, and northern no-flow boundaries.

Response: *All figures resized to allow for binding. No-flow boundaries shown.*

Comment: Section 6.3.1.3 paragraph one and Table 6.3.2 reservoir conductance do not agree. Please clarify and adjust as needed.

Response: *Verified values and modified the table.*

Comment: Please provide a reference for the U.S. population census shapefiles in the text on page 6-12 and in the Reference Section.

Response: *Used census tiger data from the Edwards-trinity Plateau model data published on the TWDB GAM website. Metadata for these shapefile list the sources as "Data Source(s): Census Tiger data from the Geography Network (www.geographynetwork.com) and Census Population data from the Texas State Data Center (txsdc.tamu.edu).*"

Comment: Section 6.3.1.7 references Table 6.3.32. Please update to Table 6.3.3.

Response: *Updated.*

Comment: Section 6.3.2.1 and Table 6.3.4 discuss a zone approach for distribution of hydraulic conductivities. Please provide a map showing the spatial extent of the zones initially used and/or reference Figure 8.1.2.

Response: *Changed discussion of the zone approach for distributing hydraulic conductivity zones to section 8.1.*

Comment: Figure 6.3.1 should include the x, y coordinates of the northwest corner of the model grid in GAM coordinates.

Response: *X, Y coordinates shown.*

Comment: Restate the final paragraph on page 6-15. This is the final report.

Response: *Final paragraph restated.*

7.0 MODELING APPROACH

Comment: Please review the entire Section 7 for tense agreement and other grammatical errors.

Response: *Section reviewed and errors corrected.*

Comment: Section 7.3 states pumpage from Region E (Far West Texas) instead of Region F was used for the predictive runs. Please update to Region F for the Lipan GAM and confirm the correct data was used.

Response: *Changed text to "Region F" and verified that the correct data was in the model.*

8.0 STEADY-STATE MODEL

Comment: Section 8.1.4 states extinction depths were not varied from initial distribution. Figure 8.1.4 shows all extinction depths at 47 feet. Table 6.3.3 lists crops with extinction depths of 6.9. Please clarify if a zone for crops was implemented.

Response: *Updated table to reflect extinction depths in the model.*

Comment: The caption for Figure 8.1.2 is unreadable. Please resize figure so that full caption appears above binding.

Response: *Figure resized.*

Comment: Section 8.1.5 references Table 8.2, please update to Table 8.1.1.

Response: *Table caption updated*

Comment: Section 8.3.2 references Table 8.2.1, please correct.

Response: *Changed to 8.3.1*

Comment: Contours shown as observed in Figure 8.3.1 do not appear to match contours in Figure 4.3.5. Please explain and adjust as needed.

Response: *Contours shown in Figure 4.3.5 are based on all available data in the study area. Much of this data is considered unfit for model calibration. Many of the data points used for contouring the water levels in section 4 are outside the active portion of the model. In some wells, the geologic formation is either unidentified or outside of the scope of this model. Only data with good quality control was used in this calibration.*

Comment: Table 8.3.1 and Table 8.5.1 are identical. Please delete Table 8.5.1 and reference 8.3.1.

Response: *Table 8.5.1 deleted.*

9.0 TRANSIENT MODEL

Comment: Correct reference to Table 9.2.1 to Table 9.3.1 in Section 9.3.

Response: *Corrected reference.*

Comment: Section 6.3.1.5 states transient calibration period was 1980 to 1989 and the verification period was 1990 to 1999. Section 7.1.1 states the transient verification period was from 1991 through 2000. Section 9.0 states the time period of 1980-89 was used for calibration and the time period 1990-1999 was used for verification. Section 9.4 lists 1980-1990 as calibration phase and 1990-2000 for the verification phase. Section 9.4.1 reverts to 1980 to 1989 as the calibration time period. Please consistently report the same time period used in the model and adjust all references in the report, including figures, so they agree with the model.

Response: *Investigated, verified and correct the four modeling periods. Steady-state calibration uses 1980 stress conditions to simulate a quasi-steady-state system. The simulation time is set very long so that by the end of the simulation, changes in storage have approached zero and are neglible from one stress period to the next. Transient calibration period is from 1980 through 1989 (10 years). The transient calibration simulations start with stress period one being the* $1x10^7$ *day steady-state simulation. Then stress period two represents the first of the transient stress periods and is 1980 with the same stresses the steady-state model. The transient verification simulation period is from 1990-1999 (10 years). The steady-state and transient calibration and verification models are all combined into one model input file with 21 stress periods. Stress period one is* $1x10^7$ *days, with stress periods 2 – 21 have a length of 365.25 days each.*

Comment: Contours shown as observed in Figure 9.4.1 do not appear to match contours in Figure 4.3.6. Please explain and adjust as needed.

Response: *Contours shown in Figure 4.3.6 are based on all available data in the study area. Much of this data is considered unfit for model calibration.*

Some of the wells only have one or two data points in there historical records. Many of the data points used for contouring the water levels in section 4 are outside the active portion of the model. In some wells, the geologic formation is either unidentified or outside of the scope of this model. Only data with good quality attributes was used in this calibration.

Comment: Please complete discussion on what the results in Figure 9.4.2 indicate in Section 9.4.1.1. Also last paragraph in section 9.4.1.1 mentions a mean residual of –10.80, Table 9.4.1 does not list this. Please confirm and adjust as needed.

Response: *Finished discussion verified and changed the mean residual in the table.*

Comment: Contours shown as observed in Figure 9.4.3 do not appear to match contours in Figure 4.3.7. Please explain and adjust as needed.

Response: *Contours shown in Figure 4.3.7 are based on all available data in the study area. Much of this data is considered unfit for model calibration. Some of the wells only have one or two data points in there historical records. Many of the data points used for contouring the water levels in section 4 are outside the active portion of the model. In some wells, the geologic formation is either unidentified or outside of the scope of this model. Only data with good quality attributes was used in this calibration.*

Comment: Section 9.4.2.1 mentions Figure 9.4.5, which is to show changes from 1980 to 1999. Please update report with this Figure.

Response: *Figure added.*

Comment: RMSE at 0.16 is too high to be acceptable in table 9.4.2

Response: *Found error in calculation (took the RMS error and divided by the difference between the minimum residual and the maximum residual, not the range in observed heads) and updated the table so the correct value is listed.*

Comment: Last sentence first paragraph on page 9-20 must be re-written

Response: *rewrote last sentence.*

Comment: Section 9.5 lists figures 9.xx, please update with the appropriate figures.

Response: *Fixed figure captions*

Comment: Please complete the discussion at the end of section 9.6 about Figure 9.6.1.

Response: *Completed.*

Comment: Figure 9.7.2 shows different locations for wells 43-38-617 and 43-39-802 when compared to Figures 9.7.1 and 9.7.3. According to Figure 9.1.1 please reverse the locations of the hydrographs in Figure 9.7.2.

Response: *Locations were switched; error corrected.*

10.0 PREDICTIONS

Comment: Please cite references for precipitation and Quad 607 in text and Reference Section for drought-of-record discussion on page 10-4.

Response: *Cited reference as “http://hyper20.twdb.state.tx.us/Evaporation/evap.html”*

Comment: Section 10.2, please revise first sentence to reflect predictive pumpage was derived from Regional Water Planning Group data which contained four of the six pumping categories previously used during calibration of the model.

Response: *Done*

Comment: Section 10.3, please revise first sentence to reflect the use of data from the RWPG for the predictive pumpage used in the model. Using data delivered with the sixteen RWPG reports, TWDB staff summed allocated supplies and strategies and compared the total against the demand per individual water user group. If the total exceeded the individual water user group's demand, a weighted approach was applied so total supplies/strategies did not exceed demand.

Response: *Done*

Comment: Please use spell check on sections 10.2 and 10.5.

Response: *Done*

13.0 CONCLUSIONS

Comment: Please include references for materials, information, and data cited.

Response: *No references needed*

15.0 REFERENCES

Comment: Please update section with previous comments concerning reference information not cited or documented in the Reference Section.

Response: *Updated*

Comment: Please cite last name then first name or initials. Please use comma after year. For example, 'Bush, P.W., Ardis, A.F., and Wynn, K.H., 1993, Historical potentiometric surface of the…'.

Response: *Updated*

MODEL FILES AND PUMPAGE:

Comment: TWDB staff extracted pumpage from the input model files and compared the summed results at the county level to the raw pumpage summed at the county level. While not all of the historic raw pumpage categories were aquifer-specific, we expect the summed pumpage in the model for a specific county to either match the raw data or be less than the estimates for the entire county. Since the predictive dataset contained only aquifer specific data even though the aquifer may not cover an entire county, the comparison between the well.dat file and raw data should match reasonably well, if not exactly. For Concho and Tom Green counties we expected to see the historical pumpage in the model to be consistently lower or slightly lower than the total countywide pumpage (see Figures 1 and 3) and the predictive pumpage to match exactly (Figures 2 and 4). Please review the pumpage files used in the model, adjust as needed, and/or provide a detailed table outlining stress periods to dates so users can easily extract various pumpage datasets from the well.dat files by year/stress periods. Please review, clarify, and if needed adjust the pumpage in all of the study area to more reasonably match the data the provided.

Response: *Investigated the irrigation pumping and it became evident that Concho County irrigation pumping was allocated incorrectly or completely ignored. Original pumping was allocated by taking the total irrigation pumping reported in Tom Green County and distributing this over the active model domain where irrigation pumping occurs. Some of this pumping was in Concho County, however, reported Concho County irrigation was not included in the model. This has been rectified and new model simulations were completed.*

Further investigation into Lipan GAM pumping revealed that both manufacturing and Livestock pumping had been misallocated similar to irrigation pumping. These errors were fixed in the final simulations.

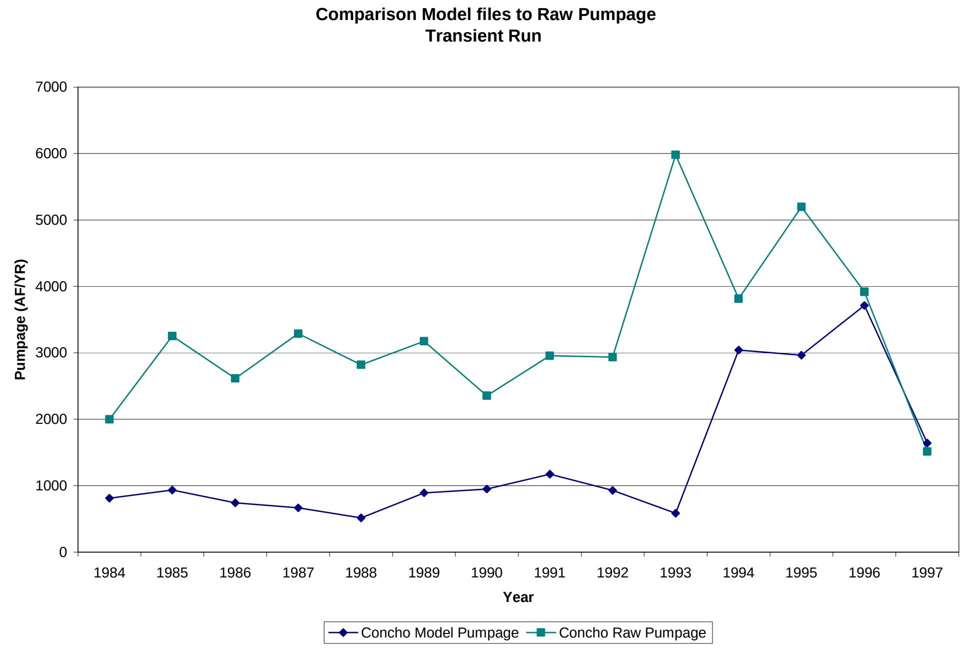

Figure A-1. Comparison of total county groundwater pumpage for selected years 1984 to 1997 to pumpage extracted from the Lipan model for Concho County.

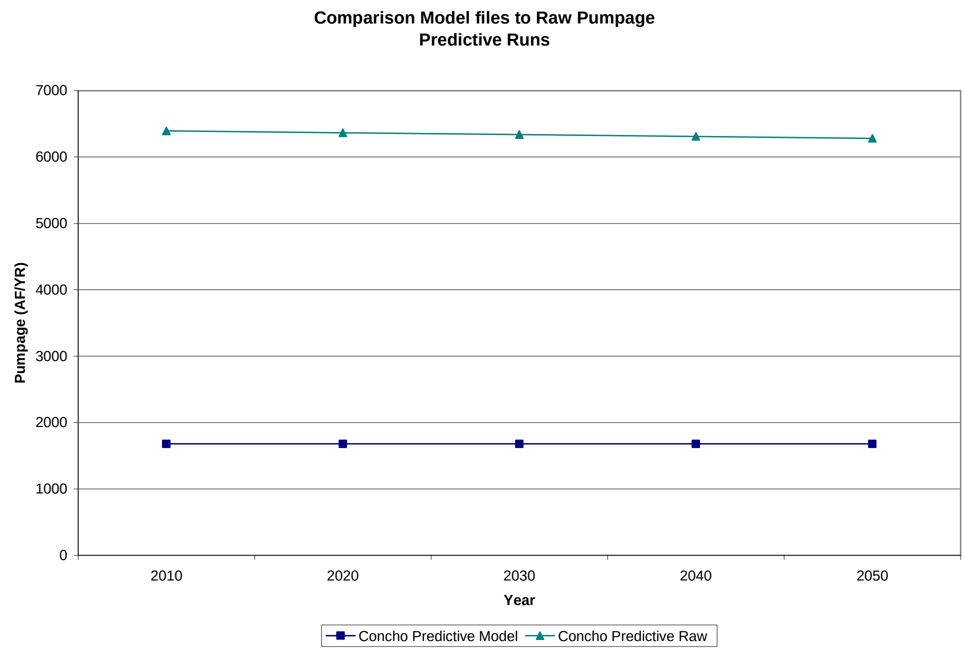

Figure A-2. Comparison of predictive pumpage assigned to Lipan in Concho County to predictive model pumpage files for Lipan aquifer.

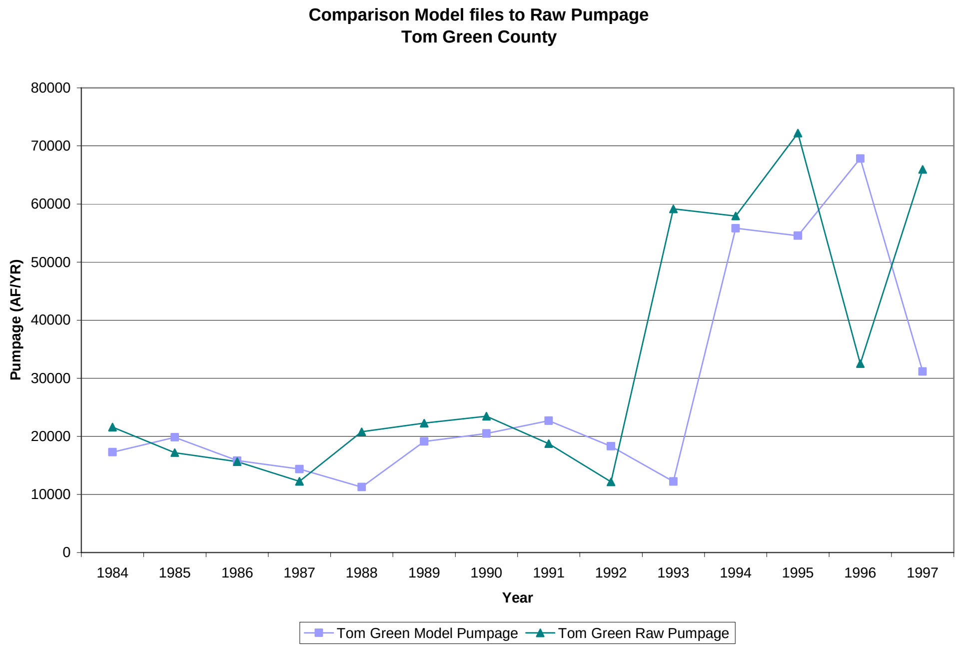

Figure A-3. Comparison of total county groundwater pumpage for selected years 1984 to 1997 to pumpage extracted from the Lipan model for Tom Green County.

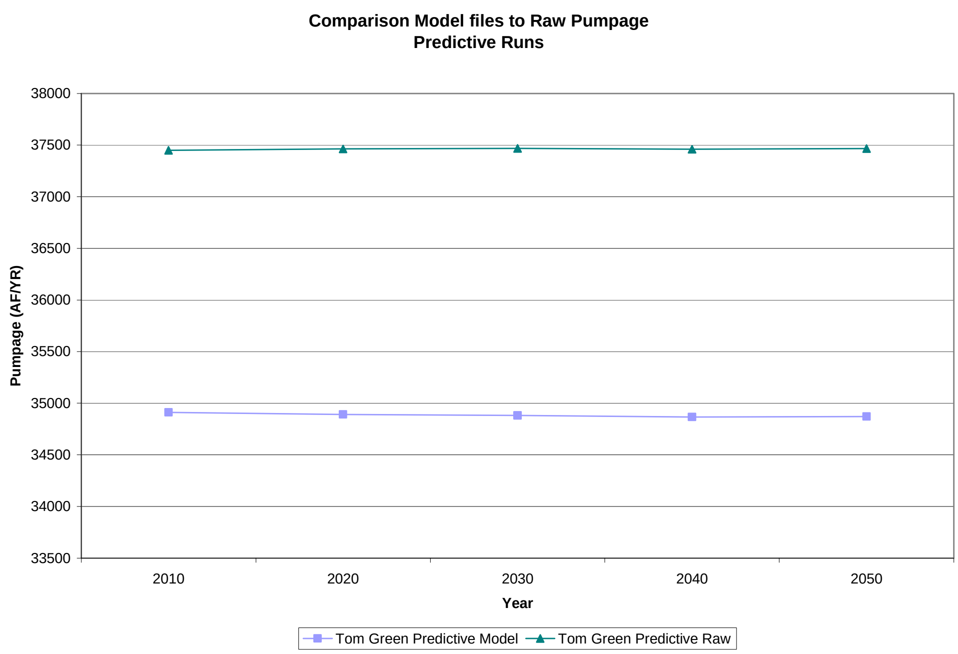

Figure A-4. Comparison of predictive pumpage assigned to Lipan in Tom Green County to predictive model pumpage files for Lipan aquifer.