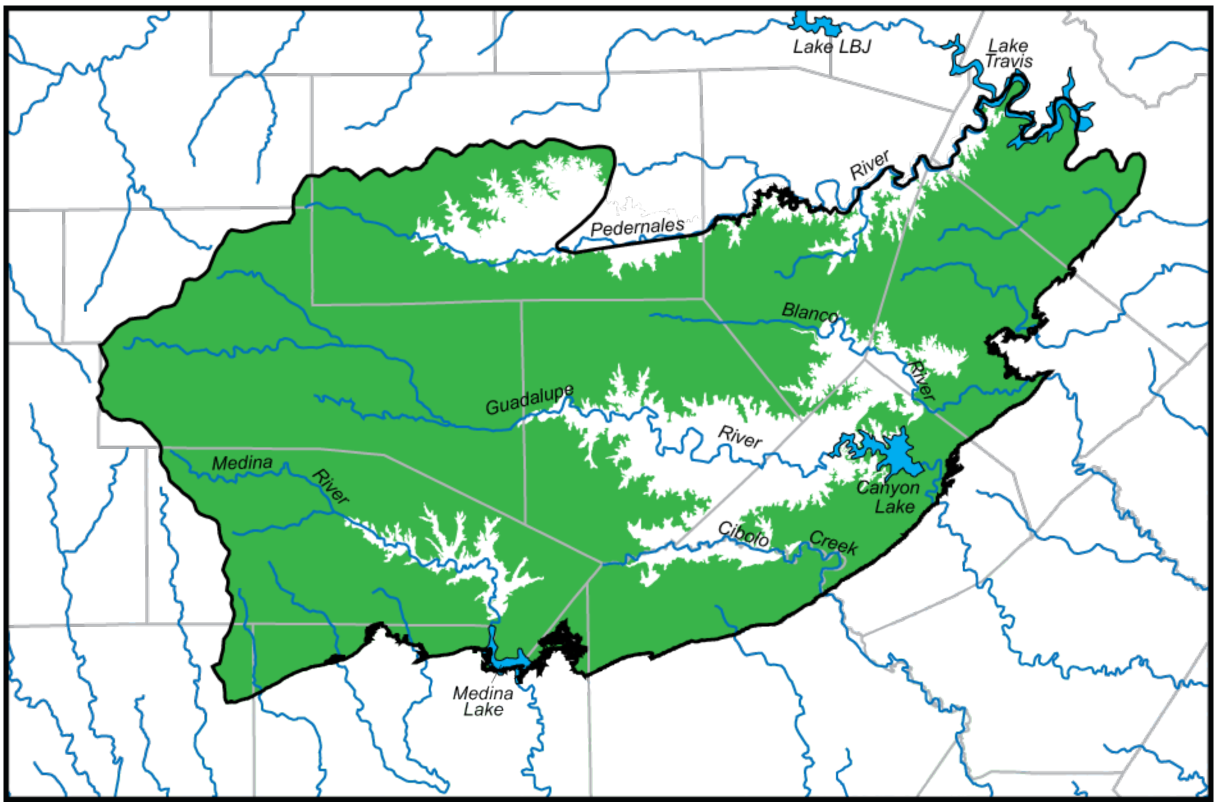
Groundwater Availability Model for the Hill Country Portion of the Trinity Aquifer System, Texas



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> Dr. Jones was the project manager for this work and was responsible for oversight of the project, organization of the report, the modeling approach and the steady-state and transient model calibration.

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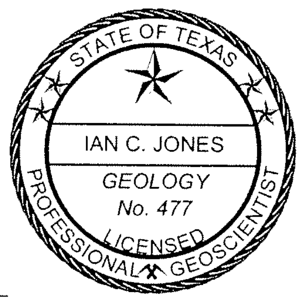

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> Mr. Anaya changed the map projection of the model and assisted with revising the structural geology.

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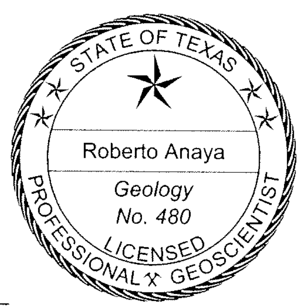

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Dr. Wade revised the structural geology that was used in the model.

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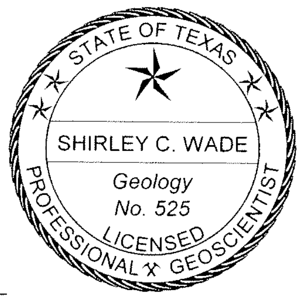

1.0 Executive Summary

Mace and others (2000) constructed a groundwater availability model simulating groundwater flow through the Hill Country portion of the Trinity Aquifer System as a groundwater resource management tool. The purpose of this report is to document updates to this earlier model. The model is being updated by: (1) adding the Lower Trinity Aquifer as an additional layer to the model, (2) revising the spatial distribution of parameters, such as recharge and pumping, and (3) calibrating to steady-state water-level and river discharge conditions for 1980 and historical transient water-level and discharge conditions for 1981 through 1997. The calibrated model can be used to predict future water-level changes that may result from various projected pumping rates and/or changes in climatic conditions.

Our conceptual model subdivides the Hill Country portion of the Trinity Aquifer System into three main components: the Upper, Middle, and Lower Trinity aquifers. The Upper Trinity Aquifer is composed of the upper member of the Glen Rose Limestone. The Middle Trinity Aquifer is composed of the lower member of the Glen Rose Limestone, Hensell Sand, and Cow Creek Limestone. The Lower Trinity Aquifer is composed of the Sycamore Sand, Sligo Formation, and Hosston Formation. The Middle and Lower Trinity aquifers are separated by the Hammett Shale which acts as a confining unit and is not explicitly included in the model. The model study area also includes easternmost parts of the Edwards-Trinity (Plateau) Aquifer.

Recharge in the updated model is a combination of infiltration of precipitation that falls on the aquifer outcrop and infiltration from losing intermittent streams within the model area. Estimates of recharge due to infiltration of precipitation in this updated model vary spatially and are equivalent to 3.5 to 5 percent of average annual precipitation. The highest of these recharge rates coincide with the Balcones Fault Zone. In addition to recharge from precipitation, there is also recharge from streamflow losses in the downstream parts of the Cibolo Creek watershed to the underlying aquifers of about 70,000 acre-feet per year .

Groundwater in the aquifer generally flows towards the south and east. The Hill Country portion of Trinity Aquifer System discharges naturally as baseflow to gaining streams, such as the Guadalupe, Blanco, and Medina rivers, and as cross-formational flow to the adjacent Edwards (Balcones Fault Zone) Aquifer. This cross-formational flow accounts for about 100,000 acre-feet per year of discharge. Pumping discharge from the Hill Country portion of the Trinity Aquifer System increased over the period 1980 through 1997. This increase in pumping is most apparent in Bexar, Hays, Kendall, and Kerr counties — counties adjacent to the two largest metropolitan areas in the region, San Antonio and Austin. Some of these counties have experienced a doubling of pumping over this period.

The updated model does a good job of reproducing observed water-level fluctuations. Comparison of measured and simulated 1997 water levels indicates a mean absolute error of 57 feet, or approximately 5.3 percent of the range of measured water levels. This is a slight improvement over the original model. Overall, the updated model also does a good job of mimicking baseflow fluctuations. The ability of the model to simulate spring discharge varies widely. Simulating discharge to springs using a regional-scale model is often difficult because of spatial and temporal scale issues. Of seventeen springs, six display a good comparison between measured and simulated discharge values.

The main improvements in the updated model over the original model are due to the addition of the Lower Trinity Aquifer to the model and the revised recharge distribution. The addition of the Lower Trinity Aquifer is important because the Lower Trinity Aquifer is an increasingly important source of groundwater in the study area. The revision of the recharge distribution in the updated model along with associated changes in the hydraulic conductivity distribution takes into consideration the major contribution to recharge from Cibolo Creek and will result in better simulation of groundwater flow in Bexar and surrounding counties.

2.0 Introduction

This report describes updates to the earlier developed groundwater availability model for the Hill Country portion of the Trinity Aquifer System by Mace and others (2000). These updates include: (1) addition of the Lower Trinity Aquifer to the model, (2) revisions to the model layers' structural geometry, and recharge, hydraulic conductivity, and pumping distribution, and (3) changes to the model calibration periods to bring the model in line with Texas Water Development Board groundwater availability modeling standards that were developed after the earlier model was constructed (http://www.twdb.state.tx.us/gam/GAM_documents/ GAM_RFQ_Oct2005.pdf).

In this report, we use the term Trinity Aquifer System. The term aquifer system has not previously been used in Texas Water Development Board publications but is often used by the United States Geological Survey, for example, the Edwards-Trinity Aquifer System (Barker and others, 1994), where multiple aquifers are grouped together. In this case, the Hill Country portion of the Trinity Aquifer System is subdivided into the Upper, Middle and Lower Trinity aquifers.

The Trinity Aquifer System is an important source of groundwater to municipalities, industries, and landowners in the Hill Country. Rapid population growth and recent droughts have increased interest in the Trinity Aquifer System and have increased the need for quantitative tools to assist in the estimation of groundwater availability in the area. Many groundwater conservation districts and the groundwater management area in the region need to assess the impacts of groundwater pumping and drought on the groundwater resources of the area. Regional water planning groups are required to plan for future water needs under drought conditions and are similarly interested in the groundwater availability of the Hill Country.

Several studies have noted the vulnerability of the Hill Country portion of the Trinity Aquifer System to drought and increased pumping. Ashworth (1983) concluded that heavy pumping is resulting in rapid water-level declines in certain areas and that continued growth would result in continued water-level declines. Bluntzer (1992), Simpson and others (1993), and Kalaswad and Mills (2000) noted that intense pumping has resulted in water-level declines, decreased well yields, increased potential for the encroachment of saline groundwater into the aquifer, and depletion of baseflow in nearby streams.

Calibrated groundwater flow models are simplified mathematical representations of groundwater flow systems that can be used to refine and confirm the conceptual understanding of a groundwater flow system. Once the model is successfully calibrated, it can be used as a quantitative tool to investigate the effects of pumping, drought, and different water management scenarios on the groundwater flow system.

In this study, we enhanced and re-calibrated the three-dimensional finite-difference groundwater flow model for the Hill Country portion of the Trinity Aquifer System to improve our conceptual understanding of groundwater flow in the region; and develop a management tool to support water planning efforts for regional water planning groups, groundwater conservation districts, groundwater management areas, and river authorities in the study area. This report describes the construction and re-calibration of the numerical model owing to the addition of the Lower Trinity Aquifer and revisions to recharge, hydraulic conductivity, and pumping distribution to the earlier model.

Our general approach involved (1) revising the conceptual groundwater flow model, (2) organizing and distributing aquifer parameters for the model, (3) calibrating a steady-state model for 1980 water level conditions, and (4) calibrating a transient model for the period 1981 through 1997. This report describes the study area, previous work, hydrogeologic setting used to develop the conceptual model, and model calibration results.

3.0 Study Area

The study area is located in the Hill Country of south-central Texas and includes all or parts of Bandera, Bexar, Blanco, Comal, Gillespie, Hays, Kendall, Kerr, Kimble, Medina, Travis, and Uvalde counties (Figure 3-01). Hydrologic boundaries define the extent of the study area. These boundaries include (1) major faults of the Balcones Fault Zone in the east and south, (2) presumed groundwater flow paths in the west, and (3) aquifer outcrops and/or rivers in the north (Figure 3-01). Because we selected groundwater flow paths to the west to assign a model boundary, the study area does not include the entire Hill Country area, such as parts of western Bandera and northeastern Uvalde counties, and includes the easternmost parts of the Edwards-Trinity (Plateau) Aquifer System (Ashworth and Hopkins, 1995) in Bandera, Gillespie, Kendall, and Kerr counties (Figure 3-02).

The study area includes parts of three regional water-planning areas: the Lower Colorado Region (Region K), the South Central Texas Region (Region L), and the Plateau Region (Region J) (Figure 3-03). The study area includes all or parts of several groundwater conservation districts including: Bandera County River Authority and Ground Water District, Blanco-Pedernales Groundwater Conservation District, Cow Creek Groundwater Conservation District, Edwards Aquifer Authority, Hays Trinity Groundwater Conservation District, Headwaters Groundwater Conservation District, Hill Country Underground Water Conservation District, Kimble County Groundwater Conservation District, Medina County Groundwater Conservation District, Trinity Glen Rose Groundwater Conservation District, and Uvalde County Underground Water Conservation District (Figure 3-04). The study area approximately coincides with Groundwater Management Area 9 (Figure 3-05). The study area also extends over four major river basins, the Colorado, Guadalupe, San Antonio and Nueces rivers, and five river authorities: the Lower Colorado River Authority (that includes Blanco and Travis counties in the study area), the Guadalupe-Blanco River Authority (that includes Comal, Hays, and Kendall counties in the study area), the Upper Guadalupe River Authority (that includes Kerr County), the Nueces River

Authority (that includes Bandera, Medina, and Uvalde counties), and the San Antonio River Authority that includes Bexar County in the study area (Figure 3-06).

3.1 Physiography and Climate

The study area is located along the southeastern margin of the Edwards Plateau region in a region commonly referred to as the Texas Hill Country (Figure 3-07). The Texas Hill Country is also known as the Balcones Canyonlands sub-region, a deeply dissected terrain formed by the head-ward erosion of major streams between the Edwards Plateau and the Balcones Escarpment (Thornbury, 1965; Riskind and Diamond, 1986). Land-surface elevations across the study area range from 2,400 feet above sea level in the west to about 600 feet along eastern margin of the study area (Figure 3-08).

The more massive and resistant carbonate members of the Edwards Group form the nearly flat uplands of the Edwards Plateau in the west and the topographic divides in the central portion of the study area (Figure 3-07). The differential weathering of alternating beds of limestone and dolostone with soft marl and shale in the upper member of the Glen Rose Limestone form the characteristic stair-step topography of the Balcones Canyonlands. In general, the upper member of the Glen Rose Limestone is much less resistant to erosion than the overlying Edwards Group caprock.

The study area is characterized by a sub-humid to semi-arid climate. A gradual decrease in average annual precipitation occurs from east to west (35 inches to 25 inches) due to increasing distance from the Gulf of Mexico (Carr, 1967; Figure 3-09). Additionally, local precipitation is highest in the central part of the study area and decreases to the north and south. Historical annual precipitation varies from less than 10 inches to more than 60 inches (Figure 3-10). Precipitation has a bimodal distribution during the year with most of the rainfall occurring in the spring and fall (Figure 3-11). During the spring, weak cold fronts begin to stall and interact with warm moist air from the Gulf of Mexico. During the summer, sparse rainfall is due to infrequent convectional thunderstorms. In early fall, rainfall is due to more frequent convectional thunderstorms and occasional tropical cyclones that make landfall along the Texas coast. Rainfall frequency continues to increase in late fall as cold fronts once again begin to strengthen and interact with the warm moist air masses of the Gulf of Mexico.

The average annual maximum temperature ranges from 76°F in the west to 78°F in the east and south (Figure 3-12). Average monthly temperatures range from about 60°F during winter months to about 95°F during summer months (Larkin and Bomar, 1983). The average annual (1950 to 1979) gross lake surface evaporation is more than twice the average annual precipitation and ranges from 63 inches in the east to 68 inches in the west (Figure 3-13). Seasonally, average monthly gross lake surface evaporation varies from about 2.5 inches during winter months to more than 9 inches during summer months (Larkin and Bomar, 1983).

3.2 Geology

Lower Cretaceous rocks of the Trinity Group that compose the Hill Country portion of the Trinity Aquifer System overlie unconformably Paleozoic rocks in the study area (Figure 3-14). These Lower Cretaceous rocks consist of (from oldest to youngest), the Hosston Formation (known as Sycamore Sand where it outcrops at the surface), Sligo Formation, Hammett Shale, Cow Creek Limestone, Hensell Sand, lower and upper members of the Glen Rose Limestone, and the Fort Terrett and Segovia Formations of the Edwards Group (Figure 3-14). The Trinity Group sediments are locally covered by Quaternary alluvium along streams and rivers and capped by Edwards Group sediments in the west.

The stratigraphic units of the Hill Country portion of the Trinity Aquifer System were deposited during a period of rifting and subsidence in the ancestral Gulf of Mexico (Barker and others, 1994). These units were deposited on the landward margin of a broad continental shelf under shallow marine conditions. The Llano uplift was a dominant structural high, forming islands of Precambrian metamorphic and igneous rock and Paleozoic sedimentary rock that were sources of terrigenous sediment occurring in the Trinity Group (Figure 3-15).

The Hosston Formation is dominantly composed of siliciclastic siltstone and sandstone in up-dip areas and dolomitic mudstone and grainstone down-dip derived from the Llano Uplift (Barker and others, 1994). This formation, which is up to 900 feet thick, grades upward into the Sligo Formation and where it is exposed at the surface is known as the Sycamore Sand. The Sycamore Sand is composed of quartz sand and gravel up to 50 feet thick (Barker and others, 1994). The Sycamore Sand also contains some feldspar and dolomite derived from the Llano Uplift.

The Sligo Formation is composed of up to 250 feet of evaporites, limestone and dolostone (Barker and others, 1994). The evaporites were deposited in a supratidal environment while the limestone and dolostone were deposited in an intertidal environment. In the up-dip regions, the Sligo Formation sediments display greater a contribution of terrestrial sediments from the Llano Uplift (Barker and others, 1994).

The Hammett Shale is highly burrowed and is made up of mixed clay, silt, and calcareous mud up to 130 feet thick (Barker and others, 1994). This stratigraphic unit inter-fingers vertically with the overlying Cow Creek Limestone.

The Cow Creek Limestone is a beach deposit on the southern flank of the Llano Uplift, up to 90 feet thick (Barker and others, 1994). The lower part of the Cow Creek Limestone is composed of fine- to coarse-grained calcareous sandstone. The middle part of the Cow Creek limestone is composed of silty calcareous sandstone, and the upper is composed of coarse-grained fossiliferous calcareous sandstone with poorly-sorted quartz grains and chert pebbles.

The Hensell Sand crops out in the northern part of the study area in Gillespie County (Figure 3-16). The Hensell Sand is composed of poorly cemented clay, quartz and calcareous sand, and chert and dolomite gravel up to 200 feet thick(Barker and others, 1994). The gravel beds occur at the base of this stratigraphic unit. The shallow marine deposits of the Bexar Shale Member of the Pearsall Formation are the down-dip equivalent of the Hensell Sand (Barker and others, 1994).

The Glen Rose Limestone is composed of sandy fossiliferous limestone and dolostone that is characterized by beds of calcareous marl, clay, and shale and includes thin layers of gypsum and anhydrite (Barker and others, 1994). The Glen Rose Limestone has a maximum thickness of 1,500 feet. The lower member of the Glen Rose Limestone is composed of medium-thick beds of limestone, dolostone and fossiliferous dolomitic limestone (Barker and others, 1994). The Glen Rose Limestone was deposited in a shallow marine to intertidal environment and grades northward into the terrestrial Hensell Sand. The upper member of the Glen Rose Limestone is exposed at land surface in most of the study area except where it is (1) removed by erosion exposing the lower member of the Glen Rose Limestone, and (2) overlain by the Edwards Group in the Edwards Plateau to the west and in the Balcones Fault Zone to the south and east (Figure 3-16). The upper member of the Glen Rose Limestone is characterized by a thin- to medium-bedded sequence of alternating nonresistant marl and resistant limestone and dolostone. The alternating layers of resistant and nonresistant rock results in uneven erosion that produces the "stair step" topography characteristic of much of the Hill Country.

The basal parts of the Hosston Formation, the Sycamore Sand, and up-dip parts of the Hensell Sand are mostly sandy and contain some of the most permeable sediments in the Hill Country portion of the Trinity Aquifer System (Barker and others, 1994). The Cow Creek Limestone is highly permeable in the outcrop due to carbonate dissolution and preservation of the pores but has relatively low permeability in the subsurface due to precipitation of calcite cements (Barker and others, 1994). Similarly, the lower member of the Glen Rose Limestone is more permeable in the outcrop than at depth (Barker and others, 1994). The Sligo Formation may yield small to large quantities of water (Ashworth, 1983).

The Lower Trinity Aquifer is not exposed at land surface within the study area and exists only in the southern half of the study area (Figures 3-14 and 3-16). The study area is completely underlain by sediments of the Middle Trinity Aquifer. The Upper Trinity Aquifer exists in most of the study area except where it has been removed by erosion along and near the lower reaches of the Pedernales, Blanco, Guadalupe, Cibolo, and Medina rivers (Figure 3-16). In the western part of the study area, the Fort Terrett and Segovia formations of the Edwards Group (Figure 3-16) cap the Trinity Aquifer sediments. The Edwards Group may produce large amounts of water where it is saturated and has high transmissivity.

The Llano Uplift is a regional dome formed by a massive Precambrian granitic pluton (Figure 3-15). The Llano Uplift remained a structural high throughout the Ouachita orogeny that folded and uplifted the Paleozoic rocks of this area and provided a source of sediments for terrigenous and near-shore facies of the Trinity Group (Ashworth, 1983; Barker and others, 1994). The San Marcos Arch is a broad anticlinal (upward folded ridge) extension of the Llano Uplift with a southeast plunging axis. The San Marcos Arch extends through central Blanco and southwest Hays counties (Ashworth, 1983) (Figure 3-15). This arch contributed to the formation of a carbonate platform with thinning sediments along the anticlinal axis. The Balcones Fault Zone is a northeast-southwest trending system of high-angle normal faults with down-thrown blocks towards the Gulf of Mexico (Figure 3-15). The faulting occurred along the sub-surface axis of the Ouachita fold belt as a result of extensional forces created by the subsidence of basin sediments in the Gulf of Mexico during the Tertiary Period. The last episode of movement in the fault zone is thought to have occurred in the late Early Miocene, approximately 15 million years ago (Young, 1972). The Balcones Fault Zone is a structural feature that laterally juxtaposes Trinity Group sediments against Edwards Group sediments of the Edwards (Balcones Fault Zone) Aquifer (Figures 3-15 and 3-17).

The structural geometry of Lower Cretaceous sediments in the study area are characterized by (1) a southeast regional dip, (2) an uneven base of the Trinity Group, and (3) the occurrence of the San Marcos Arch in the southeast, Llano Uplift to the north, and Balcones Fault Zone to the south and east (Figures 3-15 and 3-17). Both Trinity Group and Edwards Group sediments have a regional dip to the south and southeast. The dip increases from a rate of about 10 to 15 feet per mile near the Llano Uplift to about 100 feet per mile near the Balcones Fault Zone (Ashworth, 1983). These Lower Cretaceous sediments may be described as a series of stacked wedges that pinch out against the Llano Uplift and thicken down-dip towards the Gulf of Mexico (Figure 3-17). At the base of the Trinity Group sediments, underlying Paleozoic rocks have been moderately folded, uplifted, and eroded to form an unconformable surface upon which the Trinity Group sediments were deposited (Figure 3-17). Along the northern margin of the study area, the Middle and Upper Trinity sediments directly overlay Paleozoic and Precambrian rocks (Figure 3-17).

4.0 Previous Work

The Texas Water Development Board and the United States Geological Survey have conducted a number of hydrogeologic studies in the Hill Country area. Ashworth (1983), Bluntzer (1992), and Barker and others (1994) provide a thorough review of much of the previous geologic and hydrogeologic work done in the area.

A regional numerical groundwater flow model was developed and published for the area by the United States Geological Survey (Kuniansky and Holligan, 1994). Besides the Trinity Aquifer in the Hill Country, this United States Geological Survey model includes the Edwards-Trinity (Plateau) and Edwards (Balcones Fault Zone) aquifers and extends almost 400 miles across the state (Figure 4-01). The purpose for the United States Geological Survey model was to better understand and describe the regional groundwater flow system. Using the model, Kuniansky and Holligan (1994) defined transmissivity ranges, estimated total flow through and recharge to the aquifer system, and simulated groundwater flow from the Trinity Aquifer into the Edwards (Balcones Fault Zone) Aquifer. The two-dimensional, finite-element, steady-state model was developed as the simplest approximation of the regional flow system. The United States Geological Survey model is inappropriate for regional water planning because: (1) it does not simulate water-level changes with time, and (2) it simulates all of aquifers in the study area as a single layer. Subsequently, Anaya and Jones (2009) developed a transient finite-difference model covering a study area similar to the model by Kuniansky and Holligan (1994). The model by Anaya and Jones (2009) simulates the Trinity Aquifer System as a single layer (Figure 4-01).

The Texas Water Development Board developed a regional transient groundwater flow model for the Hill Country area of the Trinity Aquifer (Mace and others, 2000) (Figure 4-01). They calibrated this model to 1975 steady-state conditions and 1996 through 1997 transient conditions (Mace and others, 2000). This model simulated groundwater flow through the Edwards Group and the Upper and Middle Trinity aquifers. This updated model includes the Lower Trinity Aquifer previously excluded from the model by Mace and others (2000).

5.0 Hydrogeologic Setting

The hydrogeologic setting describes the aquifer, hydrologic features, and hydraulic properties that influence groundwater flow in the aquifer. We based the hydrogeologic setting for the Hill Country portion of the Trinity Aquifer System on previous work (for example, Ashworth, 1983; Bluntzer, 1992; Barker and others, 1994; Kuniansky and Holligan, 1994) and additional studies we conducted in support of the modeling effort (Mace and others, 2000). These additional studies included assembling structure maps, developing water-level maps and hydrographs, estimating baseflow to streams, investigating recharge rates, conducting aquifer tests, and assembling pumping information.

5.1 Hydrostratigraphy

The Hill Country portion of the Trinity Aquifer System is comprised of sediments of the Trinity Group and is divided into lower, middle, and upper aquifers (Figure 3-14) based on hydraulic characteristics of the sediments (Barker and others, 1994). The Lower Trinity Aquifer consists of the Hosston (and the Sycamore Sand in outcrop) and Sligo Formations; the Middle Trinity Aquifer consists of the Cow Creek Limestone, Hensell Sand, and the lower member of the Glen Rose Limestone; and the Upper Trinity Aquifer consists of the upper member of the Glen Rose Limestone. Low-permeability sediments throughout the upper member of the Glen Rose Limestone separate the Middle and Upper Trinity aquifers. The Lower and Middle Trinity aquifers are separated by the low permeability Hammett Shale except where the Hammett Shale pinches out in the northern part of the study area (Amsbury, 1974; Barker and Ardis, 1996) (Figure 3-16).

5.2 Structure

Building on the structural interpretations of Ashworth (1983) and using available drilling logs from the Hill Country Underground Water Conservation District, geophysical logs, and locations of outcrop areas, Mace and others (2000) developed structural elevation maps for the bases of the Edwards Group and the Upper and Middle Trinity aquifers (Figures 5-01 through 5-04). Mace and others (2000) collected geophysical logs from Texas Water Development Board, Edwards Aquifer Authority, Bandera County River Authority and Groundwater District, and private collections and used natural gamma logs to locate (1) the base of the Edwards Group, (2) the contact between the upper and lower members of the Glen Rose Limestone (as defined by the lower evaporite beds just above the “Corbula” marker bed or correlated equivalent), and (3) the base of the Middle Trinity sediments. Mace and others (2000) used resistivity logs to add control points in parts of the study area in the absence of gamma logs to complete the structure surfaces.

To further enhance the control of structural elevation point data, Mace and others (2000) supplemented our well log based data with outcrop elevation points. Mace and others (2000) digitized the appropriate formation contacts for the base of the Edwards Group and Upper and Middle Trinity sediments from 1:250,000 scale maps of surface geology in the area (Brown and others, 1974; Proctor and others, 1974a, b; Barnes, 1981) using AutoCAD® (Autodesk, 1997) and converted the digitized contacts into an ArcInfo® (ESRI, 1991) geographical information system line coverage. Mace and others (2000) then georeferenced the line coverage, converted it into a point coverage from the arc vertices, and intersected it with a Triangulated Irregular Network constructed from a United States Geological Survey 3-arc second digital elevation model to determine their point elevations. Mace and others (2000) compiled the structural elevation information and organized it into ArcInfo® for the base of the Middle Trinity Aquifer, the base of the Upper Trinity Aquifer, and the base of the Edwards Group sediments. Mace and others (2000) then exported the point elevations from ArcInfo® into point coordinates and imported them into Surfer® (Golden Software, 1995) for spatial interpolation (Figures 5-01 through 5-04).

As part of this project, we updated the model structure of Mace and others (2000) by revising the structure of the Middle Trinity Aquifer and adding the Lower Trinity Aquifer as a fourth layer. These changes were aided by structural interpretations from the Hays Trinity Groundwater Conservation District. The base of the Lower Trinity Aquifer was taken from the base of the Edwards-Trinity Aquifer System used in the groundwater availability model for the Edwards-Trinity (Plateau) Aquifer System by Anaya and Jones (2009). When we compared the base elevation of the Middle Trinity Aquifer from the original model (Mace and others, 2000) with the base elevation of the Lower Trinity from the Edwards-Trinity (Plateau) Aquifer System model (Anaya and Jones, 2009), we noticed that the structures were not consistent because the base of the Middle Trinity dipped below the base of the Lower Trinity in Blanco County. In order to resolve this inconsistency between the two structures we revised the base of the Middle Trinity Aquifer using data from the Texas Commission on Environmental Quality Source Water Assessment and Protection Geographical Information System database developed by the United States Geological Survey. We used the Source Water Assessment and Protection data for the base of the Middle Trinity in Blanco County and merged it with the structural surface from the original model (Mace and others, 2000) for the remainder of the model. The two surfaces were merged using a linear smoothing algorithm in ArcGIS® version 9.1 (ESRI, 2005).

We developed thickness maps by subtracting elevations for the tops and bases of the respective model layers using ArcGIS® 9.1 (Figures 5-05 through 5-08). The thickness of the relatively flat lying beds of the Edwards Group is controlled by the dendritic erosional pattern of the surface topography (Figures 5-01 and 5-05). Although mostly masked by the dendritic erosional pattern of the surface topography in the central and eastern portions of the study area, sediments of the Upper Trinity Aquifer thicken towards the Balcones Fault Zone (Figure 5-06). Sediments of the Middle and Lower Trinity aquifers also generally increase in thickness towards the Balcones Fault Zone (Figures 5-07 and 5-08).

5.3 Water Levels and Regional Groundwater Flow

We compiled water-level measurements and developed generalized steady-state water-level maps for the Edwards Group, and the Upper, Middle, and Lower Trinity aquifers in the study area. To increase the number of measurement points, we expanded our time interval to lie between 1977 and 1985 to approximate steady-state water levels for the period about 1980. If a well had multiple water-level measurements, the average measurement was chosen for contouring the water-level map.

Water levels in the aquifers generally follow topography (Figures 5-09 through 5-12). Kuniansky and Holligan (1994) noted that water levels in this area are a subdued representation of surface topography due to recharge in the uplands and discharge in the lowlands. Water-level maps indicate that water levels are influenced by the location of rivers and springs. For example, the water-level maps show that groundwater in the aquifer flows toward most of the rivers in the study area (Figures 5-09 through 5-12). In the case of the Edwards Group, groundwater flows east toward the escarpment where there are numerous springs at the geologic contact between the Edwards Group and the upper member of the Glen Rose Limestone (Figure 5-09). Barker and

Ardis (1996) also noted that water-level elevations and the direction of groundwater flow in the Trinity Aquifer System are largely controlled by the position of springs and streams.

Groundwater flows from higher water-level elevations toward lower water-level elevations. The water-level maps show that regional groundwater flow is from the northwest toward the southeast and east (Figures 5-09 through 5-12). Water-level maps also show that groundwater in the Upper, Middle, and Lower Trinity aquifers flows out of the study area to the south and east into the Edwards (Balcones Fault Zone) Aquifer (Figures 5-10, 5-11, and 5-12). The 'Discharge' section of this report discusses the estimated amount of groundwater flow from the Hill Country portion of the Trinity Aquifer System into the Edwards (Balcones Fault Zone) Aquifer.

Water levels, especially in shallow wells (less than 100-feet deep), can seasonally vary up to 50-feet (Barker and Ardis, 1996) in response to rainfall events. Some wells show relatively small changes in water level over time, for example, wells 69-04-502, 56-48-301, 57-61-803, and 58-50-120, while others show large fluctuations, for example, wells 68-19-806 and 56-63-604 (Figures 5-13 through 5-16). Wells with detailed measurements, for example, wells 68-19-806, 68-02-609, and 68-01-314, show seasonal fluctuations (Figures 5-15 and 5-16). Figures 5-13 through 5-16 suggest that overall there are no long-term trends of declining or rising water levels in the Hill Country portion of the Trinity Aquifer System and thus water levels in the 1990s will be similar to those in Figures 5-09 through 5-12.

From 1980-1997, water levels generally rose in the Upper Trinity Aquifer of Bexar County (Figure 5-17). Over the same period of time, water levels generally declined in the Middle and Lower Trinity aquifers in Bandera, Blanco, Kendall, and Kerr counties and rose, at least locally, in Bexar and Comal counties (Figure 5-18). In other parts of the study area, water levels show seasonal fluctuations but have remained fairly constant since 1980. The area with the most significant water-level decline is near the city of Kerrville in Kerr County. The largest water-level decline is approximately 40 feet in the Middle Trinity Aquifer and 85 feet in the Lower Trinity Aquifer (Figures 5-15 and 5-16). The 128-foot water-level rise in Kerr County (Well 56-63-604) can be attributed to a reduction in pumping by the City of Kerrville. Well 68-08-102, which is located near the city of Wimberley (Hays County), shows a water-level decline of approximately 45 feet between 1980 and 2000 (Figure 5-15).

5.4 Recharge

The primary sources of inflow to the Hill Country portion of the Trinity Aquifer System are rainfall on the outcrop, seepage losses through headwater creeks, and lakes during high stage levels. The outcrops in the study area are composed of the upper and lower members of the Glen Rose Limestone, Hensell Sand, and Edwards Group and receive all of the direct recharge from rainfall. The Cow Creek Limestone and Lower Trinity Aquifer sediments are not exposed at land surface in the study area and receive water by vertical leakage from overlying strata (Ashworth, 1983). Beds containing relatively low permeability sediments within the upper member of the Glen Rose Limestone impede downward percolation of interstream recharge and facilitate horizontal groundwater flow resulting in baseflow and springflow to the mostly gaining perennial streams that drain the Hill Country (Barker and Ardis, 1996; Ashworth, 1983). Recharge in the Edwards Group limestones of the northwestern portion of the study area occurs as infiltration of rainfall and losing streams. Much of this water later emerges as springs and seeps along the geologic contact between the Edwards Group and the upper member of the Glen Rose Limestone.

Sinkholes and caverns in the Glen Rose Limestone of southern Kendall, northern Bexar, and western Comal counties may transmit large quantities of water to the Hill Country portion of the Trinity Aquifer System. Karst-enhanced recharge is especially significant along Cibolo Creek between Boerne and Bulverde (Ashworth, 1983; Veni, 1994). However, because much of this recharge is quickly transmitted to the Edwards (Balcones Fault Zone) Aquifer, it has minimal effect on the Hill Country portion of the Trinity Aquifer System (Barker and Ardis, 1996; Veni, 1994).

Several investigators have estimated recharge rates for the Hill Country portion of the Trinity Aquifer System (Table 5-01). Most of them used stream baseflow to estimate recharge. Muller and Price (1979) assumed a recharge rate of 1.5 percent of average annual precipitation for their rough approximation of groundwater availability. This estimate of recharge was intended to minimize impacts of groundwater production on baseflow and groundwater flow to the Edwards (Balcones Fault Zone) Aquifer. Based on a study of baseflow gains in the Guadalupe River between the Comfort and Spring Branch gauging stations during a 20-year period between 1940 and 1960, Ashworth (1983) estimated a average annual effective recharge rate of 4 percent of average annual precipitation for the Hill Country. Kuniansky (1989) estimated baseflow for 11 drainage basins in our study area for a 28-month period between December 1974 and March 1977 and estimated an annual recharge rate of about 11 percent of average annual rainfall. However, Kuniansky and Holligan (1994) reduced this recharge rate to 7 percent of average annual precipitation to calibrate a groundwater model that included the Hill Country portion of the Trinity Aquifer System. They suggested that the numerical model did not include all the local streams accepting discharge from the aquifer. Bluntzer (1992) calculated long-term average annual baseflow from the Blanco, Guadalupe, Medina, Pedernales, and Sabinal rivers and Cibolo and Seco creeks to be 369,100 acre-feet per year. Using a long-term average annual precipitation of 30 inches per year, the recharge estimate by Bluntzer (1992) is equivalent to a recharge rate of 6.7 percent of average annual precipitation (Riggio and others, 1987). However, Bluntzer (1992) suggests that a recharge rate of 5 percent is more appropriate to account for human impacts on baseflow such as nearby groundwater pumping, streamflow diversions, municipal and irrigation return flows, and retention structures. Bluntzer (1992) also noted that baseflow was highly variable over time. Mace and others (2000) suggested that differences in recharge rates reflect biases in the record of analysis due to variation of precipitation. The higher recharge rate estimated by Kuniansky (1989) is likely due to the higher than normal precipitation between December 1974 and March 1977, her record of analysis. Ashworth's (1983) recharge rate is probably biased toward a lower value because his record of analysis includes the 1950's drought-of-record.

Mace and others (2000) developed an automated digital hydrograph-separation technique to estimate baseflow for the drainage basin defined by the Guadalupe River gauging stations between Comfort and Spring Branch. Mace and others (2000) developed this technique based on methods used by Nathan and McMahon (1990); and Arnold and others (1995). Mace and others (2000) used the program to estimate baseflow from 1940 to 1990 and adjusted parameters to attain the best fit with Ashworth’s (1983) and Kuniansky’s (1989) baseflow values for the same stream reach. Using this technique, Mace and others (2000) estimated a recharge rate of 6.6 percent of average annual precipitation. Note that the calibrated recharge rate by Mace and others (2000) is about 4 percent of average annual precipitation. All baseflow-based estimates of recharge underestimate recharge because they do not consider the component of recharge that follows the regional flow paths and bypasses the local streams. There is additional error in this methodology associated with the implied assumption that each watershed is a closed system and thus all water that recharges the aquifer discharges to the adjacent river. However, regional groundwater flow between watersheds results in underestimation of recharge in up-gradient watersheds and overestimation in down-gradient watersheds.

In the updated model, we spatially distributed recharge based on Parameter-elevation Regressions on Independent Slopes Model (PRISM) data (Daly and Taylor, 1998; Spatial Climate Analysis Service, 2004). Parameter-elevation Regressions on Independent Slopes Model is an analytical model that spatially distributes monthly, seasonal and annual precipitation. We assumed that recharge is a fraction of annual precipitation. This fraction or recharge coefficient is determined during model calibration. In addition to precipitation, we assume that the aquifer receives recharge from streamflow losses in Cibolo Creek. This recharge is estimated based on watershed modeling of the Cibolo Creek watershed by the United States Geological Survey (Ockerman, 2007). This watershed modeling indicates average annual recharge of approximately 72,000 acre-feet to the Trinity Aquifer System within the study area. The methodology used in the updated model is an improvement over the recharge estimation method used by Mace and others (2000) that was based on baseflow coefficients and precipitation distribution. In addition to the weaknesses in baseflow-based recharge estimation methods stated above, the updated model was developed using data from a study of the Cibolo Creek watershed (Ockerman, 2007) that was not available for use by Mace and others (2000).

5.5 Rivers, Streams, Springs, and Lakes

Most of the rivers in the study area arise along the eastern margin of the Edwards Plateau and descend with a steep gradient into the Hill Country (Figure 3-06). Many of these streams have upper reaches contained within narrow canyons and broaden into flat-bottomed valleys further downstream (Barker and Ardis, 1996). Three major drainage basins, including the San Antonio, Guadalupe, and Colorado rivers, traverse the study area and funnel flow towards the southeast.

Most of the rivers in the study area gain water from the Hill Country portion of the Trinity Aquifer System (Ashworth, 1983; Slade and others, 2002; Figure 5-19) and are hydraulically connected to the regional flow system (Kuniansky, 1990). These streams receive groundwater that discharges through seeps and springs that occur along the tops of impermeable units where they appear at land surface (Barker and Ardis, 1996). Much of the groundwater in local flow systems within the Hill Country portion of the Trinity Aquifer System discharges to adjacent deeply entrenched, perennial streams instead of flowing to deeper portions of the aquifer (Ashworth, 1983). Many springs issue from the Edwards Group along the margin of the Edwards Plateau in the western part of the study area (Ashworth, 1983).

Most of the rivers in the study area are perennial (Figures 5-20 through 5-26). Lower reaches of Cibolo Creek lose flow between Boerne and Bulverde where it flows over the lower member of the Glen Rose Limestone (Ashworth, 1983) (Figure 5-26). Upstream of Boerne, Cibolo Creek gains water where it flows over the upper member of the Glen Rose Limestone (Guyton and Associates, 1958, 1970; Espey, Huston, and Associates, 1982; Stein and Klemt, 1995; Mace and others, 2000). Lower reaches of most of the streams in the study area lose significant quantities of flow where they cross the recharge zone of the Edwards (Balcones Fault Zone) Aquifer (Barker and others, 1994). Most perennial rivers in the study area experience extremely low flow for brief periods during droughts (Figures 5-21 through 5-23).

The study area includes four major lakes: Lake Travis, Lake Austin, Canyon Lake, and Medina Lake (Figure 3-01). Canyon Lake and Lake Travis have maintained approximately constant lake levels (± 20 feet), although Lake Travis had large declines during droughts in the 1950s and mid-1960s (Figure 5-27). Lake Medina has much more variation in water levels and has nearly been dry on a few occasions during the drought of the 1950s (Espey, Huston, and Associates, 1989) (Figure 5-27).

Numerous springs occur in the study area (Figure 5-28). Most of these springs issue from topographically low-lying areas below the base of bluffs along rivers and streams, discharging groundwater that flows laterally along the tops of hard, more-resistant Glen Rose Limestone beds. Other springs discharge along the margin of the Edwards Plateau and contribute significant flow to the headwaters of the major rivers in the study area. Many of the spring discharge zones are characterized by phreatic vegetation, such as marsh purslane, cattails, ferns, and cypress trees, indicative of a constant supply of water (Brune, 1981). Springs that occur in the Edwards Group generally have higher discharge rates than those occurring in the lower and upper members of the Glen Rose Limestone and the Cow Creek Limestone (Table 5-02), presumably due to the cavernous nature of the Edwards Group.

5.6 Hydraulic Properties

Variations in well yields are generally a result in variation in hydraulic properties of aquifers. Well yields in the Hill Country portion of the Trinity Aquifer System are often controlled by the location of fractures and dissolution features and consequently, may vary considerably over short distances. Although the Hill Country portion of the Trinity Aquifer System as a whole is recognized by the state as a major aquifer (Ashworth and Hopkins, 1995), well yields can be low compared to other major aquifers.

Hydraulic conductivity is defined as the rate of movement of water through a porous medium under a unit gradient. For example, very porous limestone may have hydraulic conductivities greater than 1,000 feet per day, sandy limestone may range from 100 to 1,000 feet per day, while aquifers with moderate hydraulic conductivity values may range from 10 to 100 feet per day, and aquifers with low hydraulic conductivity may range from 0.1 to 10 feet per day. Transmissivity is defined as the hydraulic conductivity times the thickness of the aquifer, and thus is a measure of the rate of movement through a defined thickness of aquifer under a unit gradient.

Pumping tests in wells are conducted to order to develop estimates of hydraulic conductivity and transmissivity. Based on 15 aquifer tests, Hammond (1984) determined that hydraulic conductivity ranges from 0.1 to 10 feet per day in the lower member of the Glen Rose Limestone. Barker and Ardis (1996) thought that hydraulic conductivity probably averages about 10 feet per day in the Hill Country portion of the Trinity Aquifer System. No one has investigated vertical hydraulic conductivities, although vertical hydraulic conductivities are likely to be much lower than horizontal hydraulic conductivities, especially in the upper member of the Glen Rose Limestone. Barker and Ardis (1996) noted that recharging water moves laterally more easily atop low-permeability beds than vertically through them. Guyton and

Associates (1993) estimated that the vertical hydraulic conductivity of the Hammett Shale, Bexar Shale, and the marls of the upper member of the Glen Rose Limestone was about 0.0001 to 0.003 feet per day. In their model that included the Hill Country portion of the Trinity Aquifer System, Kuniansky and Holligan (1994) considered part of the Hill Country portion of the Trinity Aquifer System along the Edwards (Balcones Fault Zone) Aquifer to have anisotropic properties, with greater hydraulic conductivity in the direction of faulting.

Ashworth (1983) reports average transmissivities of about 230 square feet per day and 1,300 square feet per day for the Middle and Lower Trinity aquifers, respectively, and that substantially lower transmissivities are expected for the Upper Trinity Aquifer. Kuniansky and Holligan (1994) determined that transmissivity for the Hill Country portion of the Trinity Aquifer System ranged from 100 to 58,000 square feet per day. Stein and Klemt (1995) summarized 53 aquifer tests in the Glen Rose Limestone along the Edwards (Balcones Fault Zone) Aquifer and found a median transmissivity of about 220 square feet per day. The Glen Rose Limestone can be unusually permeable in outcrop and shallow subcrop in northern Bexar County and southwestern Comal County near Cibolo Creek (Kastning, 1986; Veni, 1994). Barker and Ardis (1996) developed a map of transmissivity for the Hill Country portion of the Trinity Aquifer System based on aquifer tests, geologic observation, and computer modeling. They determined that transmissivity is generally less than 5,000 square feet per day but increases from 5,000 to 50,000 square feet per day along the boundary between Comal and Bexar counties and through Kendall County and eastern Kerr County. The quartzose clastic facies of the up-dip Hensell Sand include some of the most permeable sediments in the Hill Country portion of the Trinity Aquifer System (Barker and Ardis, 1996). Ardis and Barker (1993) and Barker and Ardis (1996) surmised that the variations in transmissivity in the Hill Country are probably due more to variations in aquifer thickness than to tectonic or diagenesis. However, Barker and Ardis (1996) noted that diagenesis of stable minerals has diminished permeability in most down-gradient, subcropping strata and that the leaching of carbonate constituents has enhanced permeability in some of the outcrop.

Storativity is the volume of water released from storage per decline of hydraulic head (water pressure) and is typically less than 0.01 for a confined aquifer. Specific storage is defined as the storativity divided by the aquifer thickness. Ashworth (1983) estimates that in the Trinity Group, the confined storativity ranges between 10^{-5} and 10^{-3} (a specific storage of about 10^{-6} per foot) and that the unconfined storativity (specific yield) ranges between 0.1 and 0.3. Based on two aquifer tests, Hammond (1984) determined a storativity of 3×10^{-5} for the lower member of the Glen Rose Limestone. Although we could not locate values for the Edwards Group in the plateau area, the specific yield for the Edwards Group in the Edwards (Balcones Fault Zone) Aquifer is 0.03 (Maclay and Small, 1986, p. 68–69). Specific yield is a ratio that describes the fraction of aquifer volume that will "yield" or be released when the water is allowed to drain out of the aquifer under gravity.

To estimate hydraulic properties for the study area and expand upon previous studies, Mace and others (2000): (1) compiled available information on aquifer properties or tests from published reports and well records, (2) conducted and analyzed detailed aquifer tests in the study area, (3) used specific-capacity information to estimate transmissivity, and (4) summarized the results using statistics. Mace and others (2000) compiled aquifer property data from: (1) available literature (Meyers,1969; Hammond, 1984; Simpson and others, 1993; LBG-Guyton Associates, 1995; Bradley and others, 1997), (2) aquifer tests that they conducted in the study area, analyzing the results using the methodologies of Theis (1935), Cooper and Jacob (1946), and Kruseman and de Ridder (1994), and (3) specific-capacity (well-performance) tests from the Texas Water Development Board water-well database and used an analytical technique (Theis, 1963) to estimate transmissivity.

Mace and others (2000) developed a map of hydraulic conductivity for the Middle Trinity Aquifer, used the spatial distribution of hydraulic conductivity in each unit of the Middle Trinity Aquifer (Cow Creek Limestone, Hensell Sand, and lower member of the Glen Rose Limestone) and the relative thickness of each unit. To estimate the hydraulic conductivity of the Middle Trinity Aquifer at any given point, Mace and others (2000) weighted the hydraulic conductivity of each layer by the relative thickness of each respective layer at that point. As a result of the paucity of data from the Edwards Group and Upper Trinity Aquifers, Mace and others (2000) distributed hydraulic conductivity uniformly through the study area. The hydraulic conductivity values used in the Edwards Group and Upper Trinity Aquifer, 7 feet per day and 5 feet per day, respectively, are derived from calibration of the model by Mace and others (2000).

In the updated model, we simplified the distribution of hydraulic conductivity in the model and adjusted it during model calibration. As a result, hydraulic conductivity in the Edwards Group is uniformly distributed value of 11 feet per day, while hydraulic conductivity in the underlying Upper, Middle, and Lower Trinity aquifers was divided into two zones. One zone represents higher hydraulic conductivity values in the Balcones Fault Zone and along Cibolo Creek and the other zone represents the remainder of the aquifer (Figure 5-29). Hydraulic conductivity values for the Lower Trinity Aquifer obtained from the Texas Water Development Board groundwater database and Hays Trinity Groundwater Conservation District lie within the range 0.01 to 4.41 feet per day with a geometric mean of 0.52 feet per day. We calculated the hydraulic conductivity from specific-capacity data from the Texas Water Development Board well database using methods outlined in Mace (2001).

5.7 Discharge

Discharge from the Upper and Middle Trinity aquifers in the Hill Country portion of the Trinity Aquifer System is, from greatest to lowest, through (1) discharge to streams and springs (Ashworth, 1983), (2) lateral subsurface flow and diffuse upward leakage to the Edwards (Balcones Fault Zone) Aquifer (Veni, 1994), (3) pumping from the aquifer, and (4) vertical leakage to the Lower Trinity Aquifer. Discharge from the Lower Trinity Aquifer takes the form of pumping and vertical leakage to the overlying Middle Trinity Aquifer. The model by Kuniansky and Holligan (1994) indicates net discharge to streams from the Hill Country portion of the Trinity Aquifer System of 155,000 acre-feet per year. The volume of baseflow varies from year-to-year depending on precipitation.

The volume of water that moves laterally from the Hill Country portion of the Trinity Aquifer System into the Edwards (Balcones Fault Zone) Aquifer is not known, partially because of the difficulty in estimating the amount of flow. A number of studies have indicated, either through hydraulic or chemical analysis, that groundwater likely flows from the Hill Country portion of the Trinity Aquifer System into the Edwards (Balcones Fault Zone) Aquifer (Long, 1962; Klemt and others, 1979; Walker, 1979; Senger and Kreitler, 1984; Slade and others, 1985; Maclay and Land, 1988; Waterreus, 1992; Veni, 1994, 1995). Most of these studies have focused on the movement of groundwater from the Glen Rose Limestone into the Edwards (Balcones Fault Zone) Aquifer; however, water levels (Figures 5-10 through 5-12) suggest that groundwater from the entire Hill Country portion of the Trinity Aquifer System discharges to the south and east in the direction of the Edwards (Balcones Fault Zone) Aquifer. Some of this groundwater flows directly into the Edwards (Balcones Fault Zone) Aquifer along faults, while the remainder continues to flow in the Hill Country portion of the Trinity Aquifer System beneath the Edwards (Balcones Fault Zone) Aquifer. It is possible that groundwater that continues to flow in the Hill Country portion of the Trinity Aquifer System eventually discharges upward into the Edwards (Balcones Fault Zone) Aquifer. However, work by Hovorka and others (1996) suggest that this vertical cross-formational flow is limited. The Glen Rose Limestone in the Cibolo Creek area has been argued to be a part of the Edwards (Balcones Fault Zone) Aquifer due to the hydraulic response and continuity of the formations (George, 1947; Pearson and others, 1975; Veni 1994, 1995).

A few studies have estimated the volume of flow from the Hill Country portion of the Trinity Aquifer System into the Edwards (Balcones Fault Zone) Aquifer. Lowry (1955) attributed a five percent error between measured inflows and outflows in the Edwards (Balcones Fault Zone) Aquifer to cross-formational flow from the Glen Rose Limestone. Woodruff and Abbott (1986), citing a personal communication with Bill Klemt, report that recharge from cross-formational flow accounts for six percent of total recharge or about 41,000 acre-feet per year on average, to the Edwards (Balcones Fault Zone) Aquifer. Kuniansky and Holligan (1994) suggest pre-development groundwater discharge of 360,000 acre-feet per year from the Hill Country portion of the Trinity Aquifer System to the Edwards (Balcones Fault Zone) Aquifer. This estimate is about 53 percent of average annual recharge to the Edwards (Balcones Fault Zone) Aquifer and is probably too high (Mace and others, 2000). LBG-Guyton Associates (1995) estimated cross-formational flow from the Glen Rose Limestone to the Edwards (Balcones Fault Zone) Aquifer in the San Antonio area, excluding recharge from Cibolo Creek, to be about two percent of total recharge to the aquifer. Mace and others (2000) estimate net discharge from the Hill Country portion of the Trinity Aquifer System to the Edwards (Balcones Fault Zone) Aquifer of 64,000 acre-feet per year. Of the numerical groundwater flow models of the Edwards (Balcones Fault Zone) Aquifer, Klemt and others (1979), Maclay and Land (1988), Slade and others (1985), Wanakule and Anaya (1993), Barrett and Charbeneau (1996), and Lindgren and others (2004), only Lindgren and others (2004) includes cross-formational flow from the Hill Country portion of the Trinity Aquifer System. Maclay and Land (1988) recognize the occurrence of cross-formational flow between the Hill Country portion of the Trinity Aquifer System and the Edwards (Balcones Fault Zone) Aquifer but only as a topic for future study. Kuniansky and Holligan (1994), estimated 1974 to 1975 cross-formational flow from the Hill Country portion of the Trinity Aquifer System to be about 480,000 acre-feet per year, an order of magnitude larger than calculated cross-formational flow by Lindgren and others (2004) of about 40,000 acre-feet per year.

Groundwater also discharges from the aquifer through pumping of water wells. Lurry and Pavlicek (1991), Barker and Ardis (1996), and Kuniansky and Holligan (1994) estimated pumping from the Hill Country portion of the Trinity Aquifer System to be between 10,000 and 15,000 acre-feet per year in the 1970s. Based on information in Bluntzer (1992), about 14,000 acre-feet per year was produced from the Hill Country portion of the Trinity and Edwards-Trinity (Plateau) Aquifer Systems in the study area. Guyton and Associates (1993) estimated that about 6,350 acre-feet was pumped from the Hill Country portion of the Trinity Aquifer System in northern Bexar County in 1990 with 85 percent of production from the Middle Trinity Aquifer. Texas Water Development Board pumping data indicate that for the period 1980 through 1997 pumping from the Hill Country portion of the Trinity Aquifer System ranged from 14,000 to 24,000 acre-feet per year.

The primary categories of water use in the Hill Country portion of the Trinity Aquifer System are (1) municipal, (2) manufacturing, (3) livestock, (4) rural domestic, and (5) irrigation. Municipal and manufacturing water uses are based on reported values from the users. We associated these values with known well locations and aquifers by cross referencing the water use to the municipal and manufacturing wells through the Texas Commission on Environmental Quality municipal water-well database, the Texas Water Development Board water-well database, and through telephone interviews with water users (Figure 5-30a). We distributed livestock, rural domestic and irrigation pumping based on the spatial distribution of rangeland, non-urban population, and irrigated farmland, respectively (Figures 5-30a through 5-30d). Pumping from the Hill Country portion of the Trinity Aquifer System has been rising over time, from about 15,000 acre-feet per year in 1981 to more than 20,000 acre-feet per year by 1997 (Figure 5-31). About two-thirds of this pumping is for rural domestic and municipal uses with the remainder used by manufacturing, livestock and irrigation. The increasing pumping from the aquifer is mostly due to increasing rural domestic pumping that rose from 6,000 acre-feet per year in 1980 to more than 10,000 acre-feet per year by 1997 (Figure 5-32). Municipal pumping rose gradually from 2,500 acre-feet per year in 1981 to about 5,000 acre-feet per year in 1997. Livestock and irrigation have remained relatively constant over the period 1980 through 1997. Manufacturing pumping rose from about 2,500 acre-feet per year to about 4,400 acre-feet per year in the late 1980s and remained relatively constant after 1988. Pumping from the Hill Country portion of the Trinity Aquifer System has been progressively increasing in most counties within the study area (Figure 5-33; Tables 5-03 to 5-08). However, pumping has remained relatively constant in Comal, Kimble, Travis, and Uvalde counties. Over the period 1980 through 1997, pumping doubled in Blanco, Gillespie, Hays, and Kendall counties.

5.8 Water Quality

Total dissolved solids in groundwater are a measure of water salinity. Fresh, slightly saline, moderately saline, and very saline water have total dissolved solids of less than 1,000, 1,000 to 3,000, 3,000 to 10,000, and 10,000 to 35,000 milligrams per liter, respectively. Most groundwater in the study area is fresh to slightly saline but in some parts of the Hill Country portion of the Trinity Aquifer System groundwater is moderately saline (Figure 5-34). Although the groundwater in the Edwards Group generally has lower salinity than groundwater in the Upper, Middle, and Lower Trinity aquifers, the median total dissolved solids in groundwater is similar in the Edwards Group and Upper and Middle Trinity aquifers (Figure 5-34). The median total dissolved solids are 450, 470, and 410 milligrams per liter in the Edwards Group, Upper and Middle Trinity aquifers, respectively. In the Lower Trinity Aquifer, the median total dissolved solids is higher than the other aquifers at 760 milligrams per liter. Fresh groundwater occurs throughout the Edwards Group in the study area (Figure 5-35). In the Upper, Middle, and Lower Trinity aquifers, slightly to moderately saline groundwater typically occurs in eastern, down-dip, parts of the aquifers, especially in Blanco, Comal, Hays, Kendall, and Travis counties (Figures 5-36 through 5-38).

Groundwater in the Edwards Group is mainly calcium-magnesium-bicarbonate-type (Figure 5-39). Groundwater in the Upper Trinity Aquifer is also mainly calcium-magnesium-bicarbonate-type but progressively becomes calcium-magnesium-sulfate-type in down-dip parts of the aquifer (Figure 5-40). Groundwater in the Middle and Lower Trinity aquifers display similar ranges of geochemical compositions with the former displaying more sulfate-dominated compositions and the latter displaying greater sodium and chloride (Figures 5-41 and 5-42). With increasing depth in the Hill Country portion of the Trinity Aquifer System, groundwater compositions can be categorized into three groups: (1) calcium-magnesium-bicarbonate-type compositions, (2) groundwater compositions characterized by increasing magnesium and sulfate, and (3) groundwater compositions characterized by increasing sodium and chloride (Figure 5-43). Groundwater compositions in the Edwards Group are characteristic of Group 1, groundwater in the Upper Trinity Aquifer display Groups 1 and 2, while groundwater in the Middle and Lower Trinity aquifers displays compositions reflective of all three groups. These compositional trends can be explained by the following processes: (1) groundwater interaction with the limestone of the Edwards Group and the upper member of the Glen Rose Limestone producing the calcium-magnesium-bicarbonate type composition; (2) groundwater interaction with the dolostone and evaporites that occur within the Glen Rose Limestone, resulting in increased magnesium and sulfate in the groundwater; and (3) mixing with sodium-chloride brine migrating from depth.

Distribution of total dissolved solids, chloride, and sulfate shows no specific trend with increasing well depth. Most of the samples from the Edwards Group show no significant changes in total dissolved solids, chloride, sulfate and nitrate from the ground surface to well depths of about 3,500 feet. In the Lower Trinity Aquifer, highest groundwater salinity occurs at depth greater than 500 feet. Nitrate concentrations progressively decrease with increasing well depth in the Edwards, Upper, Middle, and Lower Trinity aquifers. Groundwater in the Edwards Group has the least nitrate with the highest nitrate concentrations occurring in the Upper and Middle Trinity aquifers.

6.0 Conceptual Model of Regional Groundwater Flow in the Aquifer

The conceptual model (Figure 6-01) is our best understanding of regional groundwater flow in the Hill Country portion of the Trinity Aquifer System. The conceptual model does not treat the Hammett Shale confining unit that separates the Middle and Lower Trinity aquifers as a distinct layer of flow. Rather, this confining unit is simulated as a zone of restricted vertical leakance between the two aquifers. When precipitation falls on the outcrop of the aquifer, much of the water evaporates, is taken up and transpired by vegetation or runs off into local streams and eventually discharges through major streams outside of the study area. About four to six percent of the precipitation infiltrates into and recharges the underlying aquifers over most of the study area. This percentage is higher in the eastern portion of the study area where the fractures of the Balcones Fault Zone facilitate higher recharge rates.

Losing streams contribute recharge to the Edwards Group in the headwater areas of the streams along the western margin of the study area (Figure 3-06a) because the Edwards Group in the plateau area has high permeability. Most of the recharge to the Edwards Group in the study area discharges along the edge of the plateau through springs, seeps, and evapotranspiration. A small amount of the flow from the Edwards Group percolates downward into the underlying Upper, Middle, and Lower Trinity aquifers.

Most of the precipitation that recharges the Upper and Middle Trinity aquifers discharges to local and major streams through baseflow to these surface-water features. An exception is Cibolo Creek, where karstification of the lower member of the Glen Rose Limestone changes the creek from a gaining stream to a losing stream between Boerne and Bulverde (Figure 3-01). Most of the remaining recharge in the aquifer discharges either through wells pumping from the aquifer or flows laterally into the Edwards (Balcones Fault Zone) Aquifer.

There are likely several short flow paths along streams where the water table is shallow. In these areas recharged precipitation likely flows a short distance and is discharged via evapotranspiration. Because of the localized nature of the flow paths and the limitations of the model grid, this evapotranspiration discharge would likely be included in discharge to streams.

Groundwater can perch on low permeability beds within the Upper Trinity Aquifer and flow laterally to springs, however, some water percolates through the Upper Trinity Aquifer into the Middle Trinity Aquifer. The Lower Trinity Aquifer is not exposed at land surface. Consequently, groundwater flow enters the Lower Trinity Aquifer through downward cross-formational flow from the Middle Trinity Aquifer and discharges by cross-formation back to the Middle Trinity Aquifer in downdip portions of the aquifers. In general, groundwater in the Hill Country portion of the Trinity Aquifer System flows from areas of higher topography to areas of lower topography, from the west to the east.

In general, lithology and local fracturing control permeability development and distributions in the Edwards Group and the Upper, Middle, and Lower Trinity aquifers. We believe that hydraulic conductivity is higher in the eastern portion of the study area, where they coincide with the Balcones Fault Zone, than in the remainder of the aquifer system. The Edwards Group in the plateau area has high vertical and horizontal permeability due to karstification. The Upper Trinity Aquifer generally has lower permeability but can be locally very permeable, especially in the outcrop. Due to the occurrence of shaley beds, the Upper Trinity Aquifer has a much lower ratio of vertical to horizontal permeability than the overlying Edwards Group. The Middle Trinity Aquifer has moderate permeability and greater ability to transmit water vertically than the Upper Trinity Aquifer. The Middle Trinity Aquifer is most permeable in the sandy outcrop area of Gillespie County. Specific yield in the limestone is primarily controlled by fractures. The Lower Trinity Aquifer is on average less permeable than the overlying aquifers, with highest values occurring in the Kerrville area.

Pumping from the Hill Country portion of the Trinity Aquifer System has been progressively rising over the period 1980 through 1997. This increasing pumping is most apparent in counties adjacent to San Antonio and Austin, the two largest cities in the region, which are Bexar, Hays, Kendall, and Kerr counties. Some of these counties have experienced a doubling of pumping over the period of time covered by this study.

7.0 Model Design

Model design includes (1) choice of code and processor, (2) discretization of the aquifer into model layers and cells, and (3) assignment of model parameters into the various model layers. The model design must agree as much as possible with the conceptual model of groundwater flow in the aquifer.

7.1 Code and Processor

Groundwater flow through the Hill Country portion of the Trinity Aquifer System was simulated using MODFLOW-96, a widely used modular finite-difference groundwater flow code written by the United States Geological Survey (Harbaugh and McDonald, 1996). This code was selected because of (1) its capabilities of simulating regional-scale groundwater processes in the Hill Country portion of the Trinity Aquifer System, (2) its documentation and wide use (McDonald and Harbaugh, 1988; Anderson and Woessner, 2002), (3) the availability of a number of third-party pre- and post-processors for facilitating easy use of the modeling software, and (4) its easy availability because it is public domain software. Processing MODFLOW Pro version 7.0.18 was used to load input data into the model and view model outputs (Chiang, 2005). Other pre- and post-processors can read source files for MODFLOW-96. This model was developed and run on a Dell Precision 490 with a 3.0 GHz Dual Core Xeon processor and 2 GB RAM running Microsoft Windows XP Professional (v. 5).

7.2 Layers and Grid

The lateral extent of the model corresponds to natural hydrologic boundaries, such as erosional limits of the aquifers, rivers, and the structural boundary with the Edwards (Balcones Fault Zone) Aquifer, and hydraulic boundaries to the west that coincide with groundwater divides. According to the hydrostratigraphy and conceptual model, we designed the model to have four layers. Layer 1 consists of the Edwards Group of the Edwards-Trinity (Plateau) Aquifer System, and Layers 2, 3 and 4 consist of the Upper, Middle and Lower Trinity aquifers, respectively.

We defined the active and inactive cells by first establishing the lateral extent of the formations in each layer using the geologic map (Figure 3-16). We assigned a cell as active if the formation covered more than 50 percent of the cell area. Please note that the spatial extents of the respective aquifers were revised slightly during model calibration to address dry cell and numerical stability issues. We did not include the thin slivers of the Edwards Group in the eastern part of the study area, for example in Blanco County, because: (1) our structure maps do not accurately represent the complexity of faulting in the area, (2) flow in some of these rocks is associated with the Edwards (Balcones Fault Zone) aquifer, and (3) in many areas these rock are discontinuous and thus groundwater flow, if any, would be difficult to simulate at the regional scale. It should be noted that we did include a part of the Edwards Group that is not recognized by TWDB as part of the Edwards-Trinity (Plateau) Aquifer in eastern Kerr County and western Kendall County. Each layer has 69 rows and 115 columns for a total of 31,740 cells in the model. All the cells have uniform lateral dimensions of 1 mile by 1 mile. We selected this cell size to be small enough to reflect the density of input data and the desired output detail and large enough for the model to be manageable. Cell thickness depended on differences in top and bottom elevations of the model layers. After we made cells outside of the model area and outside the lateral extent of each layer inactive, the model had a total of 12,976 active cells: 1,107 in Layer 1; 3,562 in Layer 2; 4,517 in Layer 3; and 3,790 in Layer 4 (Figure 7-01).

7.3 Model Parameters

We distributed model parameters, including (1) elevations of the top and bottom of each layer, (2) horizontal and vertical hydraulic conductivity, (3) specific storage, and (4) specific yield using ArcGIS® 9.1. We defined top and bottom elevations for each layer from the structure maps and land surface elevations from digital elevation models downloaded from the United States Geological Survey. We used ArcGIS® 9.1 to assign top and bottom elevations. For Layer 1 (Edwards Group), we assigned the top as the land-surface elevation and the bottom according to the structure map of the base of the Edwards Group (Figure 5-01). The top and base of Layer 2 (Upper Trinity Aquifer) were assigned according to the structure map of the Upper Trinity Aquifer (Figure 5-02). Where covered by active cells in Layer 1, the top of Layer 2 coincides with the base of Layer 1, otherwise it is defined by the land-surface elevation. The bottom of Layer 2 was defined by the base of the Upper Trinity Aquifer (Figure 5-02). Similarly, the top of Layer 3 (Middle Trinity Aquifer) was defined as the bottom of Layer 2 and the land-surface elevation where exposed (Figure 5-03). The bottom of layer 3 was assigned using the elevation of the base of the Middle Trinity Aquifer (Figure 5-03). The top of Layer 4 (Lower Trinity Aquifer) is defined as the base of the Hammett Shale, the confining unit separating the Middle and Lower Trinity aquifers (Figure 5-04). Groundwater flow through the Hammett Shale is not explicitly simulated in the model.

We initially assigned hydraulic conductivity values for Layers 1, 2, and 3 previously used in Mace and others (2000) and adjusted these values during calibration. These values were uniform values of 7 and 5 feet per in Layers 1 and 2 based on geometric mean of hydraulic conductivity data, respectively, and a distributed range of values of 0.7 to 64 feet per day in Layer 3. The initial hydraulic conductivity value we assigned to Layer 4 was 0.6 feet per day, the geometric mean of the hydraulic conductivity data for the Lower Trinity Aquifer. We initially assigned vertical hydraulic conductivity to be one-tenth the horizontal hydraulic conductivity. We simulated groundwater flow between Layers 3 and 4, through the Hammett Shale, using vertical leakance values. These vertical leakance values were initially set to be proportional to the relative thickness of the Hammett Shale in each cell. The purpose for using vertical leakance is to simulate vertical flow through the Hammett Shale confining unit without the need to simulate horizontal flow through the unit which is assumed to be small. The range of vertical leakance values is 10^{-6} to 0.8 per day (Figure 7-02). We assigned uniform values of specific storage and specific yield values in each layer. Initially assigned specific storage values are 10^{-6}, 10^{-7}, 10^{-8}, and 10^{-8} per foot in Layers 1, 2, 3, and 4, respectively. Initially assigned specific yield values are 8×10^{-4}, 5×10^{-5}, 8×10^{-5}, and 8×10^{-5} in Layers 1, 2, 3, and 4, respectively.

We assigned Layer 1 as unconfined and Layers 2 through 4 as confined/unconfined. We allowed the model to calculate transmissivity and storativity according to saturated thickness. We used units of feet for length and days for time for all input data to the model. To solve the groundwater flow equation, we used the Slice Successive Over-Relaxation solver with a convergence criterion of 0.0001 feet.

7.4 Model Boundary Conditions

Model boundary conditions are factors that control the inflow and outflow of groundwater in a numerical model. We assigned model boundary conditions for (1) recharge, (2) pumping, (3) rivers and streams, (4) reservoirs, (5) outer model boundaries, and (6) initial head conditions. We used ArcGIS® 9.1 to distribute values for model boundary conditions spatially, such as drains, general-head boundaries, recharge, and pumping.

We assigned recharge based primarily on the spatial distribution of annual precipitation over the study area (Figure 3-09). The initial recharge assigned to the model was 4.7 percent of annual precipitation. This value coincides with the value used in the groundwater availability model for the Edwards-Trinity (Plateau) Aquifer (Anaya and Jones, 2009). We also included in the recharge distribution, recharge from streamflow losses in Cibolo Creek.

We assigned pumping values in the model according to our analysis of pumping as discussed in the 'Discharge' section of this report (Figure 5-30). This model simulates the regional effects of pumping on water levels for rural domestic, municipal, irrigation, industrial, and livestock uses (Tables 5-03 through 5-08). Municipal and manufacturing pumping was distributed based on known well locations and pumping data from the Texas Water Development Board Water Use Survey. The other uses (domestic, irrigation, and livestock) were distributed throughout the model grid, reflecting the spatial distribution of associated land use. Rural domestic pumping was distributed based on the spatial distribution of population outside major urban areas that lie within the model grid. Irrigation pumping was distributed based on 1:250,000-scale land use and land cover data from United States Geological Survey. Irrigation was assumed to occur on all land classified as orchards, row crops, or small grains. Livestock pumping was also distributed based on 1:250,000-scale land use and land cover data from United States Geological Survey. Livestock pumping was assumed on all rangeland. Figure 7-03 shows the spatial distribution of total pumping for the year 1980.

We used the Drain Package of MODFLOW to represent rivers and streams in the model (Figure 7-04). This package only allows the streams to gain water from the aquifer. The River Package, which is another possible approach for simulating rivers and streams, allows streams to gain and lose water. Mace and others (2000) found that the River Package could allow unrealistic amounts of water to move from the rivers and streams into the aquifer and thus underestimate potential water-level declines due to pumping or drought. Observed streamflow losses in Cibolo Creek along the boundary between Bexar and Comal counties are simulated as recharge. The Drain Package requires a drain elevation and conductance. When the head in the aquifer is above the drain elevation, water flows out of the model through the drain. If the head in the aquifer is equal to or below the drain elevation, no flow occurs from the drain to the aquifer. Drain conductance is a measure of hydraulic resistance to flow out of the drain. We defined the drain elevation by intersecting stream-bed location with the digital elevation model in ArcGIS® 9.1. We assigned the drain conductance based on estimated width of the stream, a stream length of one mile (equivalent to the model cell size), an assumed riverbed thickness of one foot, and an assumed vertical hydraulic conductivity of 0.1 feet per day. After Mace and others (2000) calibrated the model, they investigated the sensitivity of simulated water levels to different values of drain conductance. Except for very low values, the drain conductance generally has little effect on water levels in the model (Mace and others, 2000). We also used drains to represent discharge to major springs, seepage from the erosional edge of the Edwards Group in the plateau area, and flow out of the Middle Trinity Aquifer in Gillespie County (Figure 7-04). For the springs, we assigned the drain elevation as the land-surface elevation at the spring location and an initial conductance based on an assumed one-foot thickness and the geometric mean hydraulic conductivity of the layer. For the erosional edge of the Edwards Group and flow out of the Middle Trinity Aquifer in Gillespie County, we assigned a drain elevation 10 feet above the base of Layer 1 and a drain conductance based on a one foot thickness and the geometric mean hydraulic conductivity of the layer.

We simulated the influence of Medina Lake, Canyon Lake, Lake Travis, and Lake Austin on the aquifer using MODFLOW's River Package (Figure 7-04). The River package requires hydraulic conductance of riverbed, river stage, and bottom elevation of the river. We assigned the riverbed conductance according to estimated width of the stream, a stream length of one mile (equivalent to the model cell size), riverbed thickness of one foot, and vertical hydraulic conductivity of 0.1 feet per day. We assigned the head in the river as the average lake-level elevation for the respective lakes. We defined the elevation of the riverbed by intersecting stream-bed location with the digital elevation model in ArcGIS® 9.1.

Outer model boundary conditions define the spatial extent of active flow within the respective layers in the model. In this model, the outer boundary conditions are defined by the use of no-flow and general-head boundaries. The model boundaries are generally simulated by no-flow boundaries to the north and west and general-head boundaries located in the south and east where the Hill Country portion of the Trinity Aquifer System bounds the Edwards (Balcones Fault Zone) Aquifer. The no-flow boundary in the north coincides with surface water divides in the Pedernales and Colorado River basins. The no-flow boundary in the west follows a flow path in the Edwards-Trinity (Plateau) Aquifer. Layer 4 is also bound by no-flow boundaries in the south and east based on the assumption, in response to work by Hovorka and others (1996), that there is very little groundwater flow between the Hill Country portion of the Trinity Aquifer System and Trinity Group rocks underlying the Edwards (Balcones Fault Zone) Aquifer. A no-flow boundary also exists at the base of the Lower Trinity Aquifer based on the assumption that there is no cross-formational flow between the Lower Trinity Aquifer and underlying Pre-Cretaceous rocks. To model the flow of groundwater between the Hill Country portion of the Trinity Aquifer System and the Edwards (Balcones Fault Zone) Aquifer, we used the General-Head Boundary Package of MODFLOW. We placed general-head boundary cells along the contact with the Edwards (Balcones Fault Zone) Aquifer in layers 2 and 3 (Figure 7-04). The General-Head Boundary Package requires values for hydraulic head and conductance. We assigned the hydraulic head according to the interpreted water-level map (Figure 5-03) in the area of the general-head boundary cells. We assigned the general-head boundary conductance according to the hydraulic conductivity and geometry of the cell and an assumed one-foot thickness. Conceptually, the general-head boundary conductance represents the resistance to flow between a cell in the model and a constant-head source or sink. In this case, we have used the general-head boundary to represent flow out of the study area either into the Edwards (Balcones Fault Zone) Aquifer across faults or continuing into the down-dip parts of the Trinity Aquifer System. For simplicity, we used an arbitrary thickness of unity (one foot) to define conductance.

The updating of this model included changes to the boundary conditions. In addition to the addition of the Lower Trinity Aquifer to the model, these changes include: (1) the constant-head cells that were used by Mace and others (2000) to simulate reservoirs were replaced by river cells, (2) river cells simulating Lake Travis were removed from Layer 2 and now only appear in Layer 3, (3) the spatial extent of Medina Lake was revised, (4) the spatial distribution of recharge was revised to account for the effects of the Balcones Fault Zone and recharge from Cibolo Creek. The constant-head cells were converted to river cells because constant-head provide an unlimited, unrestricted source of water when impacted by nearby pumping and with therefore produce unrealistic high water level adjacent to the constant-head cells. On the other hand, the River Package in MODFLOW include a conductance parameter that can be used to restrict flow and would therefore allow water levels to fall to more realistic values in response to pumping. Although the potential exists to produce unrealistically high flows from the River Package (similar to the use of constant heads), amounts of water to the groundwater flow system under periods of high pumping, proper attention to boundary elevation and conductance can mitigate this effect. During model calibration, minor adjustments were made to the outer model boundary conditons to address dry cell and numerical stability issues.

8.0 Modeling Approach

Model calibration involves the adjustment of parameters until the model results of groundwater elevations and base flow discharge reasonably match measured field data. Our approach for calbrating the model included two major steps: (1) calibrating a steady-state model and (2) calibrating a transient model.

The steady-state model was developed first to facilitate easier calibration because some parameters, such as aquifer storage and water-level variations over time, do not need to be taken into consideration. In the steady-state model, calibration only requires consideration of spatial variations of all input parameters within the aquifer. We calibrated the steady-state model to reproduce water levels for 1980, reproducing the 1977 through 1985 water-level measurements (Figure 5-09 through 5-12). We used the steady-state model to investigate (1) recharge rates, (2) hydraulic properties, (3) boundary conditions, (4) discharge from the Hill Country portion of the Trinity Aquifer System into the Edwards (Balcones Fault Zone) Aquifer, (5) groundwater flow budget, and (6) sensitivity of model results to different parameters.

Our approach for calibrating the model was to match water levels and groundwater discharge to rivers (for steady-state conditions) and water-level and groundwater discharge fluctuations (for transient conditions) using our conceptual understanding of the flow system. We quantified the calibration, or goodness of fit between the simulated and measured water-level values, using the mean absolute error:

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

Where ***MAE*** is the mean absolute error, ***n*** is the number of calibration points, $\boldsymbol{h_m}$ is the measured hydraulic head at point *i*, and $\boldsymbol{h_s}$ is the simulated hydraulic head at point *i*. The mean absolute error is the mean of the absolute value of the differences in measured and simulated hydraulic head (Anderson and Woessner, 2002). Our standards for calibration included: 1) the mean absolute error must be less than 10 percent of the measured hydraulic-head drop across the model area and 2) the error shall not be biased by areas with considerably more control points than other areas. Once we completed the steady-state model, we used the framework of the model to develop a transient model for the years 1980 through 1997 using annual stress periods.

Please note that the first stress period in the transient model is 1,000,000 days long and represents the 1980 steady-state model. The transient model allowed us to test how well the model could reproduce water-level fluctuations in the aquifer. We calibrated the transient model by adjusting aquifer storage values to minimize the difference between simulated and measured water-level variations.

9.0 Steady-State Model

Once we assembled the input datasets and constructed the framework of the model, we calibrated the steady-state model and assessed the sensitivity of the model to different hydrologic parameters.

9.1 Calibration

We calibrated the model to measured water levels for 1977 through 1985 used to represent 1980 water levels. We chose the year 1980 for our steady-state model because it fell within a period of relatively stable water-levels in the Hill Country portion of the Trinity Aquifer System. We adjusted recharge and spatial distribution of hydraulic conductivity and general-head boundary conductance to calibrate the steady-state model.

We assigned recharge into three zones based on varying aquifer characteristics and recharge pathways: (1) Balcones Fault Zone, (2) areas outside the fault zone, and (3) Cibolo Creek. We varied recharge during the calibration process, resulting in a final recharge rate of 5 percent of average annual precipitation in the Balcones Fault Zone, along the eastern margin of the study area, and 3.5 percent of average annual precipitation throughout the remainder of the model area. Along Cibolo Creek, we set recharge equivalent to measured streamflow loss of about 70,300 acre-feet per year (Figure 9-01).

We also adjusted hydraulic conductivity during model calibration. In the calibrated model, we assigned a uniform hydraulic conductivity value of 11 feet per day to the Edwards Group. Assigned hydraulic conductivity values in the Upper Trinity Aquifer are 150 feet per day along Cibolo Creek, 15 feet per day within the Balcones Fault Zone, and 9 feet per day in the remainder of the aquifer. The two lower hydraulic conductivities, within and outside the Balcones Fault Zone, fall within the range of measured hydraulic conductivity in the Upper Trinity Aquifer. The highest hydraulic conductivities in the Upper Trinity Aquifer which lie along part of Cibolo Creek can be justified based on work done by Kastning (1986) and Veni (1994) that indicated very high hydraulic conductivity near the creek. In the Middle Trinity Aquifer, we assigned a uniform hydraulic conductivity of 7.64 feet per day, the geometric mean of the hydraulic conductivity values used by Mace and others (2000), for the portion of the aquifer outside the Balcones Fault Zone. In the Balcones Fault Zone portion of the Middle Trinity Aquifer, we assigned a uniform hydraulic conductivity of 15 feet per day. In the Lower Trinity Aquifer, we assigned hydraulic conductivity values of 16.7 and 1.67 feet per to the Balcones Fault Zone and the remainder of the aquifer, respectively.

The calibration process resulted in only minor changes to drain conductance values in individual cells. We increased general-head boundary conductance values by factors of 5 and 2.5 in layers 2 to 3, respectively, to facilitate increased inter-aquifer flow between the Hill Country portion of the Trinity Aquifer System and the Edwards (Balcones Fault Zone) Aquifer due to the large amounts of recharge flowing from the Cibolo Creek.

Inter-aquifer flow between the Middle and Lower Trinity aquifer through the Hammett Shale are simulated using vertical leakance. We varied vertical leakance spatially based on the Hammett Shale thickness. Vertical leakance values decrease with increasing Hammett Shale thickness reaching a maximum value where the Hammett Shale is absent. Vertical leakance values lie in the range 10^{-6} to 0.8 per day.

Simulated water levels from the calibrated steady-state model are fairly close to measured water levels, and display no apparent spatial biases (Figure 9-02). The mean absolute error of the calibrated model is 54 feet, which is approximately 4 percent of the 1,700-foot range of measured water levels (Figure 9-03). This indicates that the average difference between measured and simulated water levels in the model is 54 feet —acceptable because the result lies within the 10-percent target for model calibration. Water balance discrepancies are also acceptable, approaching 0 percent.

In addition to the comparison of measured and simulated water levels, we compared measured streamflow and simulated drain discharge to indicate how well the model reproduces groundwater discharge to major streams in the study area (Figures 9-04 and 9-05). There is general agreement between measured stream discharge of Barton Creek, Blanco River, Guadalupe River, Hondo Creek, Medina River, Onion Creek, and Pedernales River indicating that the steady-state model does a reasonable job of reproducing baseflow to streams.

The water budget of the steady-state model indicates that total groundwater flow through the model is approximately 321,000 acre-feet per year (Table 9-01). Of this flow, about 60 percent discharges to streams, springs, and reservoirs, and 35 percent discharges through cross-formational flow to the Edwards (Balcones Fault Zone) Aquifer. About 5 percent of groundwater discharge is due to well pumping, mostly for municipal and rural domestic uses.

We used the calibrated model to investigate the volume of recharge to and groundwater moving between the different aquifers (Table 9-02). The total volume of recharge to the aquifer due to precipitation falling on the land surface and streamflow loss from Cibolo Creek is about 304,000 acre-feet per year. About 50 percent of the recharge in the study area occurs in the Upper Trinity Aquifer while 20 and 30 percent of recharge occurs in the Edwards Group and Middle Trinity Aquifer, respectively. Recharge to the Lower Trinity Aquifer is insignificant. In the model, very small amounts of recharge to the Lower Trinity Aquifer occur along the Pedernales River where the overlying Middle Trinity Aquifer is thin and may not be saturated. About 20 percent of the water that recharges the Edwards Group flows into the Upper Trinity Aquifer. The total inflow of water to the Upper Trinity Aquifer, including infiltration of precipitation and cross-formational flow, is about 166,000 acre-feet per year. About 40 percent of the total inflow into the Upper Trinity Aquifer flows into the Middle Trinity Aquifer. Total inflow into the Middle Trinity Aquifer is about 153,000 acre-feet per year. According to the model, slightly less water enters the Middle Trinity Aquifer through cross-formational flow than through direct infiltration on the outcrop. Based on our conceptual model, total groundwater circulation in the Lower Trinity Aquifer is a relatively minor component of the total groundwater budget of the Hill Country portion of the Trinity Aquifer System. In this steady-state model, net cross-formational flow from the Middle Trinity Aquifer to the Lower Trinity Aquifer is approximately equal to total pumping from the Lower Trinity Aquifer.

The model shows that over 100,000 acre-feet per year of groundwater flows out through the general-head boundary along the eastern and southern margins of the model. This groundwater flows from the Upper and Middle Trinity aquifers into the Edwards (Balcones Fault Zone) Aquifer. Some of this groundwater flows directly from the Trinity Aquifer System into the Edwards (Balcones Fault Zone) Aquifer and some continues to flow in the portion of the Trinity Aquifer System that underlies the Edwards (Balcones Fault Zone) Aquifer (Ashworth and Hopkins, 1995). Presumably, groundwater moves down-dip in the Trinity Aquifer System and eventually discharges upward into the Edwards (Balcones Fault Zone) Aquifer.

The model results show that the flow of groundwater across the general-head boundary is much less in the northeastern part of the boundary than the central and southwestern parts (Table 9-03). The groundwater flow across the general-head boundary is 260 acre-feet per year per mile for the boundary within Travis and Hays counties, reaches a maximum of 1,700 acre-feet per year per mile in Comal and Bexar counties, and is 490 acre-feet per year per mile within Medina, Bandera, and Uvalde counties. This numerical result is qualitatively supported by the measured potentiometric surface which shows groundwater generally flowing perpendicular to the boundary in Comal, Bexar, and Medina counties and sub-parallel to the boundary in Travis and Hays counties (Figure 9-02). The spatial distribution of groundwater flow between the Trinity Aquifer System and the Edwards (Balcones Fault Zone) Aquifer is likely influenced by the large amounts of recharge taking place along Cibolo Creek in Bexar and Comal counties. Faults also have greater displacements to the east and therefore may act as more effective barriers to flow.

9.2 Sensitivity Analysis

After we completed calibration of the steady-state model, we analyzed the input parameters to assess the sensitivity of model results to respective input parameters: vertical and horizontal hydraulic conductivity, general-head boundary conductance, drain conductance, river conductance, pumping, and recharge. Sensitivity analysis is a method of quantifying uncertainty of the calibrated model related to uncertainty in the estimates of respective aquifer parameters, stresses, and boundary conditions (Anderson and Woessner, 2002). Determining the sensitivity of the model to specific parameters offers insights into the uniqueness of the calibrated model. Sensitivity analysis identifies which parameters have the greatest influence on water levels and groundwater discharge to springs and streams. A model is sensitive to a specified input parameter if relatively small changes in that parameter result in relatively large changes in simulated water levels. In other words, calibration is possible only over a narrow range of values and, consequently, model uncertainties are relatively low. A model is insensitive if relatively large changes of a specific input parameter produce small water-level changes. Insensitivity results in higher uncertainties because the model will remain calibrated over a large range of input parameter values. Sensitivity is analyzed by systematically varying parameter values and noting changes in water levels over the calibrated model. The water-level changes are quantified by calculating the Mean Difference (*MD*) as follows:

$$MD = \frac{1}{n}\sum_{i=1}^{n}\left(h_{sen} - h_{cal}\right)$$

where: n is the number of points, h_{sen} is the simulated water level for the sensitivity analysis, and h_{cal} is the calibrated water level. The Mean Difference is positive if water levels are higher than calibrated values and negative if they are lower than calibrated values.

Water levels in the model are most sensitive to recharge and horizontal hydraulic conductivity, and to a lesser extent, to vertical hydraulic conductivity (Figure 9-06). The model is insensitive to pumping, and general-head boundary, drain, and river conductance. The insensitivity to pumping can be attributed to the fact that pumping is a relatively minor component of the overall aquifer water budget. Insensitivity to drain and general-head boundary conductance can be attributed to high conductance values of up to 10^9 square feet per day. Consequently, in order to have much of an effect on water levels, drain and general-head boundary conductance would probably have to be lowered by several orders of magnitude. Additionally, the effects of drain and general-head boundary conductance are local. As a result, varying drain and general-head boundary conductance only produces water-level changes close the boundaries and does not have widespread effects throughout the model.

10.0 Transient Model

Once we calibrated the steady-state model to 1980 conditions, we proceeded to calibrate the model for transient conditions for the period 1980 through 1997 (Table 10-01).

10.1 Calibration

We simulated water-level fluctuations during the period 1980 through 1997 using annual stress periods for 1981 through 1997. Calibration was achieved by adjusting storage parameter values, specific storage, and specific yield until the model responses approximated water-level fluctuations observed in wells in the model area. Specific yield is applicable to the unconfined parts of the aquifer and is defined as the volume of water that an unconfined aquifer releases from storage per unit surface area of aquifer per unit decline in the water level (Domenico and Schwartz, 1990). Specific storage is applicable to the confined parts of the aquifer and is defined as a measure of the volume of water per unit volume of aquifer rock that enters or leaves storage per unit change in water level (Domenico and Schwartz, 1990). Specific storage and specific yield are important factors in transient calibration because they influence water-level responses to changes in recharge and discharge. Low specific storage or specific yield values result in water-level fluctuations that are larger and more rapid than those associated with higher specific storage or specific yield values. This difference occurs because less water is required to produce a given water-level change.

Using annual stress periods, we simulated water-level fluctuations due to recharge and pumping variations during the period 1980 through 1997. We found that specific storage values of 10^{-5}, 10^{-6}, 10^{-7}, and 10^{-8} per foot for the Edwards Group, and the Upper, Middle, and Lower Trinity aquifers, respectively, and specific-yield values of 0.008, 0.0005, 0.0008, and 0.0008 for the

Edwards Group, and the Upper, Middle, and Lower Trinity aquifers, respectively, worked best for reproducing observed water-level fluctuations (Table 10-02).

The model does a good job of reproducing observed water-level fluctuations in some areas but not as well in other areas (Figures 10-01 through 10-05). Note that baseline shifts in water levels in Figure 10-02 are often due to the influence of local-scale conditions not represented in the regional model or errors in our parameterization of the aquifer data. Although there are limitations, the model does a good job of reproducing year-to-year water-level variations in most wells. Comparison of measured and simulated 1990 and 1997 water levels indicate mean absolute errors of 52 and 57 feet, respectively, or approximately 3.5 and 5.3 percent of the range of measured water levels (Table 10-03; Figure 10-04).

Table 10-04 shows the water budgets for the respective model layers in 1980, 1990, and 1997. Simulating discharge to springs using a regional-scale model is often difficult because of spatial and temporal scale issues. Table 10-05 shows simulated and measured discharge for selected springs in the study area. It should be noted that the measured discharge values represent single snapshots in time that: (1) in most cases did not fall within the 1980 through 1997 transient model period, and (2) may not be representative of average discharge from the spring during the transient modeling period because spring discharge varies widely over time. Simulated discharge values represent discharge averaged over each annual stress period. Additionally, springs are often discharge sites for highly localized flow systems that can not be simulated in regional models. The result is that apparent ability of the model to simulate spring discharge varies widely. Of seventeen springs, six display a good comparison between measured and simulated discharge values. Simulated spring discharge from springs with the highest measured discharge values differ from measured values by about an order of magnitude. Most springs in the study area represent discharge from highly localized flow systems within the aquifer system that are characterized by short flow paths. The localized nature of these flow paths and the limitations of the regional model grid, result in much of the spring discharge being included in baseflow discharge to streams. Overall, the model also does a good job of mimicking baseflow fluctuations (Figure 10-06).

10.2 Sensitivity Analysis

Upon completion of transient model calibration, we assessed the storage parameters to determine the sensitivity of the model to variation of specific yield and specific storage values. Sensitivity analysis involves systematically varying specific yield and specific storage to determine associated changes in aquifer response over the transient model run. We ran the model multiple times, lowering and then raising the calibrated specific yield and specific storage values by an order of magnitude.

Sensitivity analysis indicates that the unconfined Edwards Group (Layer 1) is sensitive to increasing specific yield input values and insensitive to specific storage input values (Figures 10-07 and 10-08). This is not surprising because MODFLOW only utilizes specific yield input values when simulating groundwater flow through an unconfined aquifer. Overall, the model is much more sensitive to specific yield than specific storage.

11.0 Limitations of the Model

All numerical groundwater flow models have limitations. These limitations are usually associated with (1) the extent of current understanding of the workings of the aquifer, (2) availability and accuracy of input data, (3) assumptions and simplifications used in developing the conceptual and numerical models, and (4) the scale of application of the model. The limitations determine the spatial and temporal variation of uncertainties in the model because calibration uncertainty decreases with increased availability of input data. Additionally, many of the assumptions, degree of simplification, and spatial resolution of groundwater flow models are influenced by availability of input data.

11.1 Input Data

Several of the input datasets for the model are based on limited information. These include structural geology, recharge, water-level data, hydraulic conductivity, specific storage, and specific yield.

Although this model's representation of aquifer hydraulic propoerties may be adequate for the regional model, it may not be appropriate for local-scale conditions. The same problem occurs in the assigning of specific storage and specific yield values in the model. The paucity of measured specific storage and specific yield values is overcome partially by calibrating the model based on observed water-level responses in the wells in the model area with the most water-level measurements over the model period.

There is no published information on the spatial distribution of recharge throughout the Hill Country portion of the Trinity Aquifer System. Calibration of recharge rates is obtained by trial-and-error during construction of the steady-state model. Application of these recharge rates to the transient model assumes that (1) a linear relationship exists between precipitation and recharge and (2) there is no threshold that must be exceeded before recharge occurs. This assumption suggests the possibility of overestimating recharge during dry periods, when all precipitation may be taken up by evapotranspiration or absorbed by dry soils. The relatively good correlation between observed and simulated water levels and stream discharge suggests that, despite uncertainties, the model water budget reasonably represents the regional groundwater budget.

Our structural maps simplify faulting along the southeastern margin of the model and smooth out the base of the Middle Trinity Aquifer in the northern part of the model. This simplification causes the model represent the regional structural controls and regional groundwater flow, but limits the ability of simulating local groundwater flow in these areas. Greater structural control may be attained with more detailed maps and a finer model grid in this area. However, this increased complexity would come at the cost of the requirement of a finer model grid and consequently much longer run times and increased computational complexity resulting increased instability of the model with no guarantee of increased model accuracy.

Water-level maps, and therefore the calibration of the model, are affected by limited information, especially in layer 1 where there are few measurements. Limited availability of wells with multiple water-levels measurements affects calibration of the transient model. Limited water-level measurements bias model calibration to areas where water levels have been measured. The difference between measured and simulated water levels can be accounted for by factors such as unavoidable simplifications incorporated into the model, and water-levels measurements not representative of the average water level for a specific period of time simulated by the model.

11.2 Assumptions

We used several assumptions to simplify construction of the model. The most important assumptions are: (1) there is no flow between the Lower Trinity Aquifer and underlying Paleozoic units, (2) the Drain Package of MODFLOW can be used to simulate discharge to streams and rivers, (3) the General-Head Boundary package of MODFLOW can be used to simulate cross-formational flow between the Hill Country portion of the Trinity Aquifer System and the Edwards (Balcones Fault Zone) Aquifer, and (4) recharge from Cibolo Creek is constant over time.

We assumed that the vertical leakance between the Middle and Lower Trinity aquifers is a function of the thickness of the Hammett shale. Most of the base of the Middle Trinity Aquifer is underlain by the Hammett Shale (Amsbury, 1974; Barker and Ardis, 1996), and restricts flow between the Middle and Lower Trinity aquifers (Ashworth, 1983).

We used the Drain Package of MODFLOW to simulate streams and rivers in the study area. The Drain Package only allows water to move from the aquifer to the streams and rivers, thus implying that the streams and rivers in the study area are gaining streams and will remain so in the future.

We used the General-Head Boundary package to simulate cross-formational flow between the Hill Country portion of the Trinity Aquifer System and the Edwards (Balcones Fault Zone) Aquifer. The spatial distribution of general-head boundary cells in the model is based on the assumption that cross-formational flow takes place where the two aquifers juxtapose along the Balcones Fault Zone. We also assumed that there is no groundwater flow from the Lower Trinity Aquifer to the Trinity rocks underlying the Edwards (Balcones Fault Zone) Aquifer.

Annual fluctuations in recharge from Cibolo Creek are small enough during the transient model period to not affect calibration, thus allowing the use of constant recharge. However, during periods of extreme drought, it is likely that recharge from Cibolo Creek will decline and eventually cease. Consequently, predictive model runs that include periods of lower precipitation and streamflow (e.g. drought-of-record) should include reduced recharge in this area.

11.3 Scale of Application

The limitations described earlier and the nature of regional groundwater flow models affects the scale of application of the model. As calibrated, this model is most accurate in assessing regional-scale groundwater issues, such as predicting aquifer-wide water-level changes and trends in the groundwater budget that may result from different proposed water management strategies, on an annual timescale. Accuracy and applicability of the model decreases when moving from addressing regional- to local-scale issues because of limitations of the information used in model construction and the model cell size that determines spatial resolution of the model. Consequently, this model is not likely to accurately predict water-level declines associated with a single well or spring because (1) these water-level declines depend on site-specific hydrologic properties not included in detail in regional-scale models and (2) the cell size used in the model is too large to resolve changes in water levels that occur over relatively short distances. Addressing local-scale issues requires a more detailed model, with local estimates of hydrologic properties, or an analytical model. This model is more useful in determining the impacts of groups of wells or well fields distributed over a few square miles. The model can be used to predict changes in ambient water levels rather than actual water-level changes at specific locations, such as an individual well.

12.0 Future Improvements

The Texas Water Development Board plans periodically to update, and thus improve, its groundwater availability models. This model may be improved by incorporating greater complexity or hydrologic information that was not available when it was updated. Model uncertainty may be reduced with additional information on streamflow, hydraulic properties, water-level elevations, and recharge.

Additional hydraulic head measurements and aquifer-test data are required for the Hill Country portion of the Trinity Aquifer System. This information can be used to improve calibration of the model by increasing the number and spatial distribution of sites and the frequency of measurements for comparing measured and simulated water levels. Aquifer tests will facilitate determination of whether improving the model by more complex spatial distribution of hydraulic conductivity, specific storage, and specific yield can be justified.

Future updates of this model might include using the Stream-flow Routing Package (Prudic, 1989) to simulate streams. Using the Stream-flow Routing Package would simulate two-way interaction between the aquifer and rivers or streams. This is a potentially superior alternative to the Drain Package and may allow better simulation of recharge from Cibolo Creek.

13.0 Conclusions

We updated a finite-difference groundwater flow model that can be used to predict water-level changes in response to specified pumping and drought scenarios. The updated model has four layers — the Edwards Group, and the Upper, Middle, and Lower Trinity aquifers — and 12,976 active cells, each with a uniform grid size of 1 mile by 1 mile. We developed the conceptual model of groundwater flow and defined aquifer properties based on a review of previous work and studies we conducted on water levels, structure, recharge, and hydraulic properties. The process of updating the model included: (1) adding the Lower Trinity Aquifer as an additional layer to the model, (2) revising the structure and spatial distribution of parameters, such as recharge and pumping, and (3) calibrating to steady-state conditions for 1980 and historical transient conditions for the period 1980 through 1997.

The calibrated model does a reasonable job of matching the water-level distribution and water-level fluctuations in the aquifer. The steady-state model has an overall mean absolute error of 54 feet, about 3.5 percent of the hydraulic-head drop across the study area. Calibration of the steady-state model indicates in an average recharge rate of about 5 percent of average annual precipitation in the Balcones Fault Zone portion of the aquifer and 3.5 percent in the remainder of the aquifer. Estimated recharge from Cibolo Creek averages about 70,000 acre-feet per year. Calibrated hydraulic conductivity is 11 feet per day in the Edwards Group, 9 to 150 feet per day in the Upper Trinity Aquifer, 7.6 to 15 feet per day in the Middle Trinity Aquifer, and 1.7 to 17 feet per day in the Lower Trinity Aquifer. Water levels in the model are most sensitive to changes in (1) recharge, (2) horizontal hydraulic conductivity, and (3) vertical hydraulic conductivity. We also calibrated values of vertical hydraulic conductivity, specific storage, and specific yield for the aquifer.

We found that over 300,000 acre-feet per year of water flows through the aquifer, mostly in the Upper and Middle Trinity aquifers. Of the total flow, almost all is derived from infiltration of precipitation, with minor amounts from inflow from reservoirs and the adjacent Edwards (Balcones Fault Zone) Aquifer. The model estimates that about 100,000 acre-feet per year of groundwater flows from the Upper and Middle Trinity aquifers to the Edwards (Balcones Fault Zone) Aquifer.

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Table 5-01. Estimates of recharge rates to the Hill Country portion of the Trinity Aquifer System as a percentage of average annual precipitation.

Literature source	Recharge rate (inches per year)	Percent value
Muller and Price (1979)	0.5	1.5
Ashworth (1983)	1.3	4.0
Kuniansky (1989)	3.6	11.0
Kuniansky and Holligan (1994)	2.3	7.0
Bluntzer (1992, calc.)	2.2	6.7
Bluntzer (1992, est.)	1.7	5.0
Mace (2001)	2.2	6.6
Mace and others (2000)	1.3	4.0
Wet Rock Groundwater Services (2008)	3.1	9.5
Anaya and Jones (2009)	1.4	4.7

Table 5-02. Estimated flow for selected springs in the study area (see Figure 5-28) (from Mace and others, 2000).

Spring	Estimated flow (gallons per minute)	Formation	Remarks
1	150	Edwards Group and associated limestone	Measured on 4/13/67
2	100	Edwards Group and associated limestone	Measured on 4/12/67, reported flow never ceased
3	100	Edwards Group and associated limestone	
4	2,500	Edwards Group and associated limestone	Measured on 3/31/66, reported flow never ceased
5	310	Edwards Group and associated limestone	Measured on 3/11/70
6	480	Edwards Group and associated limestone	Measured on 3/11/70, owner's trough spring
7	100	Edwards Group and associated limestone	Measured on 6/15/66, never ceased flowing
8	20	Upper member of the Glen Rose Limestone	Measured on 7/13/76
9	75	Lower member of the Glen Rose Limestone	Measured on 7/10/75, ceased flowing in 1956
10	50	Lower member of the Glen Rose Limestone	Measured on 1/17/40
11	150	Lower member of the Glen Rose Limestone	Measured on 7/17/75, owners well #9
12	300	Lower member of the Glen Rose Limestone	
13	300	Cow Creek Limestone	Measured on 7/11/75
14	500	Cow Creek Limestone	Measured on 8/31/76, estimated flow 1,070 gpm, Jan. 1955
15	25	Lower member of the Glen Rose Limestone	Measured on 1/1/66
16	50	Upper member of the Glen Rose Limestone	Measured on 12/30/88, Bassett springs
17	50	Upper member of the Glen Rose Limestone	Measured on 5/25/73
18	9,000	Edwards Group and associated limestone	Measured on 12/20/60
19	5,000	Lower member of the Glen Rose Limestone	Measured on 8/20/91, springs discharge into Medina River

Table 5-03. Total pumping from the Hill Country portion of the Trinity Aquifer System for each county for the period 1980 through 1997 (All values are acre-feet per year).

Year	Bandera	Bexar	Blanco	Comal	Gillespie	Hays	Kendall
1980	1,084	4,120	195	1,135	1,223	1,621	1,585
1981	1,077	4,280	234	1,076	1,235	1,788	1,690
1982	1,120	4,486	230	998	1,248	1,903	1,663
1983	1,129	3,875	224	978	1,260	2,046	1,829
1984	1,182	4,359	217	916	1,273	2,059	2,115
1985	1,175	3,892	261	918	1,289	2,087	1,781
1986	1,154	4,165	312	949	1,332	2,018	1,793
1987	1,290	4,775	333	987	1,273	1,817	1,518
1988	1,374	5,774	350	1,035	1,289	1,865	2,337
1989	1,441	5,900	367	1,058	1,421	2,116	2,343
1990	1,462	7,372	386	1,080	1,440	2,093	2,185
1991	1,529	6,098	388	1,128	1,484	2,096	1,751
1992	1,528	6,227	422	1,200	1,558	2,125	1,728
1993	1,784	6,249	432	1,125	1,633	2,506	2,414
1994	1,684	6,609	413	1,199	2,308	2,539	2,482
1995	1,723	6,767	453	1,214	2,329	2,719	2,823
1996	1,709	6,814	465	1,112	2,615	2,935	3,092
1997	1,785	6,832	472	1,268	2,297	2,923	3,738

Year	Kerr	Kimble	Medina	Travis	Uvalde	Total
1980	5,994	7	63	111	11	17,148
1981	3,463	7	60	108	11	15,027
1982	3,176	6	57	101	11	15,000
1983	2,954	6	53	100	11	14,466
1984	3,517	5	50	96	11	15,799
1985	3,529	5	45	100	11	15,093
1986	3,104	7	45	110	10	14,999
1987	2,727	6	49	111	10	14,896
1988	3,135	6	49	116	10	17,342
1989	3,433	5	49	116	10	18,259
1990	3,263	5	50	117	10	19,461
1991	3,282	5	51	125	10	17,945
1992	3,787	5	57	127	11	18,775
1993	4,161	5	66	139	11	20,525
1994	3,962	5	60	134	11	21,406
1995	3,886	6	64	138	11	22,133
1996	4,439	6	62	200	12	23,460
1997	4,095	5	59	146	11	23,631

Table 5-04. Total pumping from the Hill Country portion of the Trinity Aquifer System by use category for each county for the period 1980 through 1997 (All values are acre-feet per year).

Year	Bandera	Bexar	Blanco	Comal	Gillespie	Hays	Kendall	Kerr	Kimble	Medina	Travis	Uvalde	Total Pumpage
Municipal													
1980	190	157	0	0	0	573	380	3,491	0	0	0	0	4,791
1981	168	177	0	0	0	732	404	1,042	0	0	0	0	2,523
1982	198	245	0	0	0	834	424	735	0	0	0	0	2,436
1983	193	220	0	0	0	965	500	538	0	0	0	0	2,416
1984	232	380	0	0	0	964	700	1,036	0	0	0	0	3,312
1985	199	360	0	0	0	1,150	553	1,248	0	0	0	0	3,510
1986	222	612	0	0	0	1,062	582	925	0	0	0	0	3,403
1987	204	645	0	0	0	825	449	506	0	0	0	0	2,629
1988	227	761	0	0	0	834	712	830	0	0	0	0	3,364
1989	297	869	0	0	0	1,076	737	1,023	0	0	0	0	4,002
1990	269	719	0	0	0	1,019	632	720	0	0	0	0	3,359
1991	275	612	0	0	0	979	378	658	0	0	0	0	2,902
1992	219	719	0	0	0	962	322	1,035	0	0	0	0	3,257
1993	298	719	0	0	0	1,220	412	1,178	0	0	0	0	3,827
1994	340	1,071	0	0	0	1,281	474	924	0	0	0	0	4,090
1995	322	1,213	0	0	0	1,317	566	867	0	0	0	0	4,285
1996	299	1,213	0	0	0	1,485	746	1,363	0	0	0	0	5,106
1997	331	1,213	0	0	0	1,432	999	965	0	0	0	0	4,940
Manufacturing													
1980	0	2,449	0	0	0	0	0	0	0	0	0	0	2,449
1981	0	2,449	0	0	0	0	0	0	0	0	0	0	2,449
1982	0	2,449	0	0	0	0	0	0	0	0	0	0	2,449
1983	0	1,727	0	0	0	0	0	0	0	0	0	0	1,727
1984	0	1,912	0	0	0	0	0	0	0	0	0	0	1,912
1985	0	2,516	0	0	0	0	0	0	0	0	0	0	2,516
1986	0	2,516	0	0	0	0	0	0	0	0	0	0	2,516
1987	0	3,085	0	0	0	0	0	0	0	0	0	0	3,085
1988	0	3,949	0	0	1	0	0	0	0	0	0	0	3,950
1989	0	3,949	0	0	0	0	0	0	0	0	0	0	3,949
1990	0	5,549	0	0	0	0	0	0	0	0	0	0	5,549
1991	0	4,363	0	0	0	0	0	0	0	0	0	0	4,363
1992	0	4,363	0	0	0	0	0	4	0	0	0	0	4,367
1993	0	4,363	0	0	0	0	0	7	0	0	0	0	4,370
1994	0	4,370	0	0	0	0	0	7	0	0	0	0	4,377
1995	0	4,370	0	0	0	0	0	7	0	0	0	0	4,377
1996	0	4,370	0	0	0	0	0	6	0	0	0	0	4,376
1997	0	4,370	0	0	0	0	0	7	0	0	0	0	4,377

Table 5-04. (cont.)

Year	Bandera	Bexar	Blanco	Comal	Gillespie	Hays	Kendall	Kerr	Kimble	Medina	Travis	Uvalde	Total Pumpage
Rural Domestic													
1980	570	878	39	557	832	624	564	1,654	0	21	34	7	5,780
1981	598	897	85	581	854	663	652	1,619	0	21	36	7	6,013
1982	626	915	88	587	877	705	613	1,687	0	22	35	7	6,162
1983	654	930	87	650	899	747	710	1,709	0	22	39	7	6,454
1984	683	948	87	672	922	791	803	1,820	0	22	40	7	6,795
1985	710	966	138	697	945	832	770	1,813	0	23	41	7	6,942
1986	739	984	177	728	967	874	808	1,844	0	23	48	7	7,199
1987	766	1,001	198	755	989	916	643	1,865	0	23	54	7	7,217
1988	794	1,019	210	778	1,012	959	909	1,916	0	24	54	8	7,683
1989	822	1,036	213	803	1,035	997	963	1,969	0	24	55	8	7,925
1990	850	1,054	215	828	1,057	1,031	968	2,108	0	25	54	8	8,198
1991	908	1,073	214	870	1,080	1,073	779	2,179	0	26	61	8	8,271
1992	964	1,091	225	916	1,102	1,132	722	2,222	0	27	67	8	8,476
1993	1,022	1,110	235	843	1,124	1,249	787	2,266	0	28	70	8	8,742
1994	1,078	1,128	245	905	1,146	1,217	904	2,309	0	29	77	8	9,046
1995	1,135	1,147	268	909	1,168	1,361	1,075	2,352	0	30	81	8	9,534
1996	1,193	1,165	304	859	1,190	1,418	1,234	2,396	0	31	82	8	9,880
1997	1,249	1,184	307	1,016	1,213	1,462	1,632	2,439	0	32	91	8	10,633
Irrigation													
1980	62	611	47	368	52	102	200	500	4	0	0	0	1,946
1981	58	734	45	279	70	89	221	469	4	0	0	0	1,969
1982	54	857	43	190	88	76	241	437	4	0	0	0	1,990
1983	50	979	40	101	105	63	262	406	4	0	0	0	2,010
1984	47	1,102	38	12	123	50	282	374	3	0	0	0	2,031
1985	68	0	28	0	111	64	132	204	4	0	0	0	611
1986	10	0	28	0	93	44	176	136	5	0	0	0	492
1987	124	0	28	0	30	35	176	136	5	0	0	0	534
1988	124	0	28	0	8	29	440	136	4	0	0	0	769
1989	95	0	41	0	127	0	369	191	3	0	0	0	826
1990	115	0	47	0	113	0	274	187	3	0	0	0	739
1991	115	0	47	0	127	0	274	187	3	0	0	0	753
1992	115	0	47	0	127	0	274	187	3	0	0	0	753
1993	248	0	51	0	170	0	808	396	3	0	0	0	1,676
1994	15	0	51	10	845	0	718	406	3	0	0	0	2,048
1995	14	0	54	9	841	0	808	355	4	0	0	0	2,085
1996	15	0	54	10	957	0	808	396	4	0	0	0	2,244
1997	15	0	54	9	782	0	808	396	3	0	0	0	2,067

Table 5-04. (cont.)

Year	Bandera	Bexar	Blanco	Comal	Gillespie	Hays	Kendall	Kerr	Kimble	Medina	Travis	Uvalde	Total Pumpage
Livestock													
1980	262	25	109	210	339	322	441	349	3	42	78	4	2,184
1981	252	23	104	216	311	305	413	333	3	39	72	4	2,075
1982	241	21	100	221	283	288	386	318	3	35	66	4	1,966
1983	231	18	96	227	256	271	358	302	2	32	61	3	1,857
1984	221	16	92	232	228	254	330	286	2	28	55	3	1,747
1985	198	50	96	221	232	41	326	264	2	22	59	3	1,514
1986	184	53	108	221	272	38	228	199	2	22	62	2	1,391
1987	197	44	106	232	254	40	249	219	2	26	58	2	1,429
1988	229	46	112	257	268	43	276	253	2	25	62	2	1,575
1989	227	46	113	255	259	43	274	250	2	25	61	2	1,557
1990	228	50	124	252	269	42	312	248	2	25	62	2	1,616
1991	231	50	126	258	278	44	319	258	2	25	64	2	1,657
1992	231	54	150	284	330	31	410	338	2	30	60	3	1,923
1993	216	57	146	282	339	37	407	314	2	38	69	3	1,910
1994	251	40	118	284	317	41	386	317	2	31	57	3	1,847
1995	251	37	131	296	321	41	374	305	2	34	57	3	1,852
1996	203	66	107	243	468	32	303	278	2	31	118	4	1,855
1997	190	65	111	243	302	28	298	288	2	27	55	3	1,612

Table 5-05. Total pumping from the Edwards Group by use category for each county for the period 1980 through 1997 (All values are acre-feet per year).

Year	Bandera	Bexar	Blanco	Comal	Gillespie	Hays	Kendall	Kerr	Kimble	Medina	Travis	Uvalde	Total Pumpage
Municipal													
1980	0	0	0	0	0	0	0	0	0	0	0	0	0
1981	0	0	0	0	0	0	0	0	0	0	0	0	0
1982	0	0	0	0	0	0	0	0	0	0	0	0	0
1983	0	0	0	0	0	0	0	0	0	0	0	0	0
1984	0	0	0	0	0	0	0	0	0	0	0	0	0
1985	0	0	0	0	0	0	0	0	0	0	0	0	0
1986	0	0	0	0	0	0	0	0	0	0	0	0	0
1987	0	0	0	0	0	0	0	0	0	0	0	0	0
1988	0	0	0	0	0	0	0	0	0	0	0	0	0
1989	0	0	0	0	0	0	0	0	0	0	0	0	0
1990	0	0	0	0	0	0	0	0	0	0	0	0	0
1991	0	0	0	0	0	0	0	0	0	0	0	0	0
1992	0	0	0	0	0	0	0	0	0	0	0	0	0
1993	0	0	0	0	0	0	0	0	0	0	0	0	0
1994	0	0	0	0	0	0	0	0	0	0	0	0	0
1995	0	0	0	0	0	0	0	0	0	0	0	0	0
1996	0	0	0	0	0	0	0	0	0	0	0	0	0
1997	0	0	0	0	0	0	0	0	0	0	0	0	0
Manufacturing													
1980	0	0	0	0	0	0	0	0	0	0	0	0	0
1981	0	0	0	0	0	0	0	0	0	0	0	0	0
1982	0	0	0	0	0	0	0	0	0	0	0	0	0
1983	0	0	0	0	0	0	0	0	0	0	0	0	0
1984	0	0	0	0	0	0	0	0	0	0	0	0	0
1985	0	0	0	0	0	0	0	0	0	0	0	0	0
1986	0	0	0	0	0	0	0	0	0	0	0	0	0
1987	0	0	0	0	0	0	0	0	0	0	0	0	0
1988	0	0	0	0	0	0	0	0	0	0	0	0	0
1989	0	0	0	0	0	0	0	0	0	0	0	0	0
1990	0	0	0	0	0	0	0	0	0	0	0	0	0
1991	0	0	0	0	0	0	0	0	0	0	0	0	0
1992	0	0	0	0	0	0	0	0	0	0	0	0	0
1993	0	0	0	0	0	0	0	0	0	0	0	0	0
1994	0	0	0	0	0	0	0	0	0	0	0	0	0
1995	0	0	0	0	0	0	0	0	0	0	0	0	0
1996	0	0	0	0	0	0	0	0	0	0	0	0	0
1997	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 5-05. (cont.)

Year	Bandera	Bexar	Blanco	Comal	Gillespie	Hays	Kendall	Kerr	Kimble	Medina	Travis	Uvalde	Total Pumpage
Rural Domestic													
1980	47	0	0	0	262	0	77	448	0	0	0	0	834
1981	49	0	0	0	269	0	89	439	0	0	0	0	846
1982	52	0	0	0	276	0	83	457	0	0	0	0	868
1983	54	0	0	0	283	0	96	463	0	0	0	0	896
1984	56	0	0	0	290	0	109	493	0	0	0	0	948
1985	59	0	0	0	297	0	104	492	0	0	0	0	952
1986	61	0	0	0	304	0	110	500	0	0	0	0	975
1987	63	0	0	0	311	0	87	506	0	0	0	0	967
1988	66	0	0	0	318	0	123	519	0	0	0	0	1,026
1989	68	0	0	0	326	0	131	534	0	0	0	0	1,059
1990	70	0	0	0	333	0	131	572	0	0	0	0	1,106
1991	75	0	0	0	340	0	106	591	0	0	0	0	1,112
1992	80	0	0	0	347	0	98	603	0	0	0	0	1,128
1993	84	0	0	0	354	0	107	614	0	0	0	0	1,159
1994	89	0	0	0	361	0	123	626	0	0	0	0	1,199
1995	94	0	0	0	368	0	146	638	0	0	0	0	1,246
1996	99	0	0	0	375	0	167	650	0	0	0	0	1,291
1997	103	0	0	0	382	0	221	661	0	0	0	0	1,367
Irrigation													
1980	0	0	0	0	0	0	0	0	0	0	0	0	0
1981	0	0	0	0	0	0	0	0	0	0	0	0	0
1982	0	0	0	0	0	0	0	0	0	0	0	0	0
1983	0	0	0	0	0	0	0	0	0	0	0	0	0
1984	0	0	0	0	0	0	0	0	0	0	0	0	0
1985	0	0	0	0	0	0	0	0	0	0	0	0	0
1986	0	0	0	0	0	0	0	0	0	0	0	0	0
1987	0	0	0	0	0	0	0	0	0	0	0	0	0
1988	0	0	0	0	0	0	0	0	0	0	0	0	0
1989	0	0	0	0	0	0	0	0	0	0	0	0	0
1990	0	0	0	0	0	0	0	0	0	0	0	0	0
1991	0	0	0	0	0	0	0	0	0	0	0	0	0
1992	0	0	0	0	0	0	0	0	0	0	0	0	0
1993	0	0	0	0	0	0	0	0	0	0	0	0	0
1994	0	0	0	0	0	0	0	0	0	0	0	0	0
1995	0	0	0	0	0	0	0	0	0	0	0	0	0
1996	0	0	0	0	0	0	0	0	0	0	0	0	0
1997	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 5-05. (cont.)

Year	Bandera	Bexar	Blanco	Comal	Gillespie	Hays	Kendall	Kerr	Kimble	Medina	Travis	Uvalde	Total Pumpage
Livestock													
1980	16	0	0	0	0	0	0	157	3	0	0	0	176
1981	16	0	0	0	0	0	0	150	3	0	0	0	169
1982	15	0	0	0	0	0	0	143	3	0	0	0	161
1983	15	0	0	0	0	0	0	136	2	0	0	0	153
1984	14	0	0	0	0	0	0	129	2	0	0	0	145
1985	12	0	0	0	0	0	0	119	2	0	0	0	133
1986	11	0	0	0	0	0	0	89	2	0	0	0	102
1987	12	0	0	0	0	0	0	98	2	0	0	0	112
1988	14	0	0	0	0	0	0	113	2	0	0	0	129
1989	14	0	0	0	0	0	0	112	2	0	0	0	128
1990	14	0	0	0	0	0	0	112	2	0	0	0	128
1991	15	0	0	0	0	0	0	116	2	0	0	0	133
1992	15	0	0	0	0	0	0	152	2	0	0	0	169
1993	14	0	0	0	0	0	0	141	2	0	0	0	157
1994	17	0	0	0	0	0	0	143	2	0	0	0	162
1995	17	0	0	0	0	0	0	137	2	0	0	0	156
1996	13	0	0	0	0	0	0	125	2	0	0	0	140
1997	12	0	0	0	0	0	0	130	2	0	0	0	144

Table 5-06. Total pumping from the Upper Trinity Aquifer by use category for each county for the period 1980 through 1997 (All values are acre-feet per year).

Year	Bandera	Bexar	Blanco	Comal	Gillespie	Hays	Kendall	Kerr	Kimble	Medina	Travis	Uvalde	Total Pumpage
Municipal													
1980	0	0	0	0	0	0	33	0	0	0	0	0	33
1981	0	0	0	0	0	0	38	0	0	0	0	0	38
1982	0	0	0	0	0	0	38	0	0	0	0	0	38
1983	0	0	0	0	0	0	43	0	0	0	0	0	43
1984	0	0	0	0	0	0	67	0	0	0	0	0	67
1985	0	0	0	0	0	0	48	0	0	0	0	0	48
1986	0	0	0	0	0	0	46	0	0	0	0	0	46
1987	0	0	0	0	0	0	32	0	0	0	0	0	32
1988	0	0	0	0	0	0	67	0	0	0	0	0	67
1989	0	0	0	0	0	0	69	0	0	0	0	0	69
1990	0	0	0	0	0	0	57	0	0	0	0	0	57
1991	0	0	0	0	0	0	22	0	0	0	0	0	22
1992	0	0	0	0	0	0	10	0	0	0	0	0	10
1993	0	0	0	0	0	0	22	0	0	0	0	0	22
1994	0	0	0	0	0	0	31	0	0	0	0	0	31
1995	0	0	0	0	0	0	38	0	0	0	0	0	38
1996	0	0	0	0	0	0	65	0	0	0	0	0	65
1997	0	0	0	0	0	0	103	0	0	0	0	0	103
Manufacturing													
1980	0	0	0	0	0	0	0	0	0	0	0	0	0
1981	0	0	0	0	0	0	0	0	0	0	0	0	0
1982	0	0	0	0	0	0	0	0	0	0	0	0	0
1983	0	0	0	0	0	0	0	0	0	0	0	0	0
1984	0	0	0	0	0	0	0	0	0	0	0	0	0
1985	0	0	0	0	0	0	0	0	0	0	0	0	0
1986	0	0	0	0	0	0	0	0	0	0	0	0	0
1987	0	0	0	0	0	0	0	0	0	0	0	0	0
1988	0	0	0	0	0	0	0	0	0	0	0	0	0
1989	0	0	0	0	0	0	0	0	0	0	0	0	0
1990	0	0	0	0	0	0	0	0	0	0	0	0	0
1991	0	0	0	0	0	0	0	0	0	0	0	0	0
1992	0	0	0	0	0	0	0	0	0	0	0	0	0
1993	0	0	0	0	0	0	0	0	0	0	0	0	0
1994	0	0	0	0	0	0	0	0	0	0	0	0	0
1995	0	0	0	0	0	0	0	0	0	0	0	0	0
1996	0	0	0	0	0	0	0	0	0	0	0	0	0
1997	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 5-06. (cont.)

Year	Bandera	Bexar	Blanco	Comal	Gillespie	Hays	Kendall	Kerr	Kimble	Medina	Travis	Uvalde	Total Pumpage
Rural Domestic													
1980	409	865	25	345	79	559	375	1,205	0	21	32	7	3,922
1981	429	884	54	360	81	593	434	1,180	0	21	34	7	4,077
1982	449	902	56	363	84	632	407	1,229	0	22	33	7	4,184
1983	469	917	56	402	86	669	472	1,246	0	22	38	7	4,384
1984	490	934	55	416	88	708	534	1,327	0	22	39	7	4,620
1985	509	952	88	431	90	745	512	1,322	0	23	39	7	4,718
1986	530	969	113	450	92	782	537	1,344	0	23	46	7	4,893
1987	549	987	126	467	94	821	428	1,360	0	23	51	7	4,913
1988	570	1,004	134	482	96	859	604	1,396	0	24	52	8	5,229
1989	590	1,021	136	497	99	892	640	1,435	0	24	53	8	5,395
1990	610	1,038	137	512	101	923	643	1,536	0	25	52	8	5,585
1991	651	1,058	136	539	103	961	518	1,588	0	26	58	8	5,646
1992	692	1,075	143	567	105	1,013	480	1,620	0	27	64	8	5,794
1993	733	1,094	149	521	107	1,118	523	1,651	0	28	67	8	5,999
1994	773	1,112	156	560	109	1,089	601	1,683	0	29	73	8	6,193
1995	814	1,130	170	563	111	1,218	714	1,715	0	30	77	8	6,550
1996	855	1,148	193	532	113	1,269	821	1,746	0	31	78	8	6,794
1997	896	1,166	195	629	115	1,309	1,085	1,778	0	32	87	8	7,300
Irrigation													
1980	0	0	0	0	0	0	0	0	0	0	0	0	0
1981	0	0	0	0	0	0	0	0	0	0	0	0	0
1982	0	0	0	0	0	0	0	0	0	0	0	0	0
1983	0	0	0	0	0	0	0	0	0	0	0	0	0
1984	0	0	0	0	0	0	0	0	0	0	0	0	0
1985	0	0	0	0	0	0	0	0	0	0	0	0	0
1986	0	0	0	0	0	0	0	0	0	0	0	0	0
1987	0	0	0	0	0	0	0	0	0	0	0	0	0
1988	0	0	0	0	0	0	0	0	0	0	0	0	0
1989	0	0	0	0	0	0	0	0	0	0	0	0	0
1990	0	0	0	0	0	0	0	0	0	0	0	0	0
1991	0	0	0	0	0	0	0	0	0	0	0	0	0
1992	0	0	0	0	0	0	0	0	0	0	0	0	0
1993	0	0	0	0	0	0	0	0	0	0	0	0	0
1994	0	0	0	0	0	0	0	0	0	0	0	0	0
1995	0	0	0	0	0	0	0	0	0	0	0	0	0
1996	0	0	0	0	0	0	0	0	0	0	0	0	0
1997	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 5-06. (cont.)

Year	Bandera	Bexar	Blanco	Comal	Gillespie	Hays	Kendall	Kerr	Kimble	Medina	Travis	Uvalde	Total Pumpage
Livestock													
1980	227	25	95	155	257	298	299	192	0	42	74	4	1,668
1981	218	23	91	158	236	281	280	183	0	39	69	4	1,582
1982	209	21	88	161	215	264	261	175	0	35	63	4	1,496
1983	200	18	84	165	194	247	242	166	0	32	58	3	1,409
1984	192	16	80	168	173	230	223	157	0	28	53	3	1,323
1985	172	50	83	155	176	37	221	145	0	22	56	3	1,120
1986	160	53	94	155	206	35	154	109	0	22	60	2	1,050
1987	171	44	93	163	192	36	168	121	0	26	55	2	1,071
1988	199	46	98	181	203	39	187	140	0	25	59	2	1,179
1989	197	46	99	179	196	39	185	138	0	25	58	2	1,164
1990	197	50	108	177	204	38	211	136	0	25	59	2	1,207
1991	200	50	110	181	210	40	216	142	0	25	61	2	1,237
1992	200	54	131	200	250	28	277	186	0	30	57	3	1,416
1993	187	57	128	198	257	34	276	173	0	38	66	3	1,417
1994	217	40	103	200	240	37	261	174	0	31	54	3	1,360
1995	217	37	114	208	243	37	253	168	0	34	54	3	1,368
1996	175	66	94	171	354	29	205	153	0	31	113	4	1,395
1997	164	65	97	171	229	26	202	158	0	27	53	3	1,195

Table 5-07. Total pumping from the Middle Trinity Aquifer by use category for each county for the period 1980 through 1997 (All values are acre-feet per year).

Year	Bandera	Bexar	Blanco	Comal	Gillespie	Hays	Kendall	Kerr	Kimble	Medina	Travis	Uvalde	Total Pumpage
Municipal													
1980	0	157	0	0	0	510	346	293	0	0	0	0	1,306
1981	0	177	0	0	0	666	366	200	0	0	0	0	1,409
1982	0	245	0	0	0	756	386	250	0	0	0	0	1,637
1983	0	220	0	0	0	869	457	262	0	0	0	0	1,808
1984	0	355	0	0	0	827	595	372	0	0	0	0	2,149
1985	0	341	0	0	0	1,003	469	355	0	0	0	0	2,168
1986	0	581	0	0	0	988	492	373	0	0	0	0	2,434
1987	0	613	0	0	0	724	353	318	0	0	0	0	2,008
1988	0	723	0	0	0	745	576	370	0	0	0	0	2,414
1989	0	830	0	0	0	981	596	409	0	0	0	0	2,816
1990	0	689	0	0	0	928	508	349	0	0	0	0	2,474
1991	0	587	0	0	0	882	293	347	0	0	0	0	2,109
1992	0	689	0	0	0	875	240	384	0	0	0	0	2,188
1993	0	691	0	0	0	1,098	316	441	0	0	0	0	2,546
1994	0	1,030	0	0	0	1,149	370	400	0	0	0	0	2,949
1995	0	1,166	0	0	0	1,218	442	349	0	0	0	0	3,175
1996	0	1,168	0	0	0	1,368	597	435	0	0	0	0	3,568
1997	0	1,169	0	0	0	1,313	817	356	0	0	0	0	3,655
Manufacturing													
1980	490	0	0	0	0	0	0	0	0	0	0	0	490
1981	490	0	0	0	0	0	0	0	0	0	0	0	490
1982	490	0	0	0	0	0	0	0	0	0	0	0	490
1983	345	0	0	0	0	0	0	0	0	0	0	0	345
1984	0	0	0	0	0	0	0	0	0	0	0	0	0
1985	419	0	0	0	0	0	0	0	0	0	0	0	419
1986	359	0	0	0	0	0	0	0	0	0	0	0	359
1987	441	0	0	0	0	0	0	0	0	0	0	0	441
1988	564	0	0	0	1	0	0	0	0	0	0	0	565
1989	564	0	0	0	0	0	0	0	0	0	0	0	564
1990	793	0	0	0	0	0	0	0	0	0	0	0	793
1991	623	0	0	0	0	0	0	0	0	0	0	0	623
1992	623	0	0	0	0	0	0	4	0	0	0	0	627
1993	623	0	0	0	0	0	0	7	0	0	0	0	630
1994	624	0	0	0	0	0	0	7	0	0	0	0	631
1995	624	0	0	0	0	0	0	7	0	0	0	0	631
1996	624	0	0	0	0	0	0	6	0	0	0	0	630
1997	624	0	0	0	0	0	0	7	0	0	0	0	631

Table 5-07. (cont.)

Year	Bandera	Bexar	Blanco	Comal	Gillespie	Hays	Kendall	Kerr	Kimble	Medina	Travis	Uvalde	Total Pumpage
Rural Domestic													
1980	114	13	14	212	491	65	113	0	0	0	1	0	1,023
1981	120	13	31	222	504	69	130	0	0	0	1	0	1,090
1982	125	13	32	224	517	74	122	0	0	0	1	0	1,108
1983	131	14	32	248	531	78	142	0	0	0	1	0	1,177
1984	137	14	32	256	544	83	160	0	0	0	1	0	1,227
1985	142	14	50	266	557	87	154	0	0	0	1	0	1,271
1986	148	14	64	277	571	91	161	0	0	0	1	0	1,327
1987	153	15	72	288	584	96	128	0	0	0	1	0	1,337
1988	159	15	76	297	597	100	181	0	0	0	1	0	1,426
1989	165	15	77	306	611	104	192	0	0	0	1	0	1,471
1990	170	15	78	316	624	108	193	0	0	0	1	0	1,505
1991	182	16	78	332	637	112	155	0	0	0	2	0	1,514
1992	193	16	82	349	650	119	144	0	0	0	2	0	1,555
1993	204	16	85	321	663	131	157	0	0	0	2	0	1,579
1994	216	17	89	345	676	127	180	0	0	0	2	0	1,652
1995	227	17	97	347	689	142	214	0	0	0	2	0	1,735
1996	239	17	111	328	702	148	246	0	0	0	2	0	1,793
1997	250	17	112	387	715	153	325	0	0	0	2	0	1,961
Irrigation													
1980	16	385	47	257	52	102	200	335	4	0	0	0	1,398
1981	15	462	45	196	70	89	221	314	4	0	0	0	1,416
1982	15	540	43	135	88	76	241	293	4	0	0	0	1,435
1983	14	617	40	73	105	63	262	272	4	0	0	0	1,450
1984	14	694	38	12	123	50	282	251	3	0	0	0	1,467
1985	20	0	28	0	111	64	132	137	4	0	0	0	496
1986	0	0	28	0	93	44	176	91	5	0	0	0	437
1987	36	0	28	0	30	35	176	91	5	0	0	0	401
1988	36	0	28	0	8	29	440	91	4	0	0	0	636
1989	26	0	41	0	127	0	369	128	3	0	0	0	694
1990	33	0	47	0	113	0	274	125	3	0	0	0	595
1991	33	0	47	0	127	0	274	125	3	0	0	0	609
1992	33	0	47	0	127	0	274	125	3	0	0	0	609
1993	77	0	51	0	170	0	808	265	3	0	0	0	1,374
1994	0	0	51	7	845	0	718	272	3	0	0	0	1,896
1995	0	0	54	7	841	0	808	238	4	0	0	0	1,952
1996	0	0	54	8	957	0	808	265	4	0	0	0	2,096
1997	0	0	54	7	782	0	808	265	3	0	0	0	1,919

Table 5-07. (cont.)

Year	Bandera	Bexar	Blanco	Comal	Gillespie	Hays	Kendall	Kerr	Kimble	Medina	Travis	Uvalde	Total Pumpage
Livestock													
1980	18	0	14	55	82	24	142	0	0	0	3	0	338
1981	18	0	13	58	76	24	133	0	0	0	3	0	325
1982	17	0	13	60	69	24	125	0	0	0	3	0	311
1983	16	0	12	62	62	24	116	0	0	0	3	0	295
1984	15	0	12	64	55	24	107	0	0	0	2	0	279
1985	14	0	12	66	56	4	105	0	0	0	3	0	260
1986	13	0	14	66	66	3	74	0	0	0	3	0	239
1987	14	0	13	69	62	4	81	0	0	0	3	0	246
1988	16	0	14	76	65	4	89	0	0	0	3	0	267
1989	16	0	14	76	63	4	89	0	0	0	3	0	265
1990	16	0	16	75	65	4	101	0	0	0	3	0	280
1991	16	0	16	77	67	4	103	0	0	0	3	0	286
1992	16	0	19	84	80	3	133	0	0	0	3	0	338
1993	15	0	18	84	82	3	131	0	0	0	3	0	336
1994	17	0	15	84	77	4	125	0	0	0	3	0	325
1995	17	0	16	88	78	4	121	0	0	0	3	0	327
1996	14	0	13	72	113	3	98	0	0	0	5	0	318
1997	13	0	14	72	73	2	96	0	0	0	2	0	272

Table 5-08. Total pumping from the Lower Trinity Aquifer by use category for each county for the period 1980 through 1997 (All values are acre-feet per year).

Year	Bandera	Bexar	Blanco	Comal	Gillespie	Hays	Kendall	Kerr	Kimble	Medina	Travis	Uvalde	Total Pumpage
Municipal													
1980	190	0	0	0	0	63	0	3,198	0	0	0	0	3,451
1981	168	0	0	0	0	66	0	841	0	0	0	0	1,075
1982	198	0	0	0	0	77	0	485	0	0	0	0	760
1983	193	0	0	0	0	97	0	276	0	0	0	0	566
1984	232	25	0	0	0	137	39	665	0	0	0	0	1,098
1985	199	19	0	0	0	147	36	893	0	0	0	0	1,294
1986	222	31	0	0	0	74	43	551	0	0	0	0	921
1987	204	32	0	0	0	101	64	188	0	0	0	0	589
1988	227	38	0	0	0	89	69	460	0	0	0	0	883
1989	297	40	0	0	0	95	73	614	0	0	0	0	1,119
1990	269	30	0	0	0	91	67	371	0	0	0	0	828
1991	275	26	0	0	0	98	63	311	0	0	0	0	773
1992	219	30	0	0	0	87	71	651	0	0	0	0	1,058
1993	298	28	0	0	0	122	75	737	0	0	0	0	1,260
1994	340	41	0	0	0	132	73	524	0	0	0	0	1,110
1995	322	47	0	0	0	99	87	518	0	0	0	0	1,073
1996	299	45	0	0	0	117	84	927	0	0	0	0	1,472
1997	331	43	0	0	0	119	79	609	0	0	0	0	1,181
Manufacturing													
1980	0	1,959	0	0	0	0	0	0	0	0	0	0	1,959
1981	0	1,959	0	0	0	0	0	0	0	0	0	0	1,959
1982	0	1,959	0	0	0	0	0	0	0	0	0	0	1,959
1983	0	1,382	0	0	0	0	0	0	0	0	0	0	1,382
1984	0	0	0	0	0	0	0	0	0	0	0	0	0
1985	0	2,097	0	0	0	0	0	0	0	0	0	0	2,097
1986	0	2,157	0	0	0	0	0	0	0	0	0	0	2,157
1987	0	2,644	0	0	0	0	0	0	0	0	0	0	2,644
1988	0	3,385	0	0	0	0	0	0	0	0	0	0	3,385
1989	0	3,385	0	0	0	0	0	0	0	0	0	0	3,385
1990	0	4,756	0	0	0	0	0	0	0	0	0	0	4,756
1991	0	3,739	0	0	0	0	0	0	0	0	0	0	3,739
1992	0	3,739	0	0	0	0	0	0	0	0	0	0	3,739
1993	0	3,739	0	0	0	0	0	0	0	0	0	0	3,739
1994	0	3,746	0	0	0	0	0	0	0	0	0	0	3,746
1995	0	3,746	0	0	0	0	0	0	0	0	0	0	3,746
1996	0	3,746	0	0	0	0	0	0	0	0	0	0	3,746
1997	0	3,746	0	0	0	0	0	0	0	0	0	0	3,746

Table 5-08. (cont.)

Year	Bandera	Bexar	Blanco	Comal	Gillespie	Hays	Kendall	Kerr	Kimble	Medina	Travis	Uvalde	Total Pumpage
Rural Domestic													
1980	0	0	0	0	0	0	0	0	0	0	1	0	1
1981	0	0	0	0	0	0	0	0	0	0	1	0	1
1982	0	0	0	0	0	0	0	0	0	0	1	0	1
1983	0	0	0	0	0	0	0	0	0	0	1	0	1
1984	0	0	0	0	0	0	0	0	0	0	1	0	1
1985	0	0	0	0	0	0	0	0	0	0	1	0	1
1986	0	0	0	0	0	0	0	0	0	0	1	0	1
1987	0	0	0	0	0	0	0	0	0	0	1	0	1
1988	0	0	0	0	0	0	0	0	0	0	1	0	1
1989	0	0	0	0	0	0	0	0	0	0	1	0	1
1990	0	0	0	0	0	0	0	0	0	0	1	0	1
1991	0	0	0	0	0	0	0	0	0	0	1	0	1
1992	0	0	0	0	0	0	0	0	0	0	1	0	1
1993	0	0	0	0	0	0	0	0	0	0	1	0	1
1994	0	0	0	0	0	0	0	0	0	0	2	0	2
1995	0	0	0	0	0	0	0	0	0	0	2	0	2
1996	0	0	0	0	0	0	0	0	0	0	2	0	2
1997	0	0	0	0	0	0	0	0	0	0	2	0	2
Irrigation													
1980	46	226	0	111	0	0	0	165	0	0	0	0	548
1981	43	271	0	83	0	0	0	155	0	0	0	0	552
1982	40	317	0	55	0	0	0	144	0	0	0	0	556
1983	36	362	0	28	0	0	0	134	0	0	0	0	560
1984	33	408	0	0	0	0	0	123	0	0	0	0	564
1985	48	0	0	0	0	0	0	67	0	0	0	0	115
1986	10	0	0	0	0	0	0	45	0	0	0	0	55
1987	88	0	0	0	0	0	0	45	0	0	0	0	133
1988	88	0	0	0	0	0	0	45	0	0	0	0	133
1989	68	0	0	0	0	0	0	63	0	0	0	0	131
1990	81	0	0	0	0	0	0	62	0	0	0	0	143
1991	81	0	0	0	0	0	0	62	0	0	0	0	143
1992	81	0	0	0	0	0	0	62	0	0	0	0	143
1993	171	0	0	0	0	0	0	131	0	0	0	0	302
1994	15	0	0	3	0	0	0	134	0	0	0	0	152
1995	14	0	0	2	0	0	0	117	0	0	0	0	133
1996	15	0	0	2	0	0	0	131	0	0	0	0	148
1997	15	0	0	2	0	0	0	131	0	0	0	0	148

Table 5-08. (cont.)

Year	Bandera	Bexar	Blanco	Comal	Gillespie	Hays	Kendall	Kerr	Kimble	Medina	Travis	Uvalde	Total Pumpage
Livestock													
1980	0	0	0	0	0	0	0	0	0	0	0	0	0
1981	0	0	0	0	0	0	0	0	0	0	0	0	0
1982	0	0	0	0	0	0	0	0	0	0	0	0	0
1983	0	0	0	0	0	0	0	0	0	0	0	0	0
1984	0	0	0	0	0	0	0	0	0	0	0	0	0
1985	0	0	0	0	0	0	0	0	0	0	0	0	0
1986	0	0	0	0	0	0	0	0	0	0	0	0	0
1987	0	0	0	0	0	0	0	0	0	0	0	0	0
1988	0	0	0	0	0	0	0	0	0	0	0	0	0
1989	0	0	0	0	0	0	0	0	0	0	0	0	0
1990	0	0	0	0	0	0	0	0	0	0	0	0	0
1991	0	0	0	0	0	0	0	0	0	0	0	0	0
1992	0	0	0	0	0	0	0	0	0	0	0	0	0
1993	0	0	0	0	0	0	0	0	0	0	0	0	0
1994	0	0	0	0	0	0	0	0	0	0	0	0	0
1995	0	0	0	0	0	0	0	0	0	0	0	0	0
1996	0	0	0	0	0	0	0	0	0	0	0	0	0
1997	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 9-01. Water budget for the calibrated steady-state model for 1980. All values are acre-feet per year, negative values indicate net discharge from the aquifer. (The numbers are rounded to hundreds of acre-feet.)

	In	Out	Net
Wells	0	16,700	-16,700
Streams and springs	0	164,500	-164,500
Reservoirs	9,000	28,800	-19,800
Edwards (Balcones Fault Zone) Aquifer	8,100	110,600	-102,500
Recharge	303,500	0	303,500

Table 9-02. Water budget for the respective layers in the calibrated steady-state model for 1980. All values are acre-feet per year, negative values indicate net discharge from the aquifer. (The numbers are rounded to hundreds of acre-feet.)

	Edwards Group	Upper Trinity Aquifer	Middle Trinity Aquifer	Lower Trinity Aquifer	Total
Inter-Aquifer Flow (Upper)	0	9,800	64,100	5,800	79,700
Inter-Aquifer Flow (Lower)	-9,800	-64,100	-5,800	0	79,700
Wells	-1,000	-5,100	-4,600	-6,000	-16,700
Streams and springs	-47,700	-60,900	-55,900	0	-164,500
Reservoirs	0	-2,500	-17,300	0	-19,800
Edwards (Balcones Fault Zone) Aquifer	0	-33,300	-69,200	0	-102,500
Recharge	58,500	156,200	88,700	100	303,500

Table 9-03. Water budget for the respective counties in the calibrated steady-state model for 1980. All values are acre-feet per year, negative values indicate net discharge from the aquifer. (The numbers are rounded to hundreds of acre-feet.)

County	Wells	Streams and springs	Recharge	Reservoirs	Edwards (Balcones Fault Zone) Aquifer	Lateral inflow	Lateral outflow
Bandera	-1,100	-34,300	36,900	-1,000	-1,800	25,500	-24,200
Bexar	-3,900	-9,900	39,000	0	-37,200	36,200	-24,300
Blanco	-200	-14,200	19,000	0	0	6,900	-11,500
Comal	-1,000	-3,700	40,300	-5,900	-37,900	37,600	-29,500
Gillespie	-1,200	-14,300	28,300	0	0	900	-13,700
Hays	-1,600	-18,800	21,800	0	-6,700	14,200	-9,000
Kendall	-1,600	-28,500	51,000	0	0	9,600	-30,500
Kerr	-6,000	-32,600	47,100	0	0	10,500	-19,000
Kimble	0	0	400	0	0	200	-500
Medina	0	-2,400	5,800	-2,600	-14,300	20,400	-6,900
Travis	-100	-5,200	11,900	-10,300	-2,100	6,100	-400
Uvalde	0	-500	1,800	0	-2,500	2,000	-800
Total	-16,700	-164,500	303,500	-19,800	-102,500	170,200	-170,200

Table 10-01. Stress periods of the transient model.

Stress Period	Year	Length (Days)
1	Steady-state (1980)	100,000
2	1981	365
3	1982	365
4	1983	365
5	1984	365
6	1985	365
7	1986	365
8	1987	365
9	1988	365
10	1989	365
11	1990	365
12	1991	365
13	1992	365
14	1993	365
15	1994	365
16	1995	365
17	1996	365
18	1997	365

Table 10-02. Calibrated specific yield, specific storage, and hydraulic conductivity data for the respective model layers.

Model Layer	**Aquifer**	**Specific Yield**	**Specific Storage (Per foot)**	**Hydraulic Conductivity (Feet per Day)**	
				Range	**Mean**
1	Edwards Group	0.008	1.0E-05	11	11.0
2	Upper Trinity Aquifer	0.0005	1.0E-06	9 to 150	10.4
3	Middle Trinity Aquifer	0.0008	1.0E-07	7.6 to 15	8.8
4	Lower Trinity Aquifer	0.0008	1.0E-07	1.67 to 16.7	4.4

Table 10-03. Calibration statistics for the transient model for the years 1980, 1990, and 1997. The percentage represents the mean absolute error relative to the range of measured water levels.

1980	**Mean Error**	**Mean Absolute Error**	**Mean Absolute Error (Percent)**
Overall	14	59	4%
Edwards Group	23	31	17%
Upper Trinity Aquifer	23	68	6%
Middle Trinity Aquifer	-14	53	5%
Lower Trinity Aquifer	17	58	5%

1990	**Mean Error**	**Mean Absolute Error**	**Mean Absolute Error (Percent)**
Overall	6	52	4%
Edwards Group	34	34	--
Upper Trinity Aquifer	-81	99	9%
Middle Trinity Aquifer	6	54	7%
Lower Trinity Aquifer	17	45	4%

1997	**Mean Error**	**Mean Absolute Error**	**Mean Absolute Error (Percent)**
Overall	15	57	4%
Edwards Group	26	26	--
Upper Trinity Aquifer	-44	82	7%
Middle Trinity Aquifer	10	66	7%
Lower Trinity Aquifer	26	48	5%

-- indicates too few water-level measurements to calculate percent mean absolute error.

Table 10-04. Water budget for the respective layers in the calibrated transient model for 1980, 1990 and 1997. (All values are acre-feet per year, negative values indicate net discharge from the aquifer).

1980	**Edwards Group**	**Upper Trinity Aquifer**	**Middle Trinity Aquifer**	**Lower Trinity Aquifer**
Inter-Aquifer Flow (Upper)	0	9,773	64,138	5,825
Inter-Aquifer Flow (Lower)	-9,773	-64,138	-5,825	0
Wells	-1,007	-5,157	-4,556	-5,961
Streams and springs	-47,735	-60,879	-56,013	0
Reservoirs	0	-2,519	-17,329	0
Edwards (Balcones Fault Zone) Aquifer	0	-33,224	-69,293	0
Recharge	58,516	156,135	88,910	155

1990	**Edwards Group**	**Upper Trinity Aquifer**	**Middle Trinity Aquifer**	**Lower Trinity Aquifer**
Storage	-7,960	-9,839	-5,788	-232
Inter-Aquifer Flow (Upper)	0	10,087	68,750	5,793
Inter-Aquifer Flow (Lower)	-10,087	-68,750	-5,793	0
Wells	-1,229	-6,253	-5,650	-5,732
Streams and springs	-51,290	-70,642	-64,676	0
Reservoirs	0	-3,097	-18,990	0
Edwards (Balcones Fault Zone) Aquifer	0	-37,821	-68,783	0
Recharge	70,567	186,292	100,916	180

1997	**Edwards Group**	**Upper Trinity Aquifer**	**Middle Trinity Aquifer**	**Lower Trinity Aquifer**
Storage	-12,380	-16,923	-11,8528	-447
Inter-Aquifer Flow (Upper)	0	10,329	77,150	5,297
Inter-Aquifer Flow (Lower)	-10,329	-77,150	-5,297	0
Wells	-1,504	-7,901	-8,448	-5,079
Streams and springs	-54,343	-85,266	-75,397	0
Reservoirs	0	-4,408	-23,563	0
Edwards (Balcones Fault Zone) Aquifer	0	-45,1623	-70,962	0
Recharge	78,557	226,464	118,348	240

Table 10-05. Estimated spring discharge and simulated average spring discharge rates from the calibrated transient model. The locations of these springs can be found in Figure 5-28 (All values are expressed in gallons per minute). Please note that: (1) the spring discharge measurements are single measurements collected over a wide range of conditions and time periods, (2) only two of the spring discharge measurements coincide with the calibration period, and (3) due to scale issues, the model results may not reflect the more localized flow systems that influence discharge at specific springs.

Spring	1	2	3	4	5	8	9	10	11	12	13	14	15	16	17	18	19
		Bee Caves Spring	Lynx Haven Springs	Ellebracht Springs				Cave Without A Name	Kenmore Ranch Spring #9	Edge Falls Springs	Rebecca Springs	Jacob's Well Spring		Bassett Springs			Cold Springs
Estimated Flow (gallons per minute)	15	10	10	250	31				15	30	30	50				900	500
	0	0	0	0	0	20	75	50	0	0	0	0	25	50	50	0	0
Measure Date	4/13/67	4/12/67		3/31/66	3/11/70	7/13/76	7/10/75	1/17/40	7/17/75		7/11/75	8/31/76	1/1/66	12/30/88	5/25/73	12/20/60	8/20/91
Simulated Flow (gallon per minute) 1980	139	75	82	225	330	366	33	119	0	0	0	0	6	0	0	407	441
1981	142	83	86	238	358	474	40	127	81	0	0	0	9	0	0	423	516
1982	140	78	84	217	331	350	33	115	0	0	0	0	8	0	0	407	437
1983	139	75	82	213	317	346	36	119	0	0	0	0	9	0	0	400	448
1984	139	74	82	218	321	322	32	113	0	0	0	0	7	0	0	408	419
1985	140	76	83	226	332	388	42	132	113	0	0	0	9	0	0	413	489
1986	142	84	86	241	360	466	46	134	152	0	0	0	11	0	0	429	542
1987	145	92	90	255	393	500	46	132	140	0	0	0	12	0	0	446	558
1988	142	87	88	228	358	368	32	111	0	0	0	0	7	0	0	416	442
1989	140	81	85	222	338	308	32	110	0	0	0	0	6	0	0	410	414
1990	142	85	87	236	359	392	40	125	1	0	0	0	8	0	0	428	474

1991	145	93	91	244	382	508	50	139	195	0	0	0	12	0	0	436	568
1992	146	98	94	250	404	528	56	150	351	83	0	0	13	0	0	447	626
1993	142	88	89	219	355	359	40	124	59	0	0	0	10	0	0	415	473
1994	144	92	91	242	378	426	44	129	70	0	0	0	10	0	0	432	518
1995	142	88	89	227	363	386	37	118	0	0	0	0	9	0	0	425	471
1996	142	86	88	224	350	335	31	110	0	0	0	0	7	0	0	420	419
1997	144	90	90	247	388	446	47	132	35	0	0	0	11	0	0	446	522

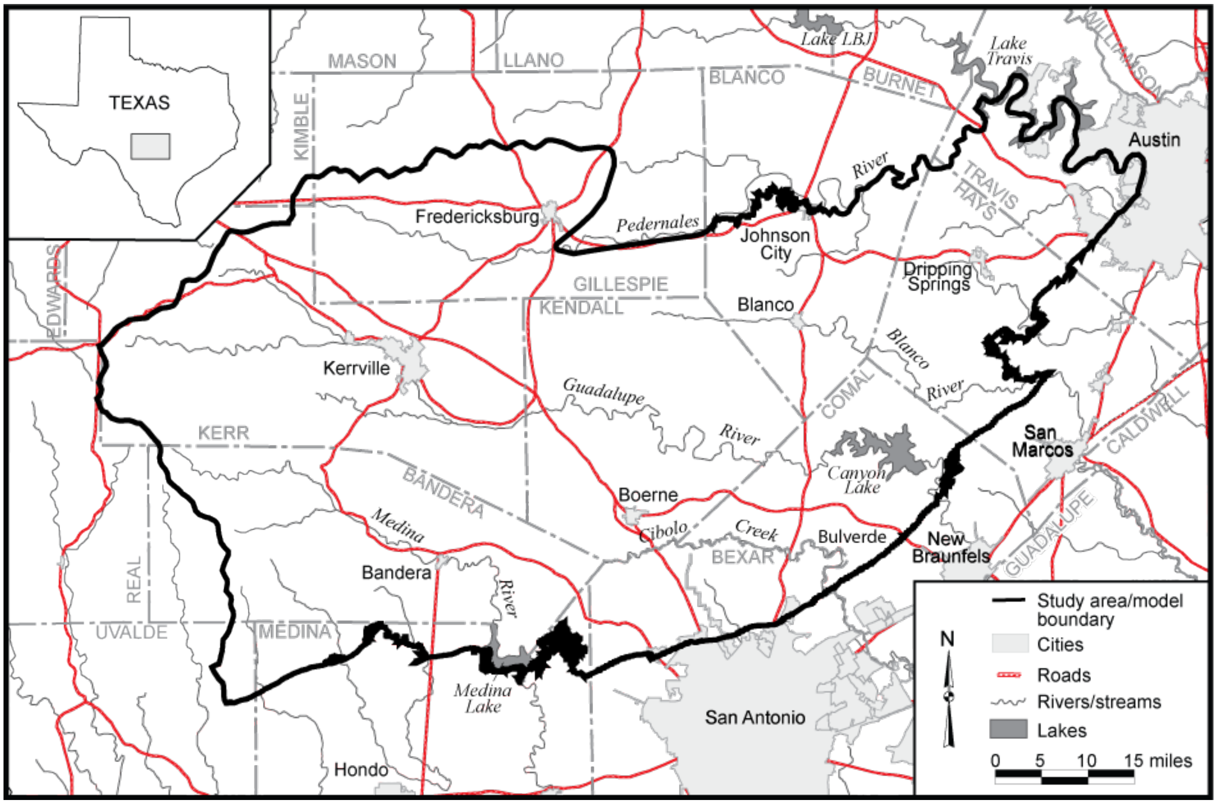


Figure 3-01. Location of the study area relative to roads, major cities and towns, lakes, and rivers (modified from Mace and others, 2000).

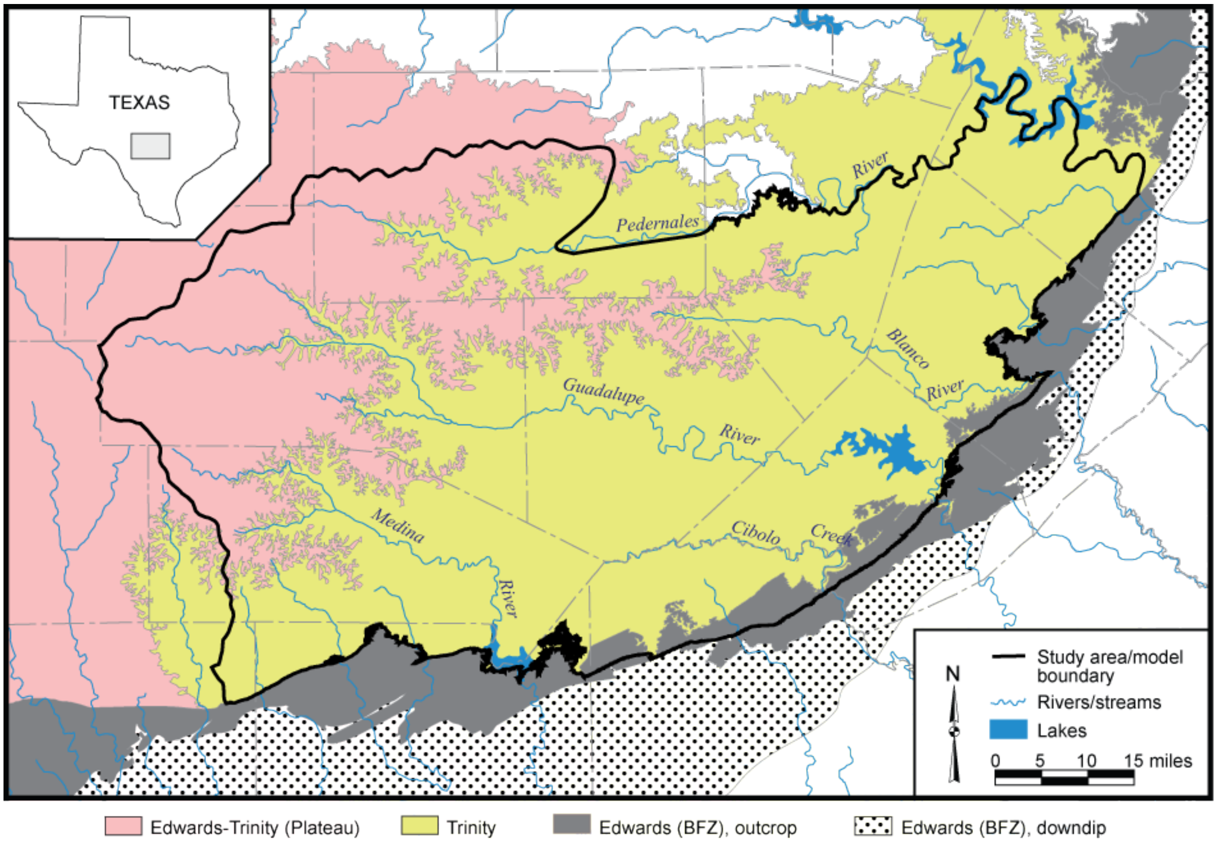


Figure 3-02. Map of outcrops of the major aquifers in the study area. Trinity sediments in the study area include sediments that are part of the Edwards-Trinity (Plateau) Aquifer System to the west and underlie the Edwards (Balcones Fault Zone) Aquifer to the south and east (modified from Mace and others, 2000).

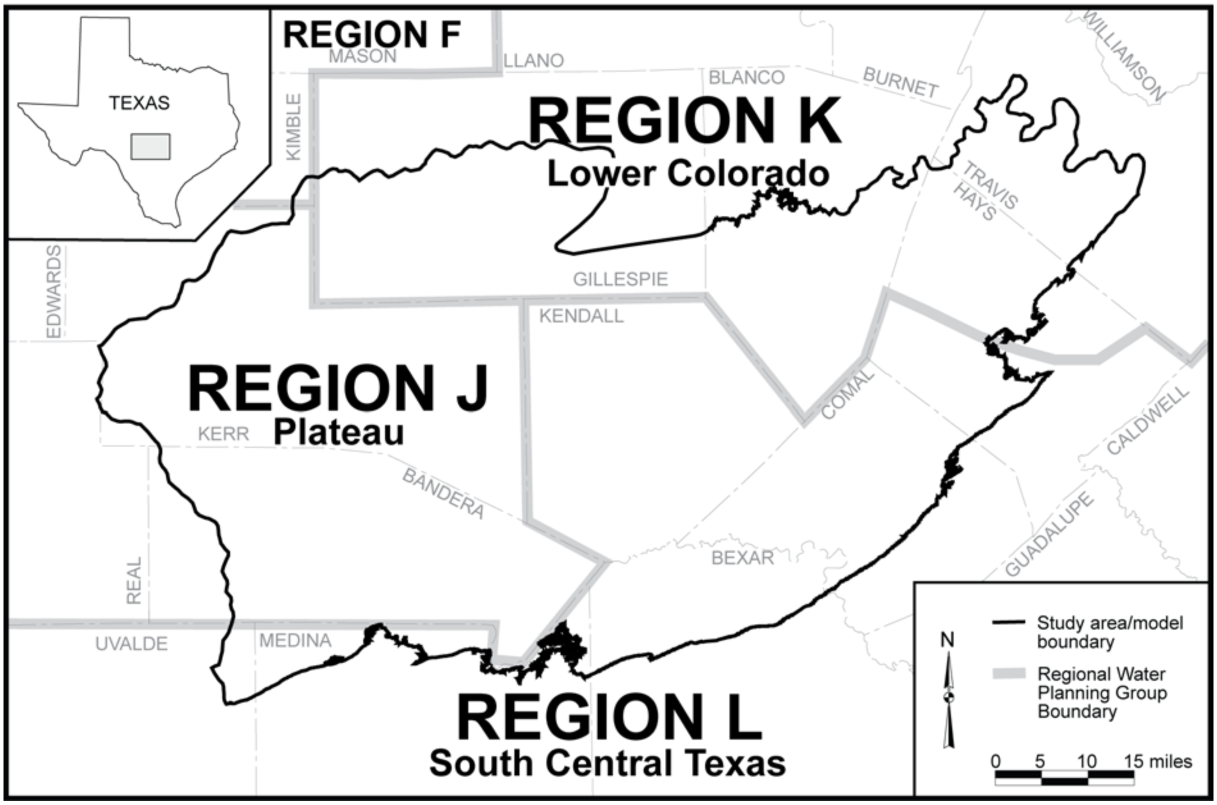


Figure 3-03. Regional water planning groups in the study area (modified from Mace and others, 2000).

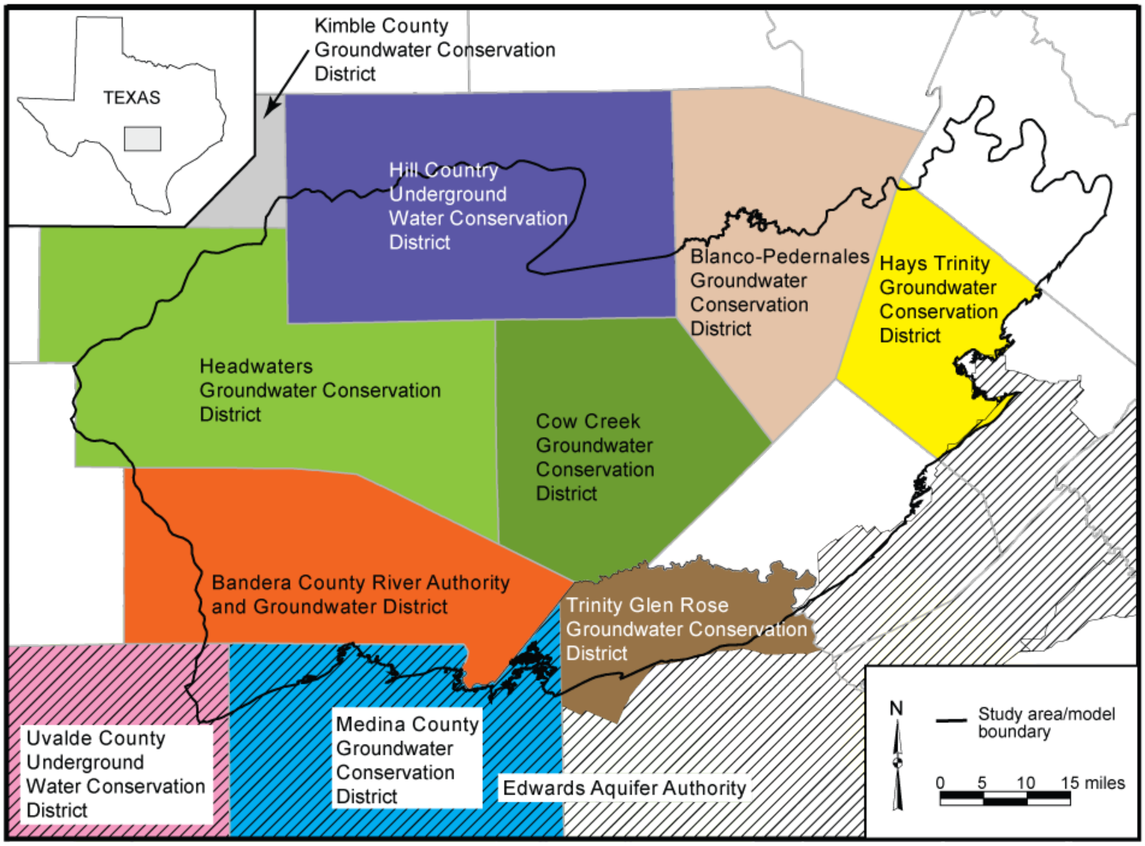


Figure 3-04. Groundwater conservation districts in the study area as of January 2008 (Area with diagonal hatch lines represent the Edwards Aquifer Authority).

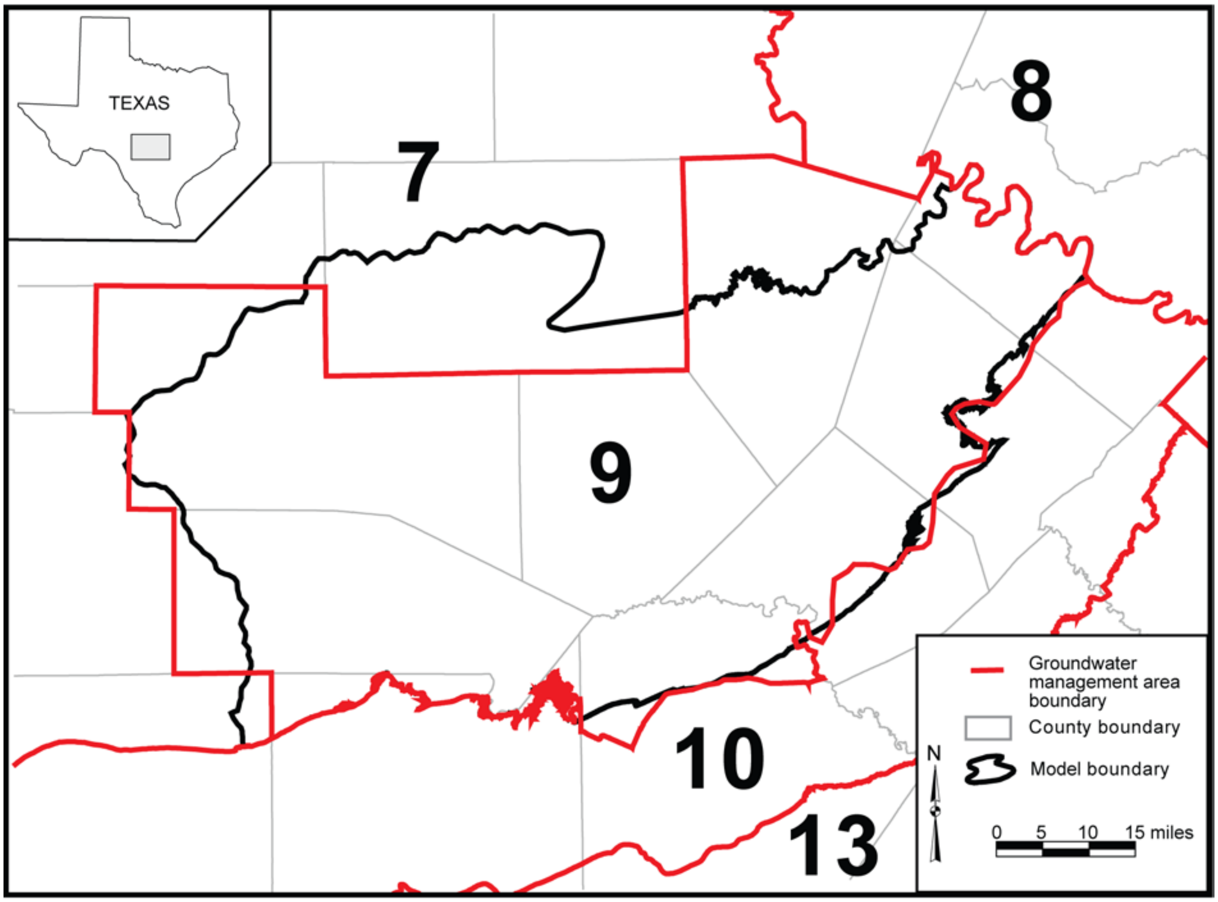


Figure 3-05. Groundwater management areas in the study area.

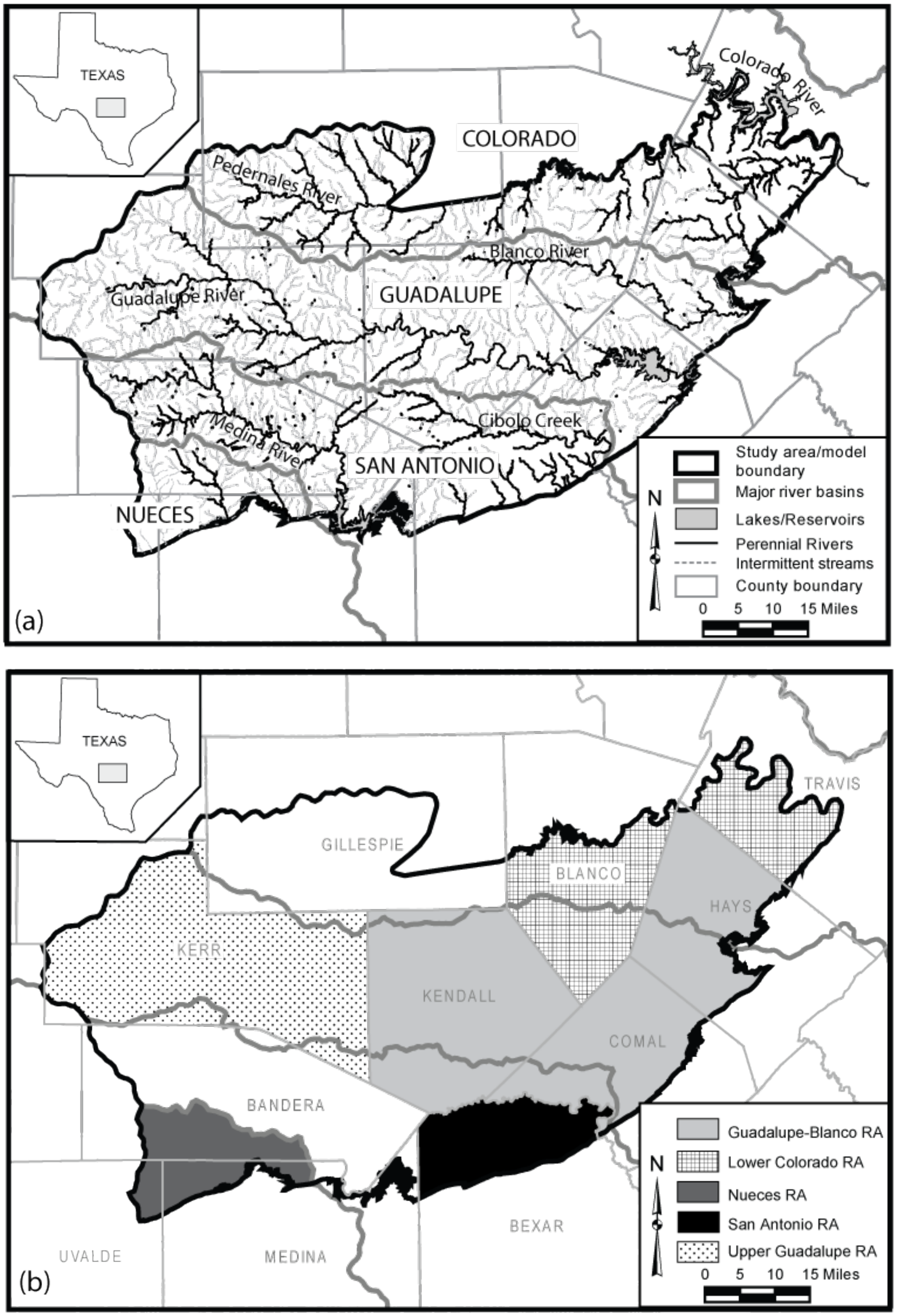


Figure 3-06. (a) Major perennial and intermittent rivers and streams in the study area. (b) River authorities in the study area.

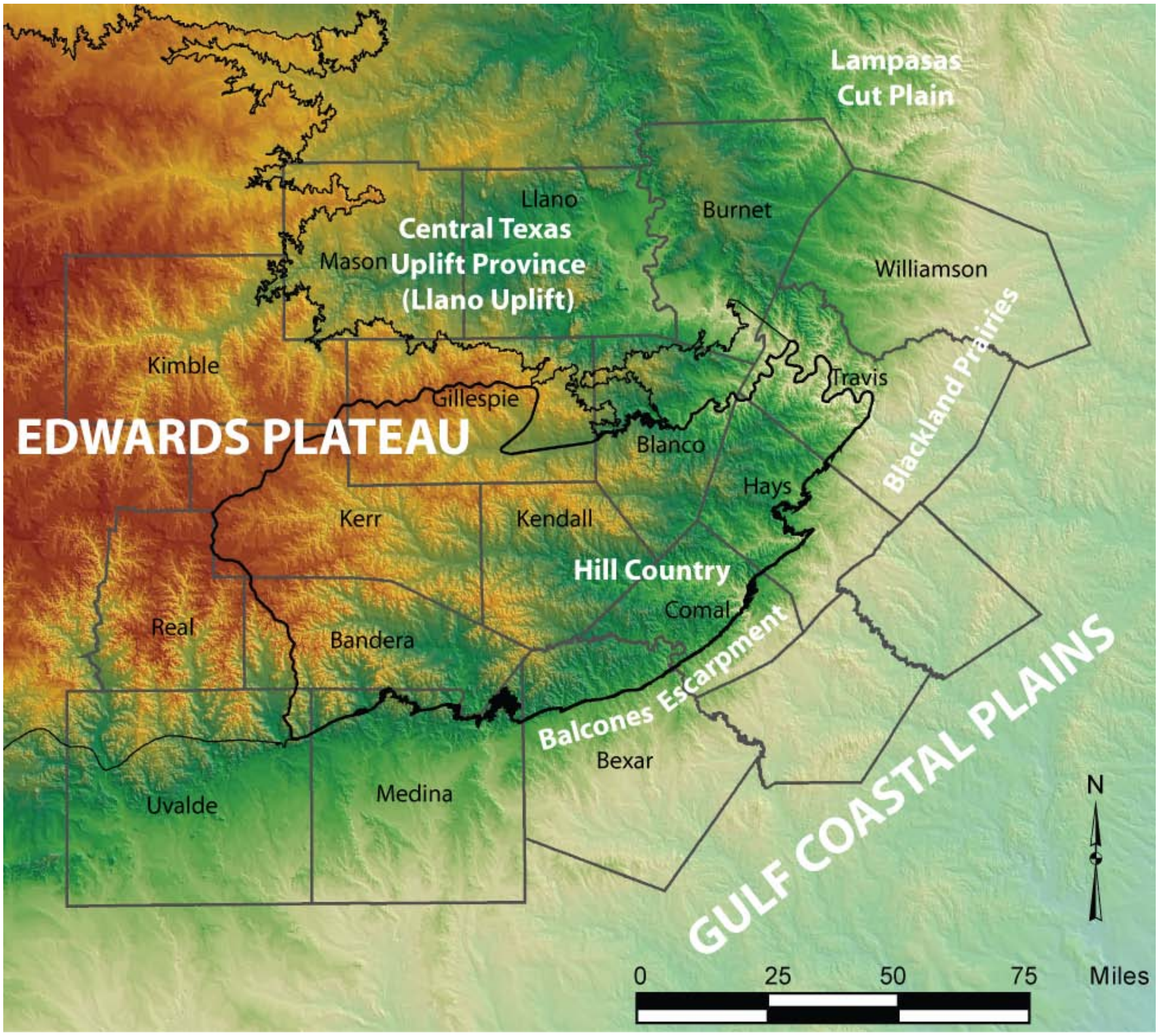


Figure 3-07. Physiographic provinces in the study area (modified from Anaya and Jones, 2009).

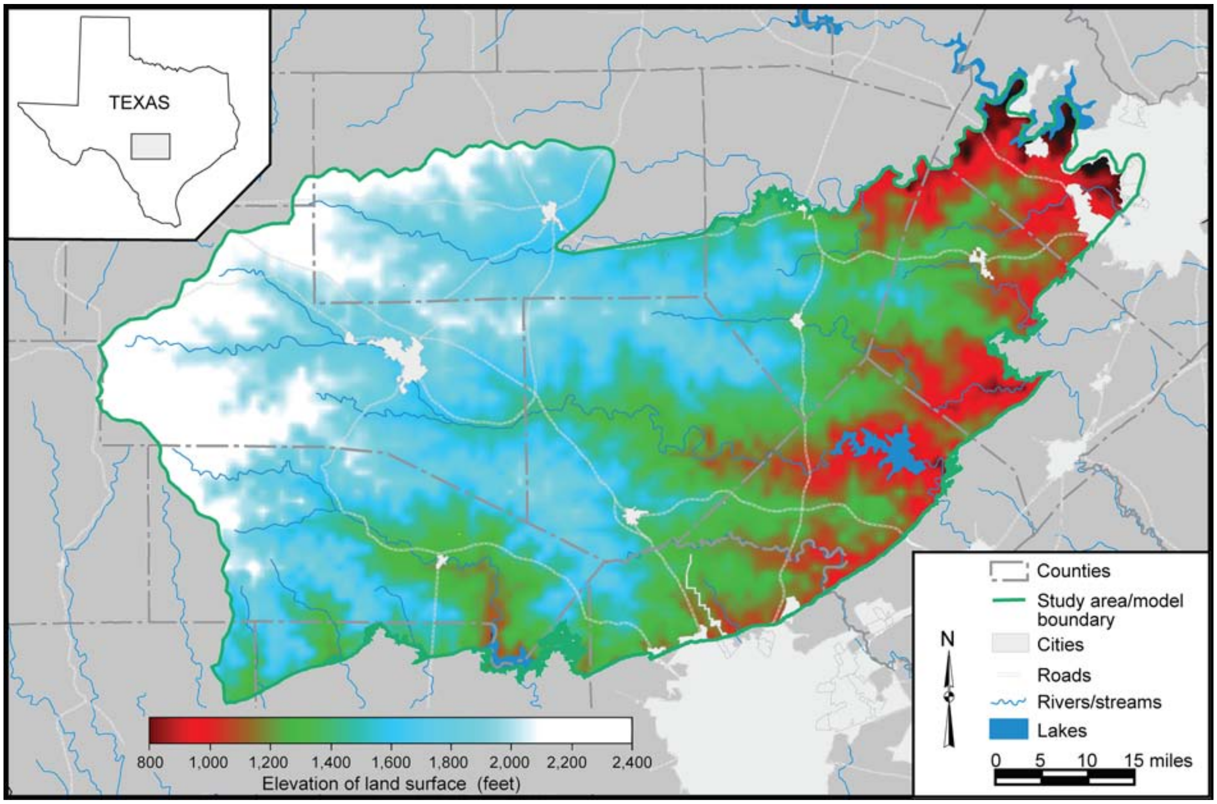


Figure 3-08. Land-surface elevation in the study area (modified from Mace and others, 2000).

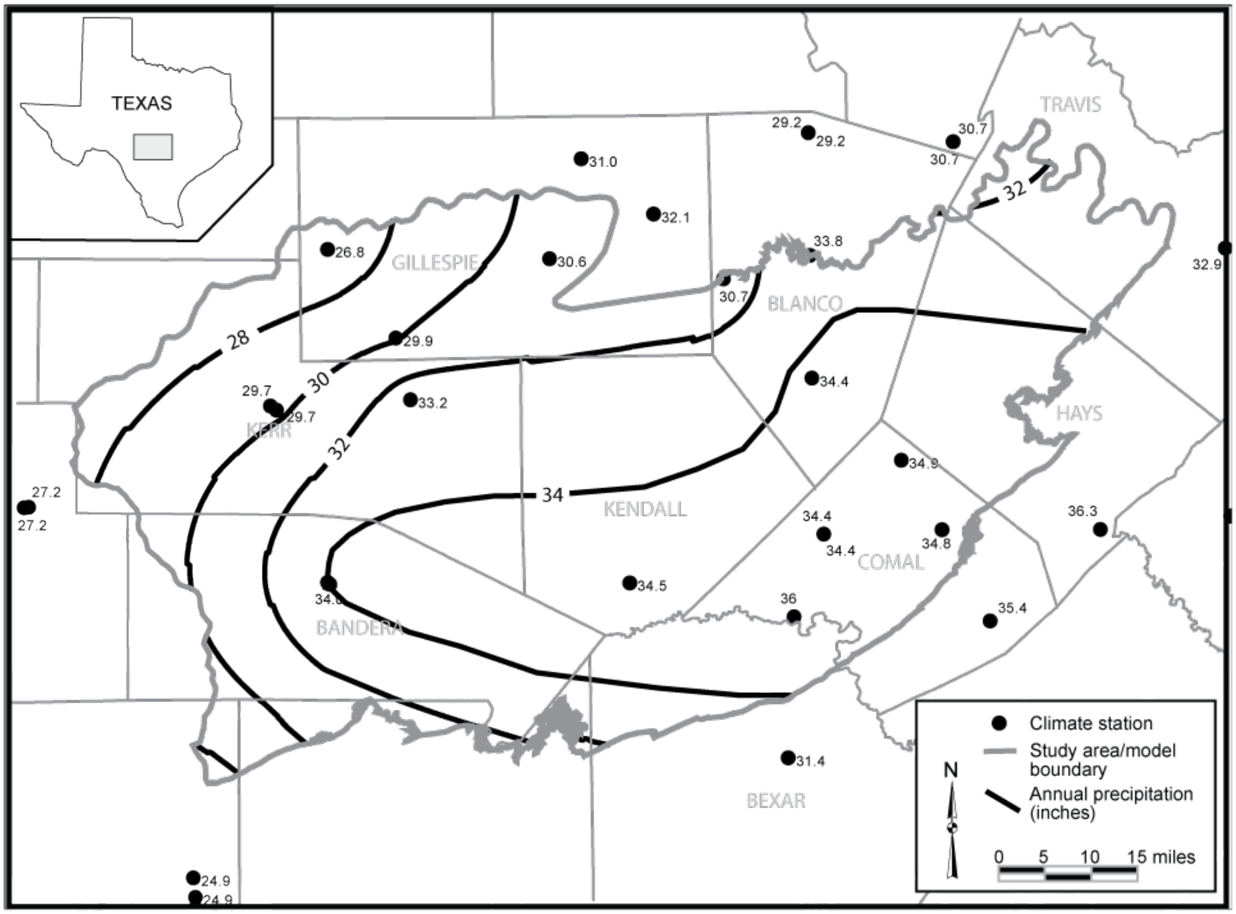


Figure 3-09. Average annual rainfall distribution for the period 1960 through 1996 (data from National Climate Data Center).

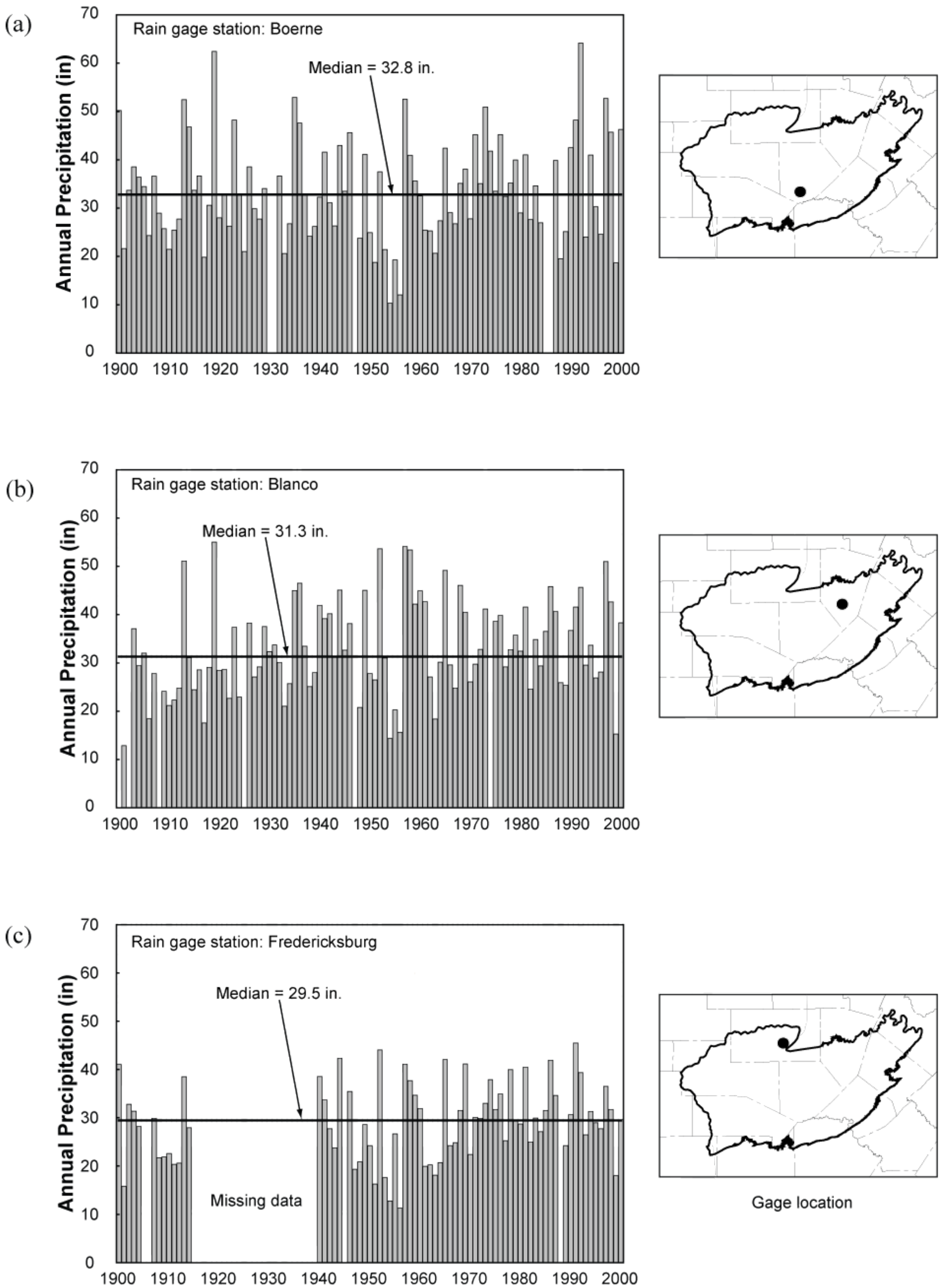


Figure 3-10. Historic annual precipitation for three rain gauge stations in the study area (modified from Mace and others, 2000).

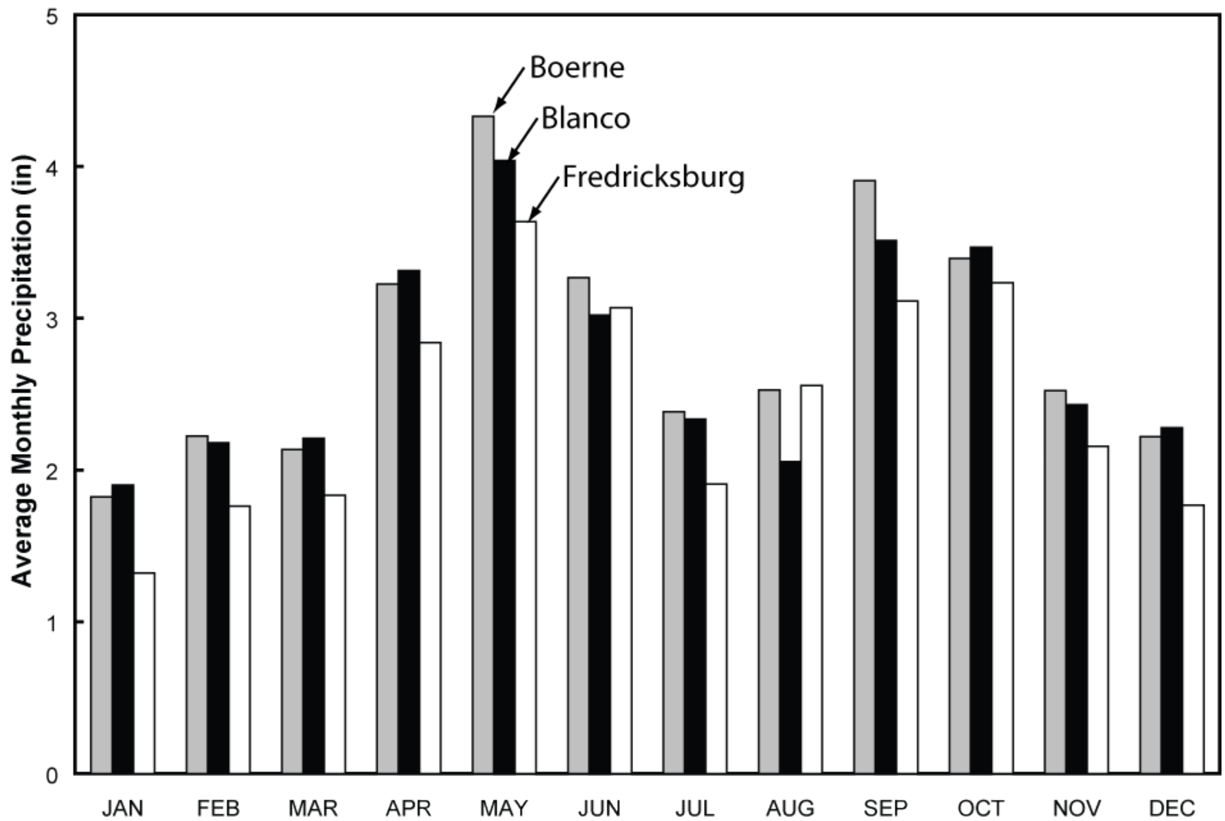


Figure 3-11. Average monthly precipitation for three rain gauges in the study area for the period 1960 through 1996 (data from National Climate Data Center).

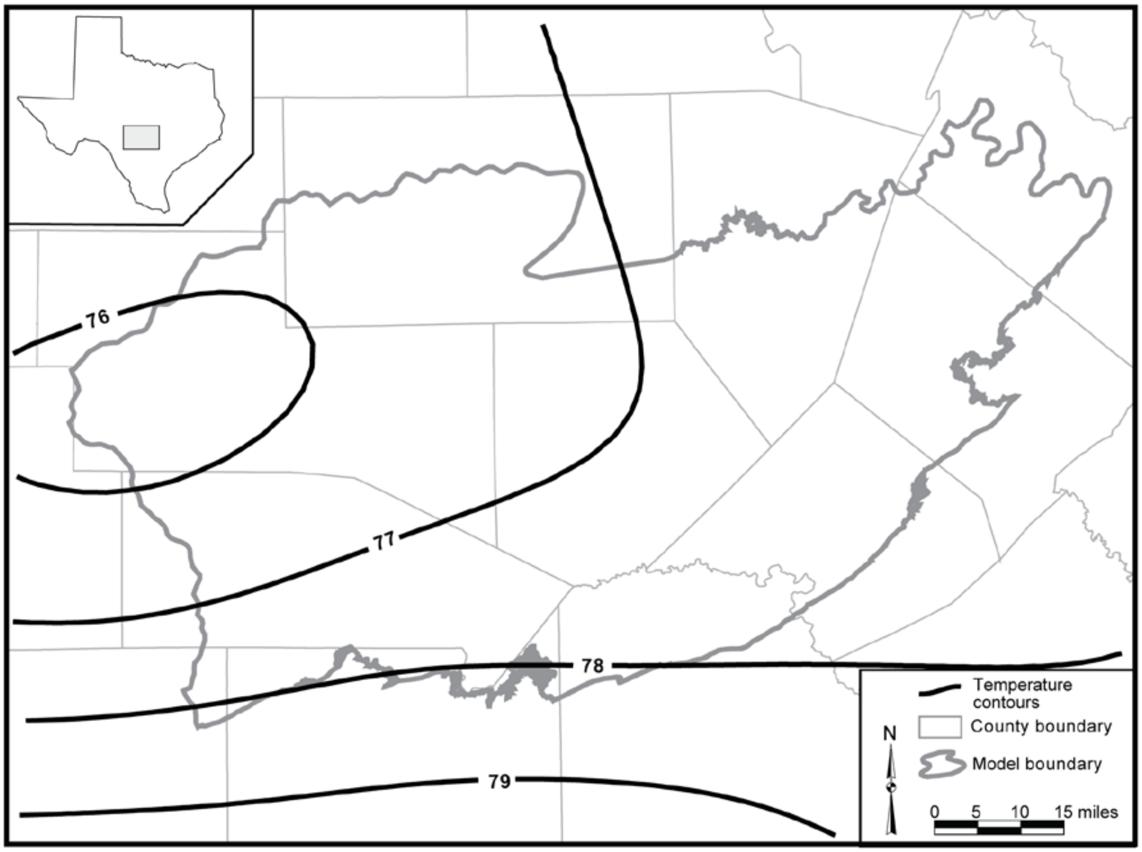


Figure 3-12. Average annual maximum temperature for 1971 through 2000. The contours are expressed in degrees Fahrenheit (modified from data from Spatial Climate Analysis Service, 2004).

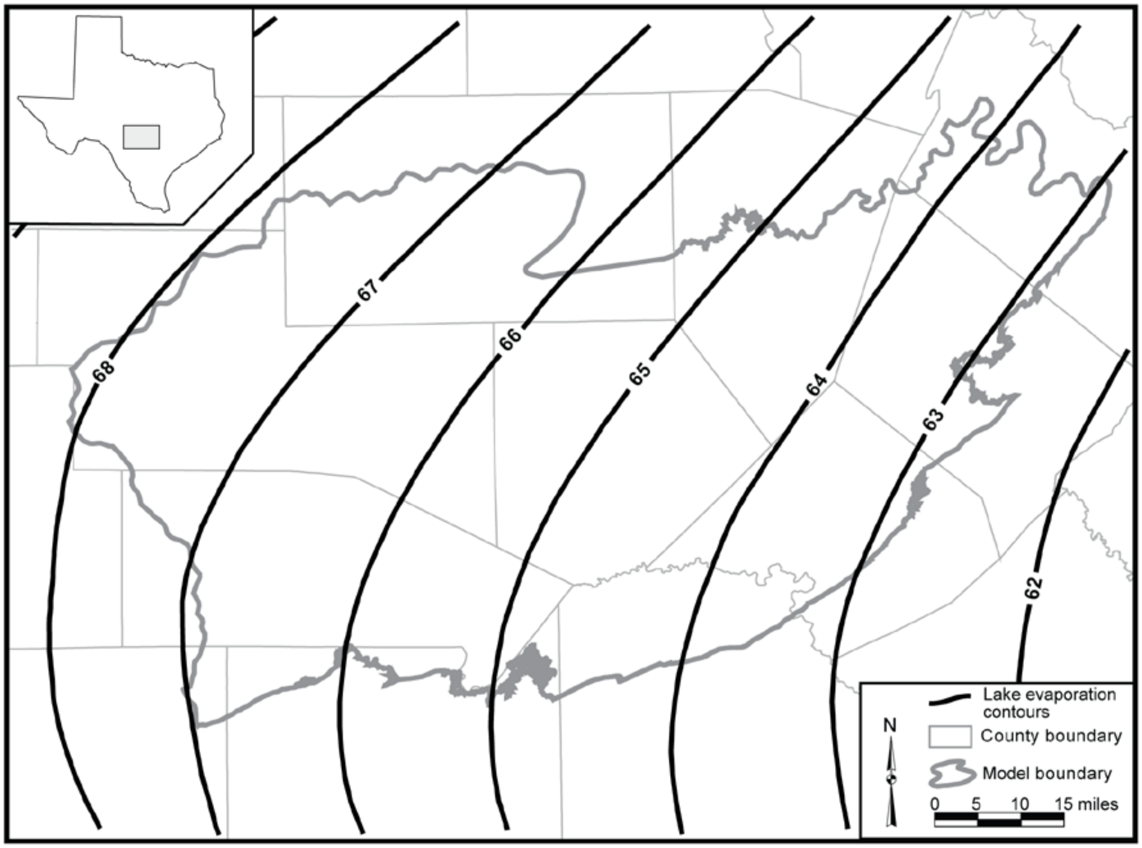


Figure 3-13. Average annual gross lake evaporation for 1950 through 1979. Contours are expressed in inches (modified from Larkin and Bomar, 1983).

ERA	SYSTEM	GROUP	STRATIGRAPHIC UNIT		HYDROLOGIC UNIT	
Cenozoic	Quaternary		Alluvium		Alluvium	
Mesozoic	Cretaceous	Edwards	Segovia Formation		Edwards Group	
			Fort Terrett Formation			
		Trinity	Glen Rose Limestone	Upper Member	Trinity Aquifer System	Upper Trinity
				Lower Member		Middle Trinity
			Hensell Sand/Bexar Shale			
			Cow Creek Limestone			
			Hammett Shale			confining unit
			Sligo Formation			Lower Trinity
			Sycamore Sand/Hosston Formation			
Paleozoic			Undifferentiated Pre-Cretaceous rock			

Figure 3-14. Stratigraphic and hydrostratigraphic column of the Hill Country area.

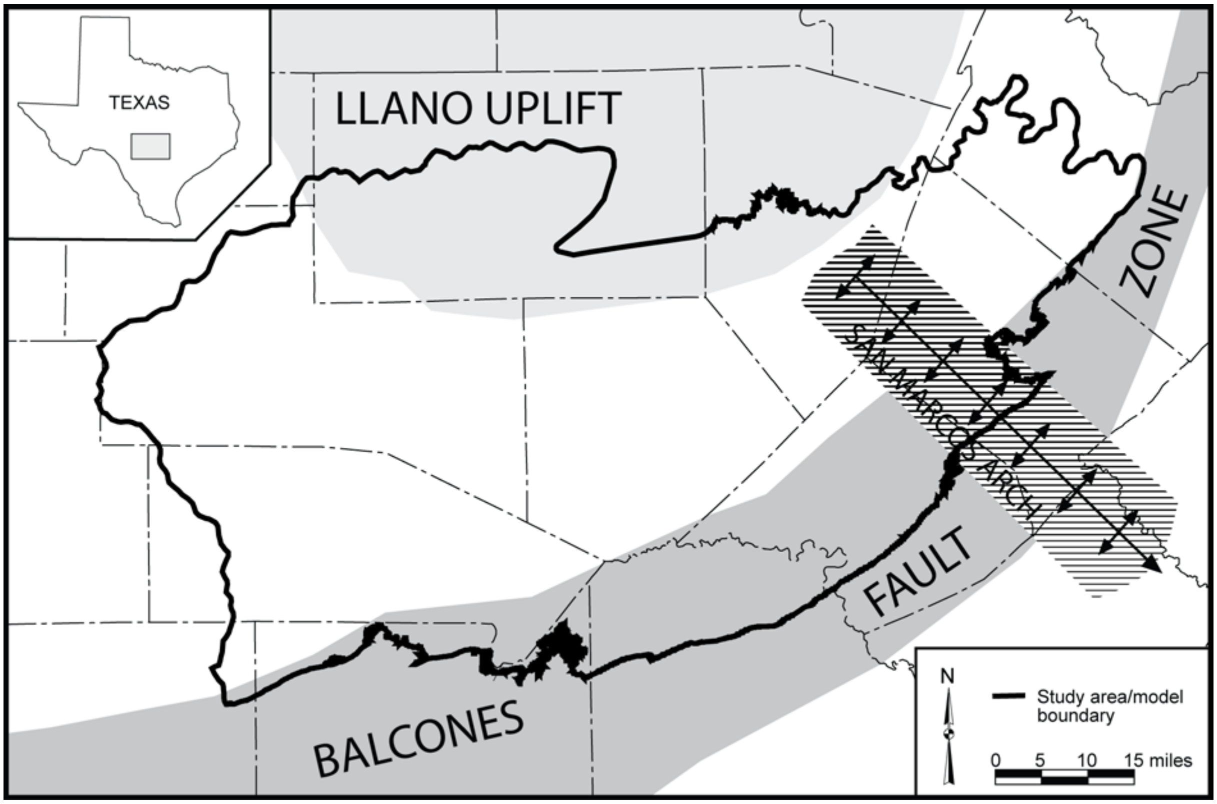


Figure 3-15. The main geologic structures in the study area (modified from Mace and others, 2000).

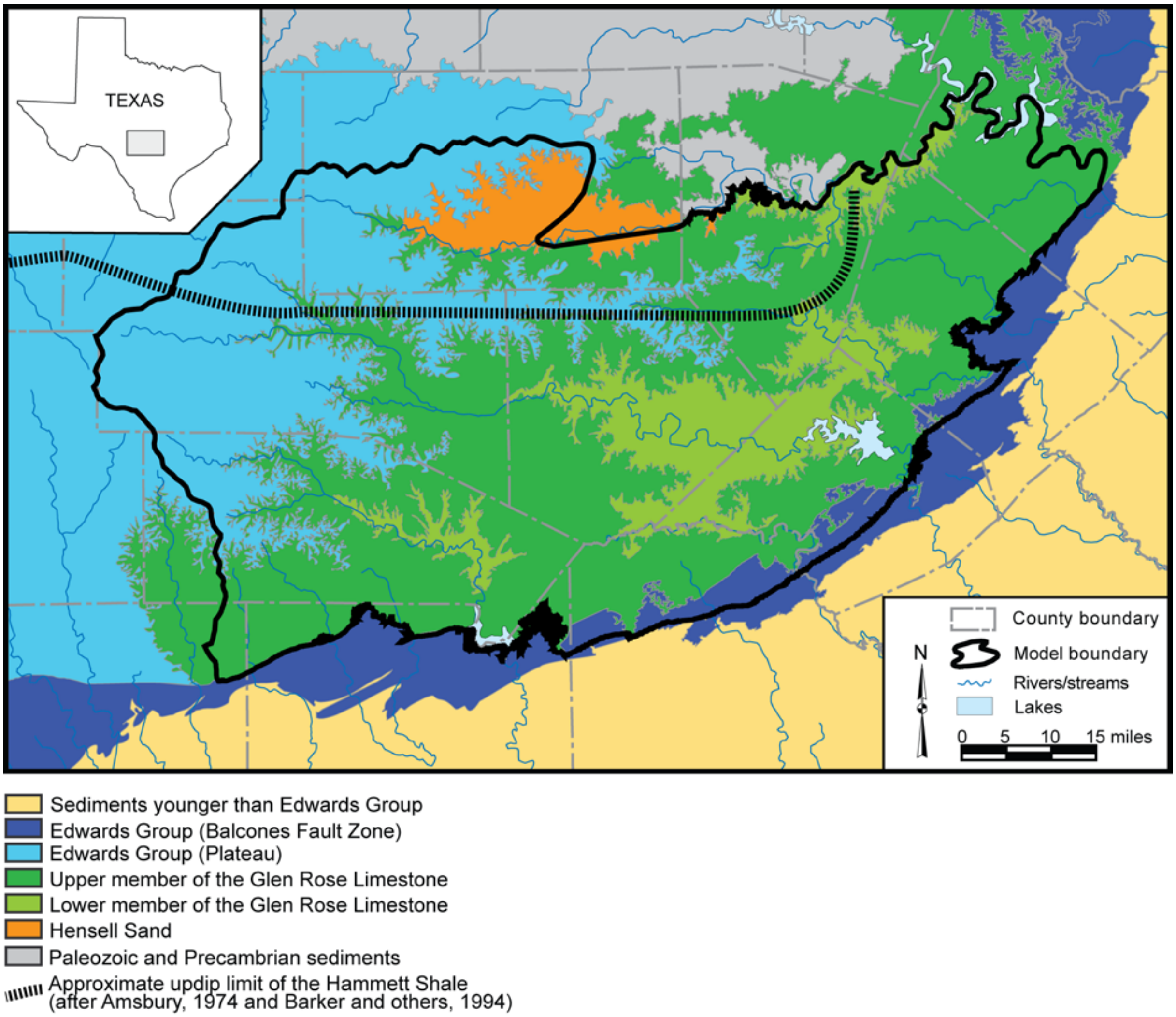


Figure 3-16. Surface geology of the study area (modified from Mace and others, 2000). Please note that this map excludes isolated outliers of the Edwards Group that overly the Upper member of the Glen Rose Limestone, some of which are included in the original and updated models.

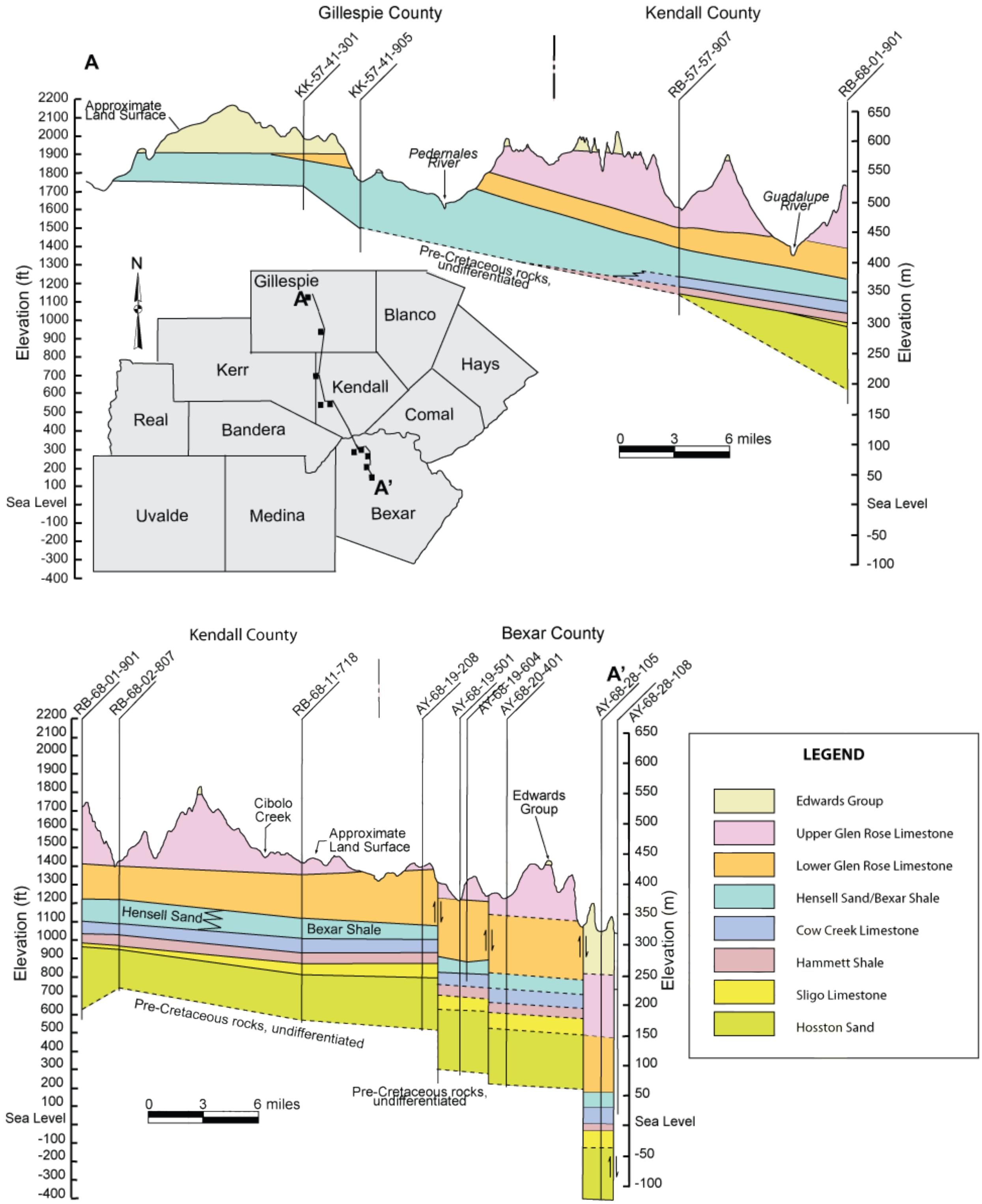


Figure 3-17. Geologic cross sections through the study area (modified from Ashworth, 1983; Mace and others, 2000). Inset map shows cross-section line AA′.

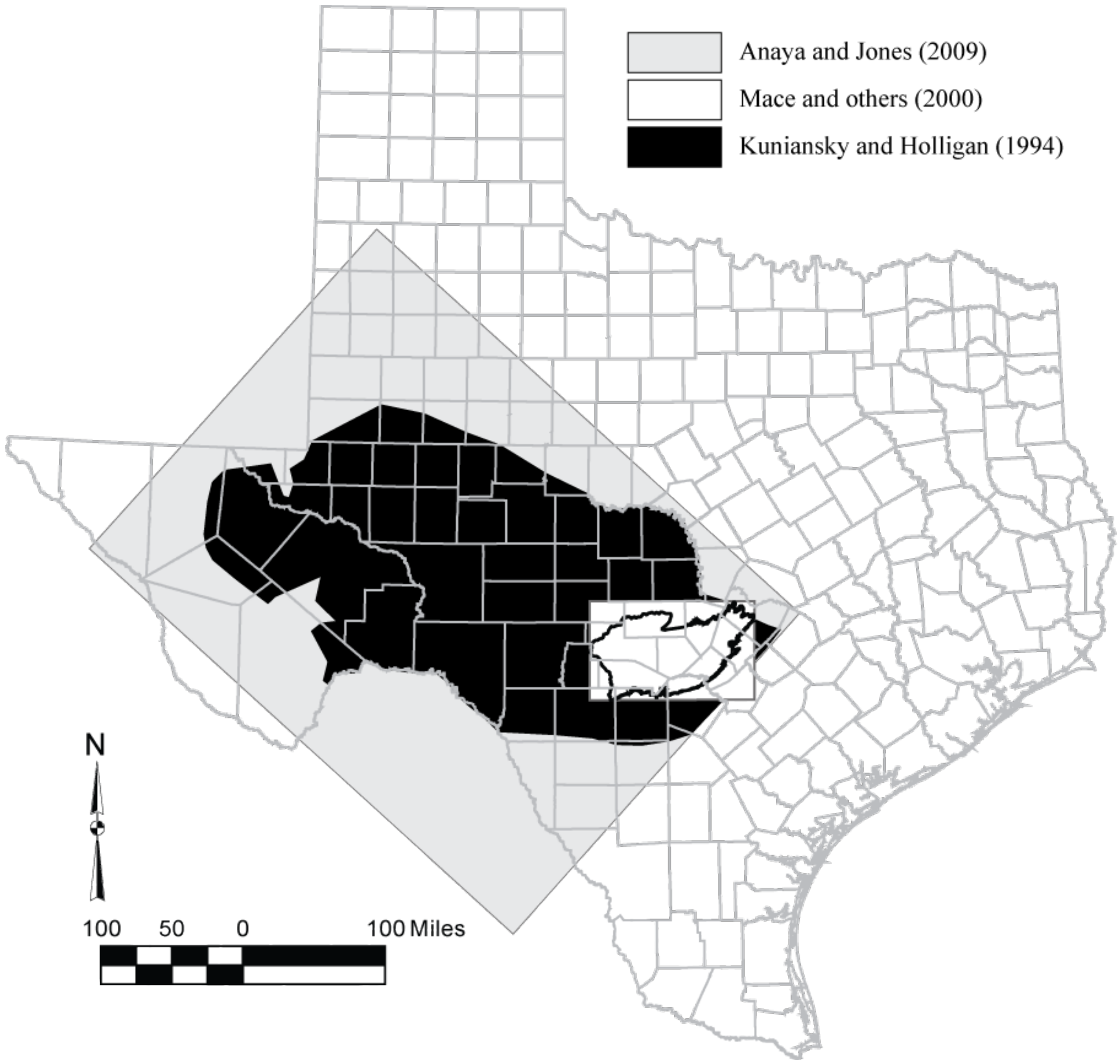


Figure 4-01. The approximate extents of previous model grids for models used for simulating groundwater flow through the study area.

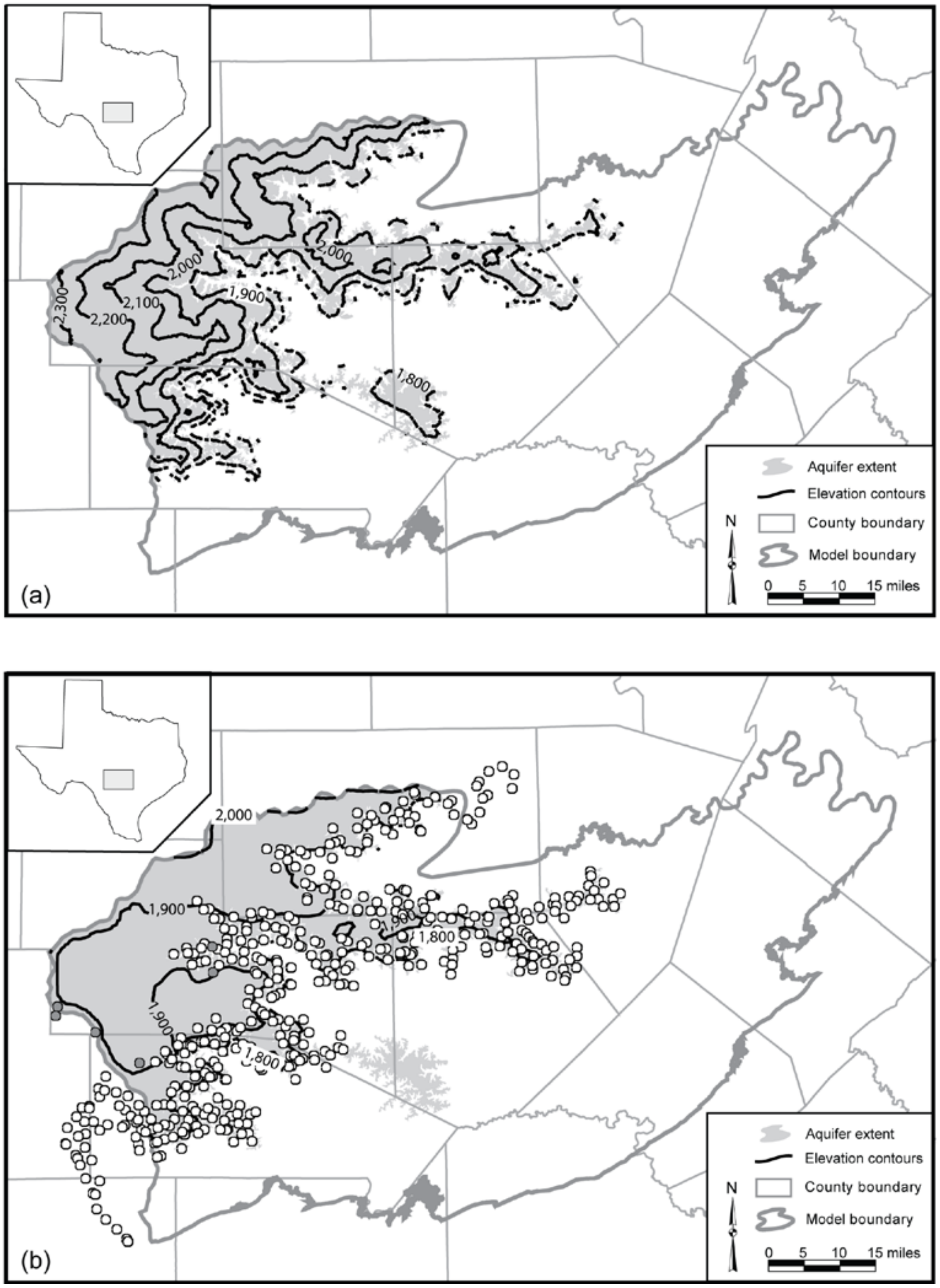


Figure 5-01. Elevations of (a) the top and (b) the base of the Edwards Group. The gray and white circles indicate control points from well logs and outcrop, respectively. The contour interval is 100 feet (modified from Ashworth, 1983; Mace and others, 2000).

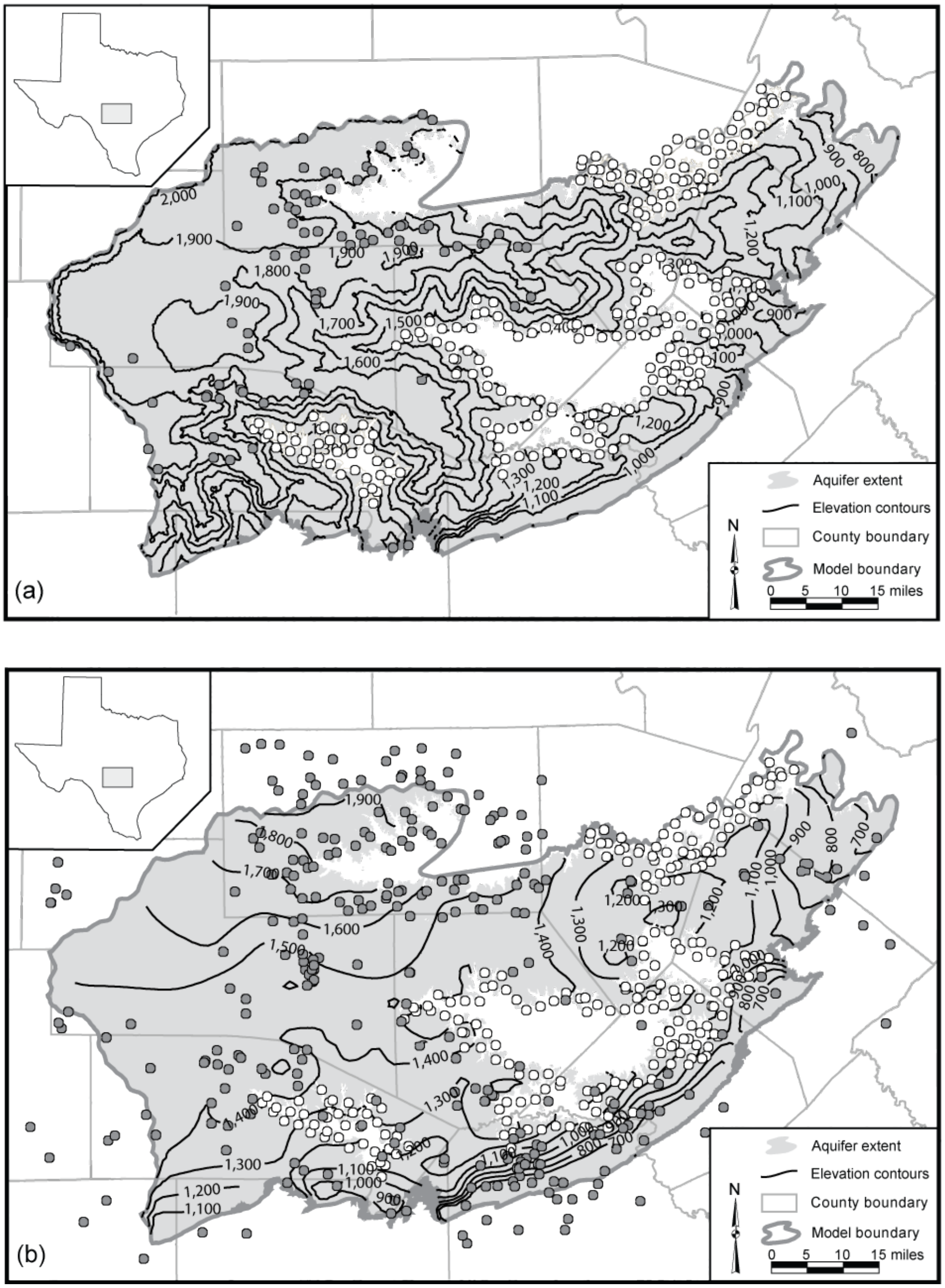


Figure 5-02. Elevation of (a) the top and (b) the base of the Upper Trinity Aquifer. The gray and white circles indicate control points from well logs and outcrop, respectively. The contour interval is 100 feet (modified from Ashworth, 1983; Mace and others, 2000).

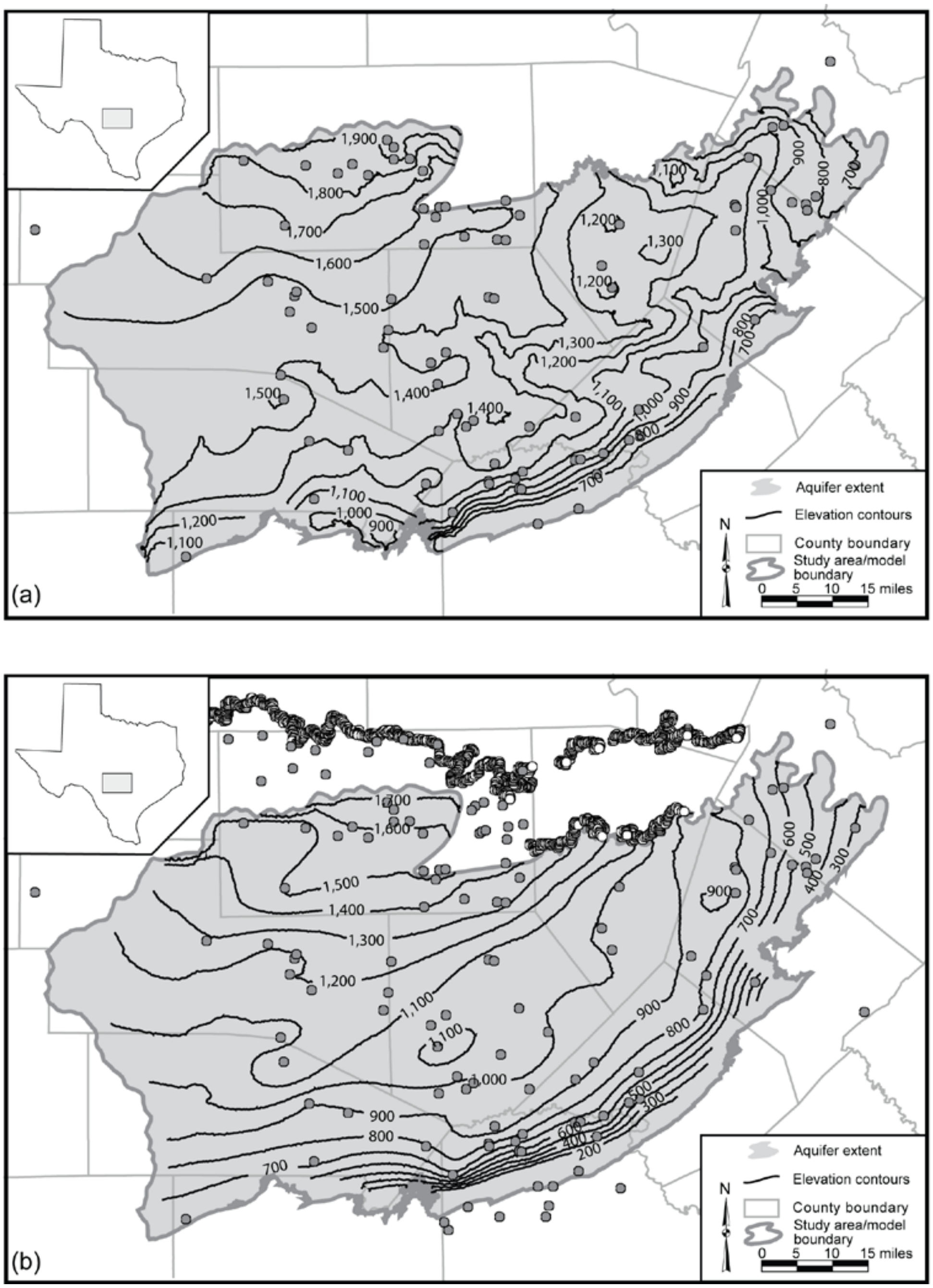


Figure 5-03. Elevation of (a) the top and (b) the base of the Middle Trinity Aquifer. The gray and white circles indicate control points from well logs and outcrop, respectively. The contour interval is 100 feet (modified from Ashworth, 1983; Mace and others, 2000).

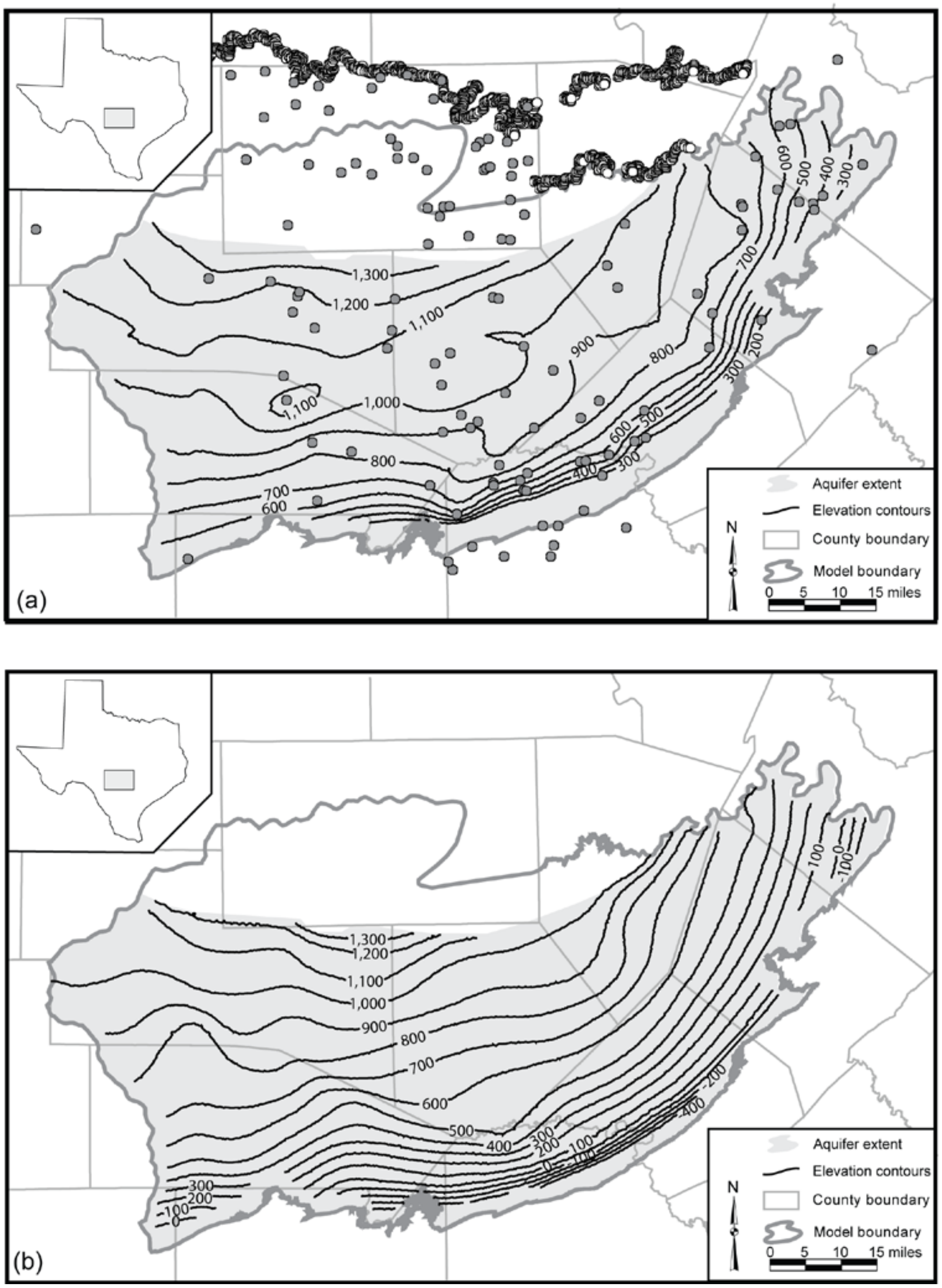


Figure 5-04. Elevation of (a) the top (modified from Ashworth, 1983; Mace and others, 2000) and (b) the base of the Lower Trinity Aquifer. The gray and white circles indicate control points from well logs and outcrop, respectively. The contour interval is 100 feet. Please note: the top of the Lower Trinity Aquifer coincides with the base of the Hammett Shale and thus differs from the base of the Middle Trinity Aquifer.

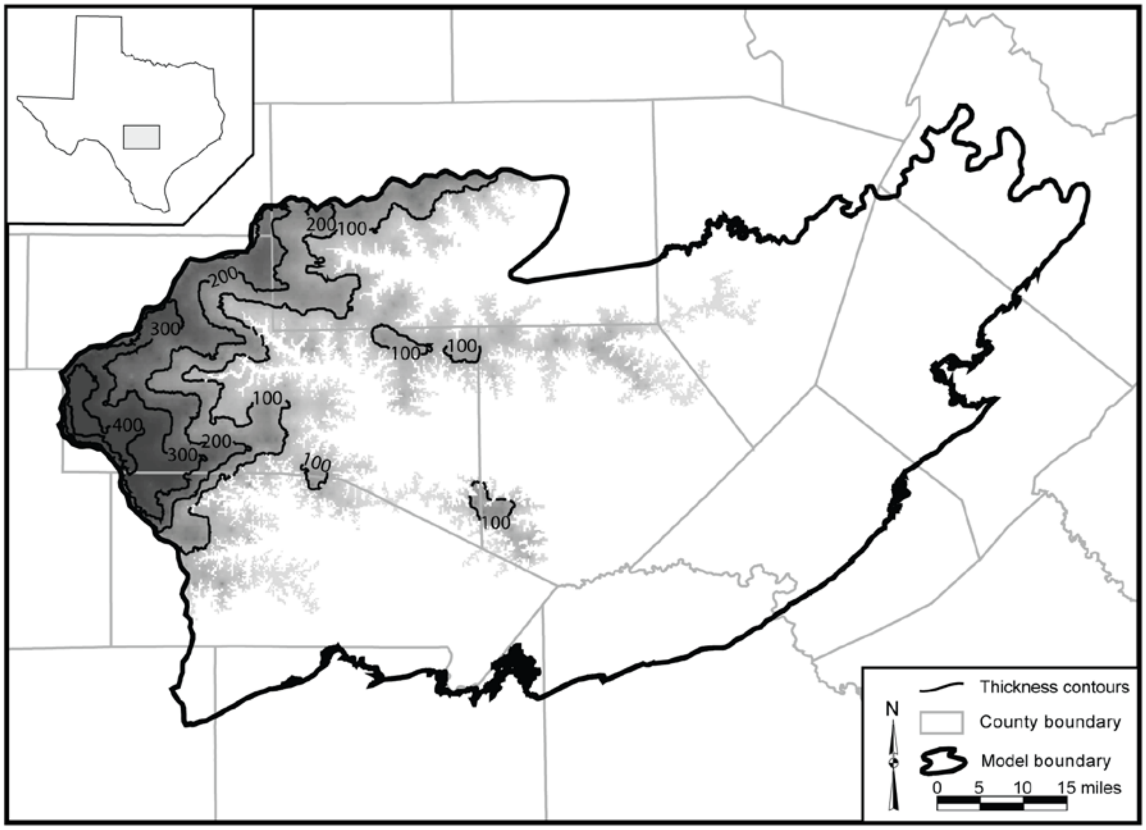


Figure 5-05. The approximate thickness of the Edwards Group in the study area. The contour interval is 100 feet.

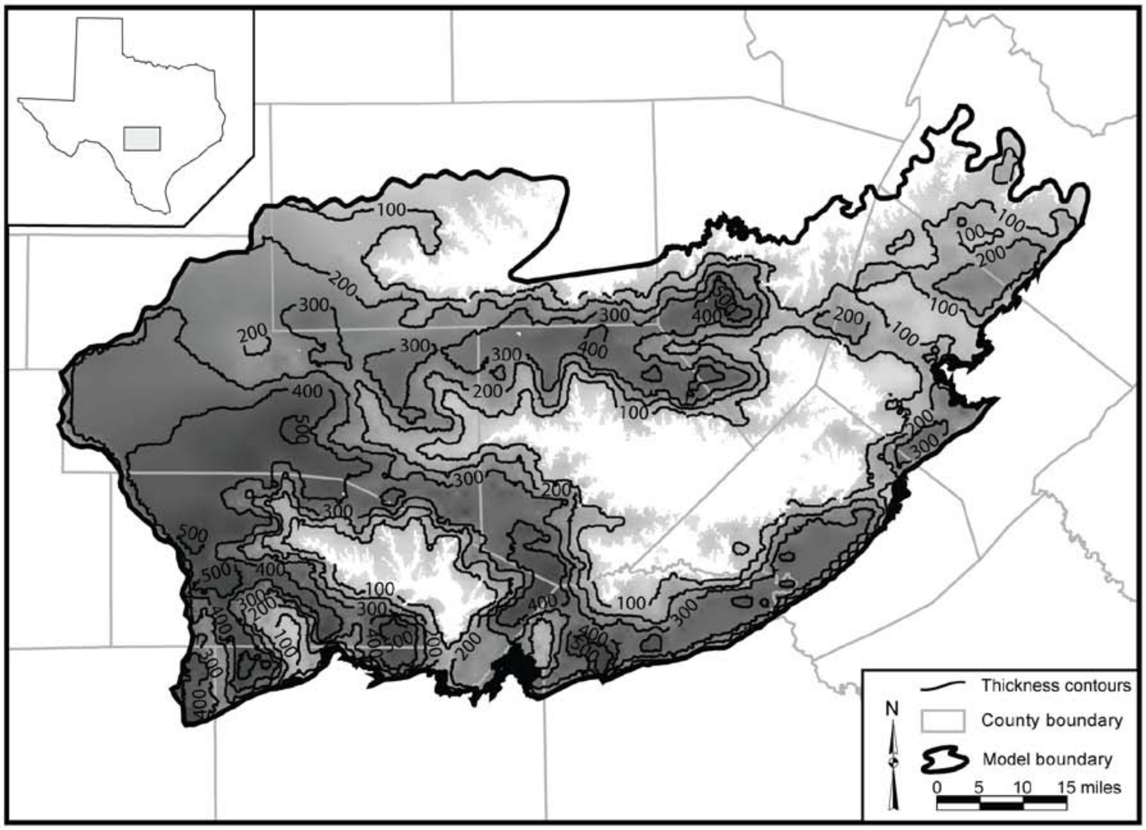


Figure 5-06. The approximate thickness of the Upper Trinity Aquifer in the study area. The contour interval is 100 feet.

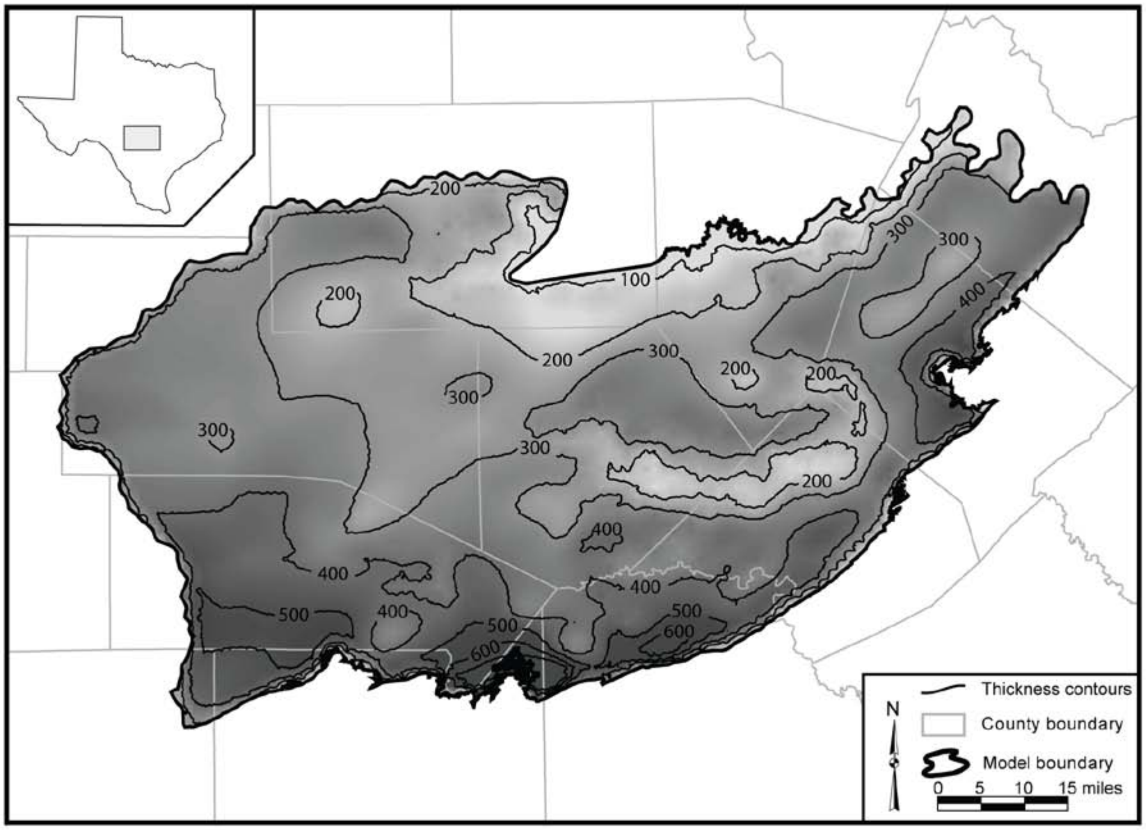


Figure 5-07. The approximate thickness of the Middle Trinity Aquifer in the study area. The contour interval is 100 feet.

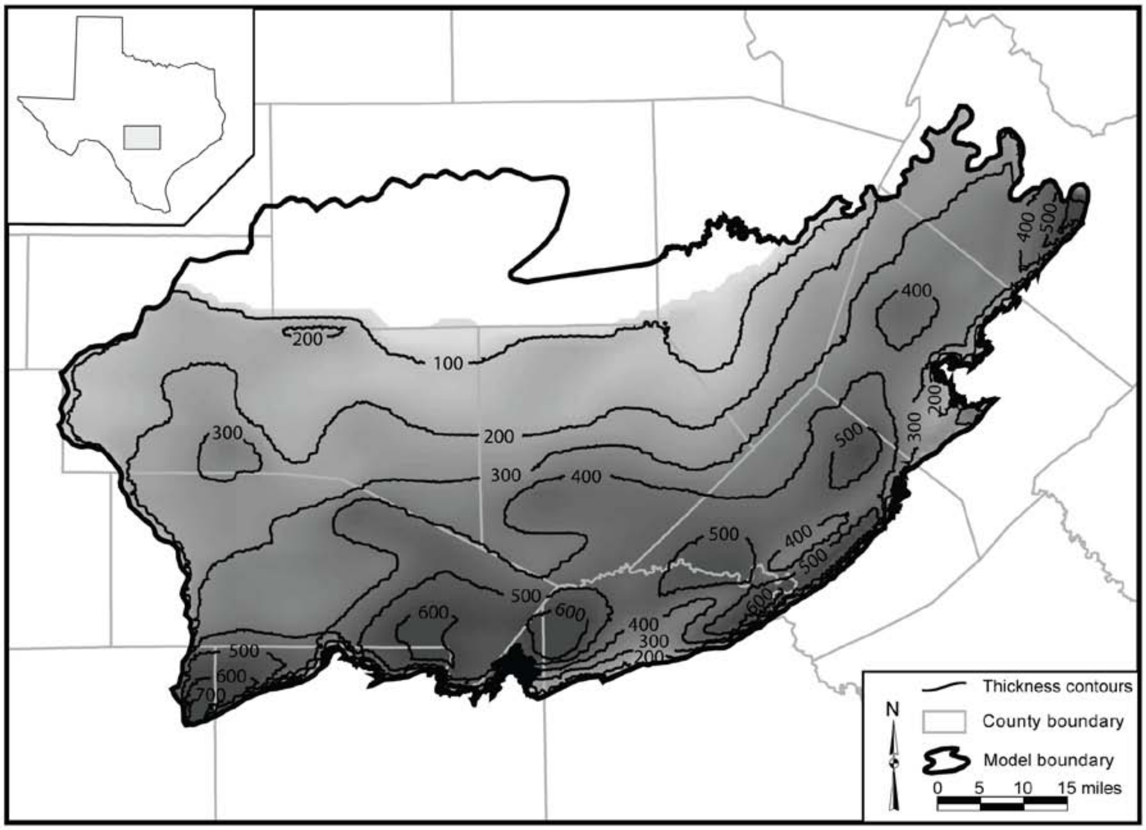


Figure 5-08. The approximate thickness of the Lower Trinity Aquifer in the study area. The contour interval is 100 feet.

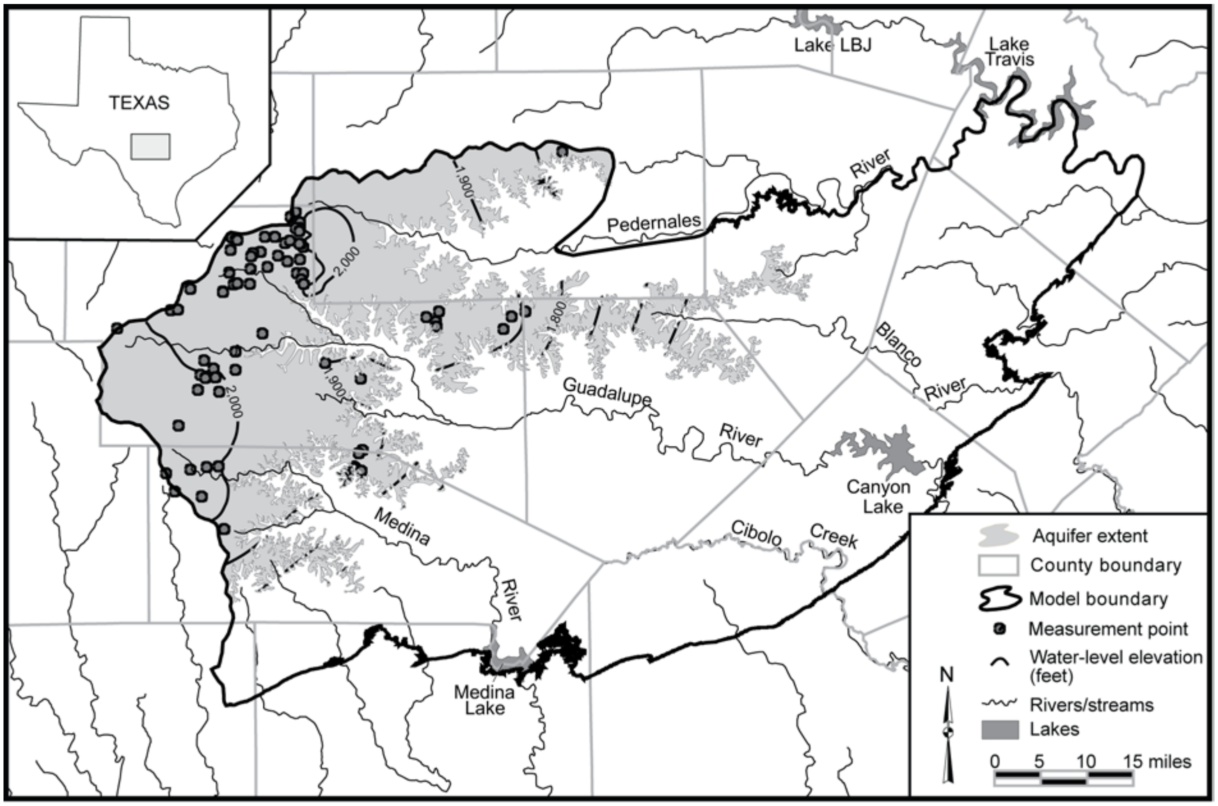


Figure 5-09. Average water-level elevations in the Edwards Group in the study area for the period 1977 through 1985. The contour interval is 100 feet.

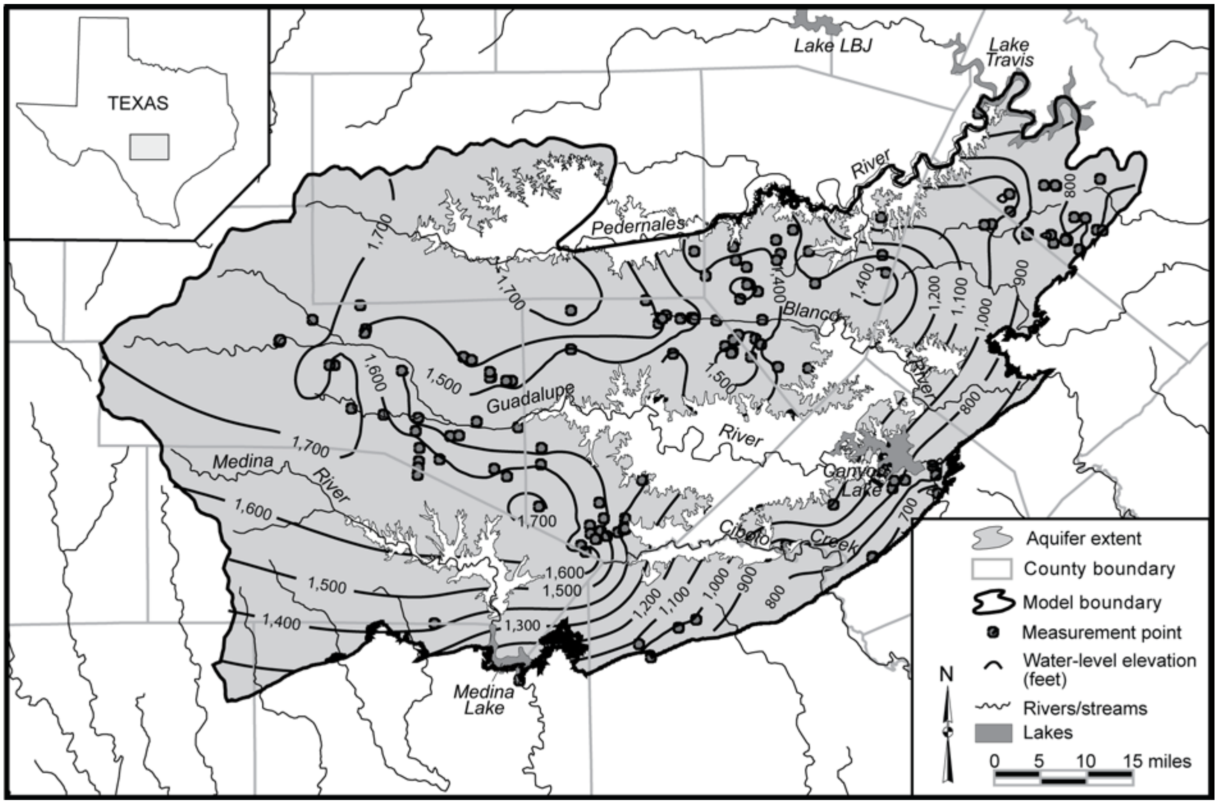


Figure 5-10. Average water-level elevations in the Upper Trinity Aquifer in the study area for the period 1977 through 1985. The contour interval is 100 feet.

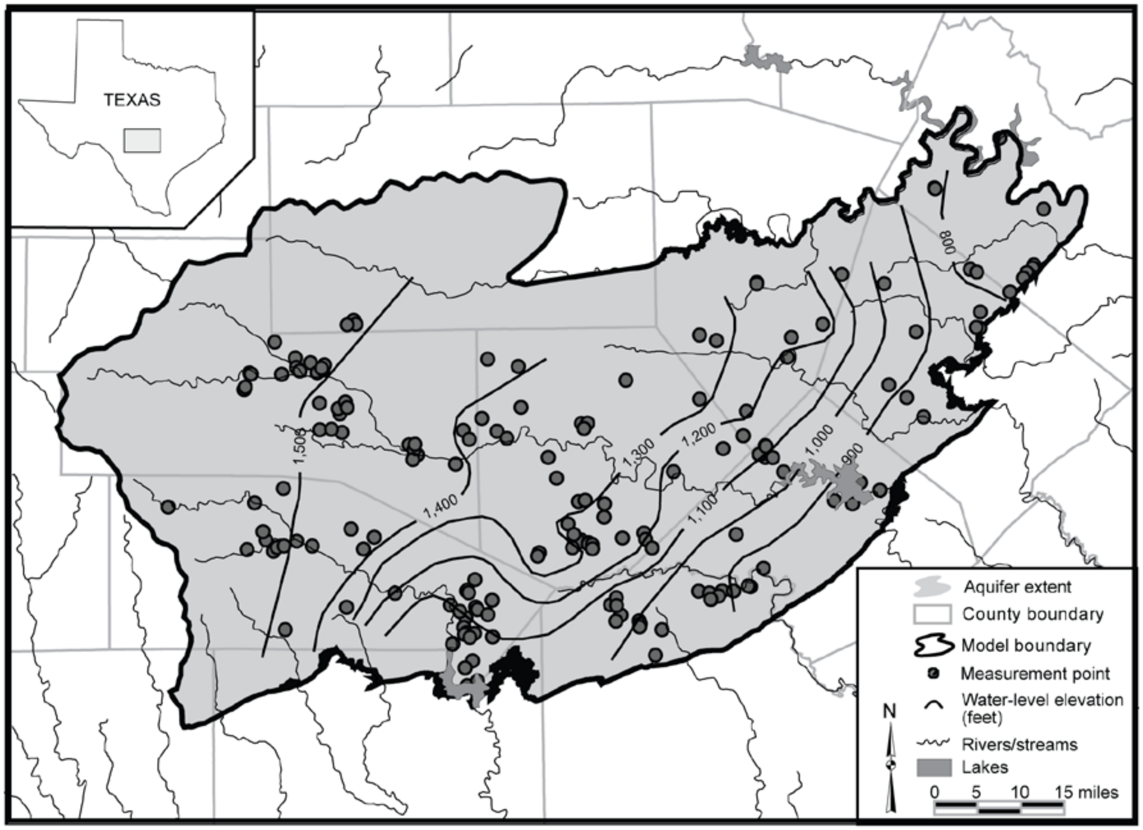


Figure 5-11. Average water-level elevation in the Middle Trinity Aquifer in the study area for the period 1977 through 1985. The contour interval is 100 feet.

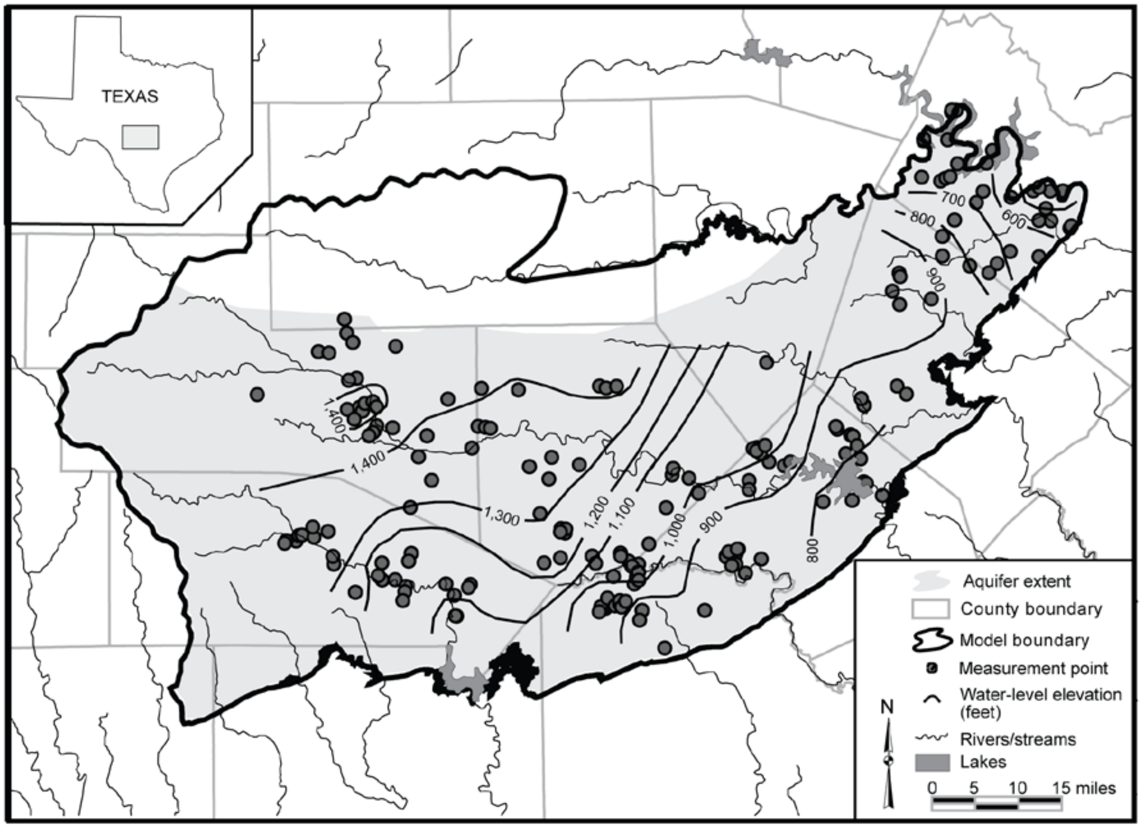


Figure 5-12. Average water-level elevation in the Lower Trinity Aquifer in the study area for the period 1977 through 1985. The contour interval is 100 feet.

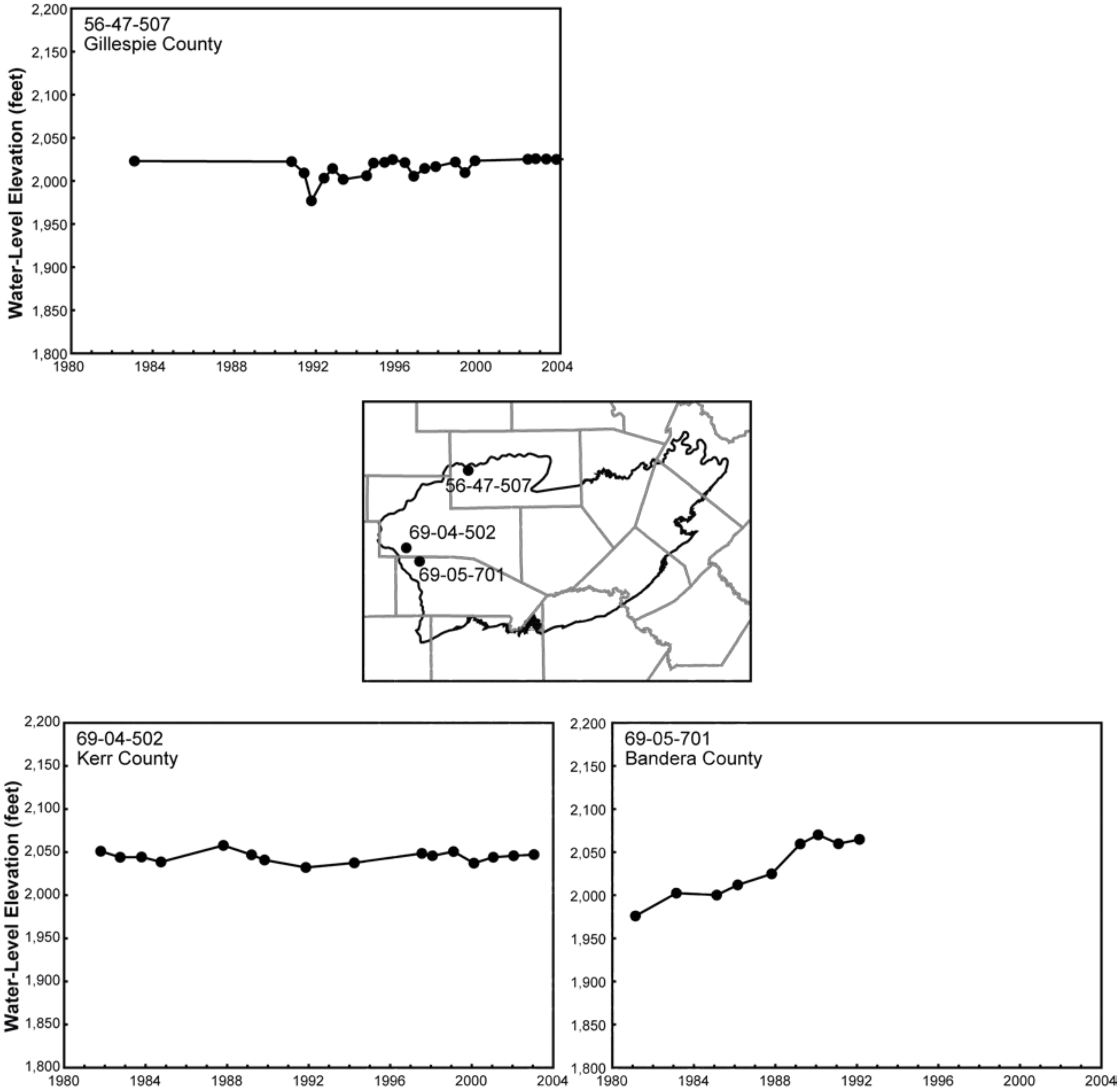


Figure 5-13. Hydrographs from selected Edwards Group wells in the study area.

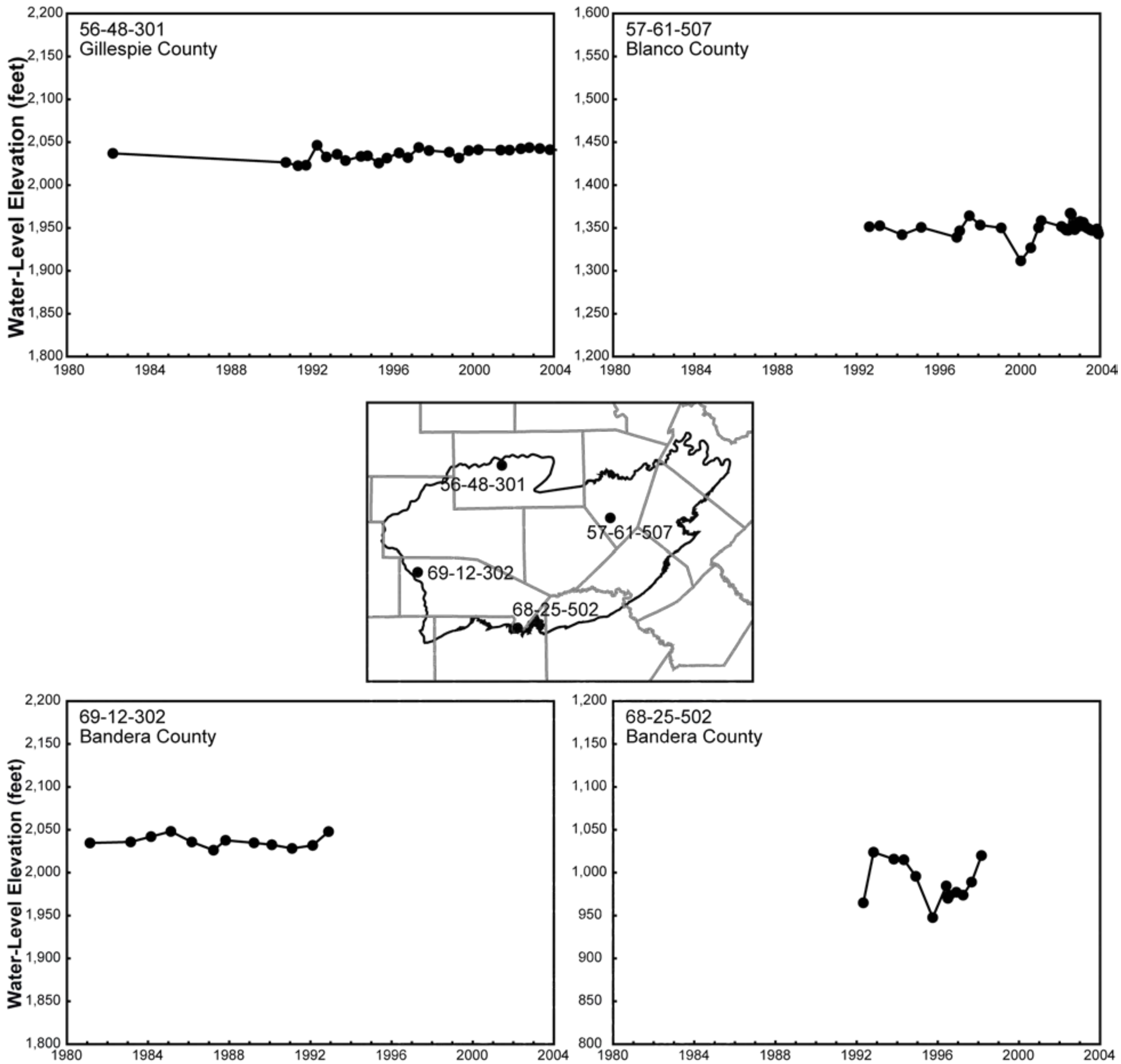


Figure 5-14. Hydrographs from selected Upper Trinity Aquifer wells in the study area.

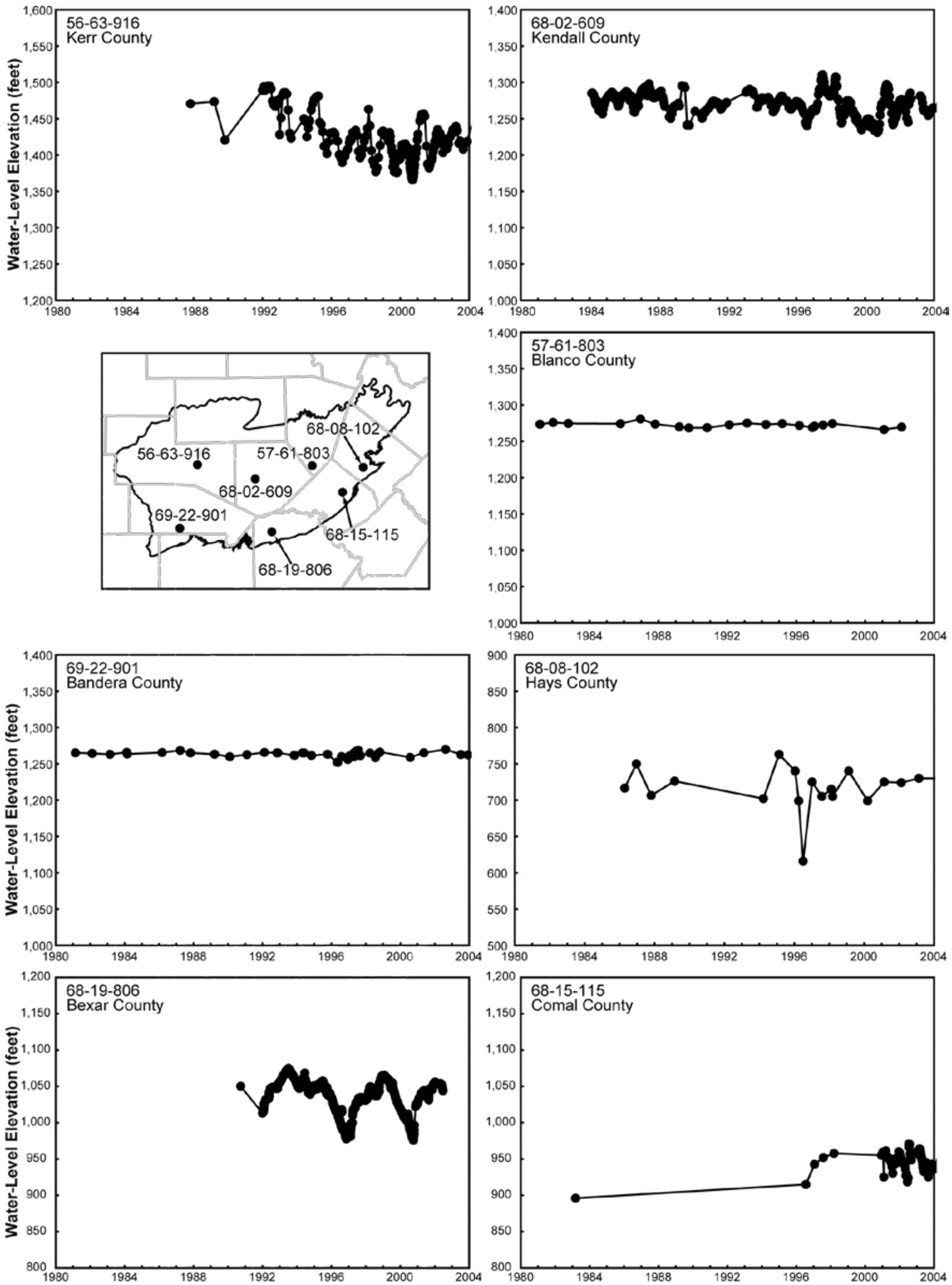


Figure 5-15. Hydrographs from selected Middle Trinity Aquifer wells in the study area.

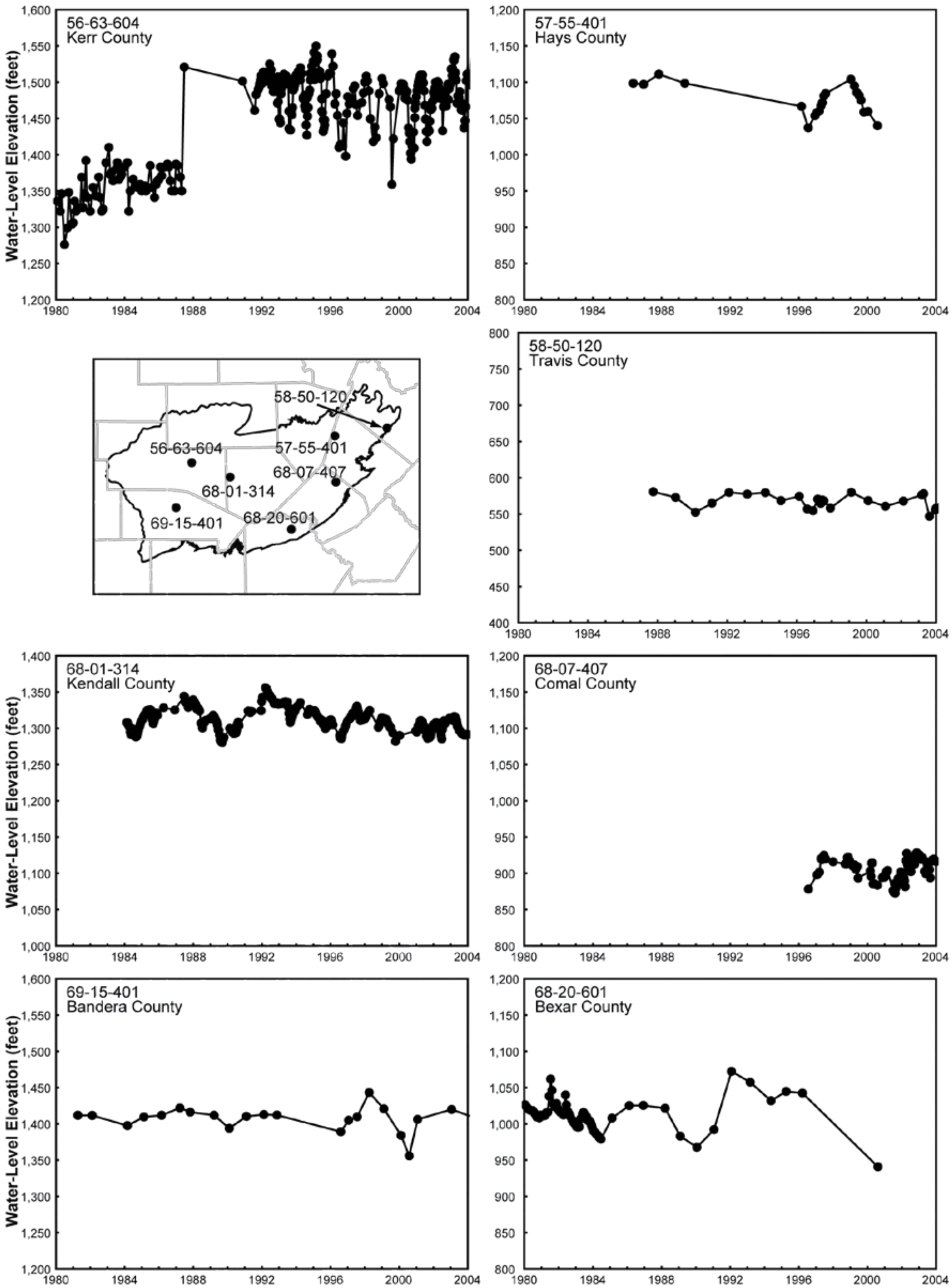


Figure 5-16. Hydrographs from selected Lower Trinity Aquifer wells in the study area.

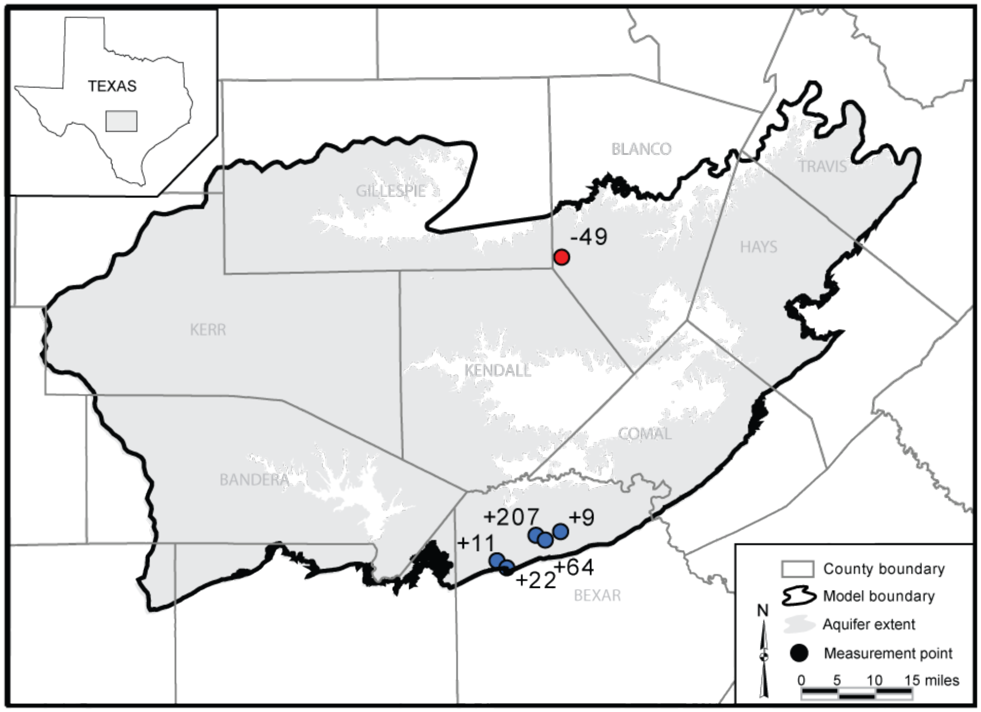


Figure 5-17. Net water-level change in the Upper Trinity Aquifer between 1980 and 1997 at selected well locations. Positive values (blue points) indicate rise in water level and negative values (red points) decline in water levels.

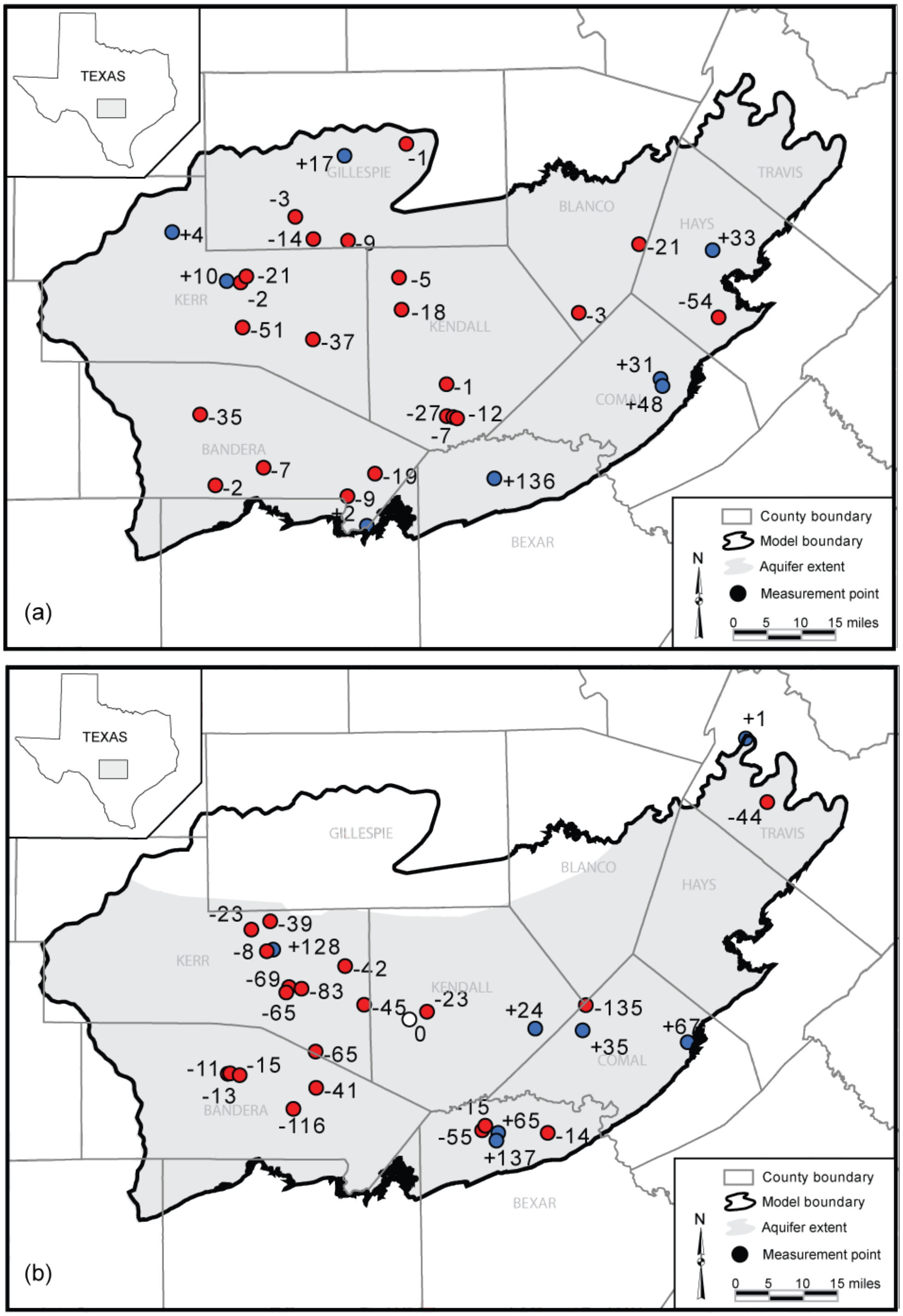


Figure 5-18. Net water-level change in (a) the Middle Trinity Aquifer and (b) Lower Trinity Aquifer between 1980 and 1997 at selected well locations. Positive values (blue points) indicate rise in water level and negative values (red points) decline in water levels.

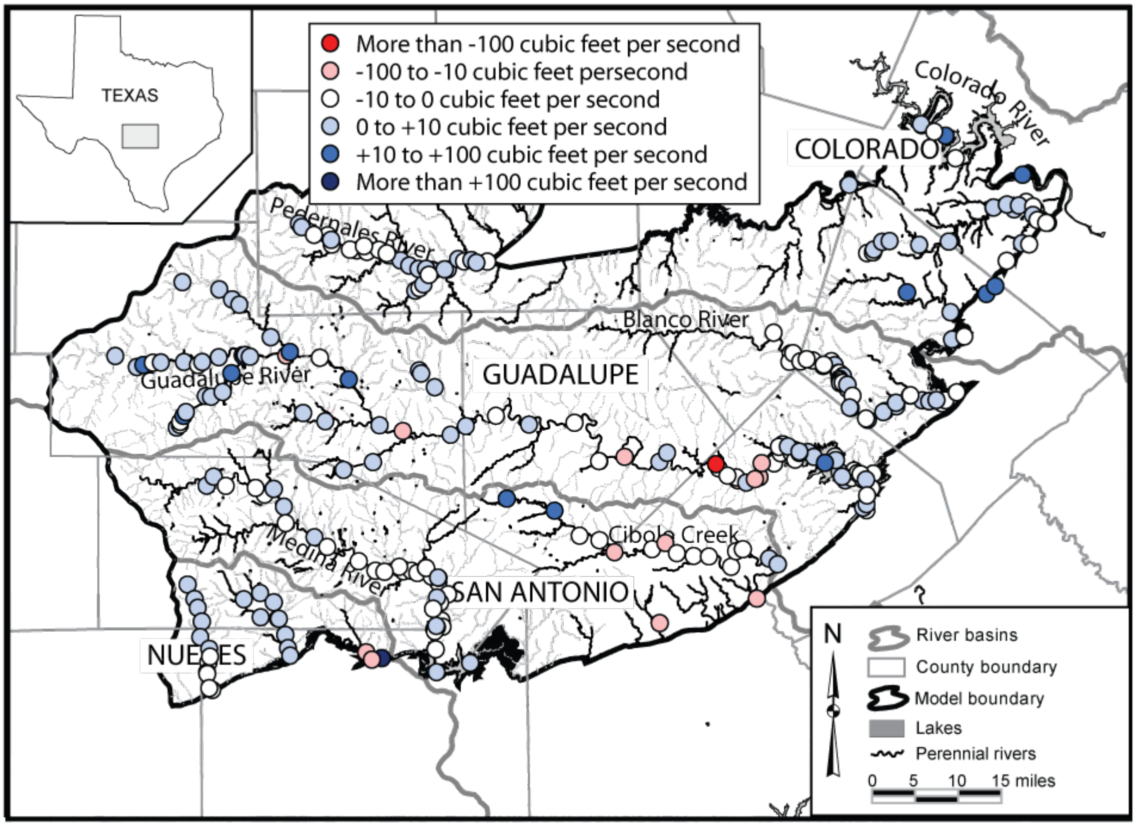


Figure 5-19. Streamflow gain (positive values) and loss (negative values) from Slade and others (2002).

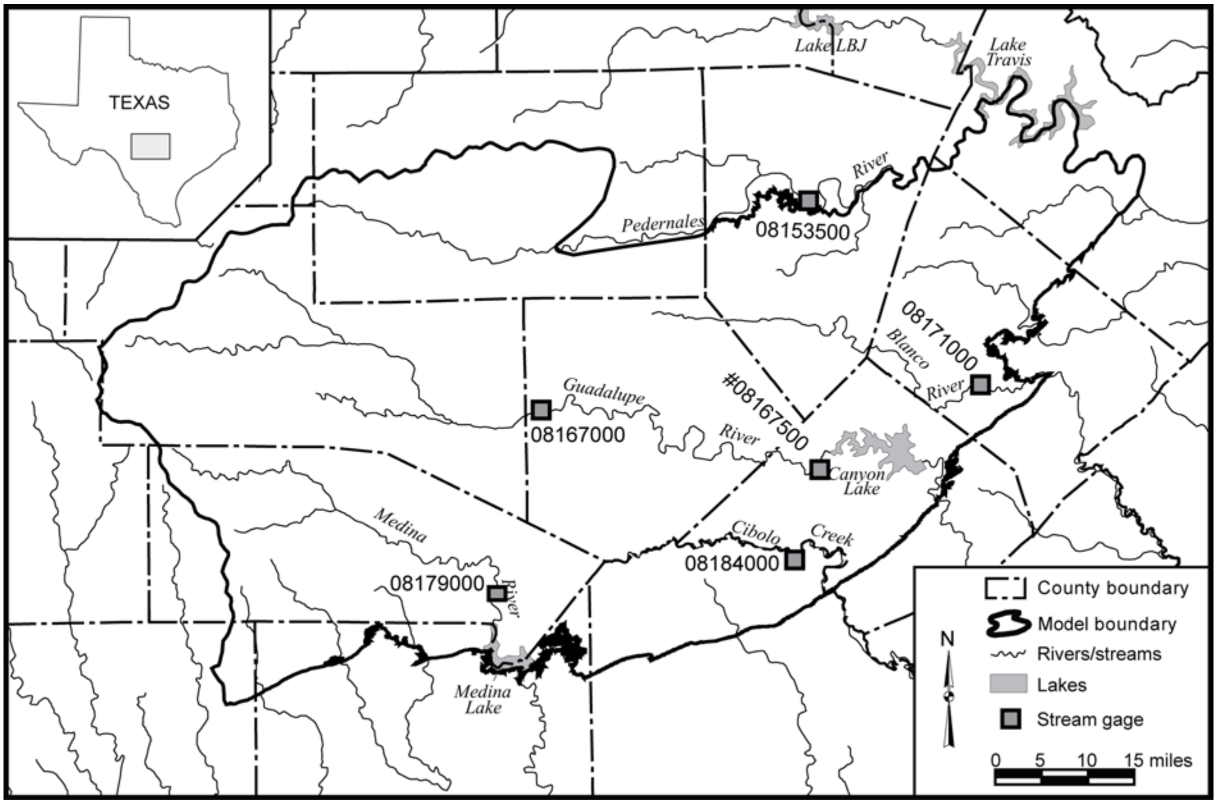


Figure 5-20. Location of stream gauges for the streamflow hydrographs shown in Figures 5-21 through 5-26 (from Mace and others, 2000).

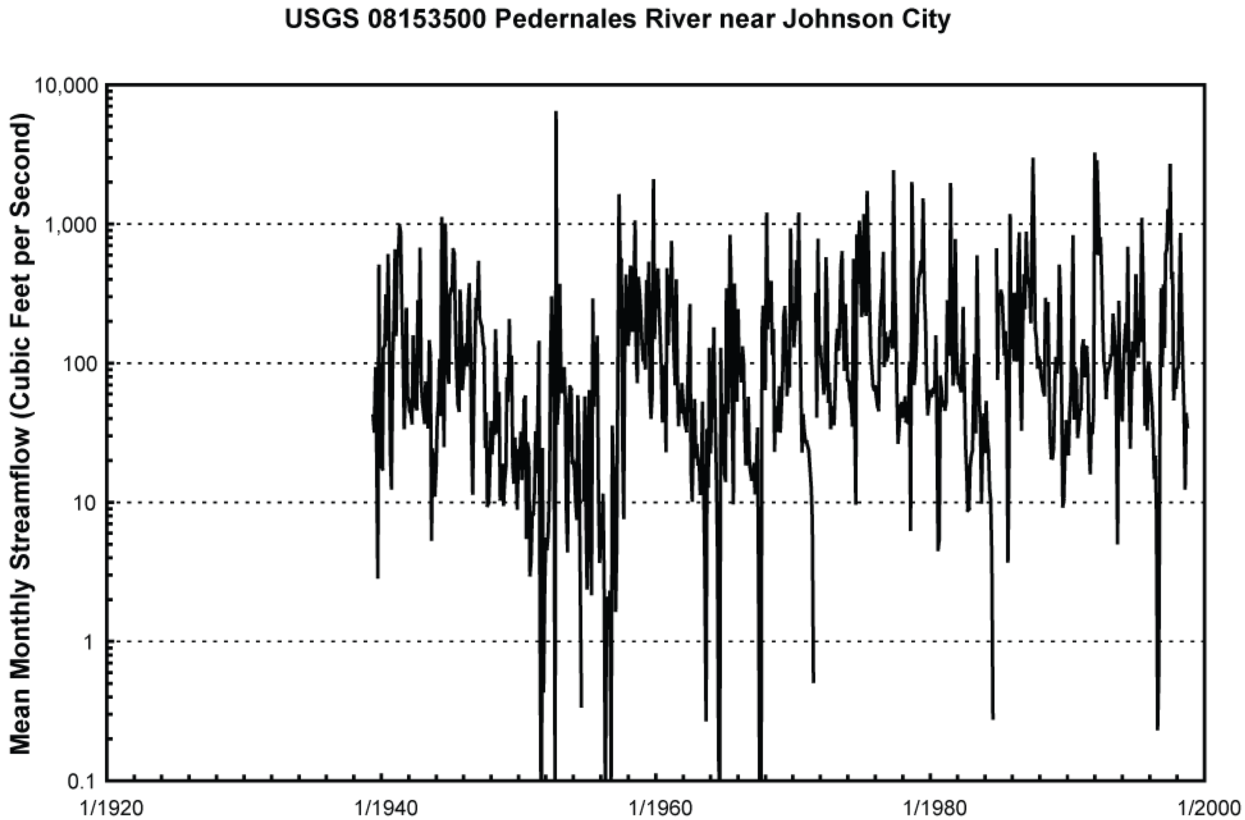


Figure 5-21. Average monthly streamflow for the United States Geological Survey gauging 08153500 on the Pedernales River near Johnson City for (a) linear and (b) logarithmic scales. The station location can be found in Figure 5-29 (from Mace and others, 2000).

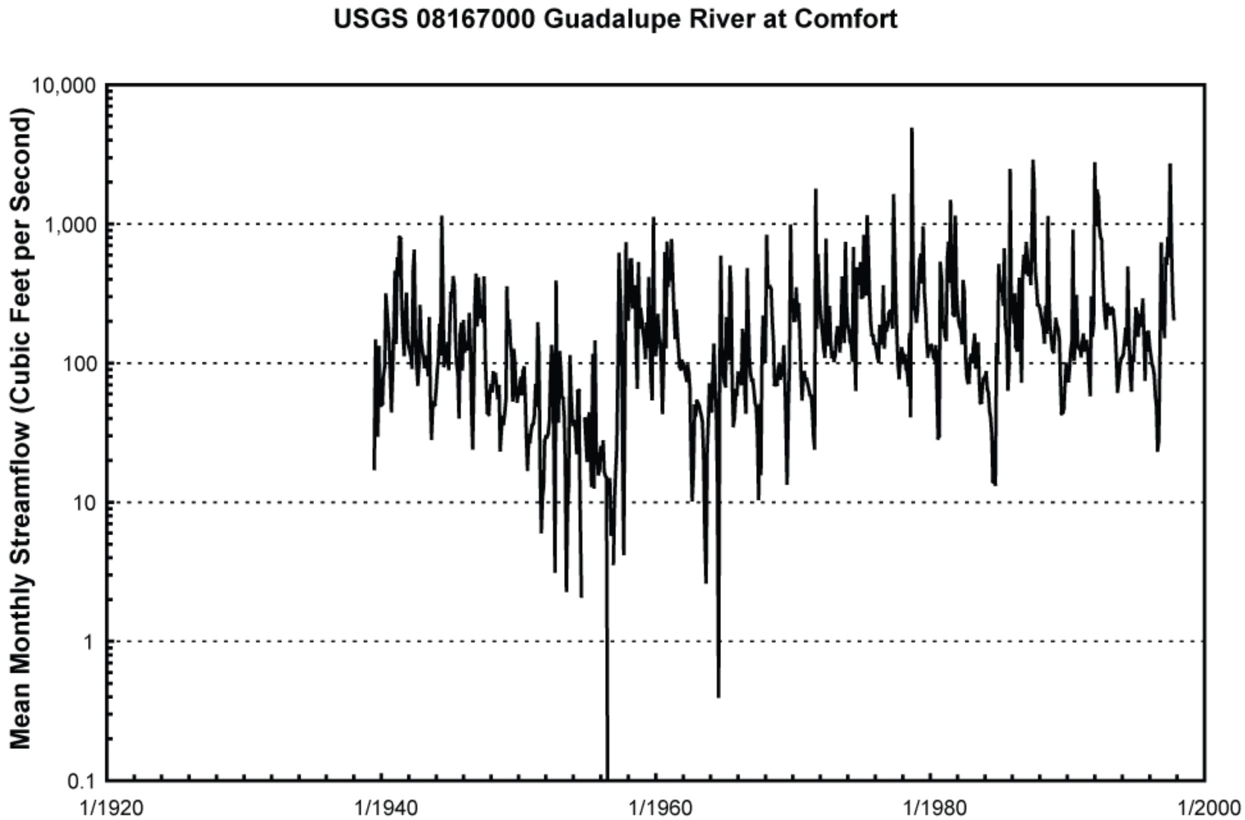


Figure 5-22. Average monthly streamflow for the United States Geological Survey gauging 08167000 on the Guadalupe River at Comfort for (a) linear and (b) logarithmic scales. The station location can be found in Figure 5-29 (from Mace and others, 2000).

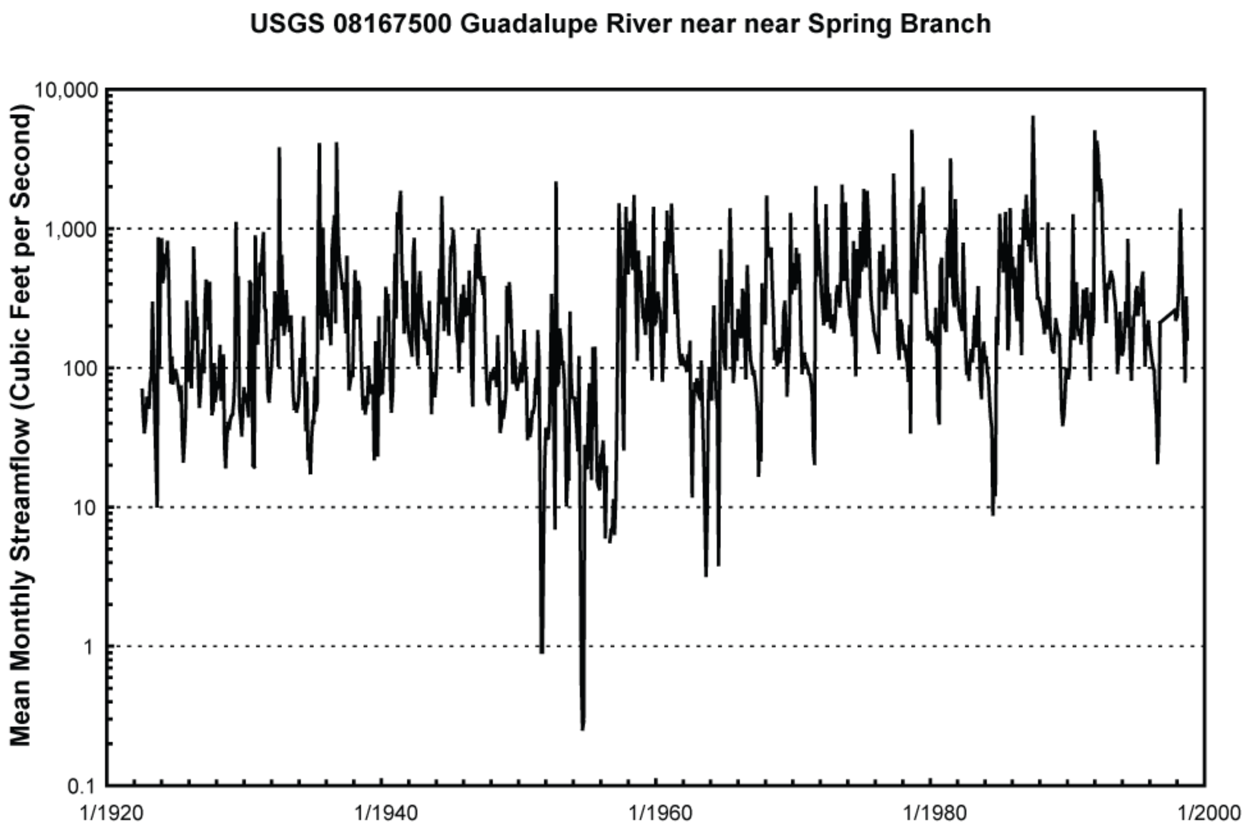


Figure 5-23. Average monthly streamflow for the United States Geological Survey gauging 08167500 on the Guadalupe River near Spring Branch for (a) linear and (b) logarithmic scales. The station location can be found in Figure 5-29 (from Mace and others, 2000).

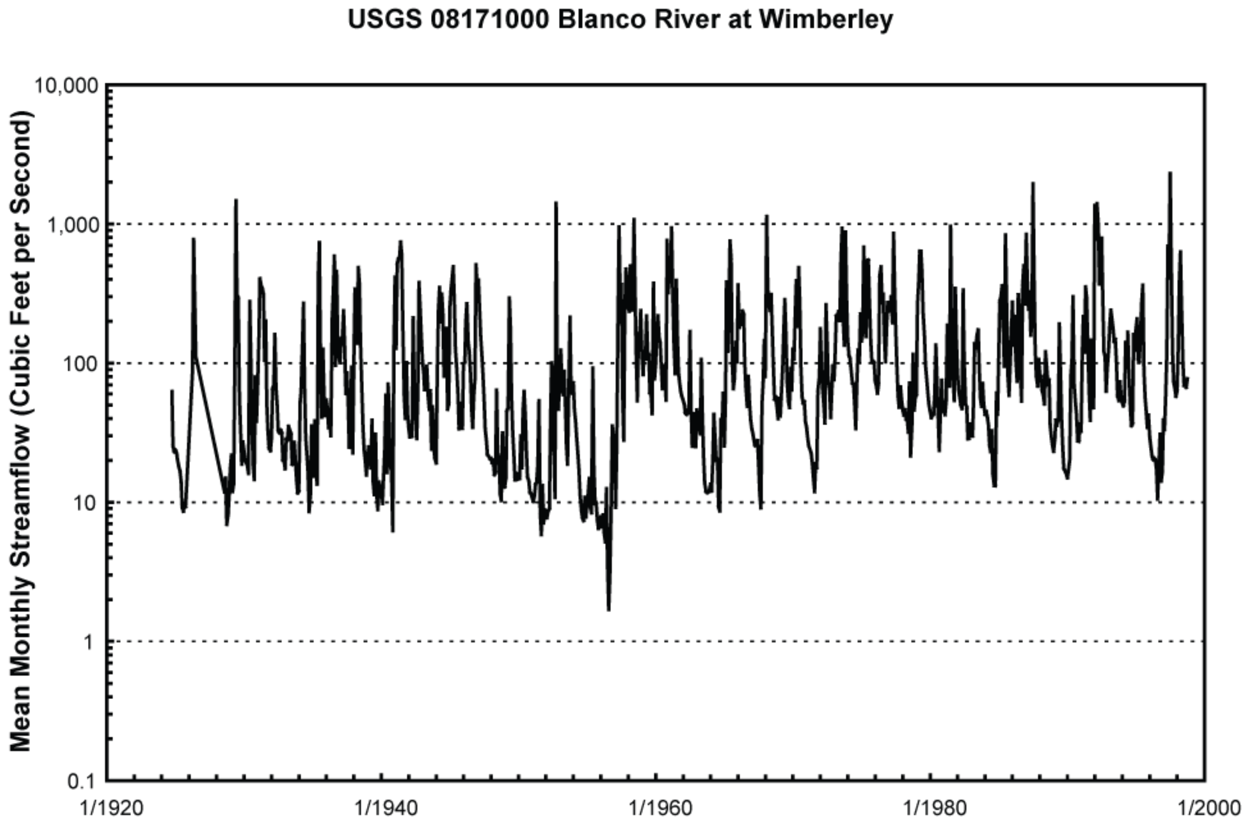


Figure 5-24. Average monthly streamflow for the United States Geological Survey gauging 08171000 on the Blanco River at Wimberley for (a) linear and (b) logarithmic scales. The station location can be found in Figure 5-29 (from Mace and others, 2000).

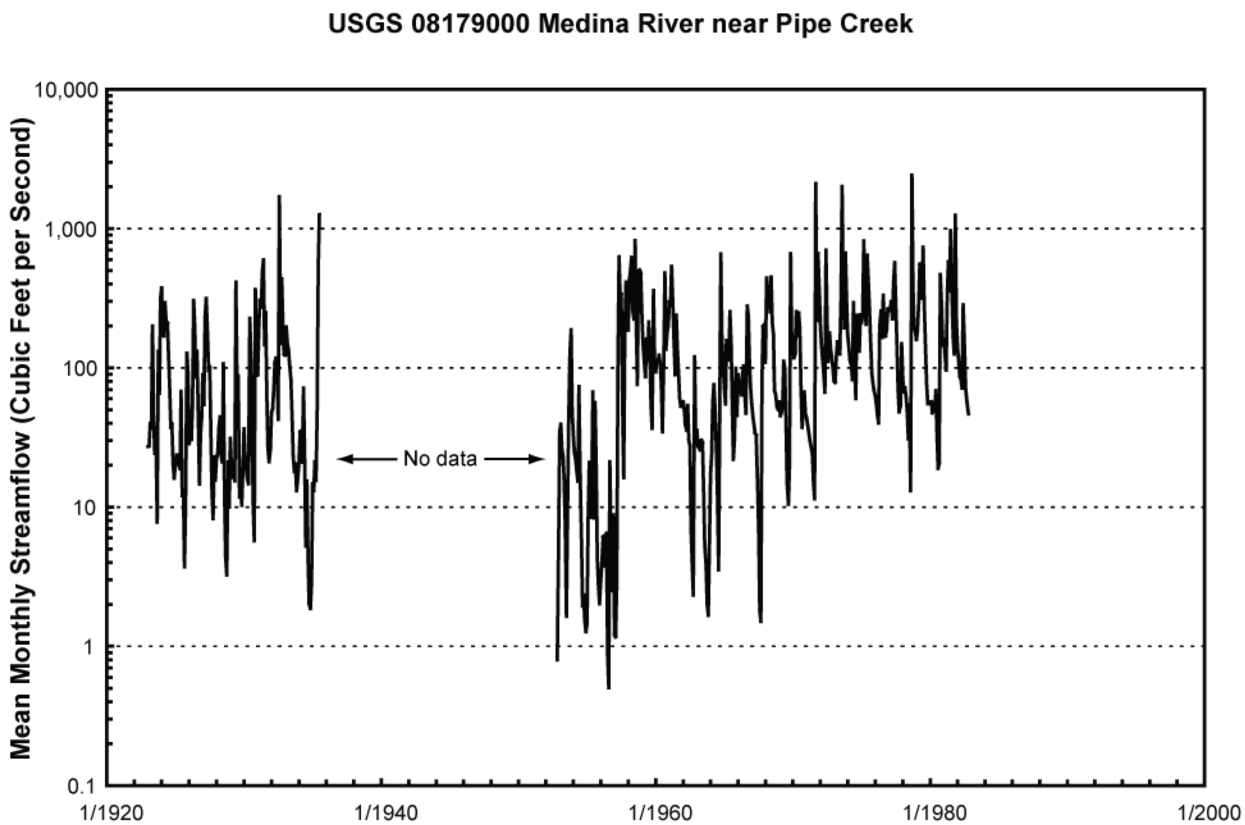


Figure 5-25. Average monthly streamflow for the United States Geological Survey gauging 08179000 on the Medina River near Pipe Creek for (a) linear and (b) logarithmic scales. The station location can be found in Figure 5-29 (from Mace and others, 2000).

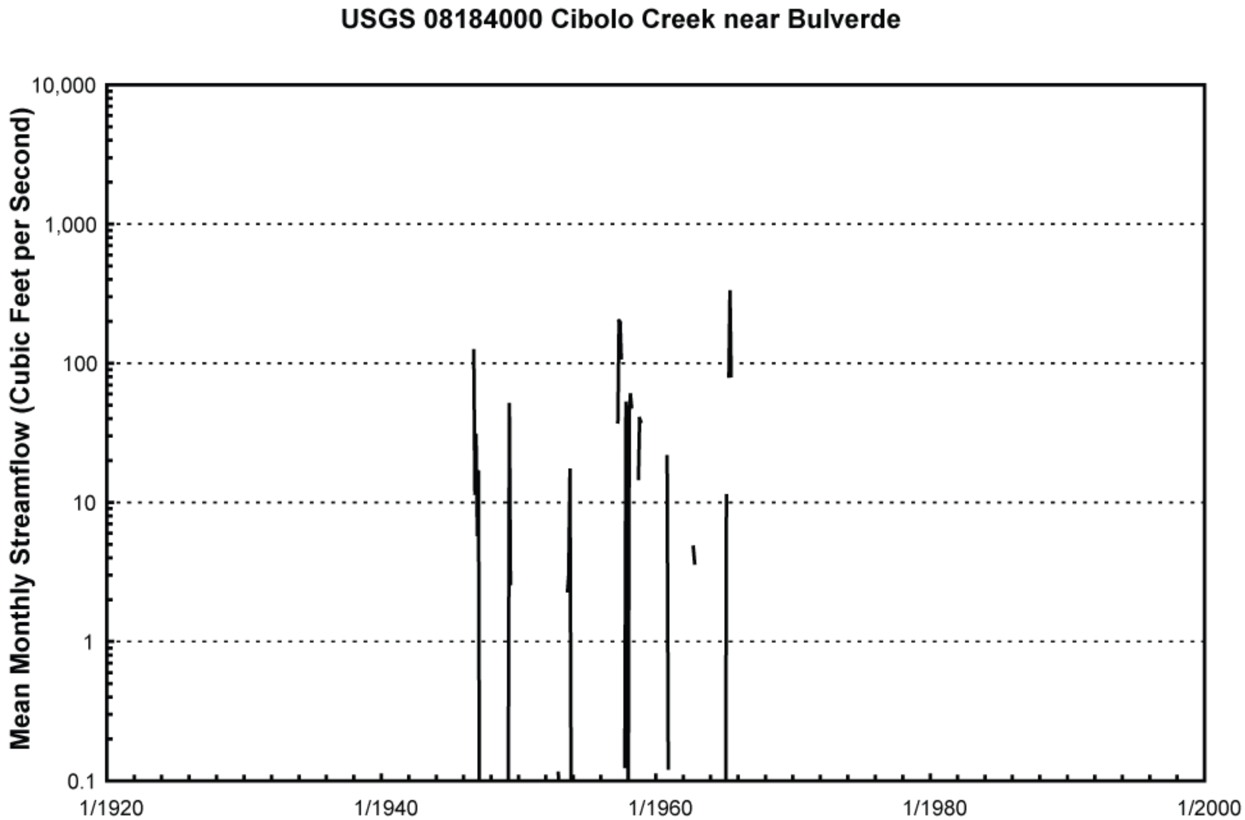


Figure 5-26. Average monthly streamflow for the United States Geological Survey gauging 08184000 on Cibolo Creek near Bulverde for (a) linear and (b) logarithmic scales. The station location can be found in Figure 5-29 (from Mace and others, 2000).

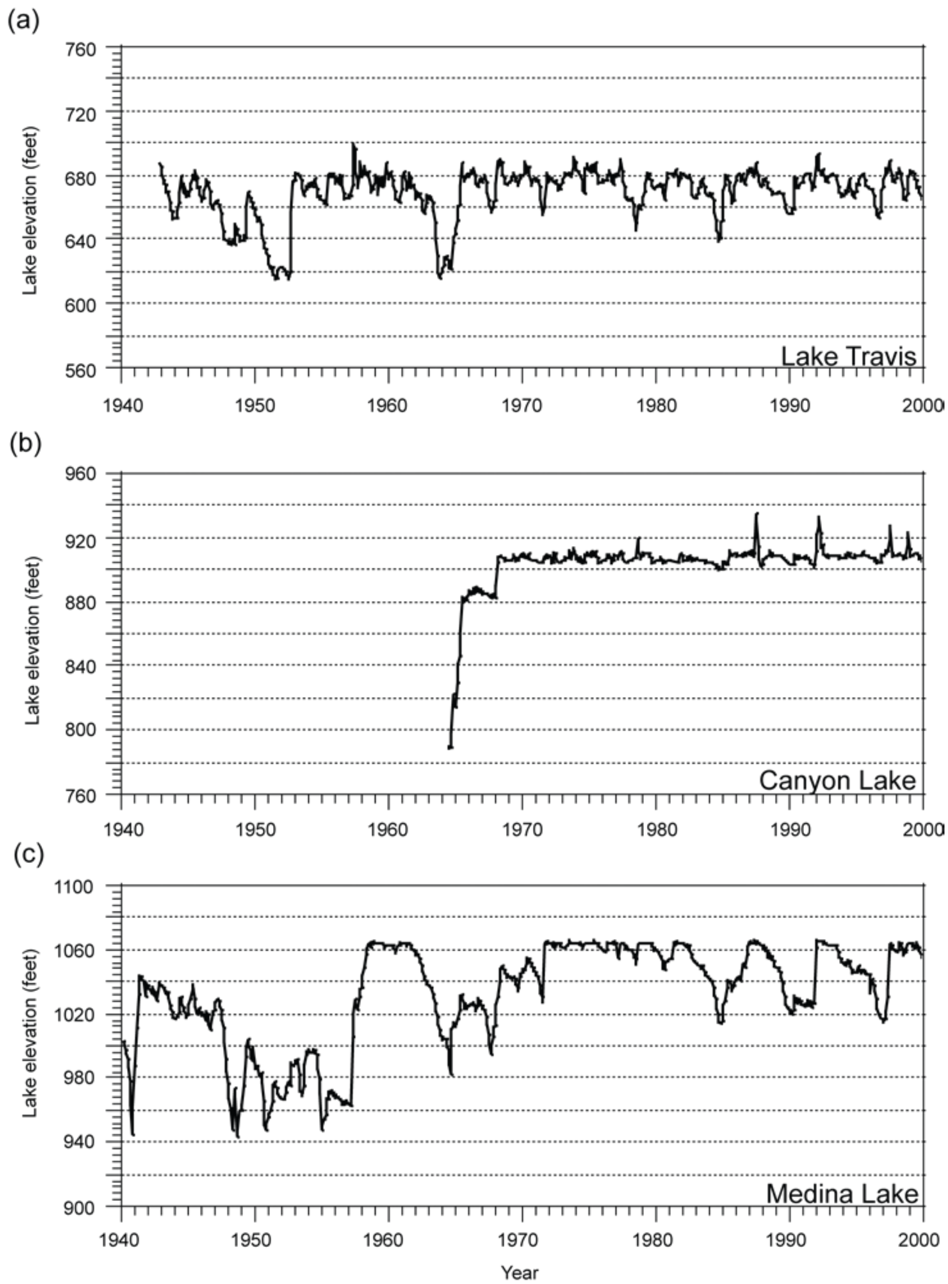


Figure 5-27. Lake-level elevations in (a) Lake Travis, (b) Canyon Lake, and (c) Medina Lake. Lake Travis water levels are from the Lower Colorado River Authority. Canyon Lake water levels are from the U.S. Army Corps of Engineers. Medina Lake water levels for the period 1940 through 1986 are from Espey, Huston, and Associates (1989). Water levels for the periods January 1987 through September 1994 and October 1997 through September 1999 are from the U.S. Geological Survey. Mace and others (2000) calculated lake levels for the period October 1994 through September 1997 by relating lake volumes from a Texas Water Development Board database to lake level using the rating curve by Espey, Huston, and Associates (1989).

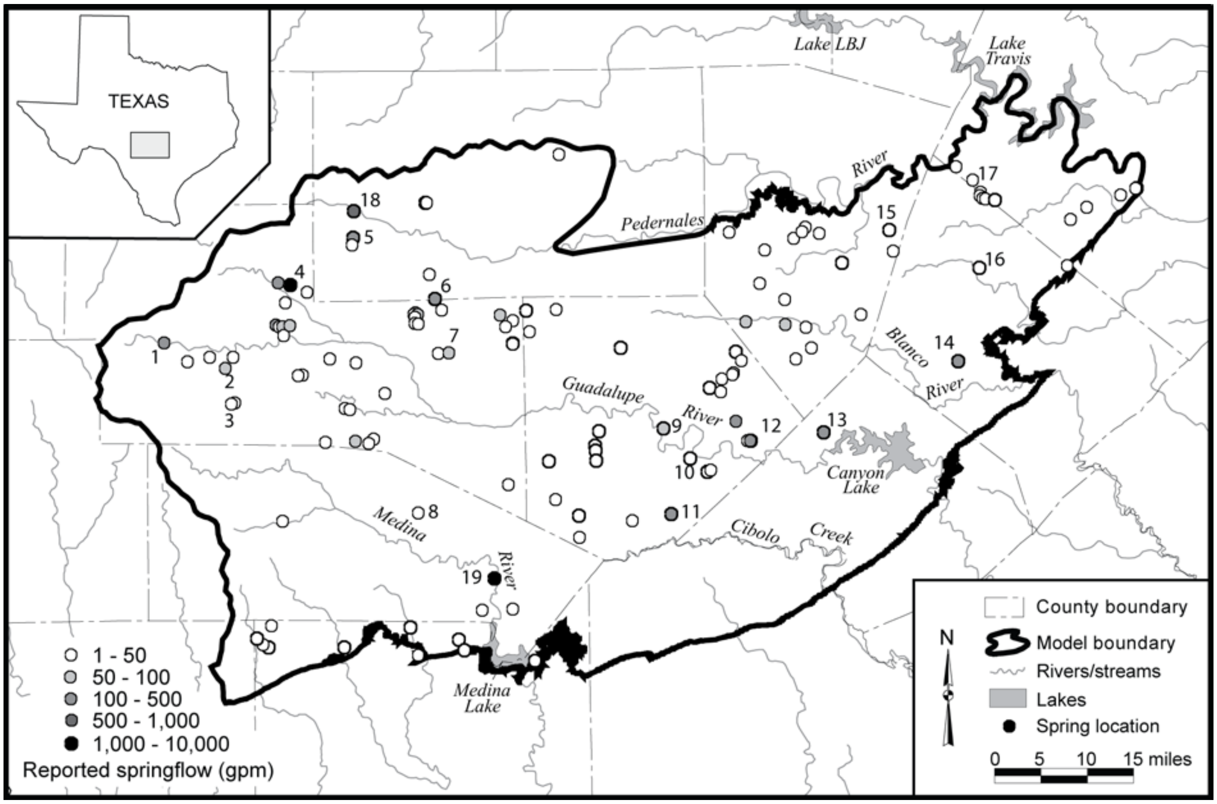
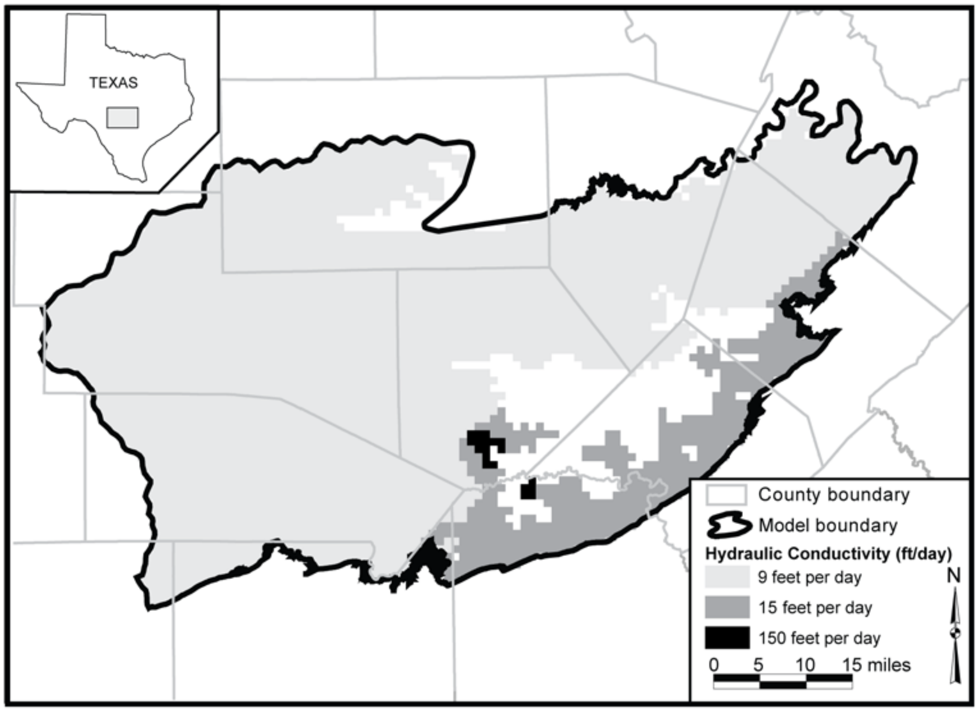
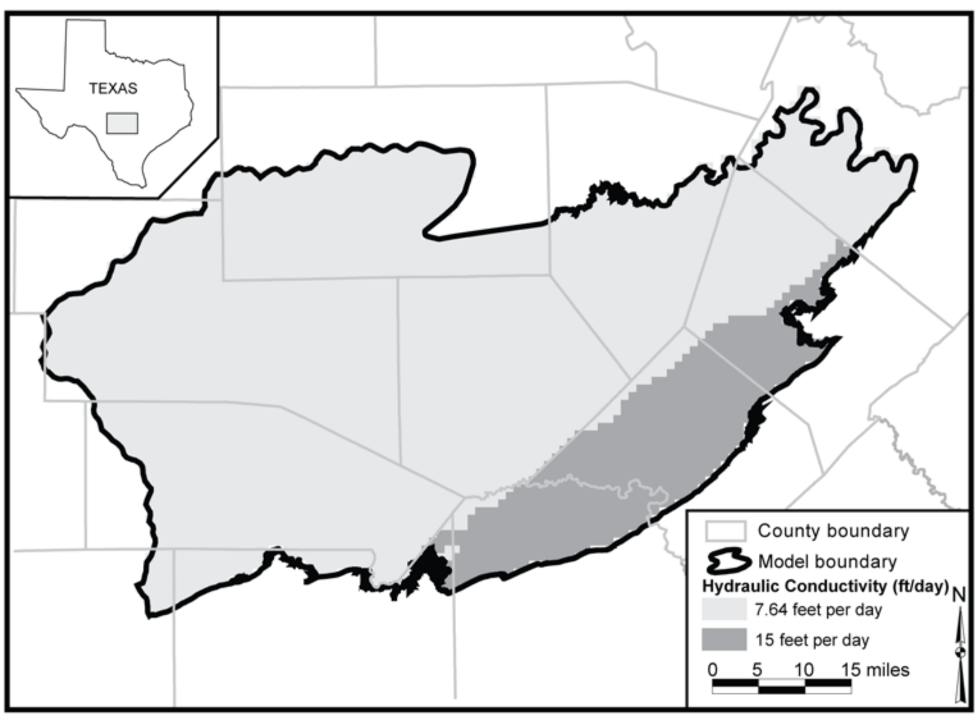


Figure 5-28. Location and estimated spring discharge in the study area. Springflow and geological formations where the numbered springs occur are included in Table 5-02 (from Mace and others, 2000).

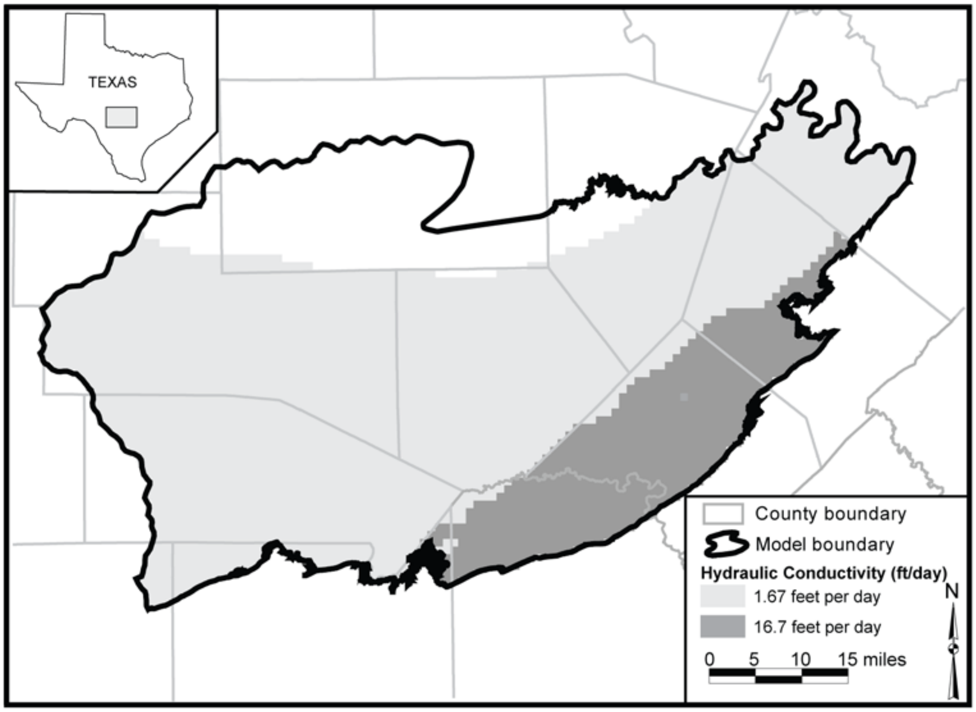


(a) Upper Trinity Aquifer



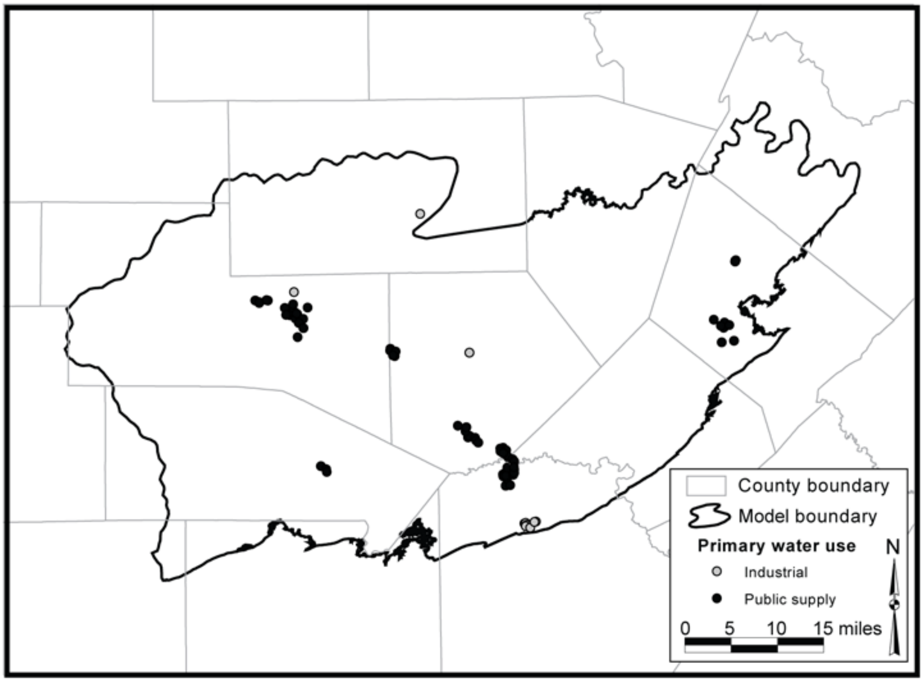
(b) Middle Trinity Aquifer

Figure 5-29. Distribution of hydraulic conductivity in the Upper, Middle, and Lower Trinity aquifers.

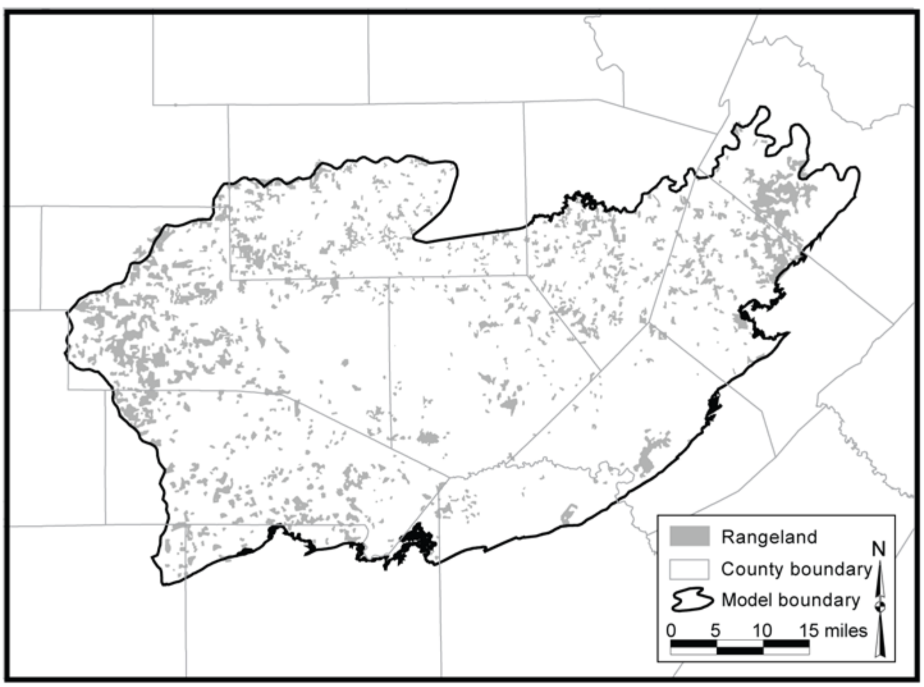


(c) Lower Trinity Aquifer

Figure 5-29. (Cont.)

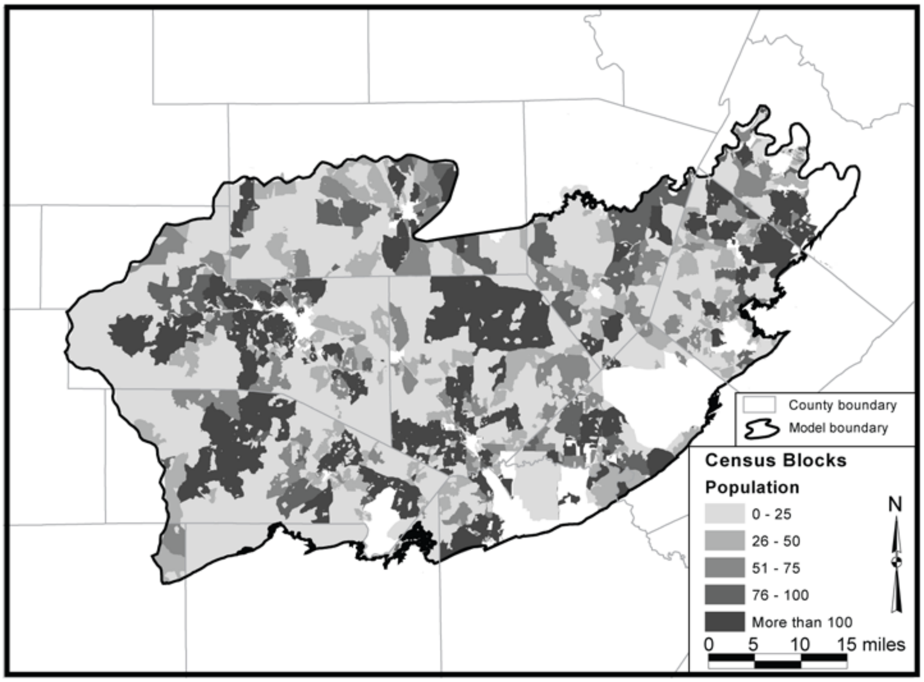


(a) Industrial and public supply wells

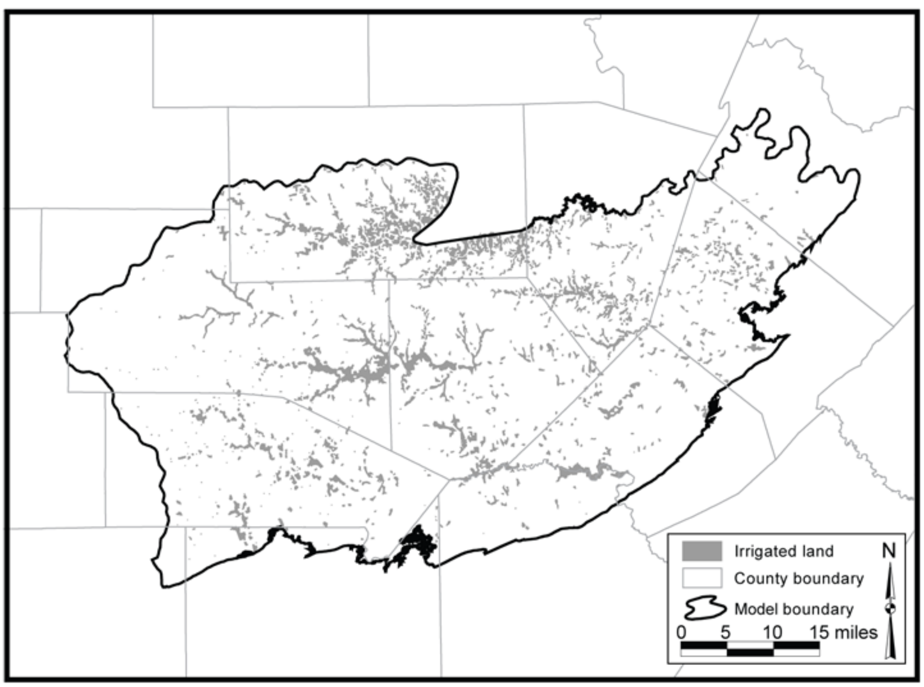


(b) Rangeland

Figure 5-30. The spatial distribution of pumping throughout the 1980 through 1997 model period for manufacturing, municipal, livestock, rural domestic, and irrigation uses are based on the spatial distribution of (a) industrial and public supply wells, (b) rangeland, (c) rural population, and (d) irrigated farmland, respectively.

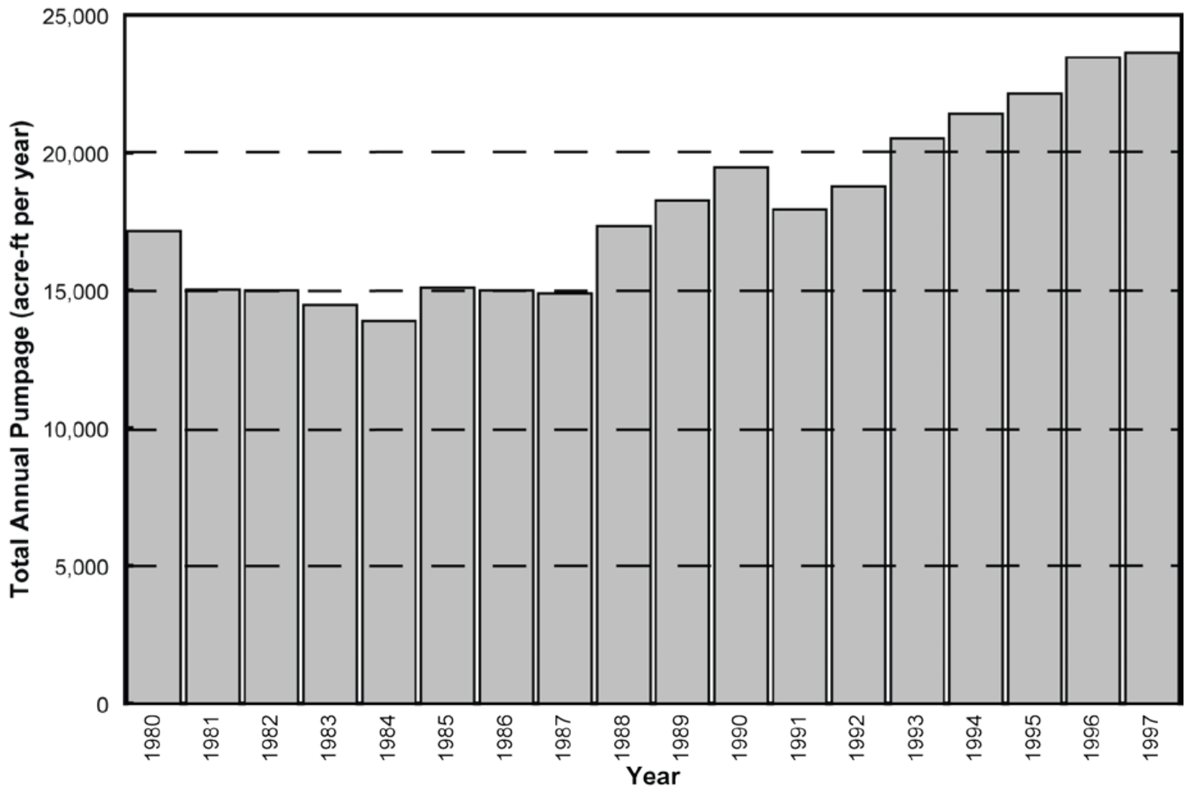


(c) Rural population distribution



(d) Irrigated land

Figure 5-30. (Cont.)



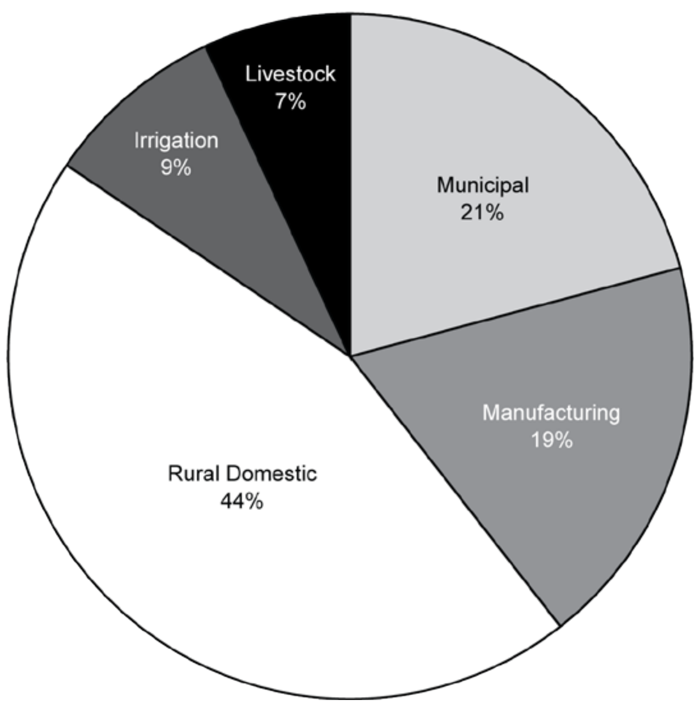


Figure 5-31. Total annual groundwater pumping from the Hill Country portion of the Trinity Aquifer System, 1980 through 1997.

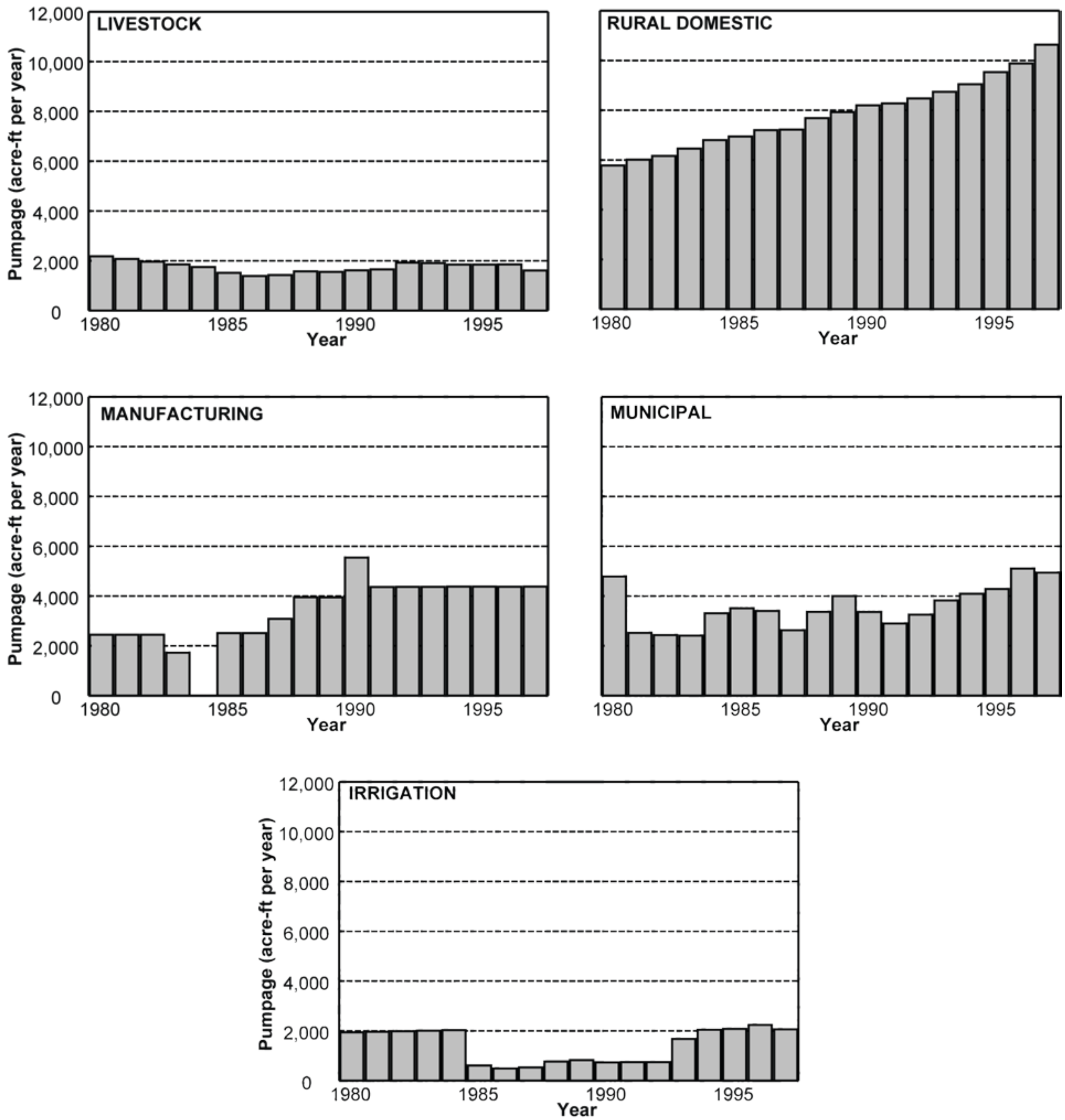


Figure 5-32. Annual groundwater pumping from the Hill Country portion of the Trinity Aquifer System for livestock, rural domestic, manufacturing, municipal, and irrigation uses, 1980 through 1997.

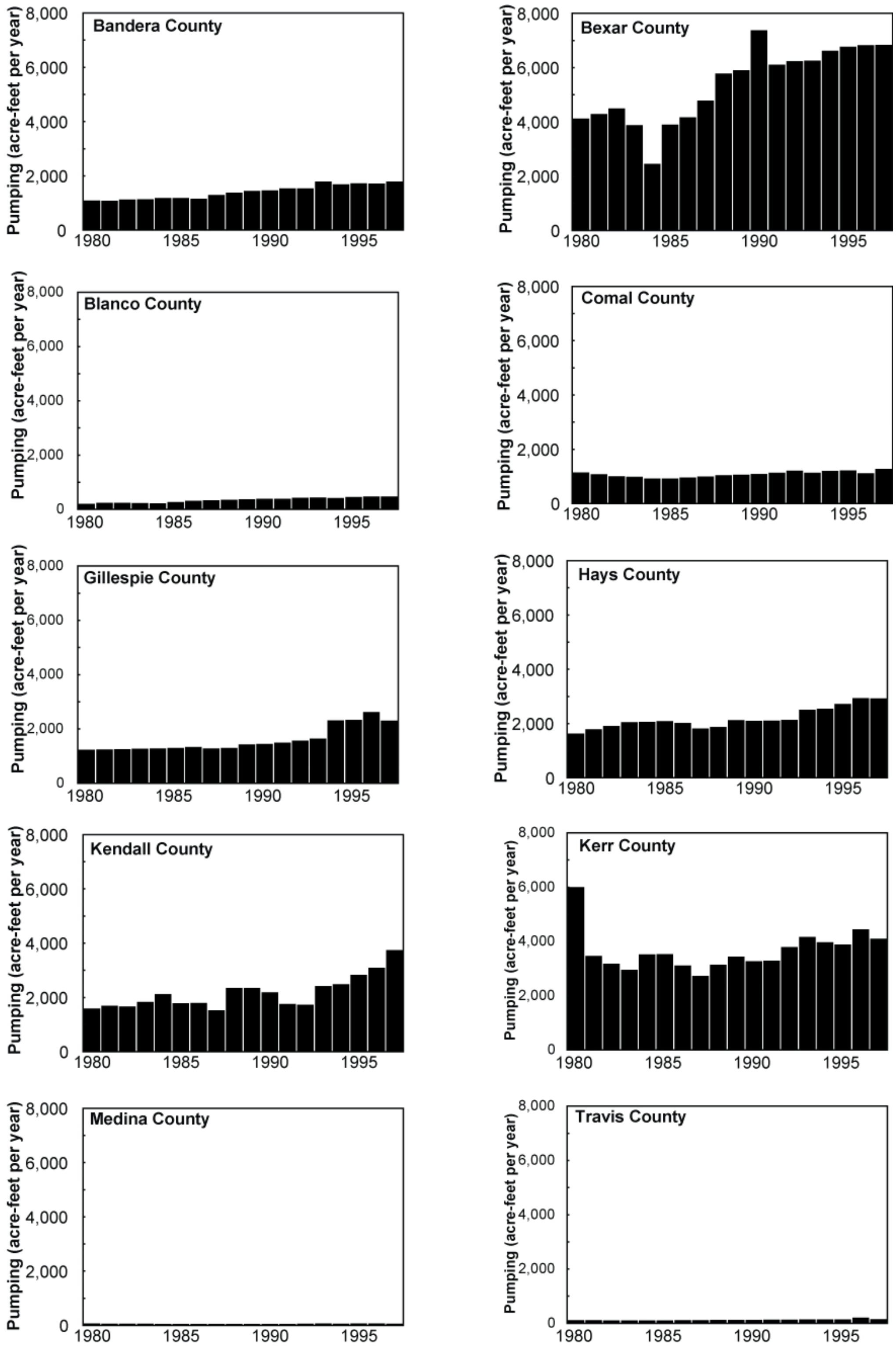


Figure 5-33. Total annual pumping from the Hill Country portion of the Trinity Aquifer System for each county in the study area.

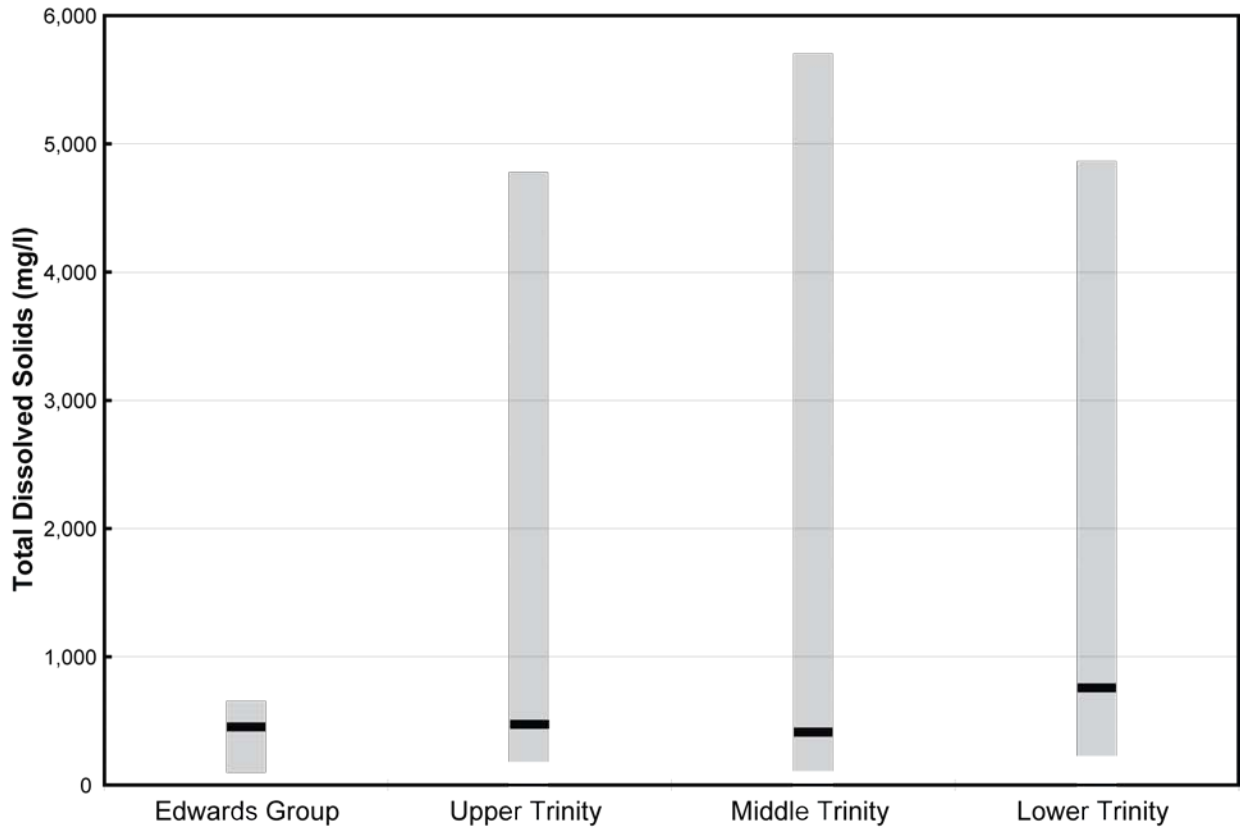


Figure 5-34. The ranges of total dissolved solids found in groundwater in the Edwards Group, and the Upper, Middle, and Lower Trinity aquifers. The black line indicates the median value for each aquifer.

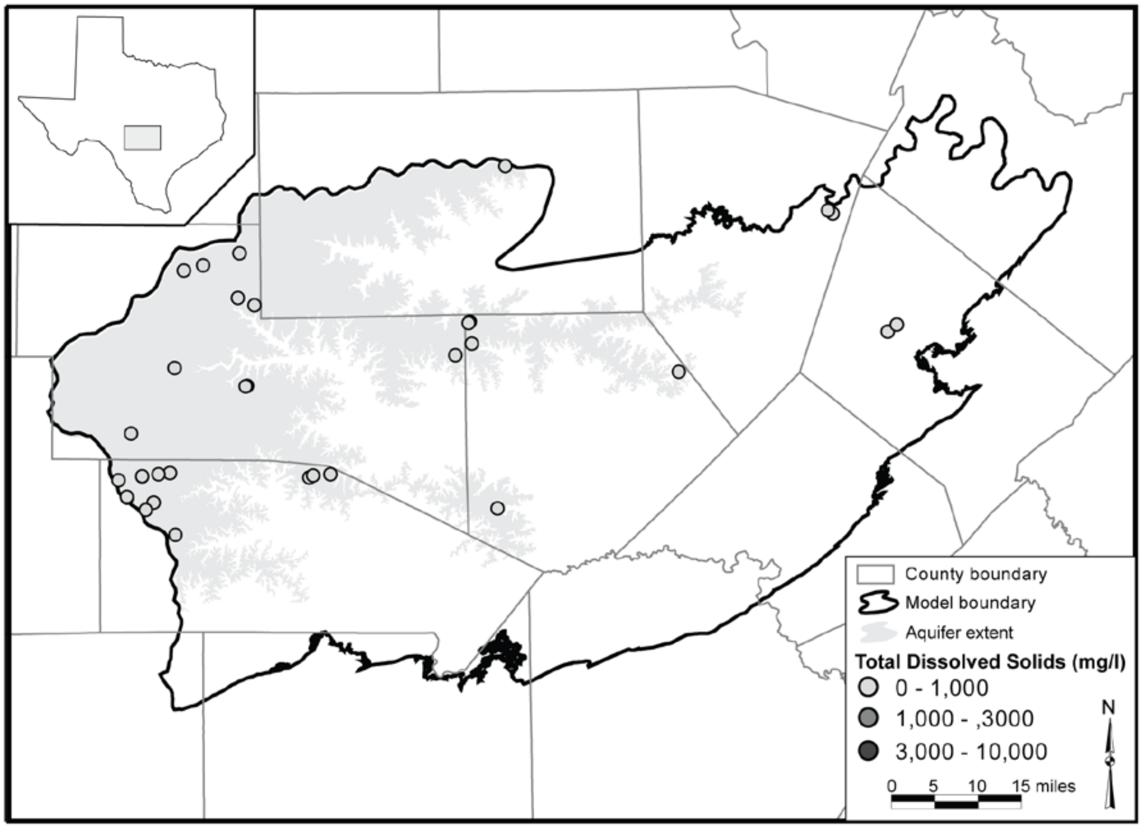


Figure 5-35. Map of total dissolved solids in the Edwards Group. mg/l = milligrams per liter.

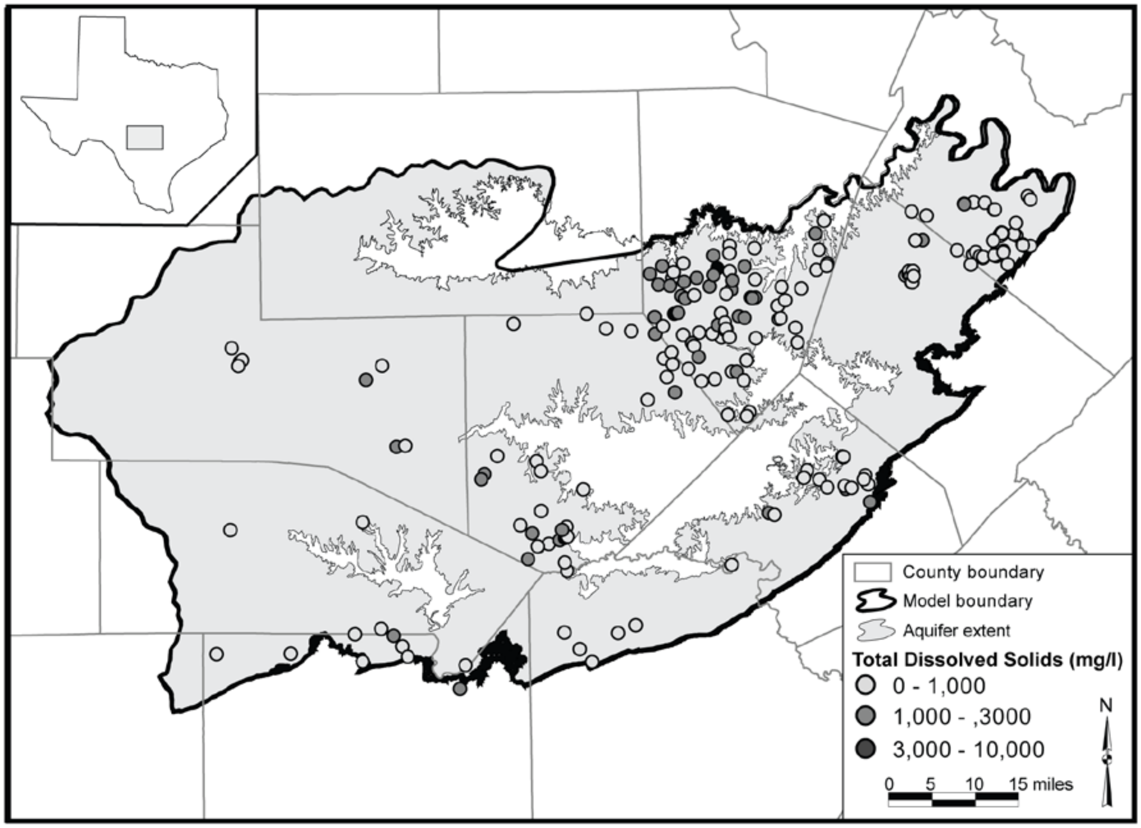


Figure 5-36. Map of total dissolved solids in the Upper Trinity Aquifer. mg/l = milligrams per liter.

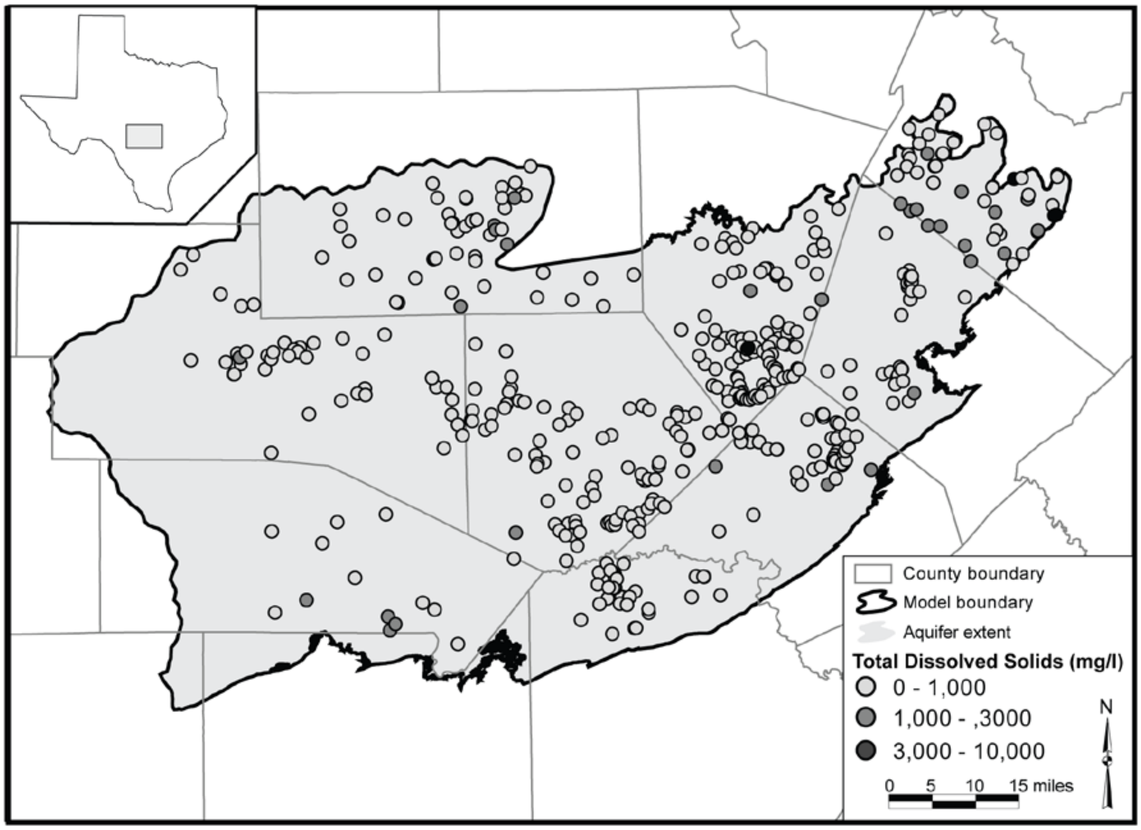


Figure 5-37. Map of total dissolved solids in the Middle Trinity Aquifer. mg/l = milligrams per liter.

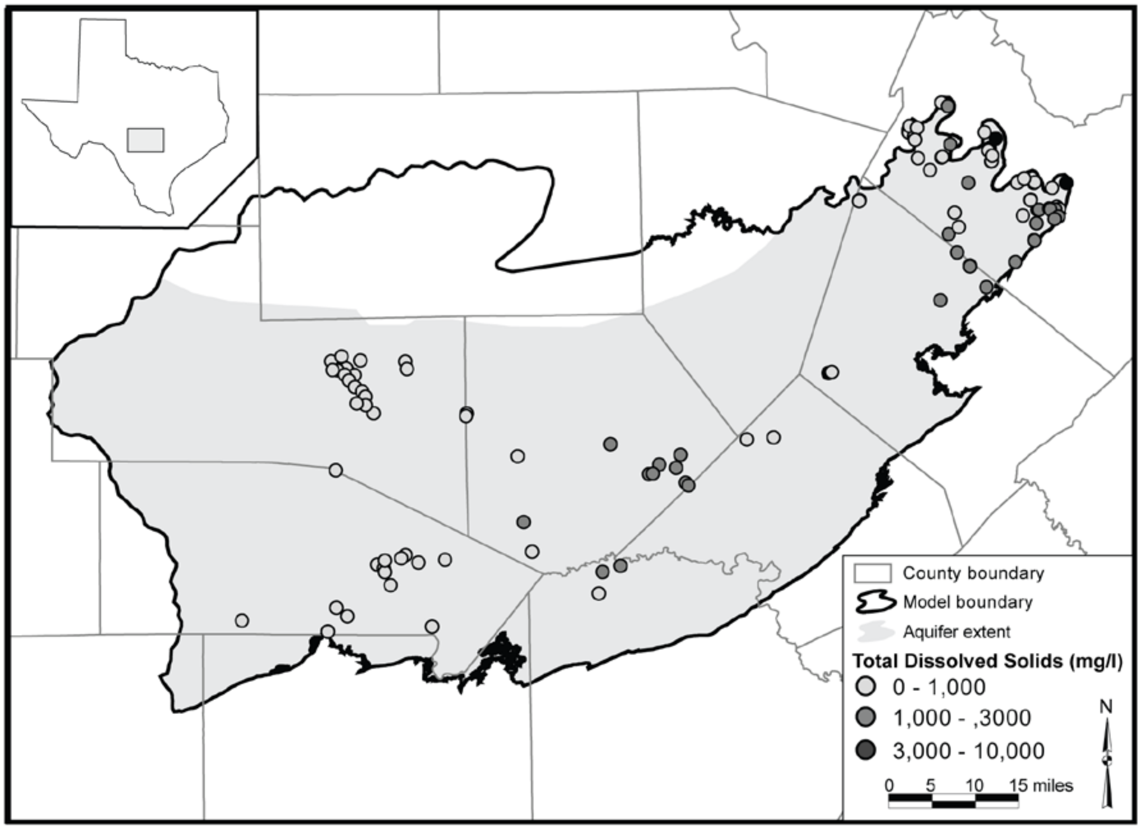


Figure 5-38. Map of total dissolved solids in the Lower Trinity Aquifer. mg/l = milligrams per liter.

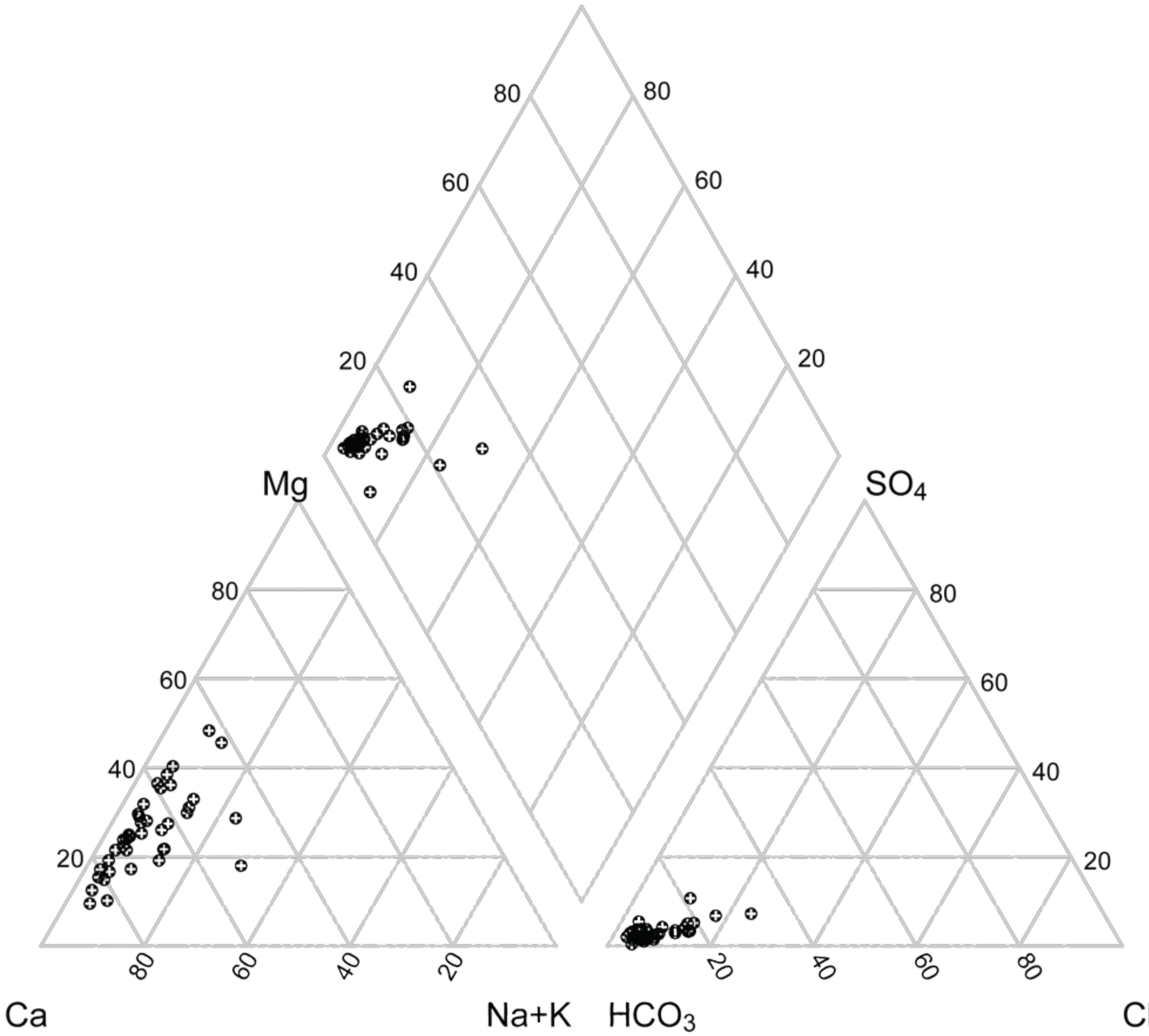


Figure 5-39. Piper diagram of groundwater from the Edwards Group Aquifer showing the relative concentrations of the major ions present in the groundwater. Ca = calcium, Mg = magnesium, Na = sodium, K = potassium, HCO_3 = bicarbonate, SO_4 = sulfate, Cl = chloride.

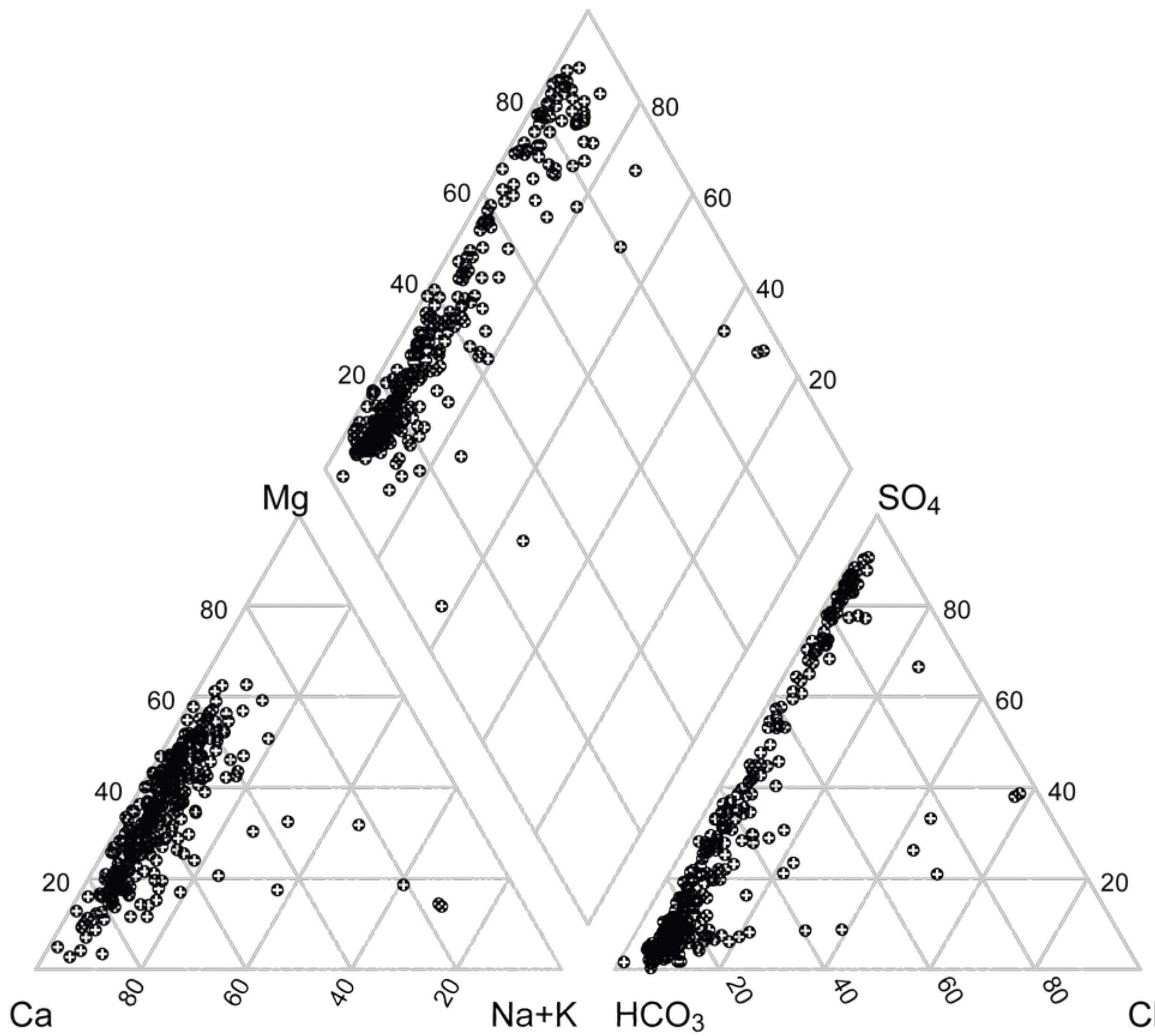


Figure 5-40. Piper diagram of groundwater from the Upper Trinity Aquifer showing the relative concentrations of the major ions present in the groundwater. Ca = calcium, Mg = magnesium, Na = sodium, K = potassium, HCO_3 = bicarbonate, SO_4 = sulfate, Cl = chloride.

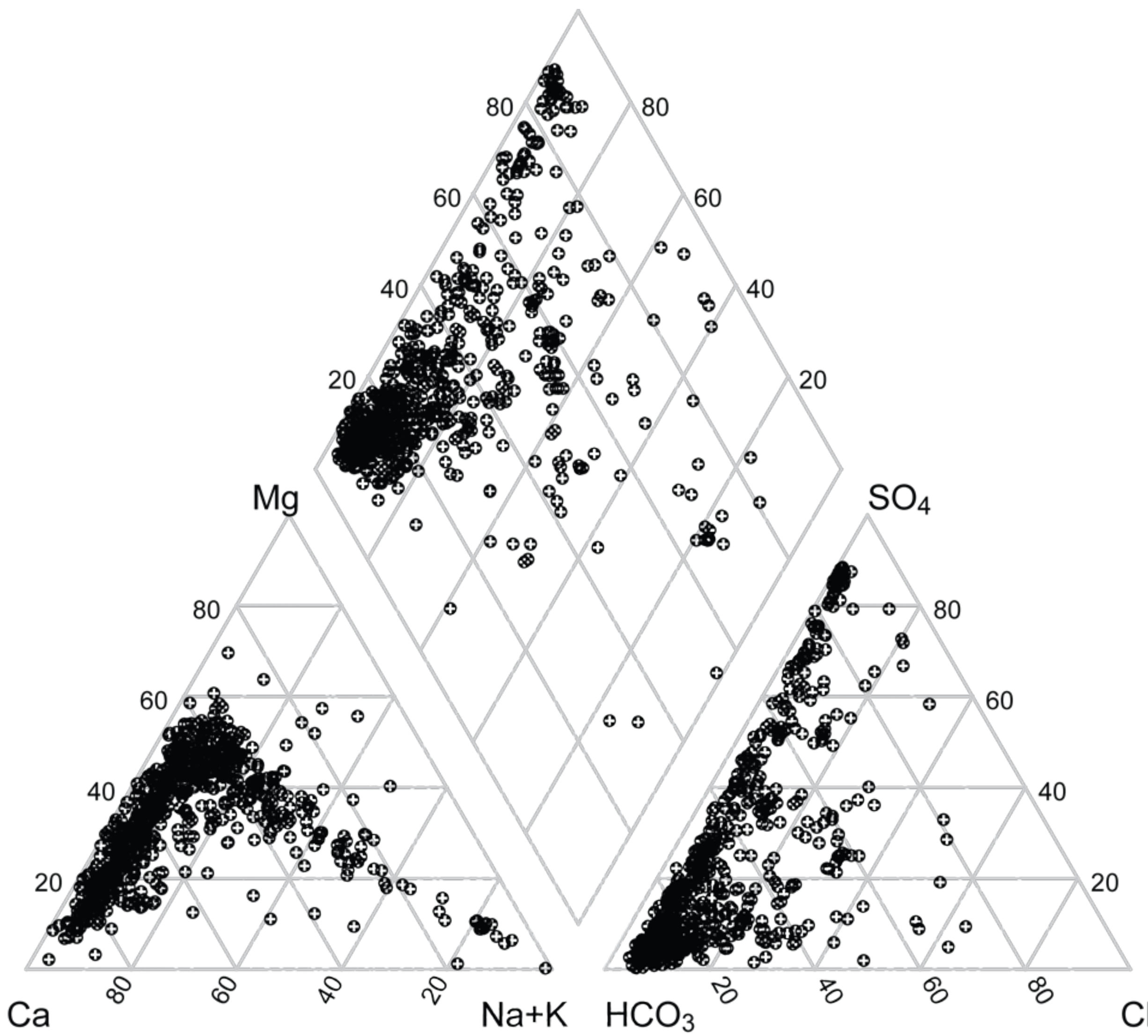


Figure 5-41. Piper diagram of groundwater from the Middle Trinity Aquifer showing the relative concentrations of the major ions present in the groundwater. Ca = calcium, Mg = magnesium, Na = sodium, K = potassium, HCO_3 = bicarbonate, SO_4 = sulfate, Cl = chloride.

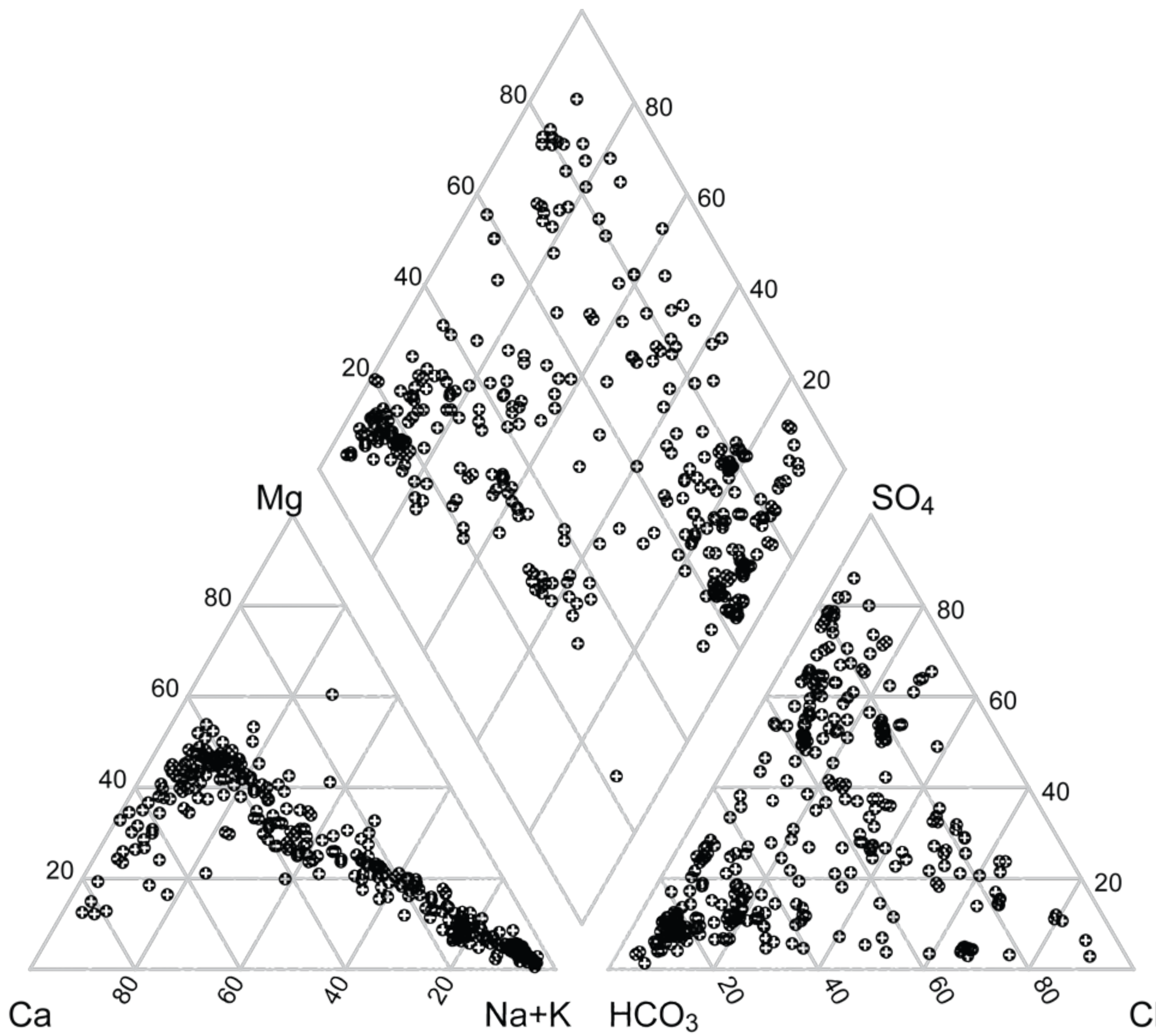


Figure 5-42. Piper diagram of groundwater from the Lower Trinity Aquifer showing the relative concentrations of the major ions present in the groundwater. Ca = calcium, Mg = magnesium, Na = sodium, K = potassium, HCO_3 = bicarbonate, SO_4 = sulfate, Cl = chloride.

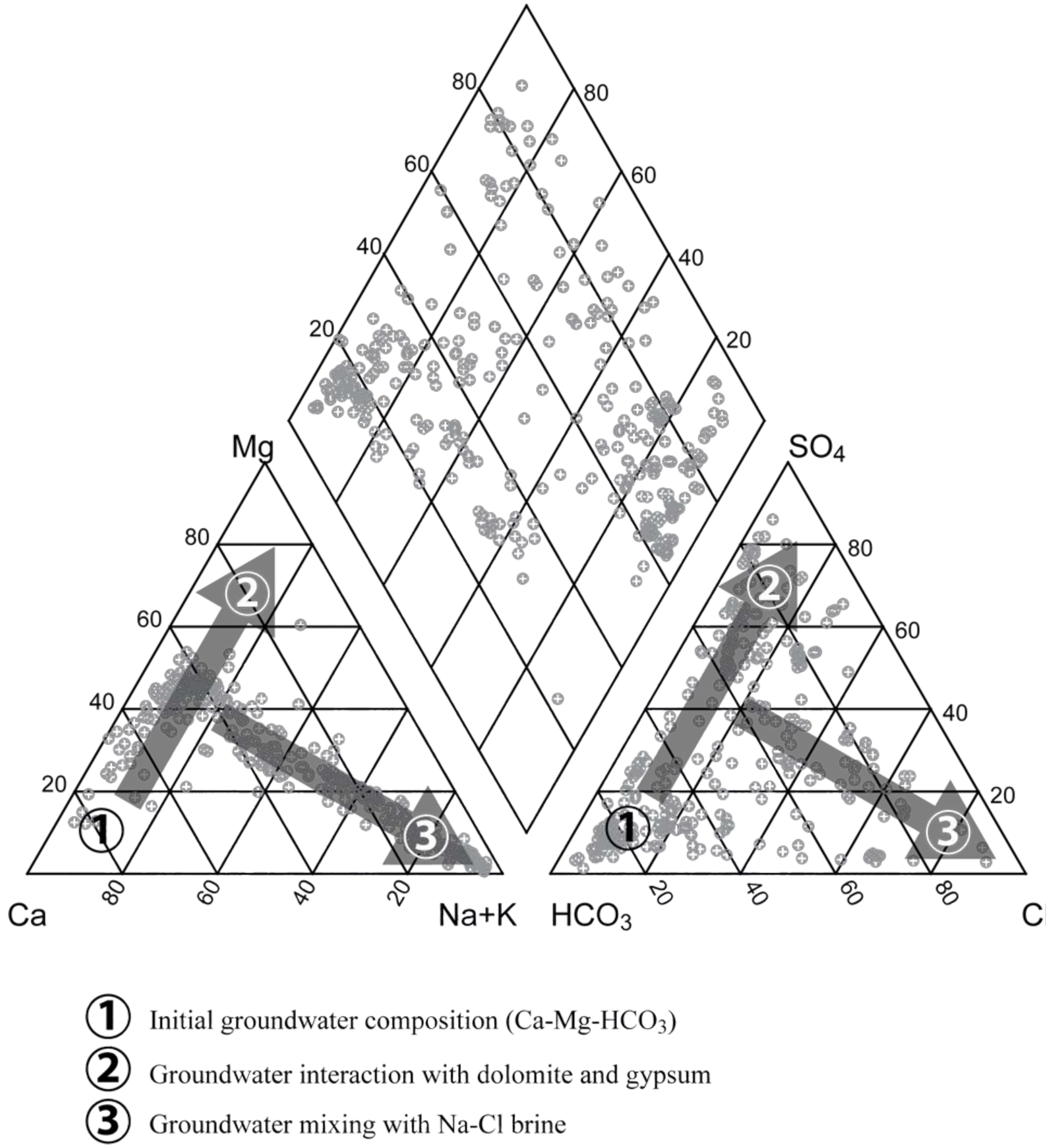


Figure 5-43. Groundwater geochemical trends that are apparent in the Hill Country portion of the Trinity Aquifer System. Ca = calcium, Mg = magnesium, Na = sodium, K = potassium, HCO_3 = bicarbonate, SO_4 = sulfate, Cl = chloride.

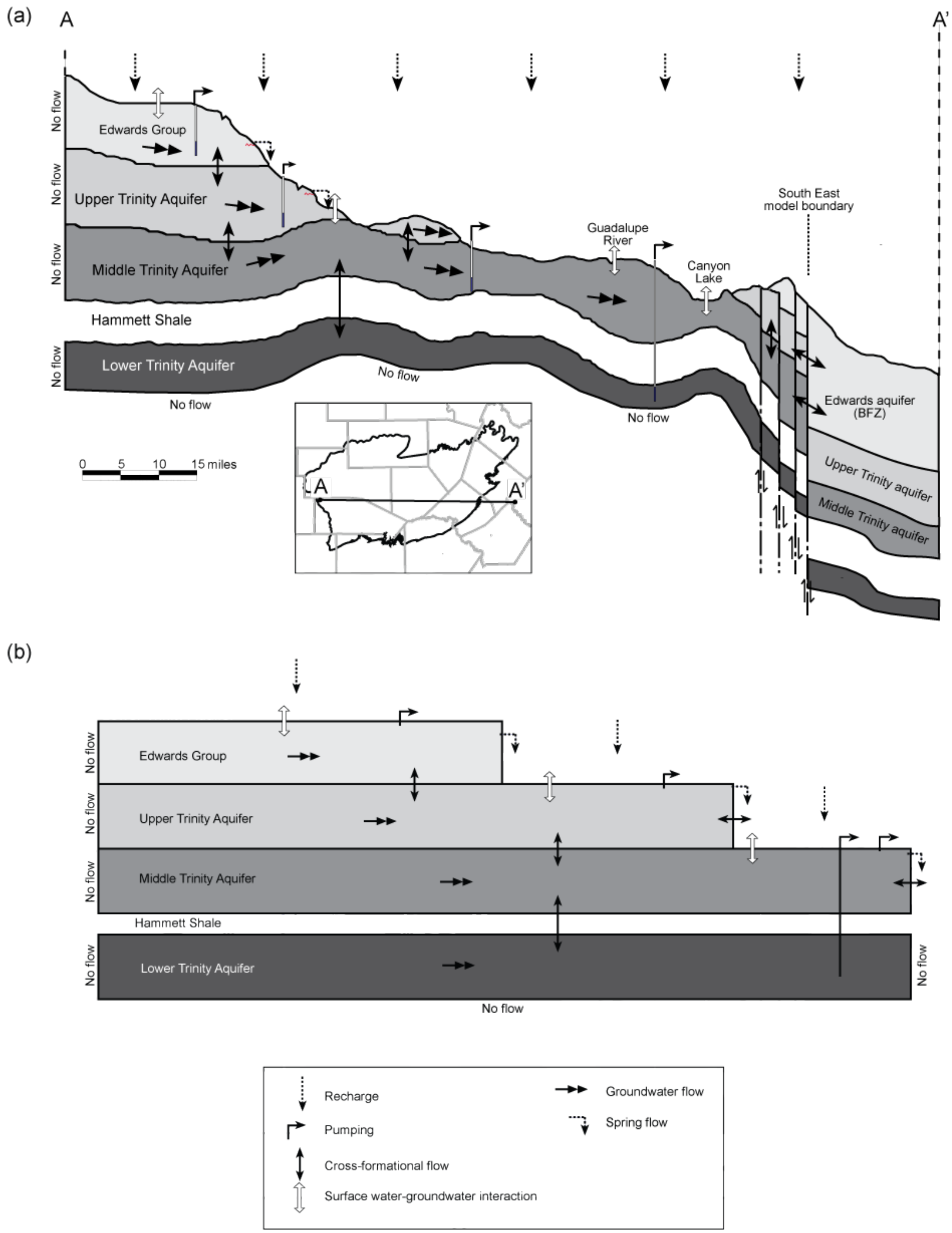


Figure 6-01. Conceptual model of the Hill Country portion of the Trinity Aquifer System. (a) Schematic cross-section through the aquifer system. (b) diagram showing the boundary conditions at the outer edge of the model, flows between the layers, and how the conceptual model translates into the numerical model (modified from Mace and others, 2000).

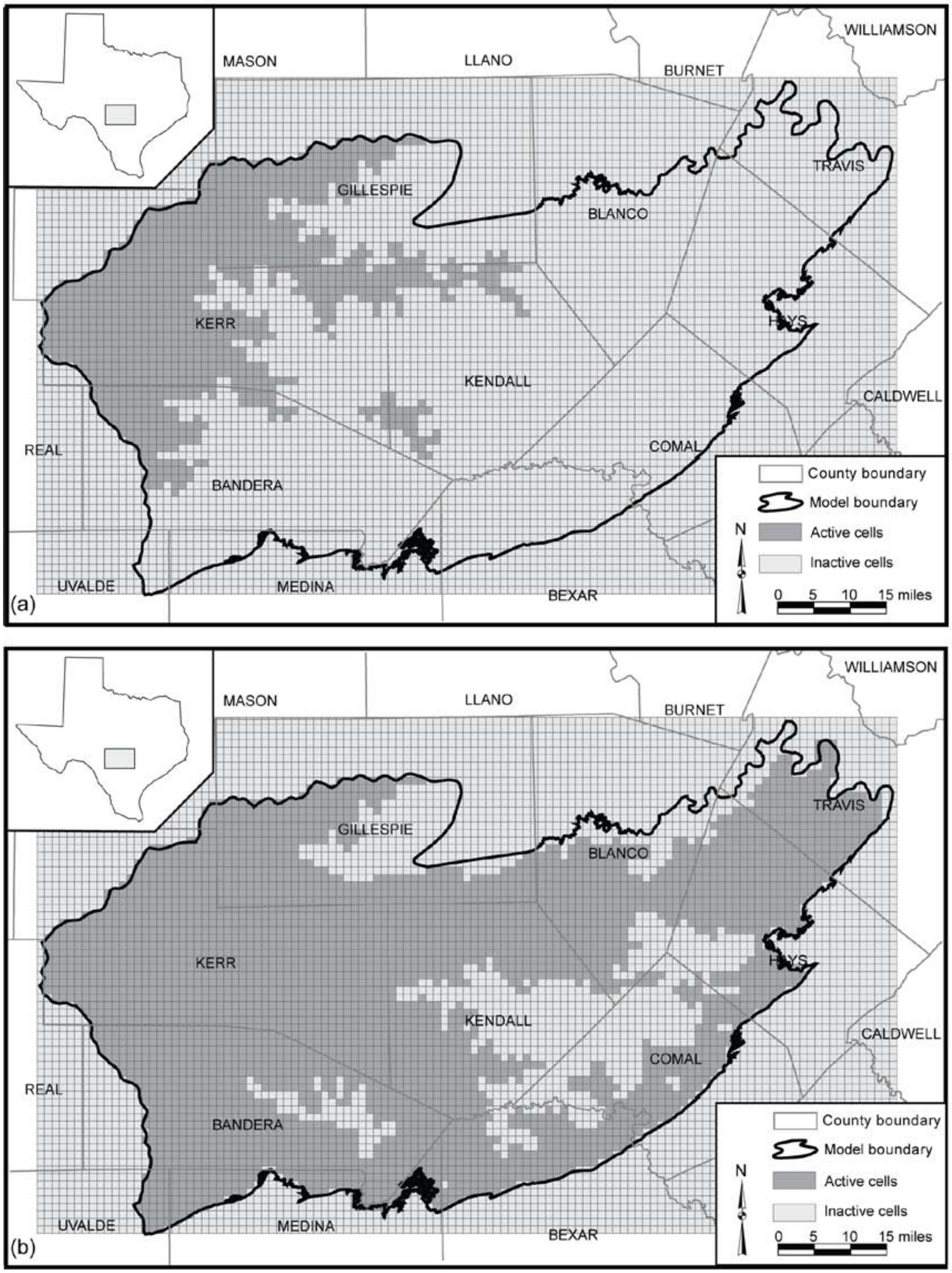


Figure 7-01. Active and inactive cells in model grid for (a) Layer 1 (Edwards Group), (b) Layer 2 (Upper Trinity Aquifer), (c) Layer 3 (Middle Trinity Aquifer), and (d) Layer 4 (Lower Trinity aquifer).

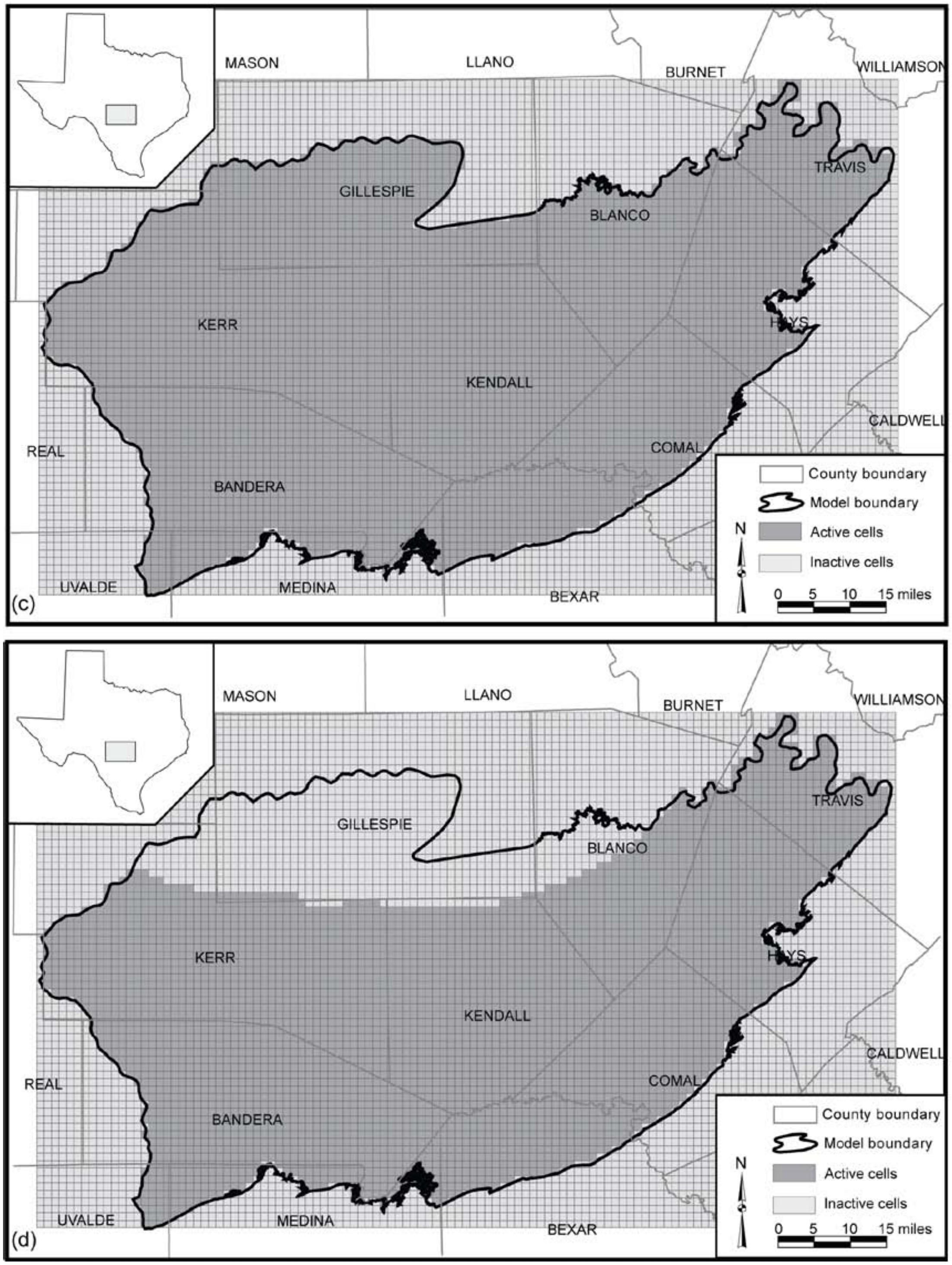


Figure 7-01. (Cont.).

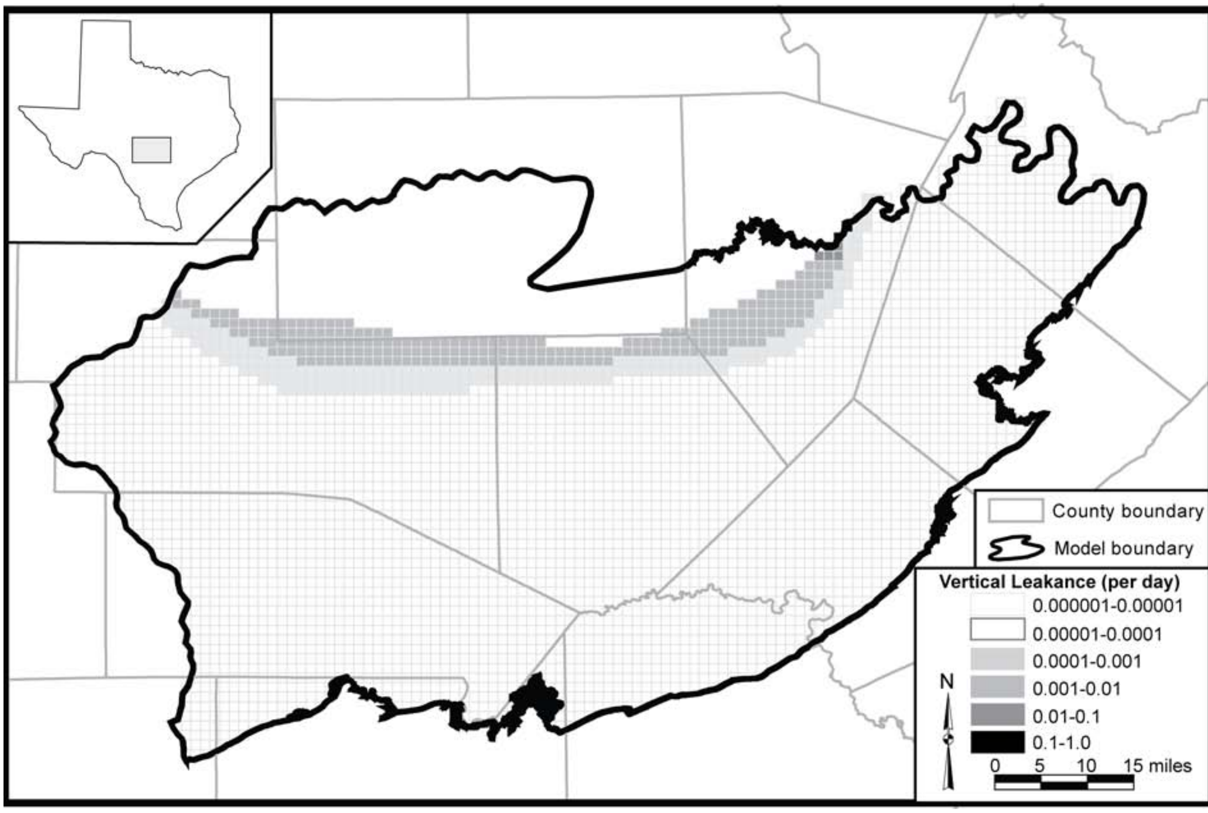


Figure 7-02. Vertical leakance between the Middle and Lower Trinity aquifers. Values expressed in per day.

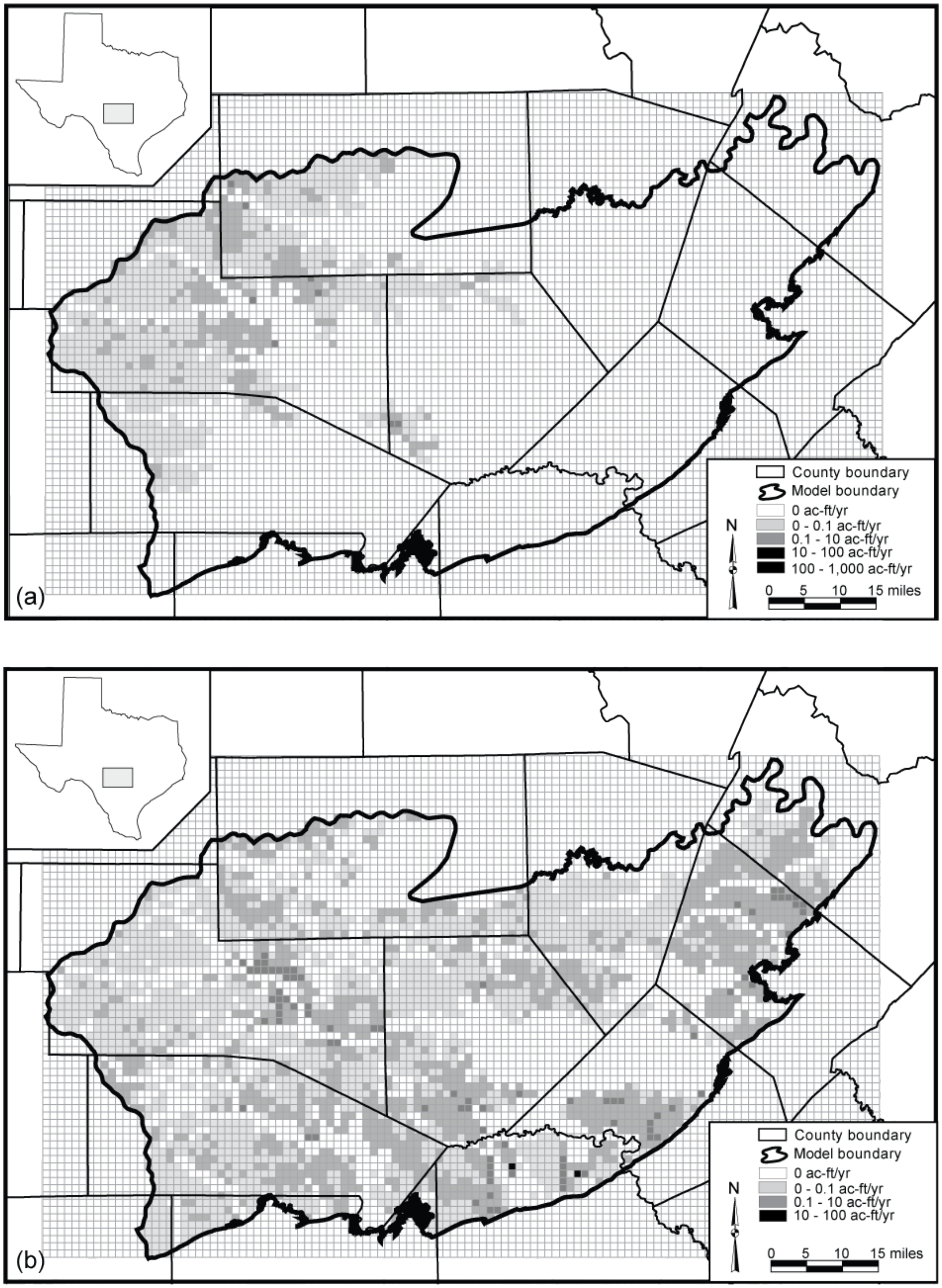
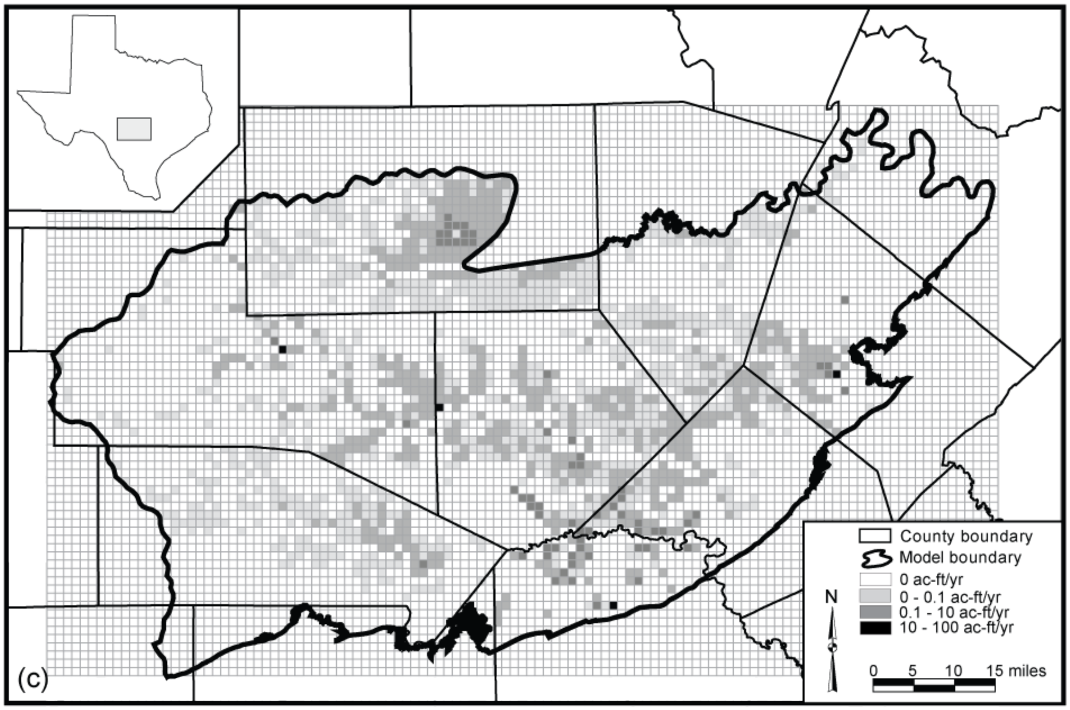


Figure 7-03. The spatial distribution of total pumping for 1980 for (a) Layer 1, (b) Layer 2, (c) Layer 3, and (d) Layer 4.



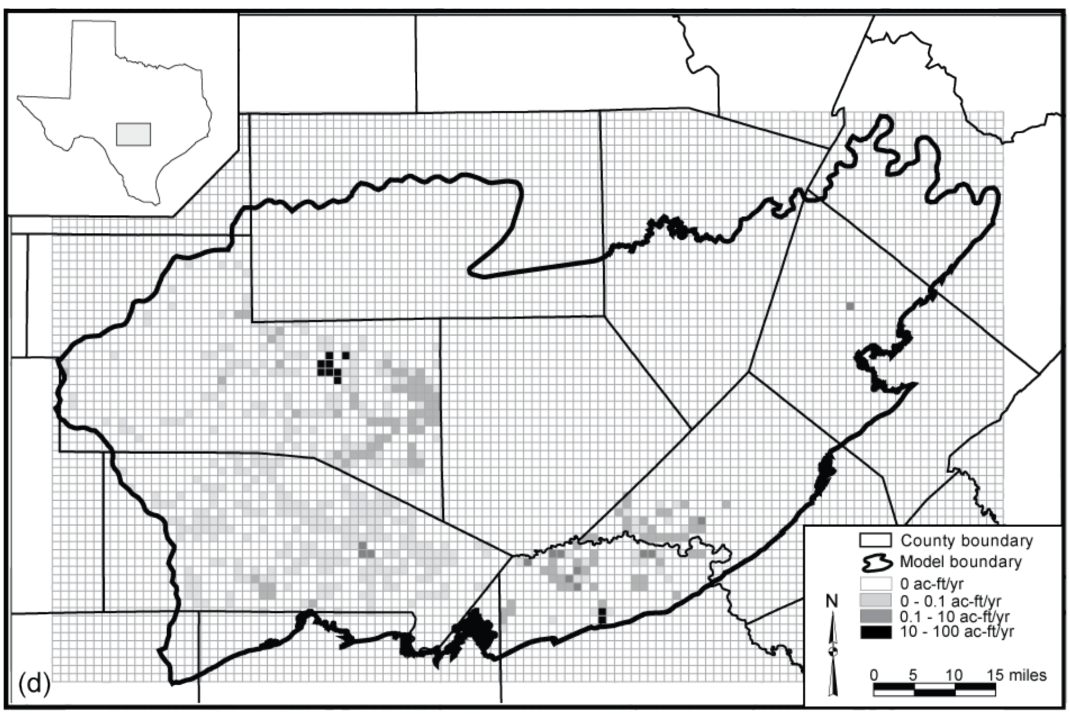


Figure 7-03. (Cont.).

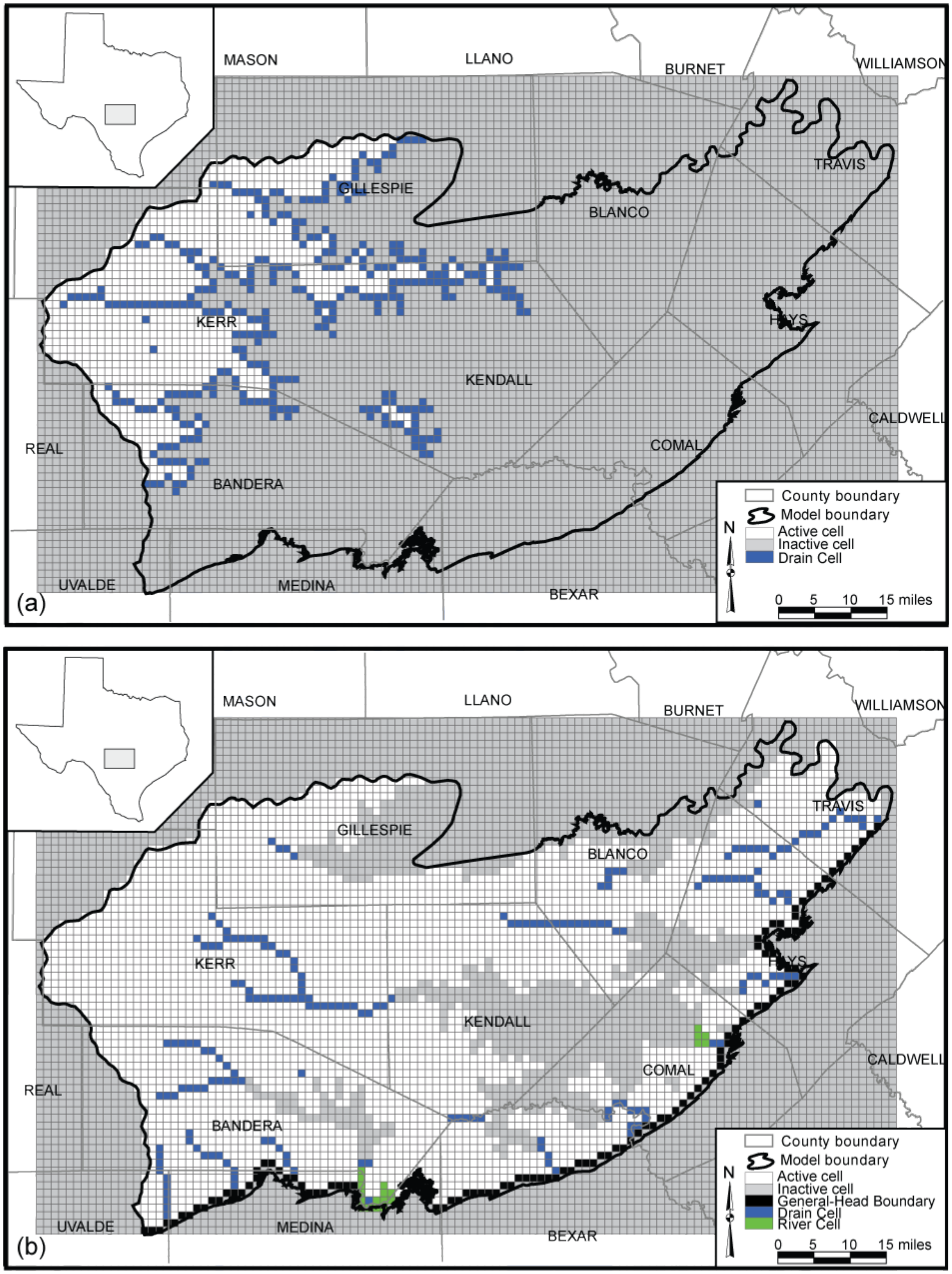


Figure 7-04. Boundary cells in model grid for (a) Layer 1, (b) Layer 2, (c) Layer 3, and (d) Layer 4.

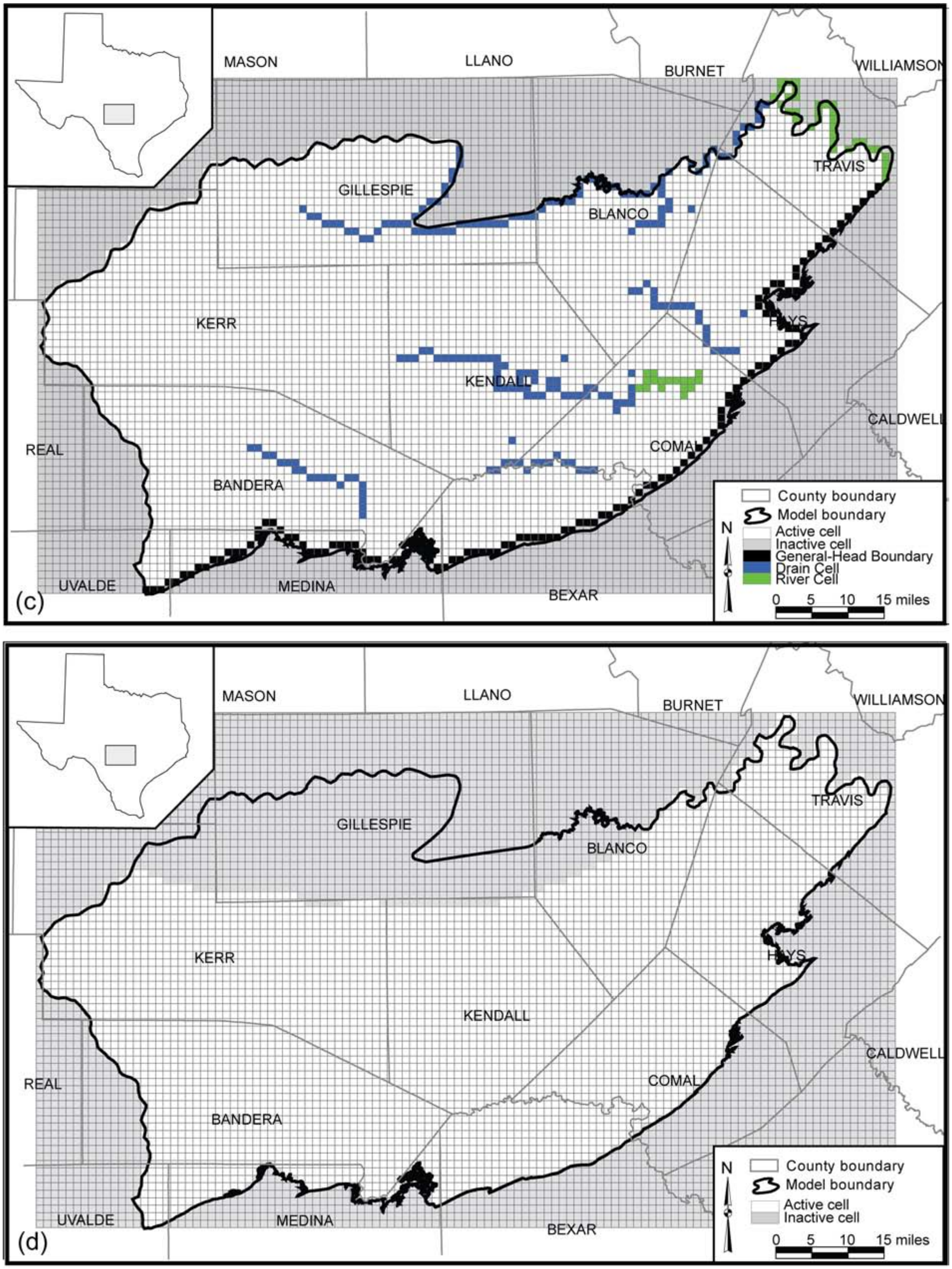


Figure 7-04. (Cont.).

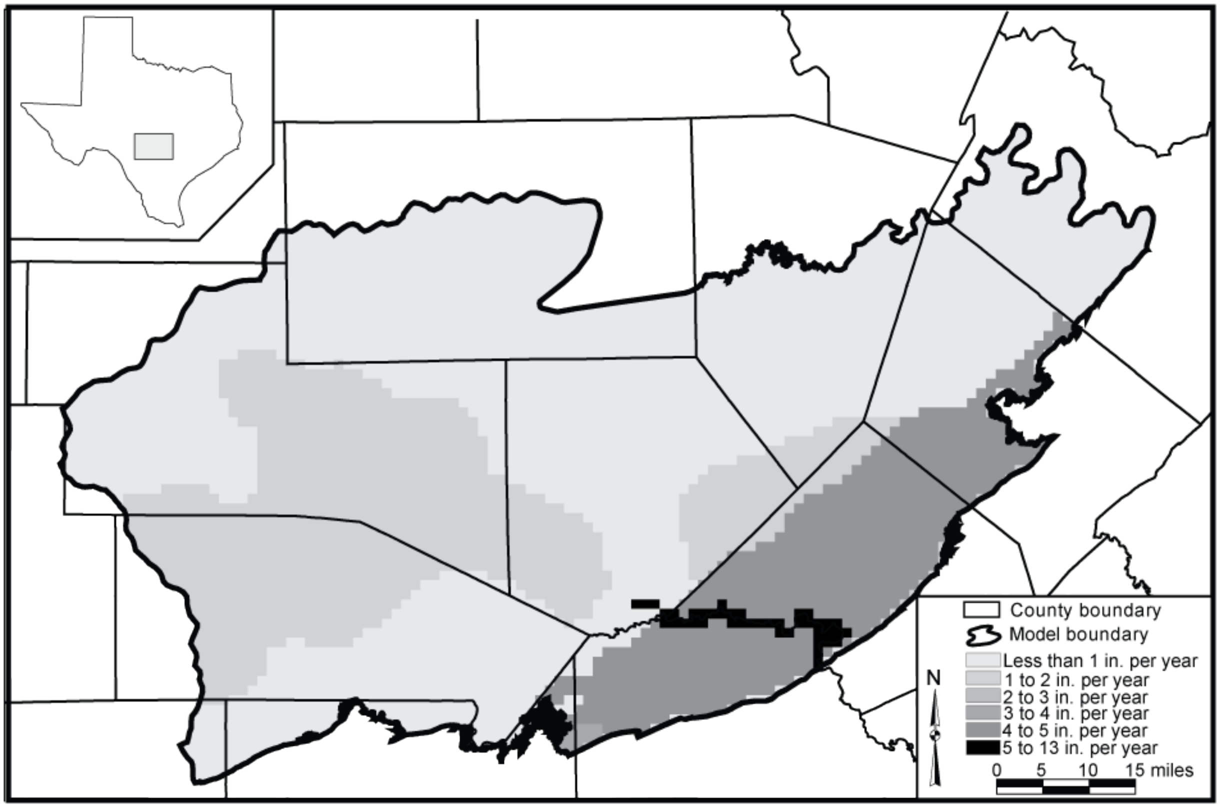


Figure 9-01. Spatial distribution of recharge for 1980. This is estimated based precipitation data for the study area and Cibolo Creek streamflow loss studies. All values are expressed in inches per year.

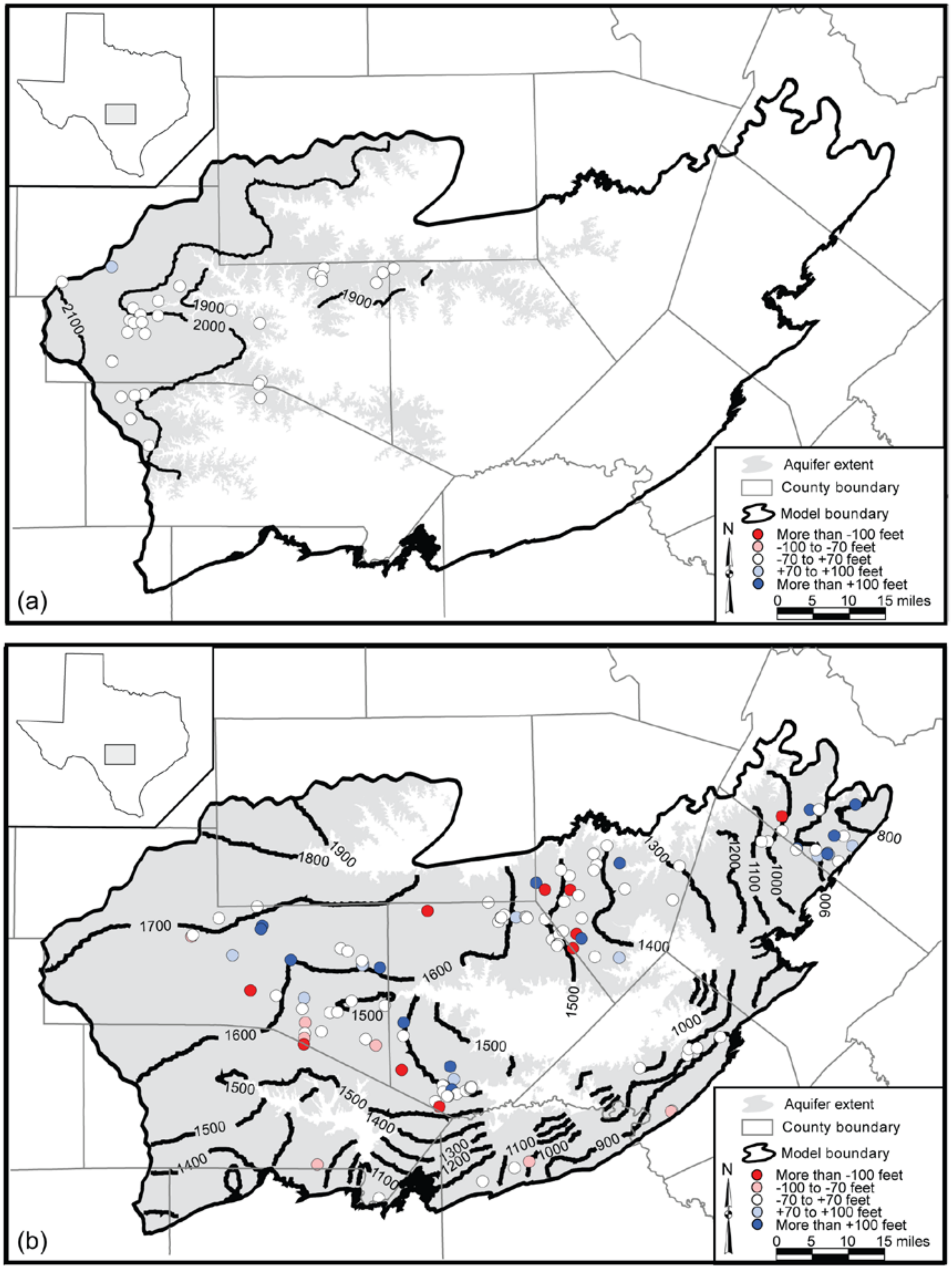


Figure 9-02. Comparison of measured and calculated water levels from the steady-state model for (a) Layer 1, (b) Layer 2, (c) Layer 3, and (d) Layer 4. The contours represent calculated water levels while the points indicate the difference between measured and simulated water levels relative to the measured water levels.

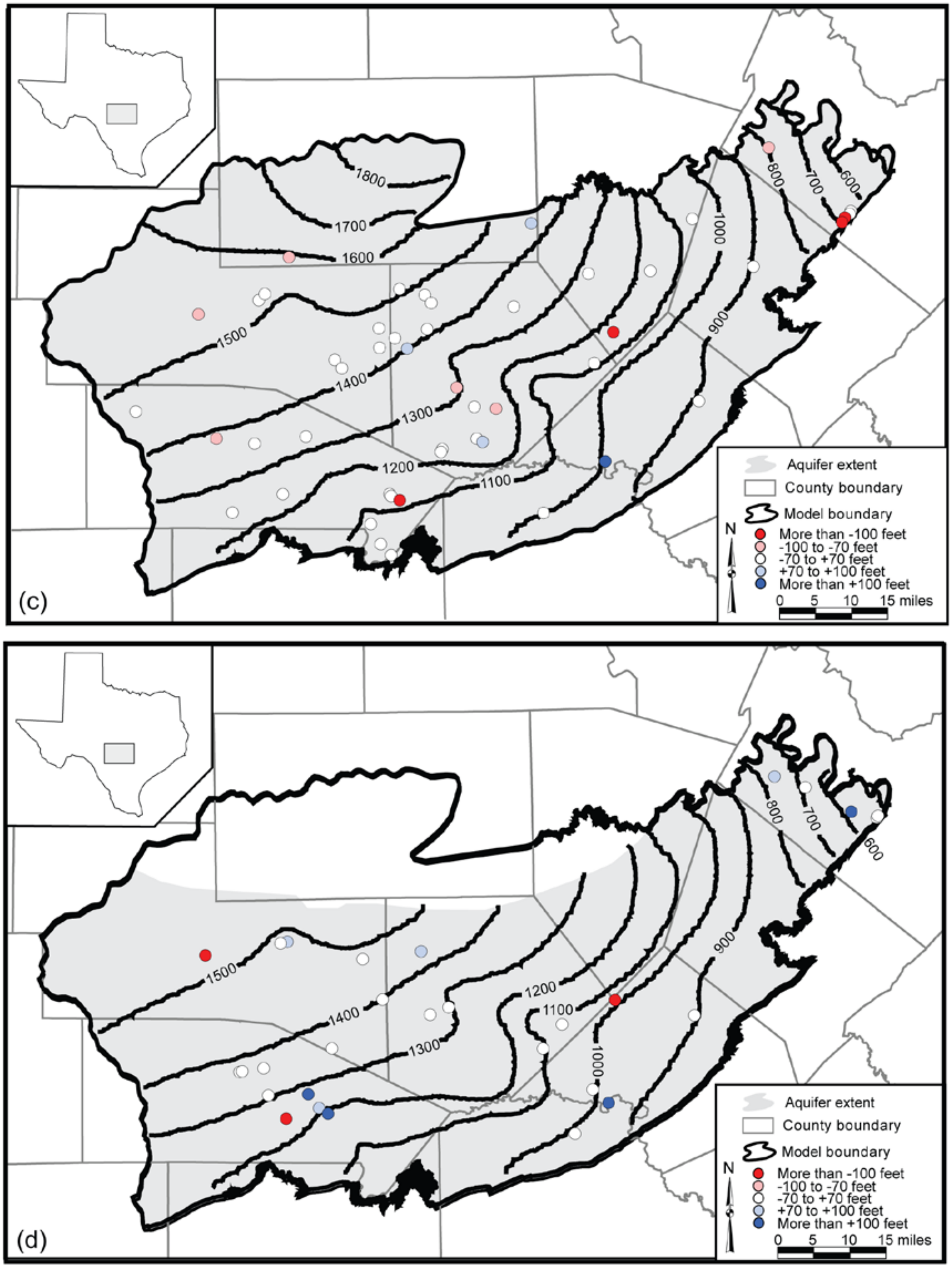


Figure 9-02. (Cont.).

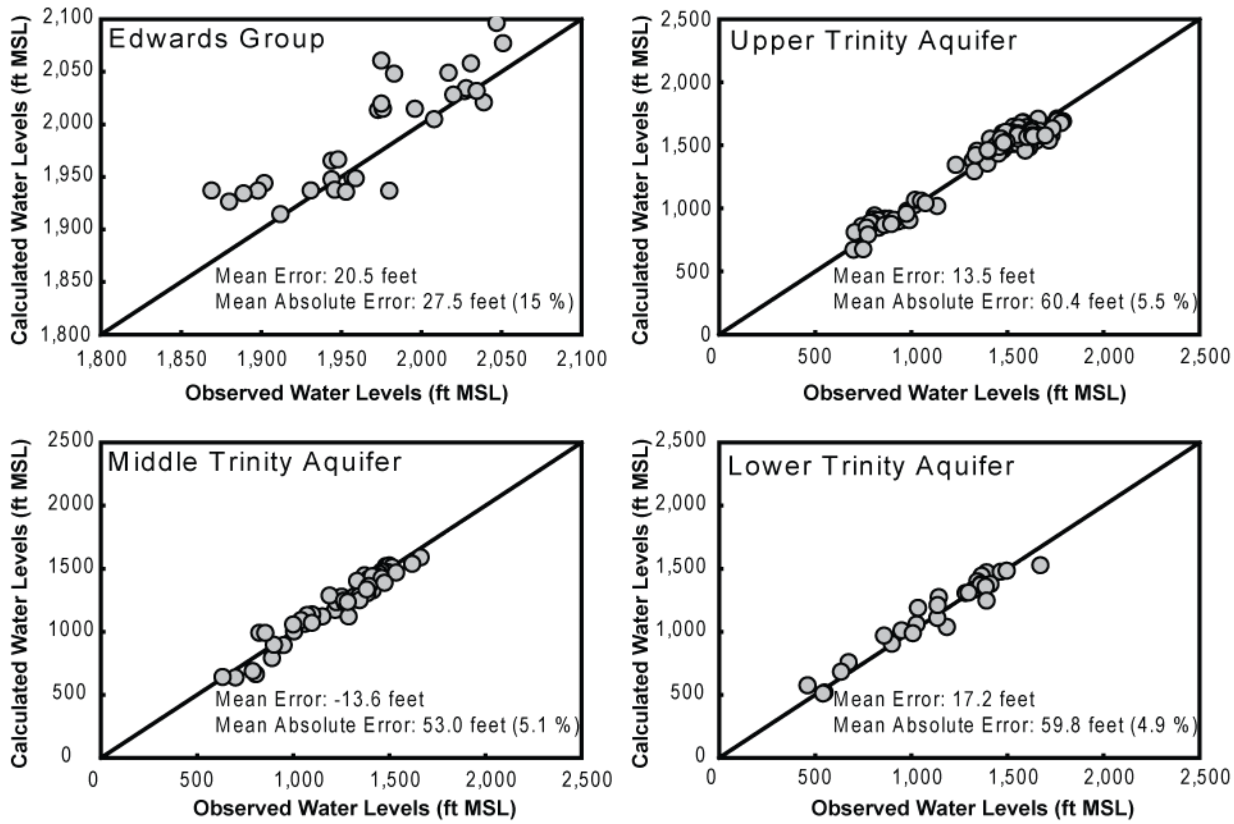
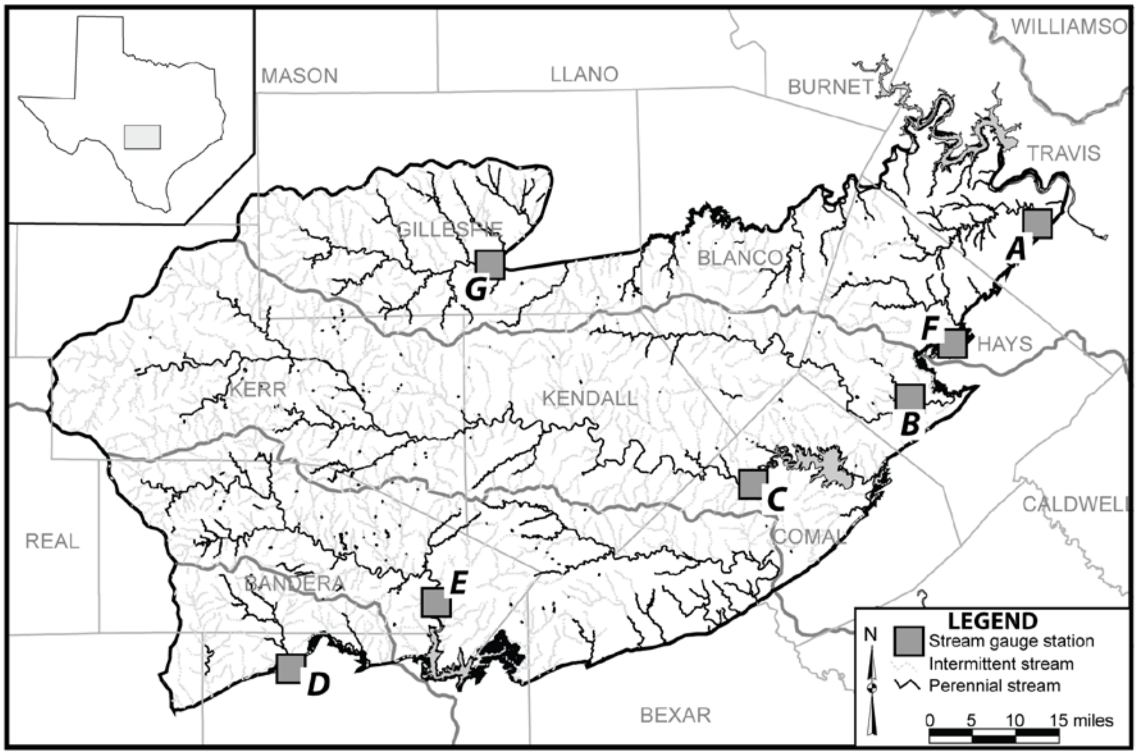


Figure 9-03. Comparison of measured and calculated water levels from the steady-state model.



A - Barton Creek at Lost Creek Blvd. near Austin
B - Blanco River at Wimberley
C - Guadalupe River near Spring Branch
D - Hondo Creek near Tarpley
E - Medina River near Pipe Creek
F - Onion Creek near Driftwood
G - Pedernales River near Fredericksburg

Figure 9-04. Locations of stream gauges used to compare measured streamflow and calculated discharge to streams from the model.

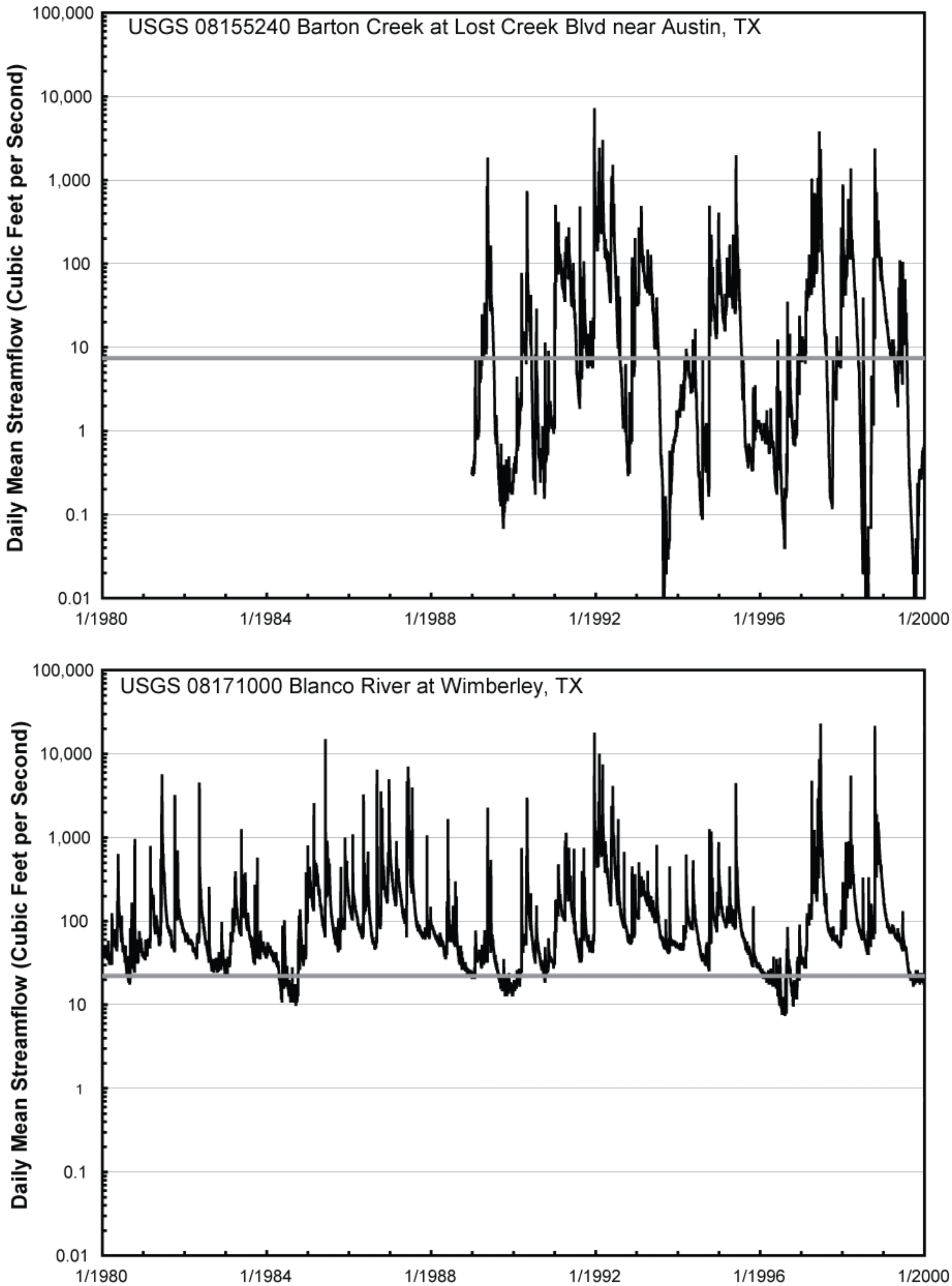
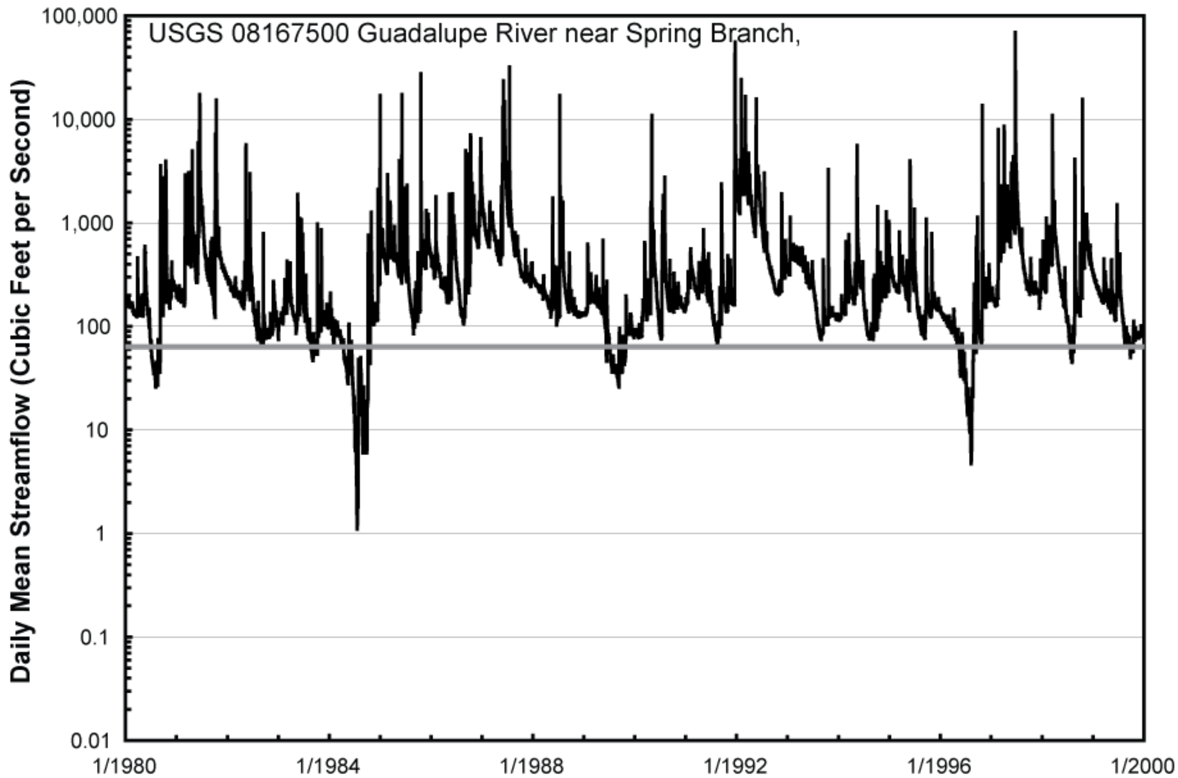


Figure 9-05. Comparison of the calculated groundwater discharge rate to perennial streams from the 1980 steady-state model (gray line) and measured streamflow data. Stream gauge locations are shown in Figure 9-04.



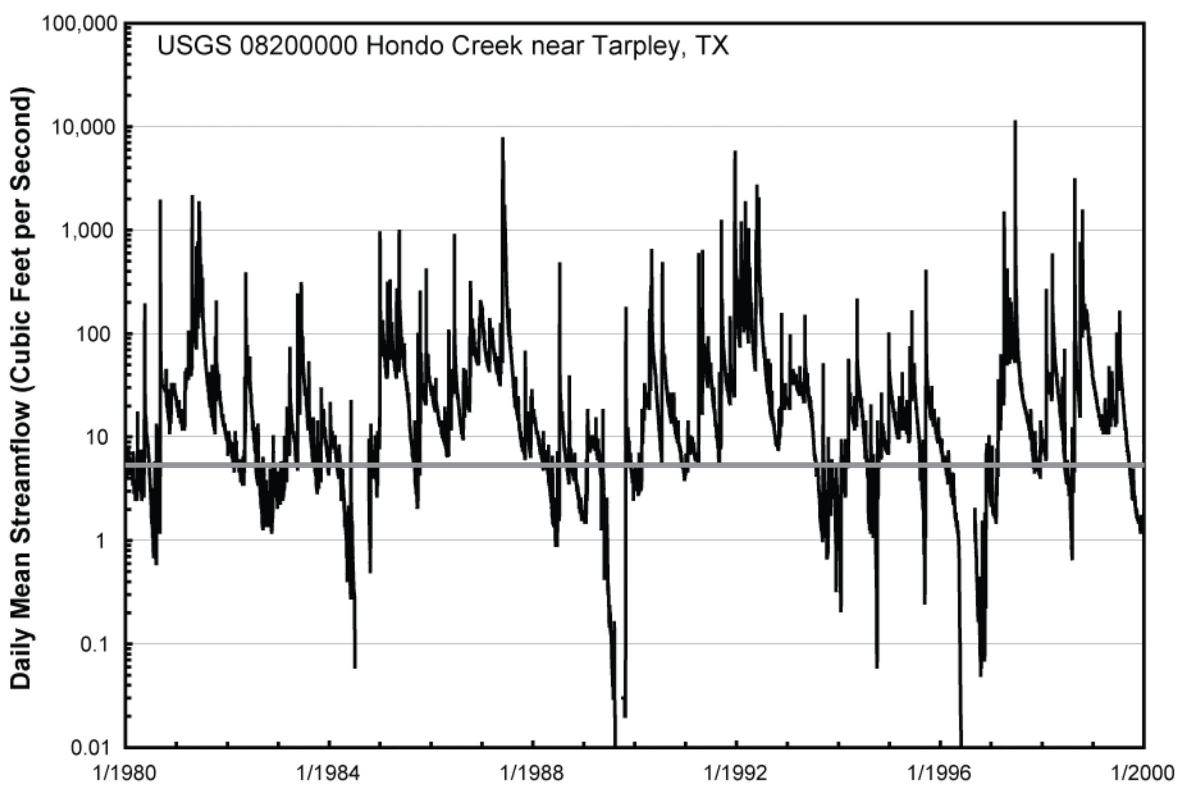
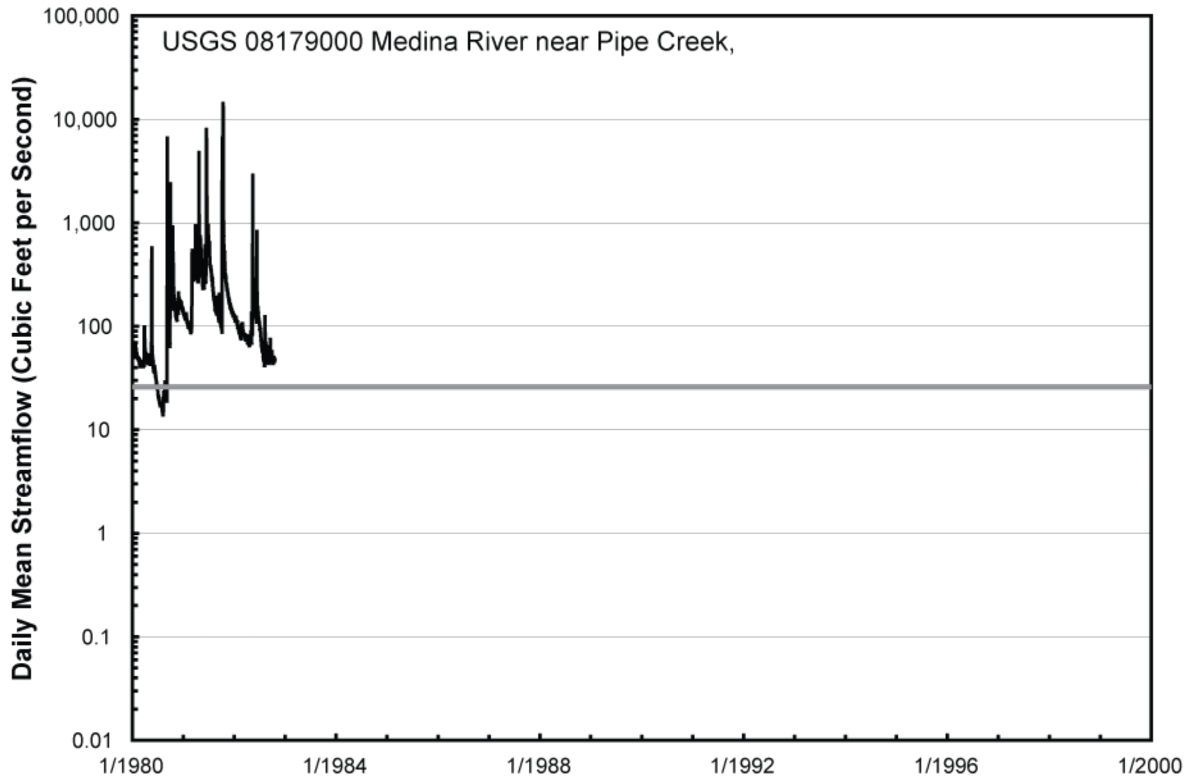


Figure 9-05. (Cont.).



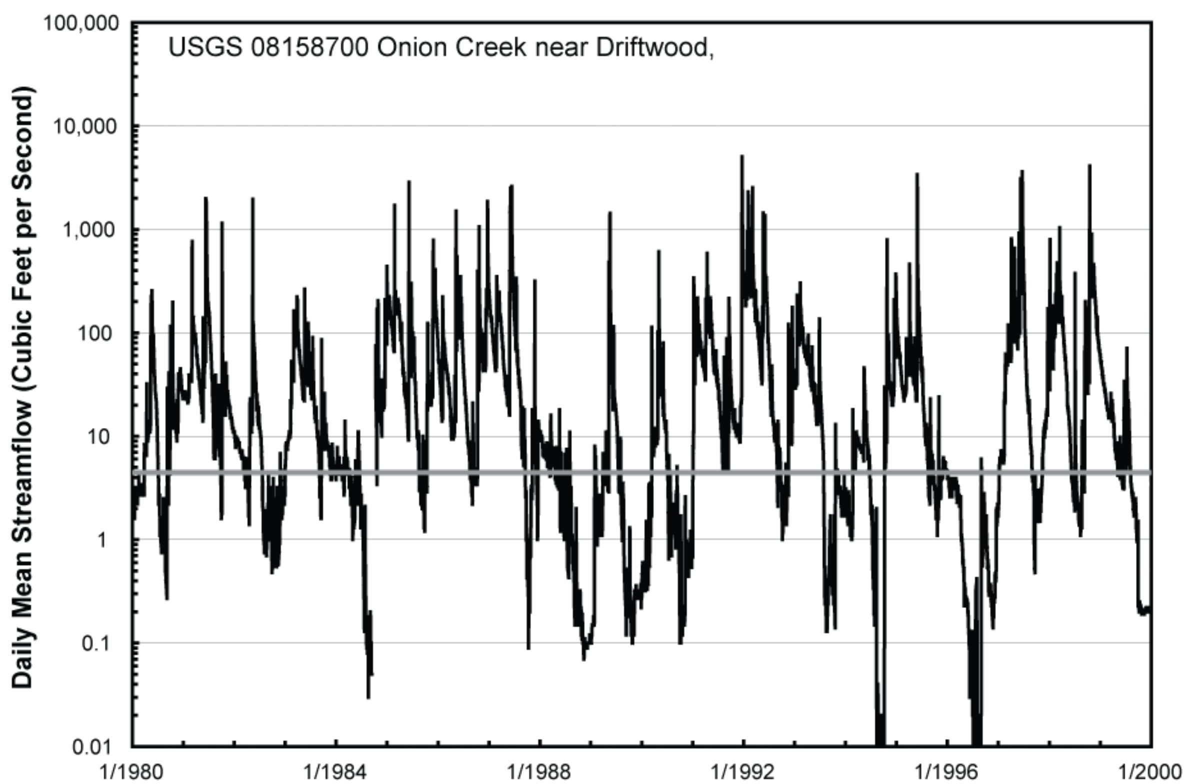


Figure 9-05. (Cont.).

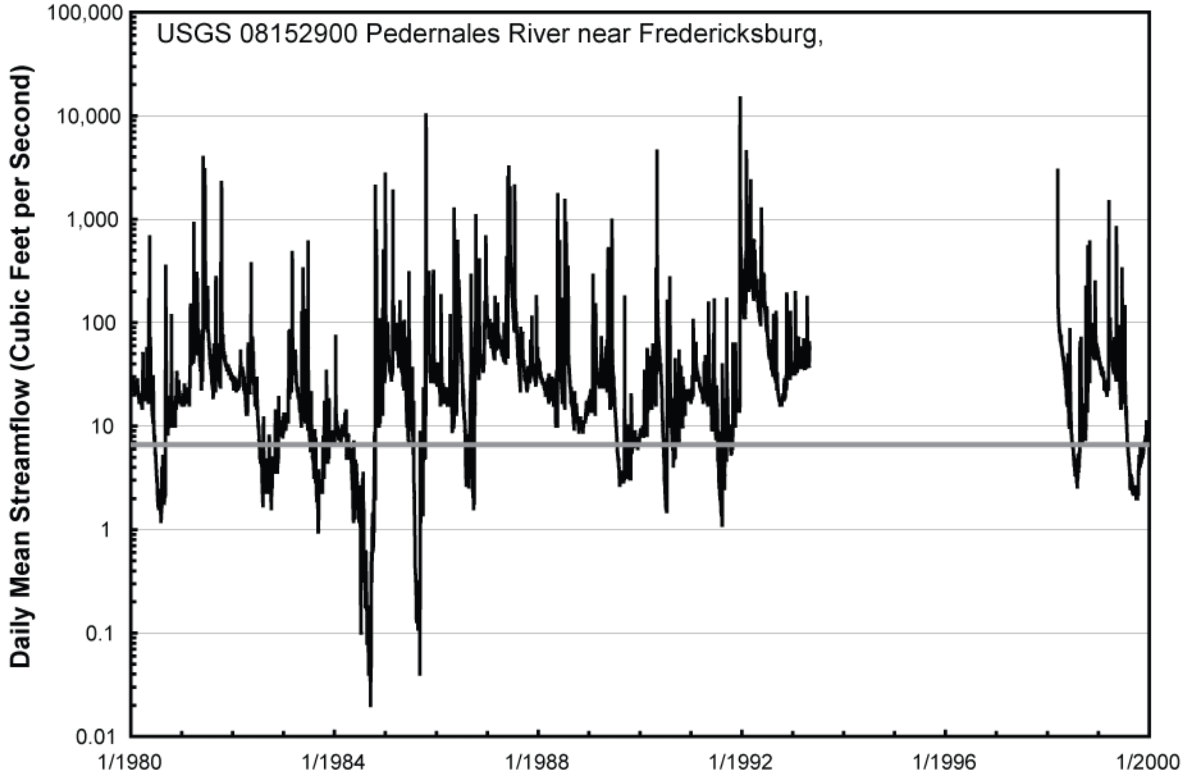


Figure 9-05. (Cont.).

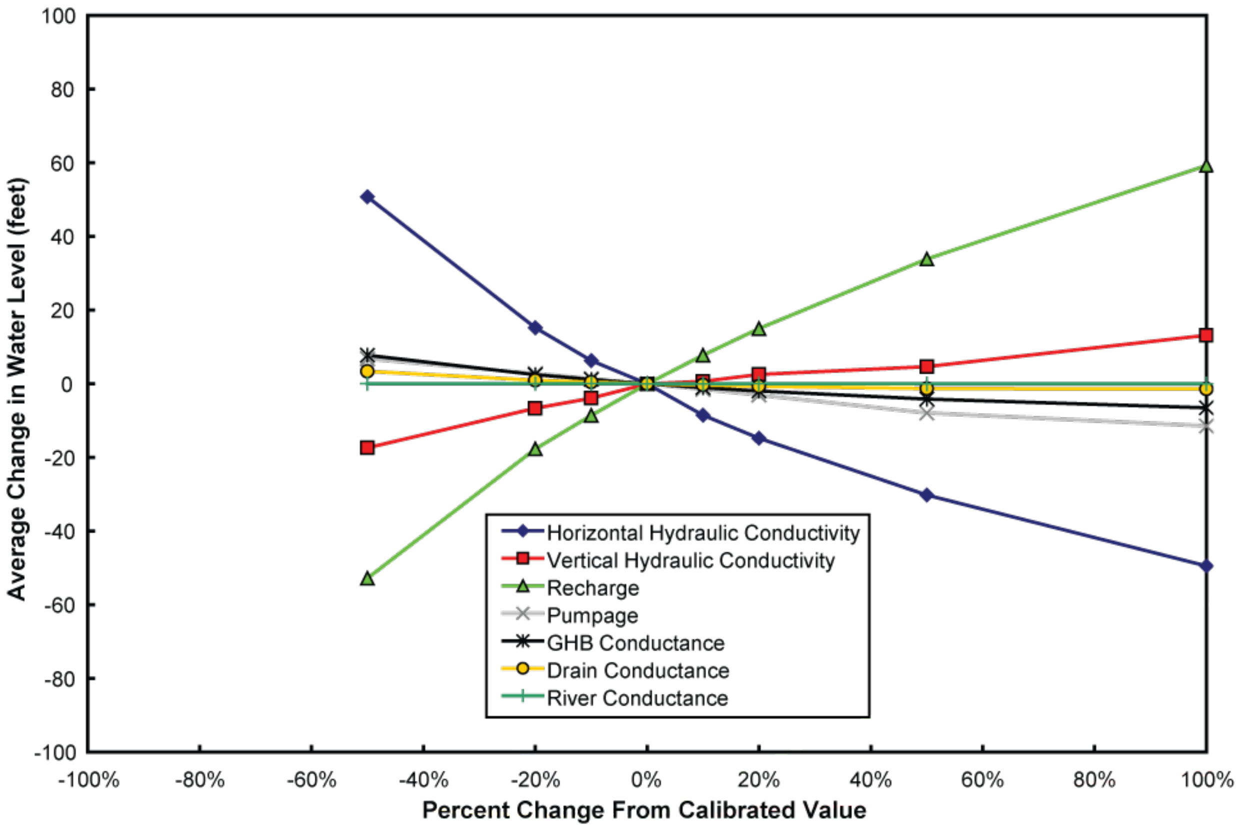


Figure 9-06. Sensitivity of calculated water levels in the steady-state model to changes in model parameters.

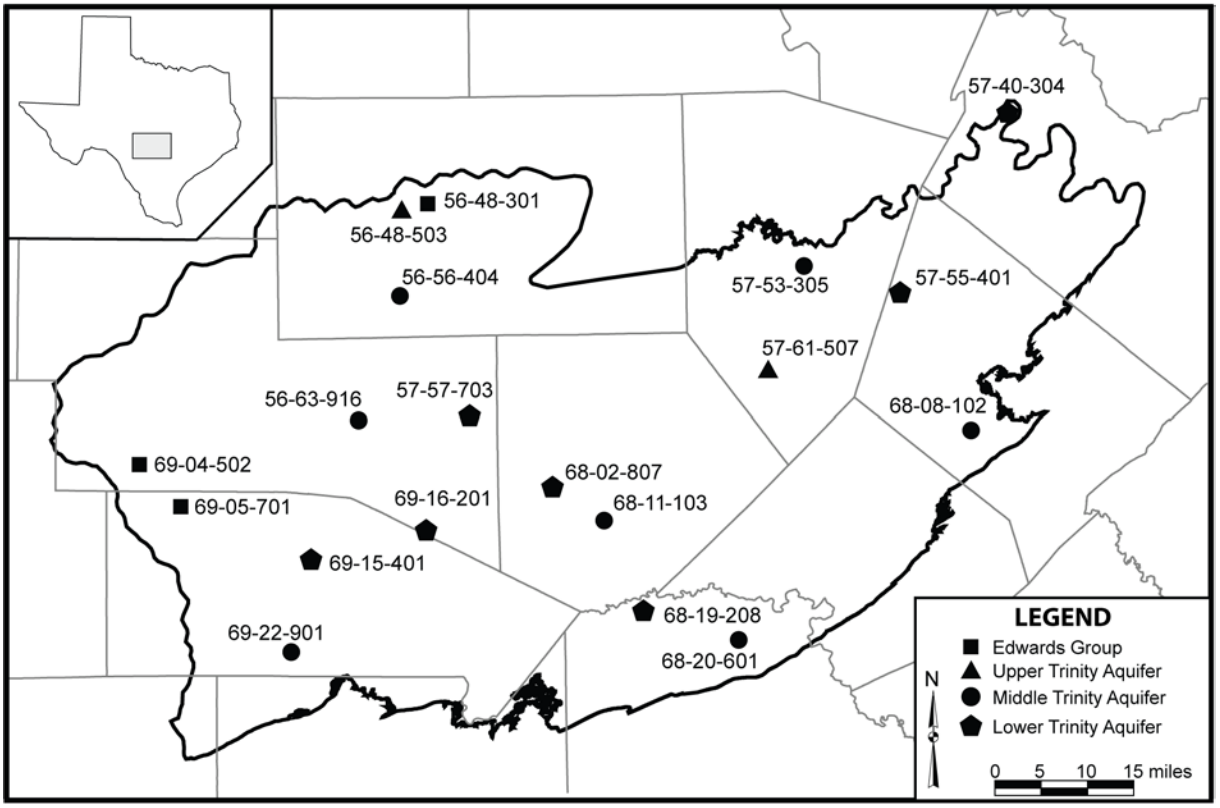


Figure 10-01. Locations of wells used to compare measured water levels over the transient period (1980 through 1997) and calculated water levels.

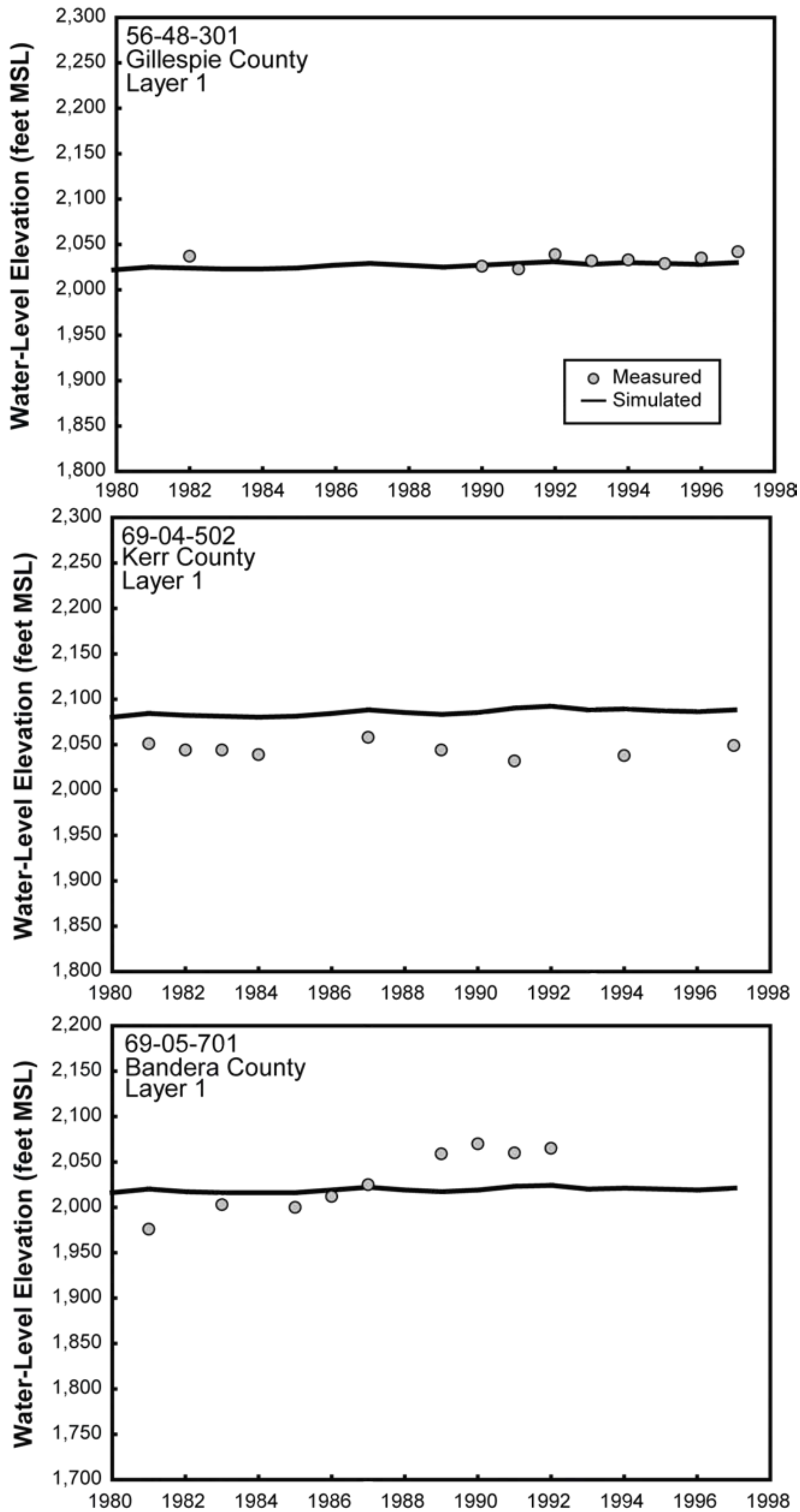


Figure 10-02. Comparison of simulated water-level fluctuations to measured water-levels. Well locations are shown in Figure 10-01.

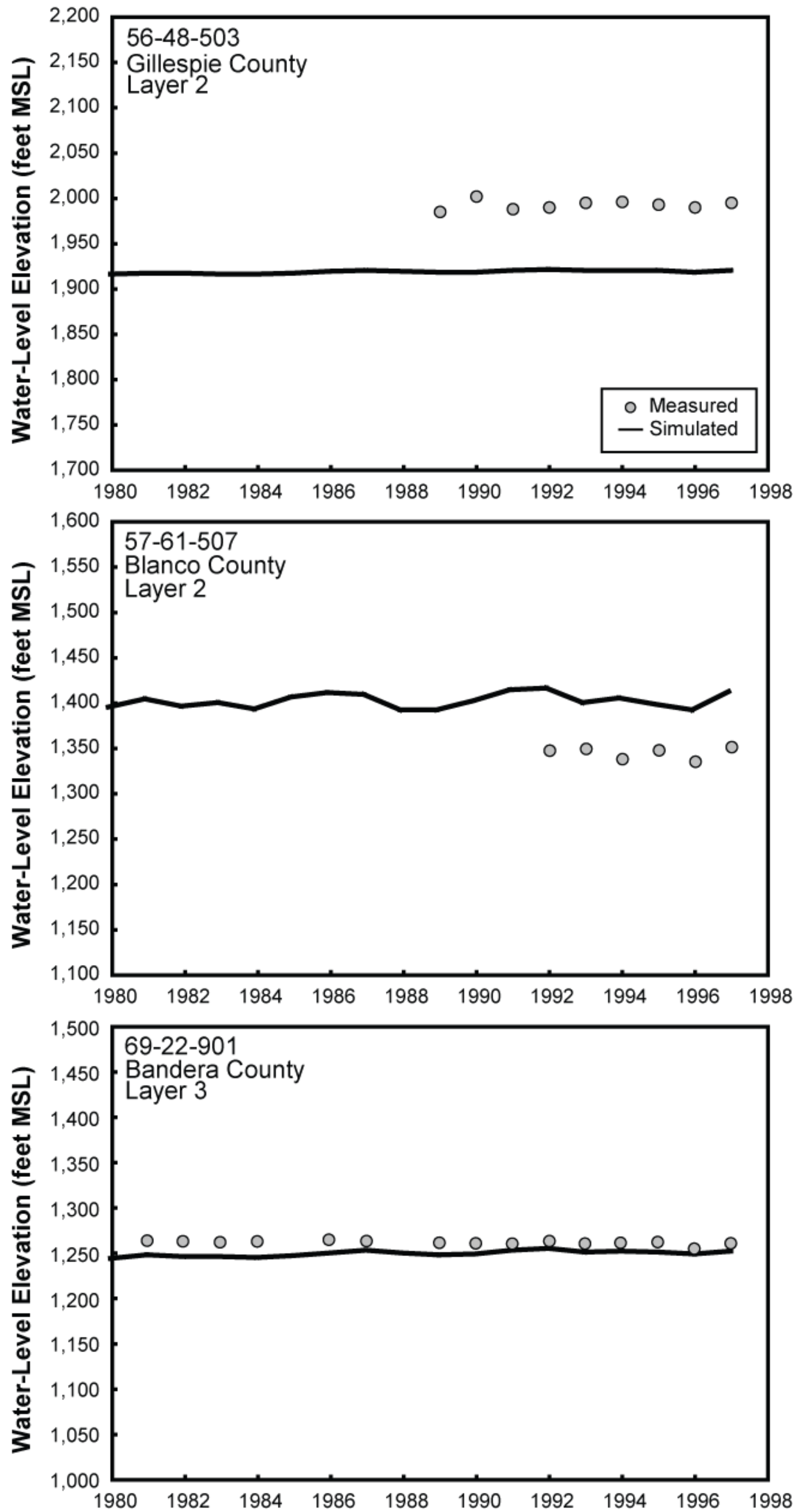


Figure 10-02. (Cont.).

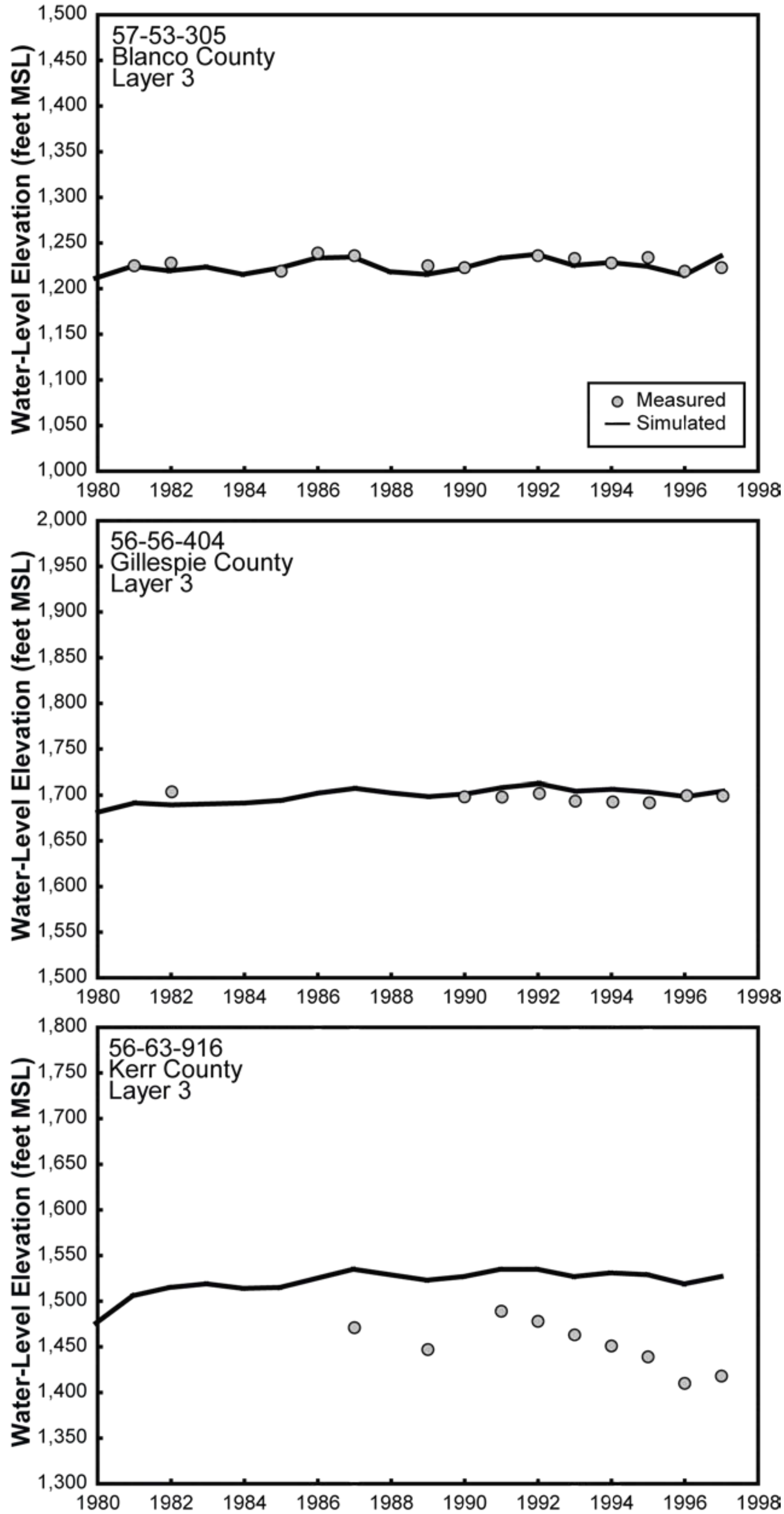


Figure 10-02. (Cont.).

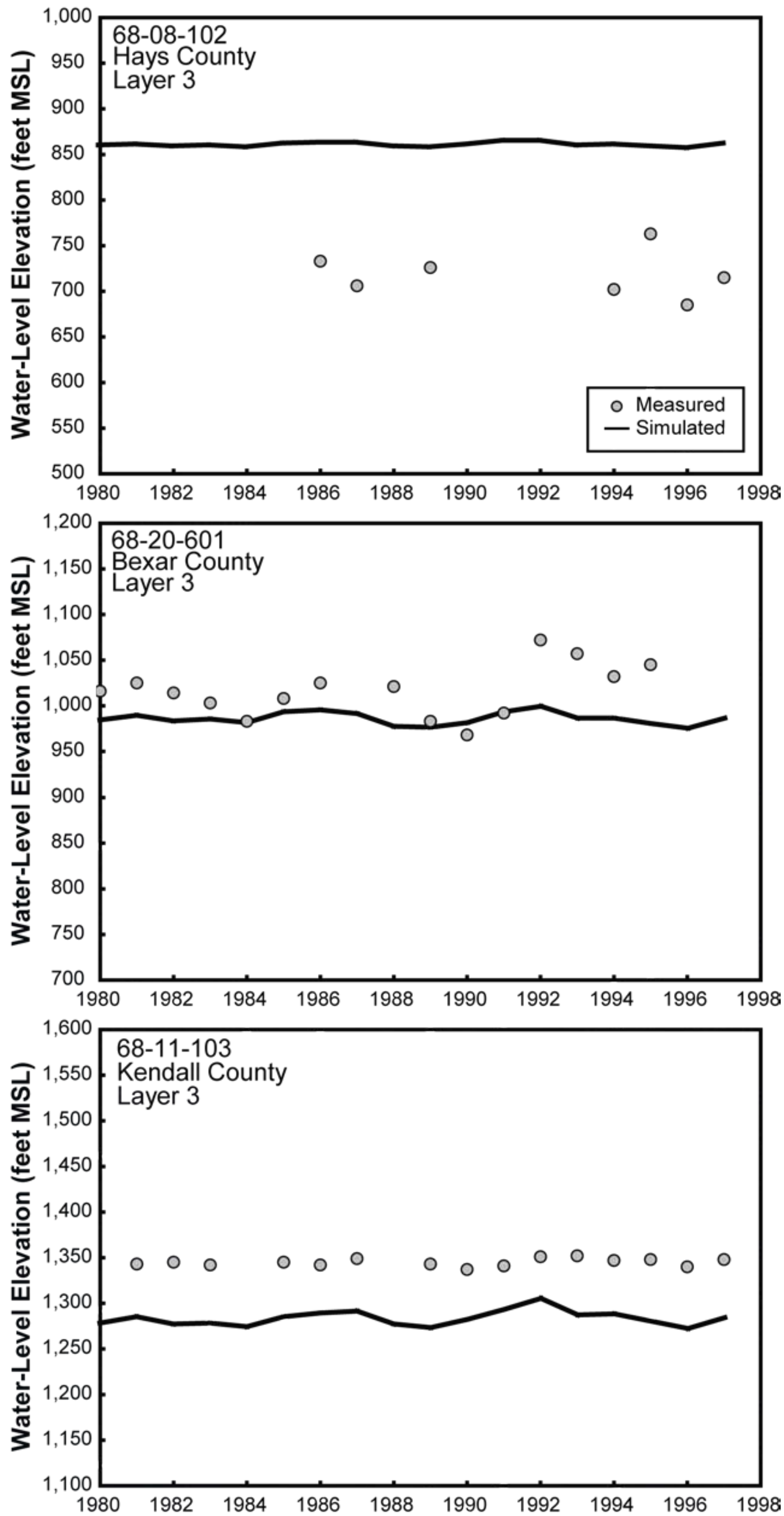


Figure 10-02. (Cont.).

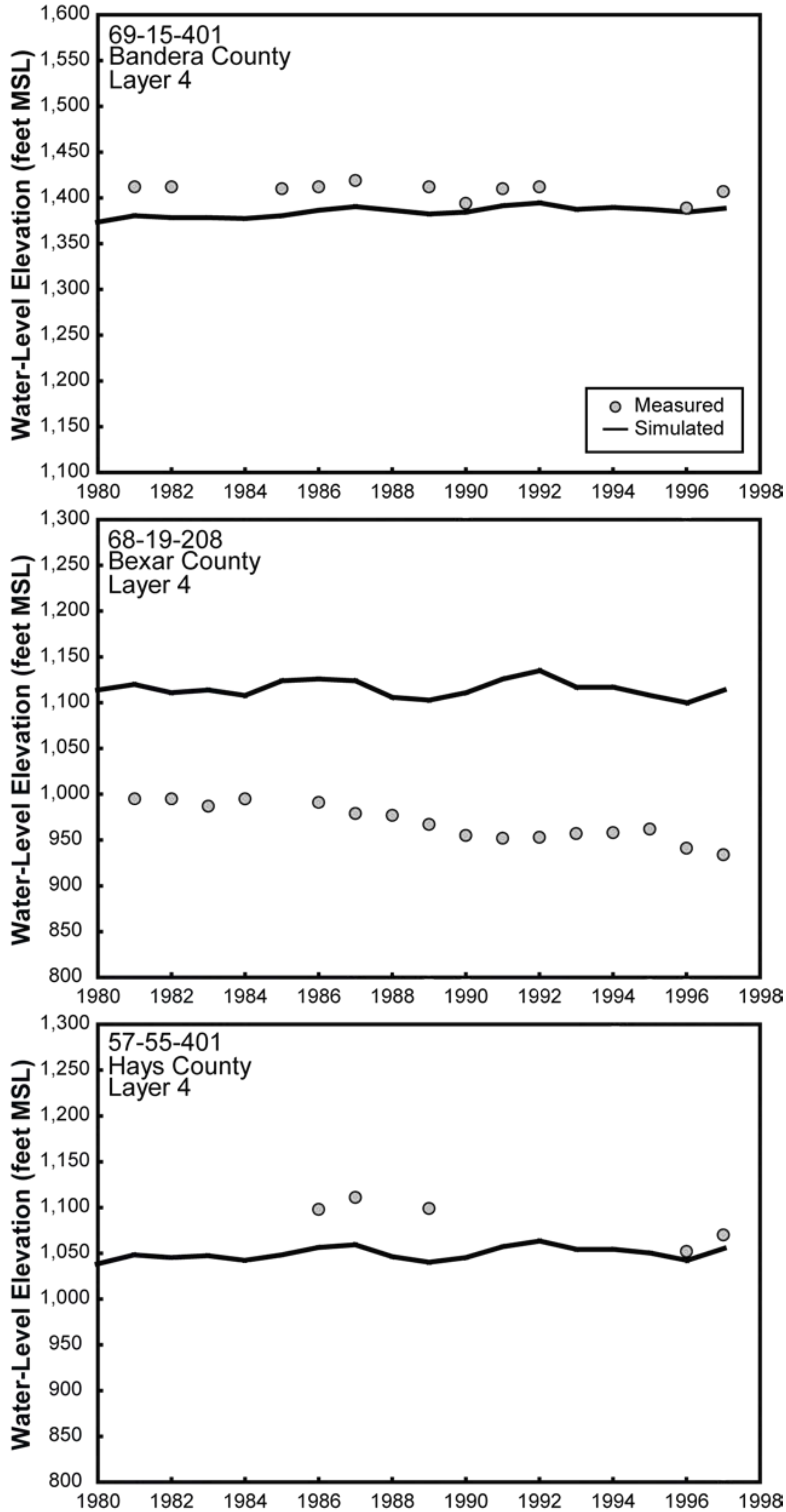
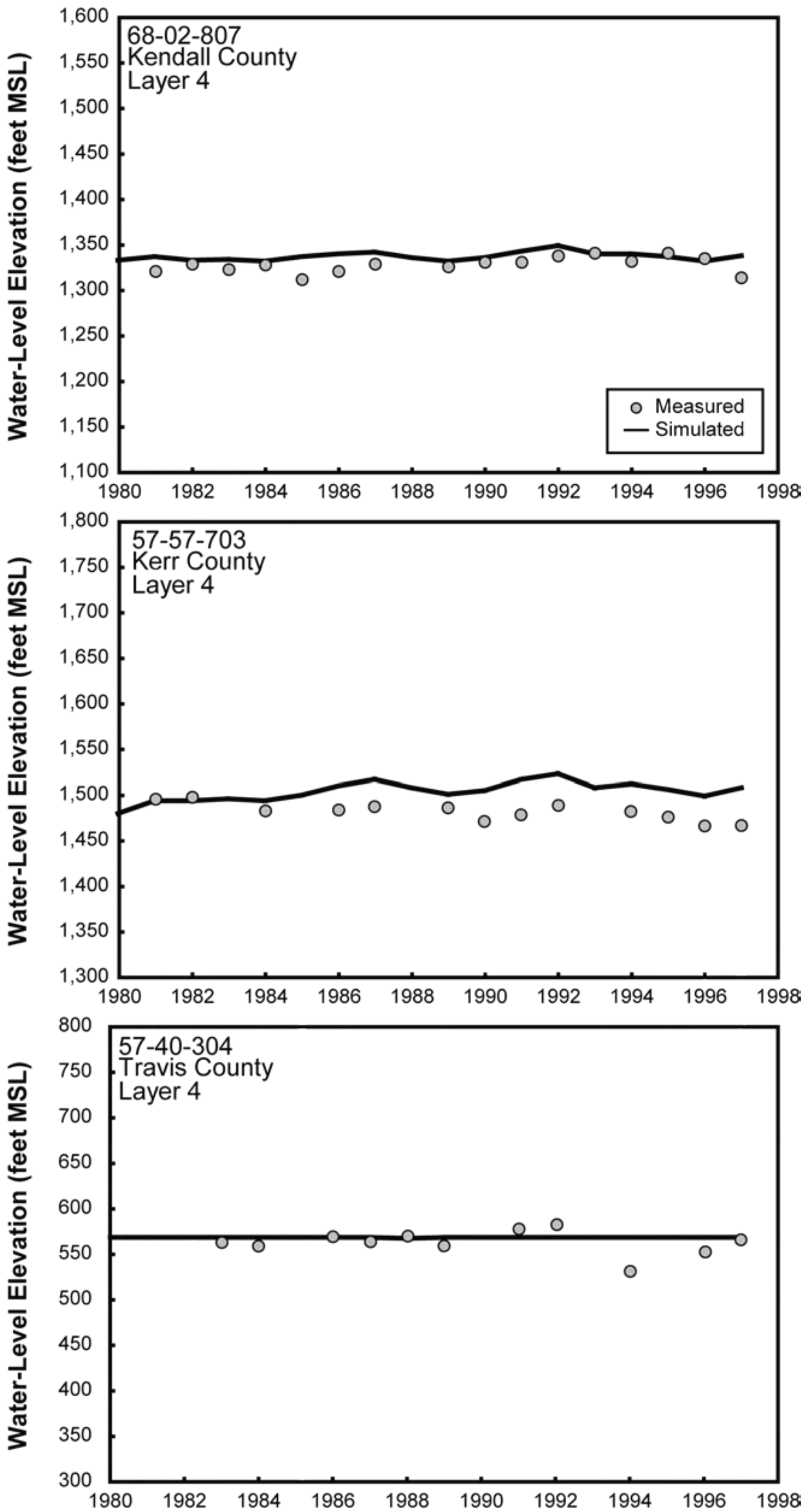


Figure 10-02. (Cont.).



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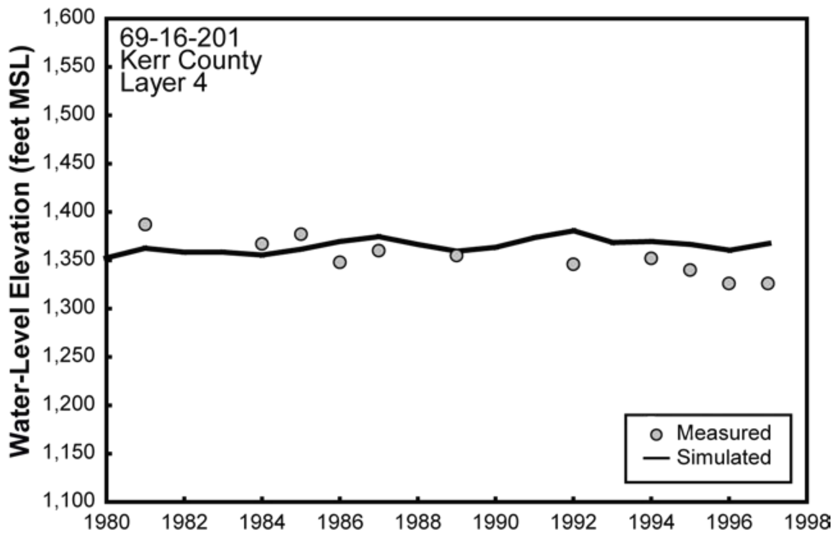


Figure 10-02. (Cont.).

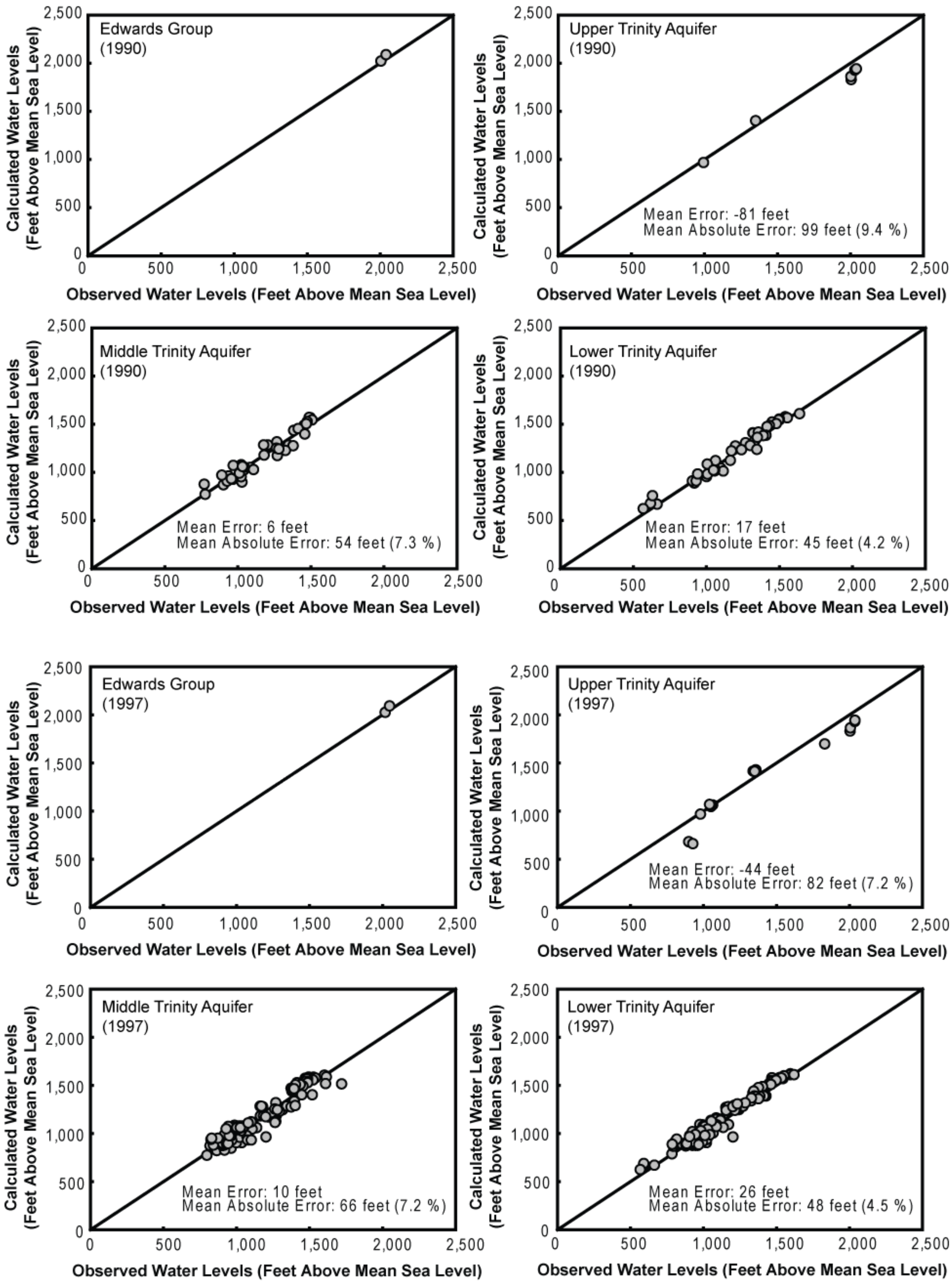


Figure 10-03. Comparison of measured and calculated water levels for 1990 and 1997 from the transient model.

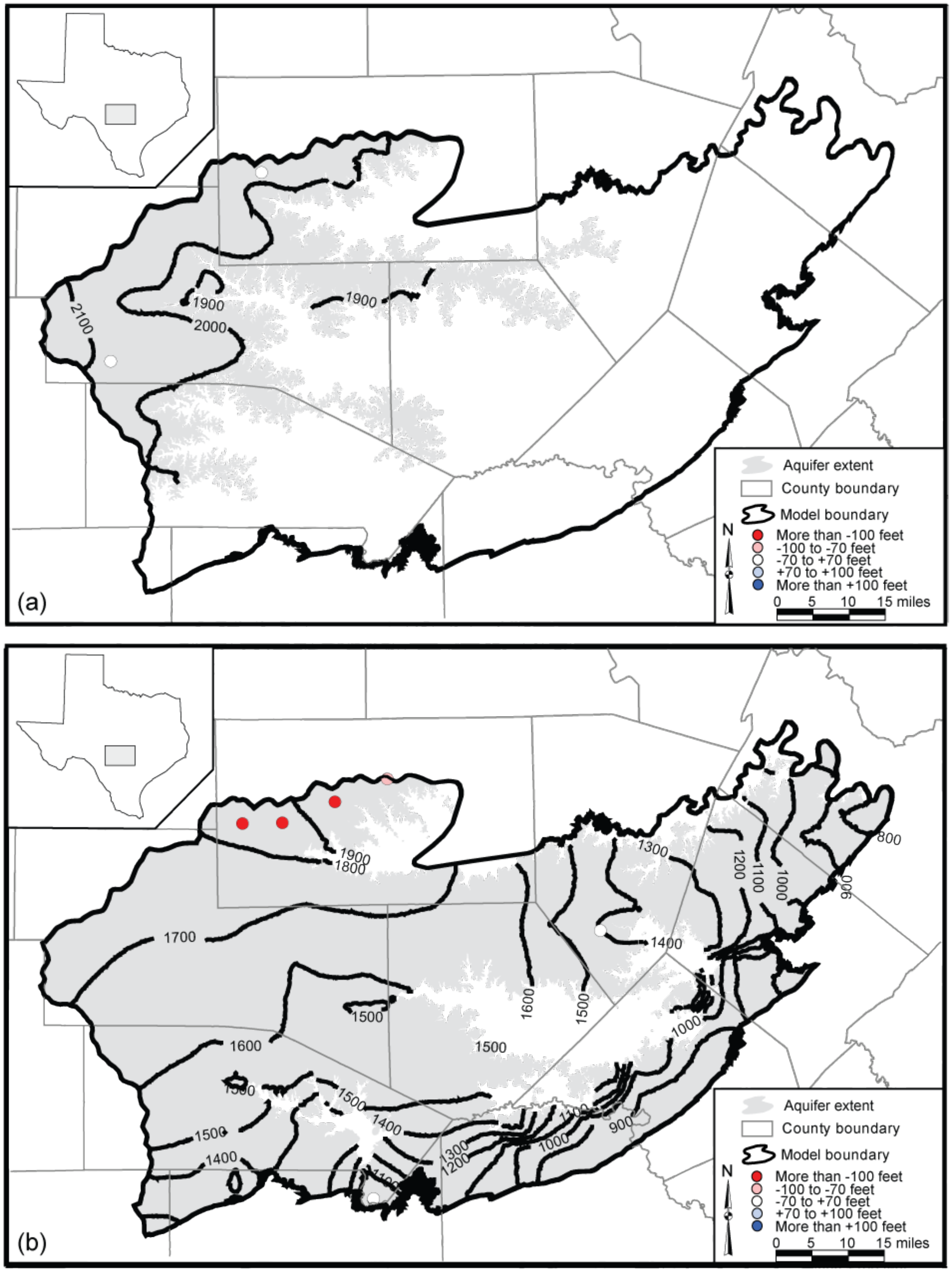


Figure 10-04. Comparison of 1990 measured and calculated water levels from the transient model for (a) Layer 1, (b) Layer 2, (c) Layer 3, and (d) Layer 4. The contours represent calculated water levels while the points indicate the difference between measured and simulated water levels relative to the measured water levels.

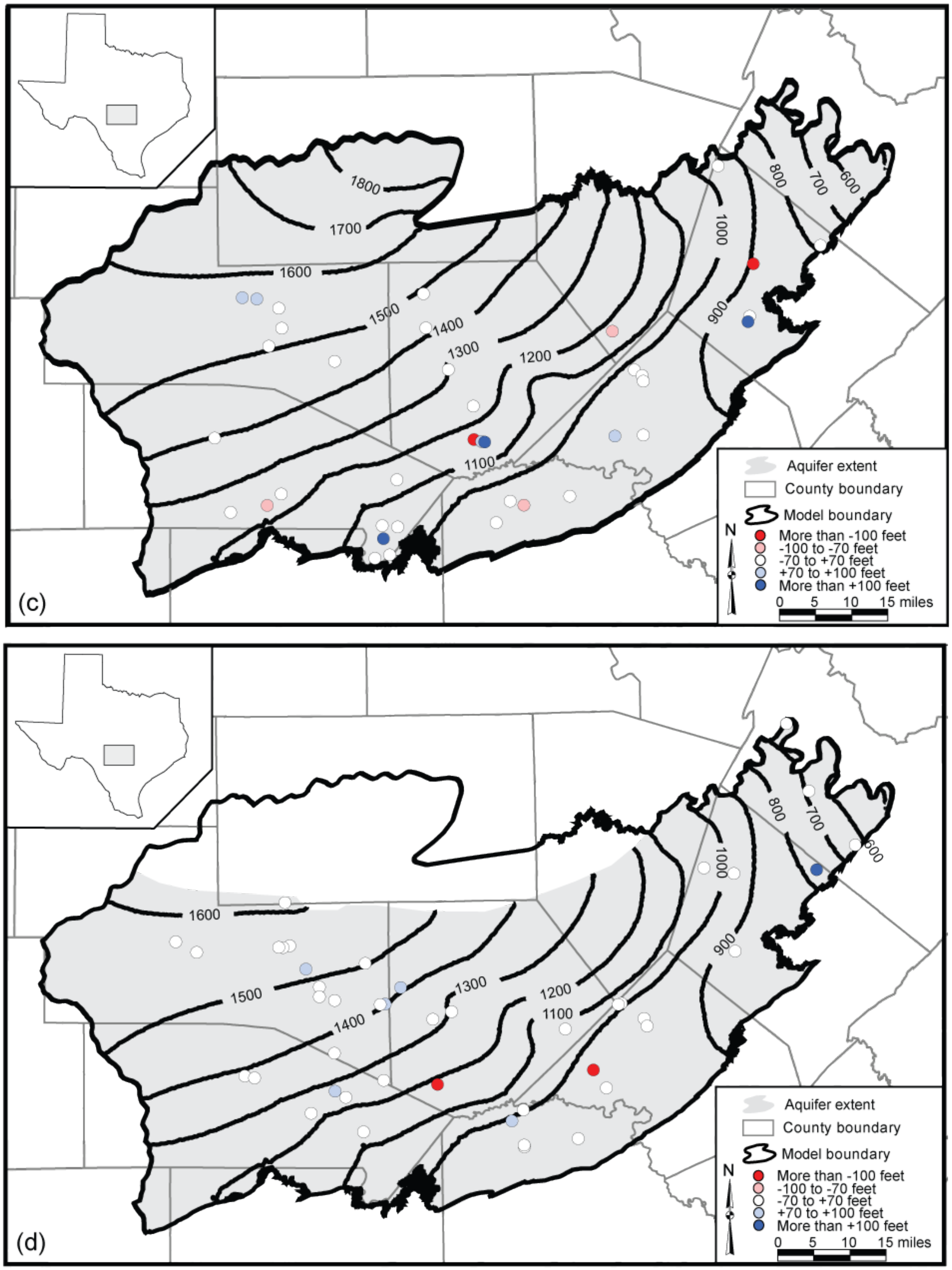


Figure 10-04. (Cont.).

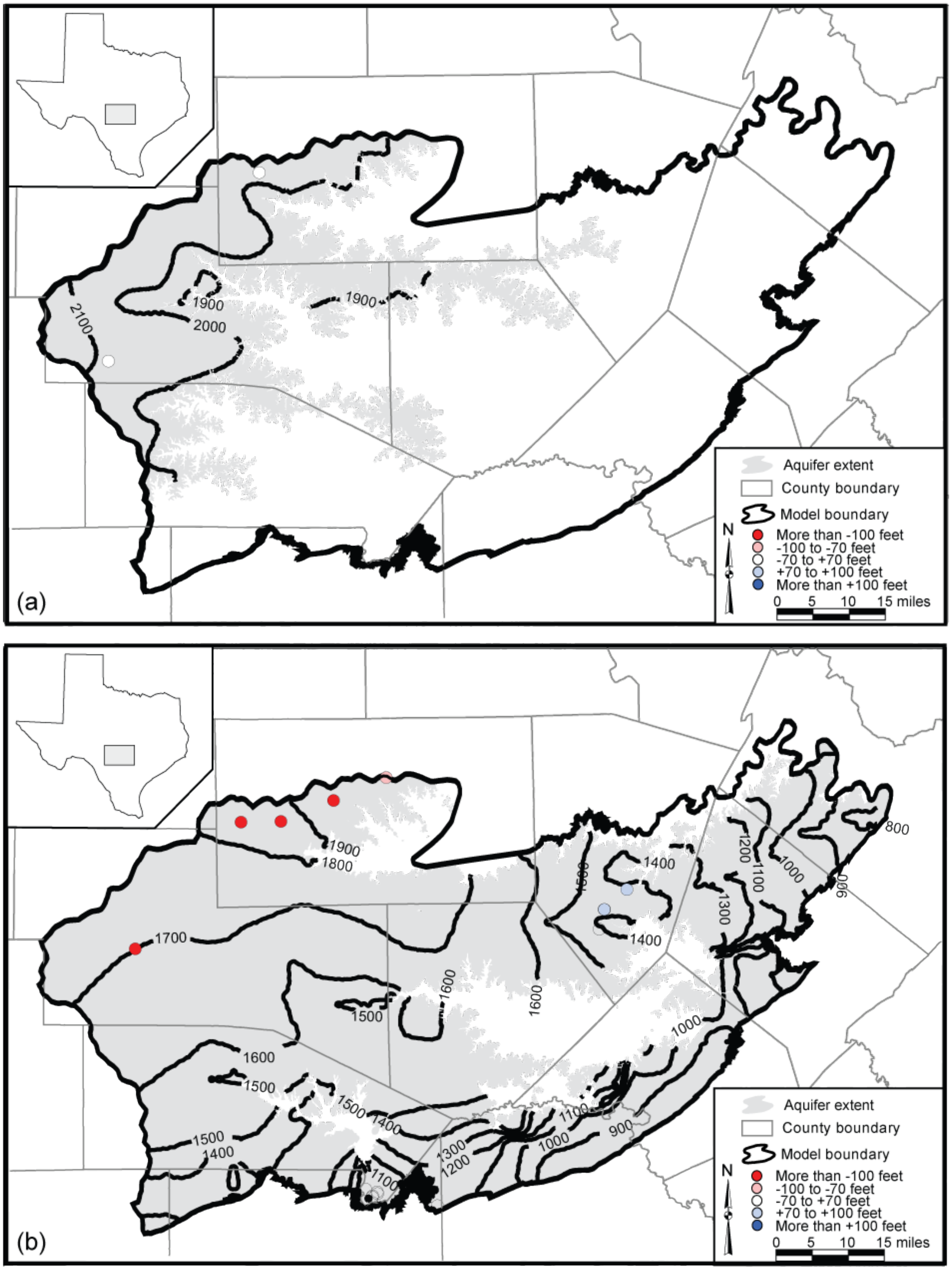


Figure 10-05. Comparison of 1997 measured and calculated water levels from the transient model for (a) Layer 1, (b) Layer 2, (c) Layer 3, and (d) Layer 4. The contours represent calculated water levels while the points indicate the difference between measured and simulated water levels relative to the measured water levels.

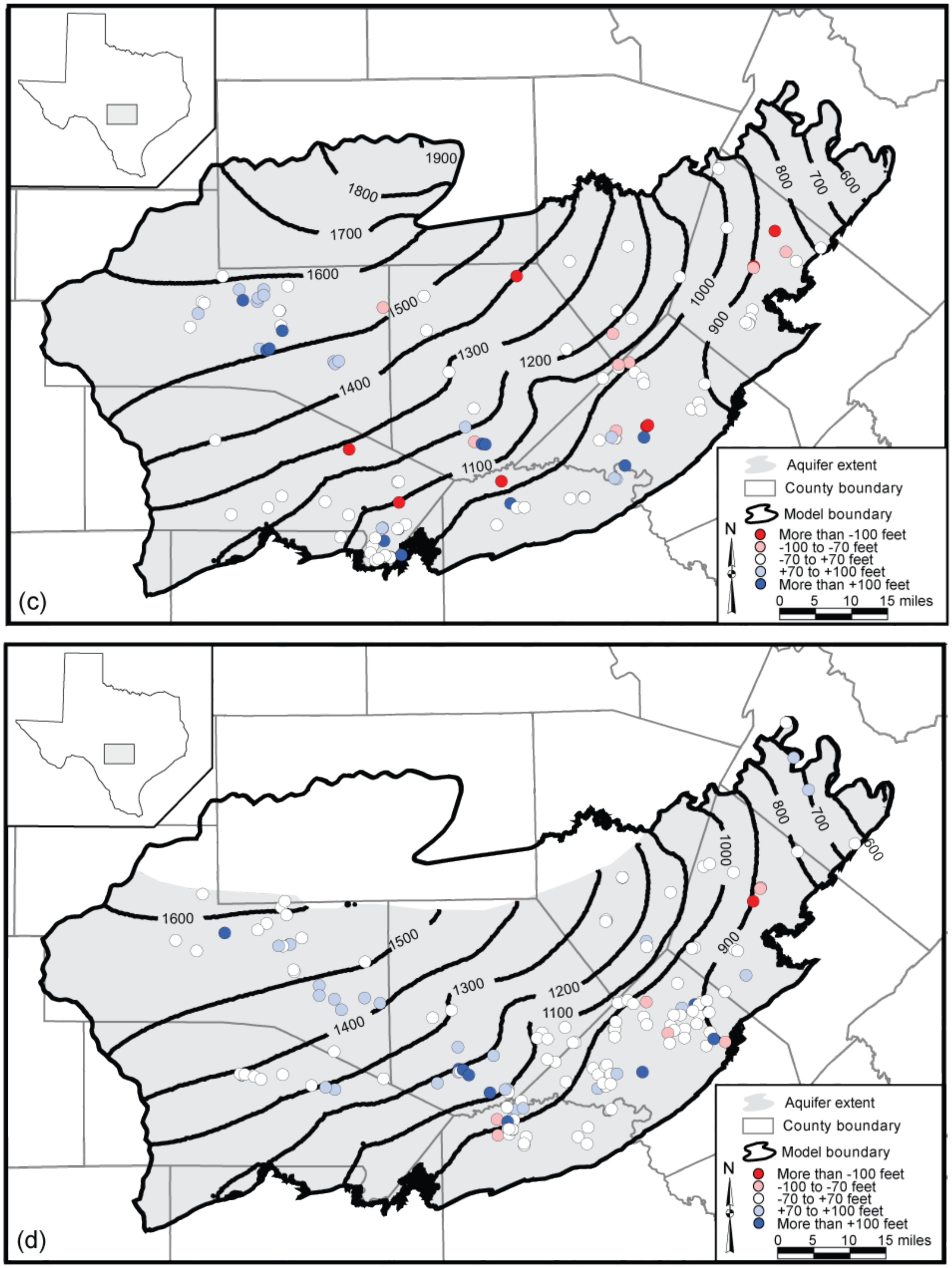
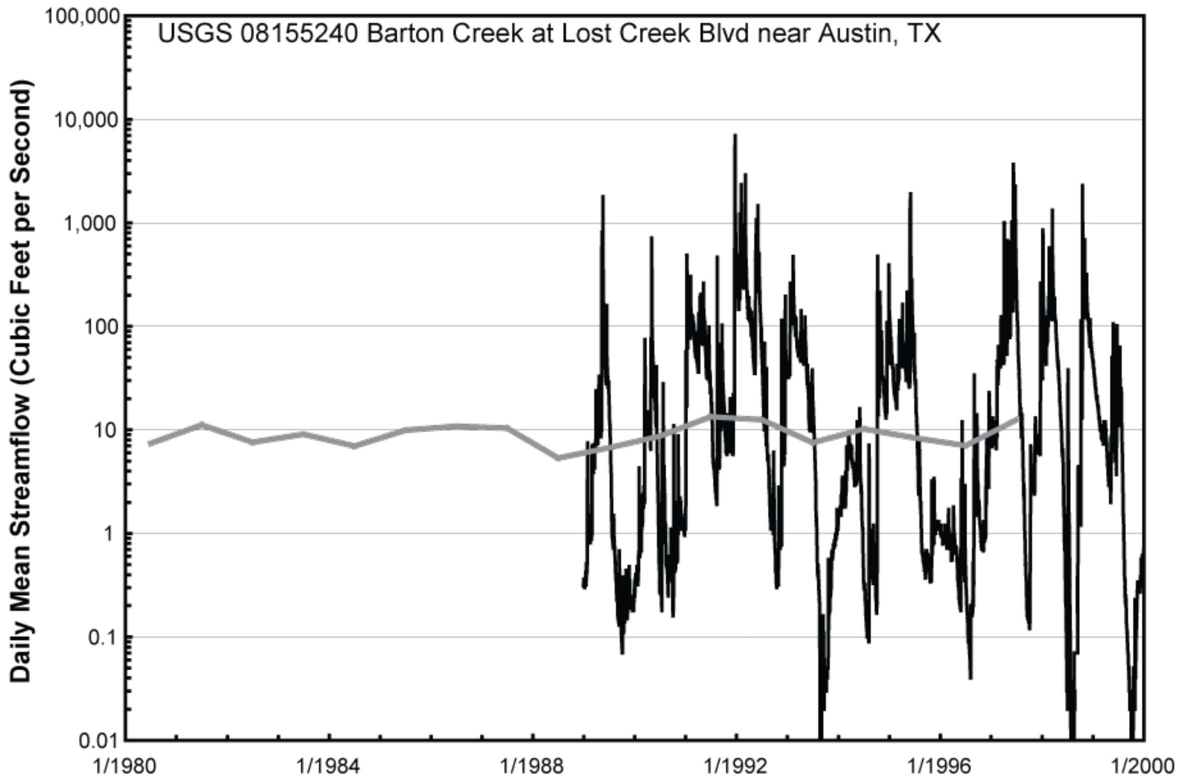


Figure 10-05. (Cont.).



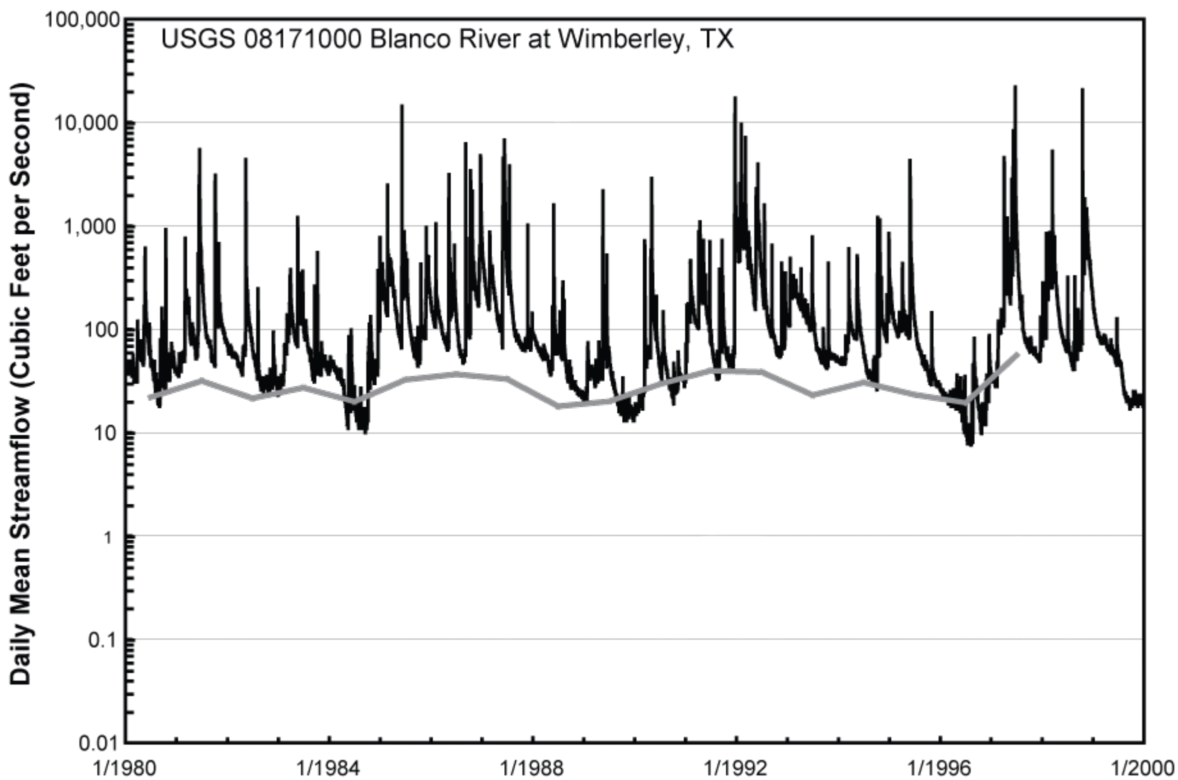


Figure 10-06. Comparison of calculated annual groundwater discharge rates to perennial streams from the transient model (gray line) and measured streamflow data. Stream gauge locations are shown in Figure 9-04.

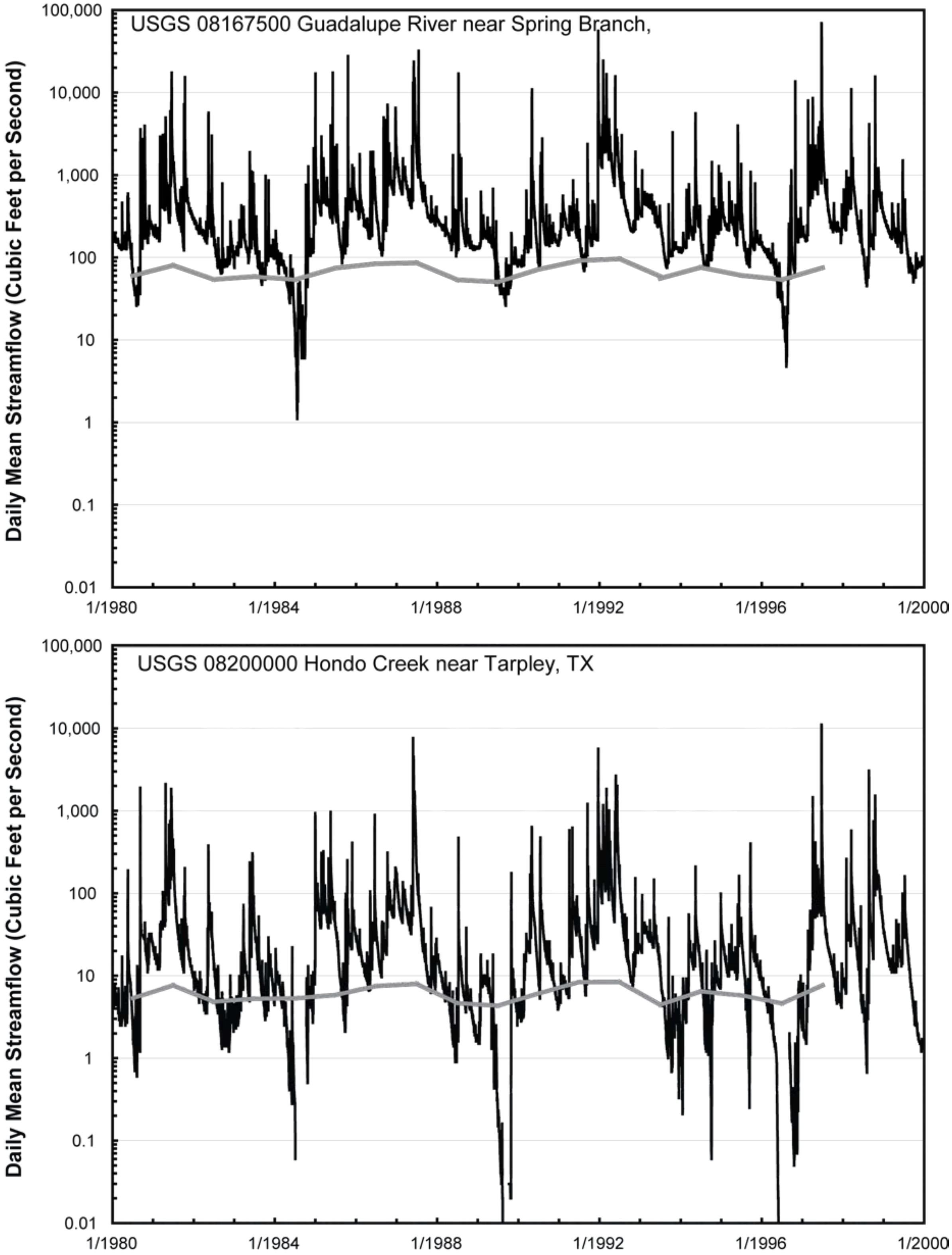
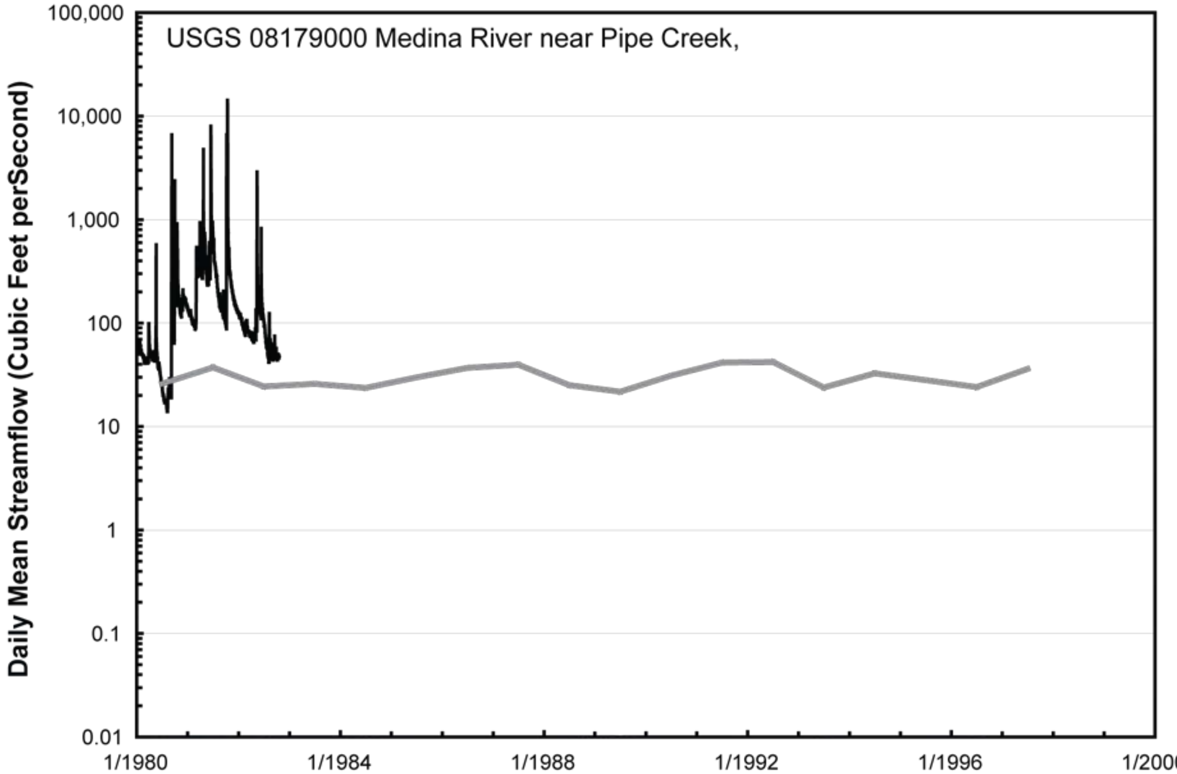


Figure 10-06. (Cont.).



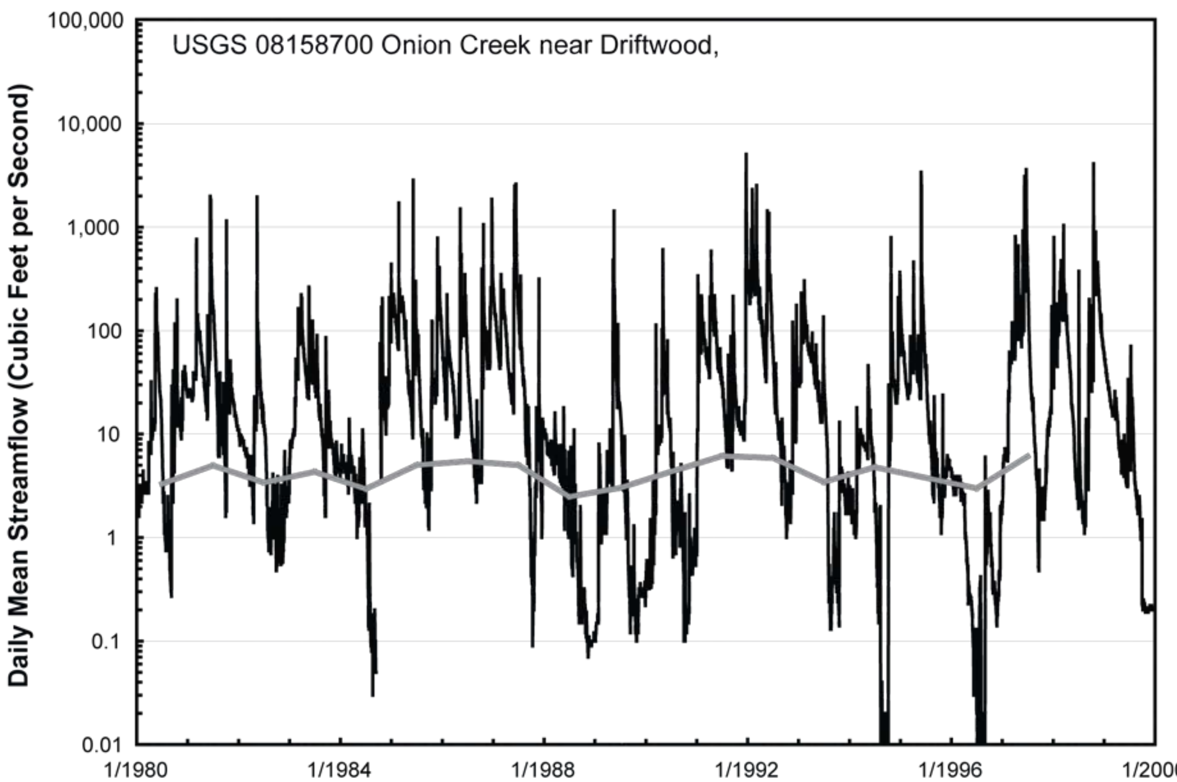


Figure 10-06. (Cont.).

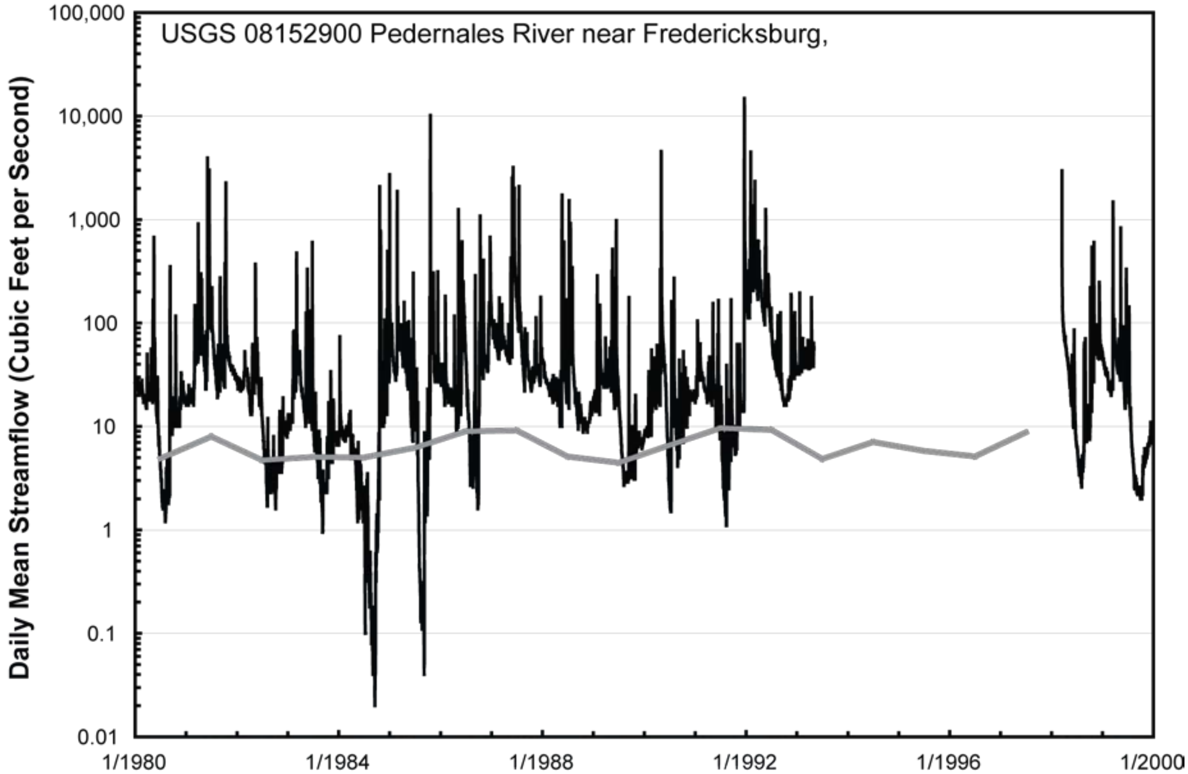


Figure 10-06. (Cont.).

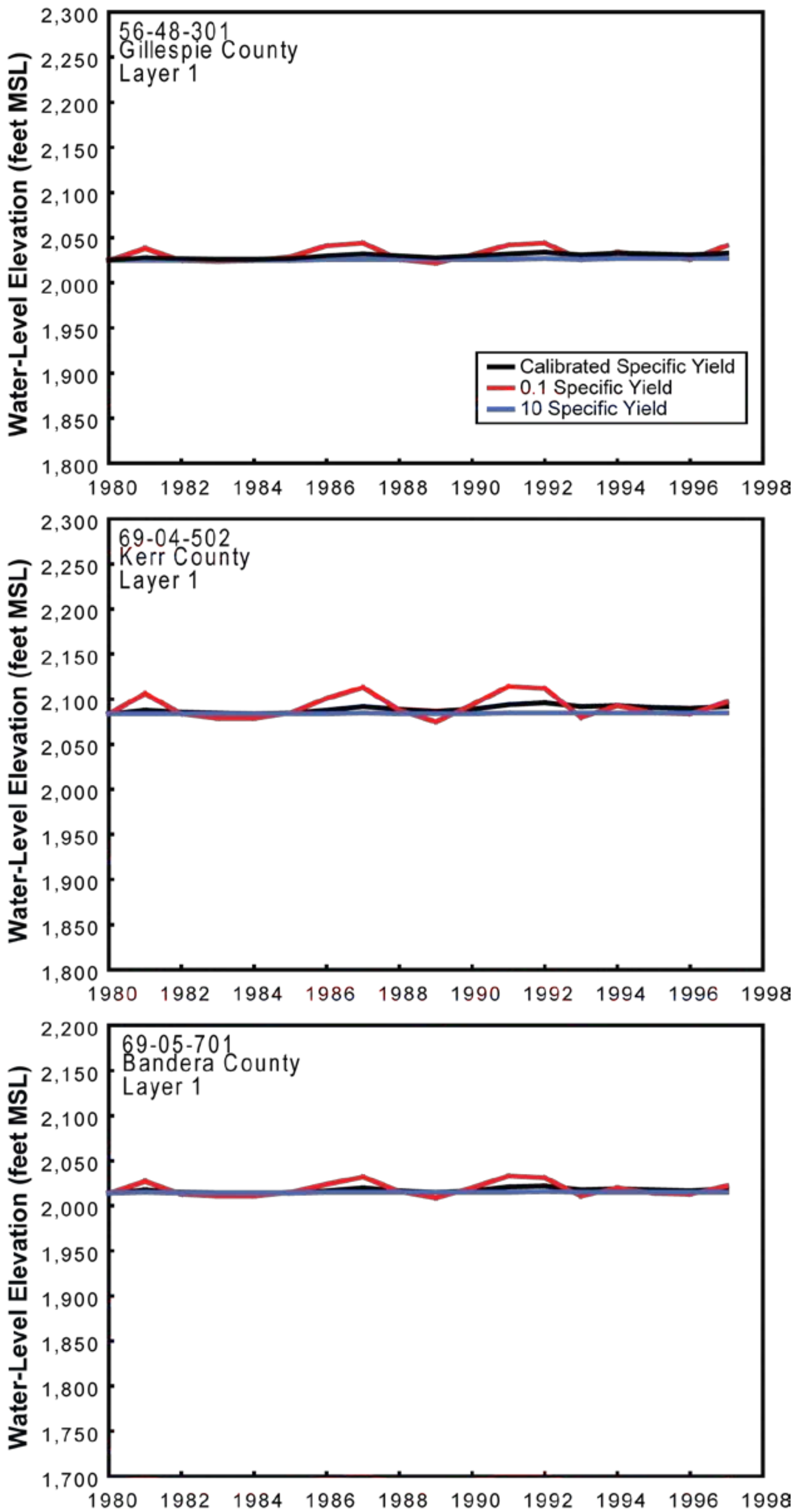


Figure 10-07. Sensitivity of the transient calibration to specific yield. The red and blue lines represent one order of magnitude lower and higher than the calibrated values, respectively, relative to calibrated specific yield values (black line).

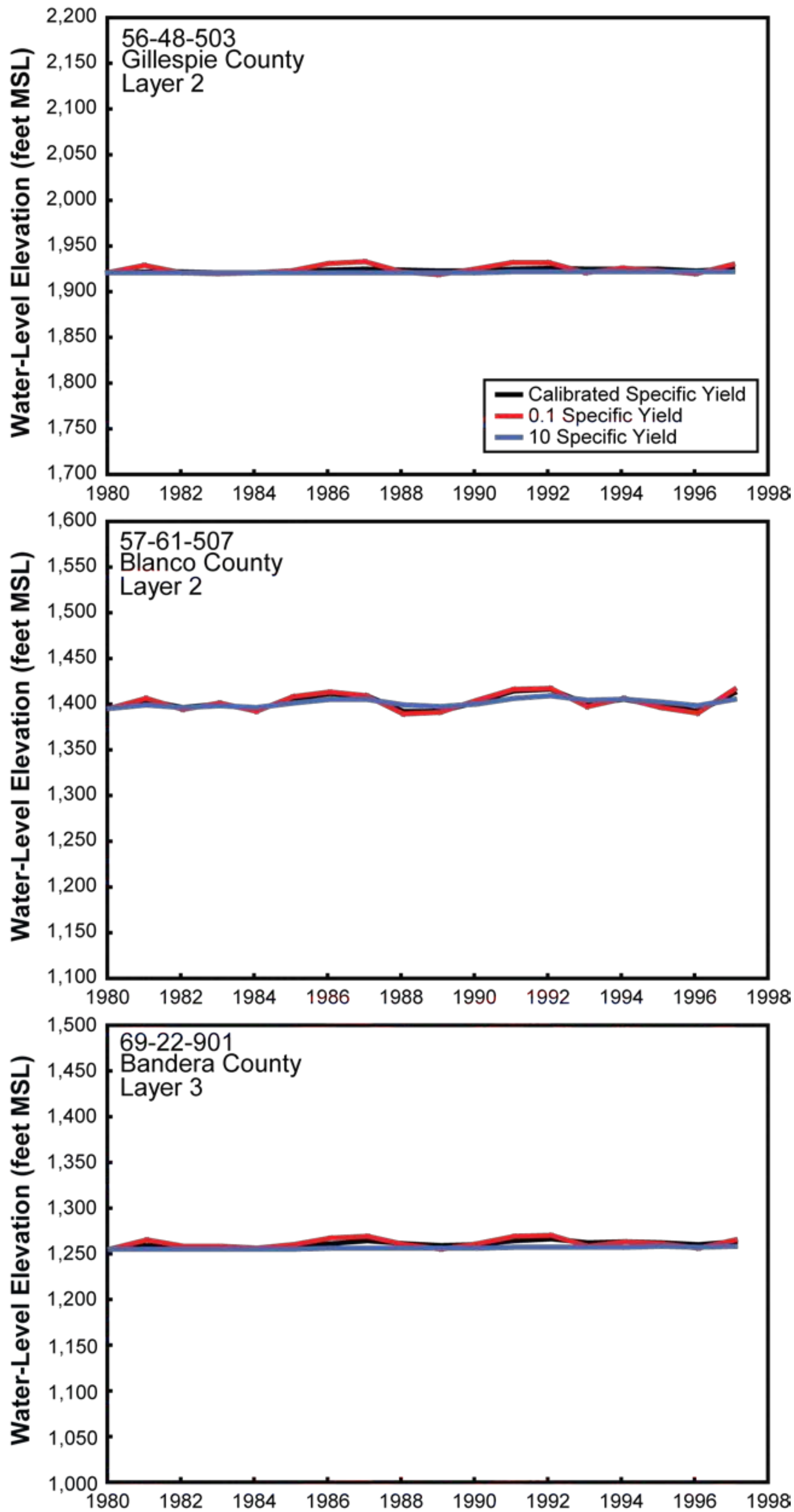


Figure 10-07. (Cont.).

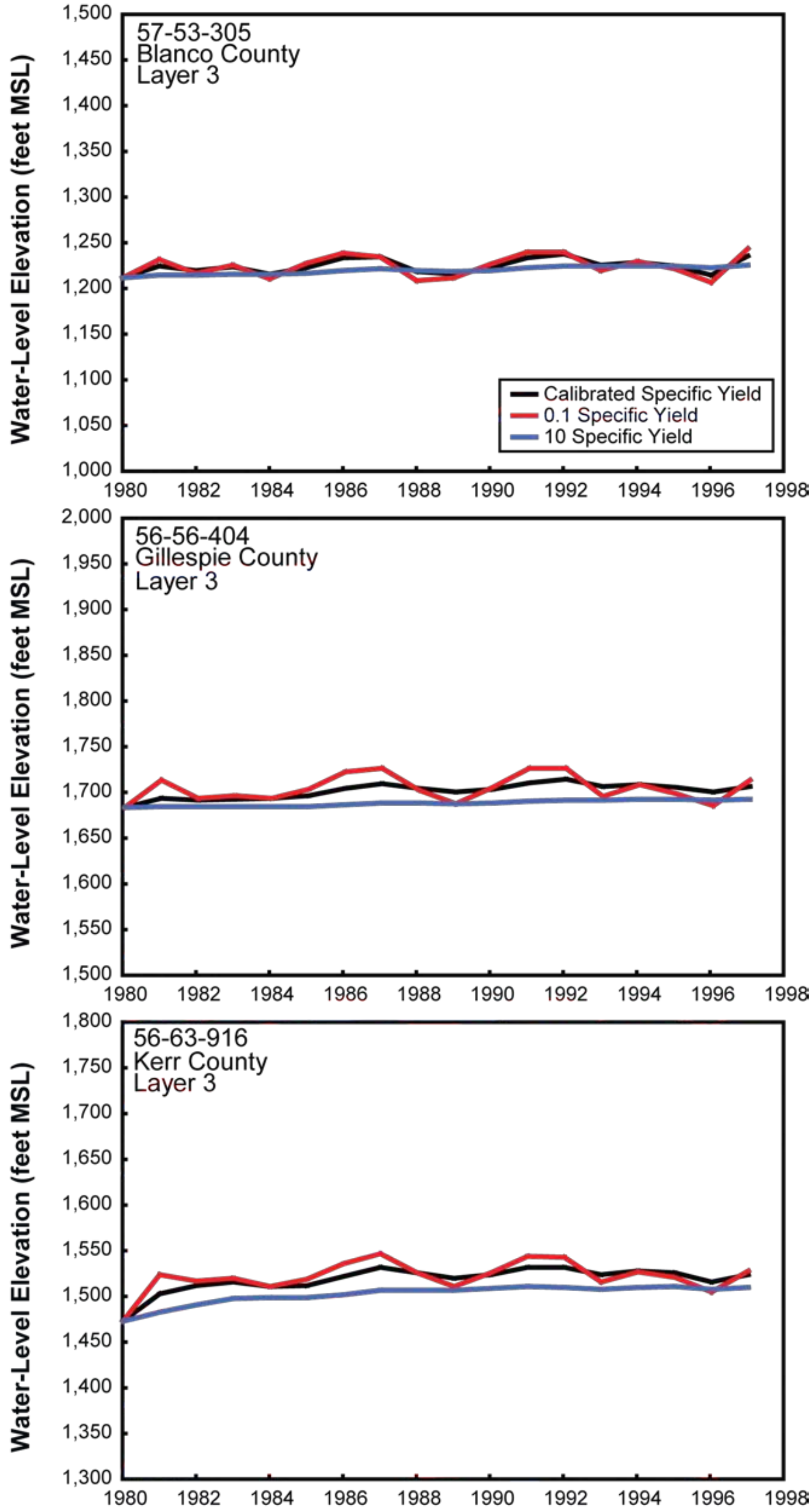


Figure 10-07. (Cont.).

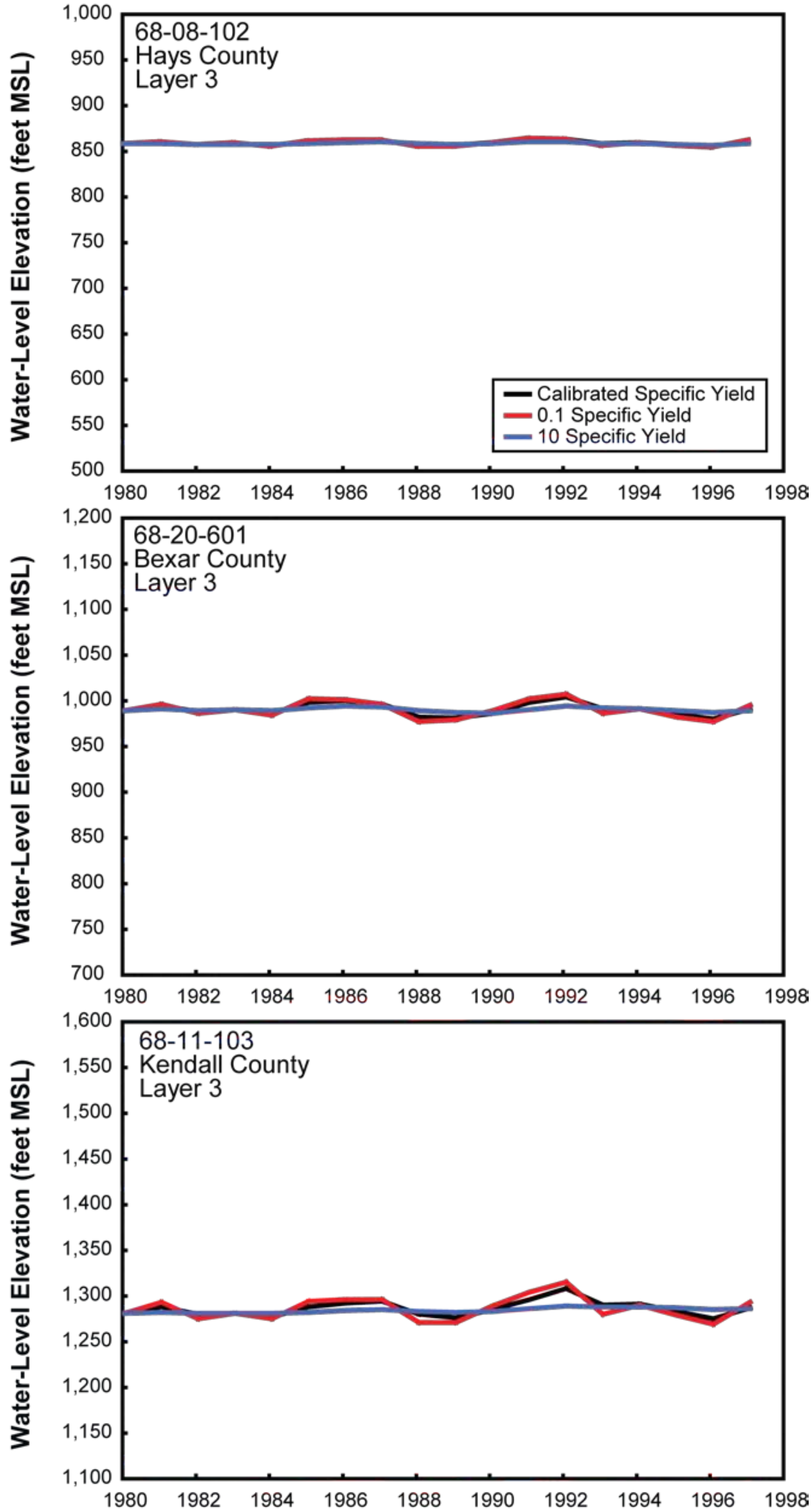


Figure 10-07. (Cont.).

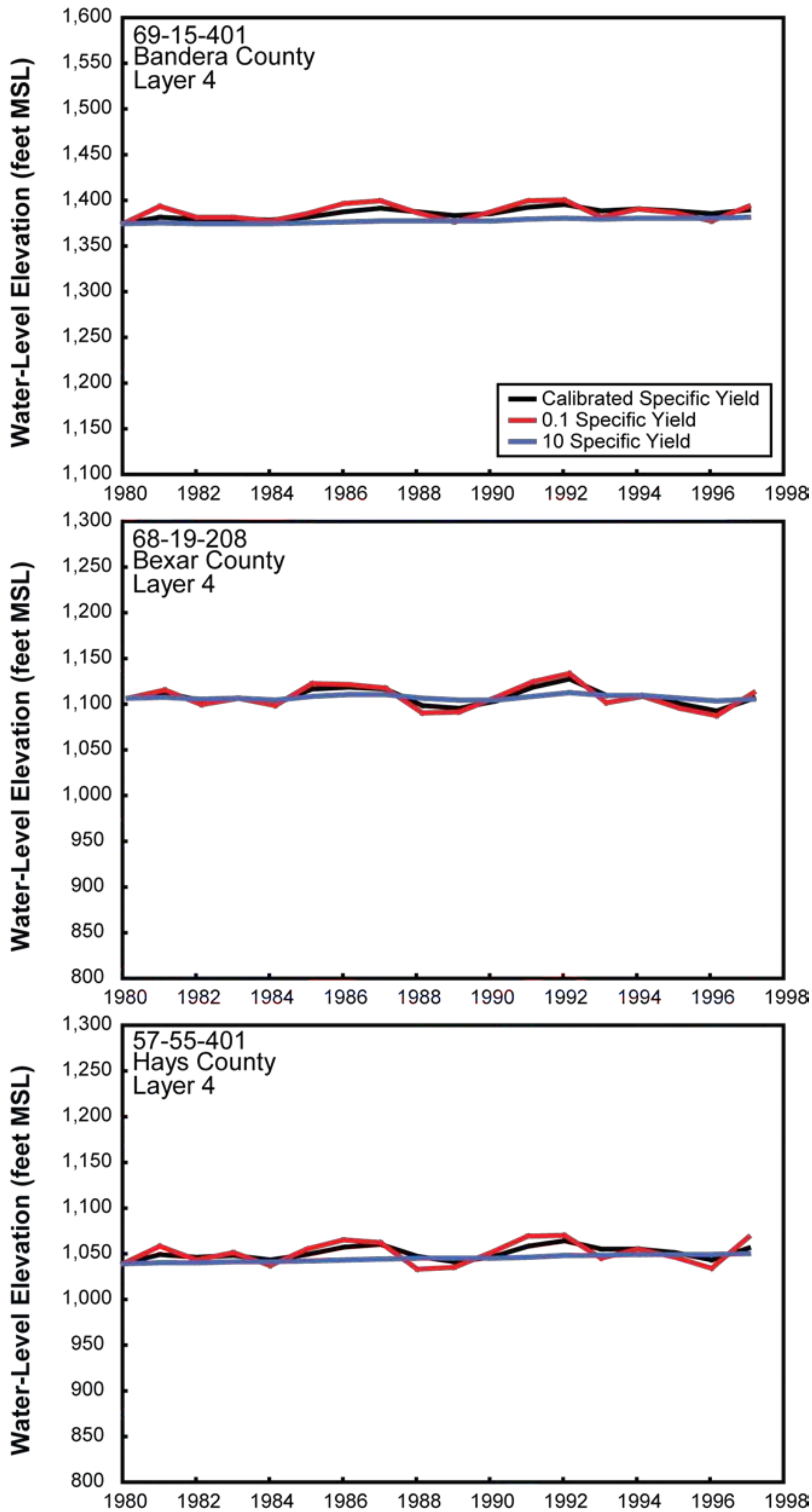


Figure 10-07. (Cont.).

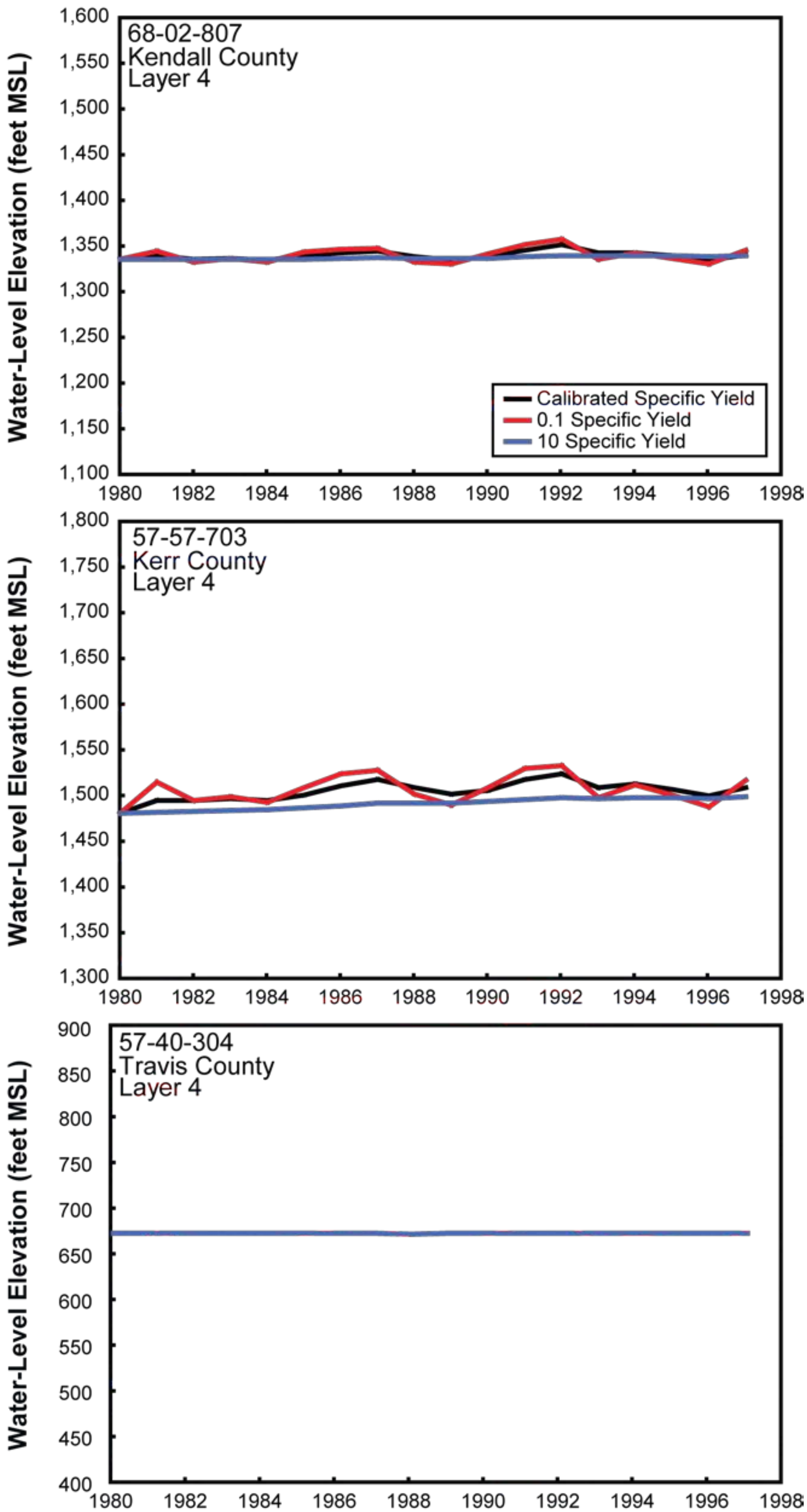


Figure 10-07. (Cont.).

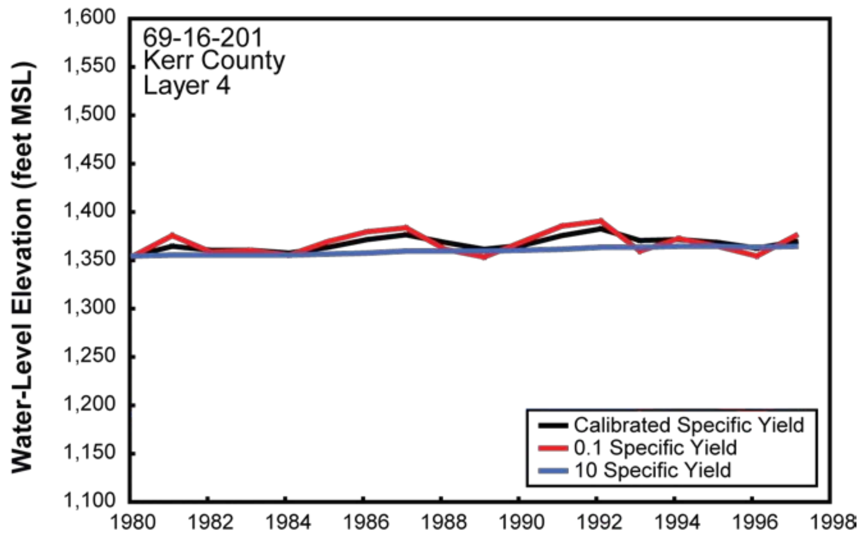


Figure 10-07. (Cont.).

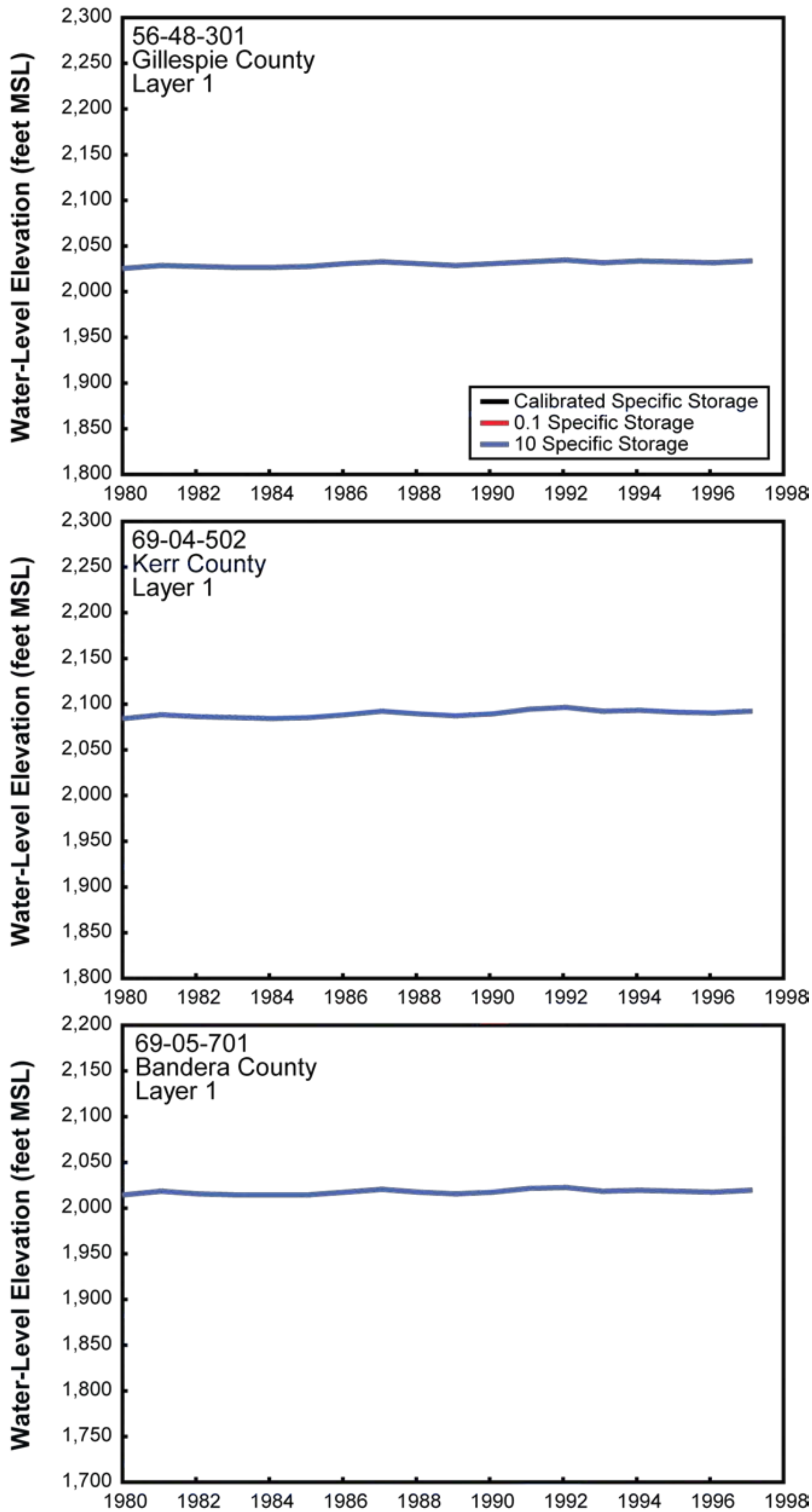


Figure 10-08. Sensitivity of the transient calibration to specific storage. The red and blue lines represent one order of magnitude lower and higher than the calibrated values, respectively, relative to calibrated specific yield values (black line).

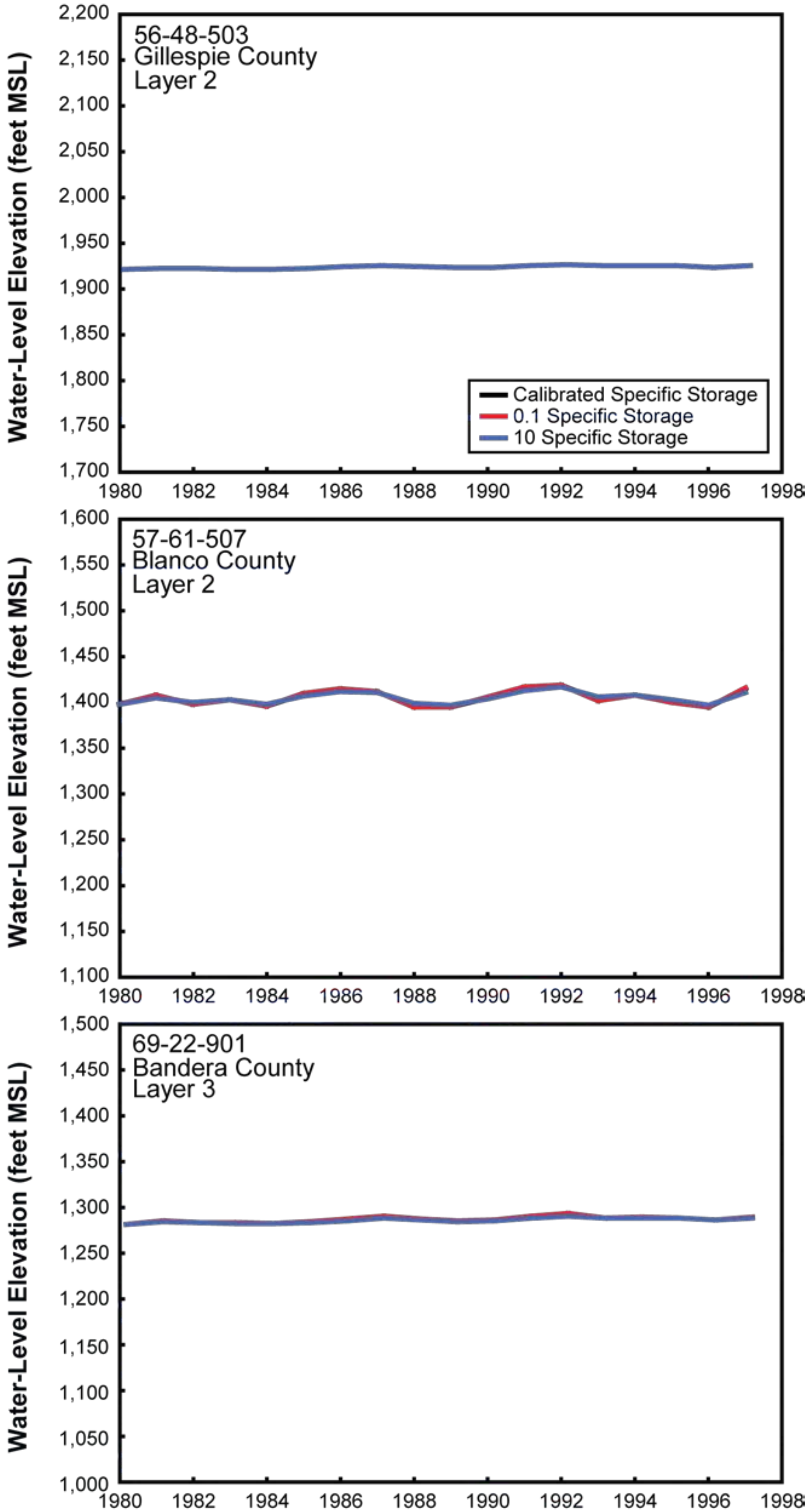


Figure 10-08. (Cont.).

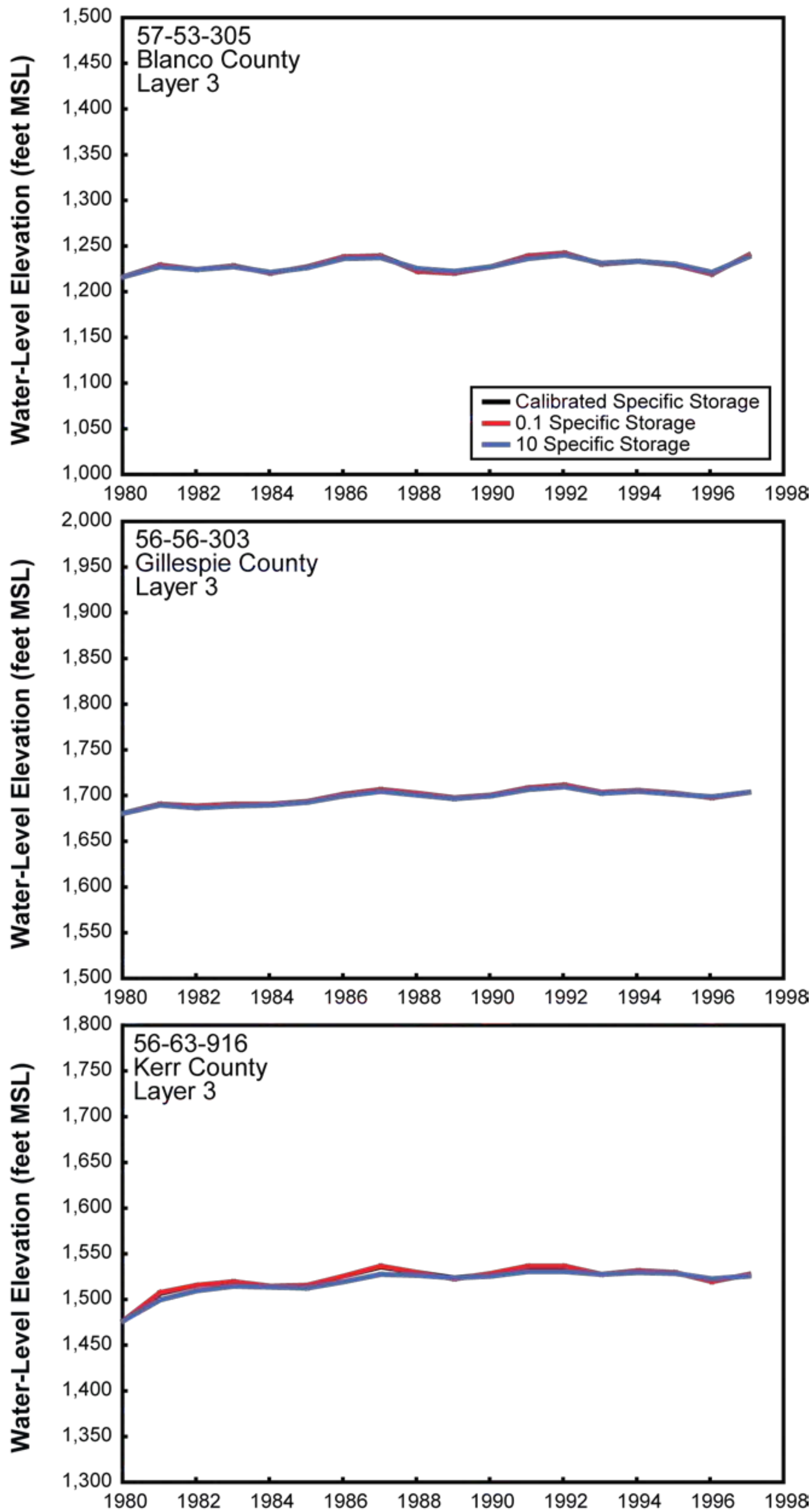


Figure 10-08. (Cont.).

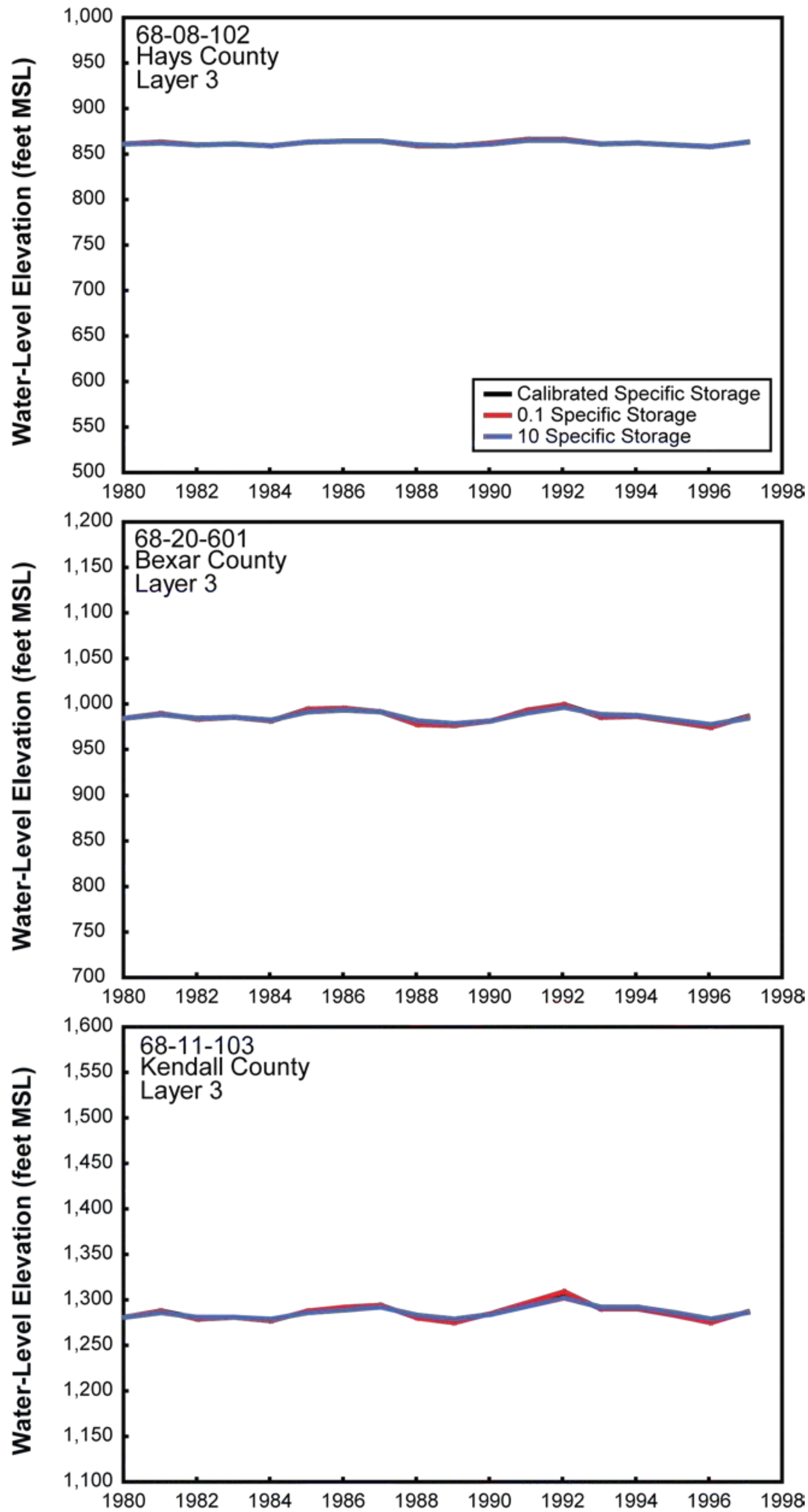


Figure 10-08. (Cont.).

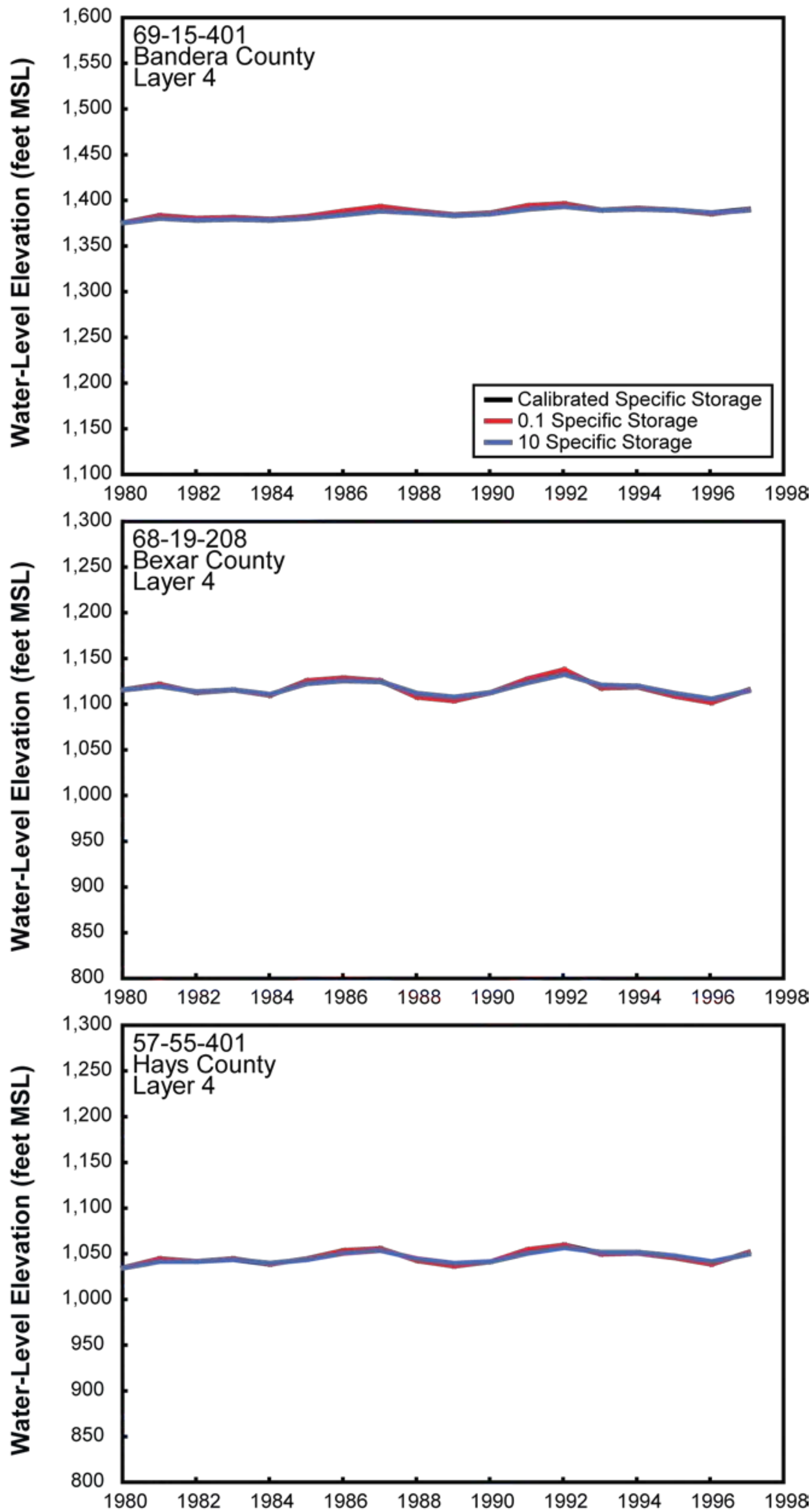


Figure 10-08. (Cont.).

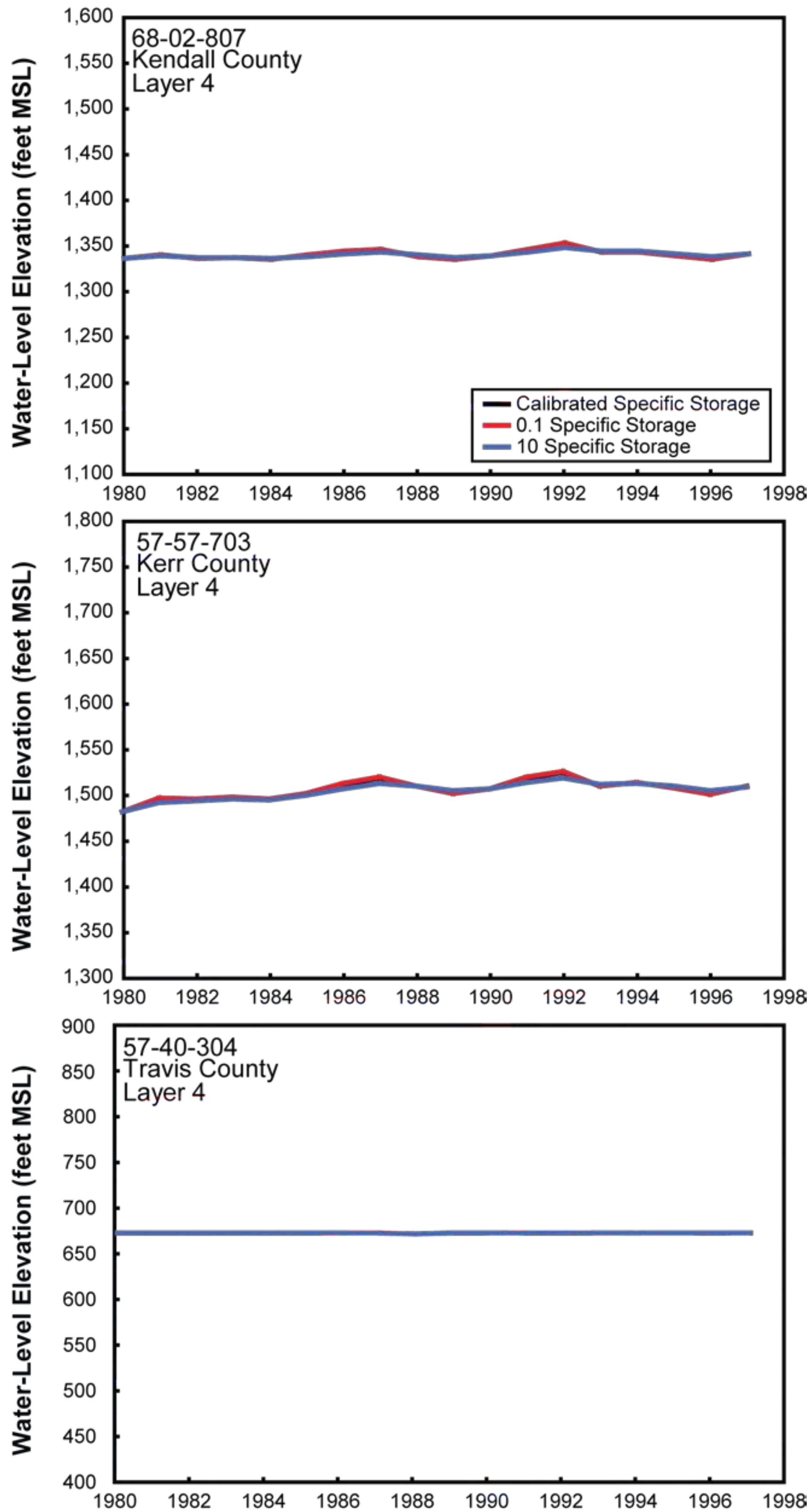


Figure 10-08. (Cont.).

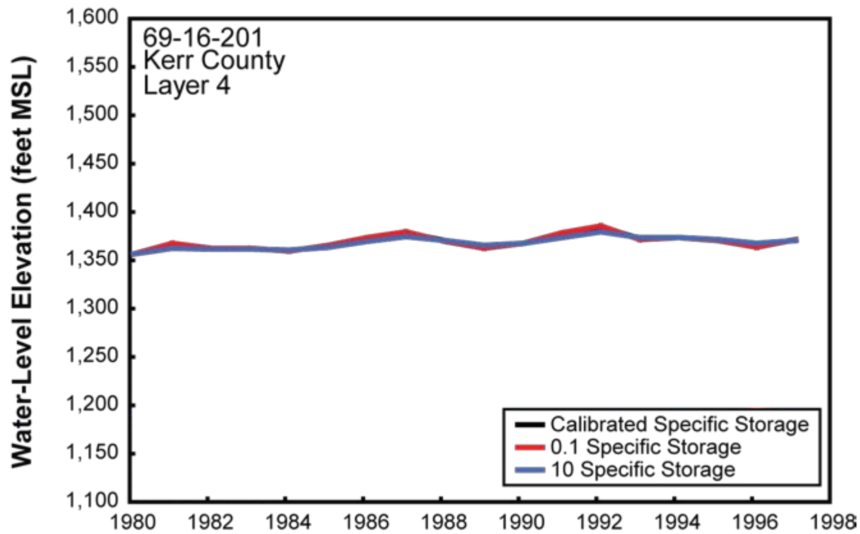


Figure 10-08. (Cont.).

Appendix: Comments and Responses

General Comments

The report is well organized, well written, and contains many quality figures. However, this report may have been prepared prior to the report writing guidelines for the Water Science and Conservation Group and therefore, some of the figures may need to be updated to meet the requirements and all acronyms except for TWDB and MODFLOW need to be spelled out. However, these editorial issues, specific to figures and clarifications or expansions of materials in the text, can be more readily addressed.

No response.

More important issues are inbred in modeling and their supporting documentation. For example, water-level residuals to match simulated and measured water levels reported for the Upper Trinity Aquifer exceed ±100 feet for several wells in the steady-state model. Per the program guidelines, please include reporting mean absolute errors by aquifers rather than lumping all aquifer together in the calculation. This will help determine whether there is any bias in the calibration by aquifer. Some of the key springs, such as the Jacob's Well springs—often considered to be indicative of the health of the aquifer— do not flow at all throughout the simulation period. This may be a significant concern for stakeholders given the importance of the springs. Underestimation of spring flow is plausible given the regional scale of the model, but to have no flow at all, is a serious concern. This may indicate that the simulated water levels are lower than the elevation head of the drains assigned to simulate springflow. No general head boundary is assigned along the Balcones Fault Zone in the east for the Lower Trinity Aquifer even though the aquifer is juxtaposed along the permeable part of the Middle Trinity Aquifer (Lower Glen Rose Limestone) in this area.

Figures 9-03 and 10-03 report calibration statistics for the respective layers in the model. The issue of the difficulty of using a regional model to simulate discharge to springs that are often part of localized flow systems is discussed in the text in Section 10.1. In the previous version of the model attempts were made to force the model to match spring discharge measurements that may not have been representative of average spring discharge. This effort produced a model with large water balance errors. To guarantee discharge to all of these springs would require much smaller grid spacing and much shorter stress periods which is difficult to justify given: (1) the absence of spring discharge data to calibrate to, (2) the available discharge measurements are as low as 25 gallons per minute, and (3) the springs are minor, accounting for less than 3 percent of total discharge to surface water bodies and less than 2 percent of total discharge from the aquifer. The decision to place a no-flow boundary along the southern and eastern boundary of the Lower Trinity Aquifer was based on previous work by Hovorka and others (1996) that indicated little groundwater flow crossing that boundary.

We have made numerous technical and editorial comments in the report. These comments need to be addressed to improve the content and quality of the report. For example, some structural control points are shown in Gillespie County that was used for developing the top and base of the Upper Glen Rose Limestone where the aquifer does not exist. A time frame of 1977 to 1985 selected for construction of water level map for the steady-state model may leave out many water-level measurements in the north and the west thus preventing an opportunity to measure quality of the calibration in these areas. Hydraulic conductivity values assigned for calibration in the aquifers are considerably higher than the previous model and therefore, need adequate explanations on how these different values were derived. For example, hydraulic conductivity assigned in the Upper Trinity Aquifer is 5 feet per day in the previous model. In the current model, hydraulic conductivity assigned in the Upper Trinity Aquifer is 9 feet per day for most of the model area and 15 feet per day along the Balcones Fault Zone. In the Lower Trinity Aquifer, hydraulic conductivity assigned for most part of the aquifer is 1.67 feet per day, an order of magnitude lower than 16.7 feet per day assigned along the Balcones Fault Zone. Calibrated hydraulic conductivity values should always be kept close to the measured values unless there is a stronger hydrogeological reasoning to change this. We suggest strengthening the arguments for using higher hydraulic conductivity values for calibration along with presentation of maps showing such measured values, if available.

The calibrated hydraulic conductivity values used in the model lie within the range of the measured data for the respective layers. These calibrated hydraulic conductivity values represent the overall effect of the actual range of hydraulic conductivity values that occur in the aquifer system. The Trinity Aquifer System is highly heterogeneous both vertically and laterally within the stratigraphic units that make up each model layer, thus it is erroneous to assume that any one value is representative of the model layer or that any two measured values are related to each other. Especially when hydraulic conductivity data: (1) are few in number, (2) are widely scattered throughout the aquifer, and (3) there is high uncertainty over the stratigraphic or hydrostratigraphic is represented by the data.

In the previous model simulated discharges to the Guadalupe, Medina, and Blanco Rivers were within 25 percent of estimated values. In the current model, simulated stream discharges may show a higher difference than this. We suggest reporting simulated discharges for 1980, 1990, and 1997 in tables.

It is not possible to do this comparison because baseflow analysis was not part of this project.

Specific Comments

1. Page 1: Executive summary does not adequately capture important elements of the report. We suggest inclusion of short descriptions on structure development, conceptual flow system, rationale for assignment of model boundaries, calibration statistics, and flows. Please compare to previous version of the model.

   Text added that is appropriate to the executive summary (Page 1).

2. Page 1, paragraph 2: Please add the Edwards Group in the write-up as it forms layer 1 of the model.

   Text added to paragraph (Page 1, paragraph 2).

3. Page 1, paragraph 3: Please verify the statement "Preliminary estimates of recharge equal four to six percent of annual precipitation over most parts of the aquifers". Recharge through the large swath of the Balcones Fault Zone is much higher, as much as 15 percent of precipitation.

   Text revised to reflect full range of recharge rates (Page 1, paragraph 3).

4. Page 5, paragraph 2: Please replace the term "carbonate sandstone" with "calcareous sandstone".

   Done (Page 5, paragraph 6).

5. Page 6, end of Section 3.2: Per GAM program guidelines, moved discussion of structural and tectonic features and cross-sections from Section 5.2 to Geology Section, please update numbering of figures as needed throughout the report.

   Done.

6. Page 8, Section 5.2: Please clarify and discuss how contributions from groundwater conservation districts were used to adjust structure in the updated model. At minimum, please discuss that information was reviewed and in agreement with our interpretation of structure.

   Text revised as appropriate.

7. Section 5.3: Per GAM program guidelines, for each model layer please include potentiometric surface maps 1980, 1990, and 1997. Please update report with potentiometric surface maps for 1990 for each layer and add a map for 1997 for the Edwards Group.

   Figures 5-13 through 5-16 along with model results indicate that potentiometric surfaces in 1990 and 1997 are essentially the same as those in 1980. In the absence of regional water-level changes it is unnecessary to show potentiometric maps for 1990 and 1997. Text added to Page 10, paragraph 2 to discuss this.

8. Section 5.3, Page 9, second to last paragraph: I suggest commenting on what may have caused the 130 foot water level rise in Kerr County shown in well number 56-63-604, in Figure 5-18.

   Text revised (Page 10, paragraph 3).

9. Page 11, paragraph 1: Recharge estimates by various authors are included in this section. Recently, Wet Rock Consultants estimated groundwater recharge for Kendall and adjacent counties that has not been discussed. Discussion of this report may be relevant given the higher recharge used in the current model in the east.

Added recharge estimate by Wet Rock Groundwater Services to Table 5-01.

10. Page 11, paragraph 2: We could not entirely agree with these statements "The recharge estimation method used by Mace and others (2000) is less accurate than recharge estimation based on precipitation because regional groundwater flow results in underestimation of recharge in upstream areas and overestimation downstream. The method used by Mace and others (2000) assumes that watersheds are closed systems with all recharge discharging to adjacent streams and does not take into account regional groundwater circulation that results in groundwater leaving or entering the watershed". This is because Mace and others (2000) used baseflow coefficients as well as precipitation distribution to estimate recharge. Perhaps, the more important difference in recharge estimation between the current and the previous model is that the previous model did not include additional recharge in the Cibolo Creek watershed and along a selected zone in the BFZ that has never been reported in the literature before.

    Revised the text but retained the criticism of the Mace and others (2000) methodology which also appears in Mace and others (2000) on Page 34, paragraph 2.

11. Section 5.5, Page 12, second paragraph: Since the stream flow plots are log plots, it's not clear that the flows ever go to zero. Therefore instead of saying perennial rivers cease flowing, I suggest "Most….experience significant decrease in flow during droughts".

    Text revised as requested (Page 12, paragraph 5).

12. Page 13, paragraph 1: Please verify whether the Lower Trinity aquifer is more transmissive as stated.

    These are the numbers reported by Ashworth in his 1983 report. They do not agree with the hydraulic property data collected for this project.

13. Section 5.6, Page 14, second paragraph: Please include a figures showing the distribution of hydraulic conductivity data for the lower Trinity, per GAM checklist of deliverables page 4 of 11, Hydraulic Properties, "A map of hydraulic conductivity for each model layer"

    A map showing the distribution of hydraulic conductivity data for the lower Trinity appears in Figure 5-29.

14. Page 15, paragraph 3: This section discusses pumpage reported by various authors. It may be pertinent to report the current pumpage information available from recent GAM Run reports.

    Current pumpage lies outside of the calibration period for this model and is therefore not relevant.

15. Section 6.0, page 17: Please include discussion on Hammett Shale as a confining unit and adjust figure appropriately. In addition, please note no flow boundary along Balcones Fault Zone for Lower Trinity or note in model development section that your conceptual model changed for this boundary.

    Done (Page 18, paragraph 1).

16. Section 6.0, page 17, fourth paragraph: I suggest mentioning that evapotranspiration is accounted for by the drain package since the loss is discussed, but the EVT package is not used.

    Done (Page 18, paragraph 3).

17. Section 7.0 page 18, last paragraph: Text notes that MODFLOW-2000 was used. Please clarify whether MODFLOW-96 or 2000 was used.

    "MODFLOW-200" changed to "MODFLOW-96" and associated reference changed (Page 19, paragraph 5).

18. Page 19, paragraph 1: Please also add that the thin slivers in the Edwards Aquifer in the east were not included in the model due to physical discontinuity between the units.

    Done (Page 20, paragraph 2).

19. Page 19, paragraph 2: Please explain in details on how the Hammett Shale was assigned in the model. This is an important element and should be discussed in some detail.

    This comment is already addressed in the following paragraph (Page 21, Paragraph 2).

20. Page 20, paragraph 3: Please define what model boundaries are before providing a list of the boundaries.

    Added a definition of model boundaries to the paragraph (Page 21, paragraph 4).

21. Page 21, paragraph 1: Please explain what are outer boundaries—areas outside the footprint of the aquifer.

    A definition of outer boundaries was added to Page 22, paragraph 4.

22. Section 7.4, page 21: Please discuss base of the model boundary as a no-flow and other assignment of no-flow boundaries. Please discuss why Colorado River was changed from constant head as it was modeled in previous version.

    Discussion of no-flow boundaries appears on Page 22, paragraph 4. Discussion of why reservoirs, including those on the Colorado River were changed from constant-head to river boundaries appears on Page 23, paragraph 2.

23. Page 21, paragraph 3: Please explain why no General Head Boundary was assigned along the Balcones Fault Zone in the east in the Lower Trinity Aquifer? The Hosston and the Sligo formations of the Lower Trinity Aquifer are in contact with appreciable segments of the Upper and Middle Trinity aquifers potentially allowing significant discharge. This is an important conceptual issue that has ramifications on the calibration of the rest of the model.

    This discussion was added to Page 23, paragraph 1.

24. Section 8.0, pages 22-23: Per GAM program guidelines, please discuss mean absolute error between measured hydraulic-head and simulated hydraulic head shall be less than 10 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 (that is, not spatially biased); please discuss statistics and what they mean - final calibration results shall report the mean absolute error and the mean error (Anderson and Woessner, 1992, p. 238-241); please discuss difference between the total simulated inflow and the total simulated outflow (that is, the water balance) shall be less than one percent and ideally less than 0.1 percent as a modeling target; and please discuss calibration targets: wells(water levels/hydrographs), springs, lakes/reservoirs, rivers/streams, et cetera.

    See Page 24, paragraph 2; Sections 9.1 and 10.1, and Table 10-03.

25. Section 8.0, page 23: please clarify if transient begins in 1980 or 1981. As it is written it appears we repeat 1980 as the steady-state and then model 1980 again as the second stress period of the transient.

    Discussion on Page 24, paragraph 3.

26. Section 8.0, page 21, last paragraph: I suggest adding a note that the steady-state model is a long stress period at the beginning of the transient model per *GAM checklist page 6 of 11 Modeling Approach -- " ..discuss including the steady-state model as part of the transient model …"*

    Done (Page 24, paragraph 3).

27. Page 22, paragraph 6: This section discusses how recharge was assigned in the steady-state model. For example, 3.5 percent of precipitation recharge for most of the model area, 5 percent of precipitation over a large swath of the Balcones Fault Zone in the east, and about 70,300 acre-feet of streamflow loss through the Cibolo Creek. After all this, the recharge amount matches the previous version of the model where precipitation was set at about 4 inches of precipitation. Need also more detailed discussion on how the recharge was assigned. Was it done using the Recharge package?

    Paragraph revised (Page 24, paragraph 5).

28. Page 23, paragraph 1: Hydraulic conductivity assigned in the Upper Trinity Aquifer is considerably higher than the previous version of the model. For example, in the previous version a uniform value of 5 was assigned for the Upper Trinity Aquifer. In the current version, assigned hydraulic conductivity values in the Upper Trinity Aquifer are 150 feet per day along Cibolo Creek, 15 feet per day within the Balcones Fault Zone, and 9 feet per day in the remainder of the aquifer. Please explain how were these values determined to be appropriate. Report should also contain measured values for comparison of the deviation of calibrated values from the measured values.

    Done (Page 25, paragraph 1).

29. Section 9.1 page 24, fourth paragraph: Please clarify statement that recharge to the Lower Trinity Aquifer is insignificant. Per the conceptual model, recharge to the Lower Trinity Aquifer should be zero.

    Done (Page 26, paragraph 1).

30. Section 10.0, page 25, third paragraph: Please include contour maps and residuals of water levels in 1990 and 1997, per *GAM checklist, page 8 of 11 Calibration, "Contour maps comparing simulated water levels to maps of the measure water levels shall be discussed for 1990 and 1997"*.

    See Figures 10-04 and 10-05.

31. Section 10.0, page 25, last paragraph: I suggest using scientific notation for the specific storage values to make them easier to read.

    Done (Page 28, paragraph 2).

32. Section 10.0, page 26, first paragraph: Please include a table listing final values for calibrated parameters for each layer per *GAM checklist, page 8 of 11 Calibration, " table of range and mean of horizontal and vertical hydraulic conductivity and storativity as used in the calibrated model"*

    See Table 10-02.

33. Page 26, paragraph 2: This section discusses the specific yields and specific storage values used for transient calibration. These values are considerably low but was kept the same as in the previous version of the model. Low storage parameters were one of the main criticisms of the previous model.

    The extremely low storage values in the Trinity Aquifer System are the result of very low porosity of the aquifer rocks which have almost no inter-granular porosity and at the regional scale have very low fracture porosity.

34. Page 26, paragraph 2: Some of the springs never flow throughout the simulation period. This may indicate that simulated water levels in part of the aquifers are considerably underestimated resulting in water level in the aquifer lying at lower than the elevation head in the drain(s).

    Most of the springs in the study area are: (1) very small with measured discharge rates as low as 25 gallons per minute, (2) reflect discharge from local scale flow systems, and (3) are a small fraction of total discharge to surface water bodies for the aquifer. A small deviation of a few feet from measured water levels, well within model standards, is all that is needed for these springs not to flow during the simulation period.

35. Section 10.1, page 26: Please include a table with calibration statistics for each model layer and include a map with the location of all wells used for the statistics per *GAM checklist, page 8 of 11 Calibration, "a table listing mean absolute error and mean error for the transient calibration per layer for 1990 and 1997 and maps showing the locations of the wells used to develop the above scatter plots."*

    See Table 10-03.

36. Section 10.1, page 26: Please provide tables of water budgets for 1990 and 1997 and a table listing stress periods and corresponding years per *GAM checklist page 8 of 11, "water budget for 1990 and 1997; a table showing stress periods and corresponding time periods for combined transient model".*

    See Table 10-04.

37. Section 10.2, page 26: Please also consider transient sensitivity analyses for recharge, pumping, and vertical K per *GAM checklist Page 8 of 11 Sensitivity Analyses, "Model parameters include … 2. vertical hydraulic conductivity, 5. recharge, 6. pumping…"*

    Measuring the sensitivity of the model to recharge, pumping, vertical hydraulic conductivity was conducted as part of steady-state model construction and it is therefore unnecessary to repeat it again. Analysis of model sensitivity to storage parameters of primary importance in transient models.

38. Tables: Please adjust font to larger than 8.

    GAM guidelines require fonts no smaller than 6 points.

39. Page 37, Table 5-01: Please insert current recharge estimate from this model calibration. Also, include Anaya and Jones (2004) estimate mentioned in the report.

    Anaya and Jones (2009) recharge was added to Table 5-01. It is not an appropriate for calibration data to appear in the supporting data section of the report.

40. Page 38, Table 5-02. Please add a column to sum up total pumpage by year.

    A column to sum up total pumpage by year was added to Table 5-03.

41. Page 55, Table 9-01: Please report values for springs. Discharge into the springs in the previous version was about 45,000 acre-feet/yr. Does the estimate for streams include springs? If so, then stream discharges are lower by as much as 33 percent than the previous version.

    One can not compare results from the previous model with Table 9-01 because they cover different time periods. Spring discharge is included with streams. The table has been revised to reflect this.

42. Page 55, Tables 9-01, 9-02, and 9-03: The model wide, by layer, and by county water budgets should agree when summed. Please adjust or discuss reasons for differences in Section 9.1.

    The differences are due to rounding off of the numbers. The tables have been revised to remove the apparent errors.

43. Page 56, Table 10-01: According to this table, some key springs including Jacob's Well Springs never flowed – an unreasonable result. It is perhaps OK to underestimate flow given the scale issue, but to have no flow at all, is a concern. Springs flowed, some less, equal or more than estimated, in Mace and others (2000).

    Most of the springs in the study area are: (1) very small with measured discharge rates as low as 25 gallons per minute, (2) reflect discharge from local scale flow systems, and (3) are a small fraction of total discharge to surface water bodies for the aquifer. A small deviation of a few feet from measured water levels, well within model standards, is all that is needed for these springs not to flow during the simulation period.

44. Page 62, Table 10-04: I calculated the recharge by aquifer for 1980 (from output.dat). I compared with the numbers in Table 10-04 of the report, it seems to me they are different (in Upper and Middle Trinity Aquifers).

    Table 10-04 has been revised to reflect the results of the latest version of the model.

45. Figures: Please update legends to include county boundary, model extent, and/or contour intervals, as appropriate.

    Done.

46. Page 57, Figure 3-01: The roads appear way too prominent in the figure. Suggest use form of grays for roads so that model boundary stands out.

    Figure revised using color.

47. Page 59, Figure 3-02: Figure does not show island of Edwards Group along Kendall, Kerr county boundary. Please update figure so it agrees with model.

This figure, taken from Mace and others (2000), shows the official aquifers in the study area. The Edwards Group outlier mentioned above does not fall, despite being included in both the previous and updated versions of the model, is not included in any of the official aquifers.

48. Page 61, Figure 3-04: Please check whether the extension of the hatched areas to represent the EAA is correct. The area also covers Medina County, Uvalde County, and Trinity Glen Rose GCDs.

Figure revised.

49. Page 65, Figure 3-09: Study area symbol in the legend does not match the figure content. What do the dots signify? Please add explanations in the legend. Why use PG seal in one map only and not in others for consistency?

Figure revised.

50. Page 67, Figure 3-11: Please report the time period for mean monthly precipitation data.

Figure caption revised as requested.

51. Page 71, Figure 3-14: Please add Bexar Shale to figure since figure 3-17 shows this unit within the study/model area. Also suggest noting unconformities on column.

Figure revised adding Bexar Shale.

52. Page 71, Figure 3-15: Only the extent of the Hammet Shale is shown on the map. Why not for the Sligo, Sycamore, and the Hosston formations?

This figure was taken from Mace and others (2000). The updip extent is important because of its influence on cross-formational flow between the Middle Trinity Aquifer (outcrop shown in this figure) and the Lower Trinity Aquifer that has no outcrop and therefore does not appear in this figure that shows surface geology.

53. Page 72, Figures 3-16: Where the caption for Figure 3-16 mentions things not on the surface geology map, you ought to add that the map also excludes all the outcrops of Hensell and Cow Creek in the Guadalupe River valley as well as along the Pedernales and Colorado Rivers in the northeastern most part of the study area. Springs from the Cow Creek and uppermost Hensell supply water to the Guadalupe River in Kendall and Comal Counties. East of Johnson City there are significant springs issuing from the Cow Creek and even the sand and limestone units of the Hammett.

The up-dip limit of the Hammett Shale is shown because it is an important factor in the model. The outcrops of the Hensell Sand and the Cow Creek Limestone in the study area are very small outcrops along the Guadalupe, Colorado, and Pedernales rivers. These outcrops are too small to appear on the map in Figure 3-16.

54. Page 72, Figures 3-17: The northern part of the A-A' cross section in Figure 3-17 is illogical and does not reflect the geology that is exposed at the surface. I doubt that there is any Lower Glen Rose in well KKL-57-41-301. The rock equivalent to the Lower Glen Rose and most of the Upper Glen Rose in that area is the Hensell. North of Fredericksburg there is only a thin unit of uppermost Glen Rose underlying the Walnut and Edwards. It makes no sense to have a wedge of Lower Glen Rose in the northern well on this cross section.

    Figure 3-17 is a cross-section by Ashworth (1983) based on interpretations of logs.

55. Page 76, Figure 5-04: There are some discrepancies in these diagrams. For the top of the Upper Trinity Aquifer, we expect to see use of outcrop control points but they don't show up in figure (a). However, these control points show up in the figure for the base of the Upper Trinity Aquifer (b). Also, note if there are structure control points from well logs in northern parts of Gillespie County then there should be outcrop points farther north from it but they are not reported. This also brings the questions whether any control points should exist in northern parts of Gillespie County as the Upper Trinity Aquifer pinches out north of the Pedernales River.

    Figure 5-02(a) was revised to show the outcrop control points. The control points in northern Gillespie County already lie outside of the study area, beyond the northern model boundary. It is unnecessary to use outcrop control point that are even farther outside of the study area to interpolate the structure.

56. Page 78, Figure 5-06: Please insert structure control points for construction of the base of the Lower Trinity Aquifer (b) as was done in (a). Also please clarify gap between base of Middle Trinity [Figure 5-05 (b)] and parts of the Lower Trinity [Figure 5-06 (a)] are the Hammett Shale in caption and in text.

    See revised caption in Figure 5-04. The base of the Lower Trinity Aquifer was taken from the groundwater availability model for the Edwards-Trinity (Plateau) Aquifer and therefore it is not appropriate to show control points.

57. Page 79, Figures 5-07 through 5-10: Please report units of measurement.

    See revised captions in Figures 5-05 through 5-08.

58. Page 83, Figures 5-11 through 5-13: Figure shows water levels for 1977 to 1985. Please explain in the text why this time window was selected. If this is to show how the water levels remained under steady-state then should we not have gone back in time, e.g., 1965 or something like that as was done before. This would have also allowed addition of more water level control points for calibration in the north and the west.

See Page 9, paragraph 3. The period 1977 through 1985 coincides with the steady-state model period and the beginning of transient model period.

59. Page 83, Figure 5-13: No water level measurements reported for most of Gillespie and western part of Kerr Counties.

    There was no water-level data available for those areas.

60. Figures 5-19 and 5-20, Net water-level change: Please clarify if difference was for 1980 to 2000 as noted in caption or 1980 to 1997 as is modeled. Please update to 1980 to 1997 as necessary and also include maps for Edwards and Upper Trinity.

    Figure 5-17 and 5-18 revised as requested. Limited water-level data prevented construction of a map for the Edwards Group.

61. Page 91, Figure 5-19 and 5-20: Please explain the two shades for measurement points in the legend.

    Captions revised to explain the different colors.

62. Page 93, Figure 5-21: Please describe the figure in the caption. What does the '+' and '– 'signify with respect to baseflow discharge?

    Figure 5-19 caption revised as requested.

63. Page 103, Figure 5-31: It appears that no hydraulic conductivity values were assigned within a few active cell areas in the Upper Trinity Aquifer. Please explain if these are inactive cells or cells turned-off to enable convergence?

    Figure 29 revised.

64. Page 119, Figure 5-45: Trend (3) could simply be a mixture with water containing higher dissolved solids but not necessarily brine. Saturated brine has as much as 319 g/l total dissolved solids. Even a small fraction of mixing with this brine would have resulted in much higher concentrations of Na and Cl and Cl/Br.

    Saturated brine is an extreme case that it is unlikely that the groundwater in the Trinity Aquifer System will encounter.

65. Page 120, Figure 6-01: Please describe figures (a) and (b) in the caption. Also, altitude scale to the left is in blue where the other lines are in black. Also, please check whether there is discordance between fig 5-02 and this figure. In Figure 5-02, Hosston (LT) is juxtaposed against the Lower Glen Rose Limestone (MT) along the BFZ but here it is not. Please adjust cross-formational flow from Lower Trinity to no flow or explain in text. Please account for Hammett Shale as a confining unit. Please clarify what a drain

represents since the conceptual model also has symbols for springs, pumpage, and surface water-groundwater interaction. Possibly re-label surface water-groundwater interaction to include “reservoirs” and re-label drains to “gaining rivers”?

Caption revised to describe (a) and (b). The altitude scale has been remove because it is a schematic cross-section. One can not compare the Figure 6-01 cross-section with Figure 5-02 because Figure 6-01 is an East-West cross-section and Figure 5-02 is oriented North-South. The text has numerous references to cross-formational flow to/from the Lower Trinity Aquifer as shown in the figure. The figure has been revised to show the Hammett Shale. “Drains” has been removed from the figure.

66. Page 121, Figure 7-01: Please explain why a few cells in Comal County were turned inactive when the aquifer is present. Some of these cells may also represent river cells?

    A few cells along the edge of the Upper Trinity Aquifer outcrop were turned off to address dry cell or stability issues (Page 20, paragraph 2). In the event that the inactive cell was a river/drain, the feature was transferred to the underlying active cell.

67. Page 123, Figure 7-02: Please explain why there is so much difference between vertical leakance values in the north and the rest of the model area. How were the leakance zones determined? Was this zone assigned to allow vertical communication between the Middle and Lower Trinity aquifers where the Lower Trinity Aquifer is absent?

    It is explained in the text that vertical leakance is inversely proportional to the thickness of the Hammett Shale confining unit and reaches a maximum in the north where the confining unit is absent (Page 21, paragraph 2).

68. Page 123, Figure 9-01: Please report the range for category >5 inches. Is this for the steady-state model? Please cite time period for recharge.

    Figure revised as requested.

69. Page 129, Figure 9-02: Please remove the simulated water level contours because they are misleading. These are water-level difference maps. These can be displayed by showing the differences either by points or contours made using these points. Please provide the range for category more than ±100 feet.

    The contours show model results and the points indicate the difference between simulated and measured water levels as indicated in the figure caption. No changes made to the figure.

70. Page 131, Figure 9-03: Please report mean error and absolute error by aquifer which will better show any bias in calibration by aquifer. Per GAM guidelines, please reference and/or provide a map showing target wells used for cross-plots by layer.

    Figure revised to show results for each aquifer on a separate graph.

71. Page 146, Figure 10-03: Please group the targets by aquifers as in the steady-state model and report the mean absolute error by aquifers. Per GAM guidelines, please reference and/or provide a map showing target wells used for cross-plots by layer.

Figure revised to show results for each aquifer on a separate graph. See Figures 10-04 and 10-05 for the maps.

Comments on the model files for the Hill Country portion of the Trinity Aquifer GAM

(1) Reviewed the recharge amount assigned along the Cibolo Creek. It was suggested in the report that an amount of 70,300 acre-feet per year of water was assigned through the Cibolo Creek as per recent USGS investigation. Cibolo Creek flows over the Upper and Lower Glen Rose Limestone. Reviewed the recharge in the Cibolo Creek for the steady-state model and found that the actual recharge through the Cibolo Creek is about 51,000 acre-feet per year. We suggest changes to the recharge rate assigned in the model to reflect the text or provide appropriate justification for assignment of the lower recharge in the model.

The 70,300 acre-feet per year represents total recharge, diffuse and stream channel recharge, to the Cibolo Creek watershed where it overlies the Trinity Aquifer System, while the 51,000 acre-feet per year value represents stream channel recharge only.

(2) Compared various parameters reported in Table 9-01 with results obtained from running the steady-state model. Small differences were noted between reported and model run results for several parameters (see table below). If the numbers were rounded to the next thousandth, please mention that in the table caption.

Parameter	Table 9-01 (ac-ft/yr)	Model run result (ac-ft/yr)
Streams	165,000	164,494
Well	17,000	16,668
Recharge	304,000	303,466
Edwards Aquifer (Balcones Fault Zone)	103,000	102,489

Table 9-01 was revised, rounding the numbers to hundreds of acre-feet. The caption was revised to indicate this.

(3) No simulated water level maps were reported in the text for the transient run. We suggest inclusion of some of the simulated water level maps for 1990 and 1997 of the transient period. Simulated water level maps show spatial distribution of water level contours and their position with respect to the streams and lakes/reservoirs. Some dry cells were noted adjacent to cells that were turned-off in the Upper Trinity Aquifer. Also, it was surprising to note that the simulated water level contours in the Lower Trinity Aquifer mimic the simulated water

levels produced in the overlying aquifers even though no streams run through the Lower Trinity Aquifer. In other words, streams assigned in the overlying aquifers have a strong effect in shaping the simulated water level contours in the Lower Trinity Aquifer which should not have been the case.

See Figures 10-04 and 10-05. It should NOT be surprising that water-level contours in the Lower Trinity aquifer mimic the simulated water levels produced in the overlying aquifers even though no streams run through the Lower Trinity Aquifer because the lowered water levels in the Middle Trinity Aquifer along the Guadalupe River will induce upward groundwater flow from the underlying aquifer. This occurs wherever there is vertical flow between aquifers. Similar relationships can be seen in the central Gulf Coast Aquifer GAM results.

(4) Water budget results for various flow parameters have not been presented for the transient period. We suggest inclusion of water budget data for 1990 and 1997 to observe changes in the various flow parameters during progression of the model calibration.

See Table 10-04.

(5) There are some differences between Table 5-03 showing pumpage data used in the model compared to data retrieved from the well file. For example, the model has 10 percent more pumping in 1984 than what is reported in Table 5-03. All other years have 3 to 4 percent less, probably due to inactive or dry cells with pumping. Please clarify in text.

Year	Total pumpage from Table 5-03 (ac-ft/yr)	Total pumpage retrieved from well file (ac-ft/yr)	Difference (ac-ft/yr)	Percent difference
1980	17,149	16,678	471	3
1981	15,029	14,543	486	3
1982	14,999	14,508	491	3
1983	14,465	13,952	513	4
1984	13,888	15,274	-1,386	-10
1985	15,093	14,564	529	4
1986	14,999	14,458	541	4
1987	14,896	14,339	557	4
1988	17,340	16,766	574	3
1989	18,259	17,671	588	3
1990	19,463	18,861	602	3
1991	17,947	17,325	622	3
1992	18,775	18,132	643	3
1993	20,525	19,890	635	3
1994	21,406	20,749	657	3
1995	22,133	21,461	672	3
1996	23,461	22,773	688	3
1997	23,631	22,927	704	3

Revised value 15,799 acre-feet per year. With this value, the percentage difference is consistent with the rest of the pumpage data. Tables 5-03, 5-04, and 5-08 have been revise to reflect the change.

(6) Suggest pulling all targets together into one location with a description of the procedure for calculating RMSE, MAE, etc. so that when the model is updated again, the statistics can easily be reproduced.

There is a spreadsheet that has that data.

(7) Figure 10-02, well 57-61-507 observed data in trans_heads2.txt does not match figure. Model results do match figure. Please revisit and update text as needed.

Revised Figure 10-02 to reflect the correct observed data.