January 2011

Groundwater Availability Model: Hill Country Portion of the Trinity Aquifer of Texas

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Report 377
June 2011

Texas Water Development Board
www.twdb.texas.gov

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Cover photo: Jacob's Well ©Todd Seibel

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Texas Water Development Board

Published and distributed by the
Texas Water Development Board
P.O. Box 13231, Capitol Station
Austin, Texas 78711-3231

June 2011
(Printed on recycled paper)

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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. We updated the model by (1) adding the Lower Trinity Aquifer as another 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, recharge of about 70,000 acre-feet per year results from streamflow losses in the downstream parts of the Cibolo Creek watershed to the underlying aquifers.

Groundwater in the aquifer generally flows toward the south and east. The Hill Country portion of the Trinity Aquifer System discharges naturally as base flow 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. In some of these counties pumping has doubled during 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 precision is a slight improvement over that of the original model. Overall, the updated model also does a good job of mimicking base-flow fluctuations. The ability of the model to simulate spring discharge varies widely. Simulating discharge to springs using a regional-scale model is commonly difficult because of spatial and temporal scale issues. Of 17 springs, 6 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 (TWDB) 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 TWDB publications but is commonly used by the U.S. 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 led to a greater 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 Company Limited and Guyton and Associates (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 base flow 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 recalibrated 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. Our goal was to 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 recalibration of the numerical model owing to the addition of the Lower Trinity Aquifer and revisions to recharge, hydraulic conductivity, and pumping distribution in 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, the 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 3-1). 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 3-1). 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 3-2).

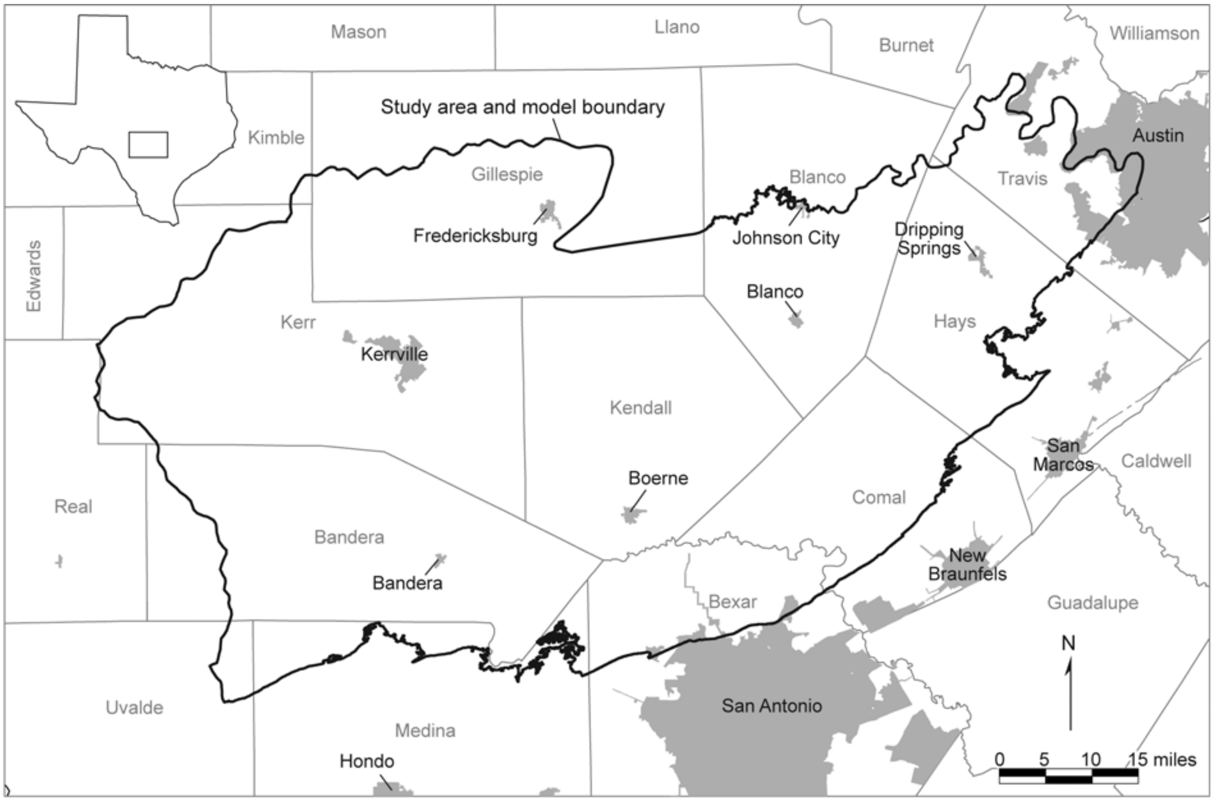


Figure 3-1. **Location of the study area relative to major cities and towns (modified from Mace and others, 2000).**

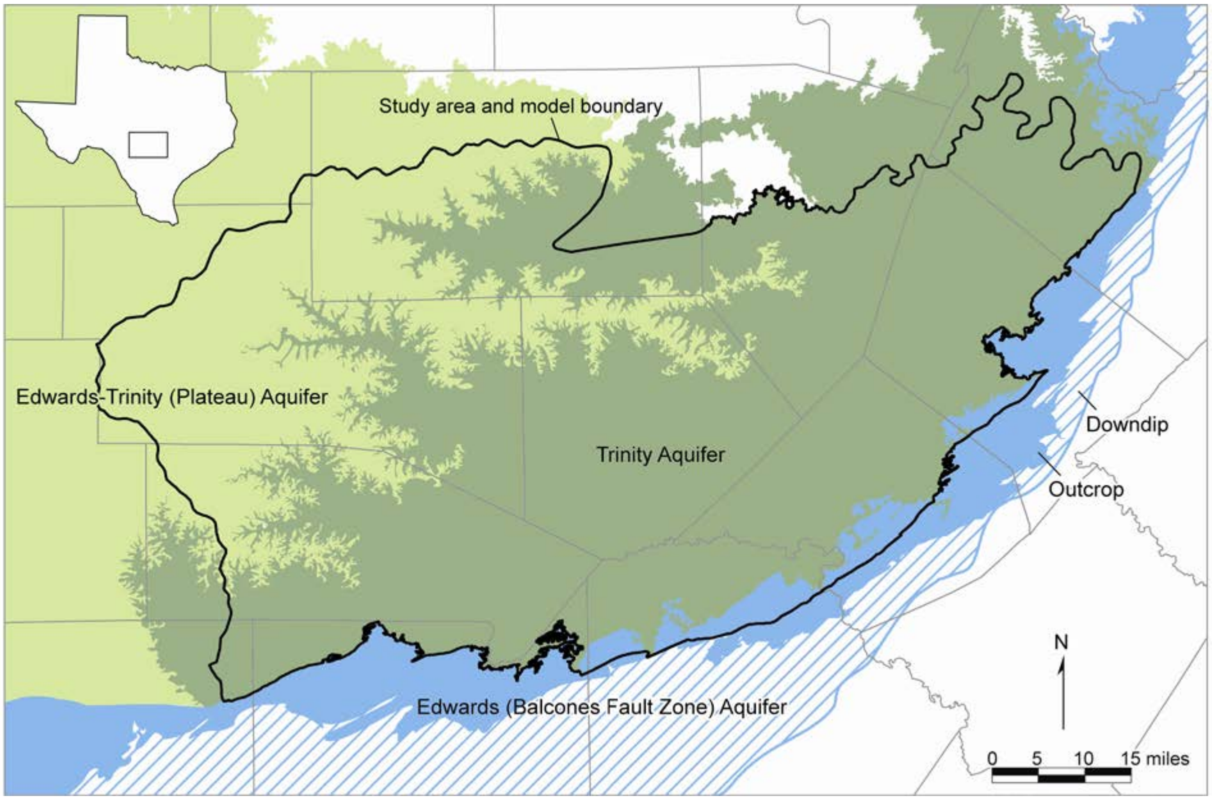


Figure 3-2. Map of outcrop of the major aquifers in the study area. Trinity sediments in the study area include sediments that are part of the Edwards-Trinity (Plateau) Aquifer System to the west and underlie the Edwards (Balcones Fault Zone) Aquifer to the south and east (modified from Mace and others, 2000).

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 3-3). The study area includes all or parts of several groundwater conservation districts, including Bandera County River Authority and Groundwater 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 3-4). The study area approximately coincides with Groundwater Management Area 9 (Figure 3-5). 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 3-6).

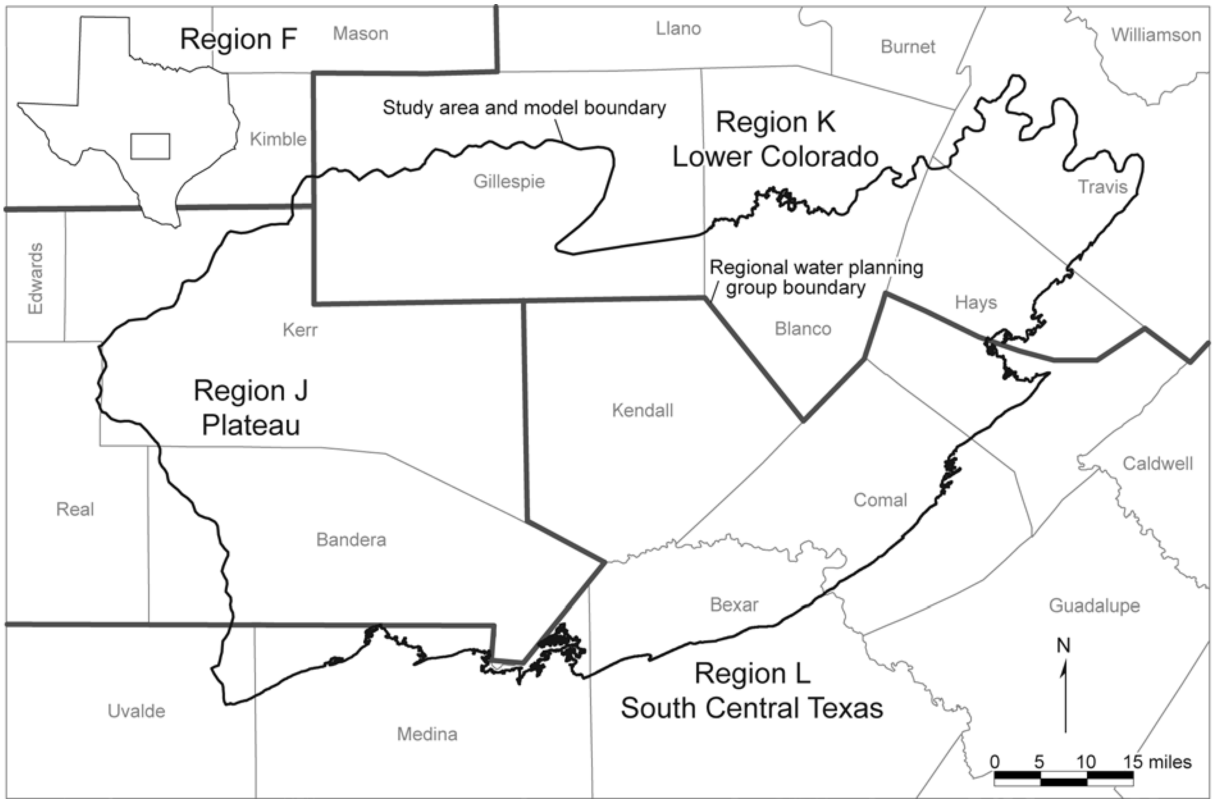


Figure 3-3. Regional water planning groups in the study area (modified from Mace and others, 2000).

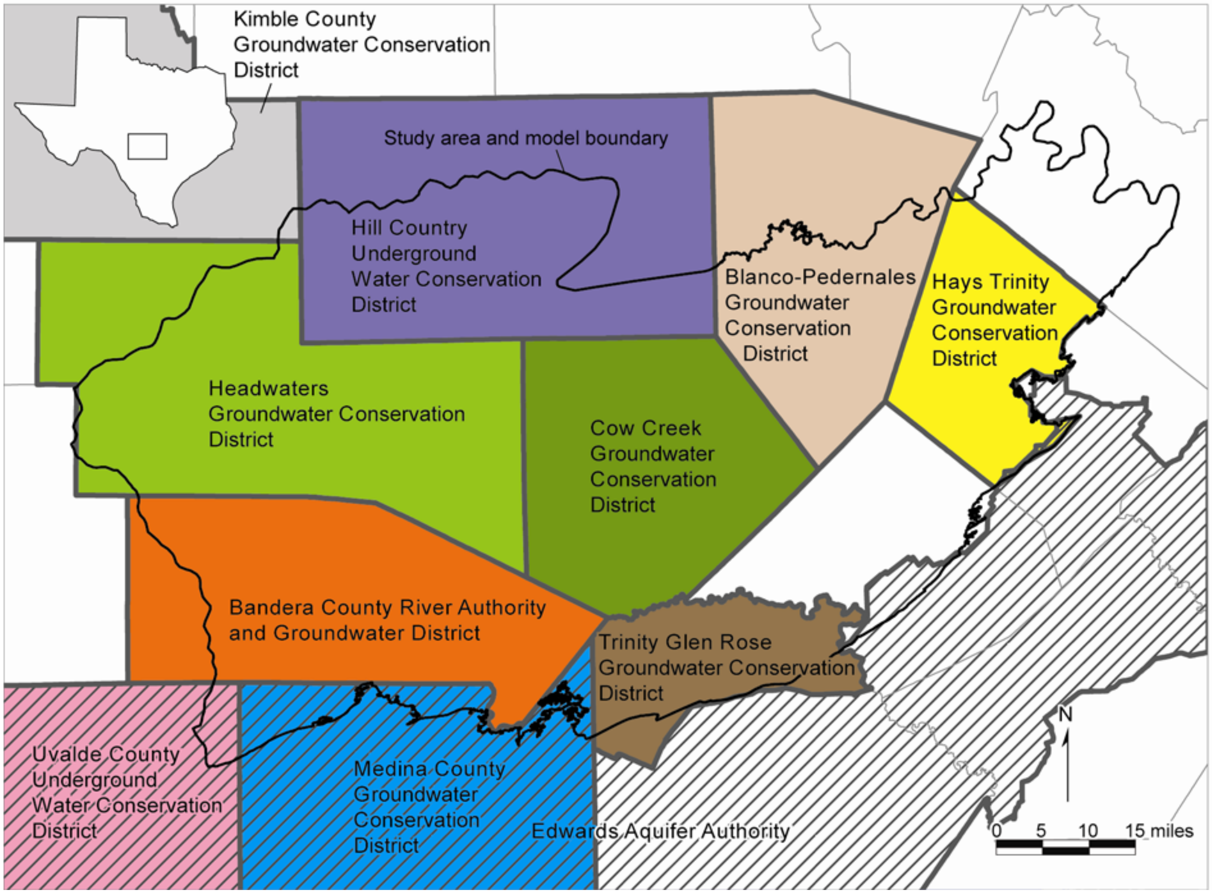


Figure 3-4. Groundwater conservation districts in the study area as of June 2011 (area with diagonal hatch lines represents the Edwards Aquifer Authority).

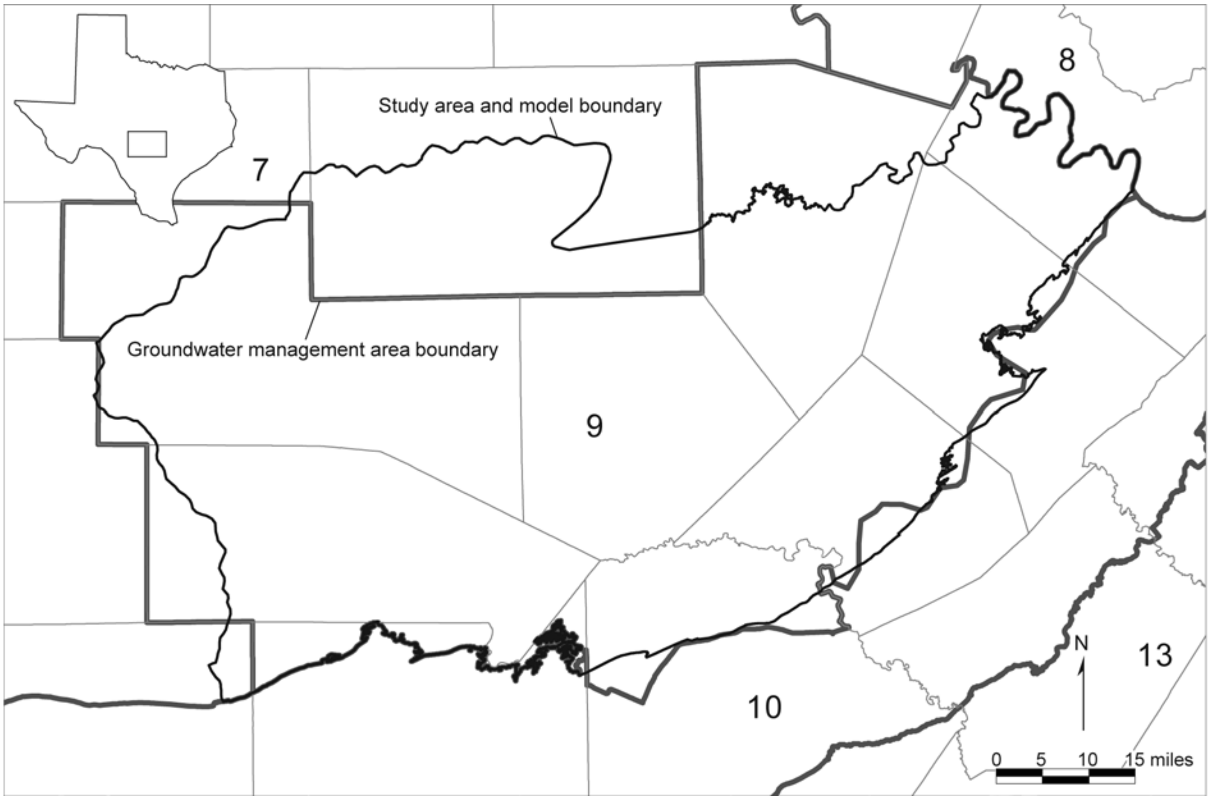


Figure 3-5. **Groundwater management areas in the study area.**

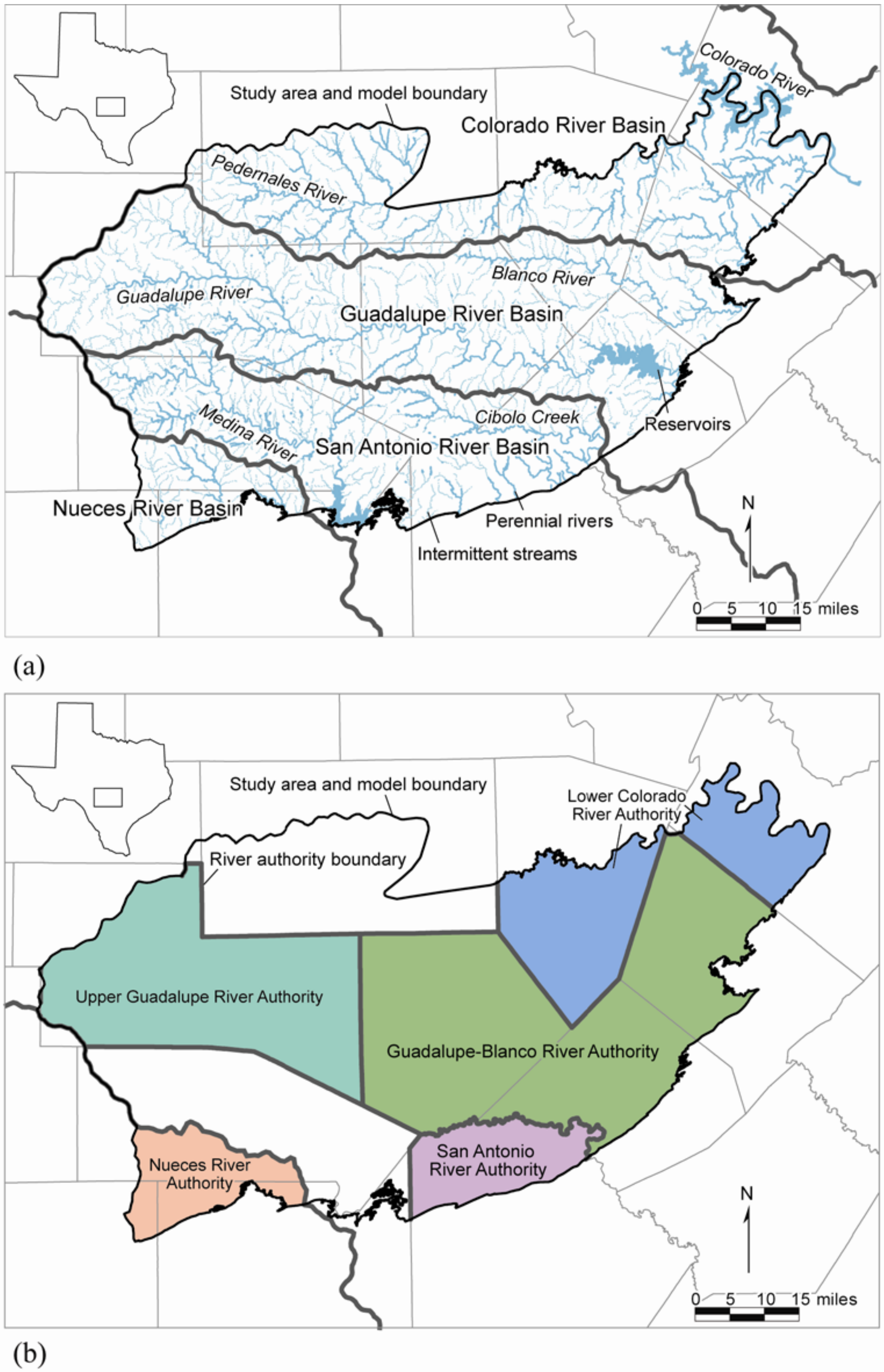


Figure 3-6. **(a) Major perennial and intermittent rivers and streams in the study area. (b) River authorities in the study area.**

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 3-7). The Texas Hill Country is also known as the Balcones Canyonlands subregion, a deeply dissected terrain formed by the headward 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 the eastern margin of the study area (Figure 3-8).

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 3-7). The differential weathering of alternating beds of limestone and dolostone with soft marl and shale in the upper member of the Glen Rose Limestone forms 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.

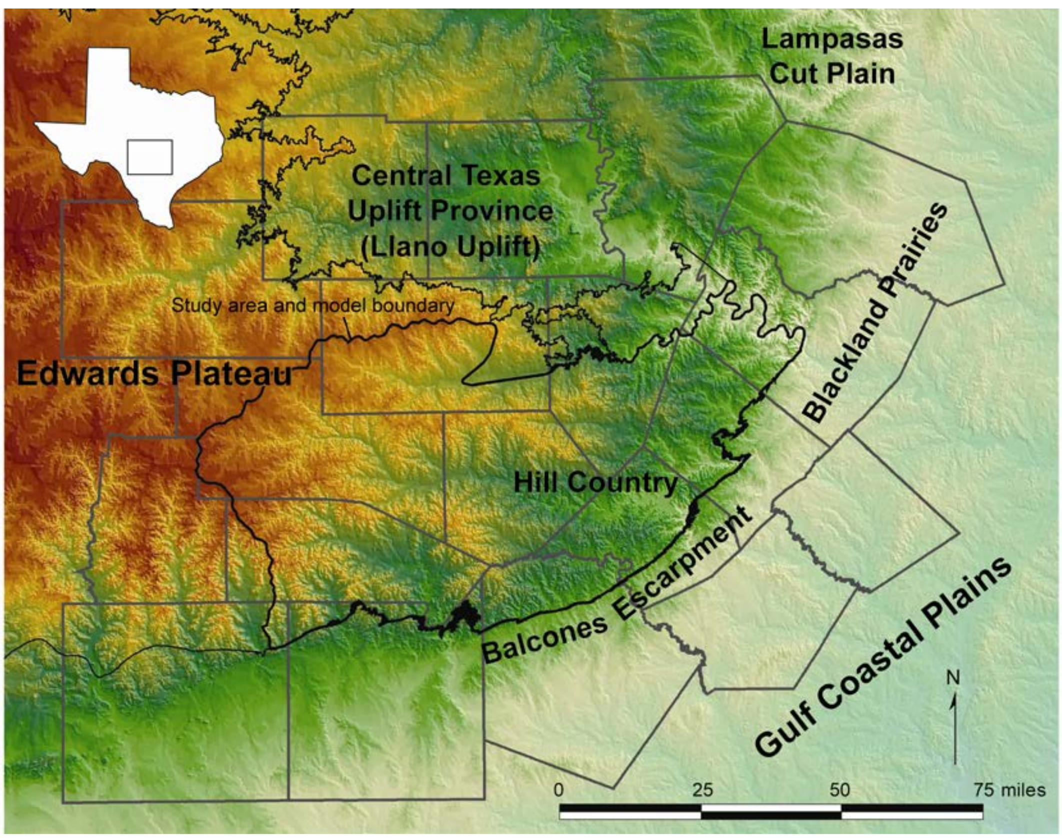


Figure 3-7. Physiographic provinces in the study area (modified from Anaya and Jones, 2009).

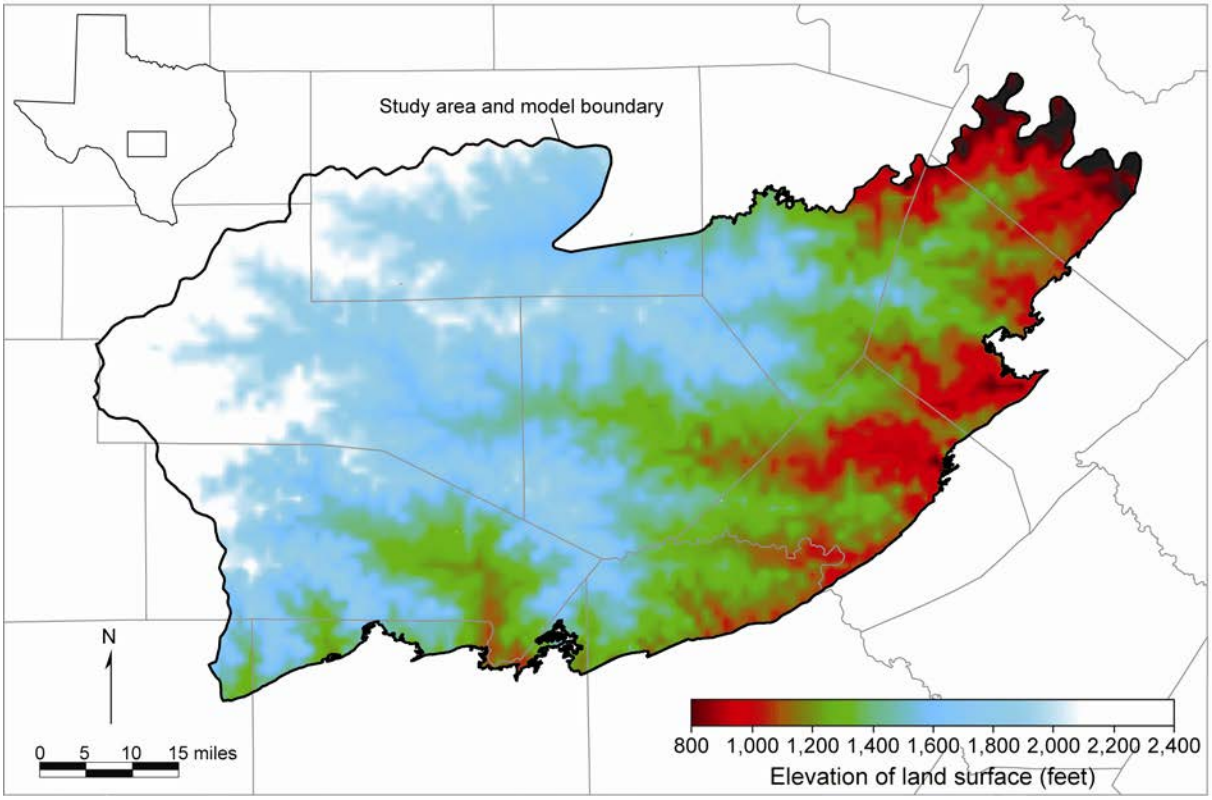


Figure 3-8. Land surface elevation in the study area (modified from Mace and others, 2000).

The study area is characterized by a subhumid to semiarid climate. Average annual precipitation gradually decreases from east to west (35 to 25 inches) owing to increasing distance from the Gulf of Mexico (Carr, 1967) (Figure 3-9). Additionally, local precipitation is highest in the central part of the study area and decreases to the north and south. Historical annual precipitation ranges 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.

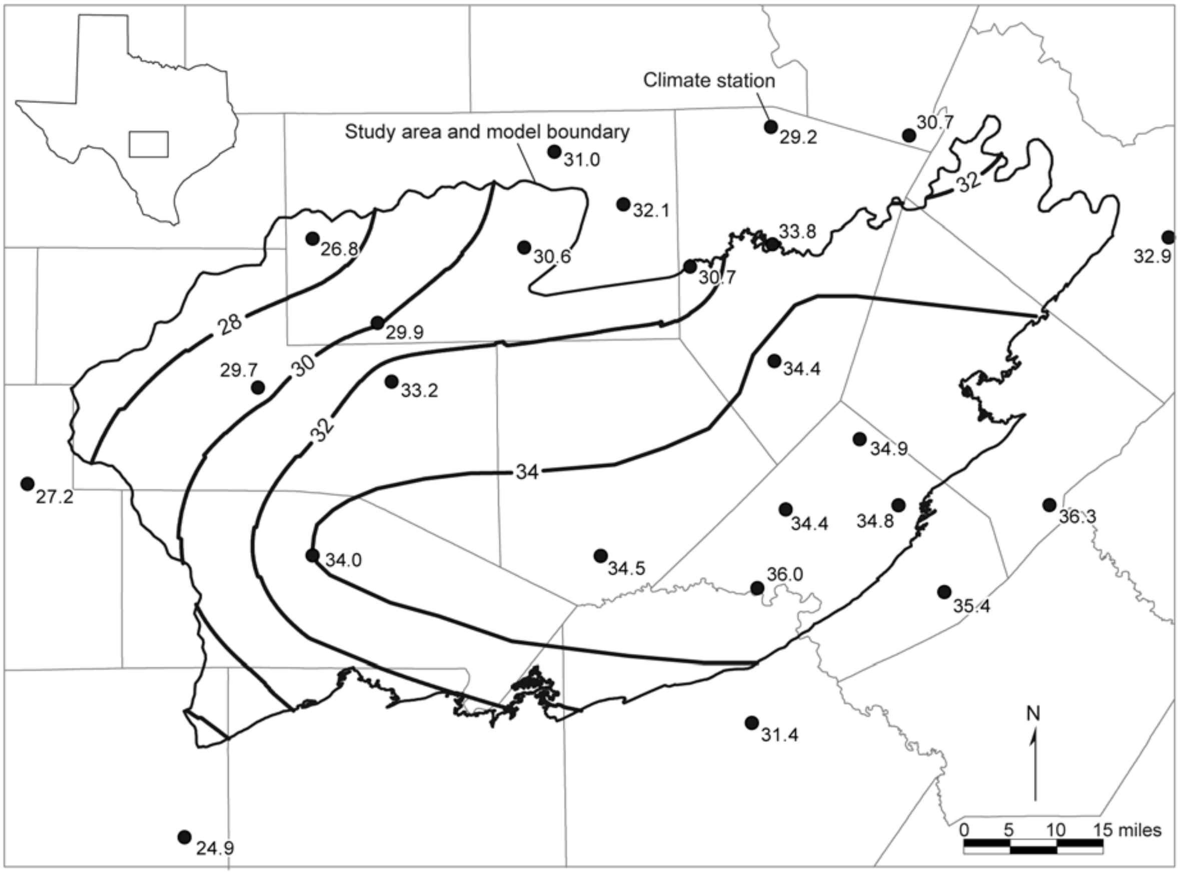


Figure 3-9. **Average annual rainfall distribution for the period 1960 through 1996 (data from National Climate Data Center). Contours represent annual precipitation in inches.**

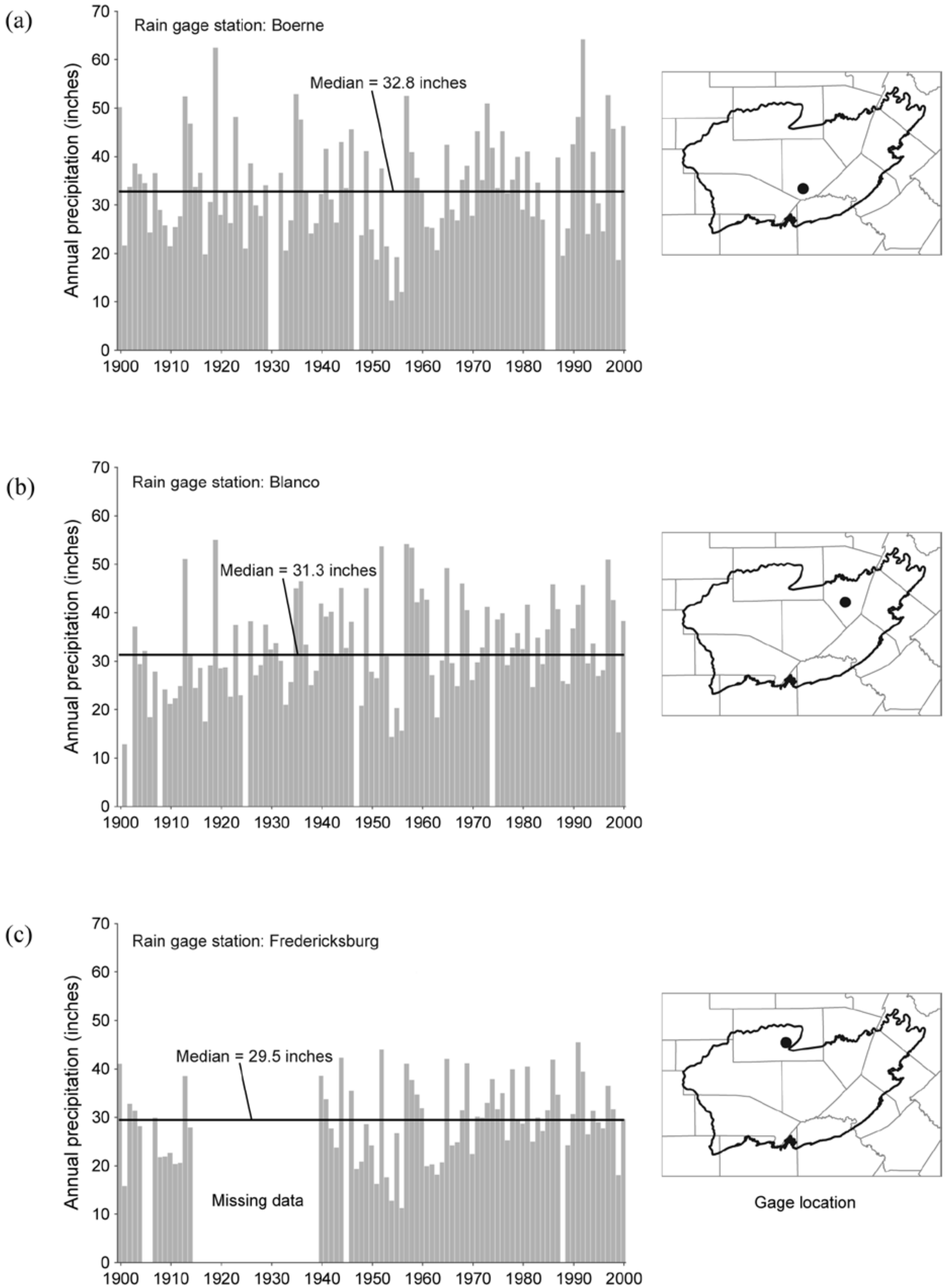


Figure 3-10. Historical annual precipitation for three rain gage stations in the study area (modified from Mace and others, 2000).

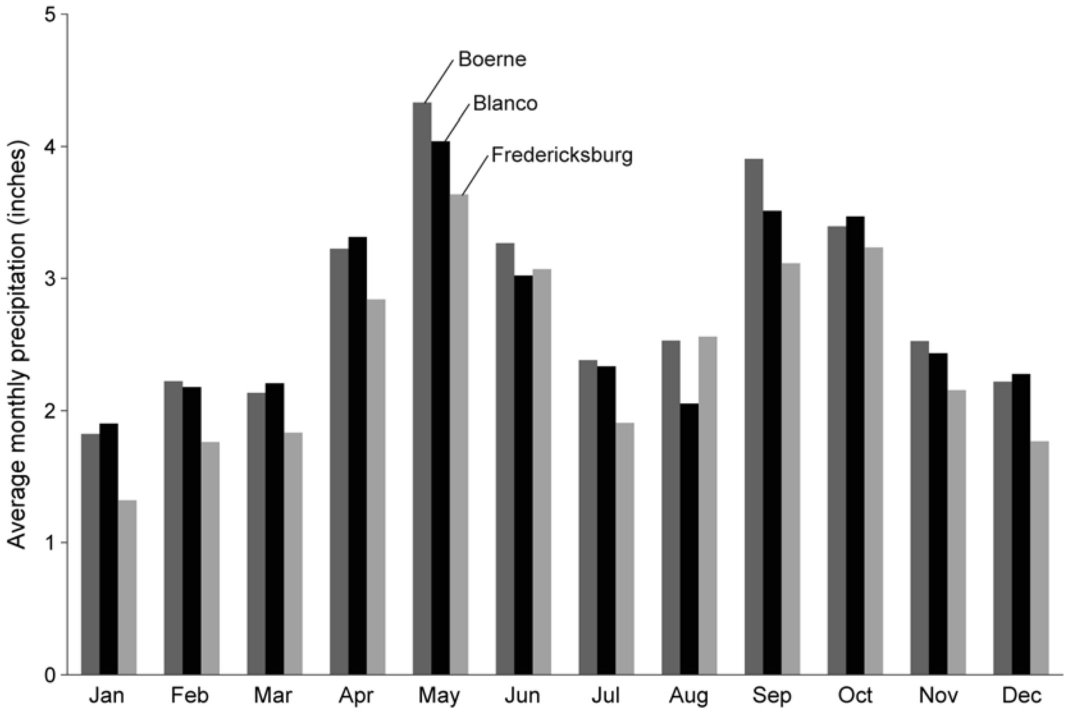


Figure 3-11. Average monthly precipitation for three rain gages in the study area for the period 1960 through 1996 (data from National Climate Data Center).

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 ranges from about 2.5 inches during winter months to more than 9 inches during summer months (Larkin and Bomar, 1983).

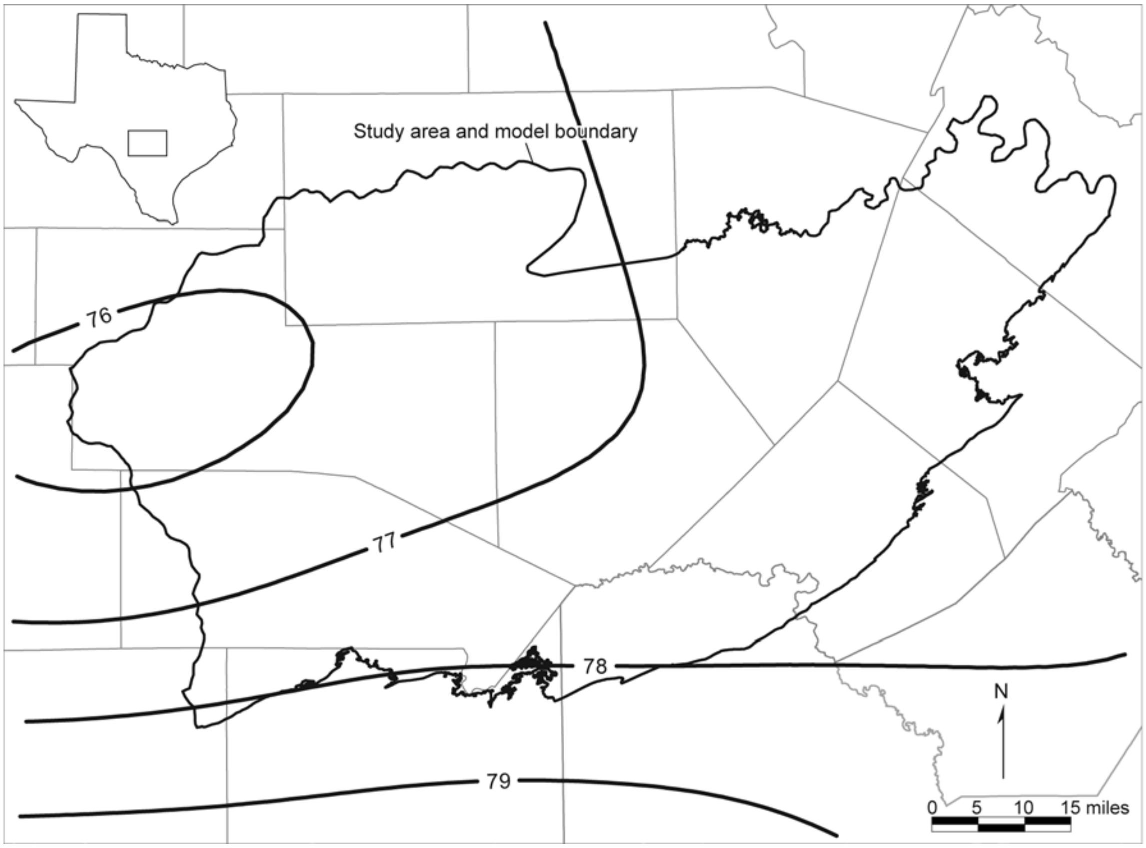


Figure 3-12. Average annual maximum temperature for 1971 through 2000. The contours are expressed in degrees Fahrenheit (modified from data from Spatial Climate Analysis Service, 2004).

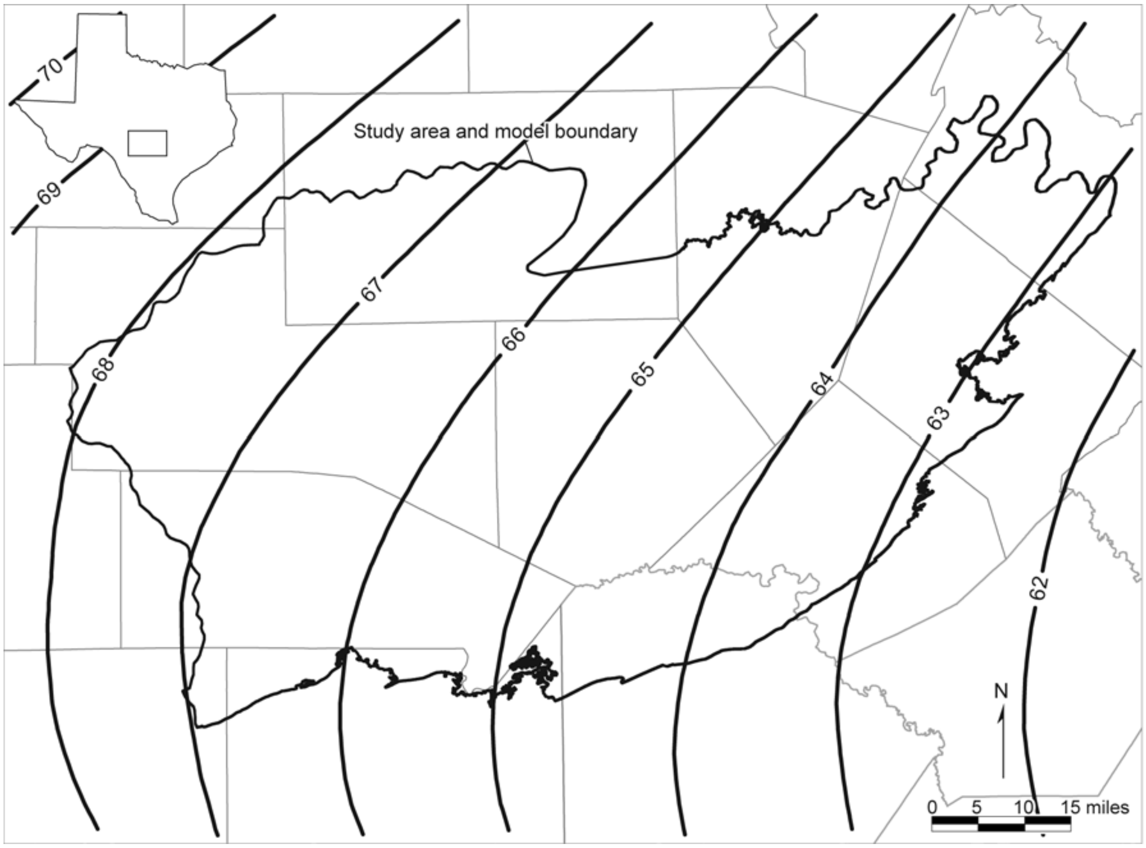


Figure 3-13. Average annual gross lake evaporation for 1950 through 1979. Contours are expressed in inches (modified from Larkin and Bomar, 1983).

3.2 Geology

Lower Cretaceous rocks of the Trinity Group that compose the Hill Country portion of the Trinity Aquifer System unconformably overlie 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 crops out 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.

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.

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).

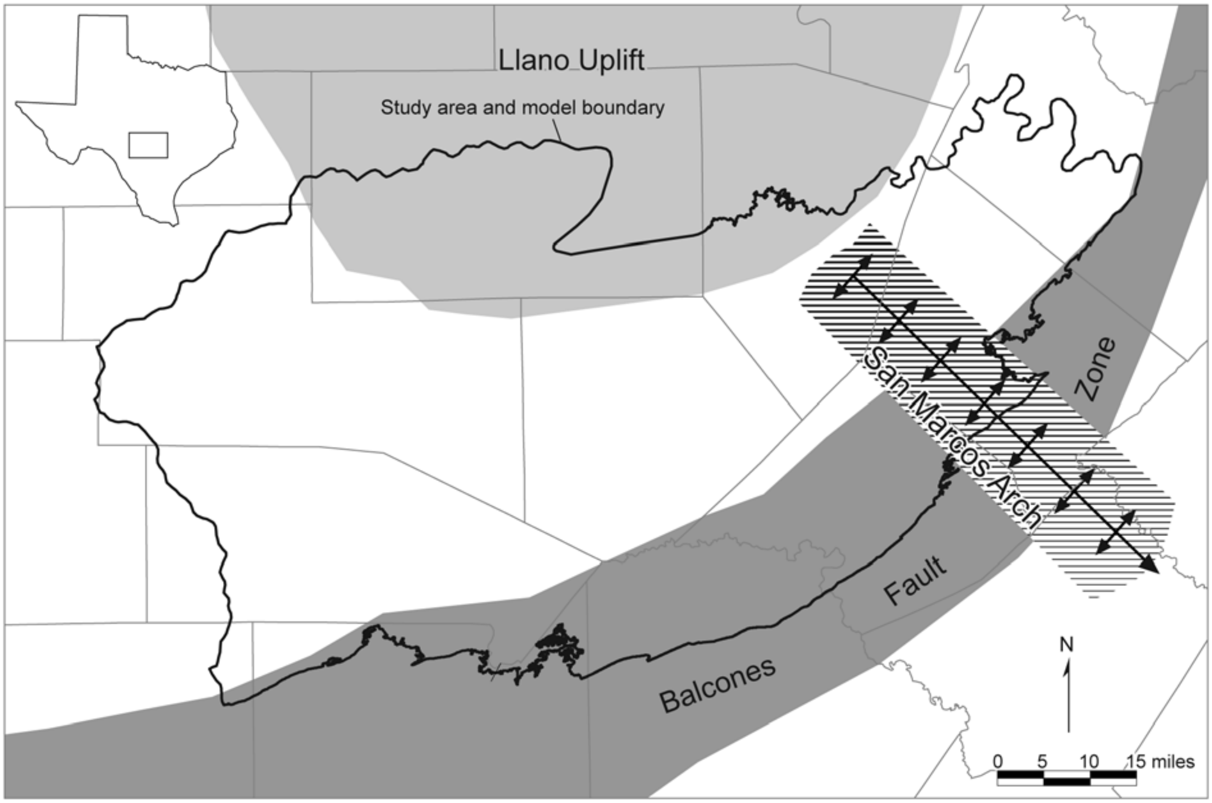


Figure 3-15. Main geologic structures in the study area (modified from Mace and others, 2000).

The Hosston Formation is dominantly composed of siliciclastic siltstone and sandstone in updip areas and dolomitic mudstone and grainstone downdip derived from the Llano Uplift (Barker and others, 1994). This formation, which is as much as 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 as much as 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 as much as 250 feet of evaporites, limestone, and dolostone (Barker and others, 1994). The evaporites were deposited in a supratidal environment, whereas the limestone and dolostone were deposited in an intertidal environment. In the updip regions, the Sligo Formation sediments display a greater 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 as much as 130 feet thick (Barker and others, 1994). This stratigraphic unit interfingers vertically with the overlying Cow Creek Limestone.

The Cow Creek Limestone, a beach deposit on the southern flank of the Llano Uplift, is as much as 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 part 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 as much as 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 downdip equivalent of the Hensell Sand (Barker and others, 1994).

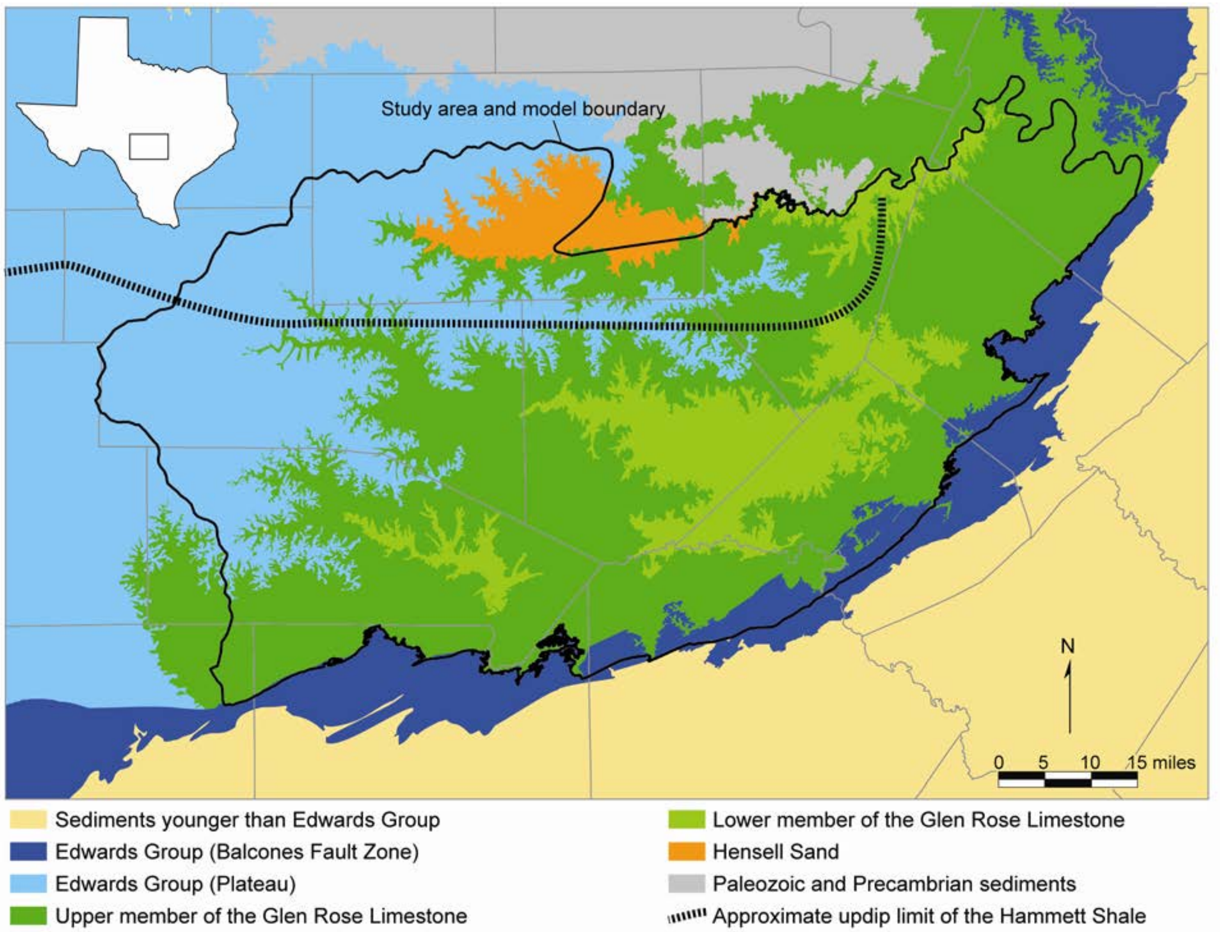


Figure 3-16. Surface geology of the study area (modified from Mace and others, 2000). Please note that this map excludes isolated outliers of the Edwards Group that overlie the upper member of the Glen Rose Limestone, some of which are included in the original and updated models. Approximate updip limit of Hammett Shale is modified from Amsbury (1974) and Barker and others (1994).

The Glen Rose Limestone is composed of sandy fossiliferous limestone and dolostone that are characterized by beds of calcareous marl, clay, and shale and include 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 result 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 updip 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 owing to carbonate dissolution and preservation of the pores but has relatively low permeability in the subsurface owing 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 downthrown blocks toward the Gulf of Mexico (Figure 3-15). The faulting occurred along the subsurface 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).

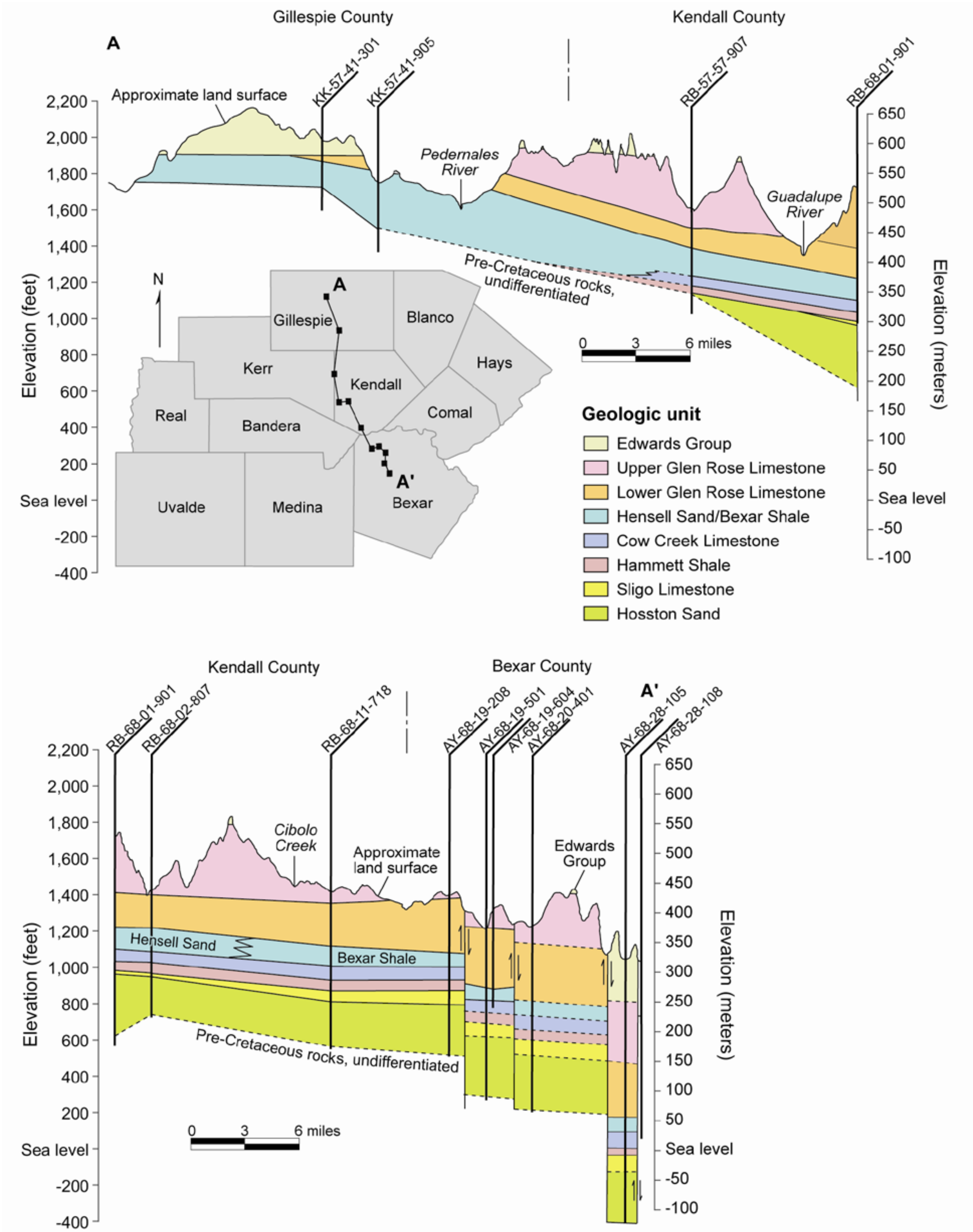


Figure 3-17. **Geologic cross sections through the study area (modified from Ashworth, 1983; Mace and others, 2000). Inset map shows cross-section line A-A´.**

The structural geometry of Lower Cretaceous sediments in the study area is 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 downdip toward 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 overlie Paleozoic and Precambrian rocks (Figure 3-17).

4.0 Previous Work

The TWDB and the U.S. Geological Survey have conducted a number of hydrogeologic studies in the Hill Country area. Ashworth (1983), Bluntzer (1992), and Barker and others (1994) provided 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 U.S. Geological Survey (Kuniansky and Holligan, 1994). Besides the Trinity Aquifer in the Hill Country, this U.S. Geological Survey model includes the Edwards-Trinity (Plateau) and Edwards (Balcones Fault Zone) aquifers and extends almost 400 miles across the state (Figure 4-1). The purpose of the U.S. 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 U.S. 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 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 that used in the model by Kuniansky and Holligan (1994). The model by Anaya and Jones (2009) simulates the Trinity Aquifer System as a single layer (Figure 4-1).

The TWDB developed a regional transient groundwater flow model for the Hill Country area of the Trinity Aquifer (Mace and others, 2000) (Figure 4-1). Mace and others (2000) calibrated this model to 1975 steady-state conditions and 1996 through 1997 transient conditions. This model simulates groundwater flow through the Edwards Group and the Upper and Middle Trinity aquifers. Our updated model includes the Lower Trinity Aquifer previously excluded from the model by Mace and others (2000).

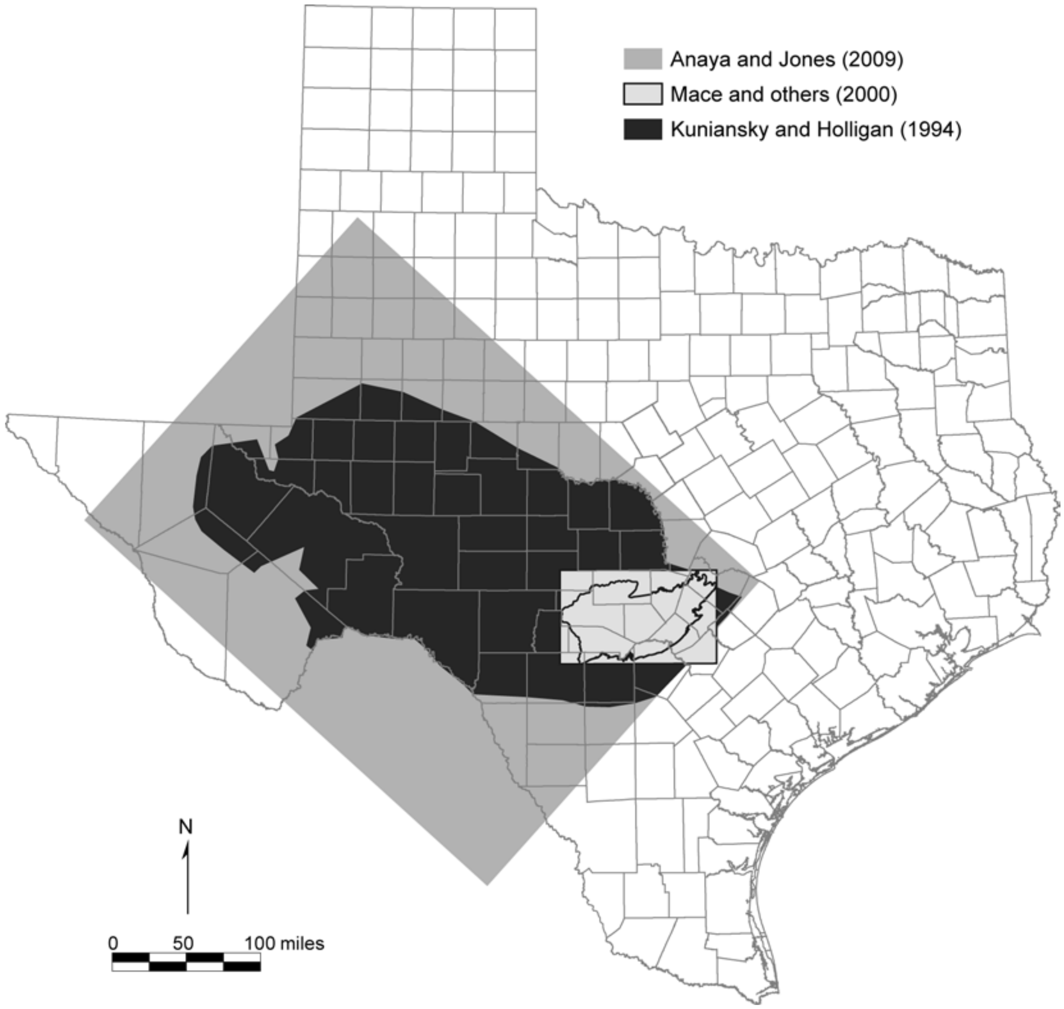


Figure 4-1. Approximate extents of previous model grids for models used for simulating groundwater flow through the study area.

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 base flow to streams, investigating recharge rates, conducting aquifer tests, and assembling pumping information.

5.1 Hydrostratigraphy

The Hill Country portion of the Trinity Aquifer System comprises sediments of the Trinity Group and is divided into lower, middle, and upper aquifers (Figure 3-14) on the basis of 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, the 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 5-1 through 5-4). Mace and others (2000) collected geophysical logs from the TWDB, 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 the geophysical-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) geographic 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 U.S. 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 5-1 through 5-4).

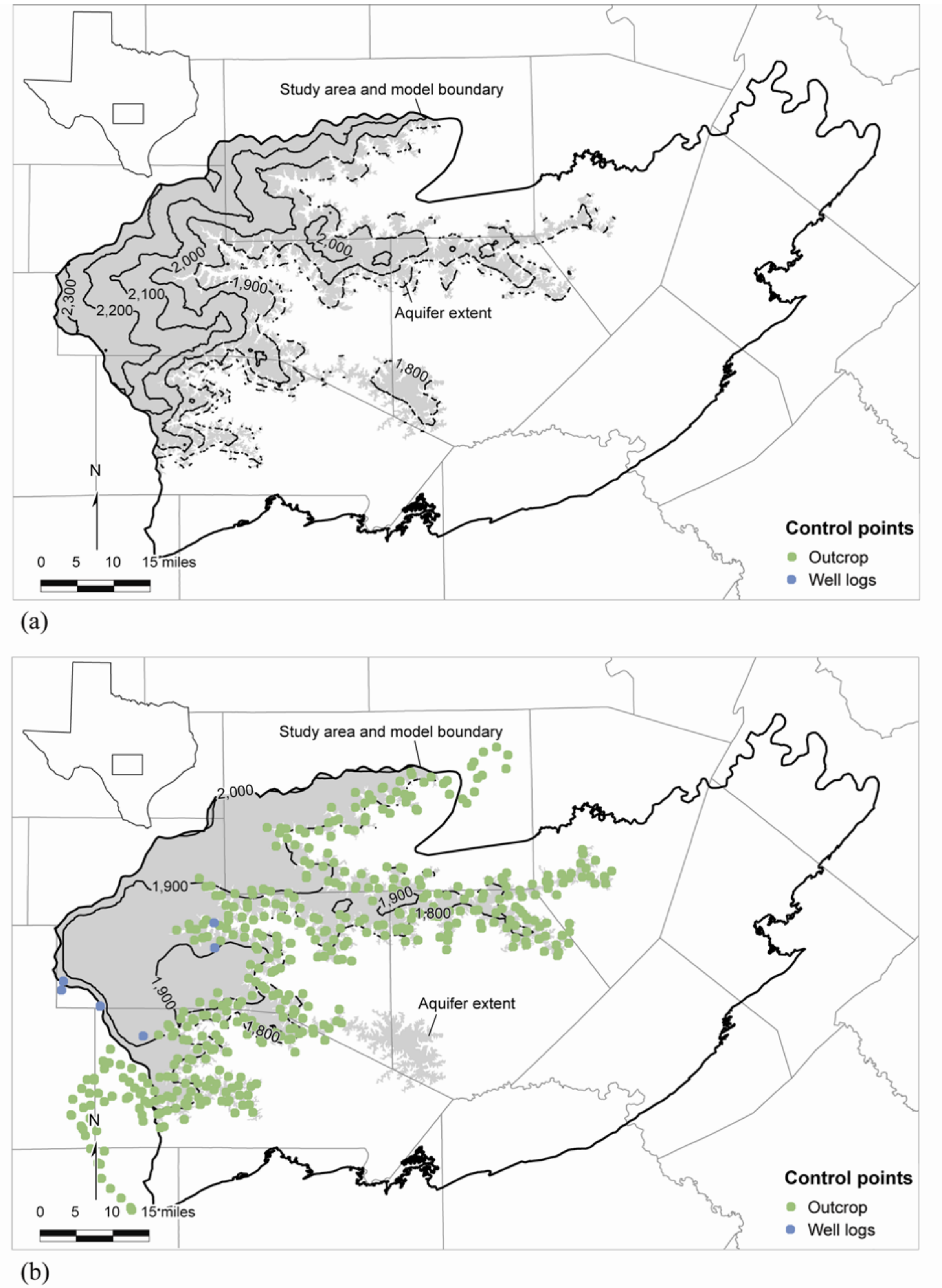
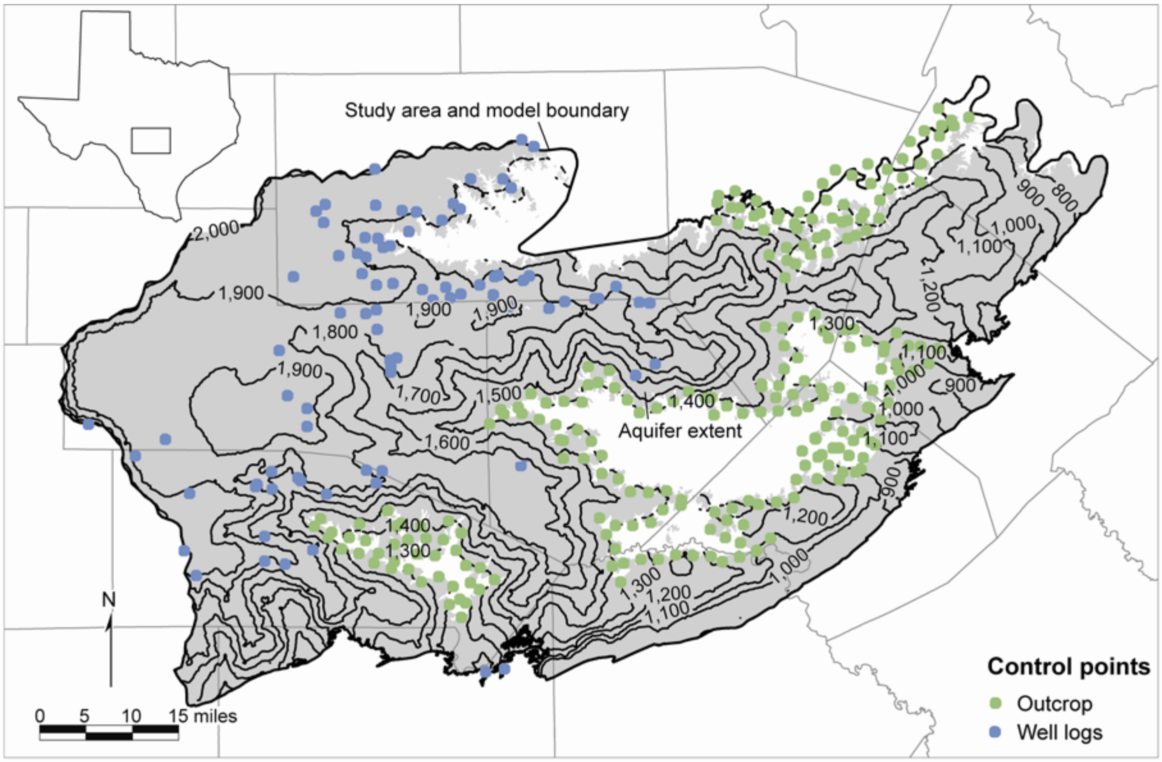
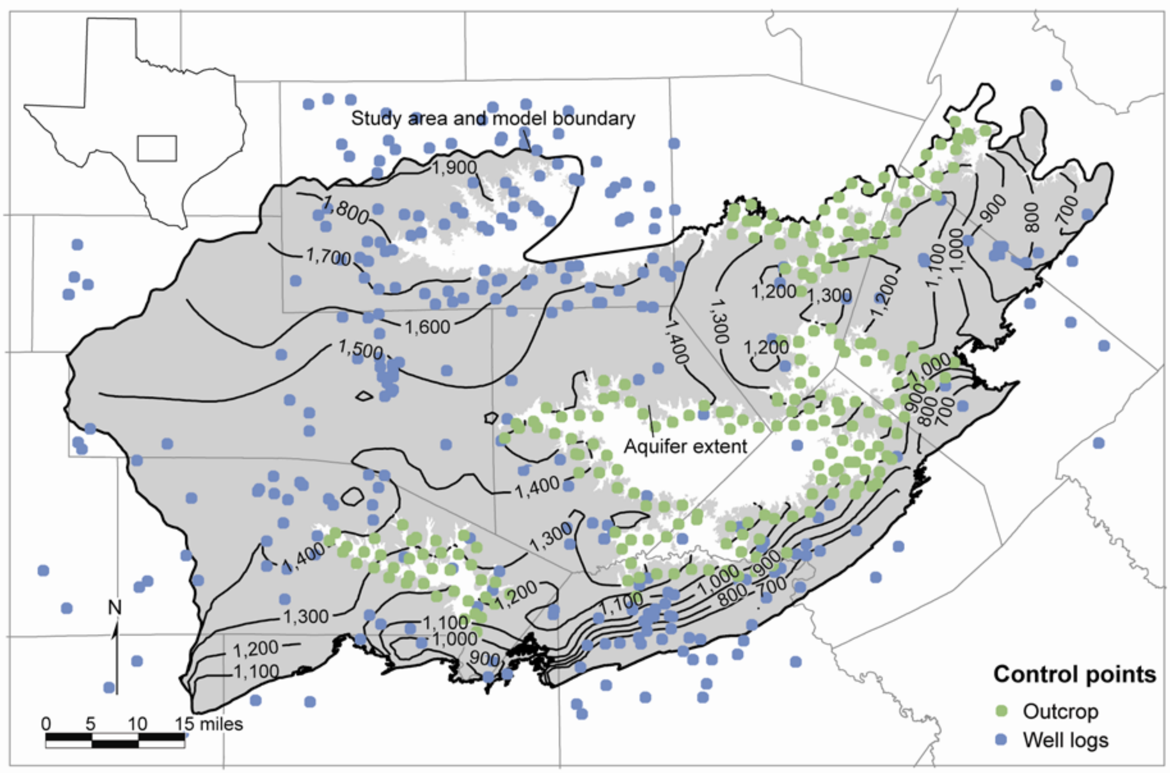


Figure 5-1. Elevations of (a) the top and (b) the base of the Edwards Group. The contour interval is 100 feet (modified from Ashworth, 1983; Mace and others, 2000).



(a)



(b)

Figure 5-2. Elevations of (a) the top and (b) the base of the Upper Trinity Aquifer. The contour interval is 100 feet (modified from Ashworth, 1983; Mace and others, 2000).

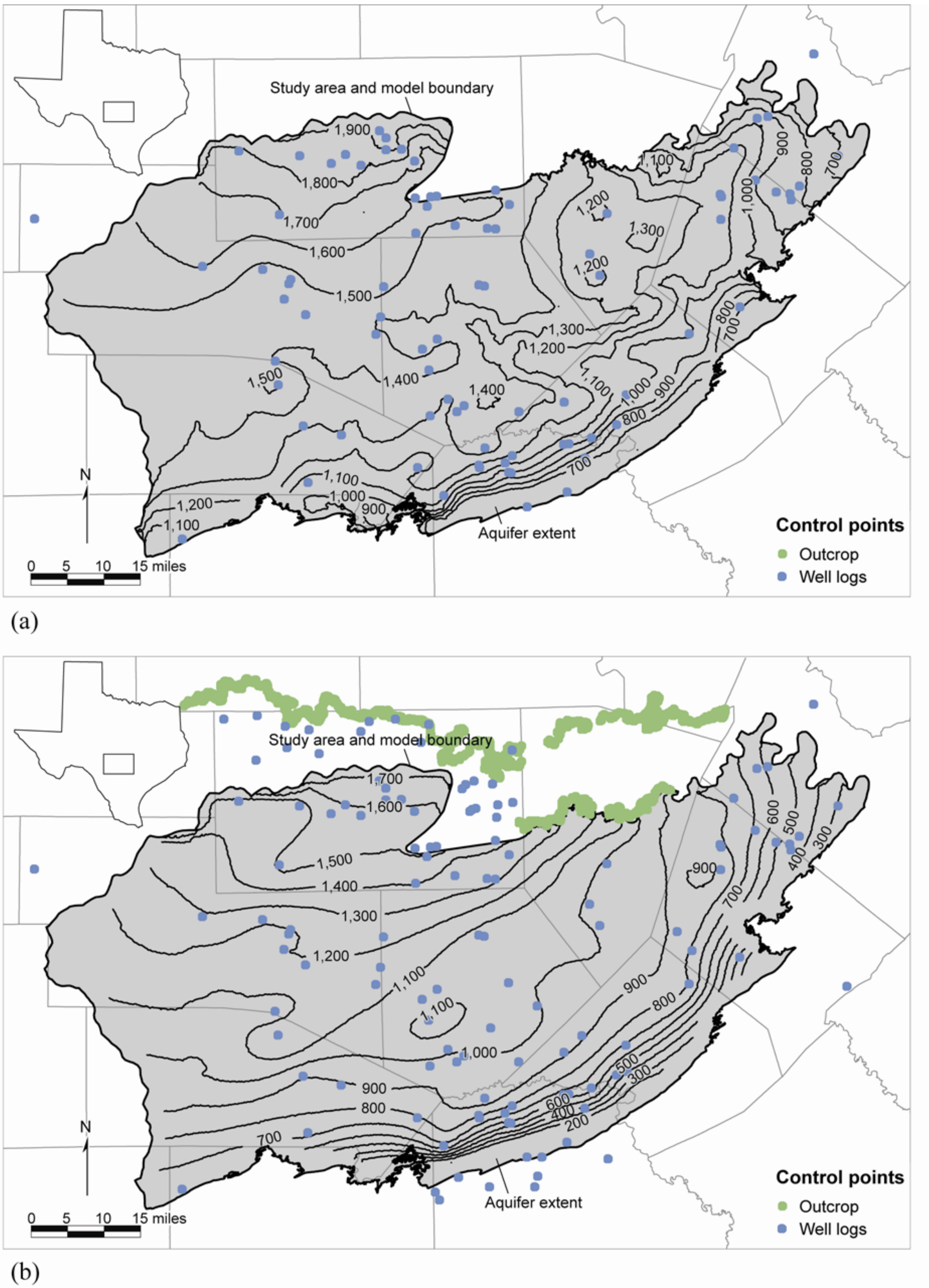
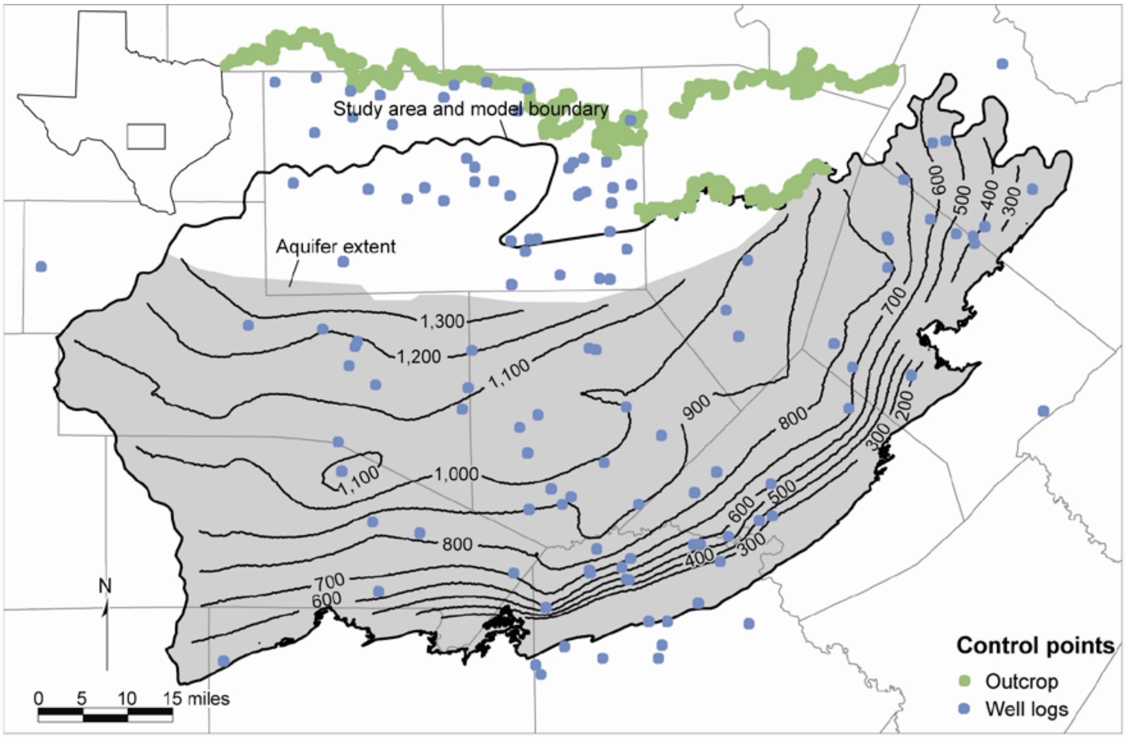
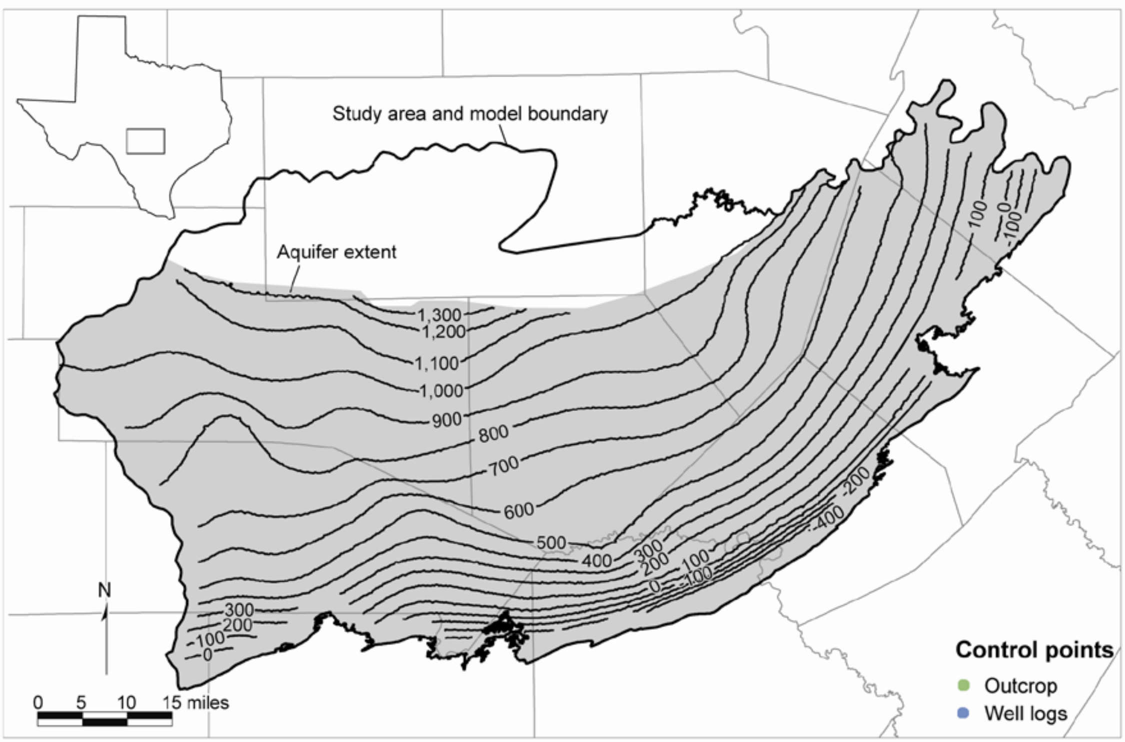


Figure 5-3. **Elevations of (a) the top and (b) the base of the Middle Trinity Aquifer. The contour interval is 100 feet (modified from Ashworth, 1983; Mace and others, 2000).**



(a)



(b)

Figure 5-4. Elevations of (a) the top (modified from Ashworth, 1983; Mace and others, 2000) and (b) the base of the Lower Trinity Aquifer. 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.

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. 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 geographic information system database developed by the U.S. 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 data from the original model (Mace and others, 2000) for the rest of the model. The two surfaces were merged through the use of 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 5-5 through 5-8). The thickness of the relatively flat lying beds of the Edwards Group is controlled by the dendritic erosional pattern of the surface topography (Figures 5-1 and 5-5). 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 toward the Balcones Fault Zone (Figure 5-6). Sediments of the Middle and Lower Trinity aquifers also generally increase in thickness toward the Balcones Fault Zone (Figures 5-7 and 5-8).

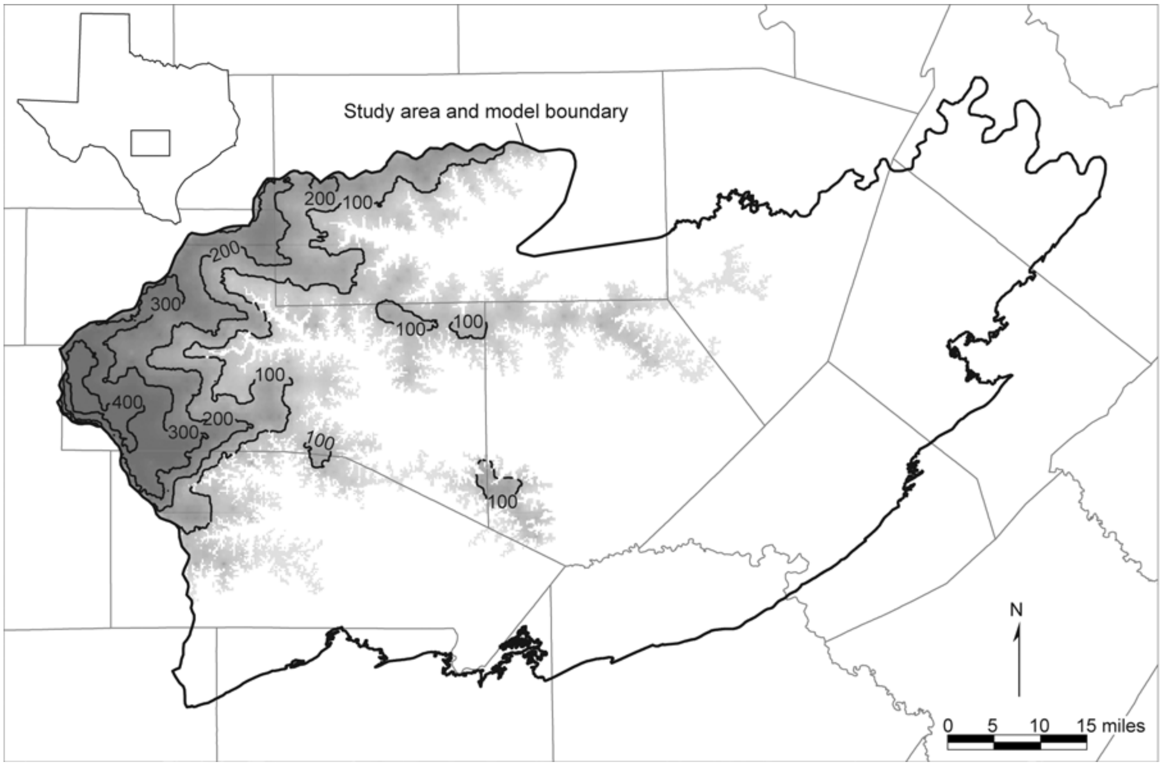


Figure 5-5. Approximate thickness of the Edwards Group in the study area. The contour interval is 100 feet.

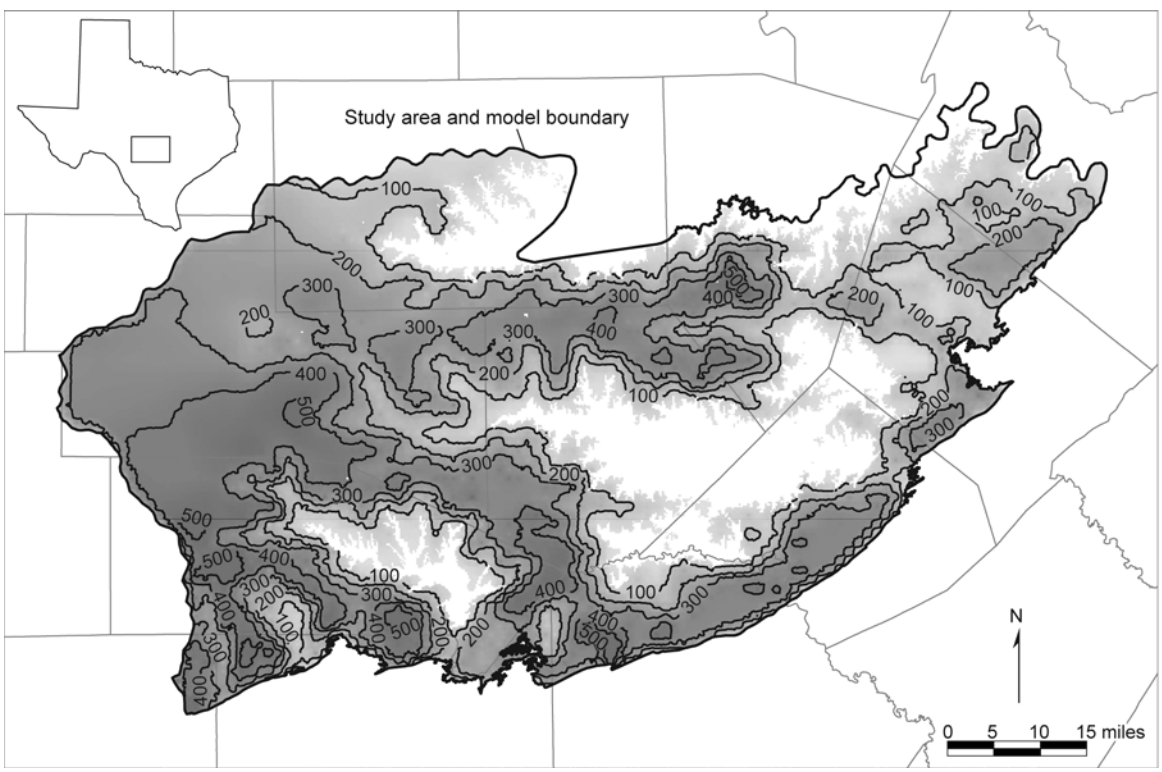


Figure 5-6. Approximate thickness of the Upper Trinity Aquifer in the study area. The contour interval is 100 feet.

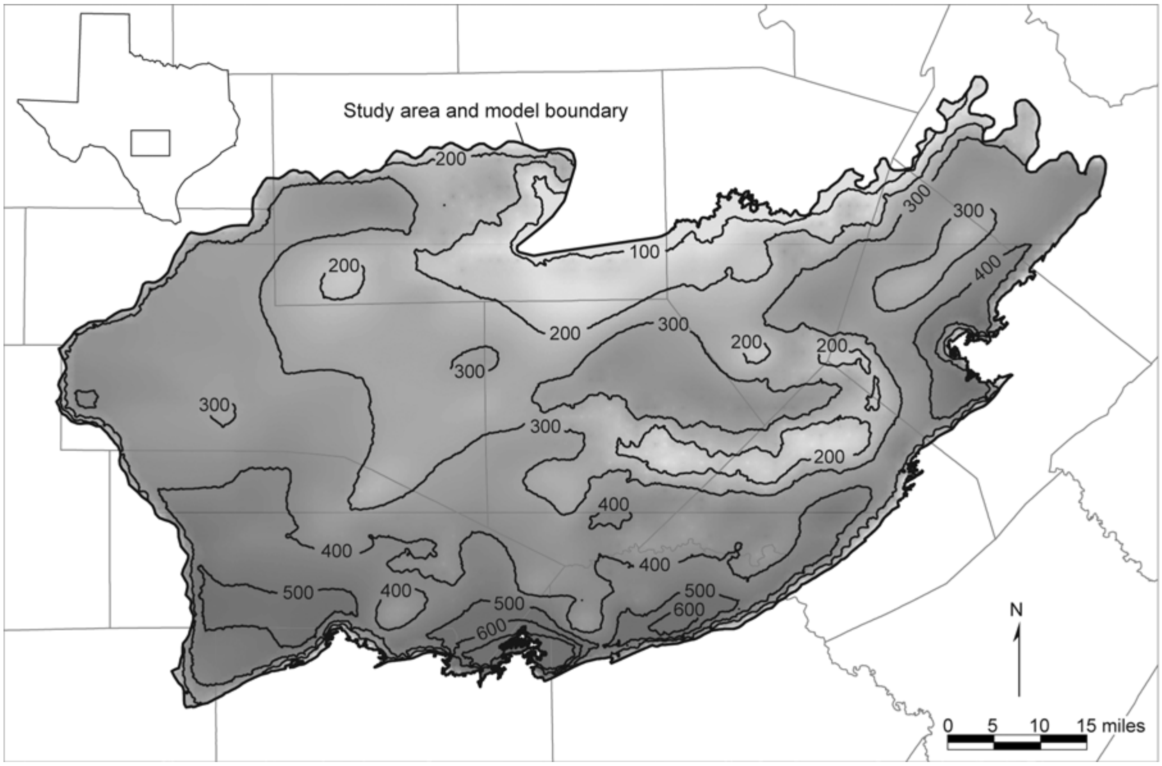


Figure 5-7. **Approximate thickness of the Middle Trinity Aquifer in the study area. The contour interval is 100 feet.**

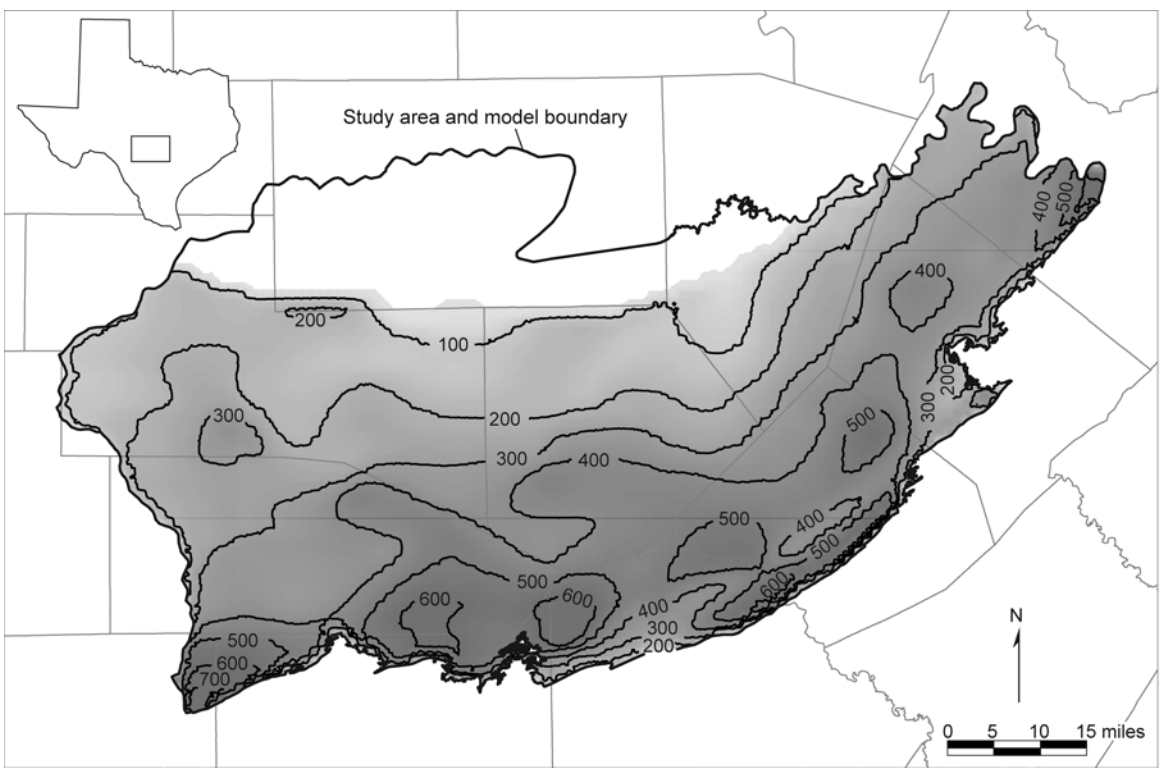


Figure 5-8. **Approximate thickness of the Lower Trinity Aquifer in the study area. The contour interval is 100 feet.**

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, we chose the average measurement for contouring the water level map.

Water levels in the aquifers generally follow topography (Figures 5-9 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 5-9 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 5-9). 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 5-9 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 through 5-12). Section 5.7 (Discharge) 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.

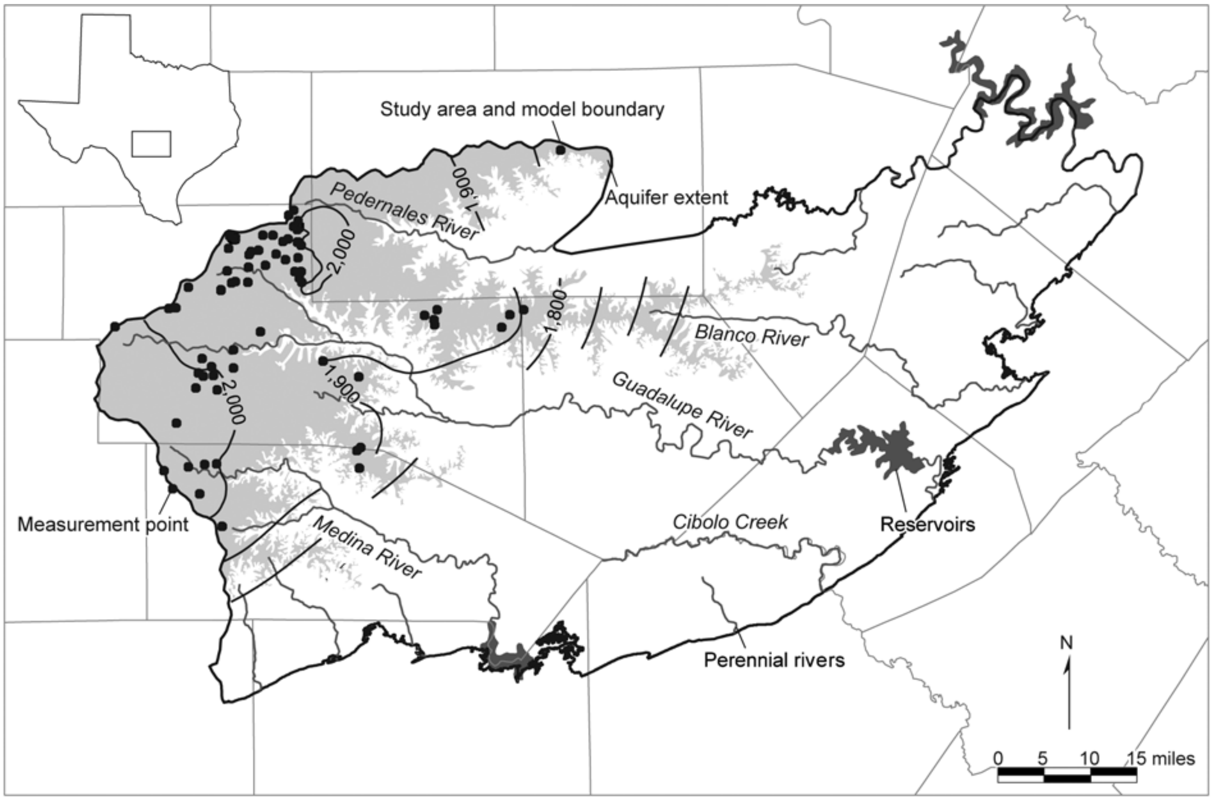


Figure 5-9. **Average water level elevations in the Edwards Group in the study area for the period 1977 through 1985. The contour interval is 100 feet.**

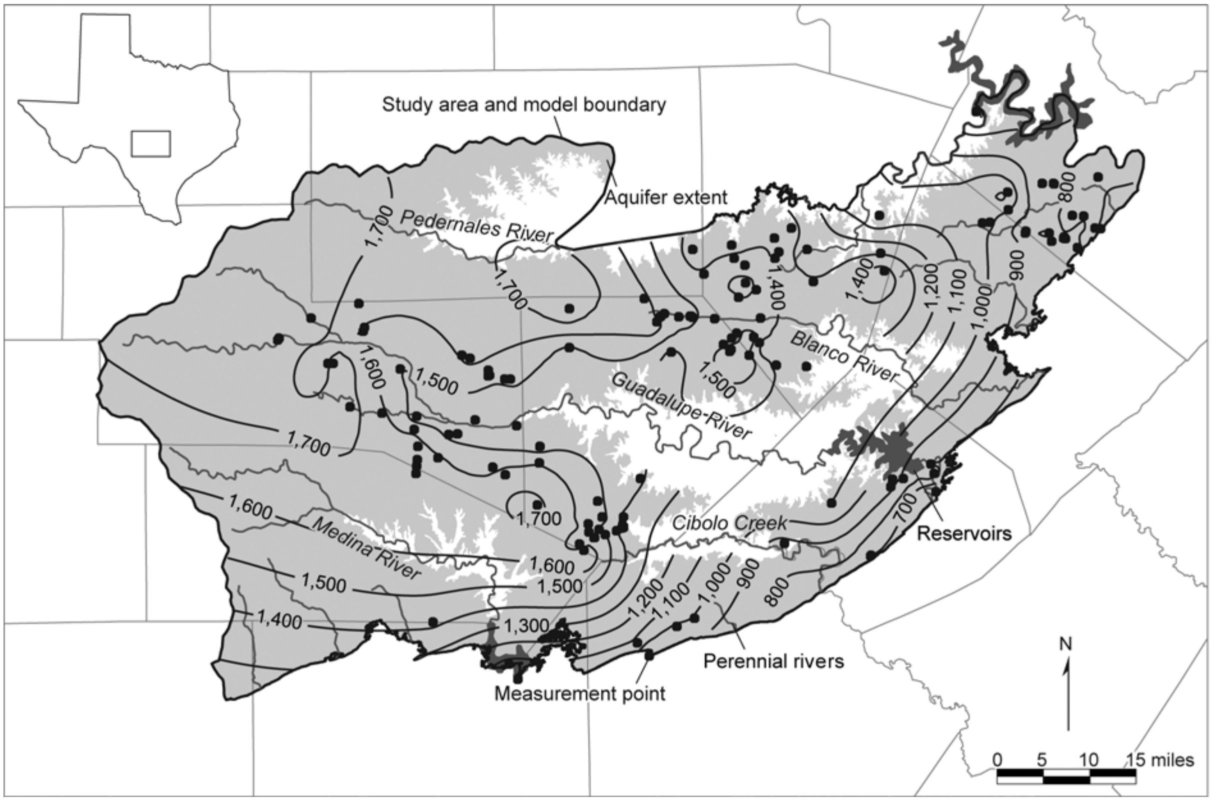


Figure 5-10. Average water level elevations in the Upper Trinity Aquifer in the study area for the period 1977 through 1985. The contour interval is 100 feet.

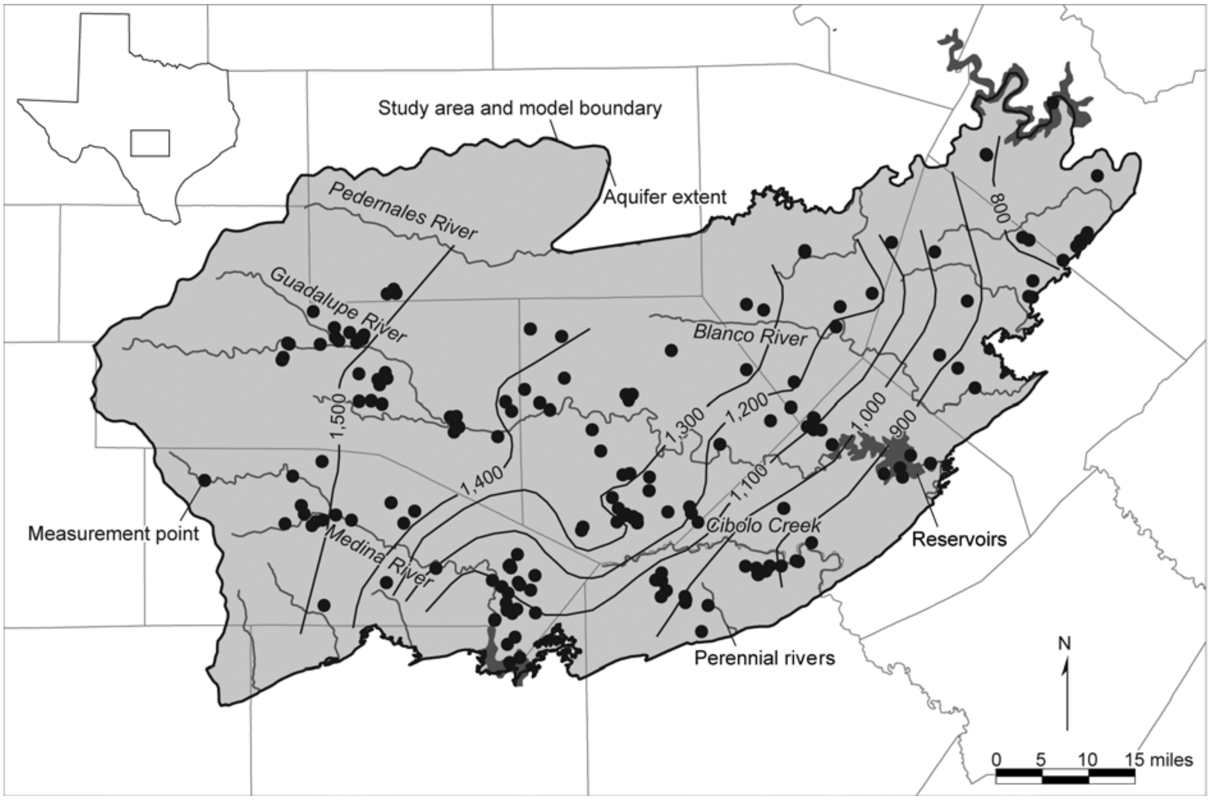


Figure 5-11. Average water level elevations in the Middle Trinity Aquifer in the study area for the period 1977 through 1985. The contour interval is 100 feet.

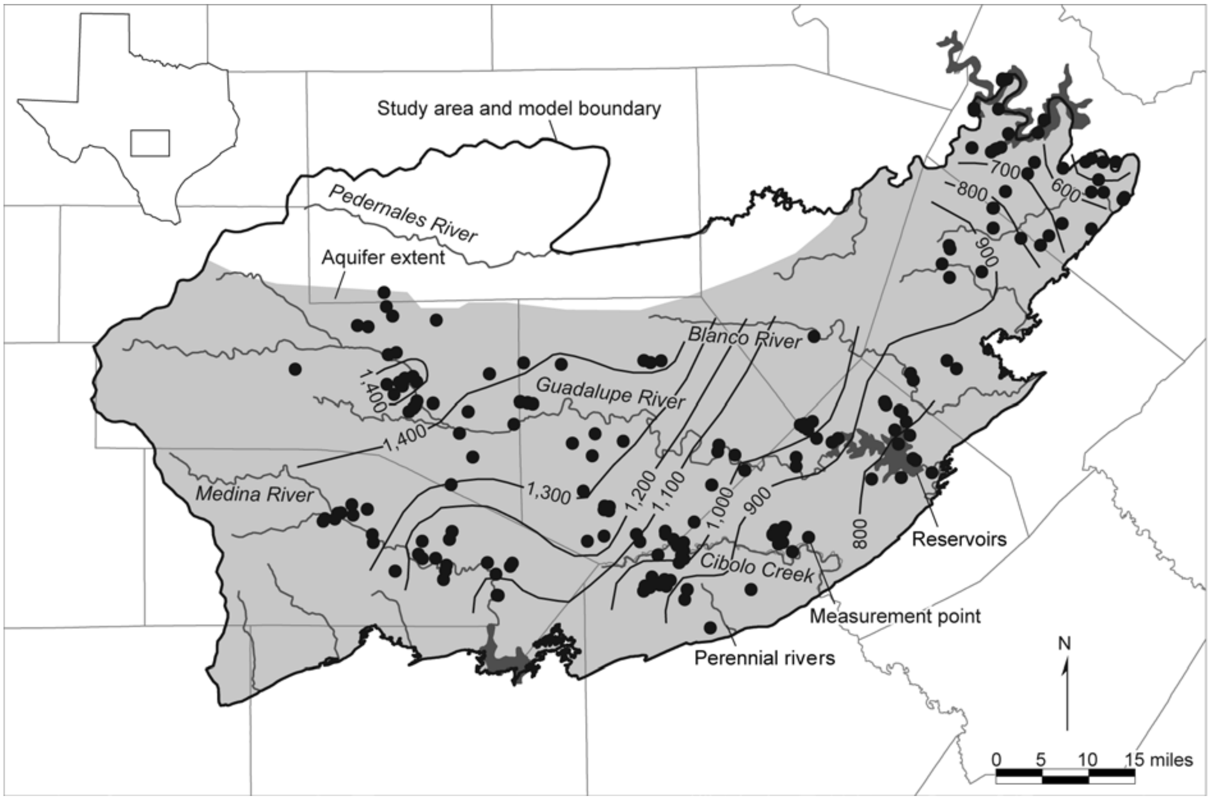


Figure 5-12. Average water level elevations in the Lower Trinity Aquifer in the study area for the period 1977 through 1985. The contour interval is 100 feet.

Water levels, especially in shallow wells (less than 100 feet deep), can seasonally vary by as much as 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, whereas 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; thus, water levels in the 1990s will be similar to those for the period 1977 through 1985 (Figures 5-9 through 5-12).

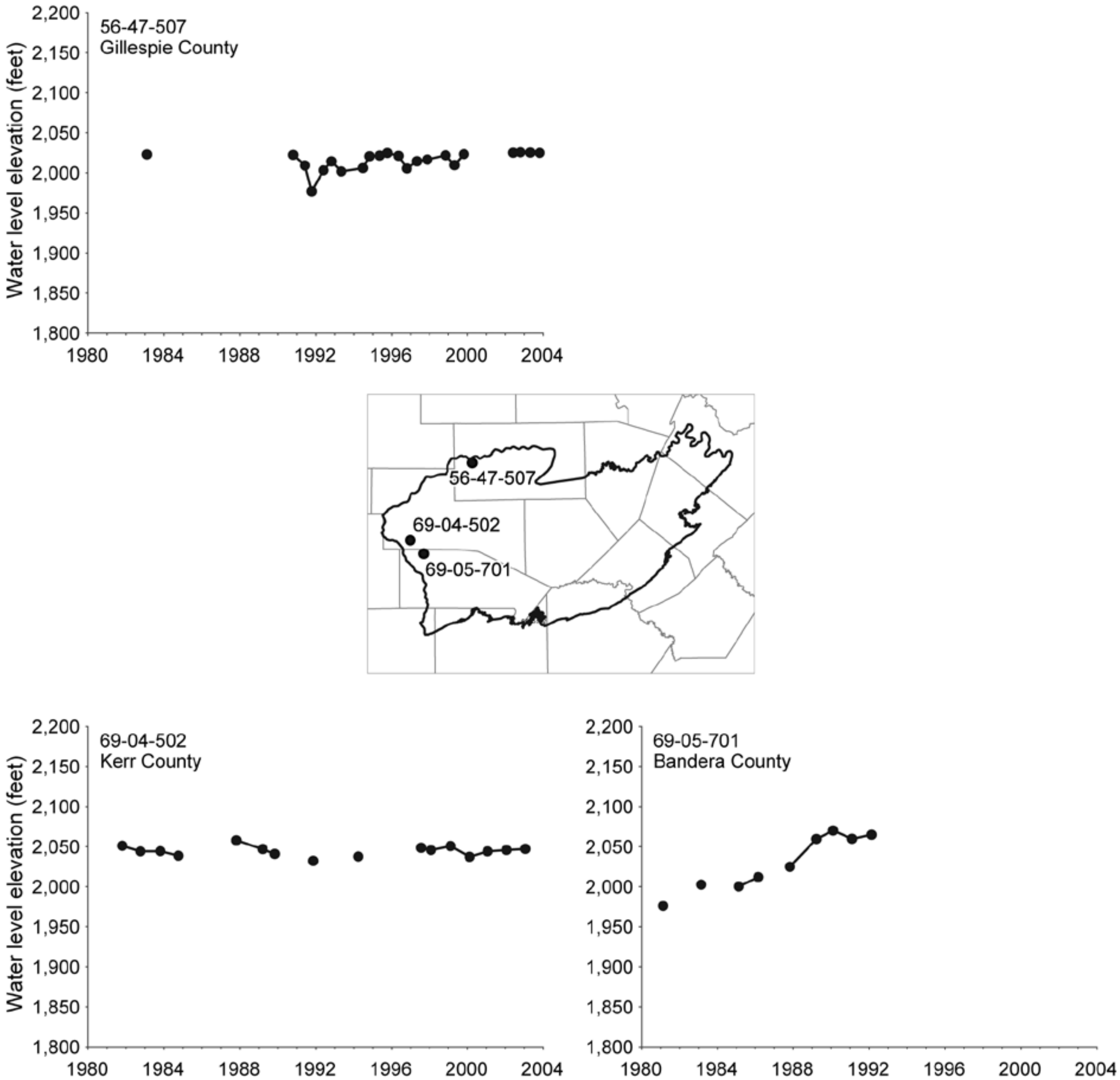


Figure 5-13. Hydrographs from selected Edwards Group wells in the study area.

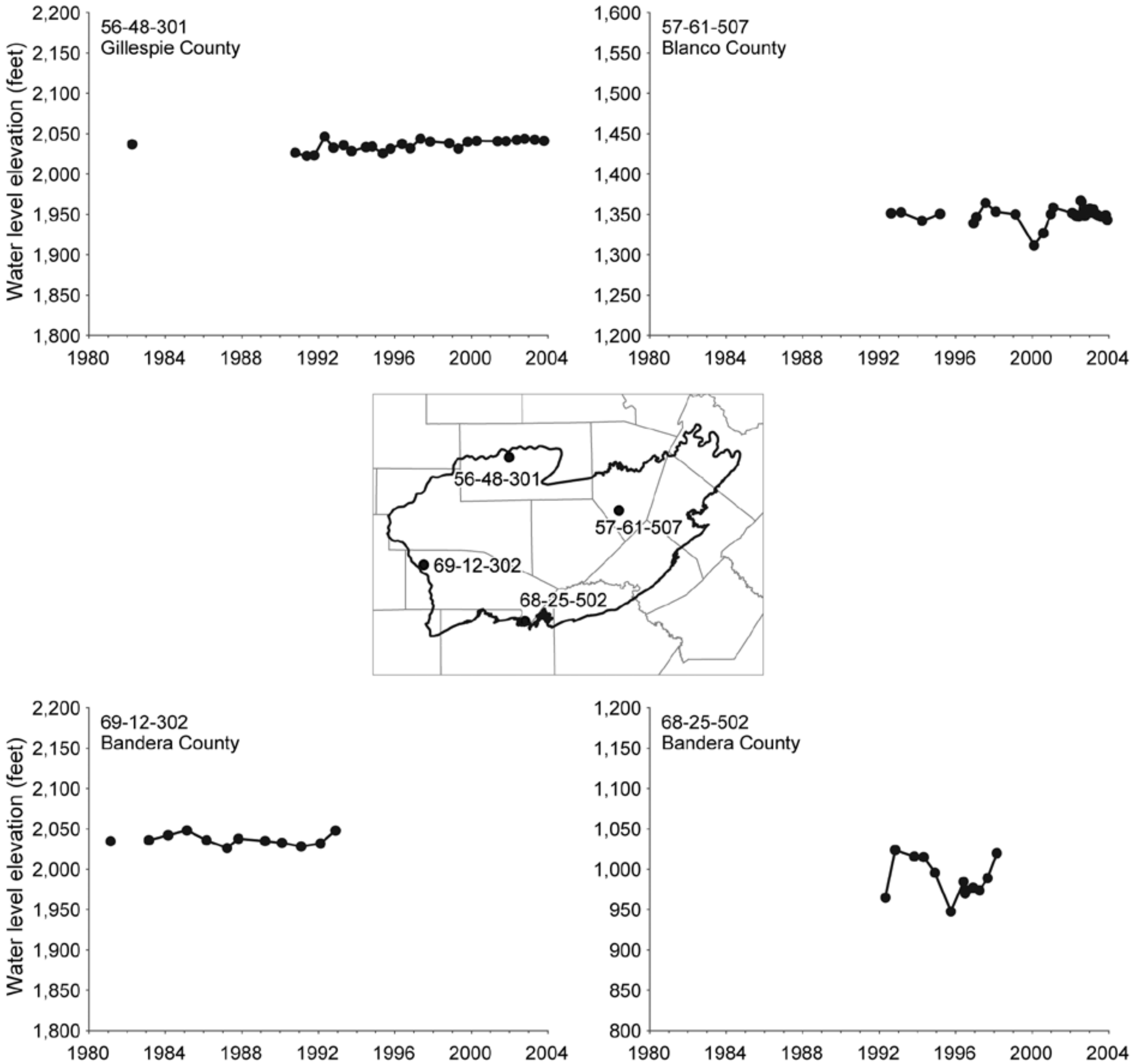


Figure 5-14. Hydrographs from selected Upper Trinity Aquifer wells in the study area.

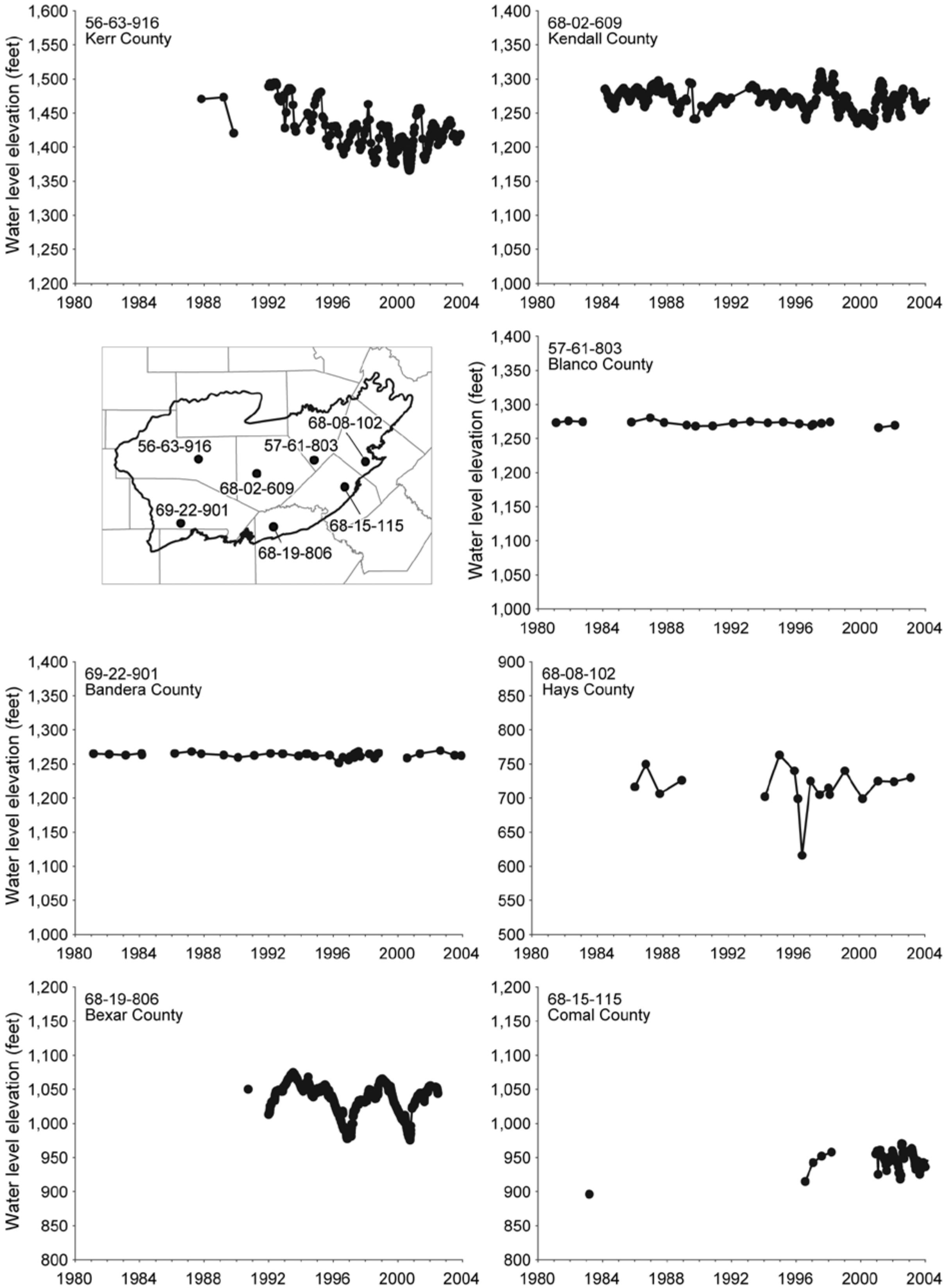


Figure 5-15. Hydrographs from selected Middle Trinity Aquifer wells in the study area.

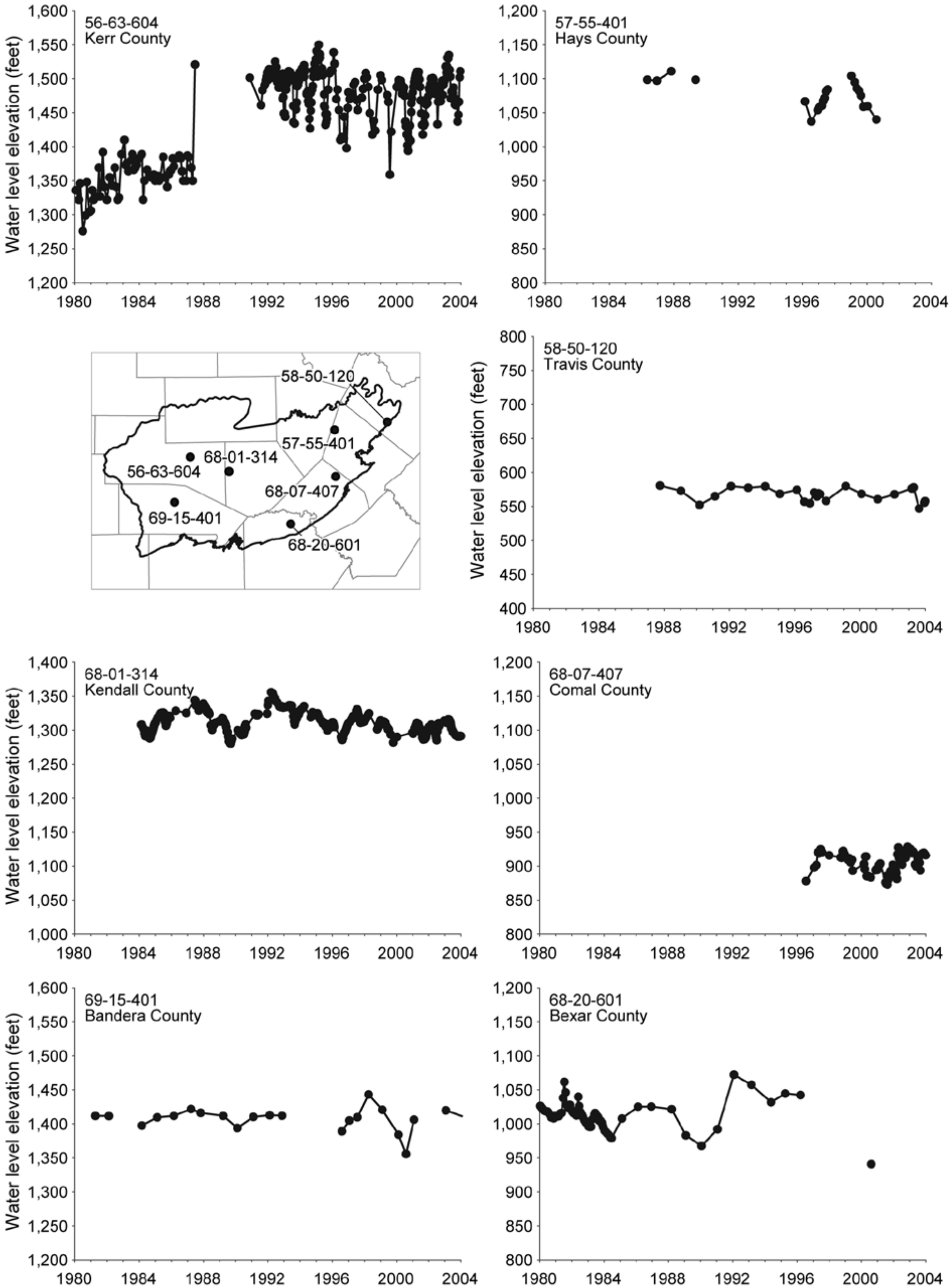


Figure 5-16. Hydrographs from selected Lower Trinity Aquifer wells in the study area.

From 1980 to 1997, water levels generally rose in the Upper Trinity Aquifer of Bexar County (Figure 5-17). Over the same period, 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 having 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).

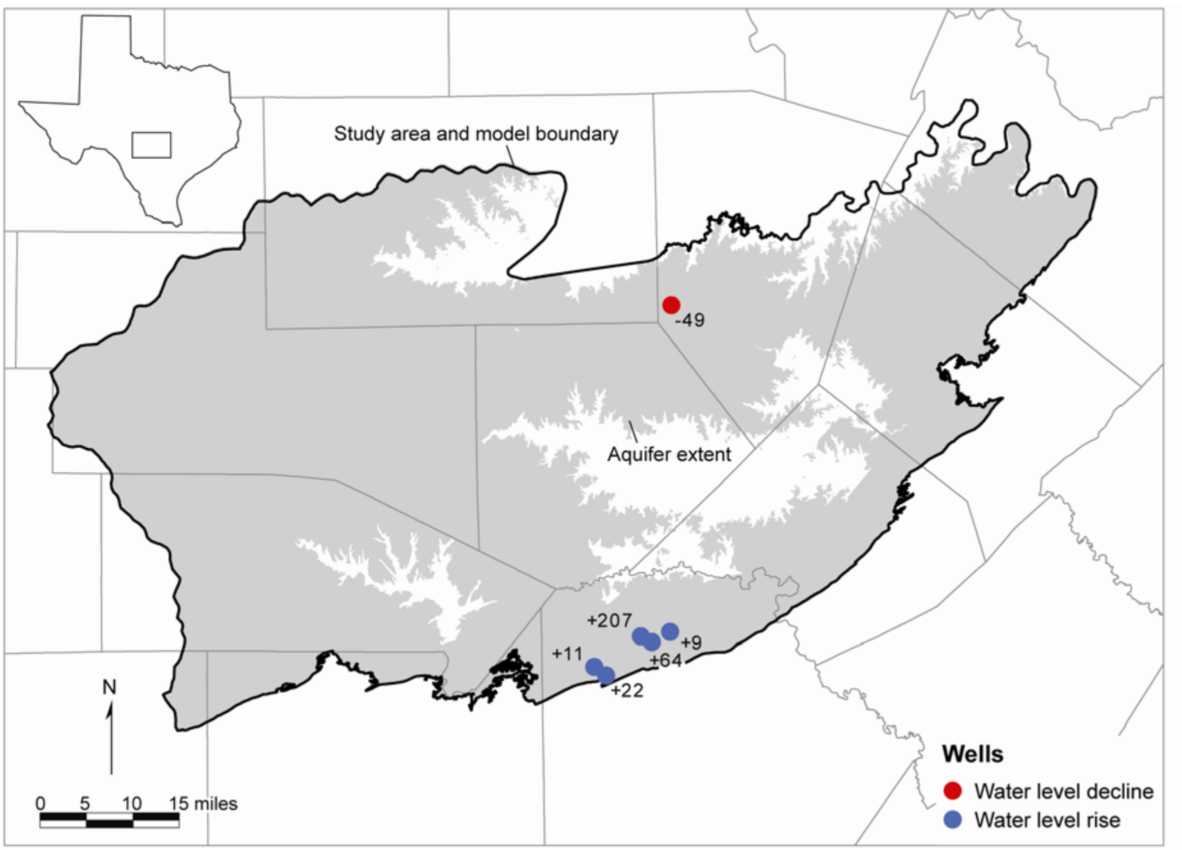


Figure 5-17. Net water level change in the Upper Trinity Aquifer between 1980 and 1997 at selected well locations.

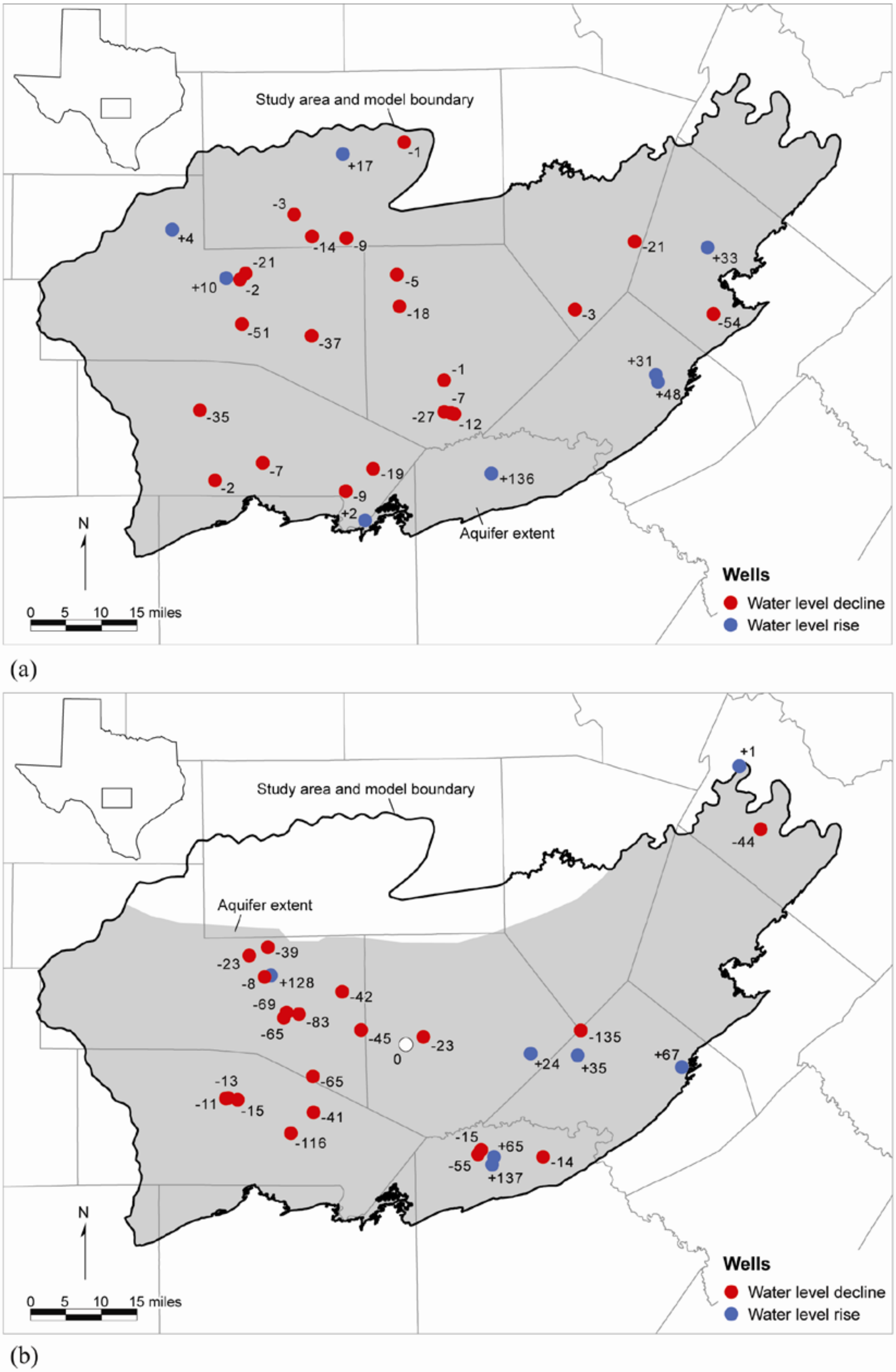


Figure 5-18. **Net water level change in (a) the Middle Trinity Aquifer and (b) Lower Trinity Aquifer between 1980 and 1997 at selected well locations. Positive values (blue points) indicate rise in water level, and negative values (red points) indicate decline in water levels.**

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 base flow and spring flow to the mostly gaining perennial streams that drain the Hill Country (Ashworth, 1983; Barker and Ardis, 1996). 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 (Veni, 1994; Barker and Ardis, 1996).

Several investigators have estimated recharge rates for the Hill Country portion of the Trinity Aquifer System (Table 5-1).

Table 5-1. 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
Bluntzer (1992, calculated)	2.2	6.7
Bluntzer (1992, estimated)	1.7	5.0
Kuniansky and Holligan (1994)	2.3	7.0
Mace and others (2000)	1.3	4.0
Mace (2001)	2.2	6.6
Wet Rock Groundwater Services (2008)	3.1	9.5
Anaya and Jones (2009)	1.4	4.7

Most of them used stream base flow 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 base flow and groundwater flow to the Edwards (Balcones Fault Zone) Aquifer. On the basis of a study of base-flow gains in the Guadalupe River between the Comfort and Spring Branch gaging stations during a 20-year period between 1940 and 1960, Ashworth (1983) estimated an average annual effective recharge rate of 4 percent of average annual precipitation for the Hill Country. Kuniansky (1989) estimated base flow 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 base flow 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) suggested that a recharge rate of 5 percent is more appropriate to account for human impacts on base flow such as nearby groundwater pumping, streamflow diversions, municipal and irrigation return flows, and retention structures. Bluntzer (1992) also noted that base flow 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 most 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 1950s' drought of record.

Mace and others (2000) developed an automated digital hydrograph-separation technique to estimate base flow for the drainage basin defined by the Guadalupe River gaging stations between Comfort and Spring Branch. Mace and others (2000) based this technique on methods used by Nathan and McMahon (1990) and Arnold and others (1995). Mace and others (2000) used the program to estimate base flow from 1940 to 1990 and adjusted parameters to attain the best fit with Ashworth's (1983) and Kuniansky's (1989) base-flow 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 base-flow-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. Additional error in this methodology is 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. Regional groundwater flow between watersheds, however, results in underestimation of recharge in up-gradient watersheds and overestimation in down-gradient watersheds.

In the updated model, we spatially distributed recharge using the Parameter-elevation Regressions on Independent Slopes Model (PRISM) data (Daly and Taylor, 1998; Spatial Climate Analysis Service, 2004). The 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 assumed that the aquifer receives recharge from streamflow losses in Cibolo Creek. This recharge is estimated on the basis of watershed modeling of the Cibolo Creek watershed by the U.S. 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 base-flow coefficients and precipitation distribution. In addition to overcoming the weaknesses in base-flow-based recharge estimation methods stated above, the updated model was further improved by 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 3-6). Many of these streams have upper reaches contained within narrow canyons and broaden into flat-bottomed valleys farther downstream (Barker and Ardis, 1996). Three major drainage basins—the San Antonio, Guadalupe, and Colorado rivers—traverse the study area and funnel flow toward 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).

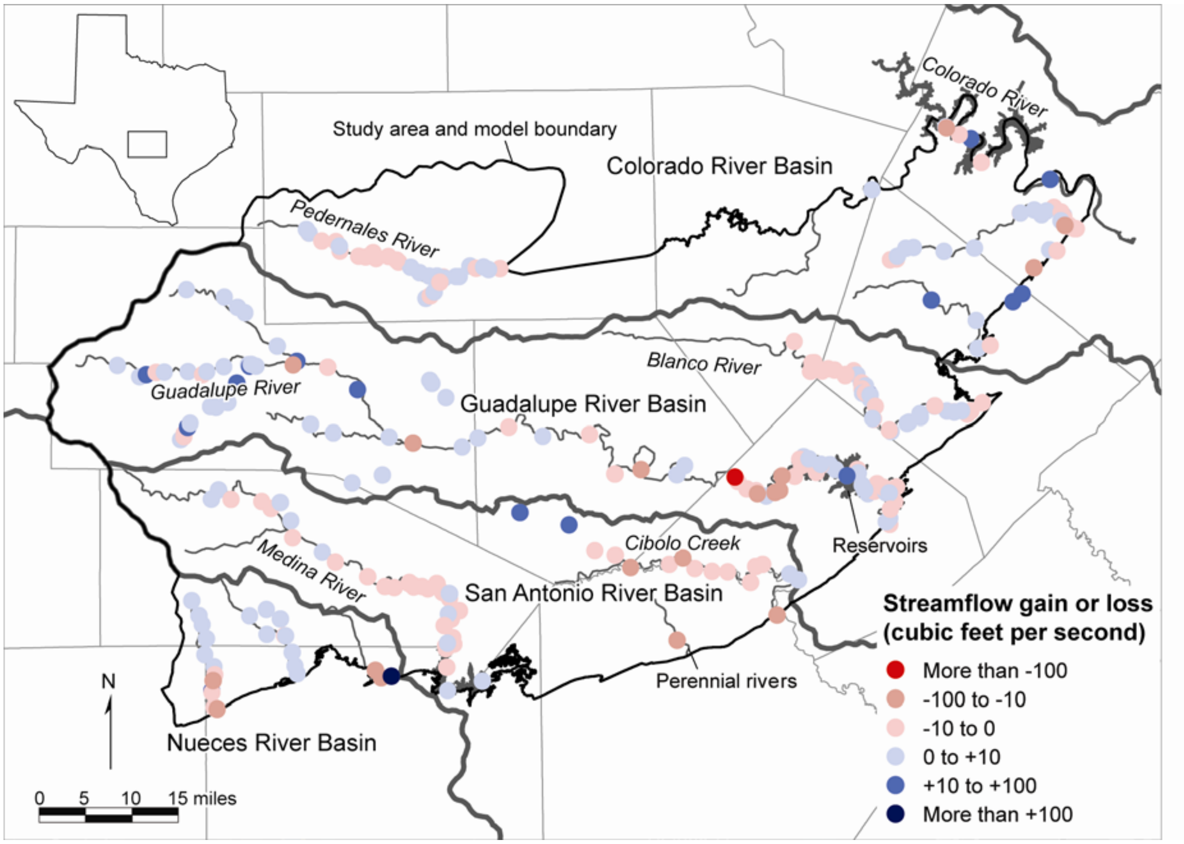


Figure 5-19. **Streamflow gain (positive values) and loss (negative values) from Slade and others (2002).**

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 the creek 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; LBG-Guyton Associates, 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 have extremely low flow for brief periods during droughts (Figures 5-21 through 5-23).

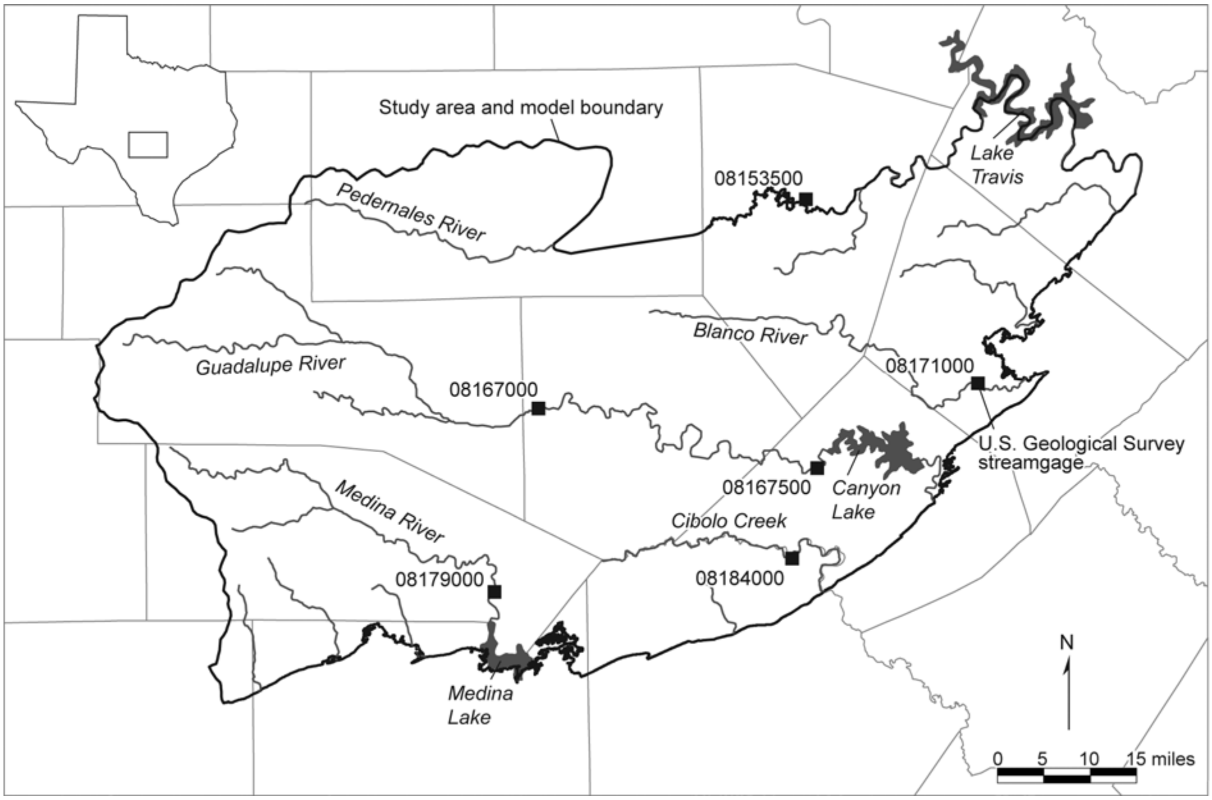


Figure 5-20. Location of streamgages for the streamflow hydrographs shown in Figures 5-21 through 5-26 (from Mace and others, 2000).

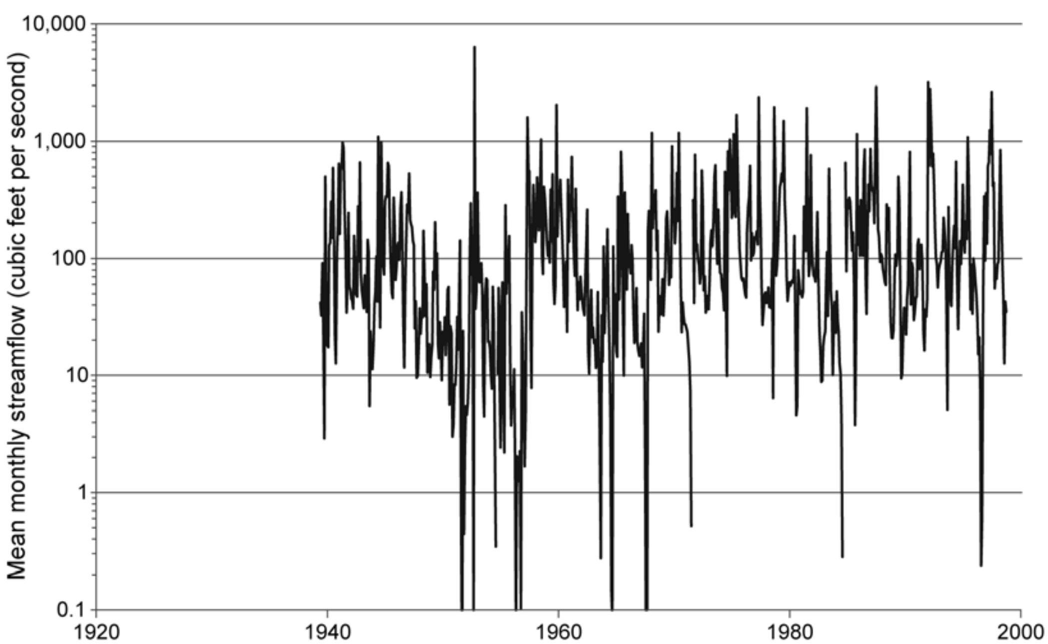


Figure 5-21. Mean monthly streamflow for the U.S. Geological Survey gaging 08153500 on the Pedernales River near Johnson City. The station location can be found in Figure 5-20 (from Mace and others, 2000).

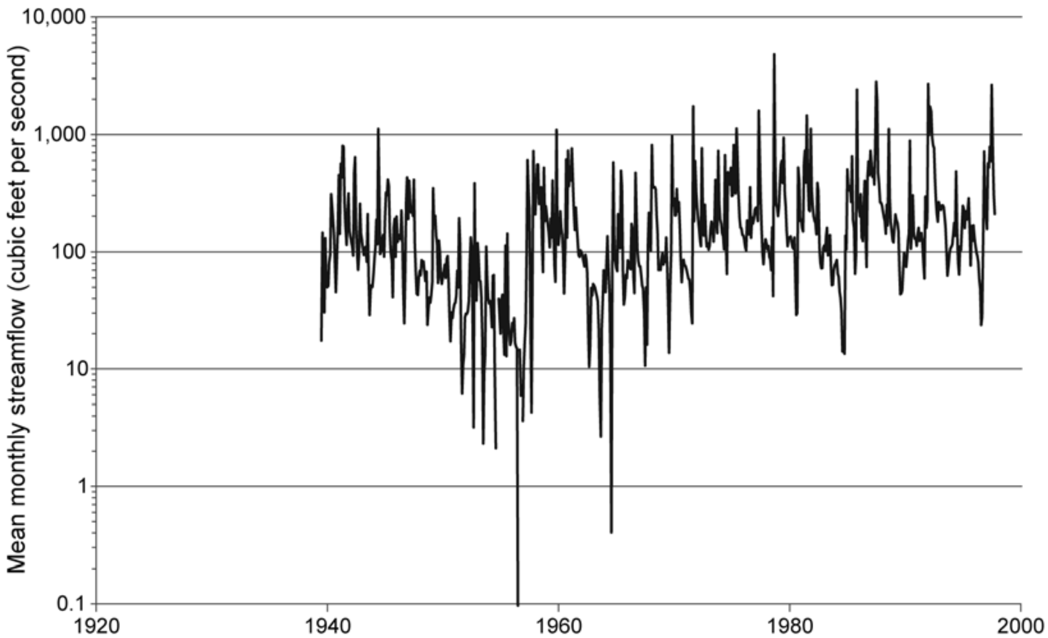


Figure 5-22. Mean monthly streamflow for the U.S. Geological Survey gaging 08167000 on the Guadalupe River at Comfort. The station location can be found in Figure 5-20 (from Mace and others, 2000).

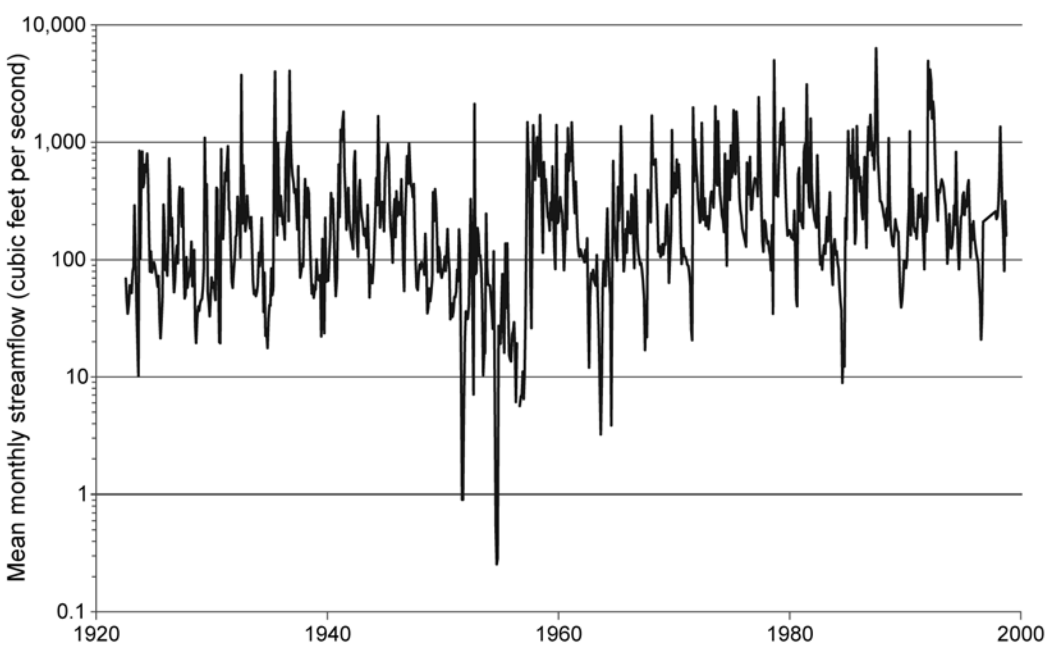


Figure 5-23. Mean monthly streamflow for the U.S. Geological Survey gaging 08167500 on the Guadalupe River near Spring Branch. The station location can be found in Figure 5-20 (from Mace and others, 2000).

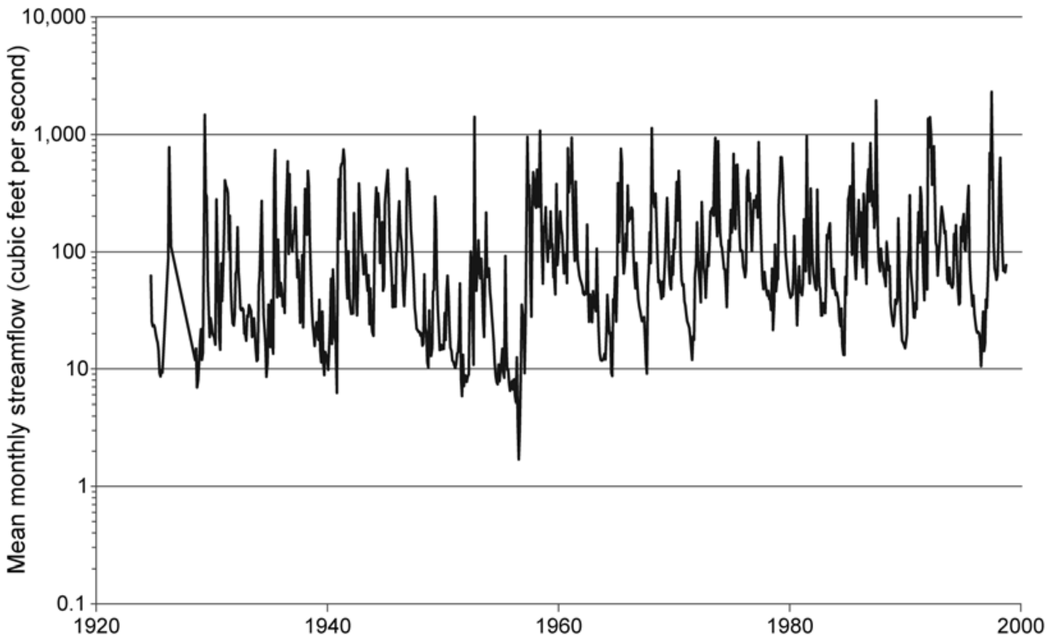


Figure 5-24. **Mean monthly streamflow for the U.S. Geological Survey gaging 08171000 on the Blanco River at Wimberley. The station location can be found in Figure 5-20 (from Mace and others, 2000).**

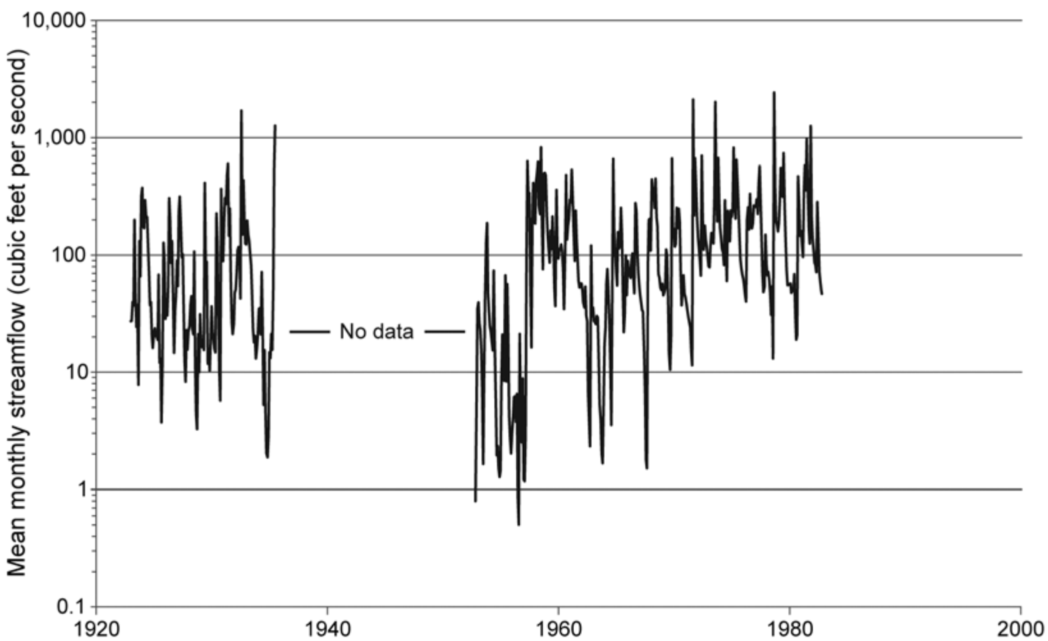


Figure 5-25. **Mean monthly streamflow for the U.S. Geological Survey gaging 08179000 on the Medina River near Pipe Creek. The station location can be found in Figure 5-20 (from Mace and others, 2000).**

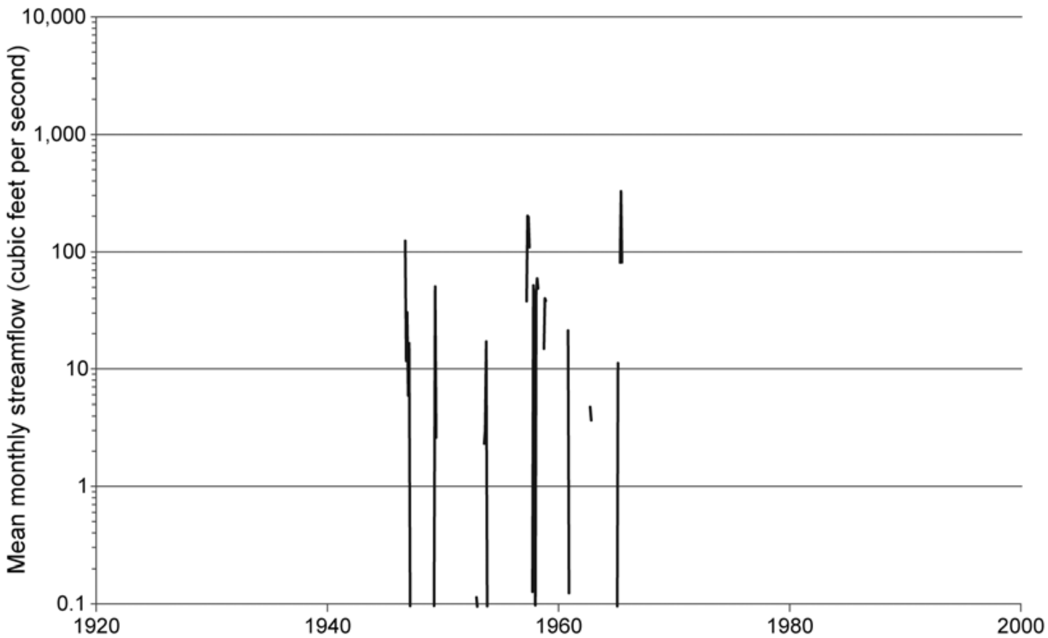


Figure 5-26. Mean monthly streamflow for the U.S. Geological Survey gaging 08184000 on Cibolo Creek near Bulverde. The station location can be found in Figure 5-20 (from Mace and others, 2000).

The study area includes four major lakes: Lake Travis, Lake Austin, Canyon Lake, and Medina Lake (Figure 3-1). 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 was nearly dry on a few occasions during the drought of the 1950s (Espey, Huston and Associates, 1989) (Figure 5-27).

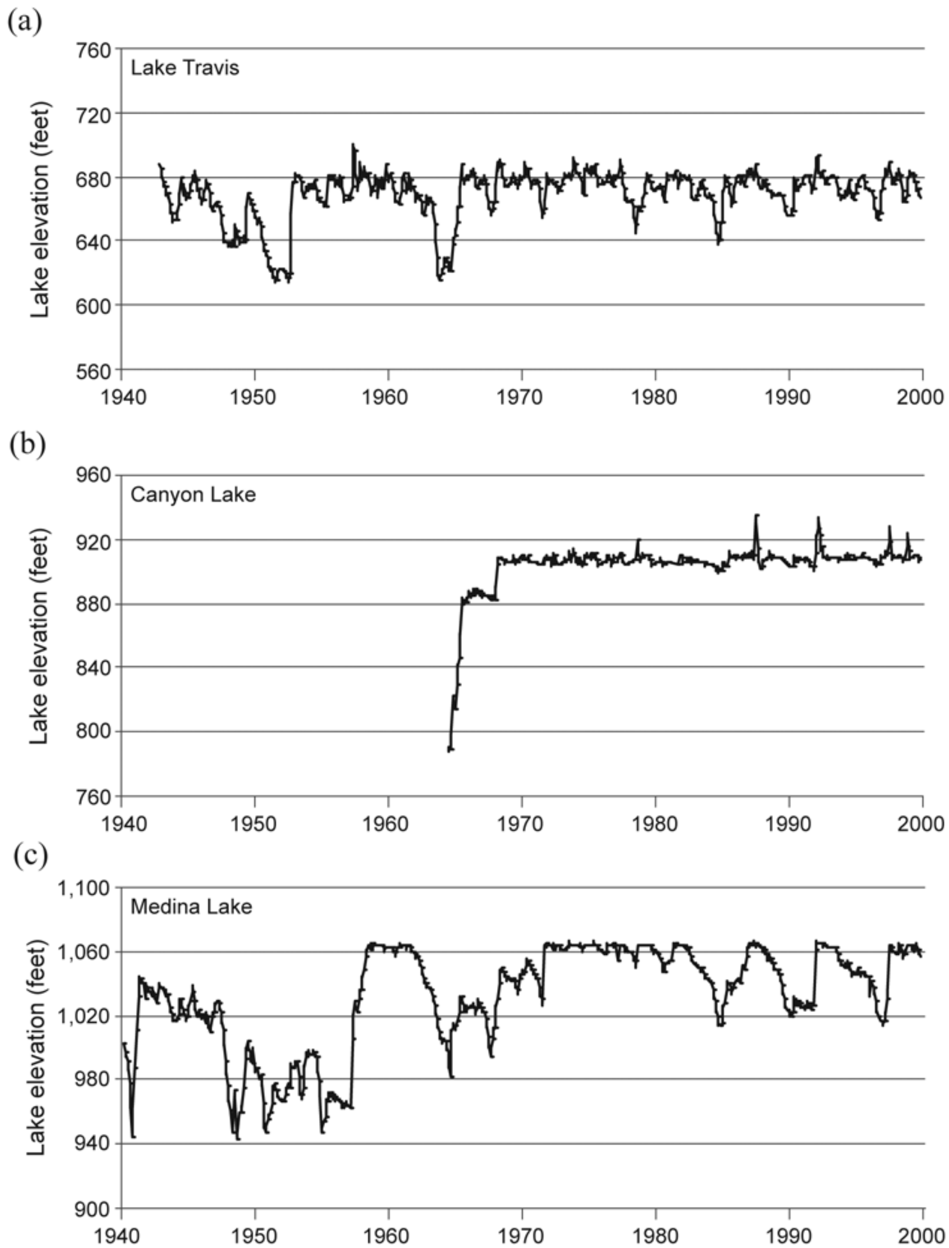


Figure 5-27. Lake-level elevations in (a) Lake Travis, (b) Canyon Lake, and (c) Medina Lake. Lake Travis water levels are from the Lower Colorado River Authority. Canyon Lake water levels are from the U.S. Army Corps of Engineers. Medina Lake water levels for the period 1940 through 1986 are from Espey, 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 TWDB database to lake level using the rate curve by Espey, Huston and Associates (1989).

Numerous springs occur in the study area (Figure 5-28). Most of these springs issue from 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 5-2), presumably because of the cavernous nature of the Edwards Group.

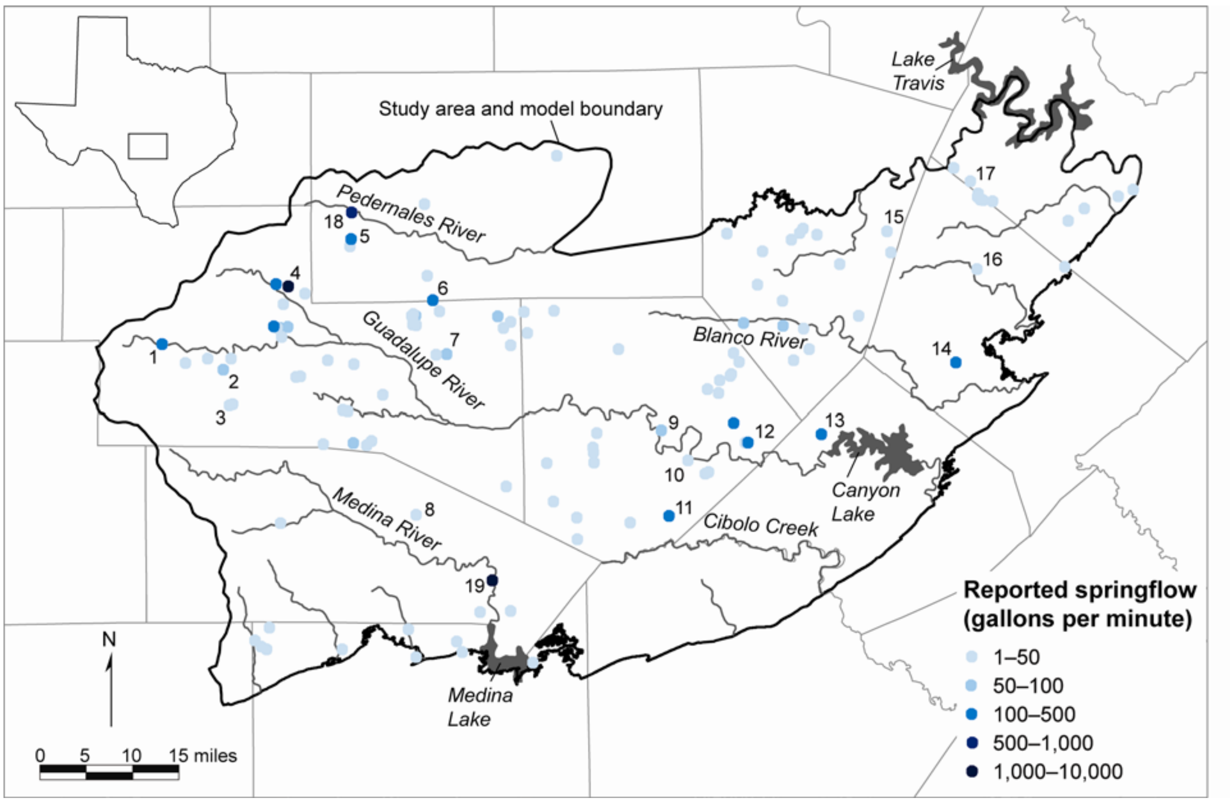


Figure 5-28. Location and estimated spring discharge in the study area. Springflow and geological formations where the numbered springs occur are included in Table 5-2 (from Mace and others, 2000).

Table 5-2. 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, reported flow never ceased
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, owner's 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 gallons per minute, January 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

5.6 Hydraulic Properties

Variations in well yields are generally a result of variation in hydraulic properties of aquifers. Well yields in the Hill Country portion of the Trinity Aquifer System are commonly 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 TWDB as a major aquifer (Ashworth and Hopkins, 1995), well yields can be low compared with those of 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, and sandy limestone may range from 100 to 1,000 feet per day, whereas aquifers having moderate hydraulic conductivity values may range from 10 to 100 feet per day, and aquifers having 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 is thus a measure of the rate of movement through a defined thickness of aquifer under a unit gradient.

Pumping tests in wells are conducted to develop estimates of hydraulic conductivity and transmissivity. On the basis of 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, the 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) reported 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 suggested 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. LBG-Guyton Associates (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 on the basis of 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 updip 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 tectonism 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.

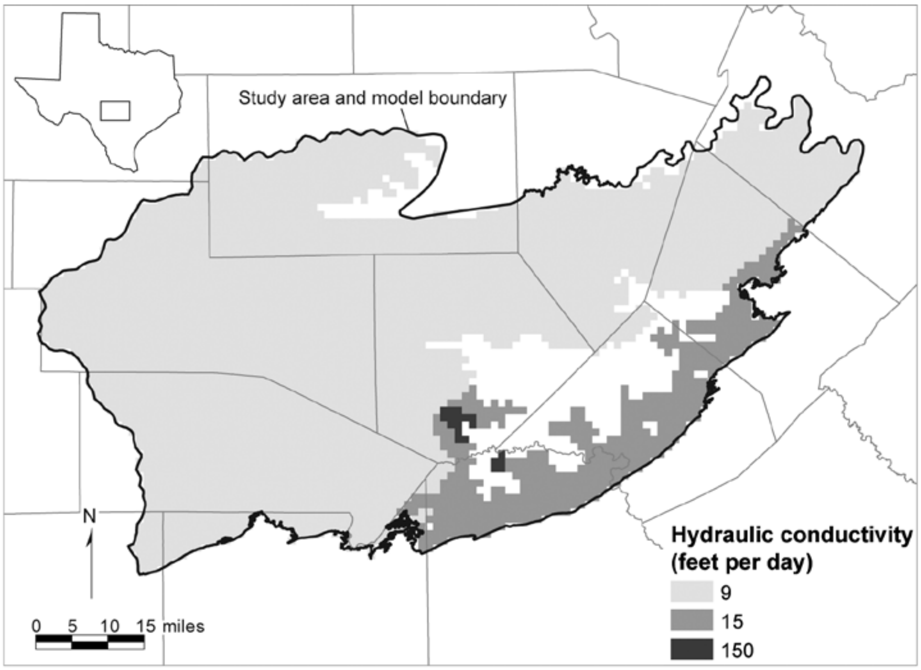
Storativity is the volume of water released from storage per decline of hydraulic head (water pressure) and is typically less than 0.01 for a confined aquifer. Specific storage is defined as the storativity divided by the aquifer thickness. Ashworth (1983) estimated that in the Trinity Group, the confined 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. On the basis of 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 Company Limited and Guyton and Associates, 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 TWDB water-well database. To estimate transmissivity, Mace and others (2000) used an analytical technique (Theis, 1963).

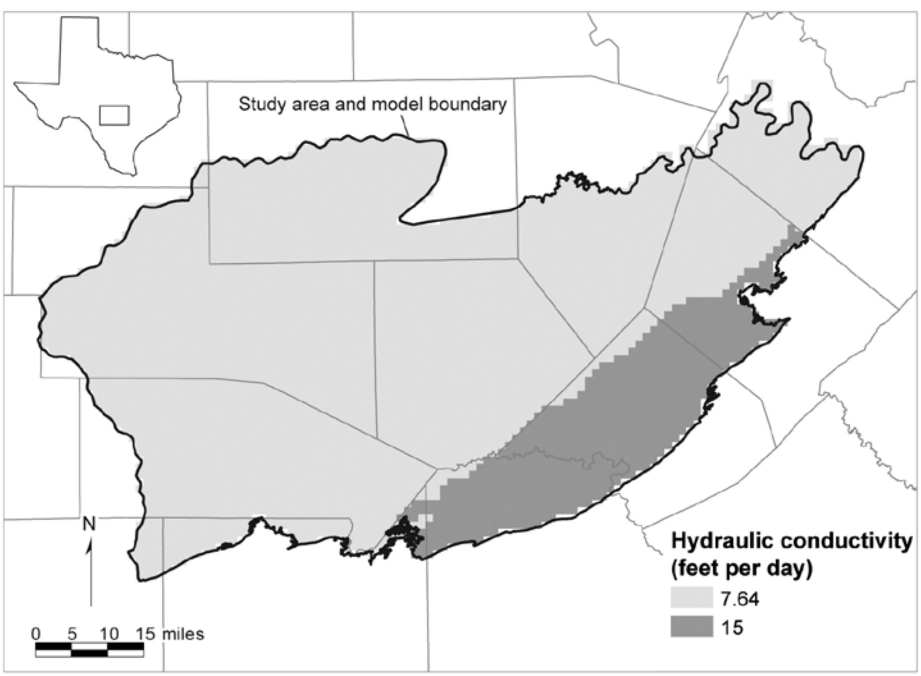
Mace and others (2000) developed a map of hydraulic conductivity for the Middle Trinity Aquifer, using the spatial distribution of hydraulic conductivity in each unit of the Middle Trinity Aquifer (Cow Creek Limestone, Hensell Sand, and lower member of the Glen Rose Limestone) and the relative thickness 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 Aquifer, 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 the uniformly distributed value of 11 feet per day, whereas hydraulic conductivity in the underlying Upper, Middle, and Lower Trinity aquifers is 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 rest of the aquifer (Figure 5-29). Hydraulic conductivity values for the Lower Trinity Aquifer obtained from the TWDB groundwater database and Hays

Trinity Groundwater Conservation District lie within the range of 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 TWDB well database using methods outlined in Mace (2001).

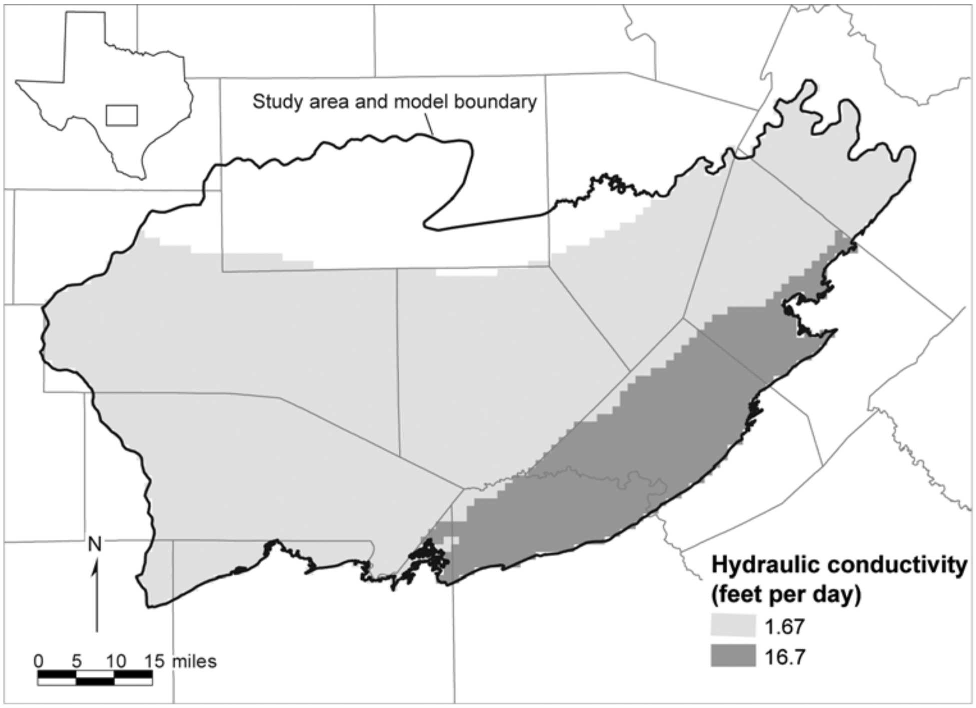


(a) Upper Trinity Aquifer



(b) Middle Trinity Aquifer

Figure 5-29. Distribution of hydraulic conductivity in the (a) Upper, (b) Middle, and (c) Lower Trinity aquifers.



(c) Lower Trinity Aquifer

Figure 5-29. (continued).

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 base flow varies from year to year depending on precipitation.

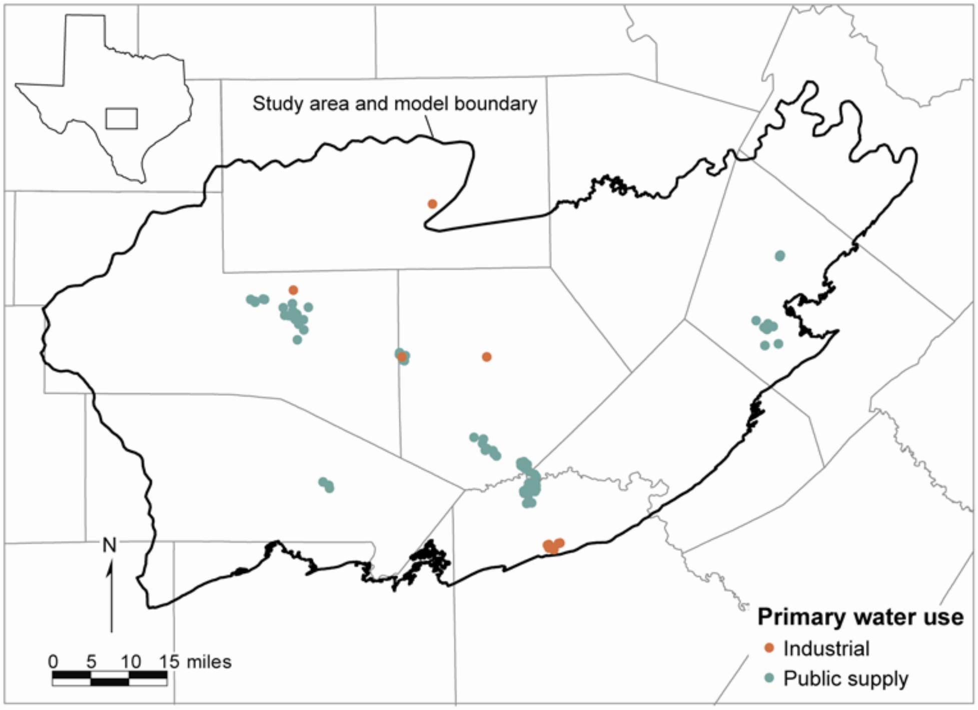
The volume of water that moves laterally from the Hill Country portion of the Trinity Aquifer System into the Edwards (Balcones Fault Zone) Aquifer is not known, partly because of the difficulty in estimating the amount of flow. A number of studies have indicated, either through hydraulic or chemical analysis, that groundwater most 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 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, whereas the rest 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) suggests 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 owing to the hydraulic response and continuity of the formations (George, 1947; Pearson and others, 1975; Veni 1994, 1995).

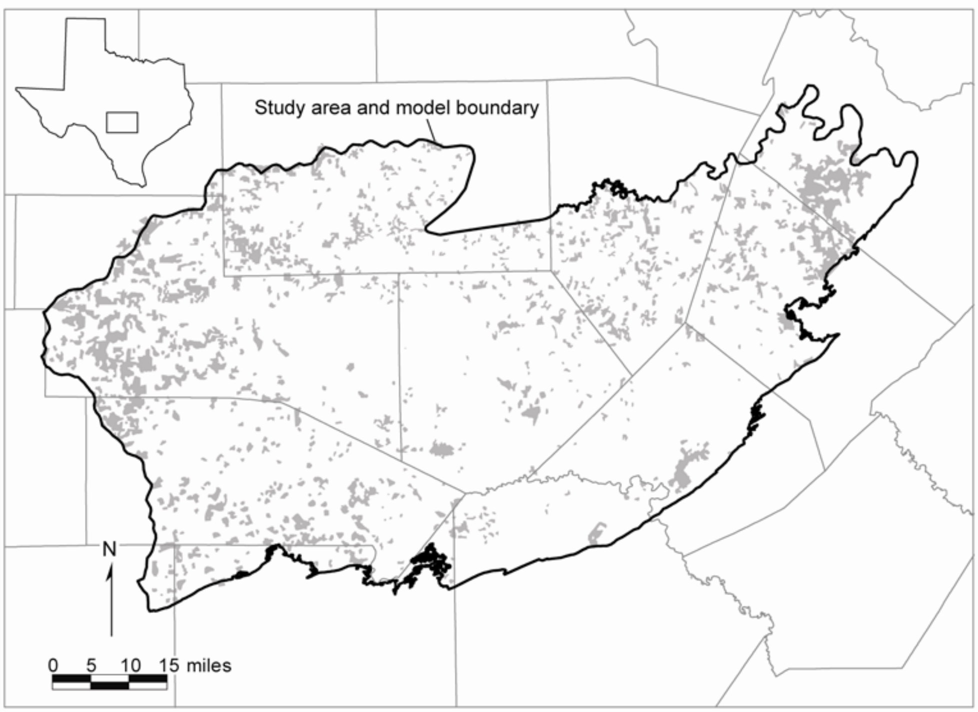
A few studies have estimated the volume of flow from the Hill Country portion of the Trinity Aquifer System into the Edwards (Balcones Fault Zone) Aquifer. Lowry (1955) attributed a 5 percent error between measured inflows and outflows in the Edwards (Balcones Fault Zone) Aquifer to cross-formational flow from the Glen Rose Limestone. Woodruff and Abbott (1986), citing a personal communication with Bill Klemt, reported that recharge from cross-formational flow accounts for 6 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) suggested predevelopment 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 2 percent of total recharge to the aquifer. Mace and others (2000) estimated 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 by Klemt and others (1979), Slade and others (1985), Maclay and Land (1988), Wanakule and Anaya (1993), Barrett and Charbeneau (1996), and Lindgren and others (2004), only that of Lindgren and others (2004) includes cross-formational flow from the Hill Country portion of the Trinity Aquifer System. Maclay and Land (1988) recognized 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. On the basis of information in Bluntzer (1992), we estimated that 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 coming from the Middle Trinity Aquifer. TWDB 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, through the TWDB water-well database, and through telephone interviews with water users (Figure 5-30a). We distributed livestock, rural domestic, and irrigation pumping on the basis of the spatial distribution of range land, nonurban population, and irrigated farm land, 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, and the rest is used for 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. Pumping for livestock and irrigation has 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 5-3 to 5-8). 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.

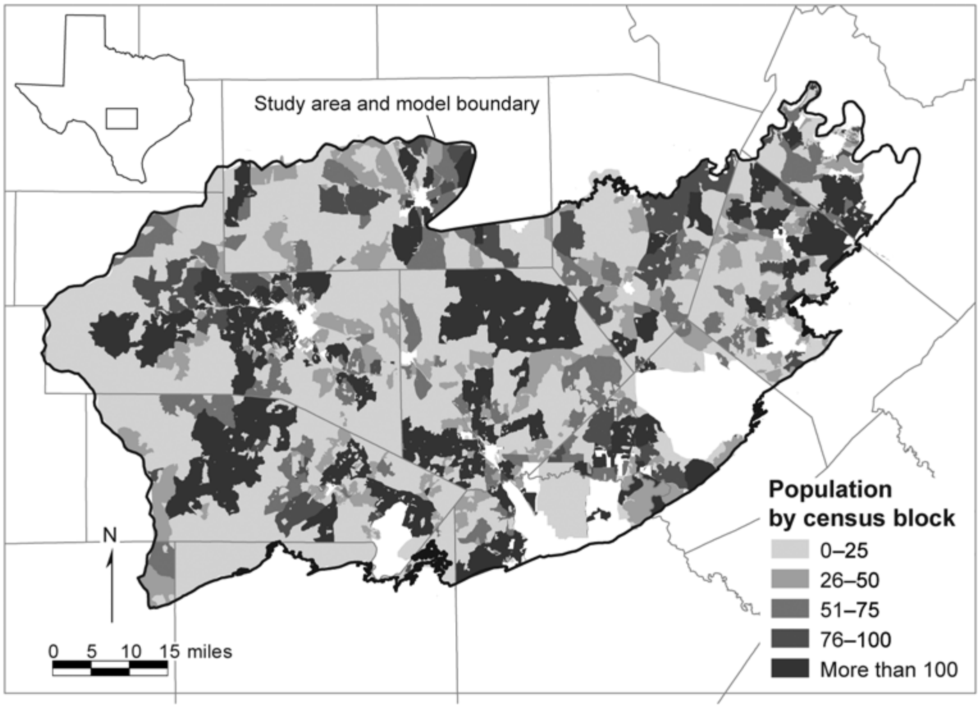


(a) Industrial and public supply wells

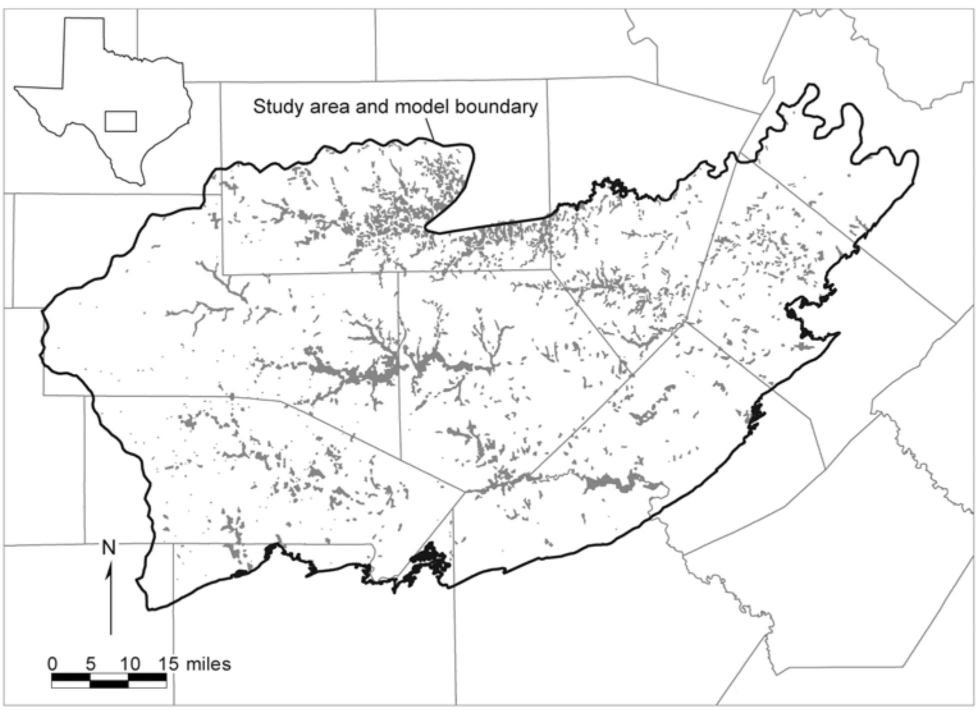


(b) Range land

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



(c) Rural population



(d) Irrigated farm land

Figure 5-30. (continued).

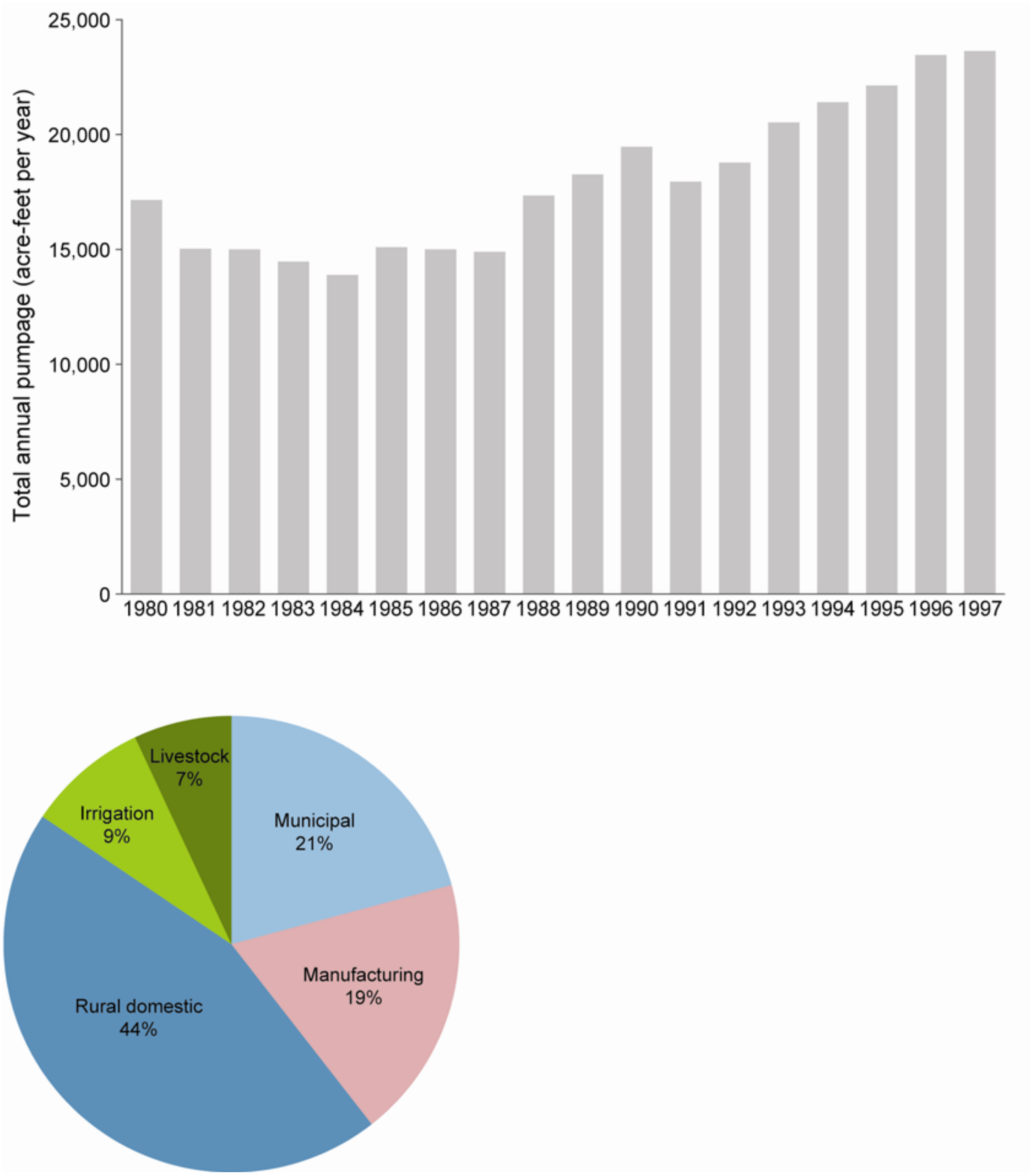


Figure 5-31. Total annual groundwater pumpage from the Hill Country portion of the Trinity Aquifer System, 1980 through 1997.

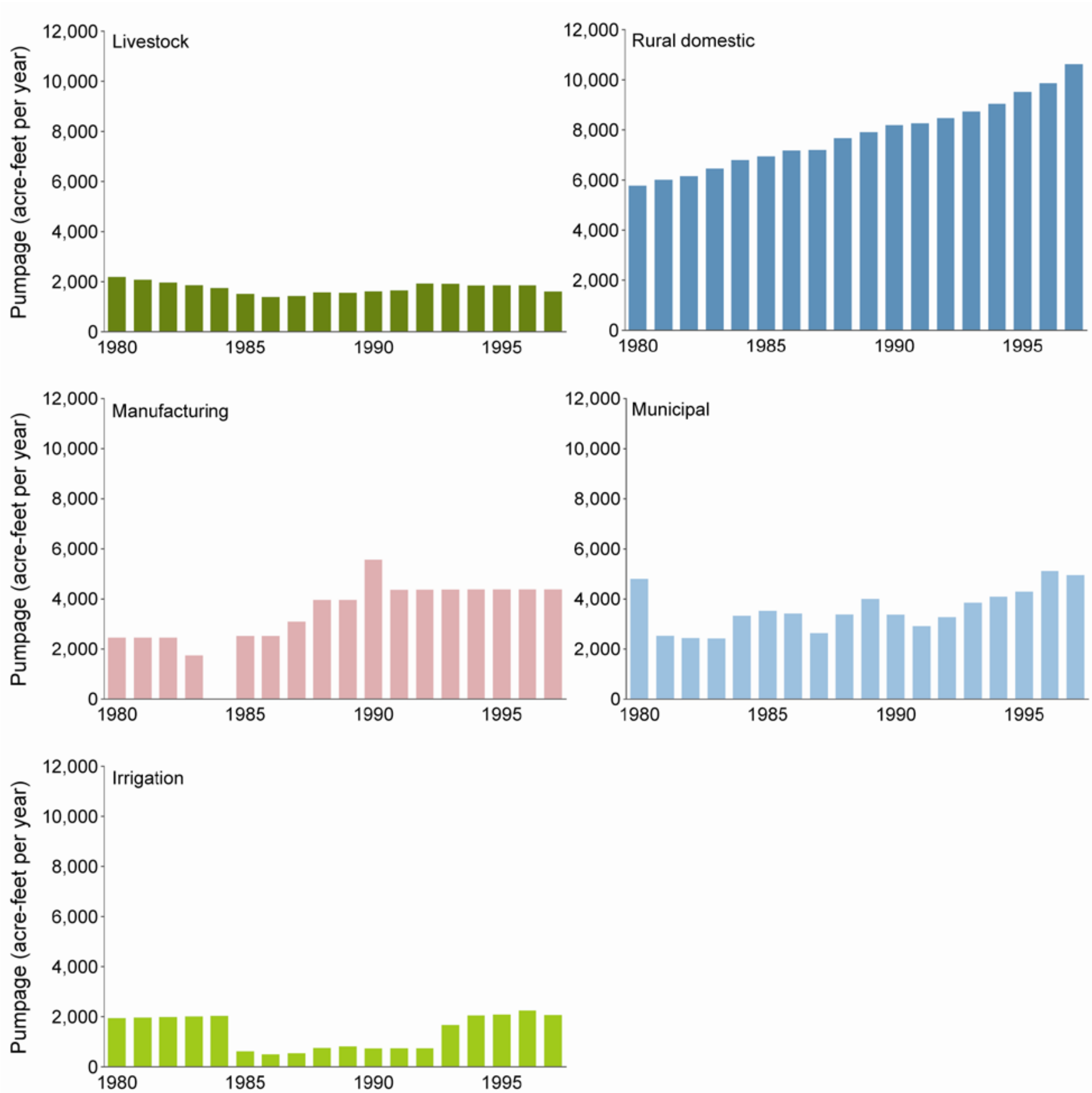


Figure 5-32. **Annual groundwater pumping from the Hill Country portion of the Trinity Aquifer System for livestock, rural domestic, manufacturing, municipal, and irrigation uses, 1980 through 1997.**

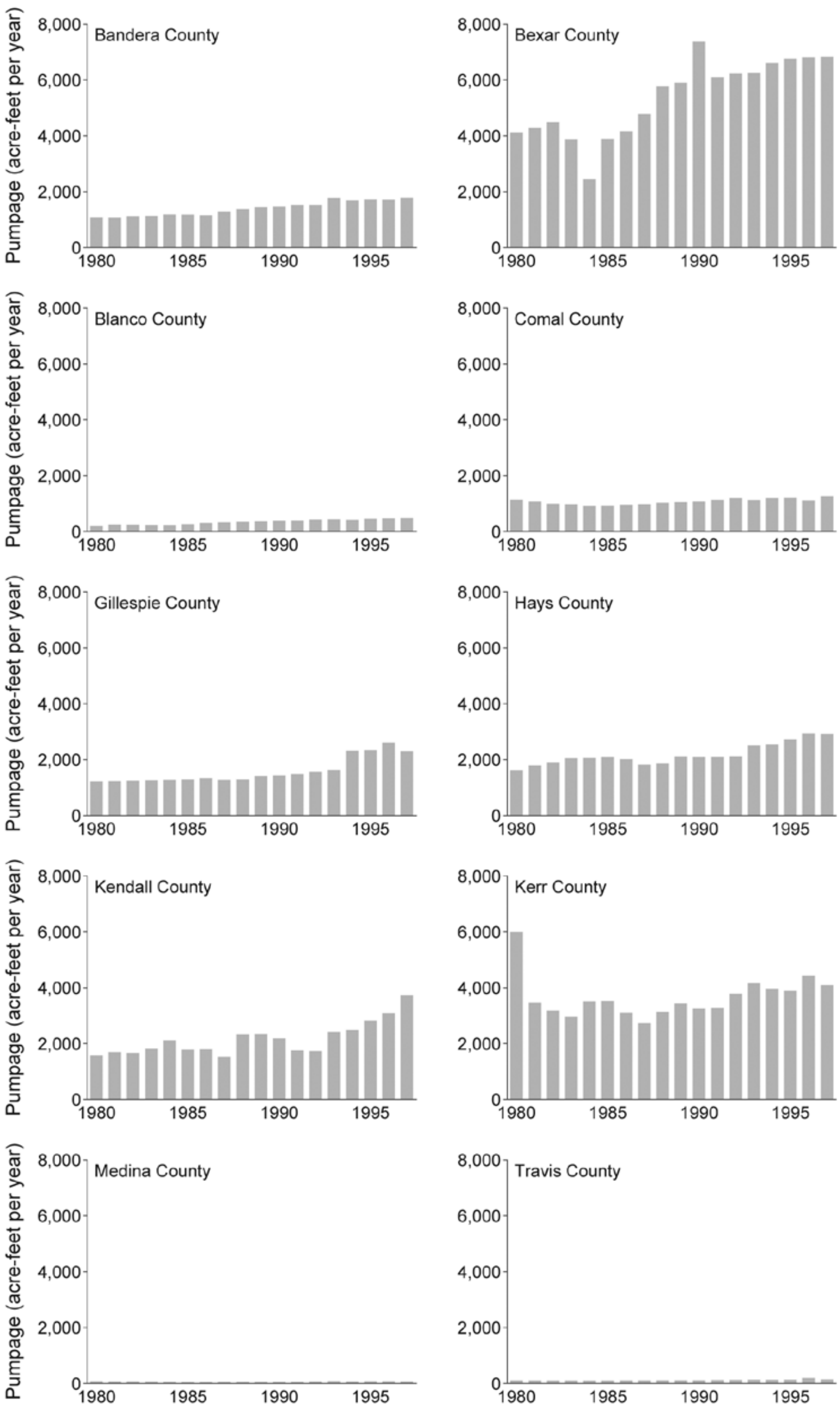


Figure 5-33. Total annual pumpage from the Hill Country portion of the Trinity Aquifer System for each county in the study area.

Table 5-3. Total pumping from the Hill Country portion of the Trinity Aquifer System for each county for the period 1980 through 1997 (all values in 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 5-4. 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 in 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 5-4. (continued).

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 5-4. (continued).

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 5-5. Total pumping from the Edwards Group by use category for each county for the period 1980 through 1997 (all values in 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 5-5. (continued).

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 5-5. (continued).

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 5-6. Total pumping from the Upper Trinity Aquifer by use category for each county for the period 1980 through 1997 (all values in 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 5-6. (continued).

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 5-6. (continued).

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 5-7. Total pumping from the Middle Trinity Aquifer by use category for each county for the period 1980 through 1997 (all values in 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 5-7. (continued).

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 5-7. (continued).

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 5-8. Total pumping from the Lower Trinity Aquifer by use category for each county for the period 1980 through 1997 (all values in 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 5-8. (continued).

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 5-8. (continued).

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

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 value of 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 and Upper and Middle Trinity aquifers, respectively. In the Lower Trinity Aquifer, the median value of total dissolved solids is higher than that of 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, downdip parts of the aquifers, especially in Blanco, Comal, Hays, Kendall, and Travis counties (Figures 5-36 through 5-38).

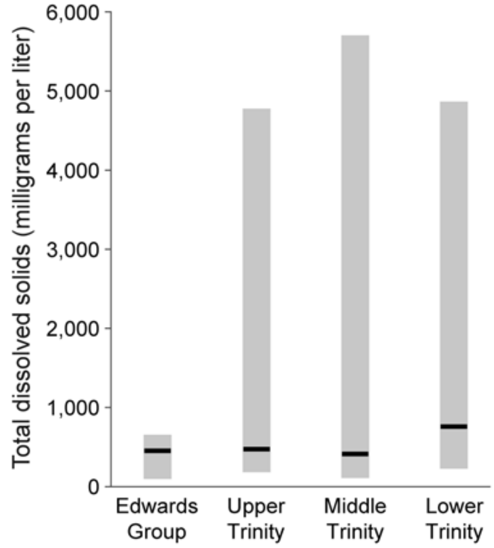


Figure 5-34. **Ranges of total dissolved solids found in groundwater in the Edwards Group and the Upper, Middle, and Lower Trinity aquifers. The black line indicates the median value for each aquifer.**

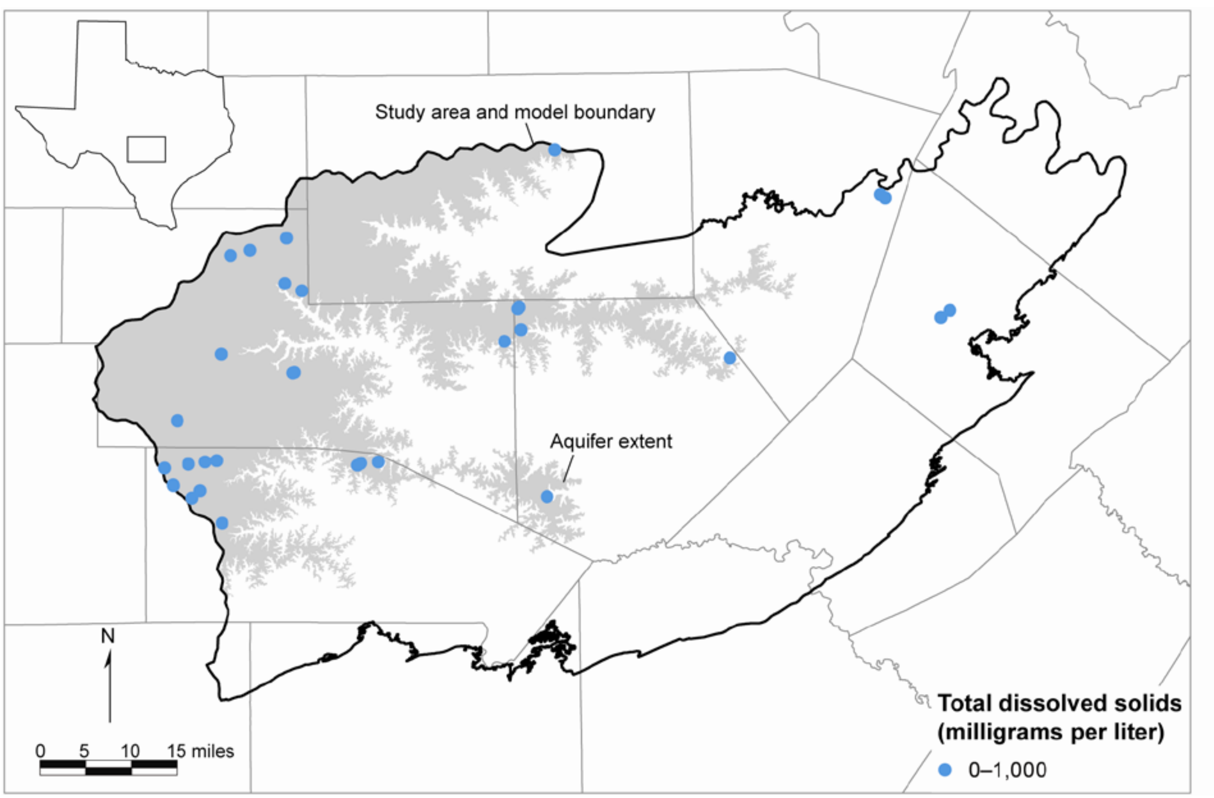


Figure 5-35. **Map of total dissolved solids in the Edwards Group.**

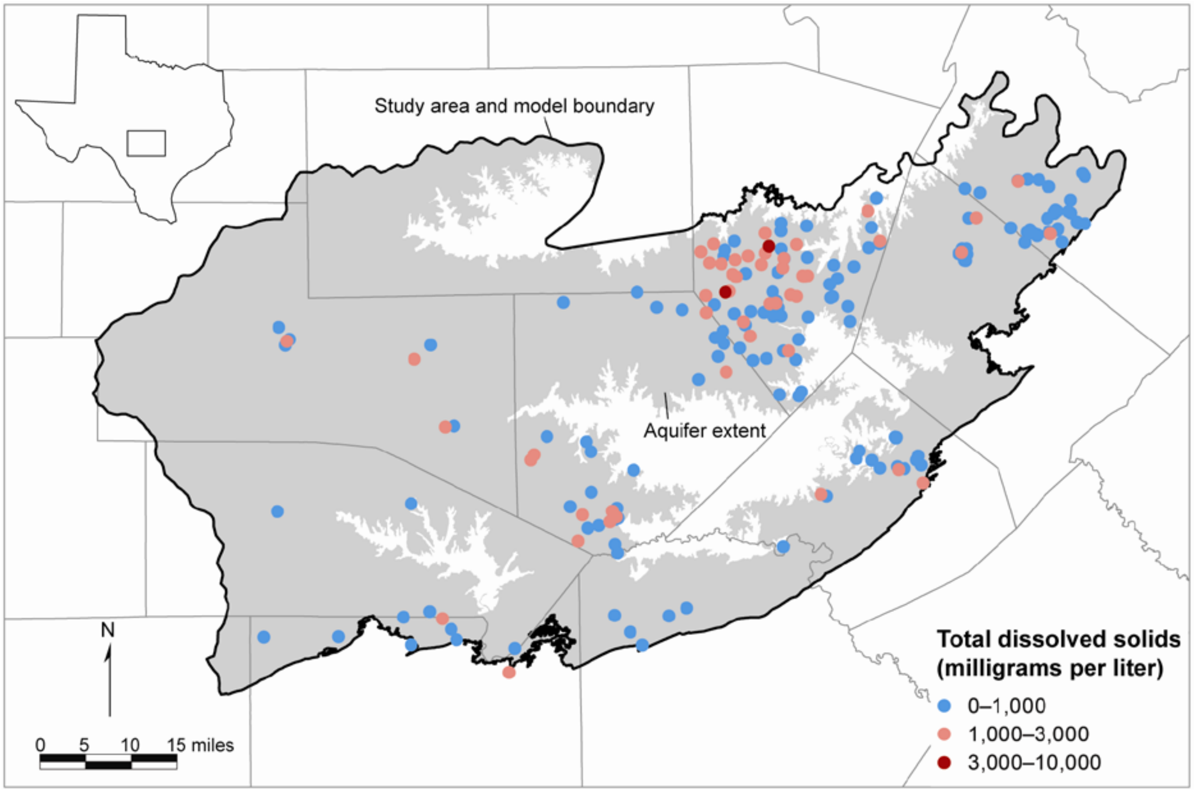


Figure 5-36. Map of total dissolved solids in the Upper Trinity Aquifer.

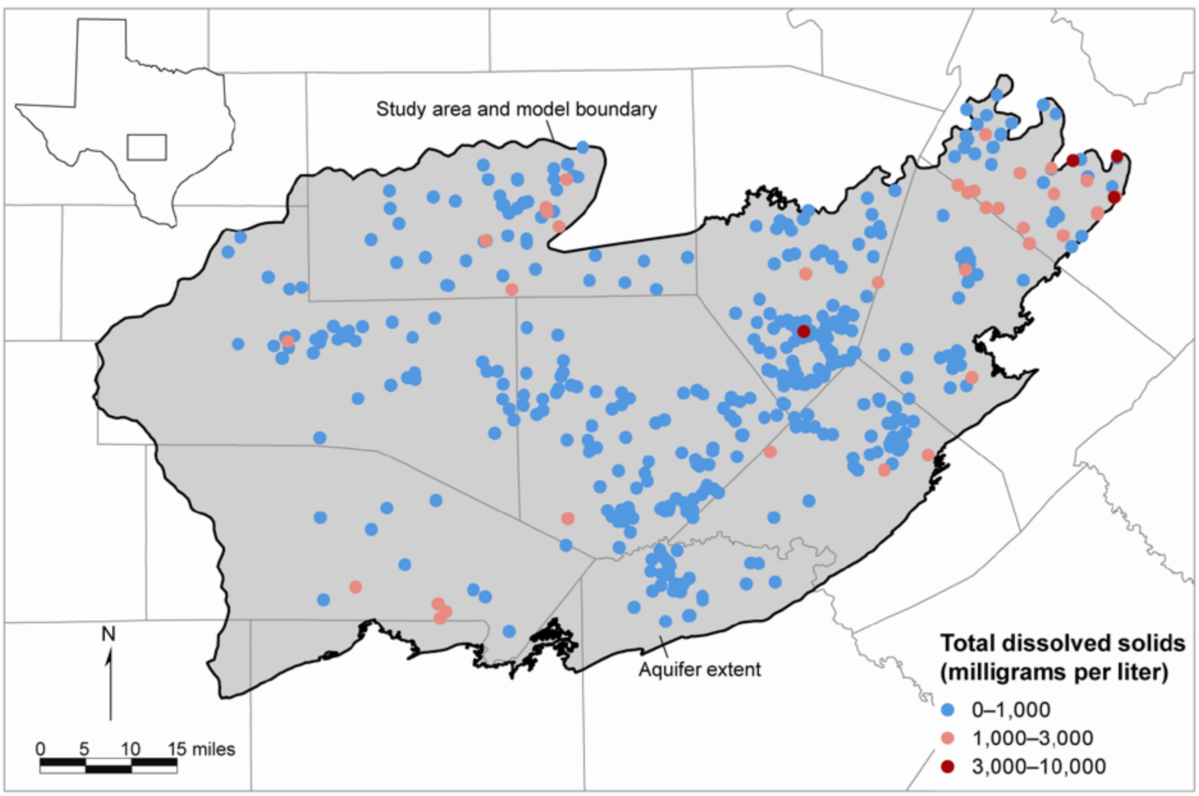


Figure 5-37. Map of total dissolved solids in the Middle Trinity Aquifer.

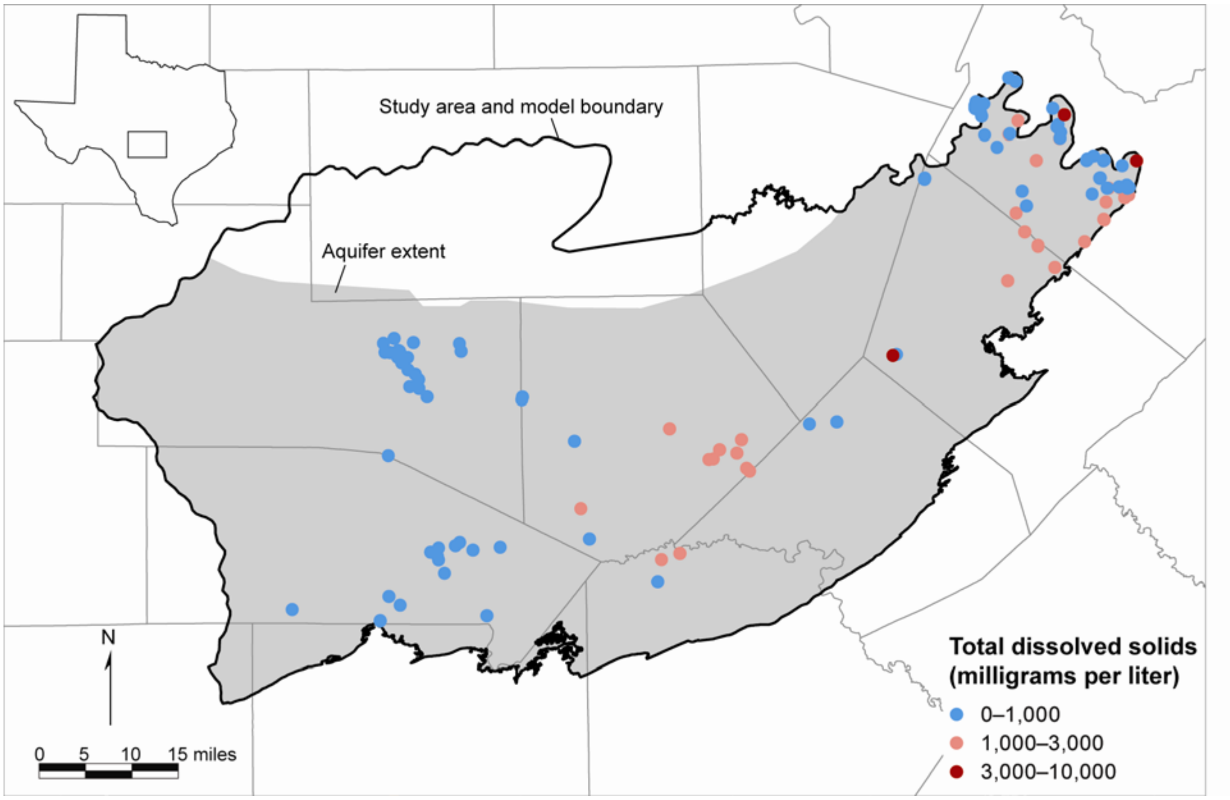


Figure 5-38. Map of total dissolved solids in the Lower Trinity Aquifer.

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 downdip parts of the aquifer (Figure 5-40). Groundwater in the Middle and Lower Trinity aquifers displays similar ranges of geochemical compositions, 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 displays Groups 1 and 2, and 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.

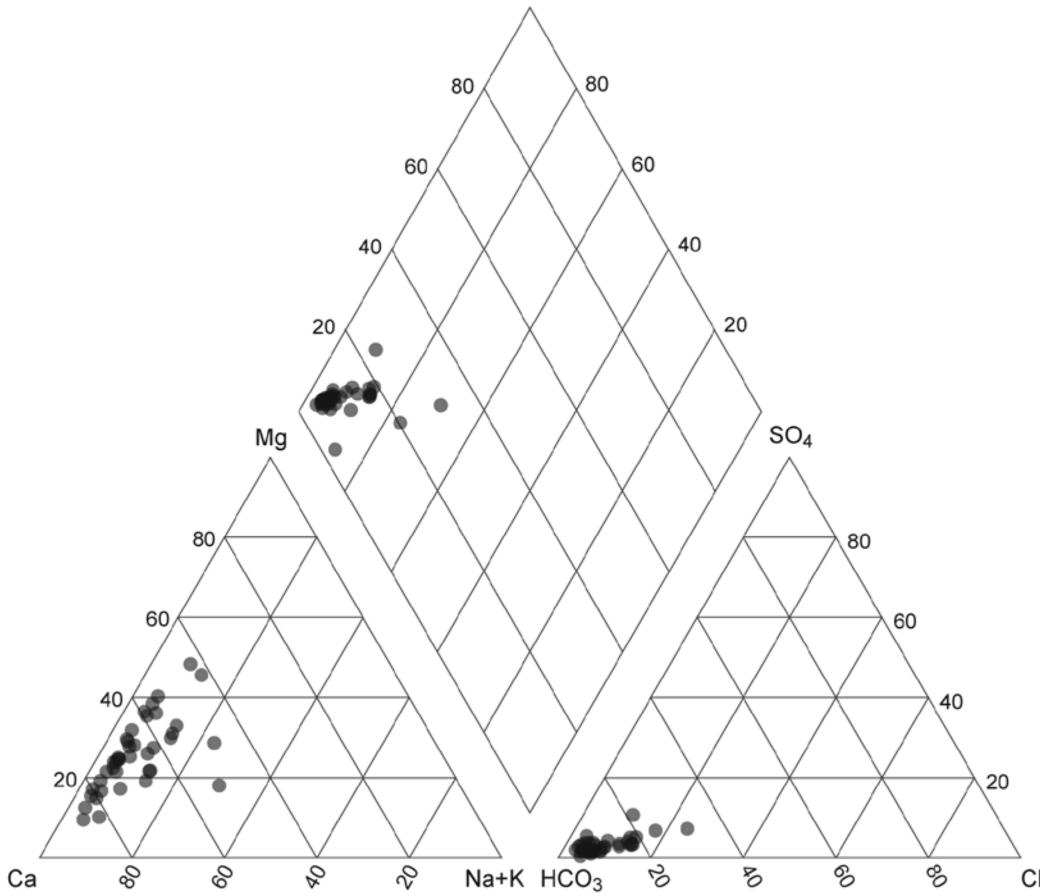


Figure 5-39. Piper diagram of groundwater from the Edwards Group showing the relative concentrations of the major ions present in the groundwater. Ca = calcium, Mg = magnesium, Na = sodium, K = potassium, HCO_3 = bicarbonate, SO_4 = sulfate, Cl = chloride.

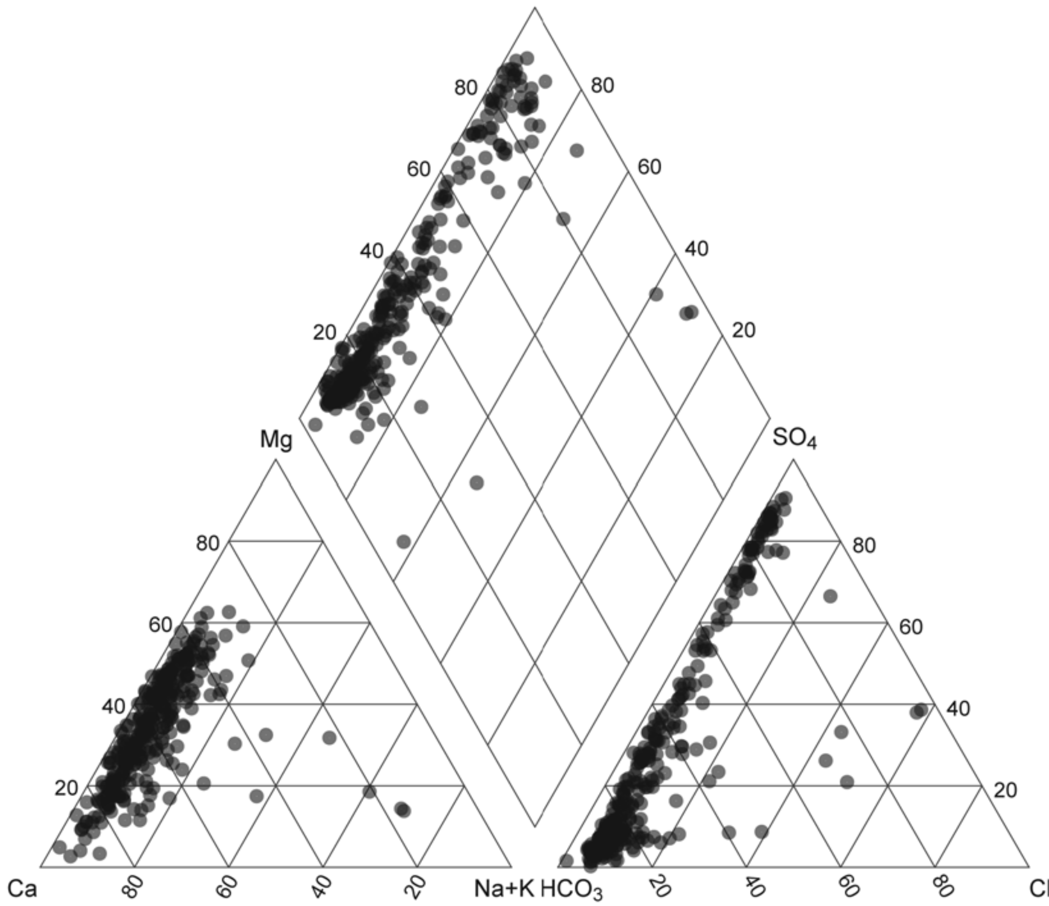


Figure 5-40. Piper diagram of groundwater from the Upper Trinity Aquifer showing the relative concentrations of the major ions present in the groundwater. Ca = calcium, Mg = magnesium, Na = sodium, K = potassium, HCO_3 = bicarbonate, SO_4 = sulfate, Cl = chloride.

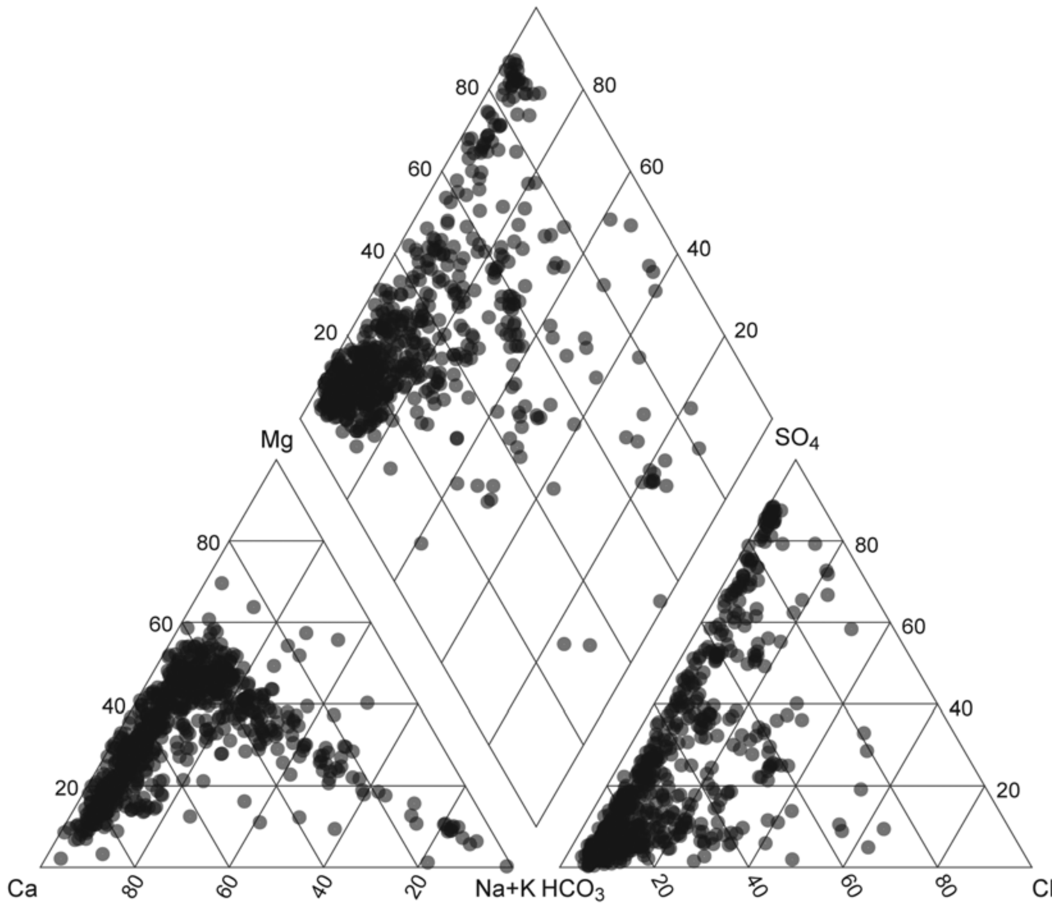


Figure 5-41. Piper diagram of groundwater from the Middle Trinity Aquifer showing the relative concentrations of the major ions present in the groundwater. Ca = calcium, Mg = magnesium, Na = sodium, K = potassium, HCO_3 = bicarbonate, SO_4 = sulfate, Cl = chloride.

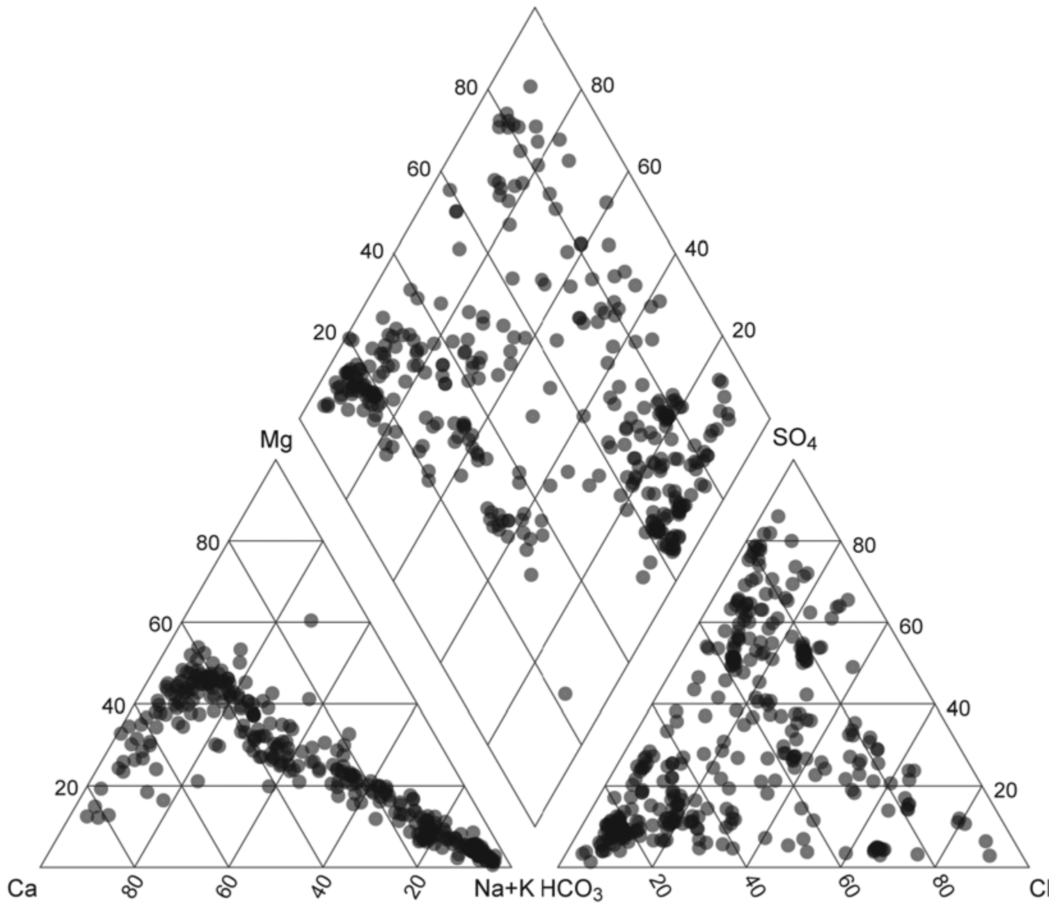


Figure 5-42. **Piper diagram of groundwater from the Lower Trinity Aquifer showing the relative concentrations of the major ions present in the groundwater. Ca = calcium, Mg = magnesium, Na = sodium, K = potassium, HCO_3 = bicarbonate, SO_4 = sulfate, Cl = chloride.**

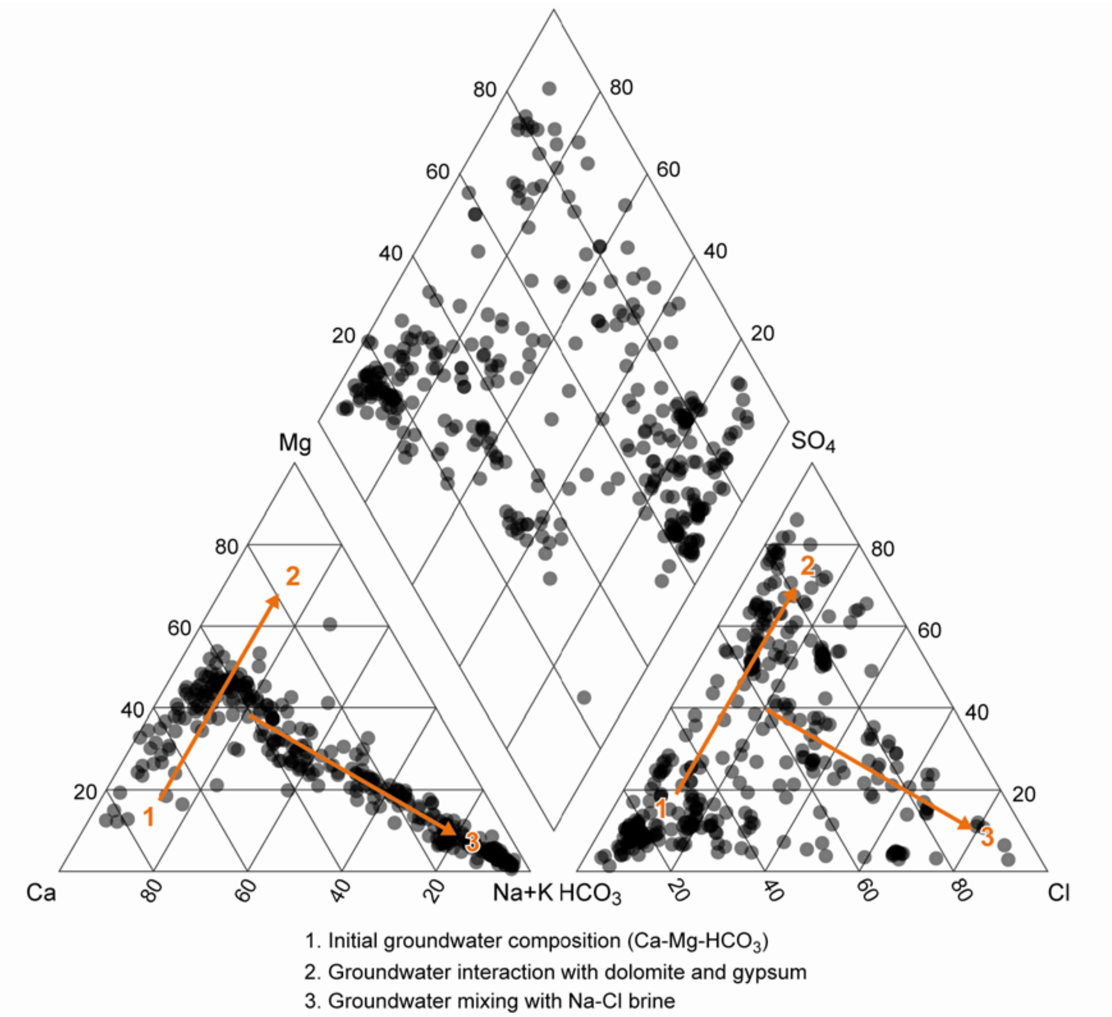


Figure 5-43. Groundwater geochemical trends that are apparent in the Hill Country portion of the Trinity Aquifer System. Ca = calcium, Mg = magnesium, Na = sodium, K = potassium, HCO_3 = bicarbonate, SO_4 = sulfate, Cl = chloride.

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 depths greater than 500 feet. Nitrate concentrations progressively decrease with increasing well depth in the Edwards Group and Upper, Middle, and Lower Trinity aquifers. Groundwater in the Edwards Group has the least nitrate, and the highest nitrate concentrations occur in the Upper and Middle Trinity aquifers.

6.0 Conceptual Model of Regional Groundwater Flow in the Aquifer

The conceptual model (Figure 6-1) is our best understanding of regional groundwater flow in the Hill Country portion of the Trinity Aquifer System.

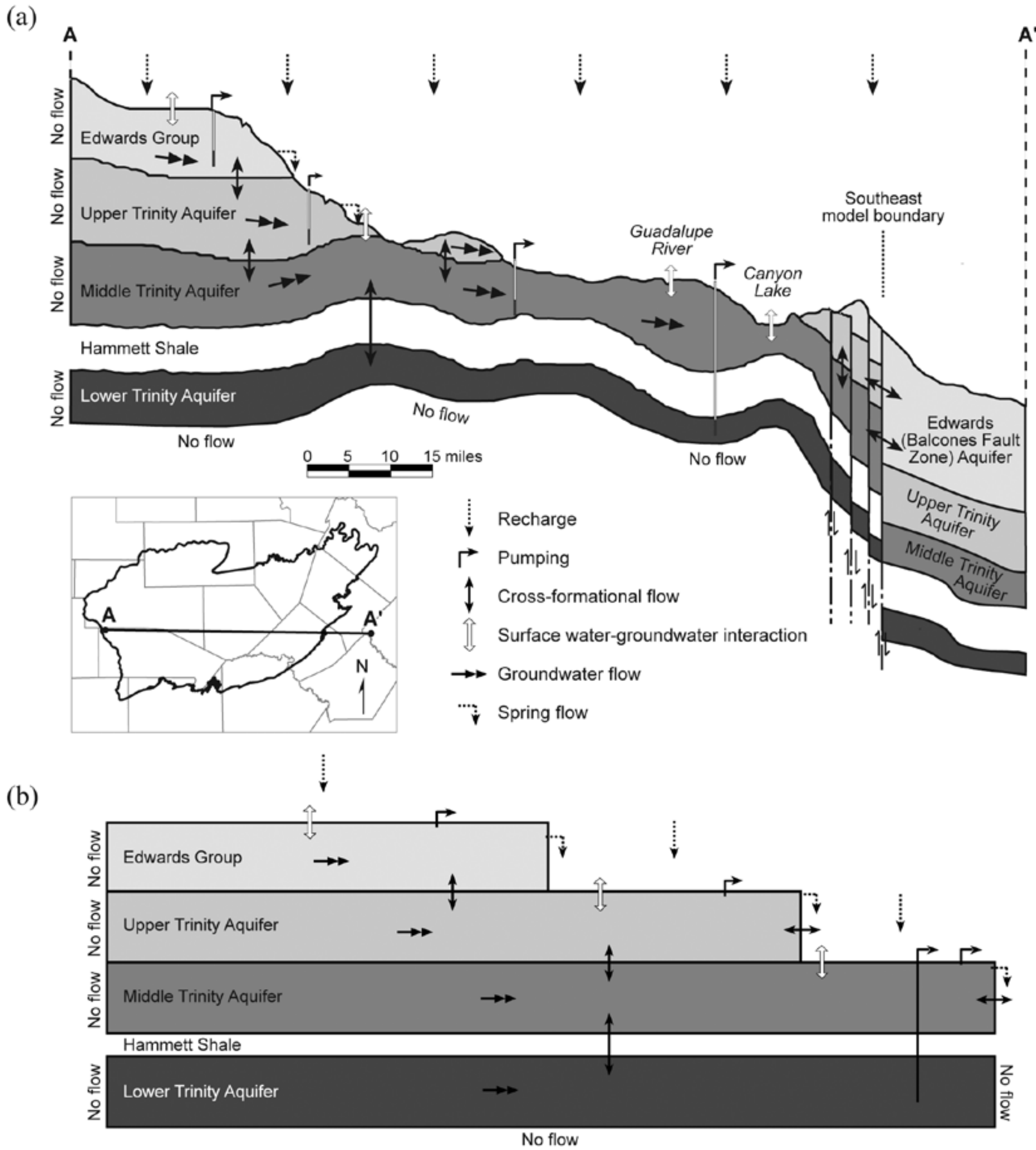


Figure 6-1. Conceptual model of the Hill Country portion of the Trinity Aquifer System. (a) Schematic cross section through the aquifer system. (b) Diagram showing the boundary conditions at the outer edge of the model, flows between the layers, and translation of the conceptual model into the numerical model (modified from Mace and others, 2000).

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 4 to 6 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 3-6a) 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 base flow 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 3-1). Most of the remaining recharge in the aquifer either discharges through wells pumping from the aquifer or flows laterally into the Edwards (Balcones Fault Zone) Aquifer.

Several short flow paths probably lie along streams where the water table is shallow. In these areas recharged precipitation most likely flows a short distance and is discharged through evapotranspiration. Because of the localized nature of the flow paths and the limitations of the model grid, this evapotranspiration discharge would most 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 think that hydraulic conductivity is higher in the eastern portion of the study area, where the higher hydraulic conductivity coincides with the Balcones Fault Zone, than in the rest 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 locally be very permeable, especially in the outcrop. Owing to the occurrence of shaly beds, the Upper Trinity Aquifer has a much lower ratio of vertical to horizontal permeability than does 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, the 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. Pumping in some of these counties has doubled 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

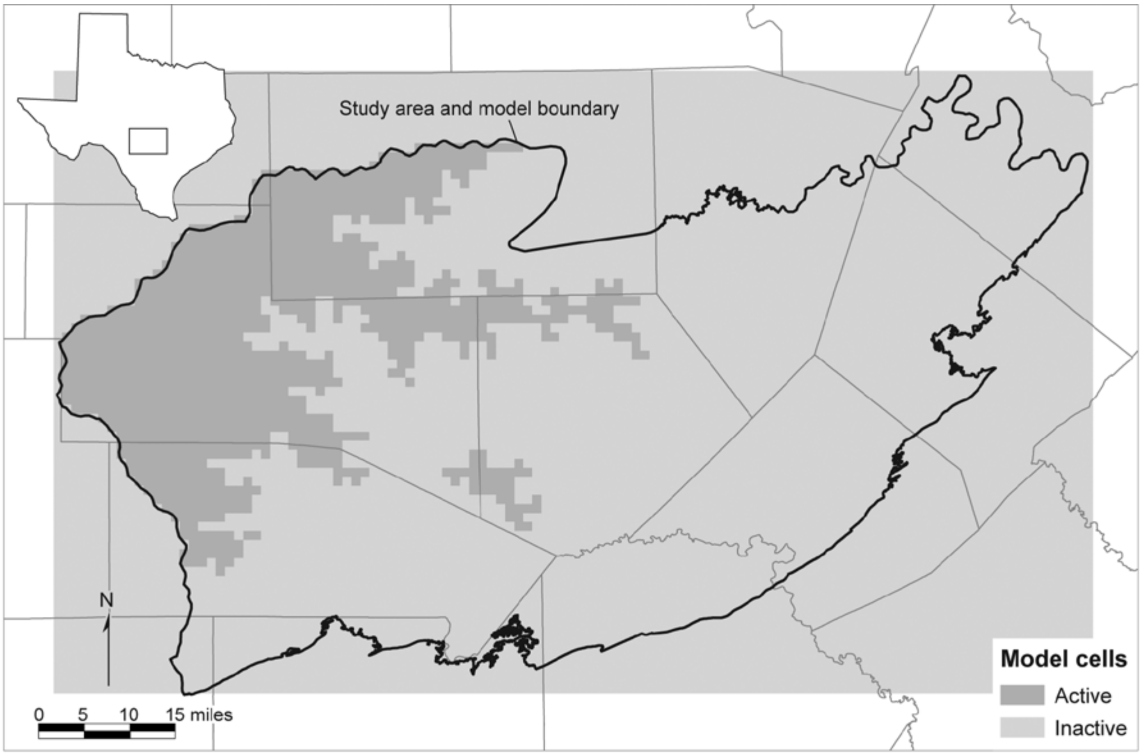
Groundwater flow through the Hill Country portion of the Trinity Aquifer System was simulated using MODFLOW-96, a widely used modular finite-difference groundwater flow code written by the U.S. Geological Survey (Harbaugh and McDonald, 1996). This code was selected because of (1) its capabilities of 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 facilitating easy use of the modeling software, and (4) its ready availability as 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 Workstation 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

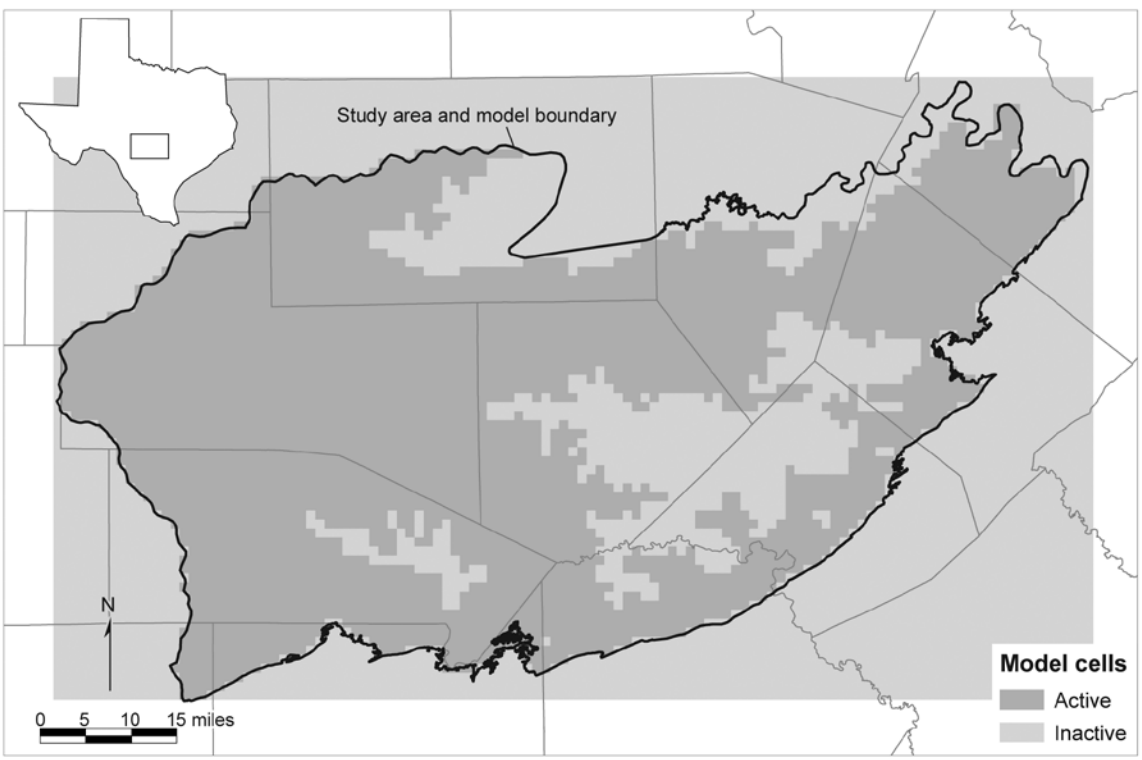
The lateral extent of the model corresponds to natural hydrologic boundaries, such as erosional limits of the aquifers, rivers, and the structural boundary with the Edwards (Balcones Fault Zone) Aquifer, and hydraulic boundaries to the west that coincide with groundwater divides. According to the hydrostratigraphy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

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 rocks 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 the 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 7-1).

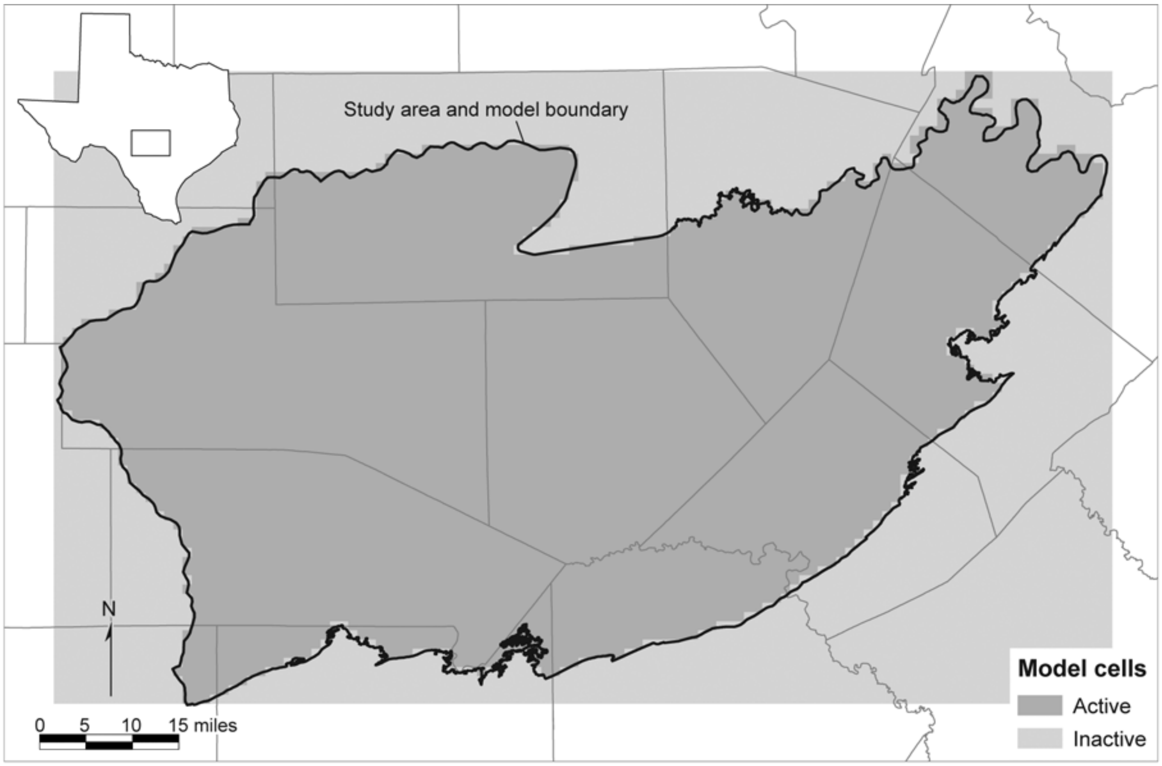


(a)

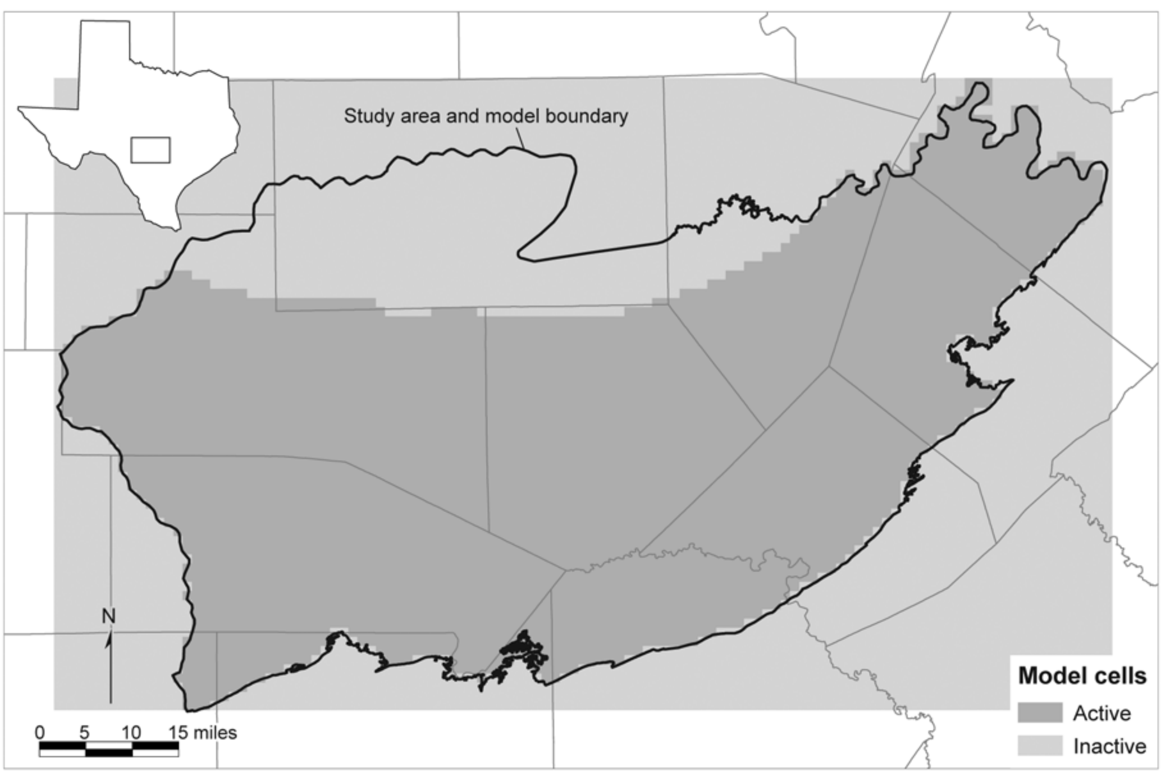


(b)

Figure 7-1. 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).



(c)



(d)

Figure 7-1. (continued).

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 U.S. 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 5-1). The top and base of layer 2 (Upper Trinity Aquifer) were assigned according to the structure map of the Upper Trinity Aquifer (Figure 5-2). 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 5-2). 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 5-3). The bottom of layer 3 was assigned using the elevation of the base of the Middle Trinity Aquifer (Figure 5-3). 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 5-4). 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 day 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 7-2). We assigned uniform values of specific storage and specific yield 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.

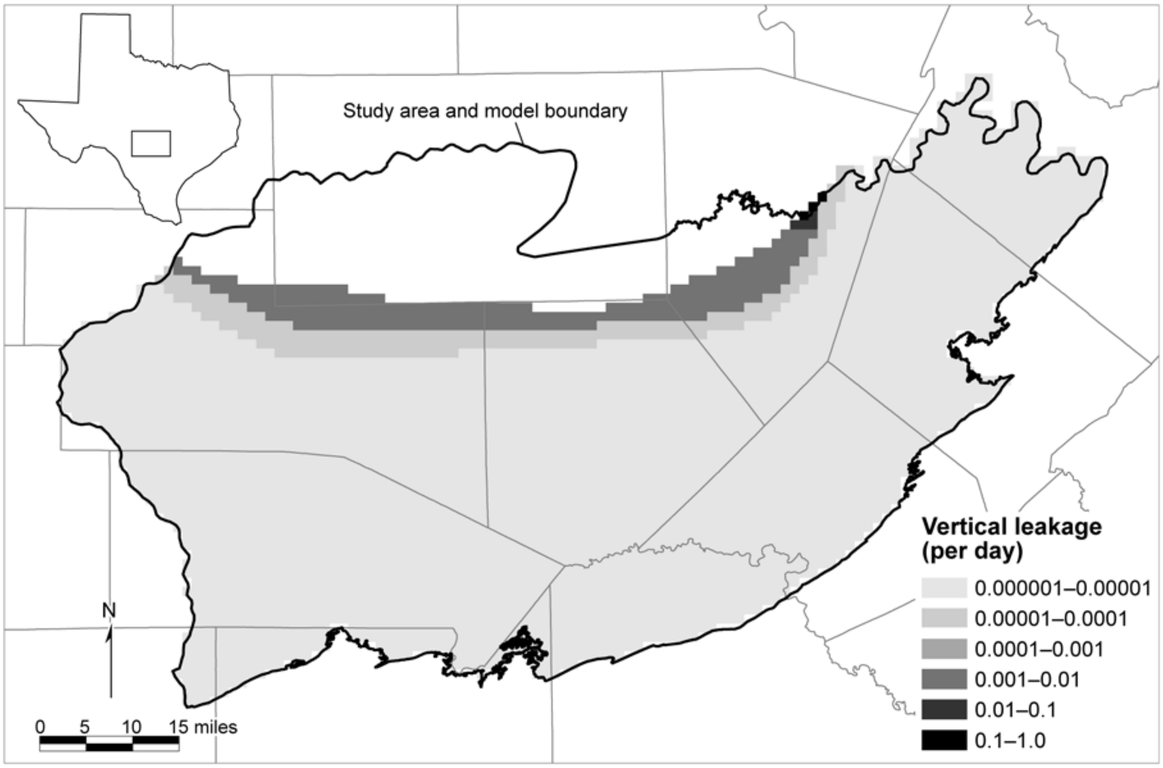


Figure 7-2. Vertical leakance between the Middle and Lower Trinity aquifers.

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.

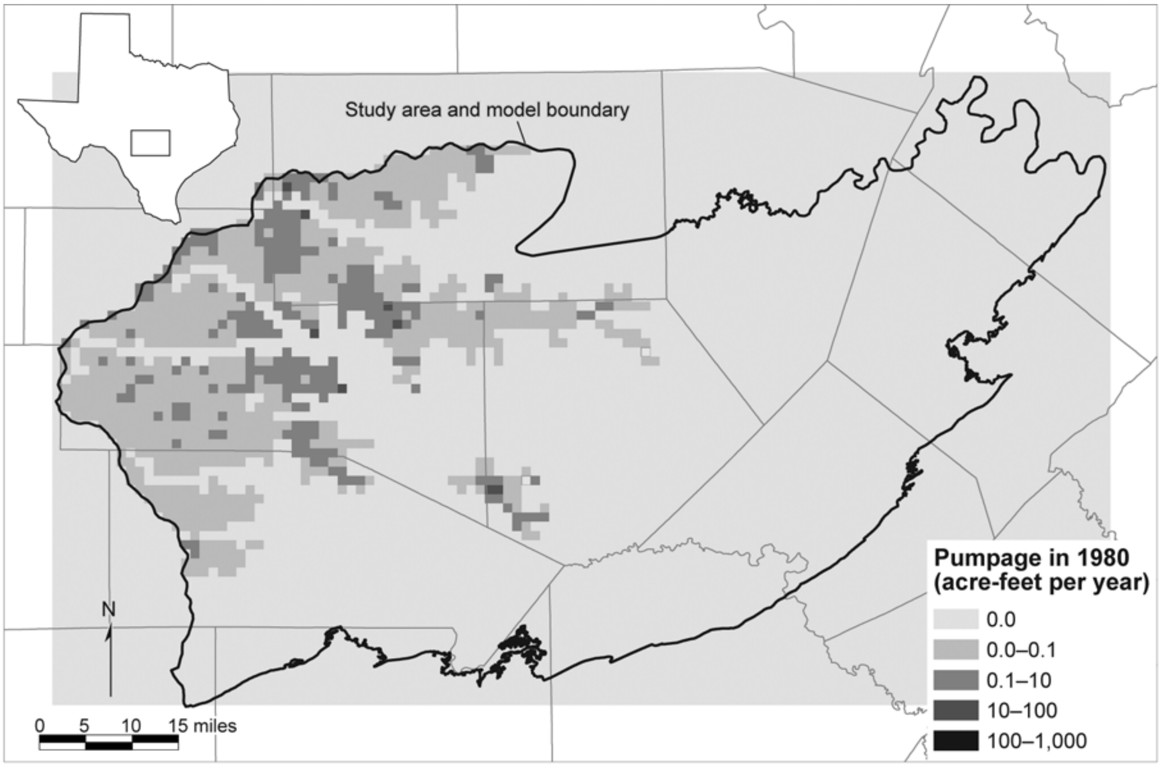
7.4 Model Boundary Conditions

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.

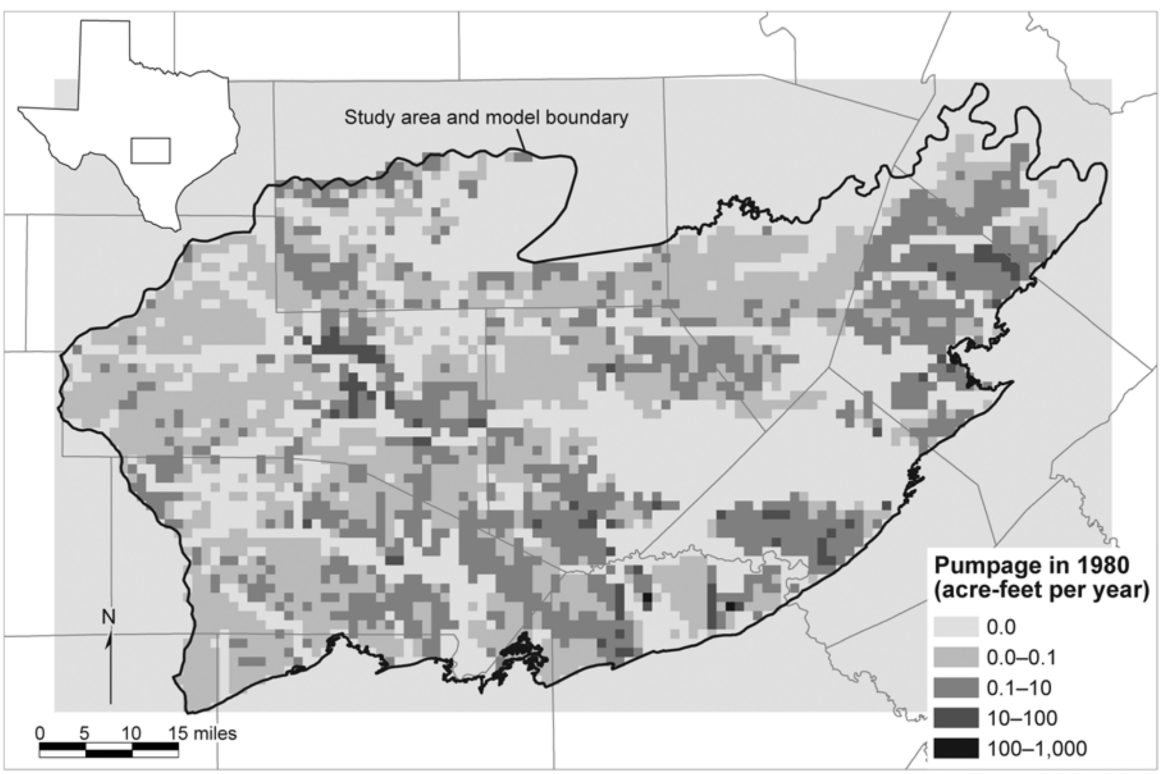
We assigned recharge primarily on the basis of the spatial distribution of annual precipitation over the study area (Figure 3-9). The initial recharge assigned to the model was 4.7 percent of annual precipitation. This value coincides with the value used in the groundwater availability model for the 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 Section 5.7 (Discharge) 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 5-3 through 5-8). Municipal and manufacturing pumping was distributed on the basis of known well locations and pumping data from the TWDB 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 on the basis of the spatial distribution of population outside major urban areas that lie within the model grid. Irrigation pumping was distributed on the basis of 1:250,000-scale land use and land cover data from the U.S. Geological Survey. Irrigation was assumed to occur on all land classified as orchards, row crops, or small grains. Livestock pumping was also distributed on the basis of 1:250,000-scale land use and land cover data from the U.S. Geological Survey. Livestock pumping was assumed on all range land. Figure 7-3 shows the spatial distribution of total pumping for the year 1980.

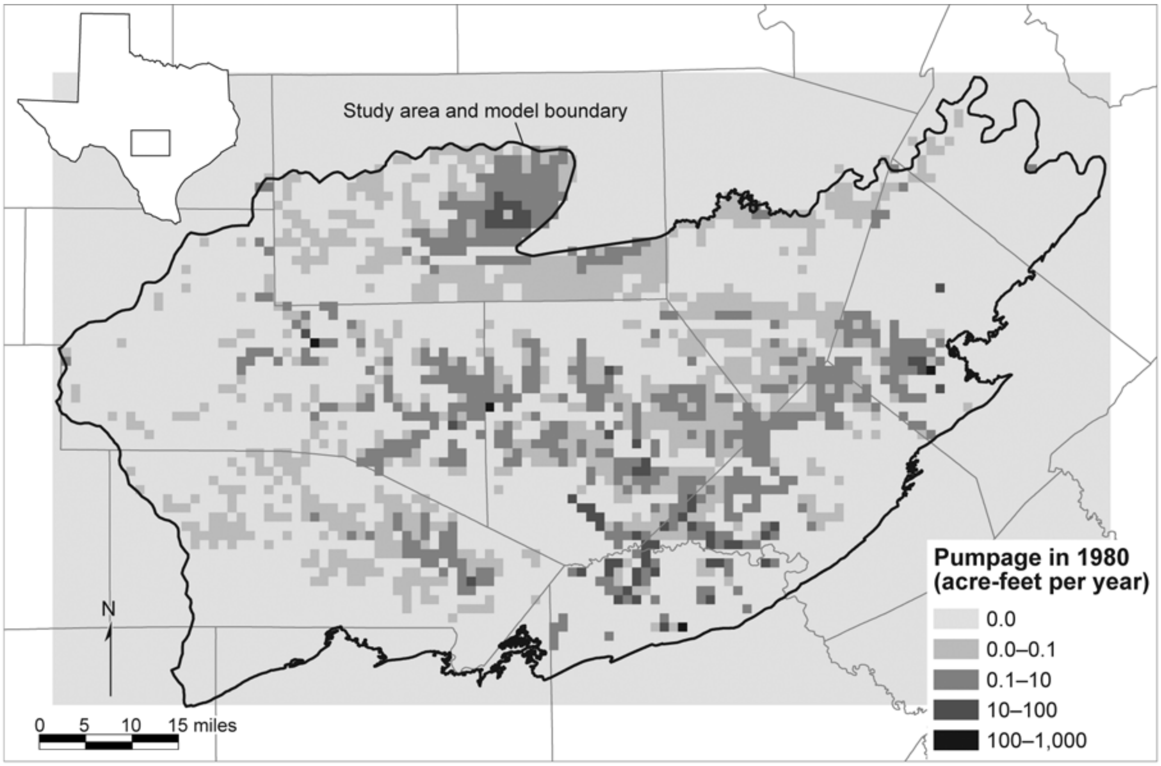


(a)

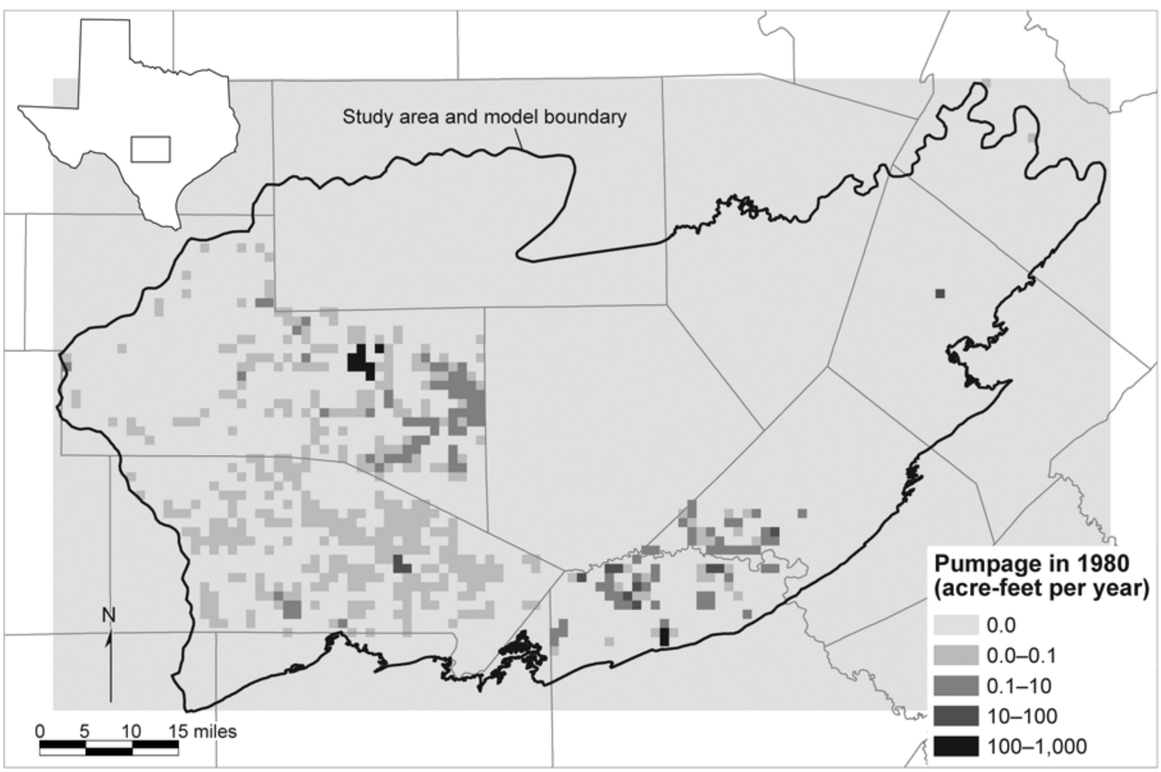


(b)

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



(c)

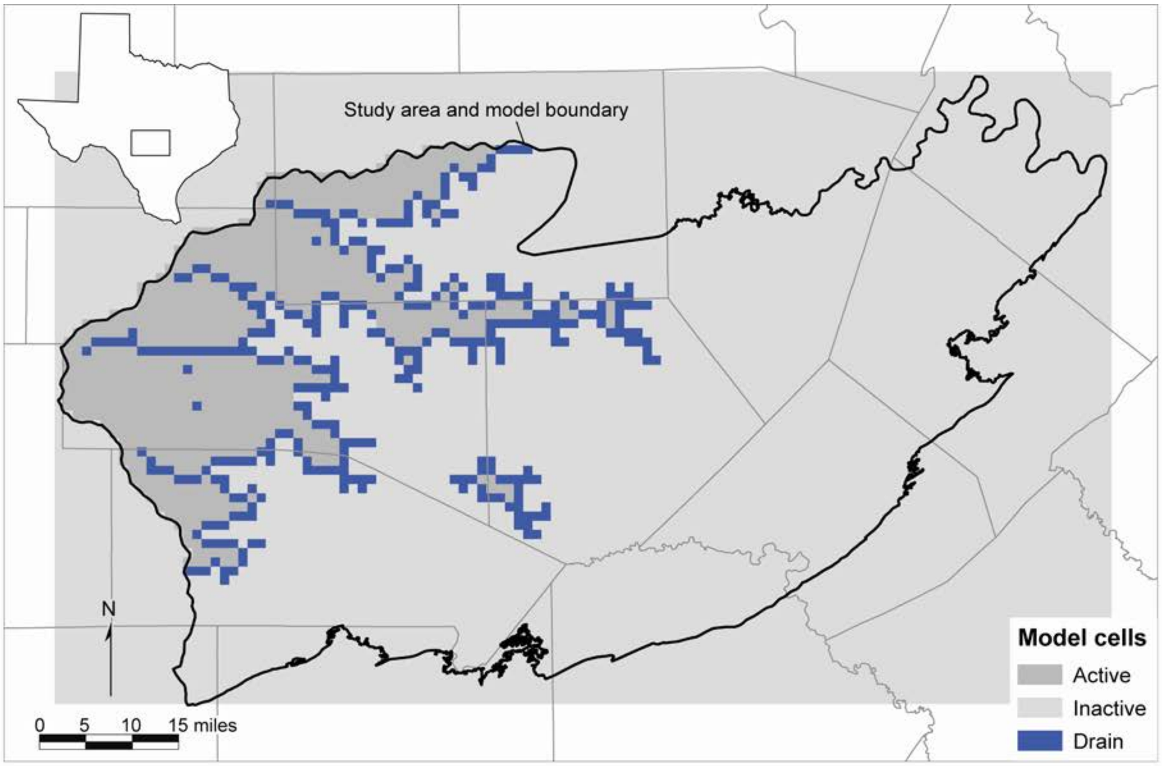


(d)

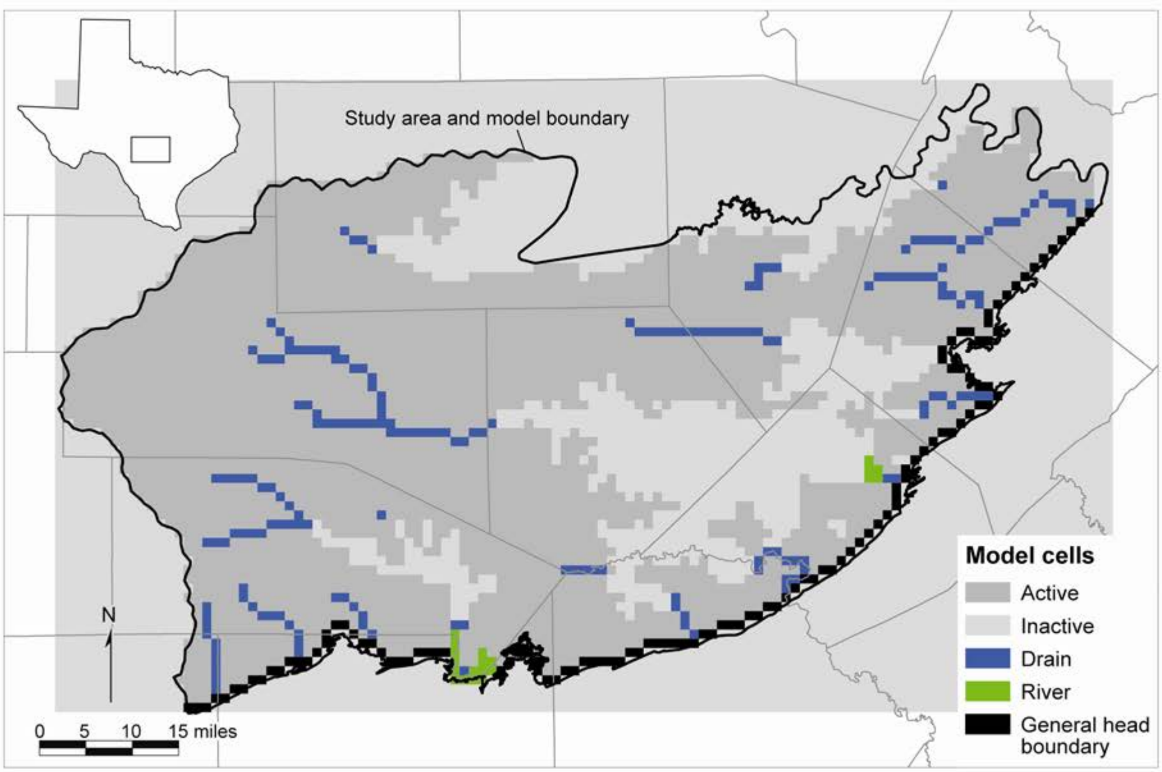
Figure 7-3. (continued).

We used the Drain Package of MODFLOW to represent rivers and streams in the model (Figure 7-4). 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 on the basis of estimated width of the stream, a stream length of 1 mile (equivalent to the model cell size), an assumed riverbed thickness of 1 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 7-4). 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 1-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 1-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 7-4). 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 1 mile (equivalent to the model cell size), riverbed thickness of 1 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.

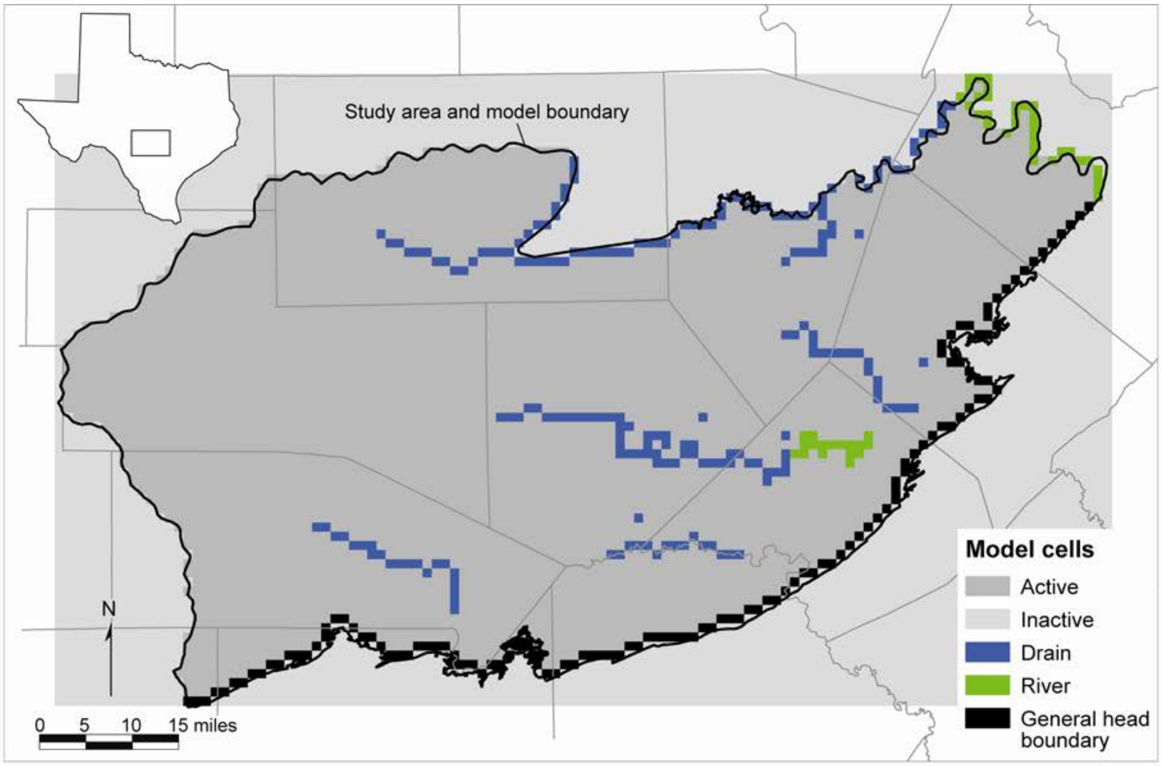


(a)

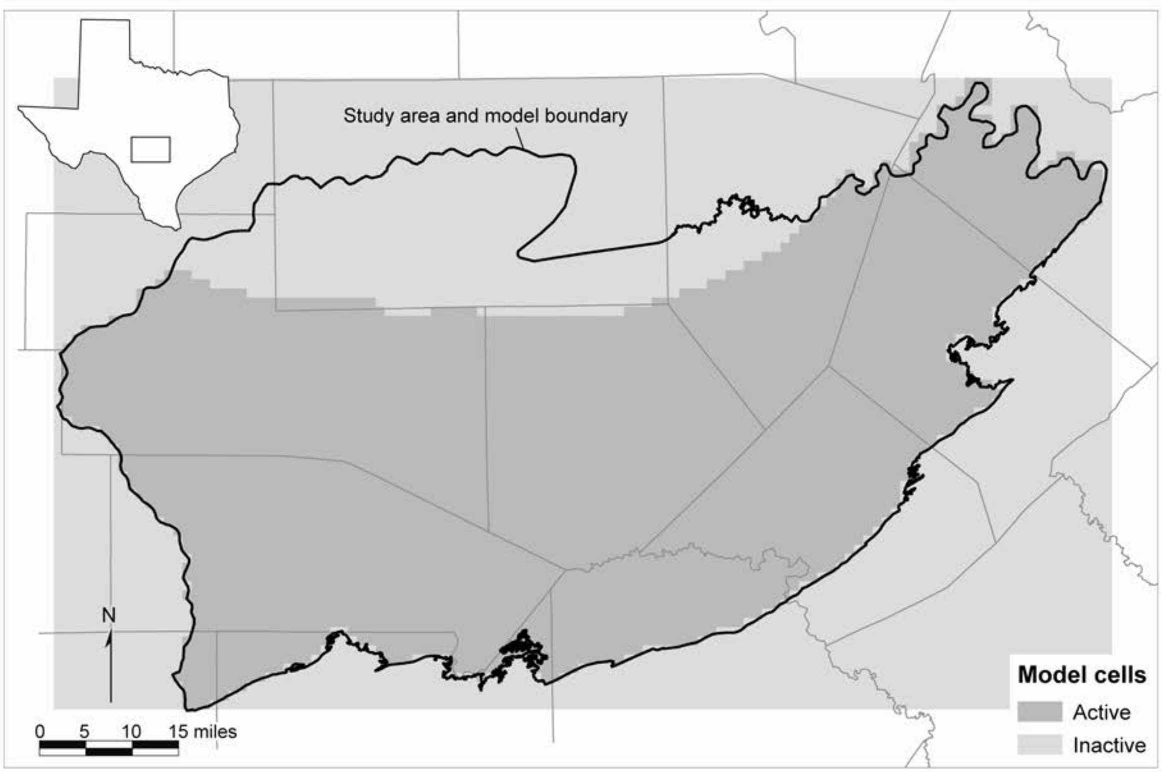


(b)

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



(c)



(d)

Figure 7-4. (continued).

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 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. We inferred that layer 4 is also bound by no-flow boundaries in the south and east on the basis of 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, a conclusion 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 7-4). 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 5-3) 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 1-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 downdip parts of the Trinity Aquifer System. For simplicity, we used an arbitrary thickness of unity (1 foot) to define conductance.

The updating of this model included changes to the boundary conditions. Besides adding the Lower Trinity Aquifer as another layer, the model comprised these changes: (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, and (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 provides an unlimited, unrestricted source of water when impacted by nearby pumping and therefore could produce unrealistically high water levels adjacent to the constant-head cells. On the other hand, the River Package in MODFLOW includes 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 and proper attention to boundary elevation and conductance can mitigate this effect. During model calibration, we made minor adjustments to the outer model boundary conditions 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 calibrating the model comprised 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 5-9 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*):

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

where *MAE* is the mean absolute error, n is the number of calibration points, h_m is the measured hydraulic head at point i, and 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 were (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 having 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 data sets 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 on the basis of 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 rest of the model area. Along Cibolo Creek, we set recharge equivalent to measured streamflow loss of about 70,300 acre-feet per year (Figure 9-1).

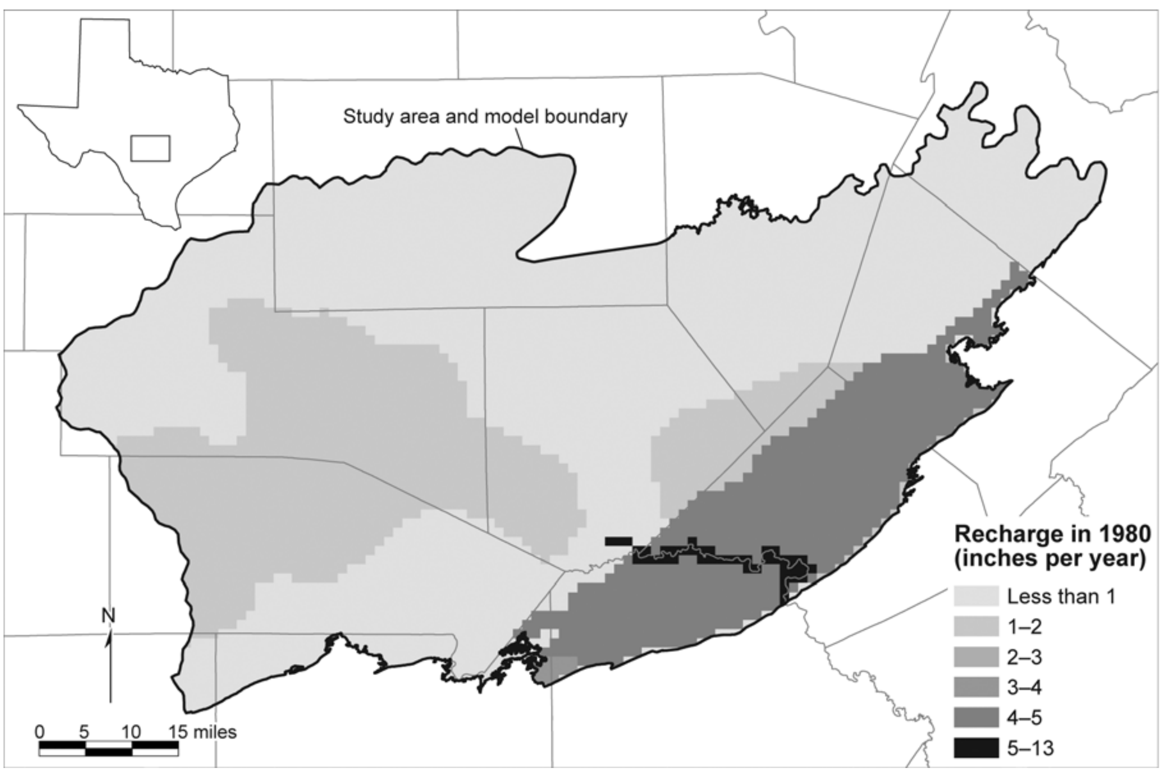


Figure 9-1. Estimated spatial distribution of recharge for 1980 based on precipitation data for the study area and Cibolo Creek streamflow loss studies.

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 rest 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 on the basis of work done by Kastning (1986) and Veni (1994) that indicates 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 day to the Balcones Fault Zone and the rest 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 and 3, respectively, to facilitate increased interaquifer flow between the Hill Country portion of the Trinity Aquifer System and the Edwards (Balcones Fault Zone) Aquifer owing to the large amounts of recharge flowing from the Cibolo Creek.

Interaquifer flow between the Middle and Lower Trinity aquifers through the Hammett Shale is simulated using vertical leakance. We varied vertical leakance spatially on the basis of 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 of 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 9-2). 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 9-3). This value 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.

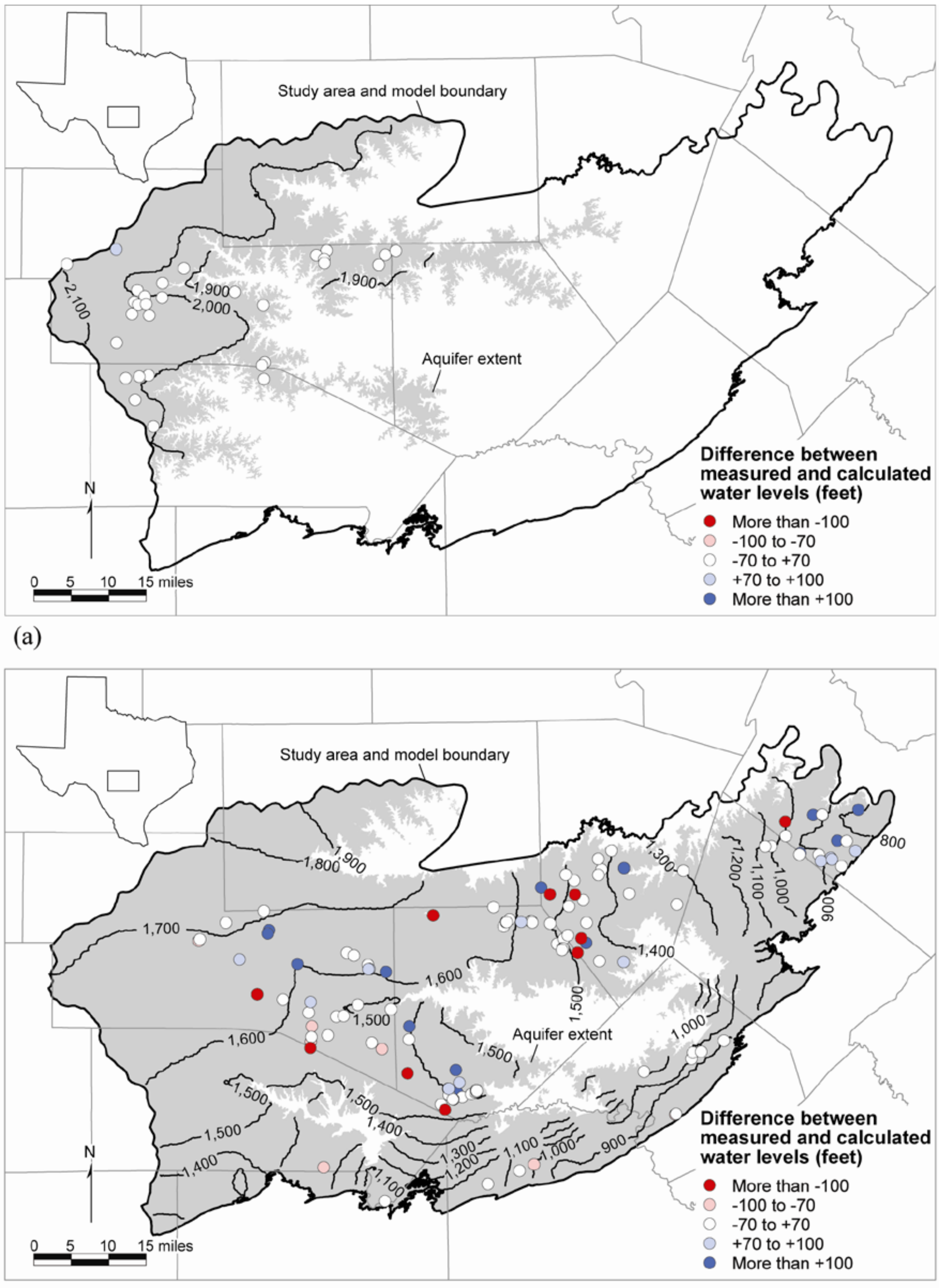
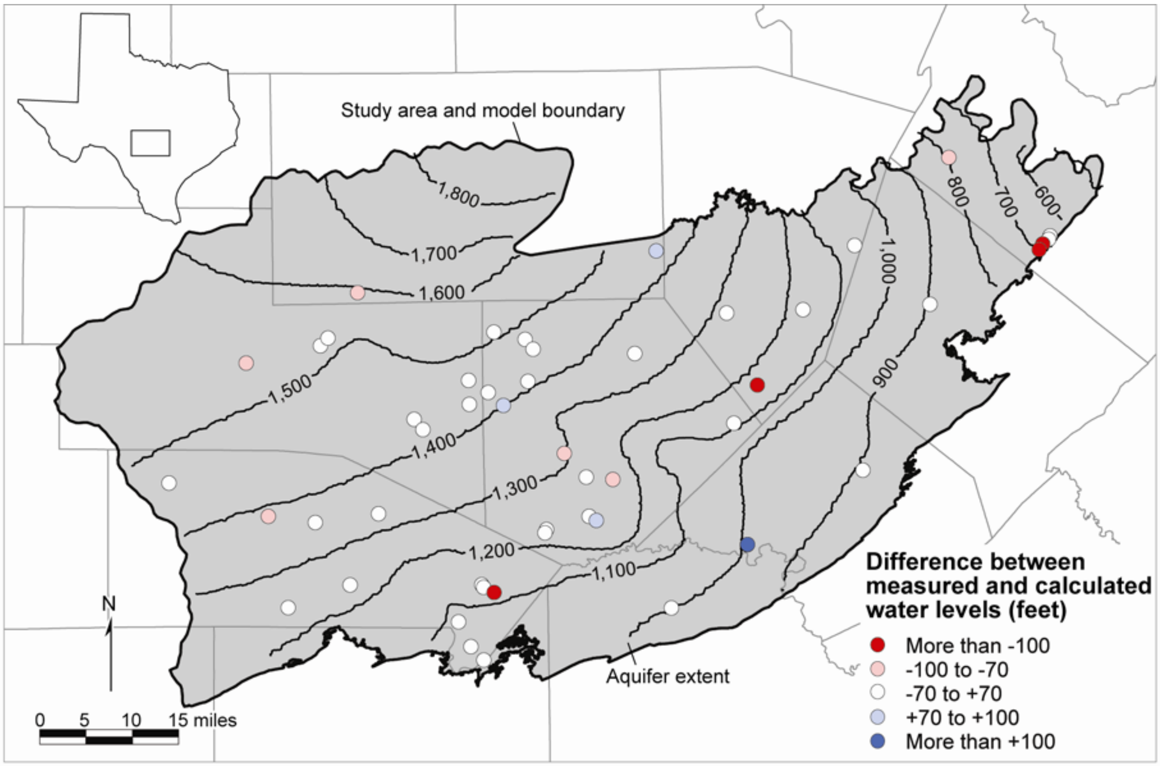
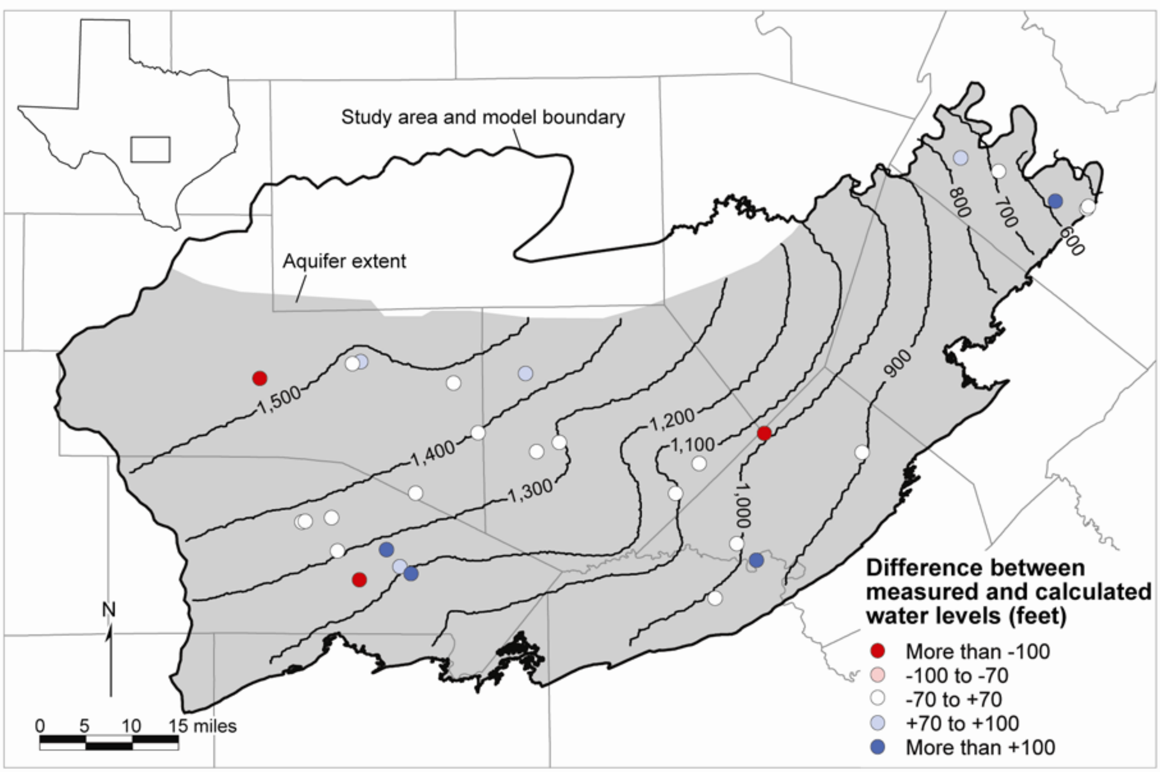


Figure 9-2. **Comparison of measured and calculated water levels from the steady-state model for (a) layer 1, (b) layer 2, (c) layer 3, and (d) layer 4. The contours represent calculated water levels, expressed in feet above sea level, whereas the points indicate the difference between measured and simulated water levels relative to the measured water levels.**



(c)



(d)

Figure 9-2. (continued).

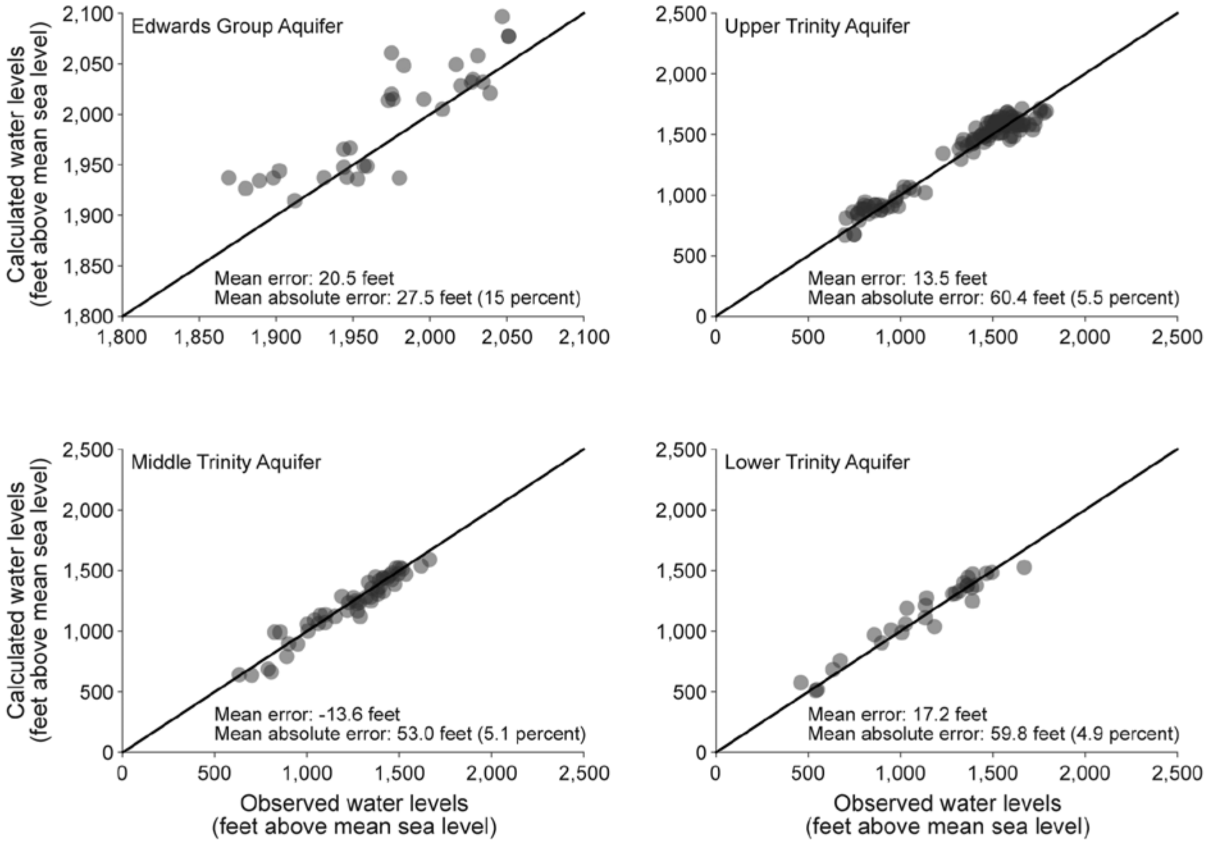


Figure 9-3. Comparison of measured and calculated water levels from the steady-state model.

In addition to comparing measured and simulated water levels, we compared measured streamflow and simulated drain discharge to determine how well the model reproduces groundwater discharge to major streams in the study area (Figures 9-4 and 9-5). General agreement between measured stream discharge of Barton Creek, Blanco River, Guadalupe River, Hondo Creek, Medina River, Onion Creek, and Pedernales River indicates that the steady-state model does a reasonable job of reproducing base flow 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 9-1). 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.

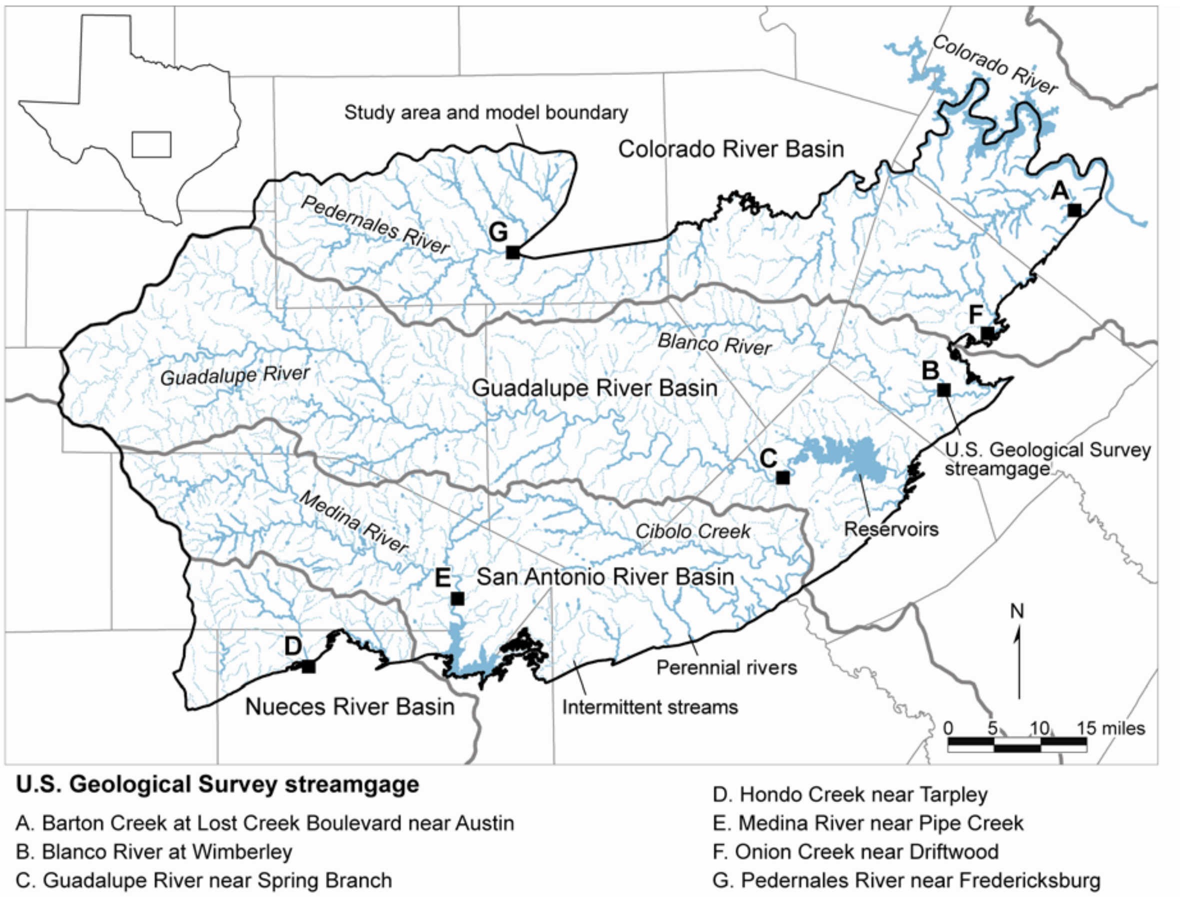


Figure 9-4. Location of streamgages used to compare measured streamflow and calculated discharge to streams from the model.

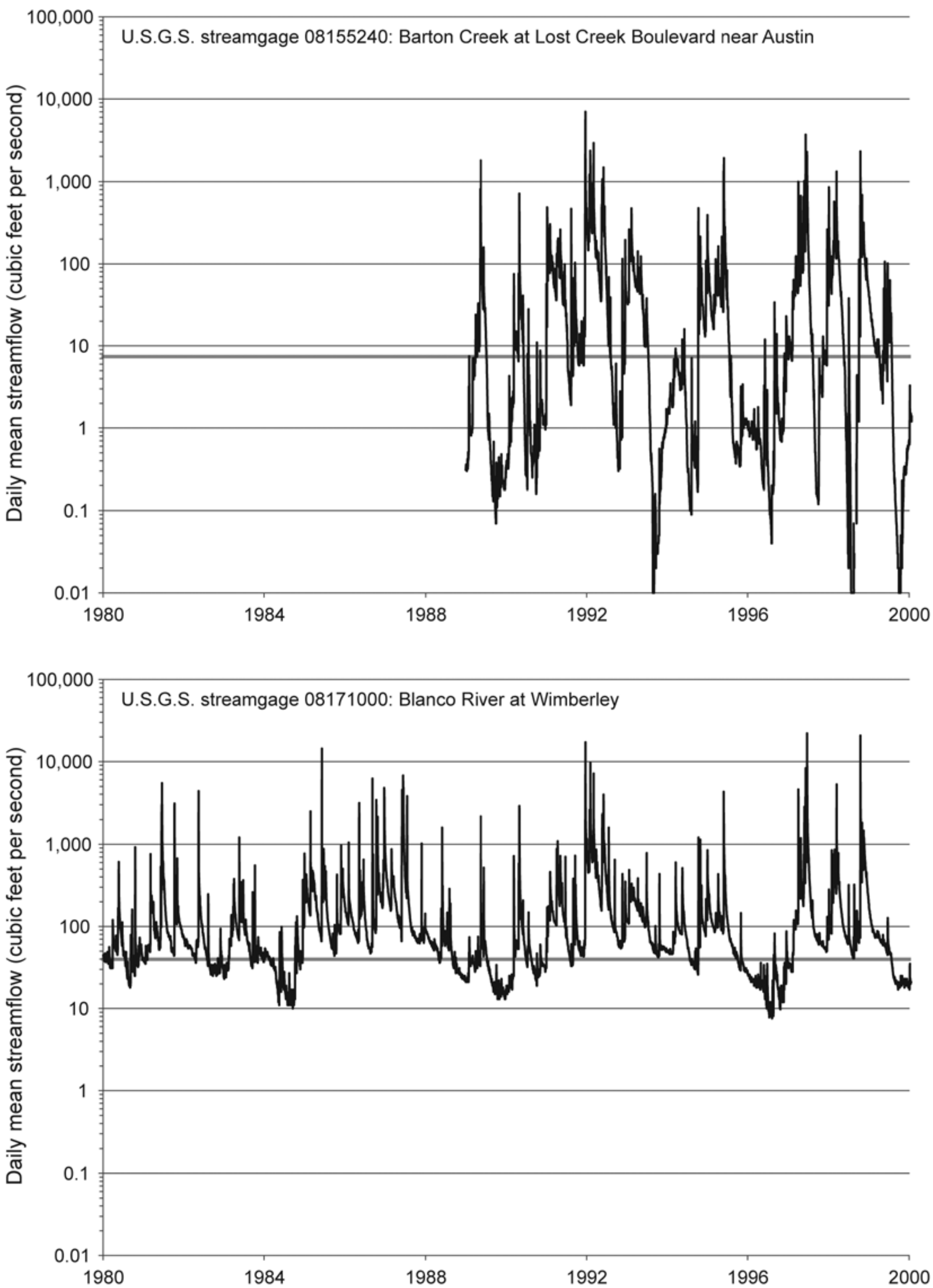
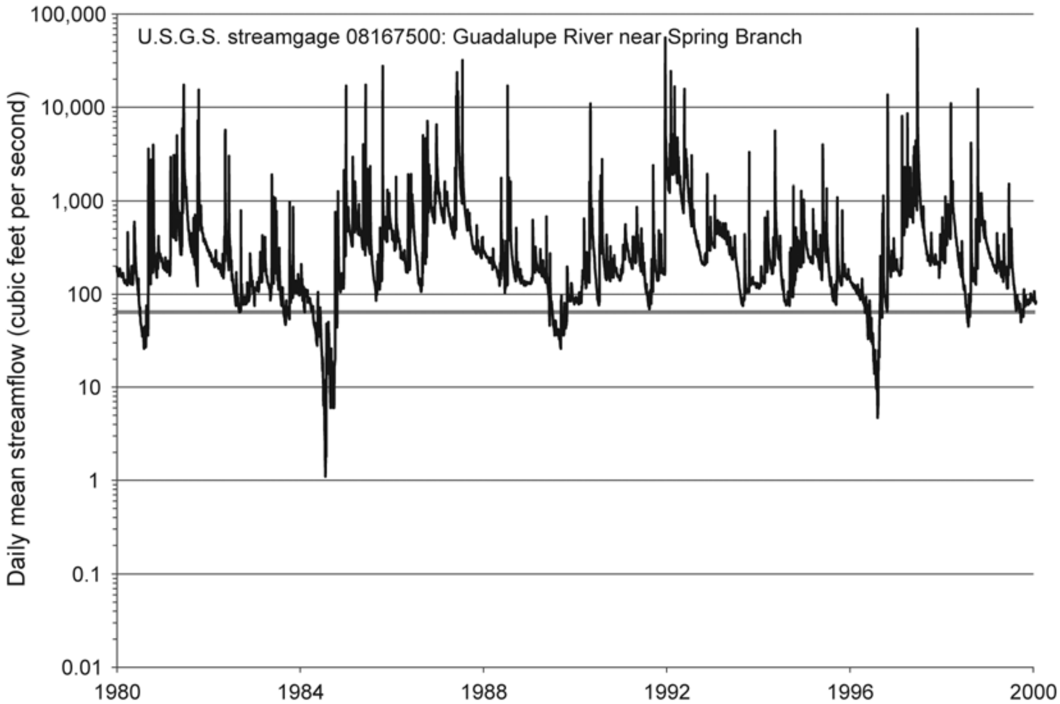


Figure 9-5. Comparison of the calculated groundwater discharge rate to perennial streams from the 1980 steady-state model (gray line) and measured streamflow data. Streamgage locations are shown in Figure 9-4. U.S.G.S. = U.S. Geological Survey



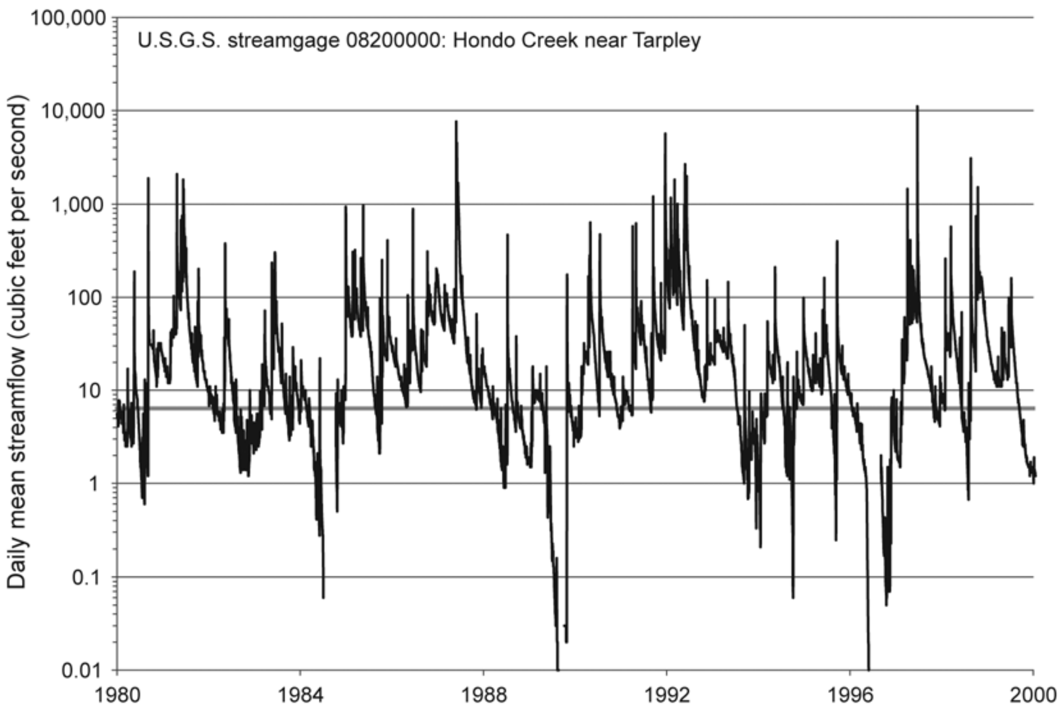
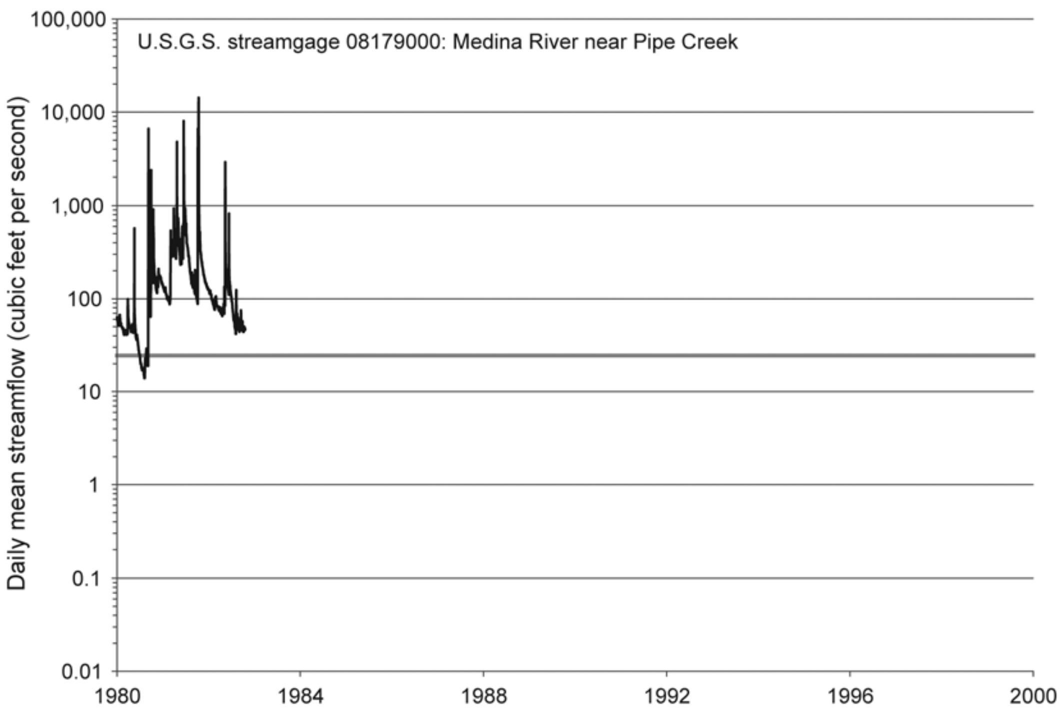


Figure 9-5. **(continued).**



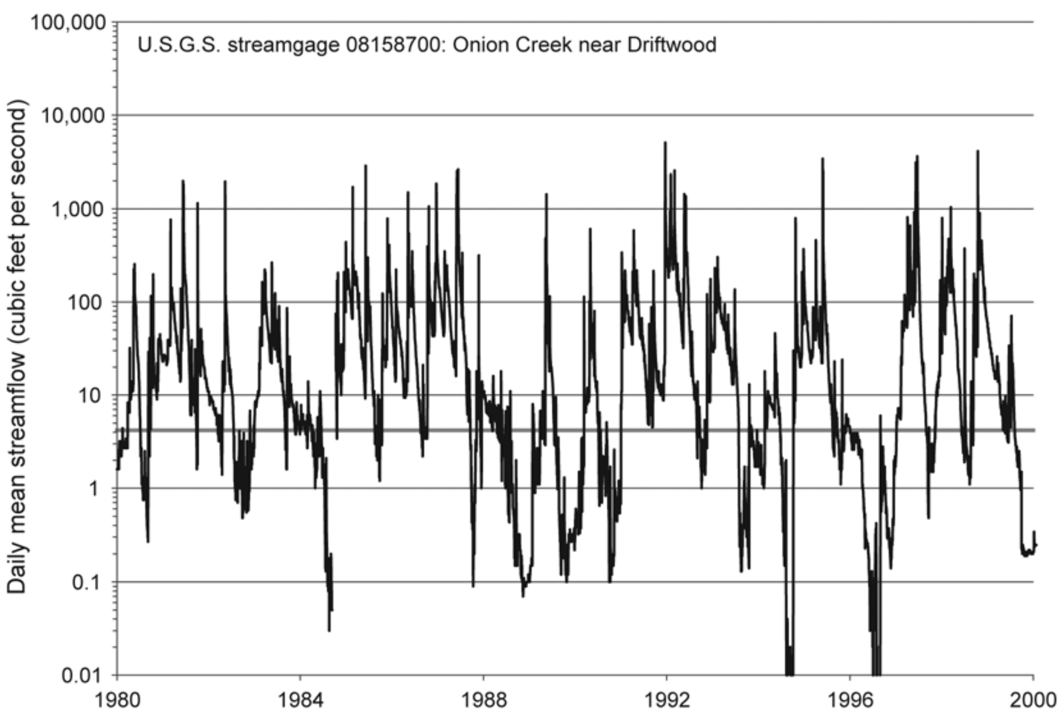


Figure 9-5. (continued).

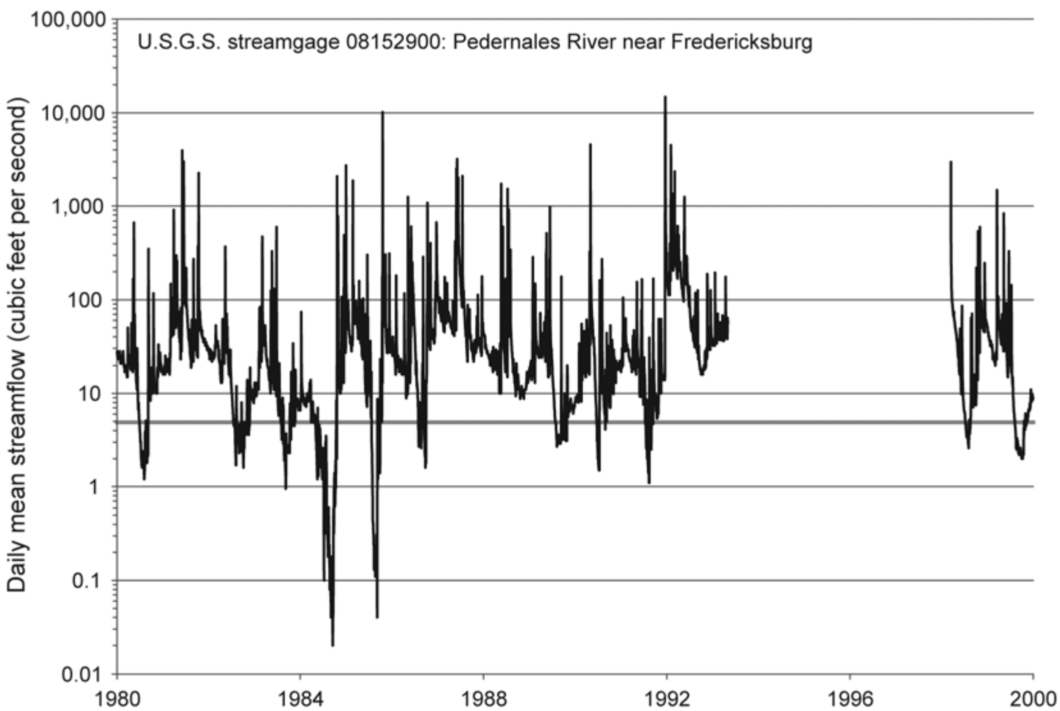


Figure 9-5. (continued).

Table 9-1. Water budget for the calibrated steady-state model for 1980 (all values in acre-feet per year, rounded to hundreds of acre-feet; negative values indicate net discharge from the aquifer).

	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
Total	**320,600**	**320,600**	**0**

We used the calibrated model to investigate the volume of recharge to and groundwater moving between the different aquifers (Table 9-2). 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, whereas 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. Our conceptual model indicates 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.

Table 9-2. Water budget for the respective layers in the calibrated steady-state model for 1980 (all values in acre-feet per year, rounded to hundreds of acre-feet; negative values indicate net discharge from the aquifer).

	Edwards Group	Upper Trinity Aquifer	Middle Trinity Aquifer	Lower Trinity Aquifer	Total
Interaquifer flow (above)	0	9,800	64,100	5,800	79,700
Interaquifer flow (below)	-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

The model shows that more than 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 downdip 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 in the central and southwestern parts (Table 9-3). 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 subparallel to the boundary in Travis and Hays counties (Figure 9-2). The spatial distribution of groundwater flow between the Trinity Aquifer System and the Edwards (Balcones Fault Zone) Aquifer is most likely influenced by the large amounts of recharge occurring along Cibolo Creek in Bexar and Comal counties. Faults also have greater displacements to the east and may therefore act as more effective barriers to flow.

Table 9-3. Water budget for the respective counties in the calibrated steady-state model for 1980 (all values in acre-feet per year, rounded to hundreds of acre-feet; negative values indicate net discharge from the aquifer).

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**

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:

$$MD = \frac{1}{n}\sum_{i=1}^{n}\left(h_{sen} - h_{cal}\right), \qquad (2)$$

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 9-6). The model is insensitive to pumping and to 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 as much as 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 to the boundaries and does not have widespread effects throughout the model.

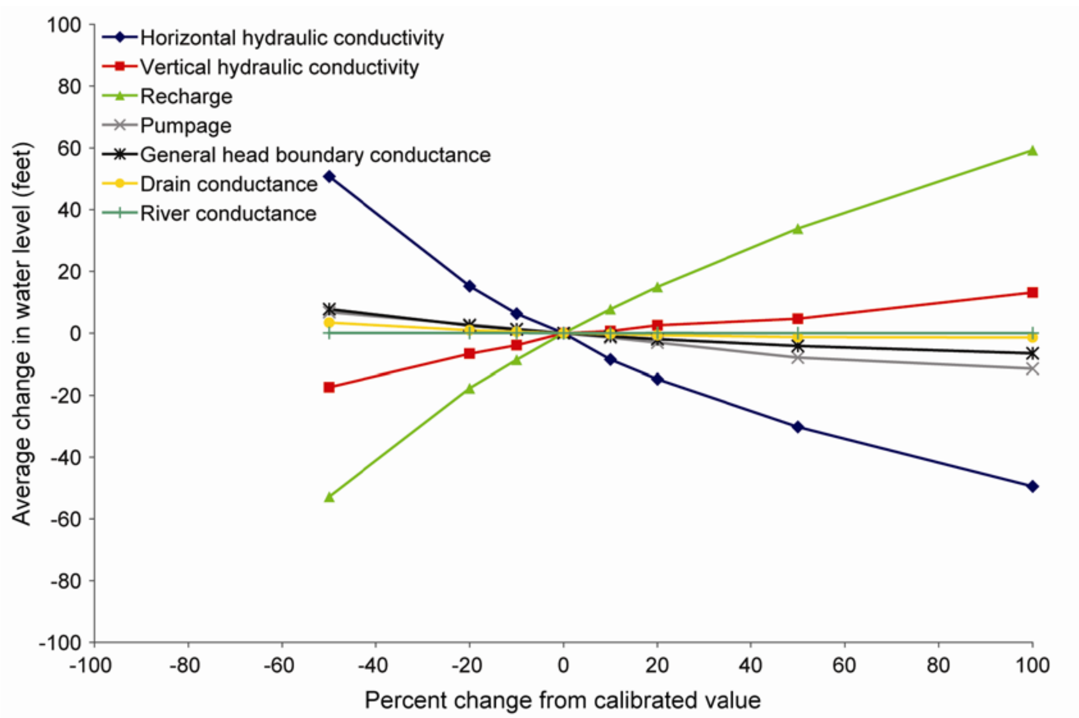


Figure 9-6. **Sensitivity of calculated water levels in the steady-state model to changes in model parameters.**

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 10-1).

Table 10-1. 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

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^{-7} 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 10-2).

Table 10-2. 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

The model does a good job of reproducing observed water level fluctuations in some areas but not as well in other areas (Figures 10-1 through 10-5). Note that baseline shifts in water levels in Figure 10-2 are commonly due to the influence of local-scale conditions not represented in the regional model or errors in our parameterization of the aquifer data. Although it has 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 indicates 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 10-3; Figure 10-4).

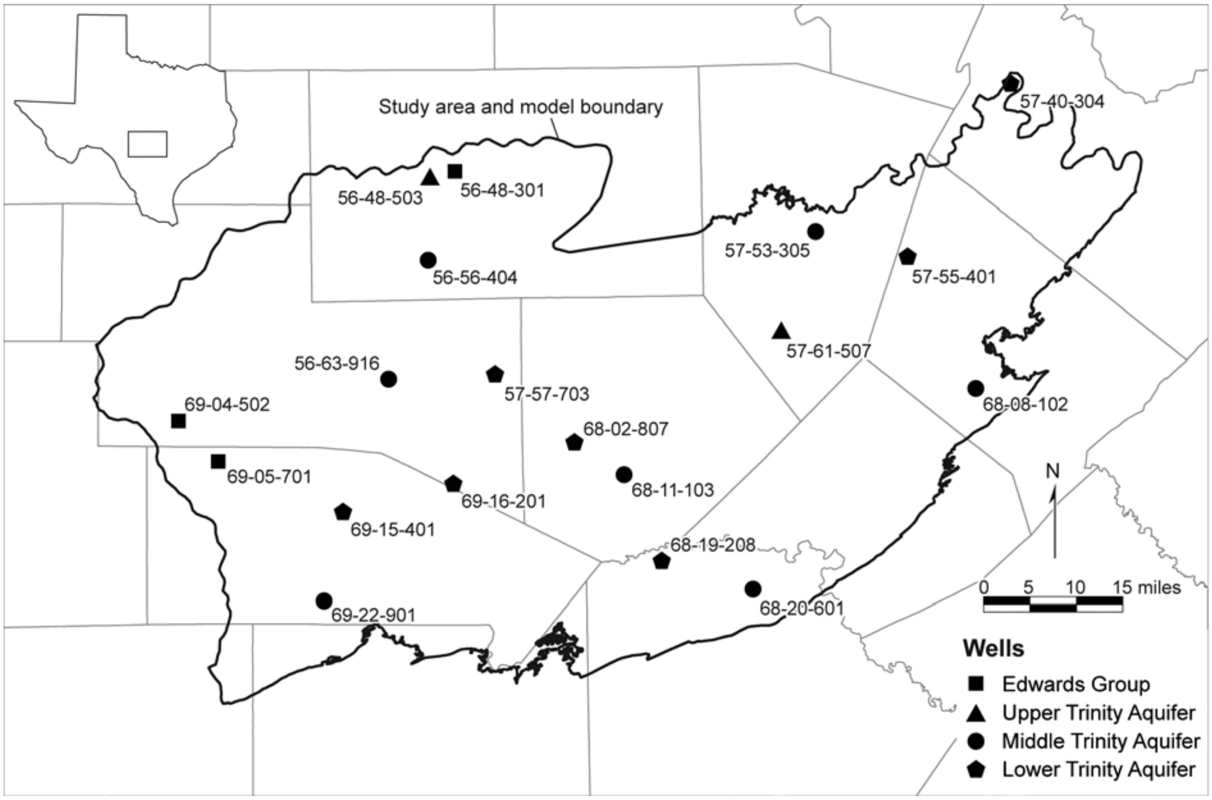


Figure 10-1. Locations of wells used to compare measured water levels over the transient period (1980 through 1997) and calculated water levels.

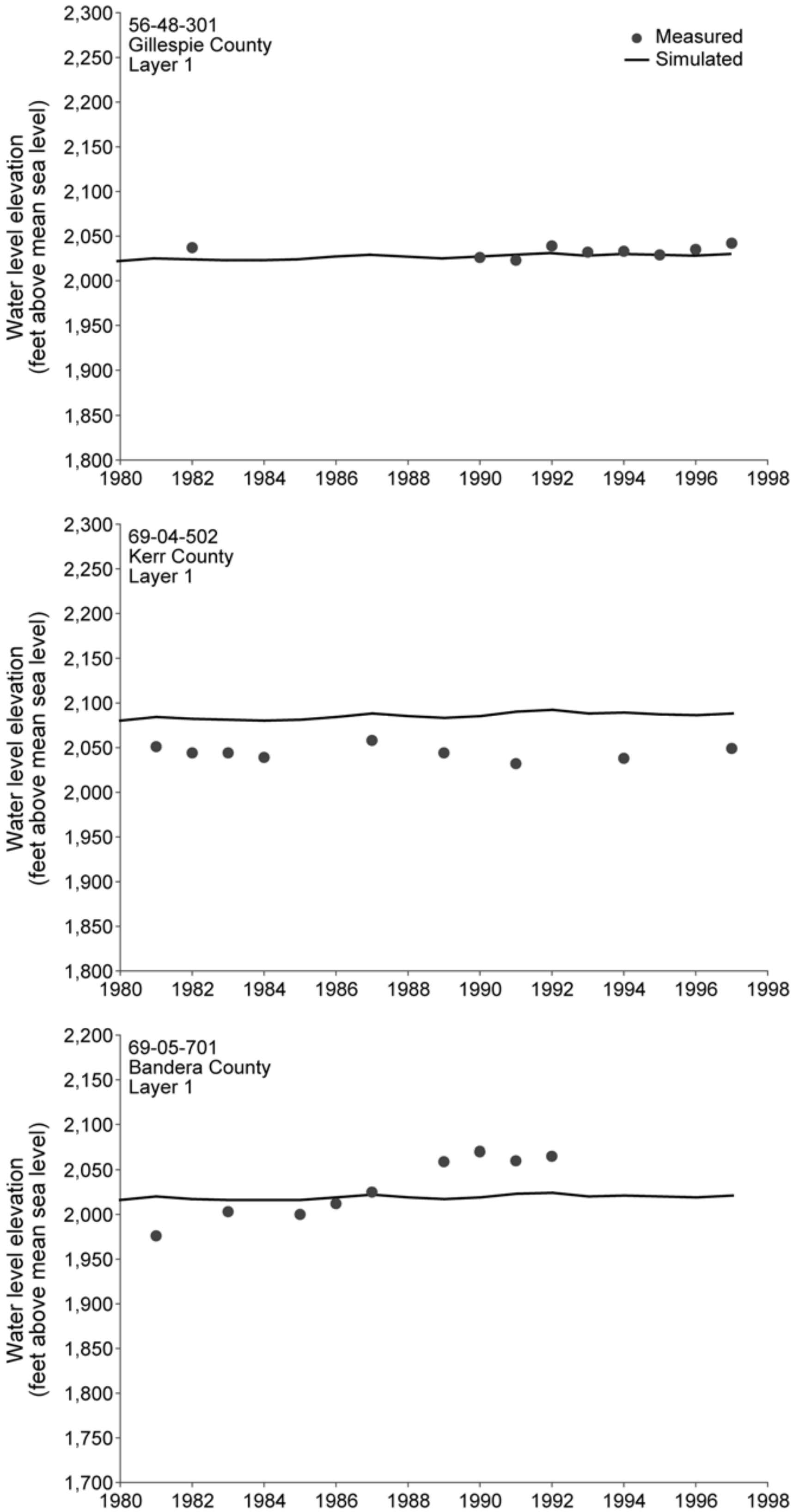
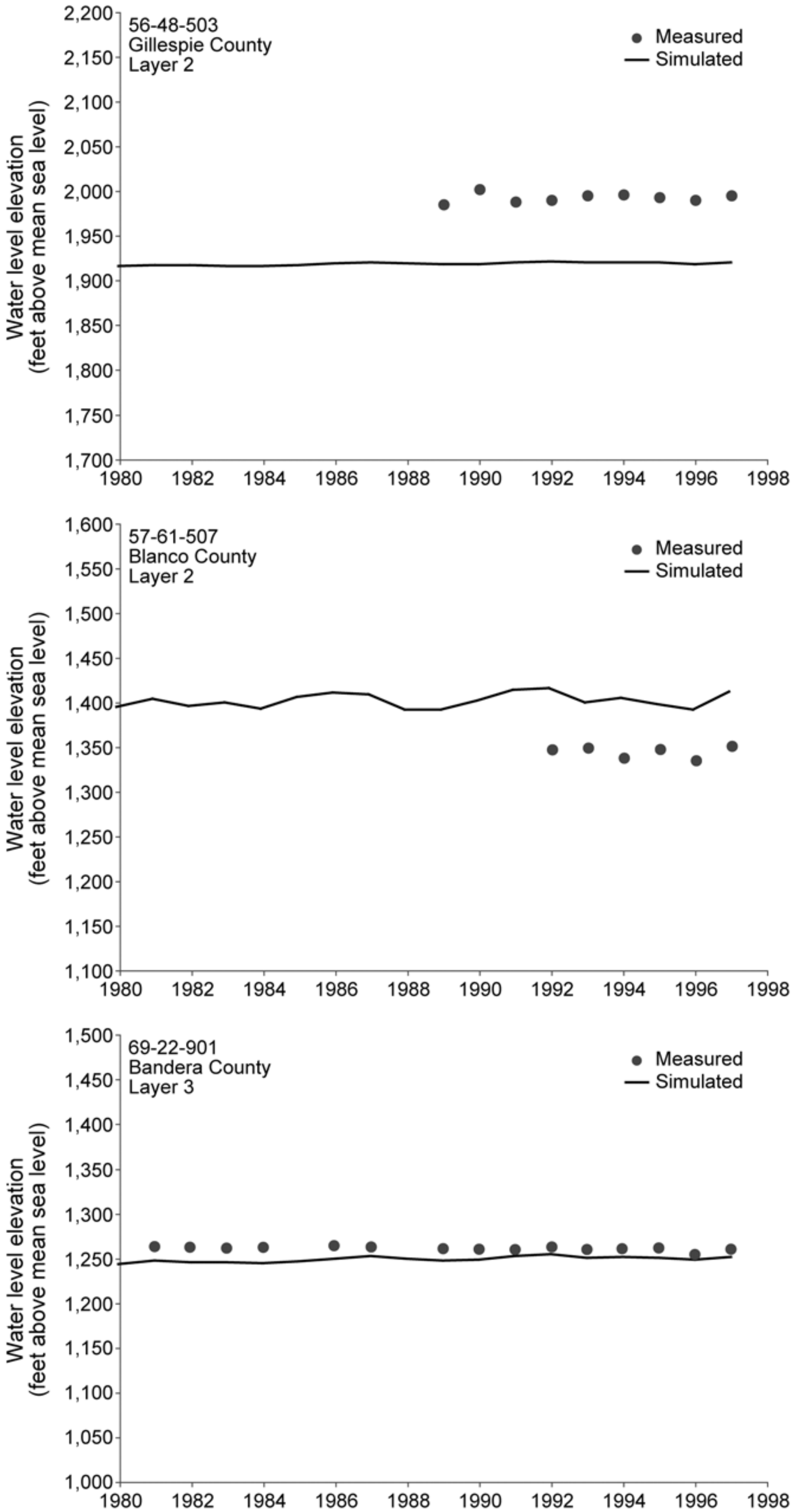


Figure 10-2. Comparison of simulated water level fluctuations to measured water levels. Well locations are shown in Figure 10-1.



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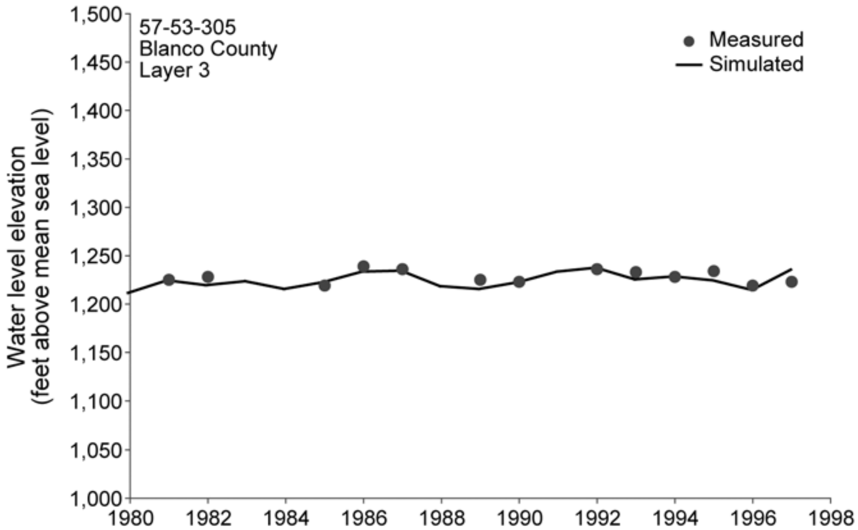

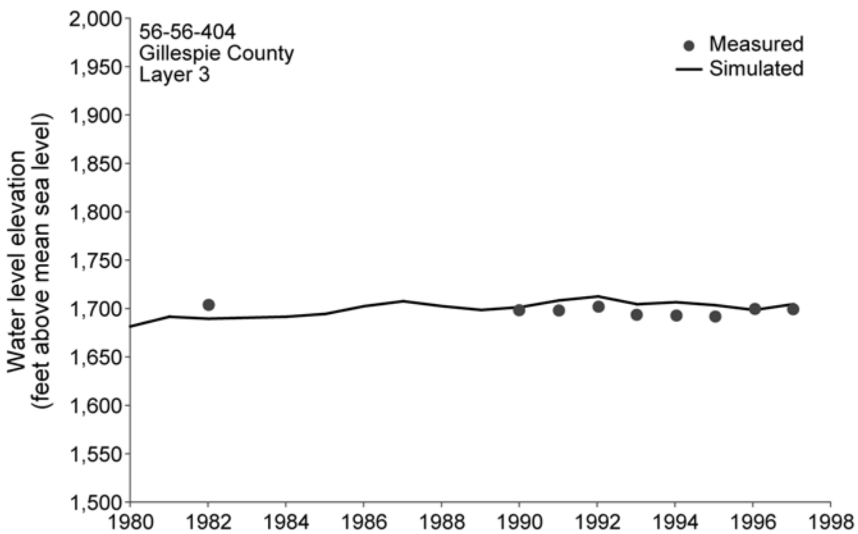

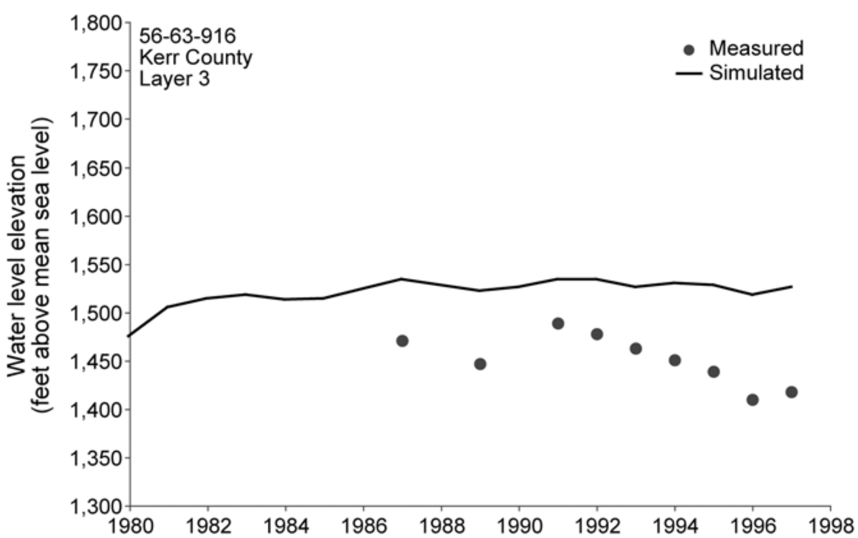

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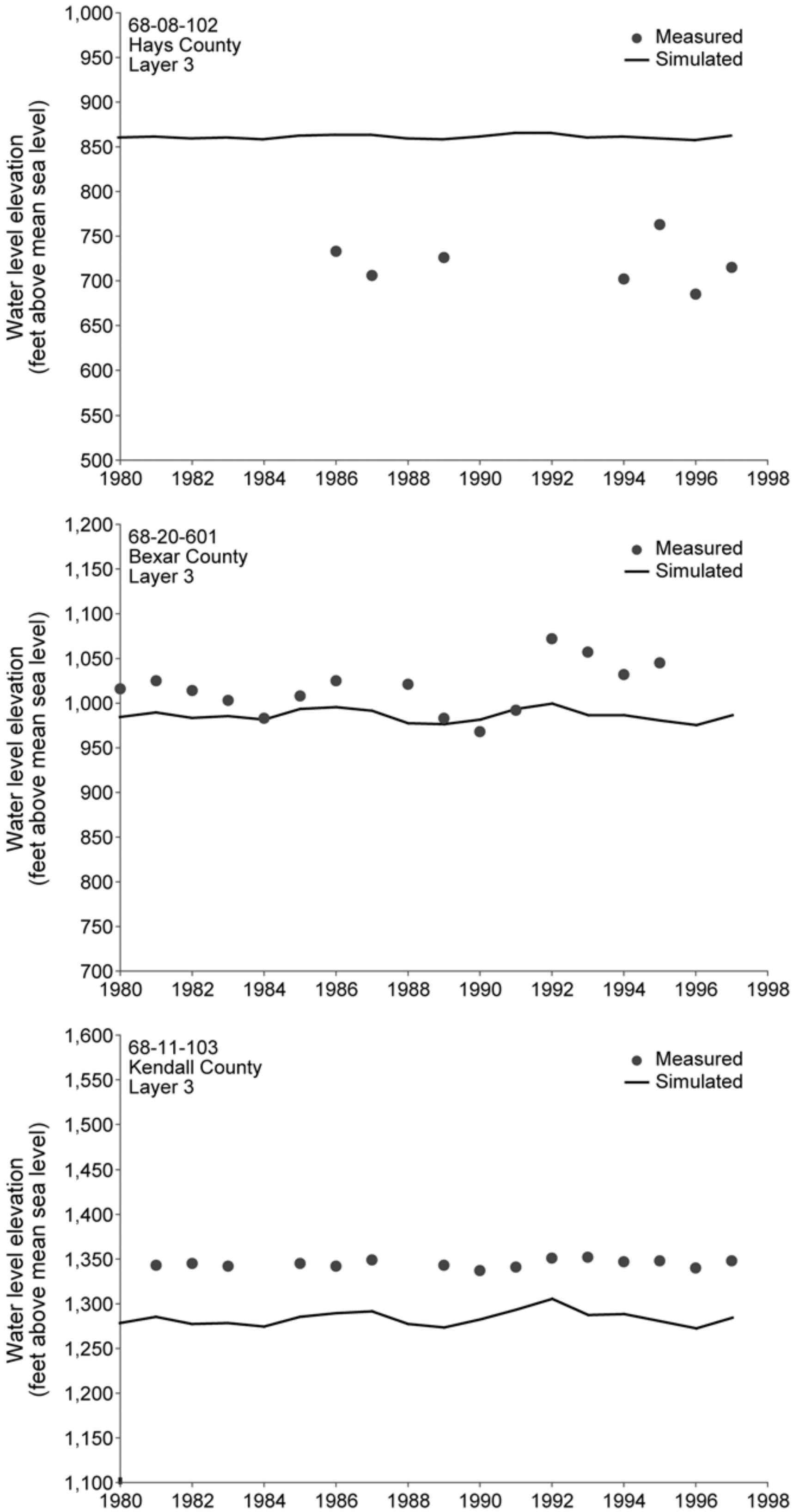

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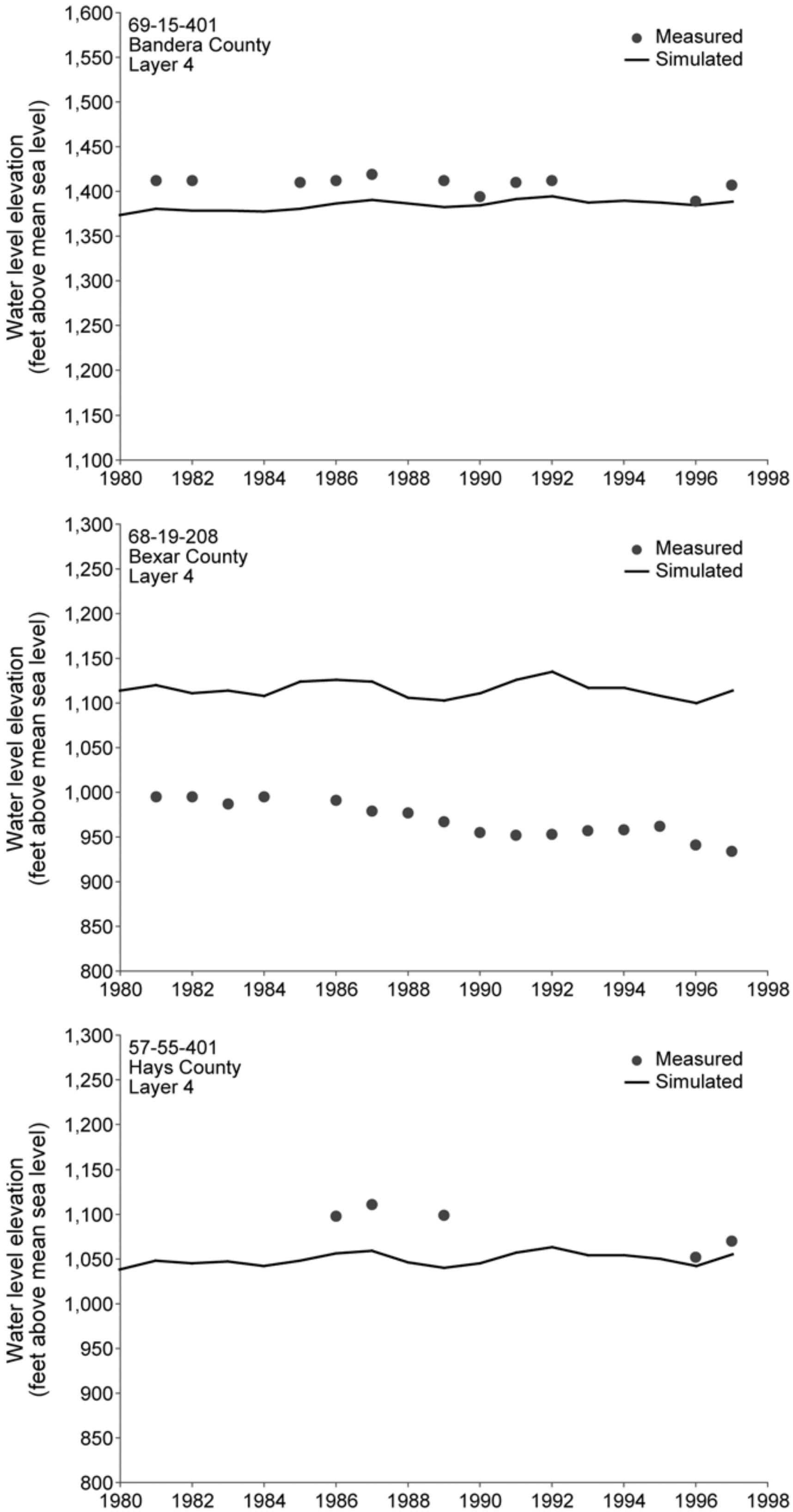

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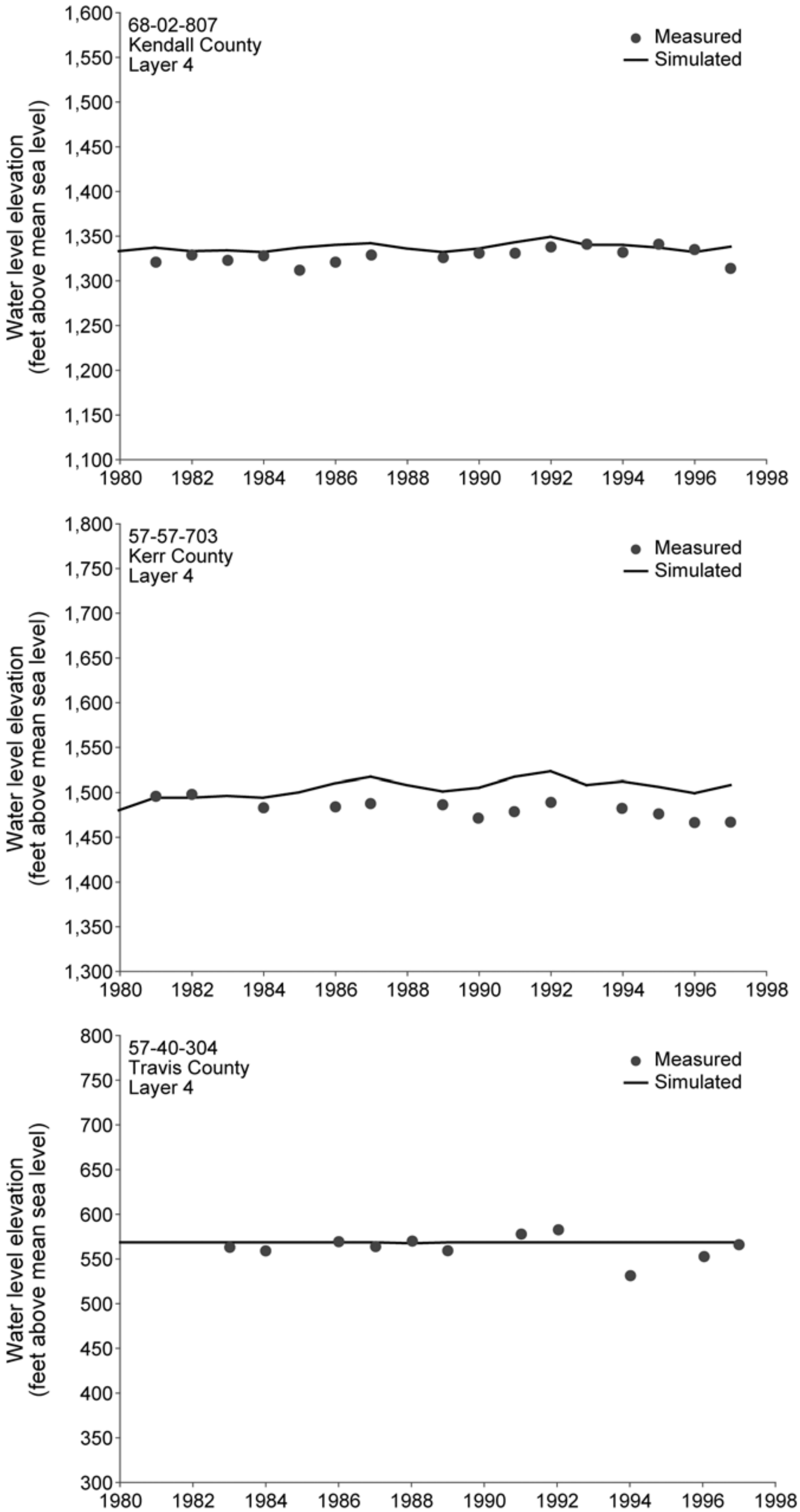

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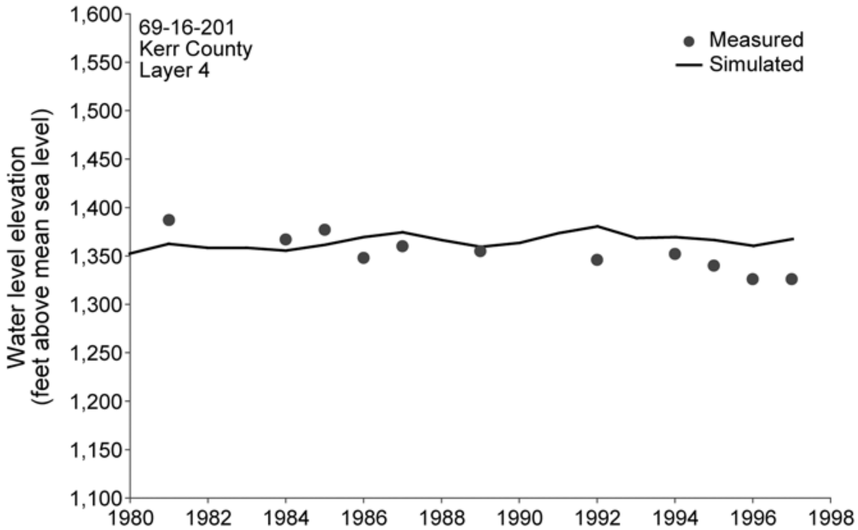

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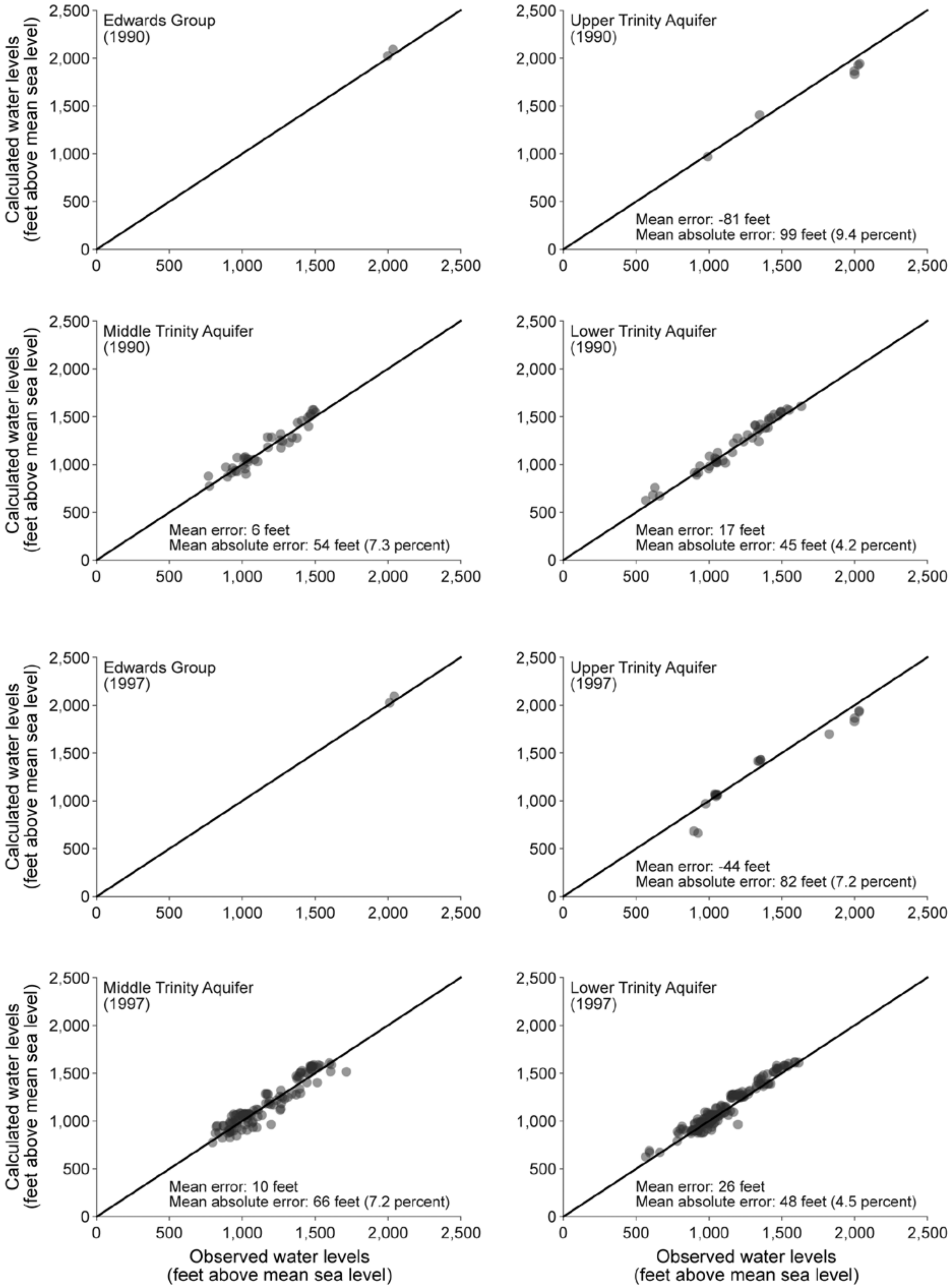
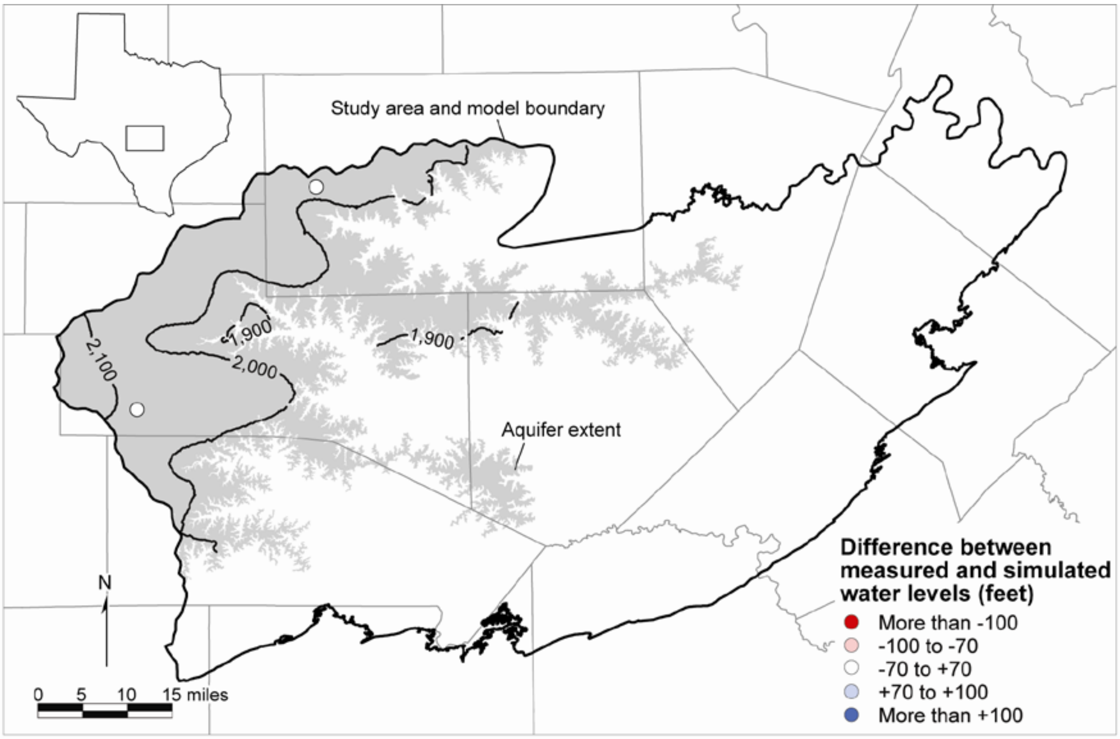
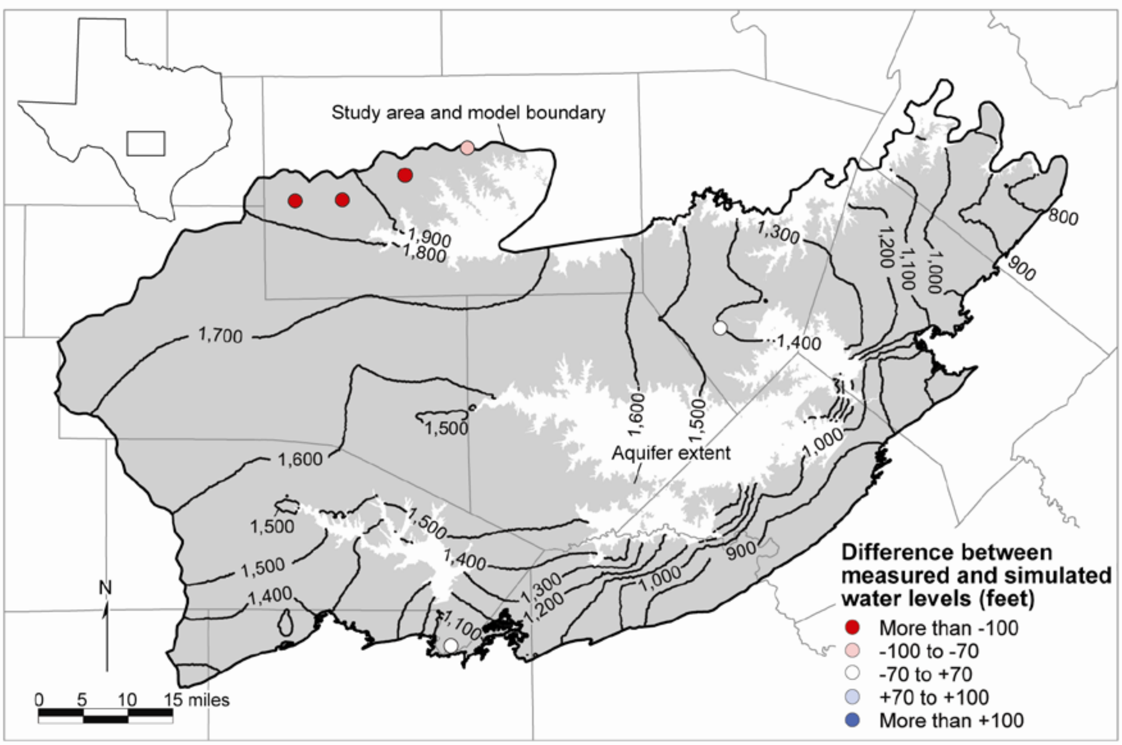


Figure 10-3. Comparison of measured and calculated water levels for 1990 and 1997 from the transient model.

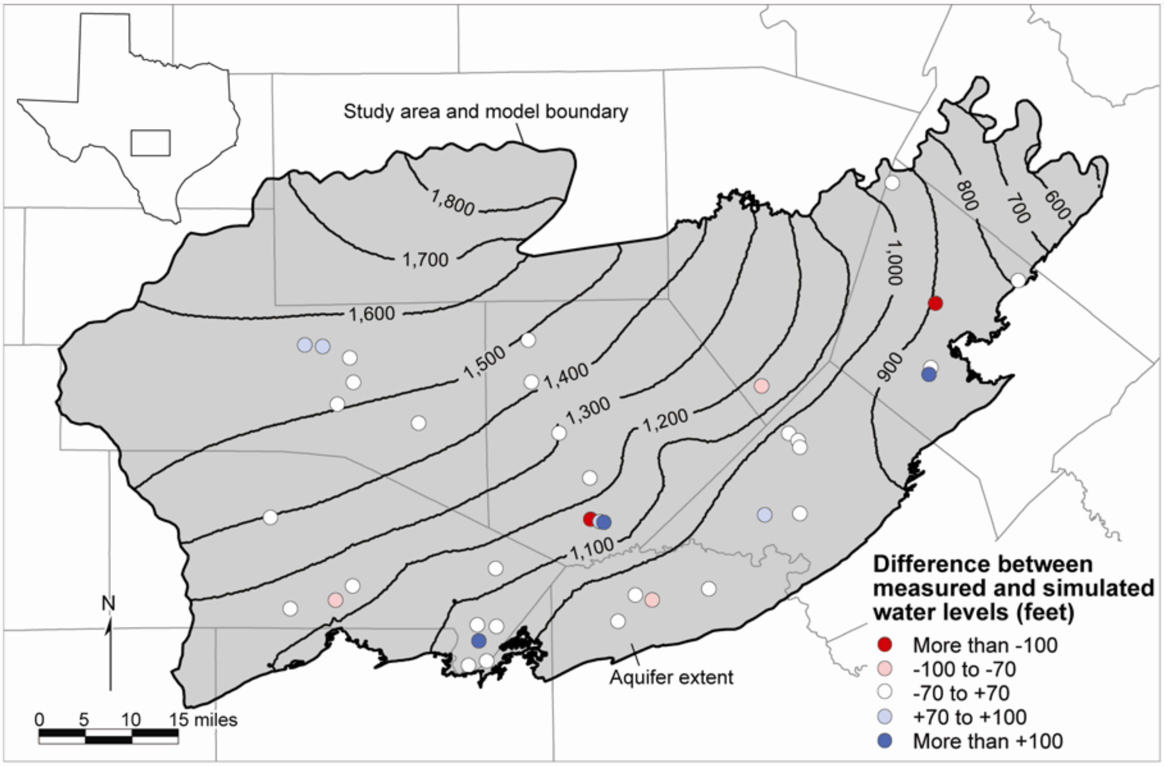


(a)



(b)

Figure 10-4. 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, expressed in feet above sea level, whereas the points indicate the difference between measured and simulated water levels relative to the measured water levels.



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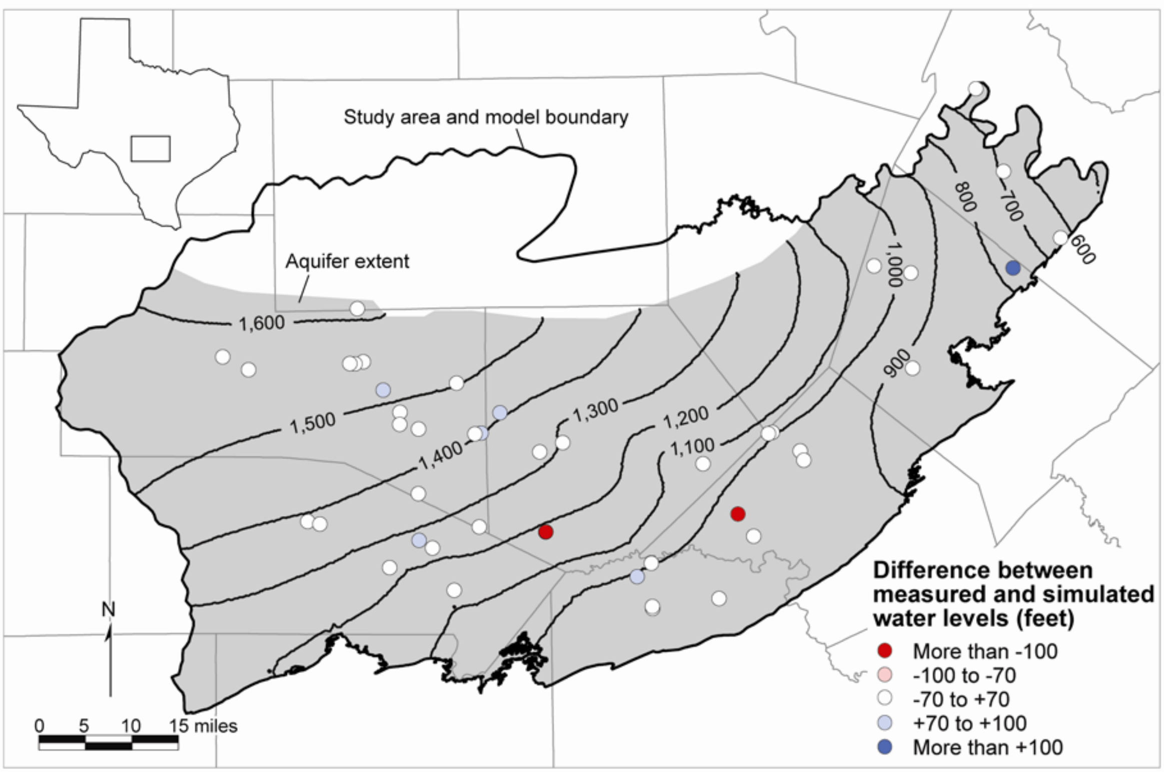
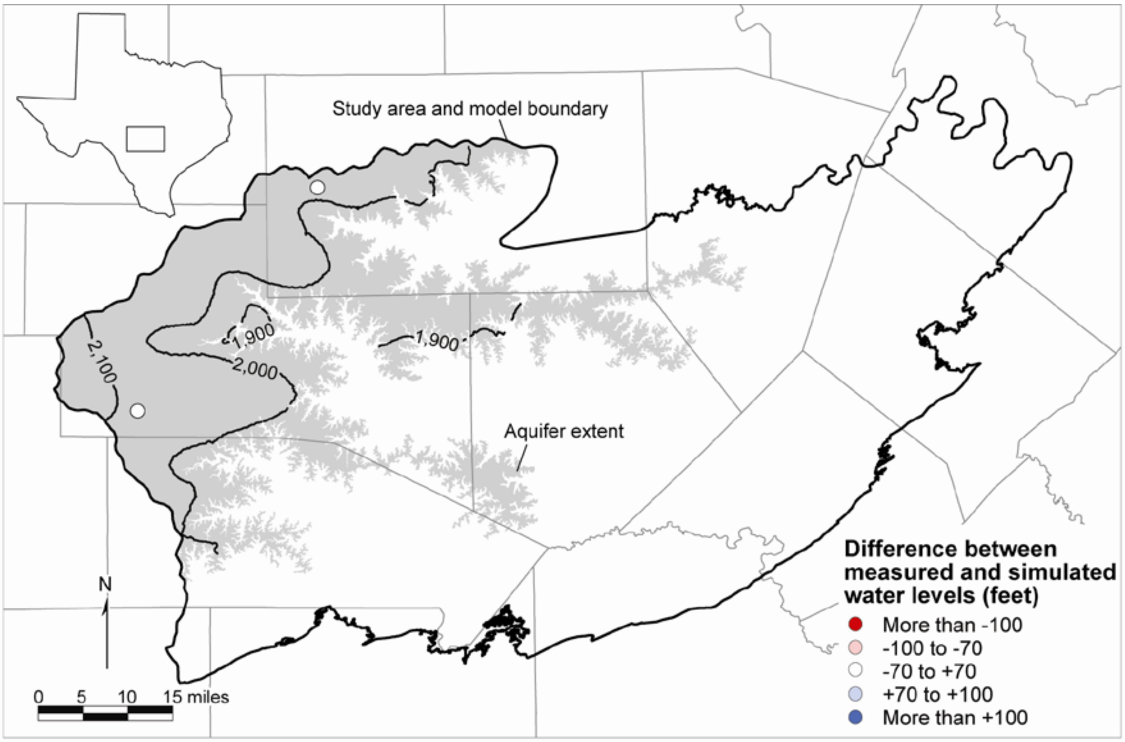
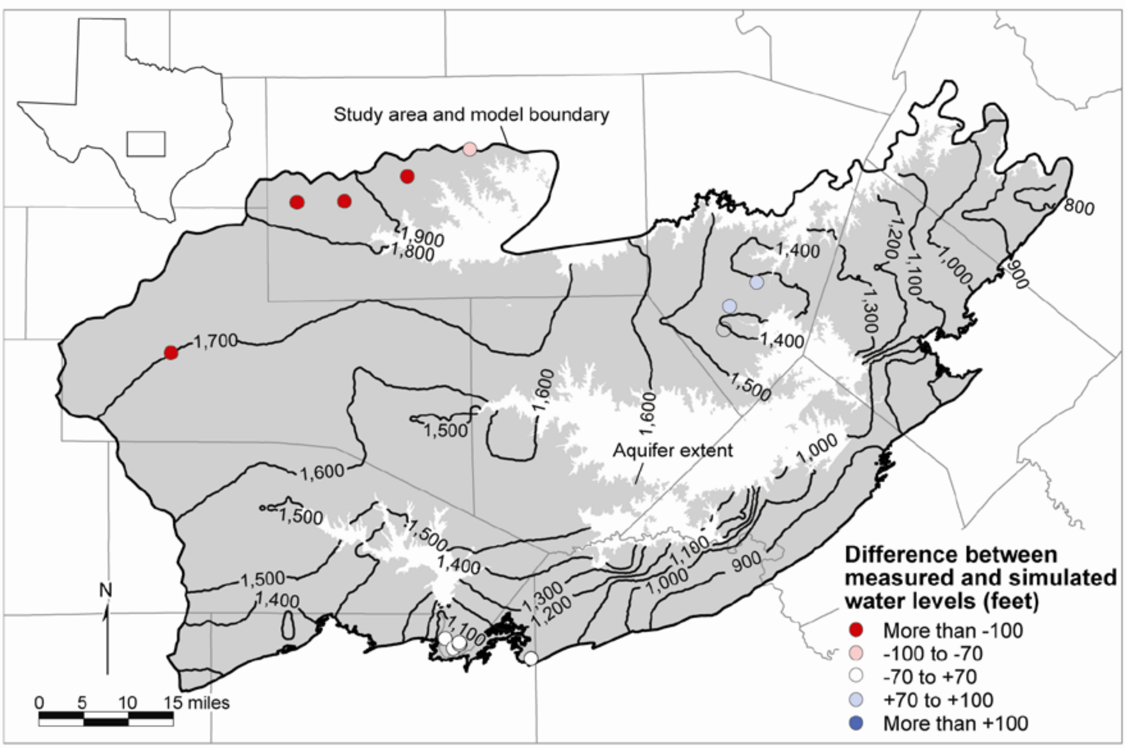


(d)

Figure 10-4. (continued).

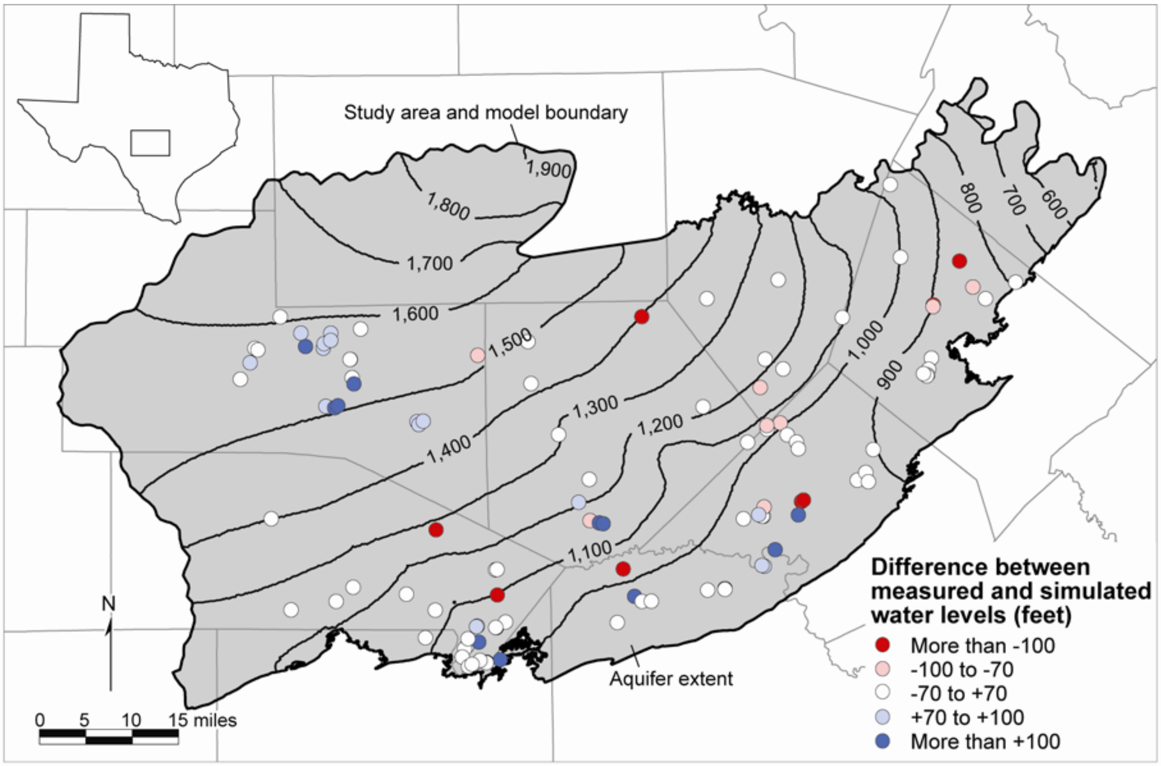


(a)

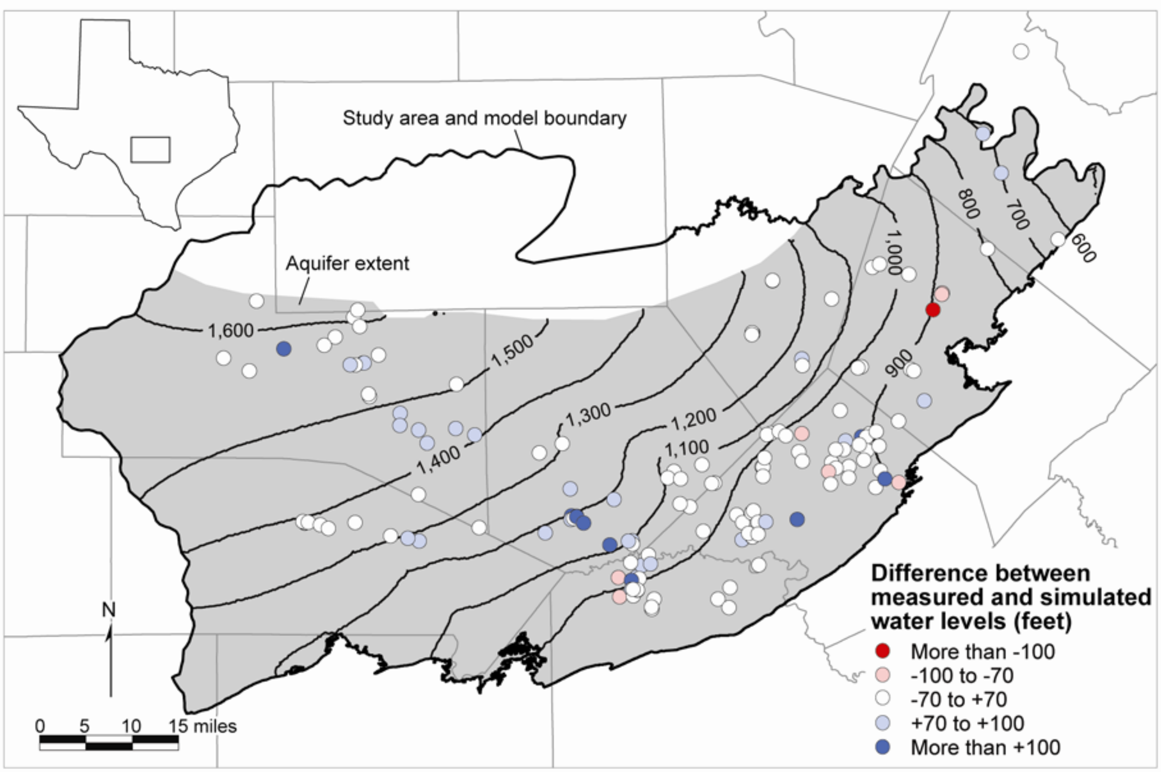


(b)

Figure 10-5. 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, expressed in feet above sea level, whereas the points indicate the difference between measured and simulated water levels relative to the measured water levels.



(c)



(d)

Figure 10-5. (continued).

Table 10-3. 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

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

Table 10-4 shows the water budgets for the respective model layers in 1980, 1990, and 1997. Simulating discharge to springs using a regional-scale model is commonly difficult because of spatial and temporal scale issues. Table 10-5 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 commonly discharge sites for highly localized flow systems that cannot be simulated in regional models. The result is that the apparent ability of the model to simulate spring discharge varies widely. Of 17 springs, 6 display a good comparison between measured and simulated discharge values. Simulated spring discharge from springs having the highest measured discharge values differs 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 base-flow discharge to streams. Overall, the model also does a good job of mimicking base-flow fluctuations (Figure 10-6).

Table 10-4. Water budget for the respective layers in the calibrated transient model for 1980, 1990, and 1997 (all values in acre-feet per year; negative values indicate net discharge from the aquifer).

1980	Edwards Group	Upper Trinity Aquifer	Middle Trinity Aquifer	Lower Trinity Aquifer
Interaquifer flow (above)	0	9,773	64,138	5,825
Interaquifer flow (below)	-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
Interaquifer flow (above)	0	10,087	68,750	5,793
Interaquifer flow (below)	-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
Interaquifer flow (above)	0	10,329	77,150	5,297
Interaquifer flow (below)	-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 10-5. Estimated spring discharge and simulated average spring discharge rates from the calibrated transient model expressed in gallons per minute. The location of these springs can be found in Figure 5-28 (all values 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) owing to scale issues, the model results may not reflect the more localized flow systems that influence discharge at specific springs.

	Spring	Estimated Flow	Date	1980	1981	1982	1983
1		150	4/13/1967	139	142	140	139
2	Bee Caves Spring	100	4/12/1967	75	83	78	75
3	Lynx Haven Springs	100		82	86	84	82
4	Ellebracht Springs	2,500	3/31/1966	225	238	217	213
5		310	3/11/1970	330	358	331	317
8		20	7/13/1976	366	474	350	346
9		75	7/10/1975	33	40	33	36
10	Cave Without A Name	50	1/17/1940	119	127	115	119
11	Kenmore Ranch Spring #9	150	7/17/1975	0	81	0	0
12	Edge Falls Springs	300		0	0	0	0
13	Rebecca Springs	300	7/11/1975	0	0	0	0
14	Jacob's Well Spring	500	8/31/1976	0	0	0	0
15		25	1/1/1966	6	9	8	9
16	Bassett Springs	50	12/30/1988	0	0	0	0
17		50	5/25/1973	0	0	0	0
18		9,000	12/20/1960	407	423	407	400
19	Cold Springs	5,000	8/20/1991	441	516	437	448

Table 10. 5 (continued).

	Spring	1984	1985	1986	1987	1988	1989
1		139	140	142	145	142	140
2	Bee Caves Spring	74	76	84	92	87	81
3	Lynx Haven Springs	82	83	86	90	88	85
4	Ellebracht Springs	218	226	241	255	228	222
5		321	332	360	393	358	338
8		322	388	466	500	368	308
9		32	42	46	46	32	32
10	Cave Without A Name	113	132	134	132	111	110
11	Kenmore Ranch Spring #9	0	113	152	140	0	0
12	Edge Falls Springs	0	0	0	0	0	0
13	Rebecca Springs	0	0	0	0	0	0
14	Jacob's Well Spring	0	0	0	0	0	0
15		7	9	11	12	7	6
16	Bassett Springs	0	0	0	0	0	0
17		0	0	0	0	0	0
18		408	413	429	446	416	410
19	Cold Springs	419	489	542	558	442	414

Table 10. 5 (continued).

	Spring	1990	1991	1992	1993	1994	1995
1		142	145	146	142	144	142
2	Bee Caves Spring	85	93	98	88	92	88
3	Lynx Haven Springs	87	91	94	89	91	89
4	Ellebracht Springs	236	244	250	219	242	227
5		359	382	404	355	378	363
8		392	508	528	359	426	386
9		40	50	56	40	44	37
10	Cave Without A Name	125	139	150	124	129	118
11	Kenmore Ranch Spring #9	1	195	351	59	70	0
12	Edge Falls Springs	0	0	83	0	0	0
13	Rebecca Springs	0	0	0	0	0	0
14	Jacob's Well Spring	0	0	0	0	0	0
15		8	12	13	10	10	9
16	Bassett Springs	0	0	0	0	0	0
17		0	0	0	0	0	0
18		428	436	447	415	432	425
19	Cold Springs	474	568	626	473	518	471

	Spring	1996	1997
1		142	144
2	Bee Caves Spring	86	90
3	Lynx Haven Springs	88	90
4	Ellebracht Springs	224	247
5		350	388
8		335	446
9		31	47
10	Cave Without A Name	110	132
11	Kenmore Ranch Spring #9	0	35
12	Edge Falls Springs	0	0
13	Rebecca Springs	0	0
14	Jacob's Well Spring	0	0
15		7	11
16	Bassett Springs	0	0
17		0	0
18		420	446
19	Cold Springs	419	522

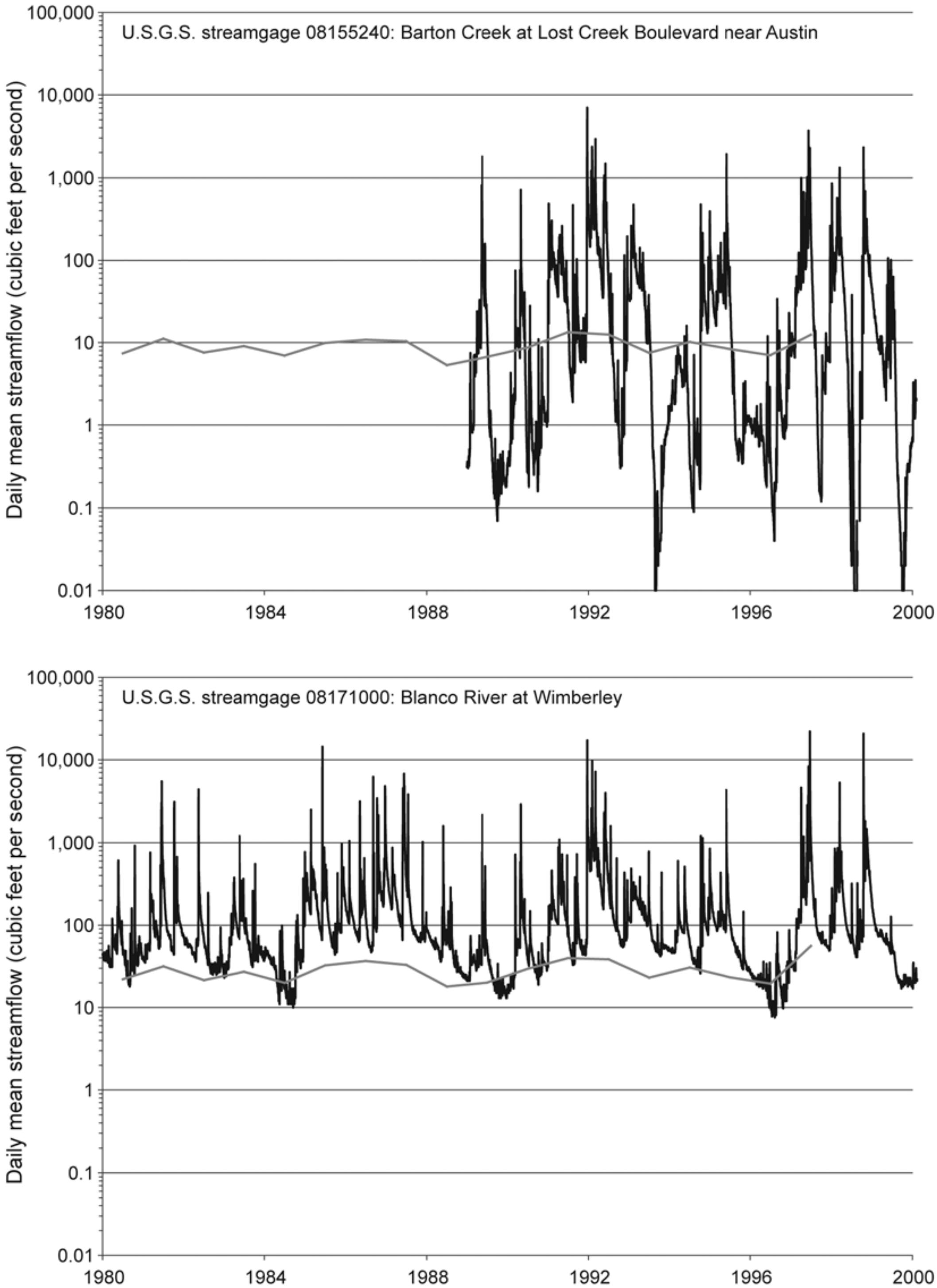
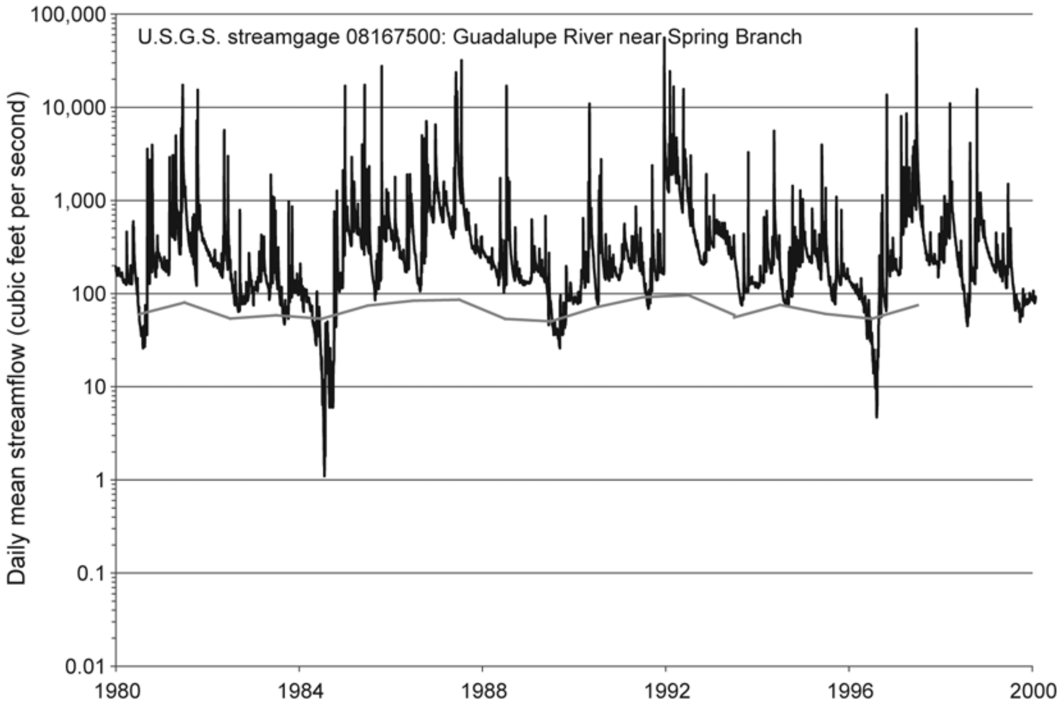


Figure 10-6. Comparison of calculated annual groundwater discharge rates to perennial streams from the transient model (gray line) and measured streamflow data. Streamgage locations are shown in Figure 9-4.



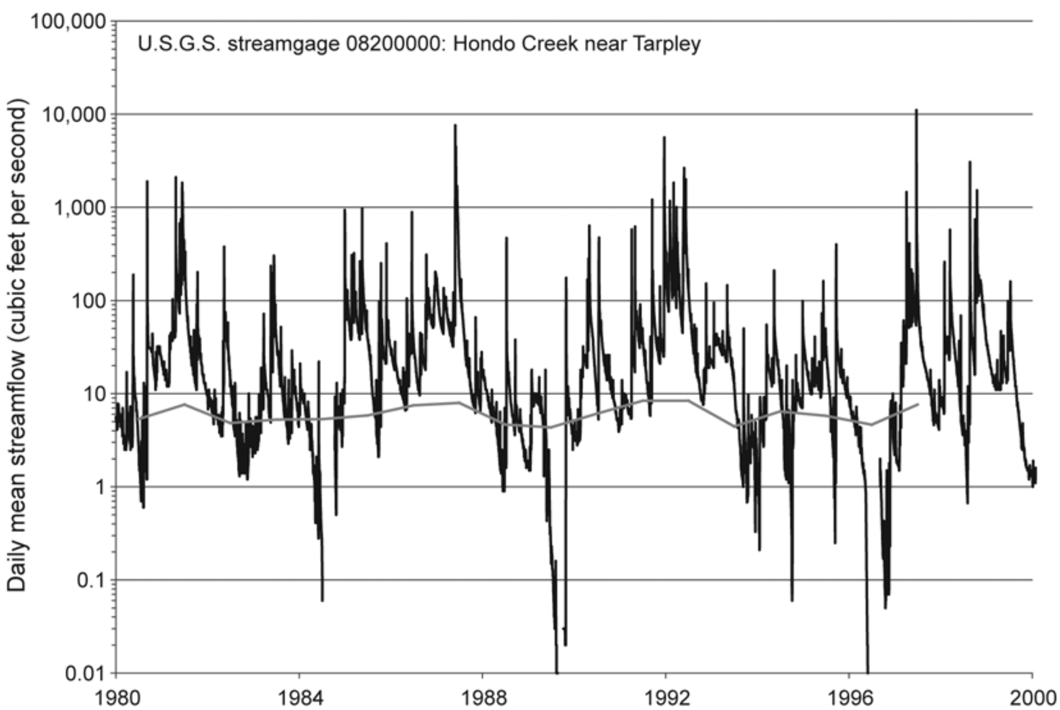
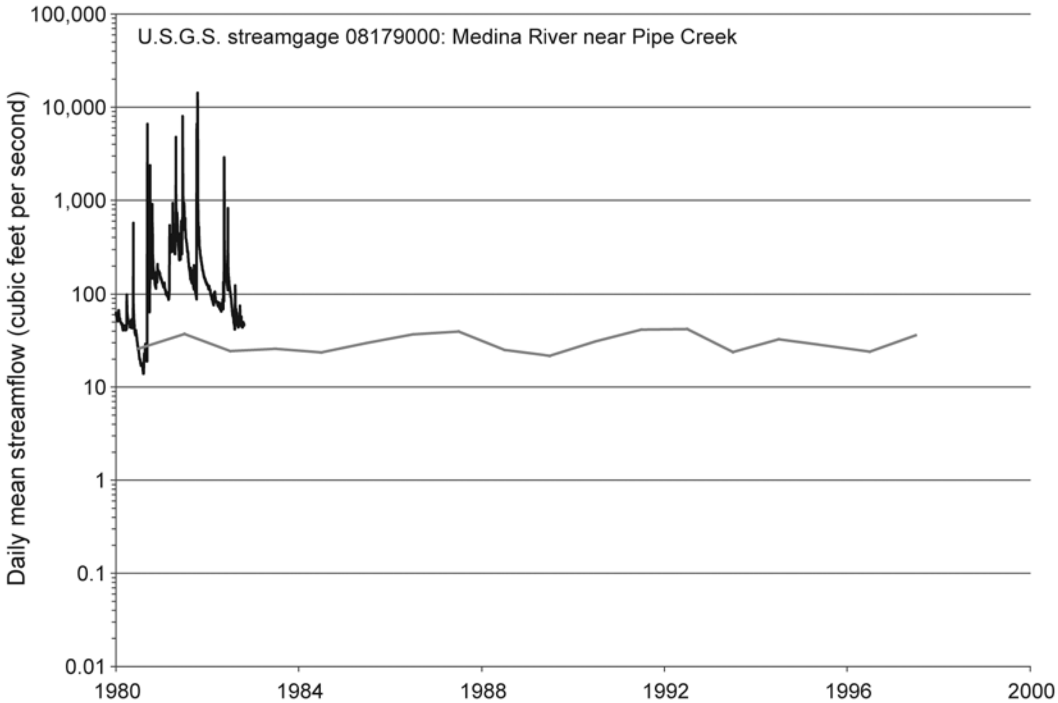


Figure 10-6. (continued).



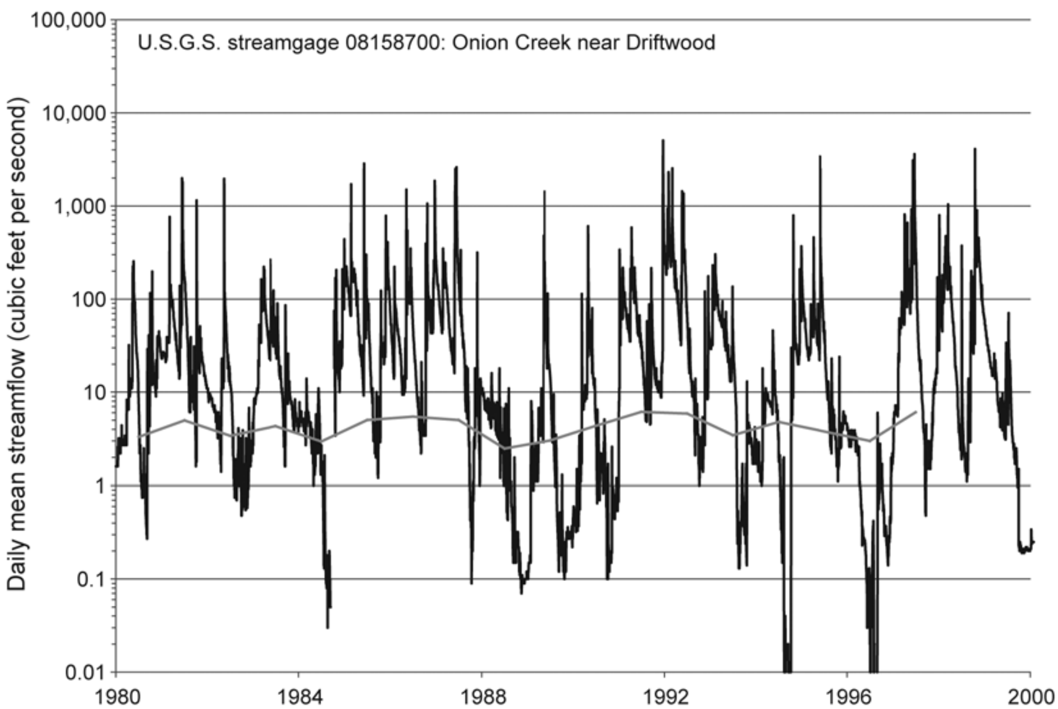


Figure 10-6. (continued).

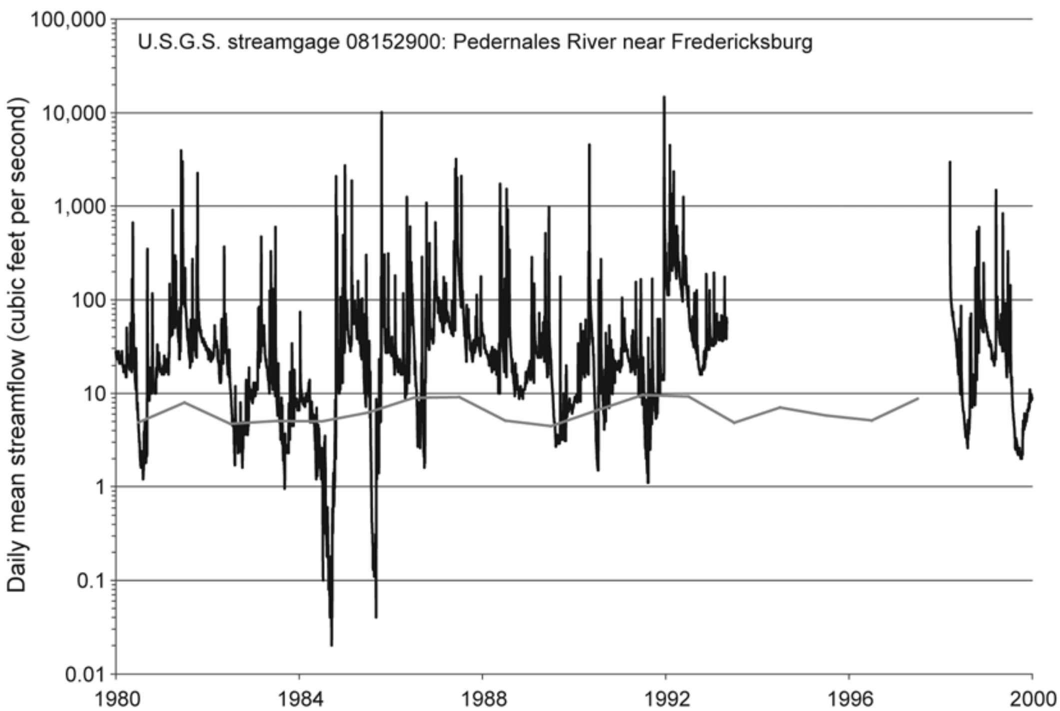


Figure 10-6. (continued).

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 10-7 and 10-8). This result 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 to specific storage.

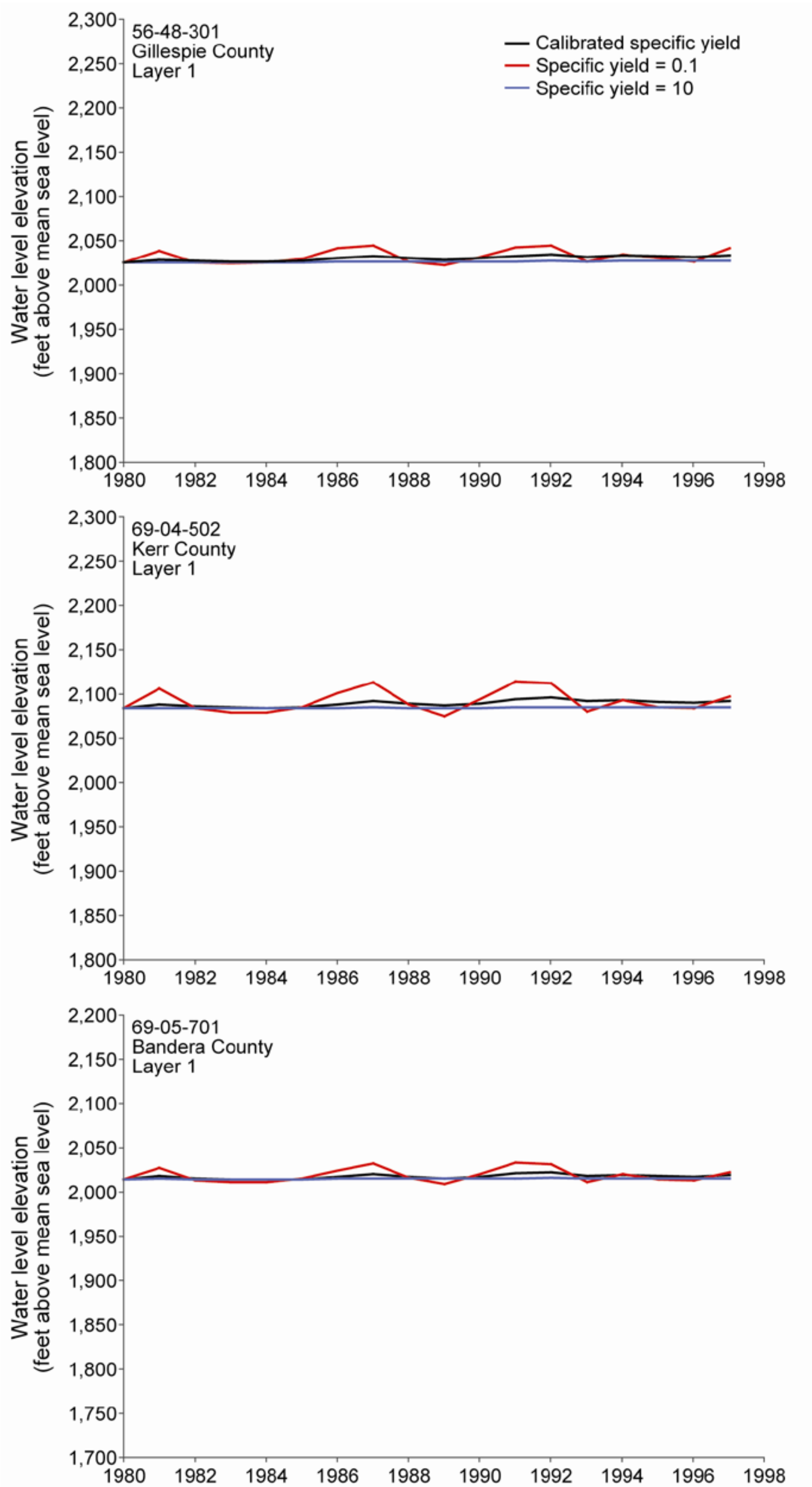


Figure 10-7. **Sensitivity of the transient calibration to specific yield. The red and blue lines represent one order of magnitude lower and higher than the calibrated values, respectively, relative to calibrated specific-yield values (black line).**

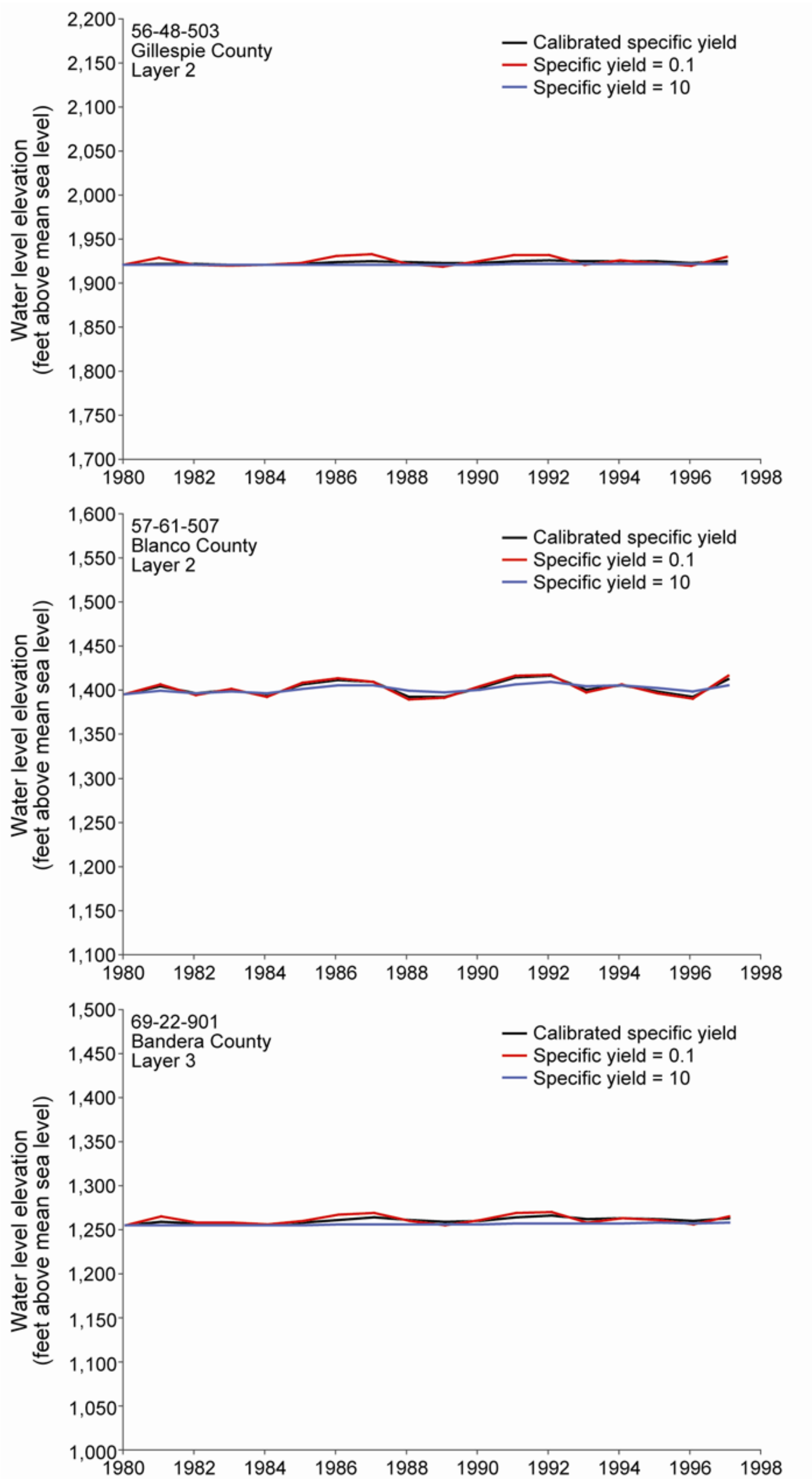


Figure 10-7. (continued).

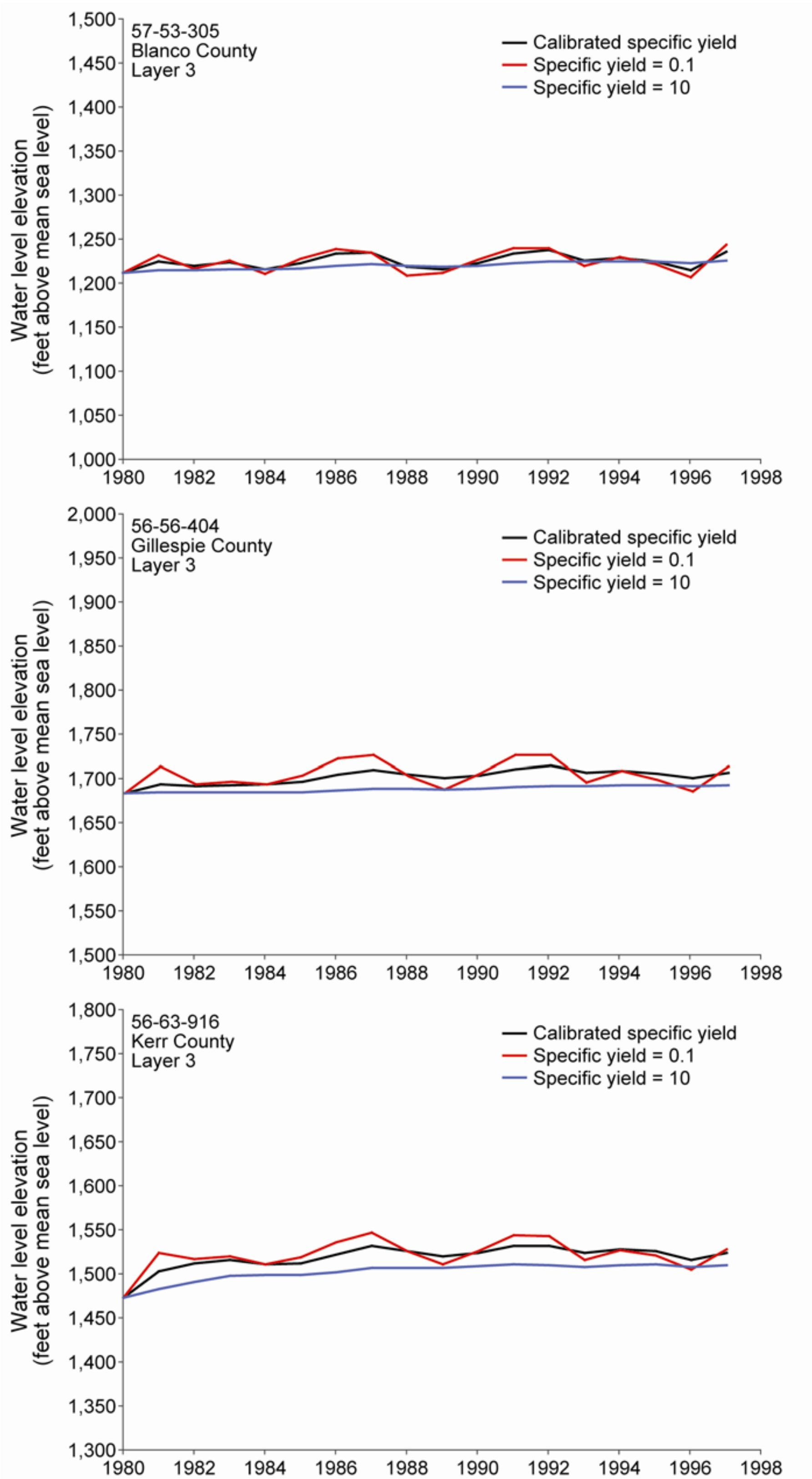


Figure 10-7. **(continued).**

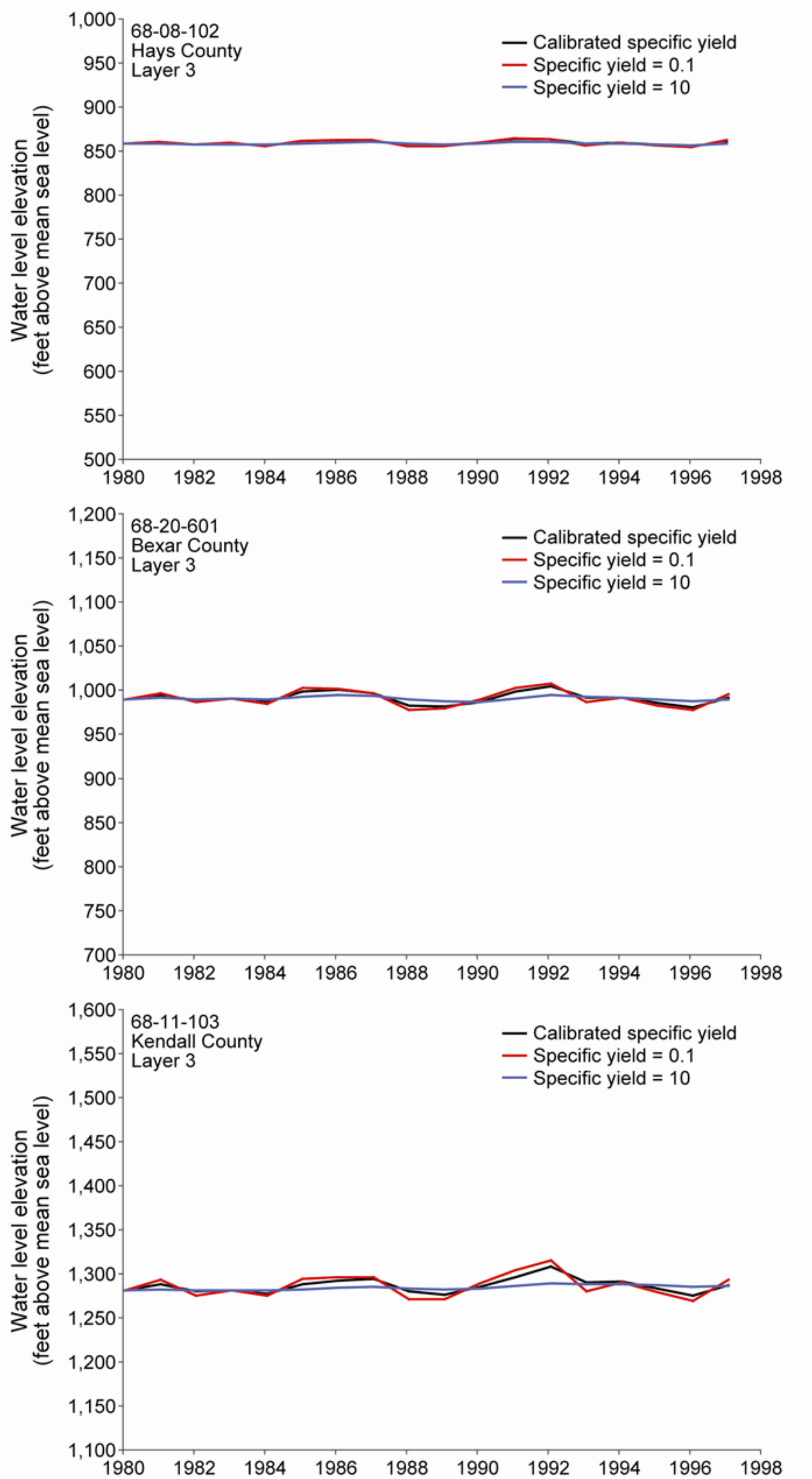


Figure 10-7. (continued).

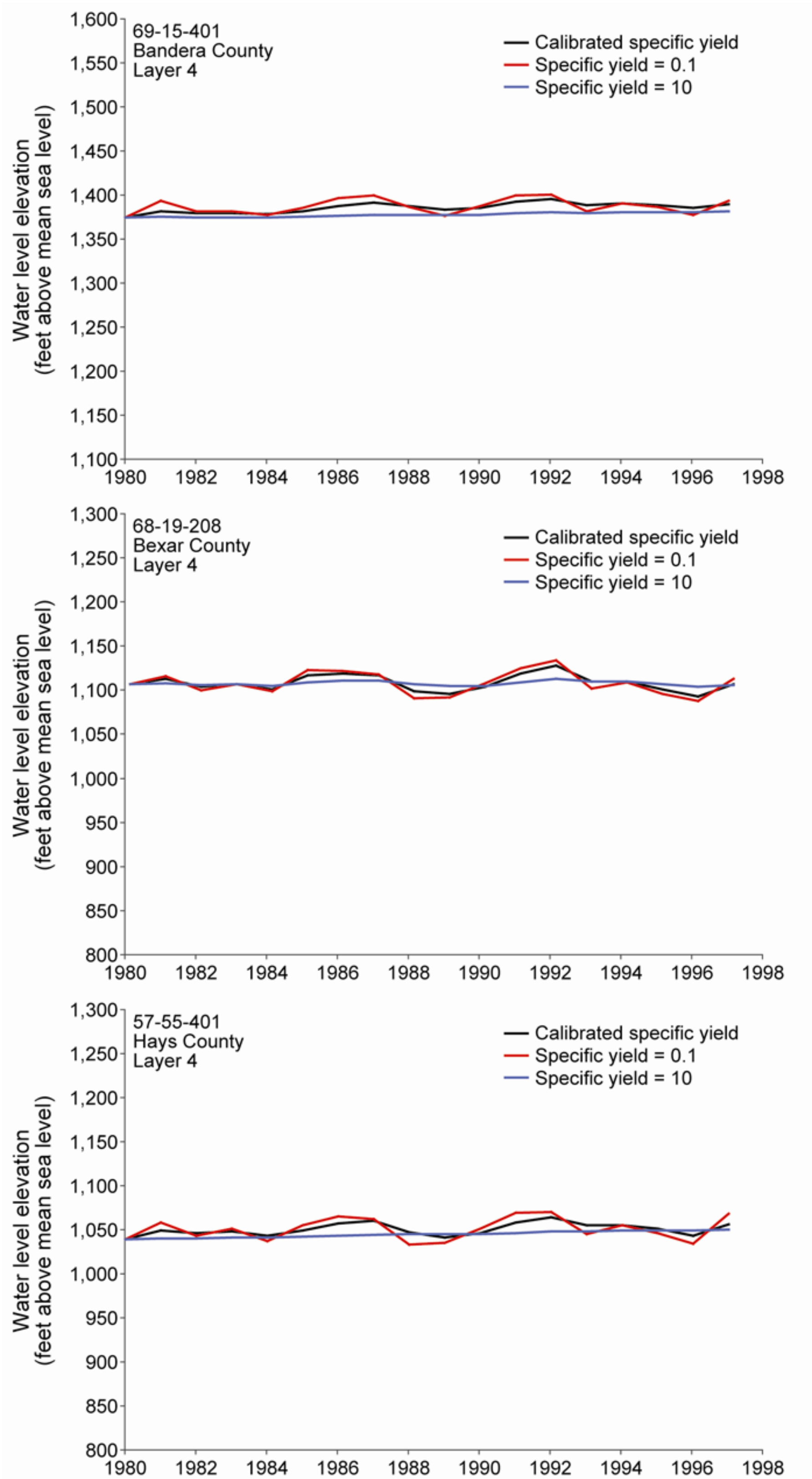


Figure 10-7. (continued).

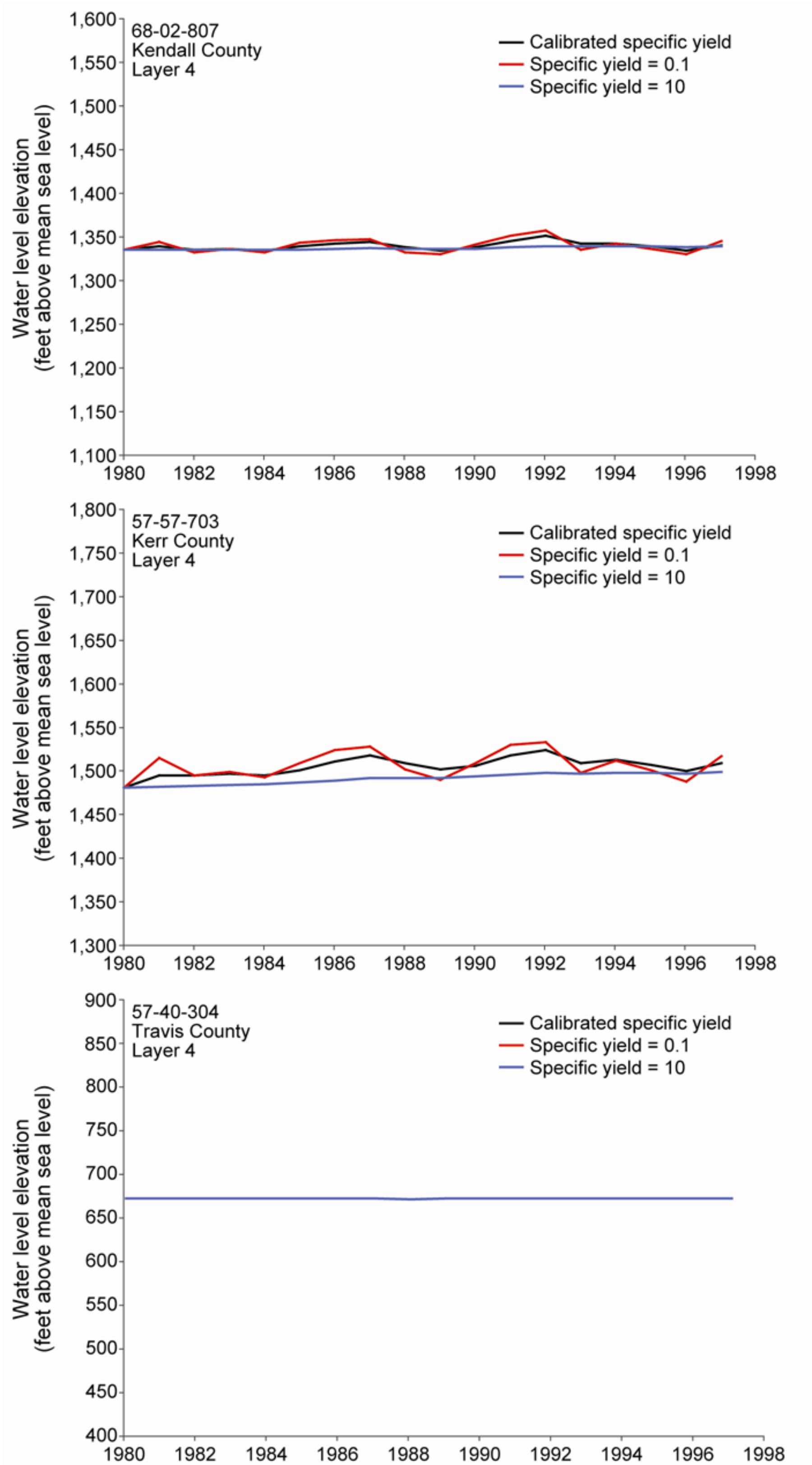


Figure 10-7. (continued).

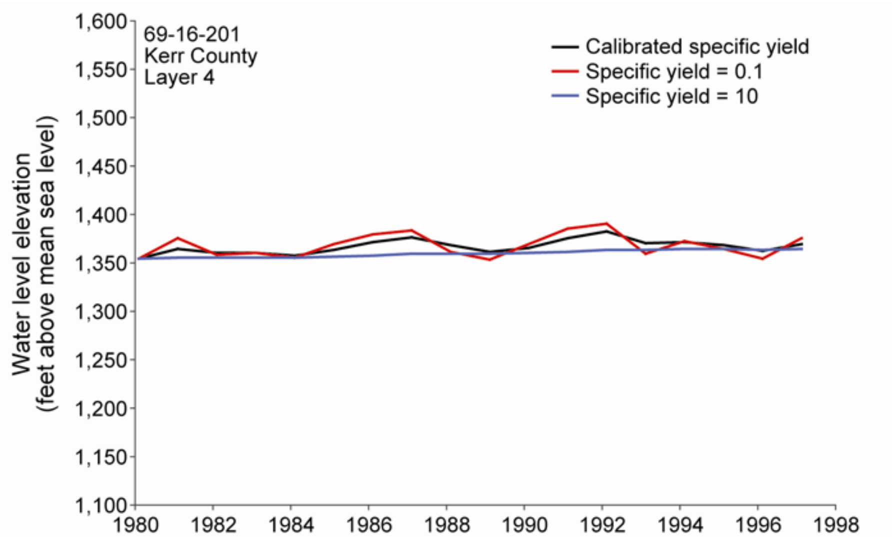


Figure 10-7. (continued).

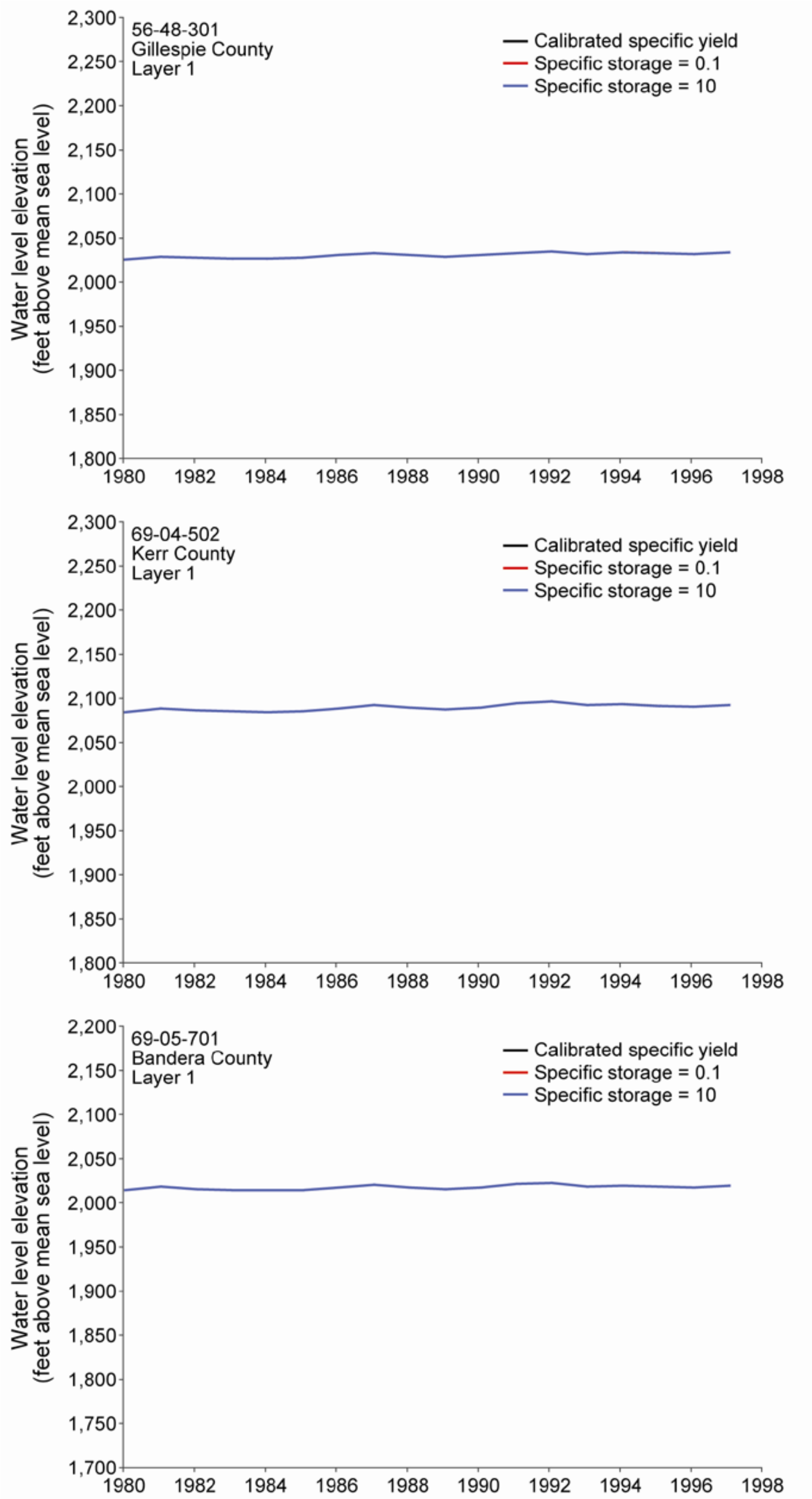


Figure 10-8. Sensitivity of the transient calibration to specific storage. The red and blue lines represent one order of magnitude lower and higher than the calibrated values, respectively, relative to calibrated specific-storage values (black line).

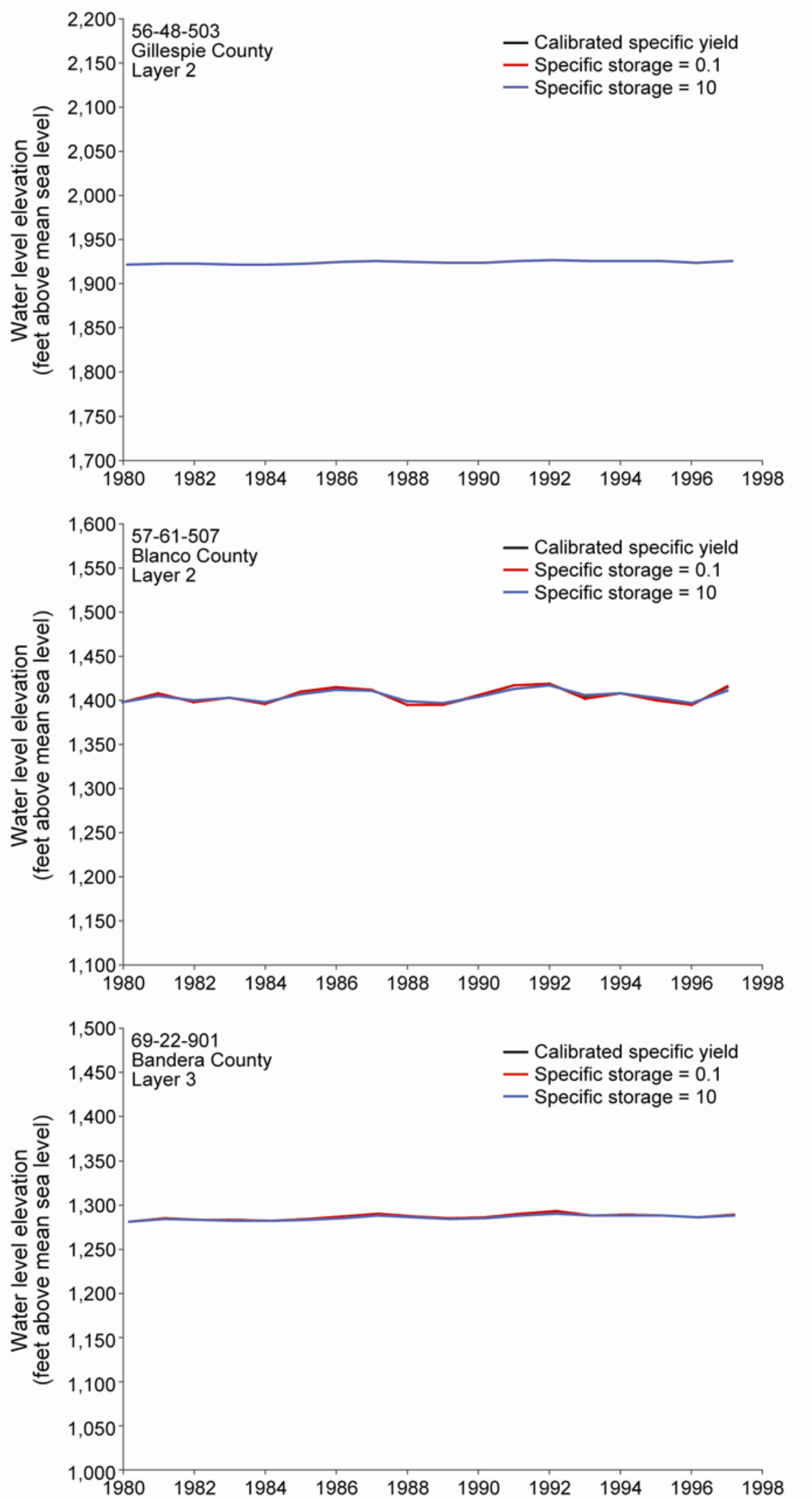


Figure 10-8. (continued).

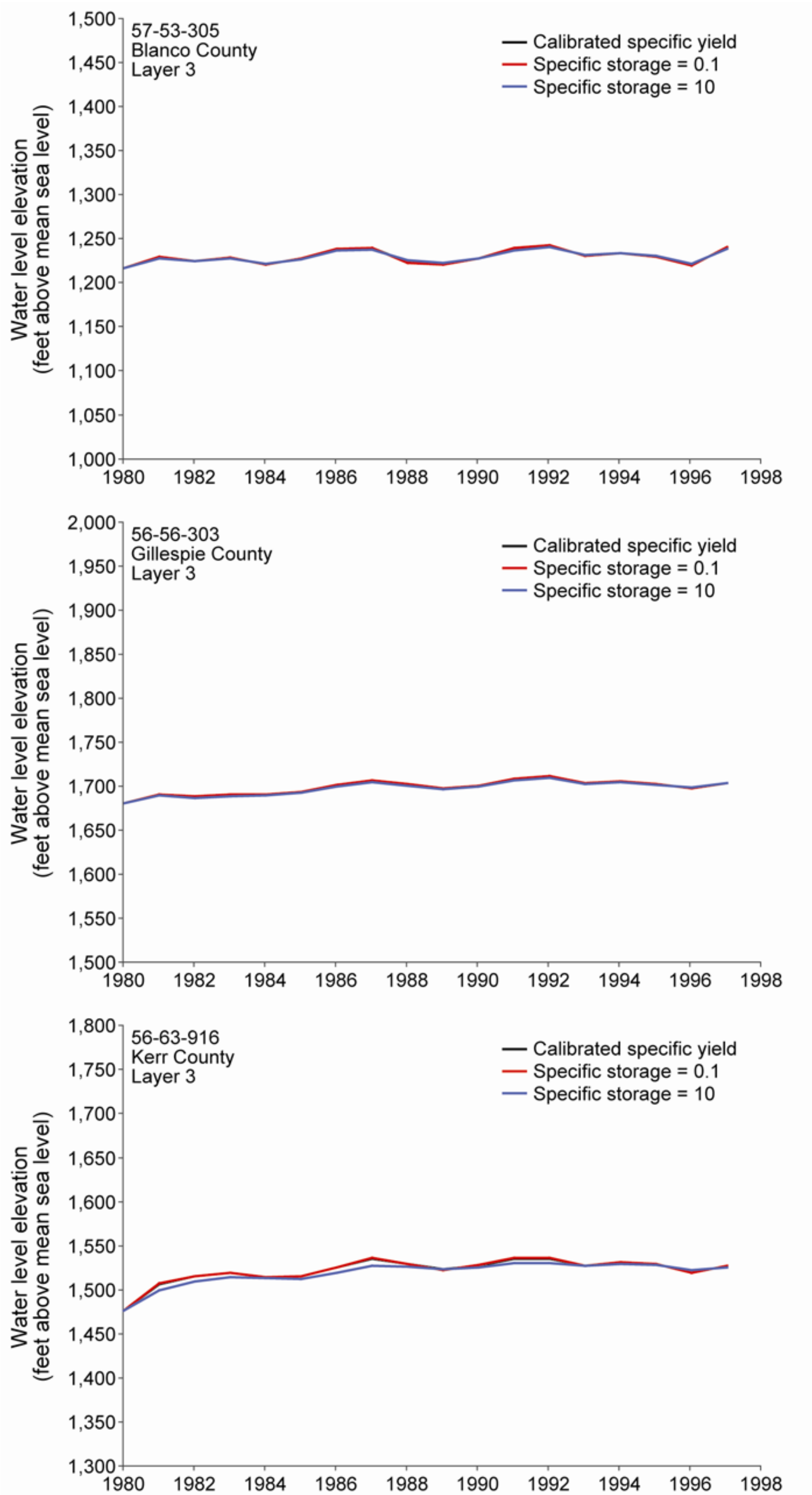


Figure 10-8. (continued).

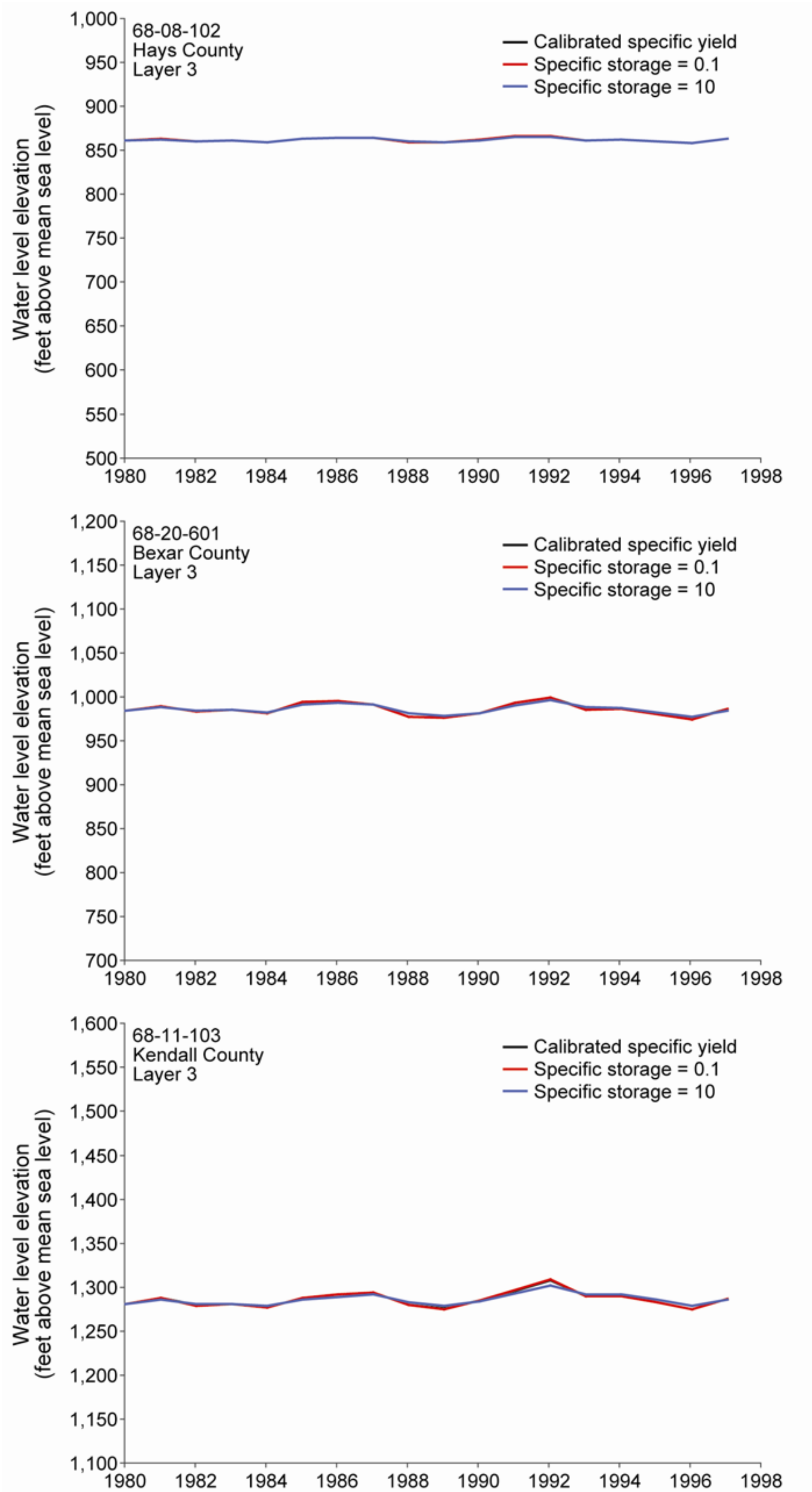


Figure 10-8. (continued).

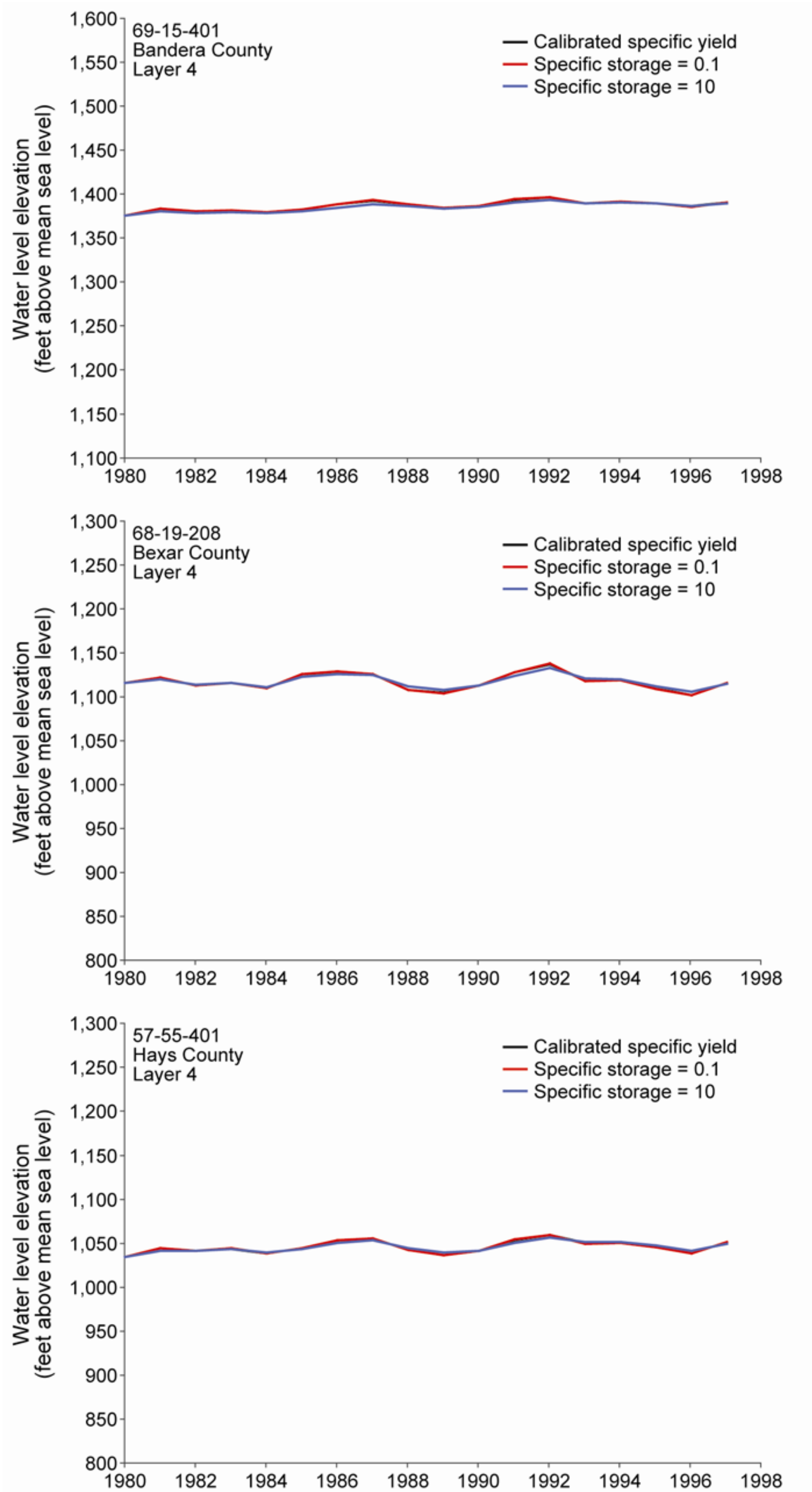


Figure 10-8. (continued).

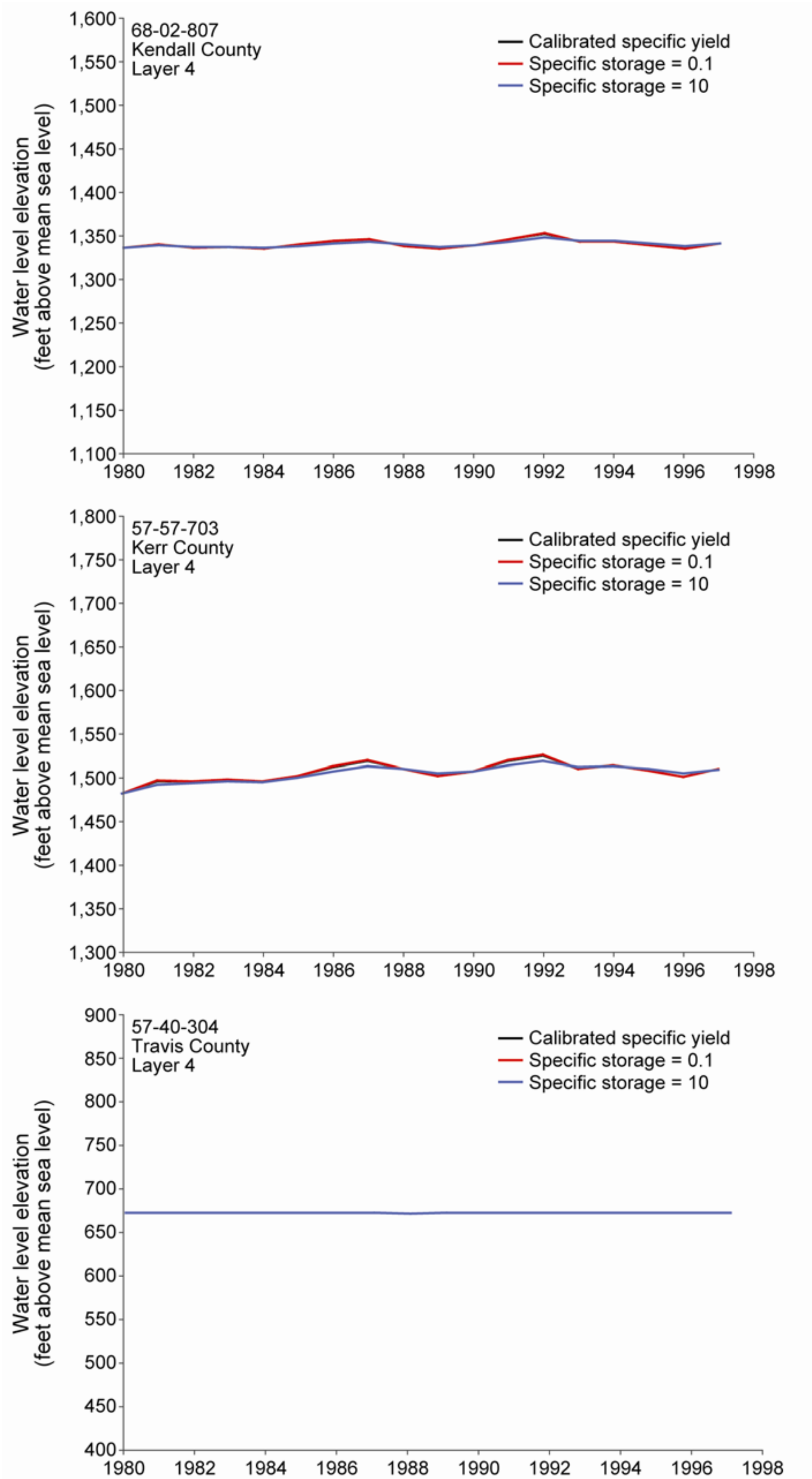


Figure 10-8. (continued).

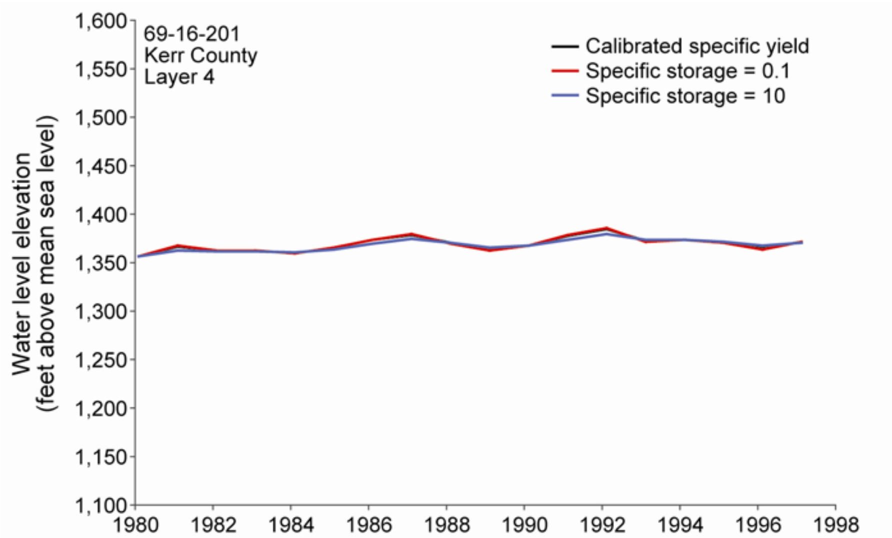


Figure 10-8. (continued).

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) the availability and accuracy of input data, (3) the 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 data sets 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 properties 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 partly overcome by calibrating the model on the basis of observed water level responses in the wells in the model area having 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 to represent the regional structural controls and regional groundwater flow but limits the ability to simulate 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 in 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 having multiple water level 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 level 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), which 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 occurs 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 not to 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 (for example, 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 affect 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 decrease 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 TWDB 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 approach 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 on the basis of 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 another 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 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 rest 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 more than 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.

14.0 Acknowledgments

Many people helped in this modeling effort. We would like to thank the Bandera County River Authority and Groundwater 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, and Trinity Glen Rose Groundwater Conservation District for their support and interest during the model development. A number of current and previous TWDB staff members have also been helpful in providing assistance and advice, including Ali Chowdhury, Scott Hamlin, Cindy Ridgeway, Eric Aschenbach, Marius Jigmond, Sarah Davidson, and Patricia Blanton. We would also like to thank Susann Doenges for serving as the editor. The support of TWDB management, including Robert Mace and Bill Hutchison, has been helpful in ensuring the successful completion of this project.

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