Groundwater Availability Model for the Edwards-Trinity (Plateau) and Pecos Valley Aquifers of Texas

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Report 373
April 2009

Texas Water Development Board
www.twdb.state.tx.us

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Geoscientist Seal

The contents of this report (including figures and tables) document the work of the following Licensed Texas Geoscientists:

Roberto Anaya, P.G. No. 480

> Mr. Anaya was the project manager for this work and was responsible for oversight of the project and also for the organization of the hydrogeologic setting and the development of the conceptual model and model design.

The seal appearing on this document was authorized on April 28, 2009 by

Roberto Anaya

Ian Jones, Ph.D., P.G. No. 477

> Dr. Jones was responsible for the modeling approach and the steady-state and transient model calibrations.

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Ian C. Jones

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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

April 2009
(Printed on recycled paper)

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1 *Executive summary*

The Edwards-Trinity (Plateau) and the Pecos Valley aquifers occupy an area of about 44,000 square miles of west central Texas. The aquifers provide the primary source of water for the Edwards Plateau and the Pecos River Valley and also sustain numerous springs and streams in the region. The sensitivity of the aquifers to drought and well discharge has elicited concerns over the availability of water from these aquifers. To help determine the amount of available groundwater, the Texas Water Development Board (TWDB) developed a numerical groundwater flow model. With some limitations, the model may be used to assist in evaluating groundwater management strategies and planning efforts and also to help in examining and assessing current and future trends in managed available groundwater based on desired future conditions for the aquifers. In addition, the public, groundwater conservation districts, and regional water planning groups now have access to a wealth of comprehensive groundwater information from the model.

The model was calibrated to steady-state conditions for 1980 and to historical transient conditions for the period 1980 through 2000. The model suggests that (1) 60 percent of the total discharge is to streams, springs, and reservoirs; (2) pumpage from wells is approximately 25 percent of the total discharge; (3) cross-formational flow across the Balcones Fault Zone boundary and into the Edwards (Balcones Fault Zone) Aquifer is about 15 percent of the total discharge; and (4) the model is generally more sensitive to variations in recharge (and, consequently, drought events) than variations in pumpage discharge, although exceptions do occur for the northwestern and southeastern parts of the aquifer. The exceptions include an area of low saturated aquifer thickness in the northwestern part of the Edwards Plateau and a region of high population density in the southeastern part of the Hill Country where the model is sensitive to both recharge and pumpage discharge. Because of its size and complexity, this model was a challenge to calibrate. The modeling root mean square error was 134 feet for the steady-state calibration and 143 feet for the transient calibration.

2 *Introduction*

The Edwards-Trinity (Plateau) and the Pecos Valley aquifers are designated as major aquifers of Texas. Located in west central Texas, the two aquifers provide the primary source of water for the Edwards Plateau and the Pecos River Valley. The aquifers also supply springflow and base flow to numerous intermittent and perennial streams in the region. The extensive variability of precipitation in this semiarid to arid region and the expected increase in pumpage from wells has raised concerns over the potential effects of drought on groundwater levels, springs, and streams.

To better understand groundwater flow in the Edwards Trinity (Plateau) and Pecos Valley aquifers, the Texas Water Development Board (TWDB) developed and calibrated a groundwater availability model for these aquifers. A groundwater availability model is a three-dimensional, numerical groundwater flow model capable of simulating regional scale groundwater flow systems. The Texas state legislature mandated the development of these state-of-the-art, computer-based models for all of the major and minor aquifers in Texas. In 2005, House Bill 1763 mandated that groundwater conservation districts evaluate and develop the desired future conditions for aquifers within their groundwater management areas, from which managed available groundwater is to be estimated. Key tools for determining managed available groundwater, the groundwater availability models help examine and assess current and future trends, evaluate groundwater management strategies, and assist with water supply planning efforts. Additionally, the groundwater availability models provide a comprehensive, single-source site of aquifer information for easy access by the public, groundwater conservation districts, and regional water planning groups.

The approach used in developing this groundwater availability model involved (1) developing a conceptual model, (2) organizing and evaluating aquifer information for input into the computer model, (3) calibrating a steady-state model to match conditions for 1980, and (4) calibrating historical transient conditions of the aquifers for the period 1980 through 2000. This report describes (1) the study area, previous aquifer investigations, and hydrogeologic setting used to develop the conceptual model; (2) the code, grid, layers, and model input data assigned during model construction; (3) the calibration and sensitivity analysis of the model during steady-state and transient conditions; (4) limitations of the model; and (5) suggestions for future model improvements.

3 *Study area*

The study area covers about 44,000 square miles of west central Texas between 97° and 105° west longitude and between 29° and 33° north latitude (Figure 3-1). It is mostly rural, with populations typically concentrated in the county seats (Figure 3-2). The largest population growth rates occur along the area's southeastern margins. Within the study area, the Edwards-Trinity (Plateau) Aquifer extends over an area of about 35,000 square miles beneath all or parts of 39 counties (Ashworth and Hopkins, 1995), and the Pecos Valley Aquifer extends over an area of about 7,000 square miles beneath all or parts of 11 counties (Figure 3-3). In preparing the 2007 State Water Plan, the Cenozoic Pecos Alluvium Aquifer was renamed as the Pecos Valley Aquifer and its boundary revised to reflect updated knowledge of the aquifer, in part, as a result of the modeling efforts of this study (TWDB, 2007).

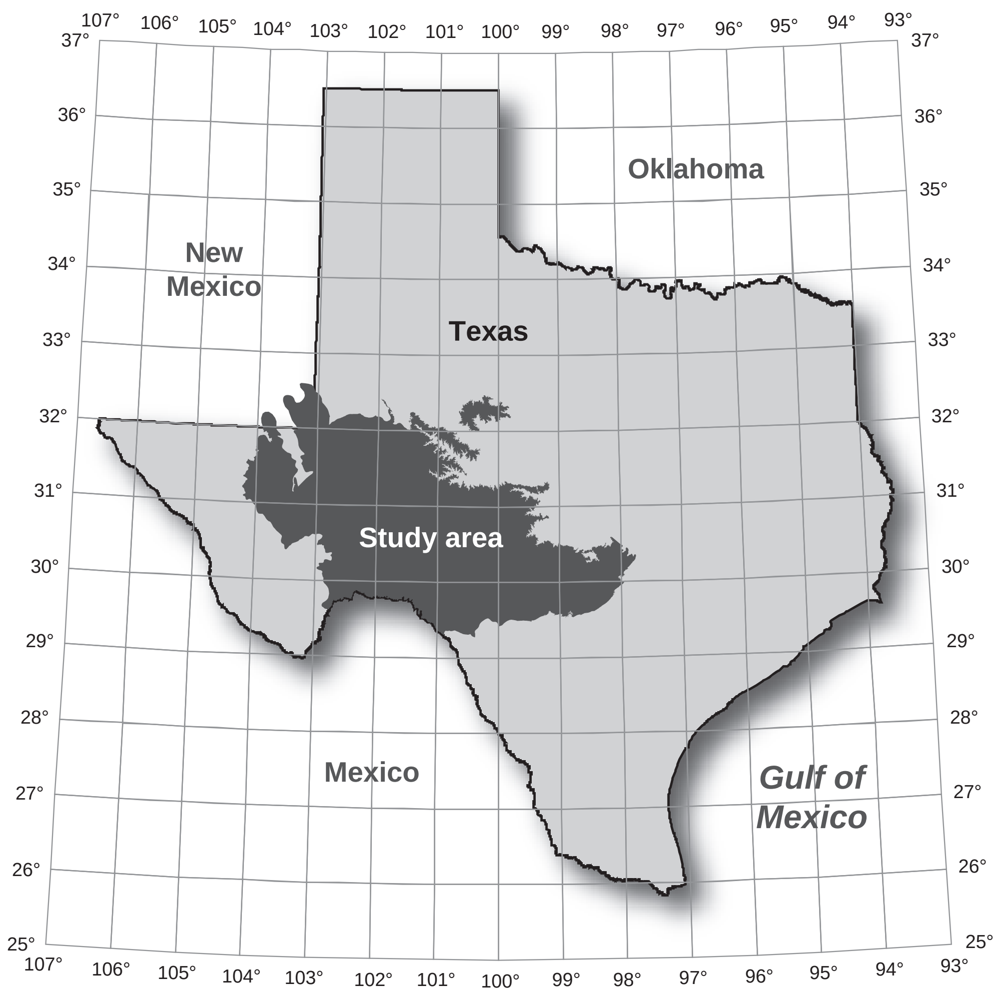

Figure 3-1. Location of the study area.

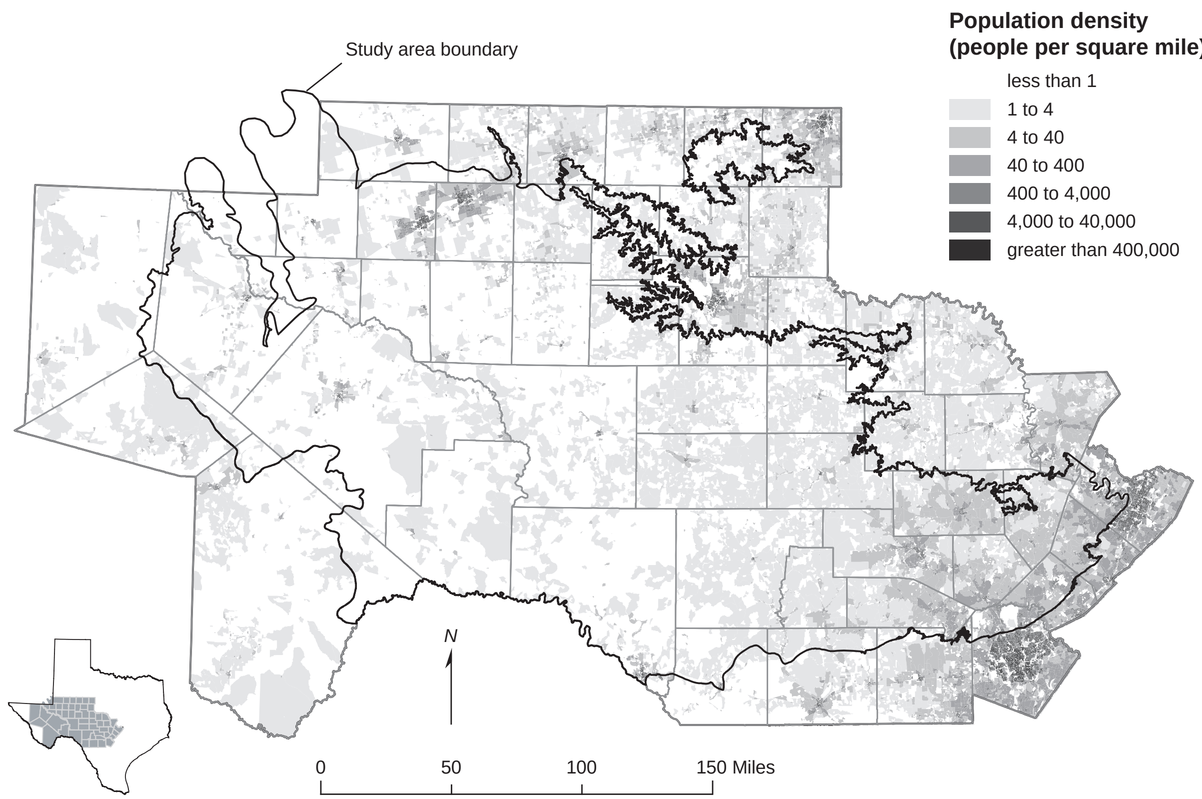

Figure 3-2. Population density from 2000 census.

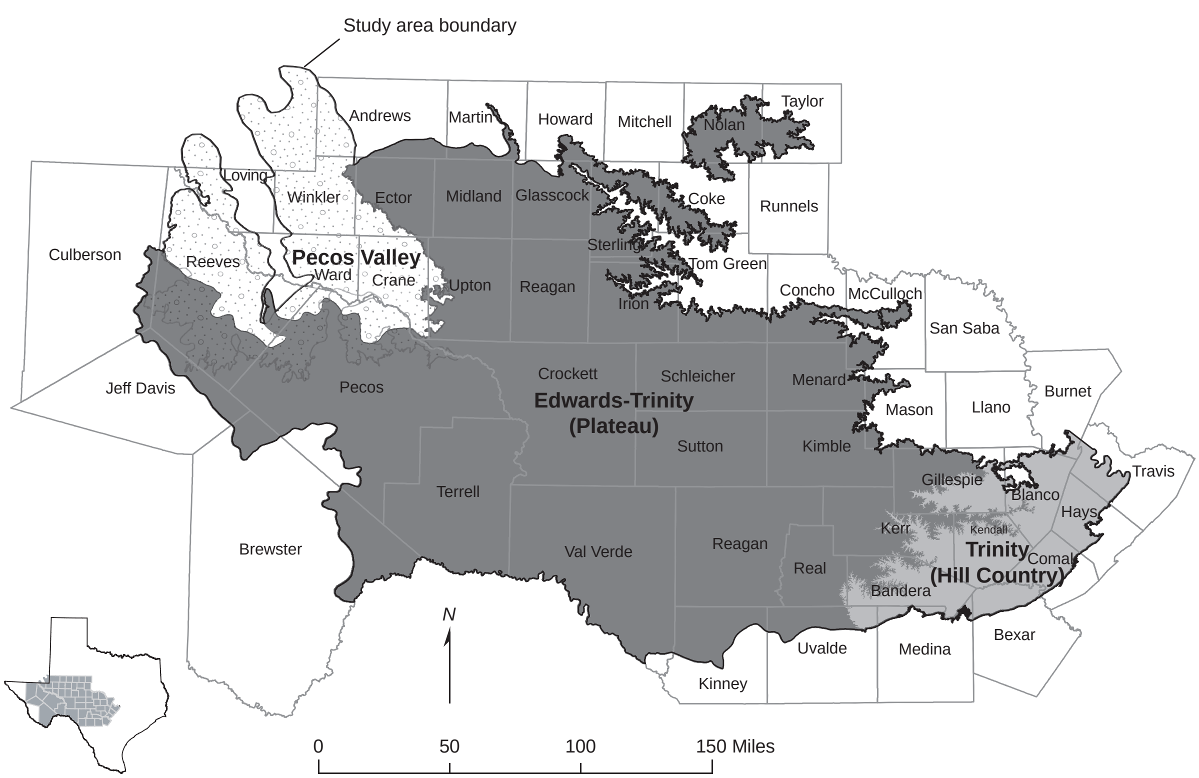

Figure 3-3. Spatial extents of the Edwards-Trinity (Plateau) and Pecos Valley aquifers and Hill Country part of the Trinity Aquifer.

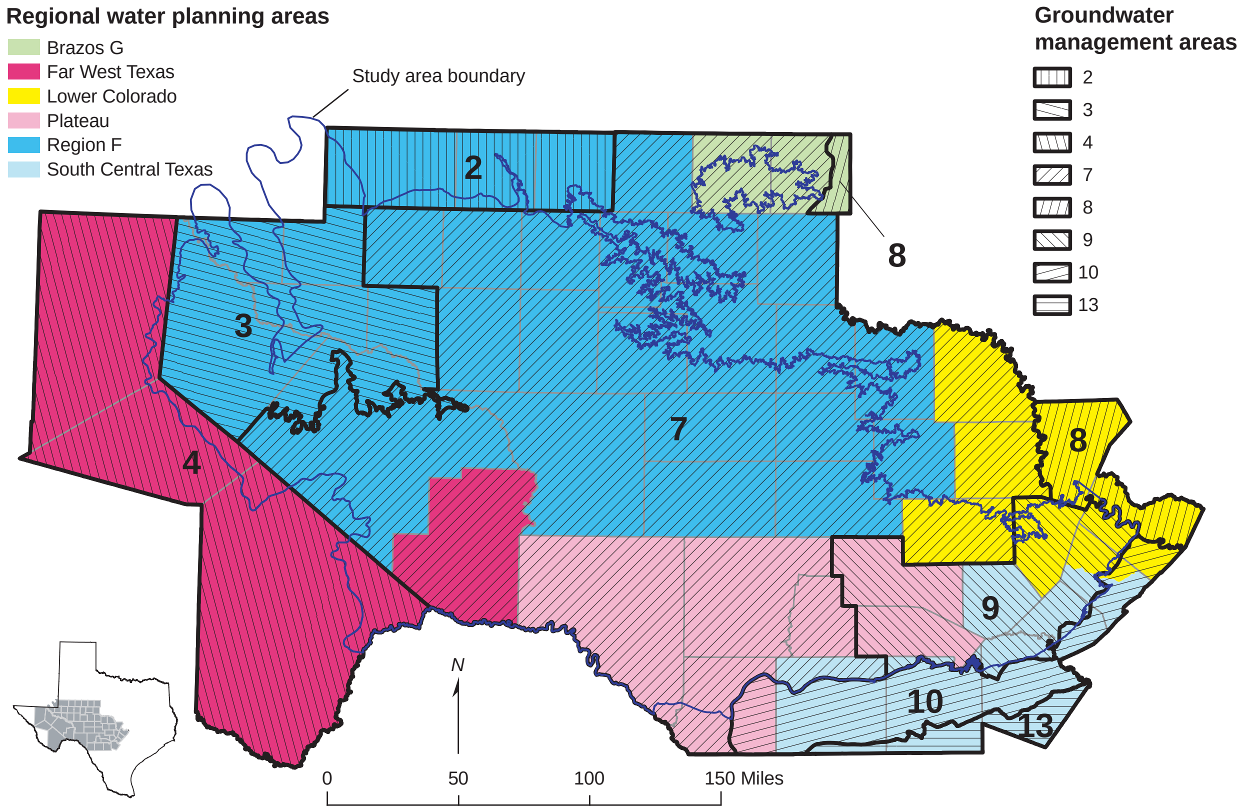

Figure 3-4. Boundaries of regional water planning areas and groundwater management areas.

The Pecos Valley Aquifer hereafter refers to an updated boundary of the formerly designated Cenozoic Pecos Alluvium Aquifer. For our modeling study, the boundary between the Pecos Valley Aquifer and the Ogallala Aquifer in Andrews and northwestern Ector counties was adjusted to coincide with the surface water divide between the Rio Grande and the Colorado River basins, which also coincides with the underlying Permian structural high known as the Central Basin Platform (TWDB, 2007). However, our modeling study does not include the recent update to the Pecos Valley Aquifer as described in the 2007 State Water Plan (TWDB, 2007), which expanded the aquifer area within parts of Loving, Winkler, Ward, Reeves, and Pecos counties. The aquifer sediments within these areas are thin and would likely not have a significant impact on the water budget of the model.

The study area also incorporates the Hill Country part of the Trinity Aquifer in the southeast, with an area of about 4,500 square miles beneath all or parts of 12 counties, because of its hydraulic connection to the Edwards-Trinity (Plateau) Aquifer (Figure 3-3). Hereafter, all discussion regarding the Edwards-Trinity (Plateau) Aquifer will include the Hill Country part of the Trinity Aquifer. The Edwards-Trinity (Plateau) and Pecos Valley aquifers are also hydraulically connected to several other major and minor aquifers of the state and are discussed in more detail in Chapter 5, Hydrogeologic Setting.

The study area falls within six regional water planning areas (Far West Texas, Lower Colorado, Plateau, Region F, South Central Texas, and Brazos G), although the aquifers are located mostly within the Region F and Plateau planning areas (Figure 3-4). The study area extends over five groundwater management areas (2, 3, 4, 7, and 9), very nearly covering the entire regional groundwater management areas of 3, 7, and 9. In addition to

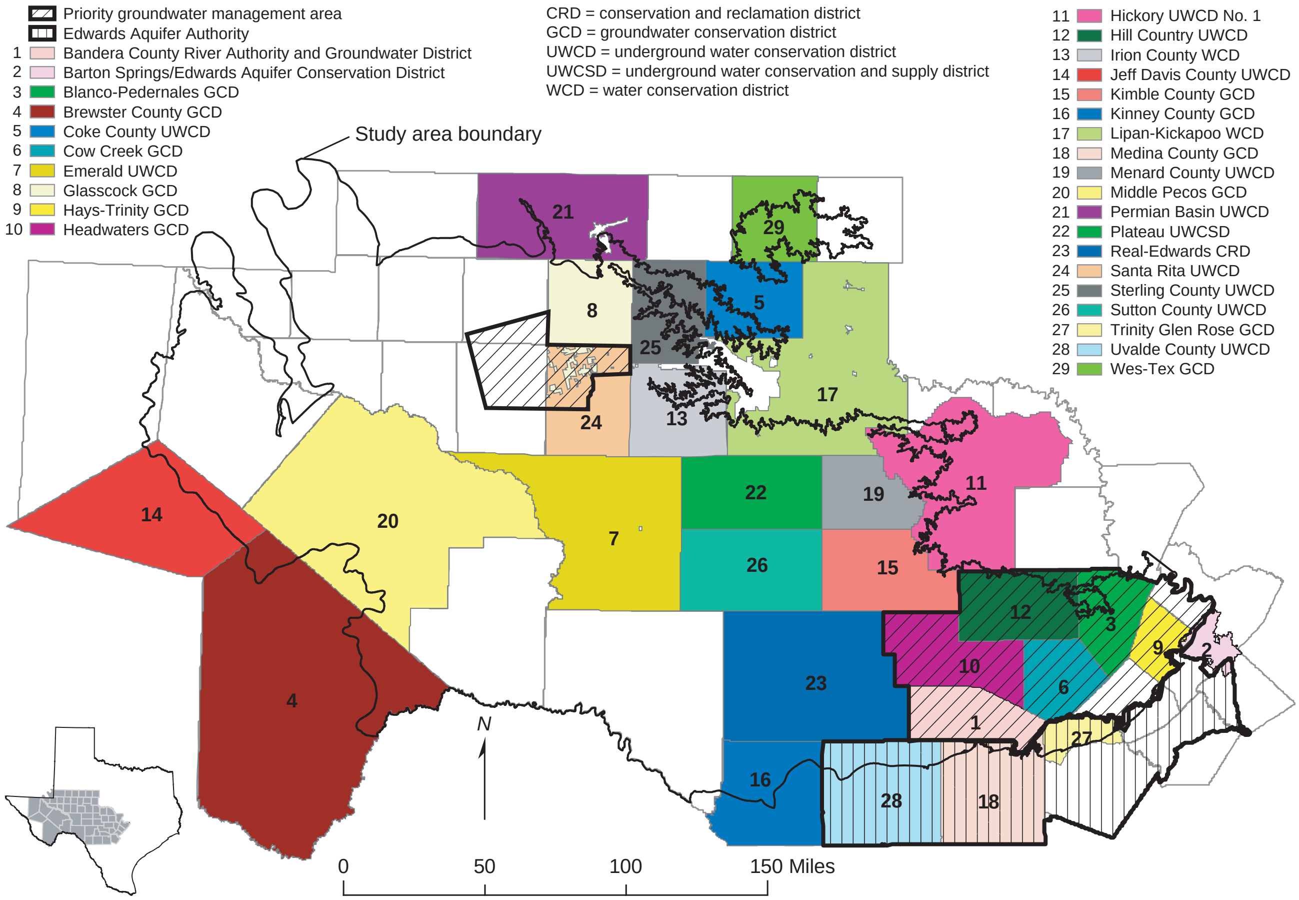

Figure 3-5. Boundaries of priority groundwater management areas, the Edwards Aquifer Authority, and groundwater conservation districts.

two priority groundwater management areas, there are now about 30 groundwater conservation districts within the study area (Figure 3-5).

3.1 PHYSIOGRAPHY

Physiography describes natural features of the landscape in the context of (1) topography and landforms, (2) surface drainage, (3) soil development, and (4) vegetation and land use—all of which reflect upon the geologic and climatic setting of the region. Numerous natural features have been designated and physiographic regions delineated for the Edwards Plateau region by Fenneman (1931), Raisz (1957), Thornberry (1965), Kier and others (1977), LBJ School of Public Affairs (1978), and Wermund (1996). Traditional physiographic regions within the study area include the Edwards Plateau, High Plains, Pecos Valley, and Central Texas sections of the Great Plains province and the Mexican Highland and Sacramento sections of the Basin and Range province (Fenneman and Johnson, 1946). A more contemporary assessment of physiographic regions within the study area consists of the Edwards Plateau (Principal), Pecos Canyons, and Stockton Plateau subprovinces of the Edwards Plateau province, the Southern High Plains subprovince of the High Plains province, the North-Central Plains province, and the Basin and Range province (Wermund, 1996). For our study, the physiography is characterized from the perspective of the lateral extents of the Edwards-Trinity (Plateau) and Pecos Valley aquifers.

3.1.1
Topography and landform

Topography refers to the surface expression of the terrain with respect to elevation. Topographic relief (the difference between the highest and lowest elevations) for the entire study area is about 4,000 feet, and elevations range from over 4,500 feet above sea level in the mountainous west to about 500 feet above sea level along the southeastern margin. Landforms refer to unique physical features of the terrain's surface with respect to recognizable shape and characteristic location. The study area consists of numerous landforms that provide insight into the geologic and climatic processes responsible for the physiographic evolution of the landscape we see today (Figure 3-6).

The landform of the Edwards Plateau is commonly described as a tableland gently sloping from about 3,000 feet elevation above sea level in the northwest to about 2,000 feet elevation above sea level in the southeast (Figure 3-7). The plateau is capped with a thick layer of Cretaceous limestone, forming one of the largest contiguous karst regions in the United States (Kastning, 1984). Although the Edwards Plateau has been in a prevailing state of erosion since ancient Cretaceous seas retreated toward the present-day Gulf of Mexico, the Balcones Fault Zone and the incidental development of the Balcones Escarpment landform helped accelerate the erosion, which became essential to the evolution of the plateau. The Balcones Escarpment is a feature so prominent that it affects regional weather (Caran and Baker, 1986) and stream drainage patterns along the southern and eastern margins of the study area. The protective Edwards limestone cap has been breached along these plateau margins by headward stream erosion over the steep escarpment, which has carved deep canyons into the softer underlying sediments to form the Balcones Canyonlands, more traditionally known as the Texas Hill Country.

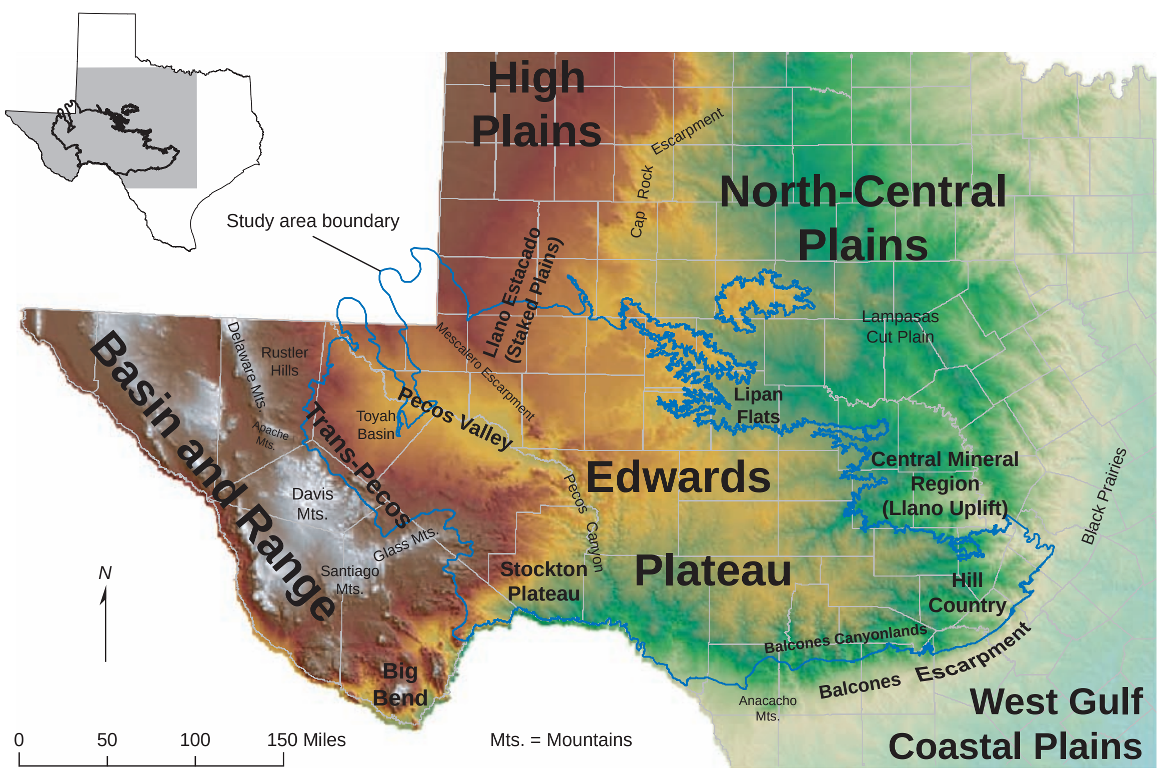

Figure 3-6. Natural landforms and physiographic regions of the Edwards Plateau and adjacent landscape.

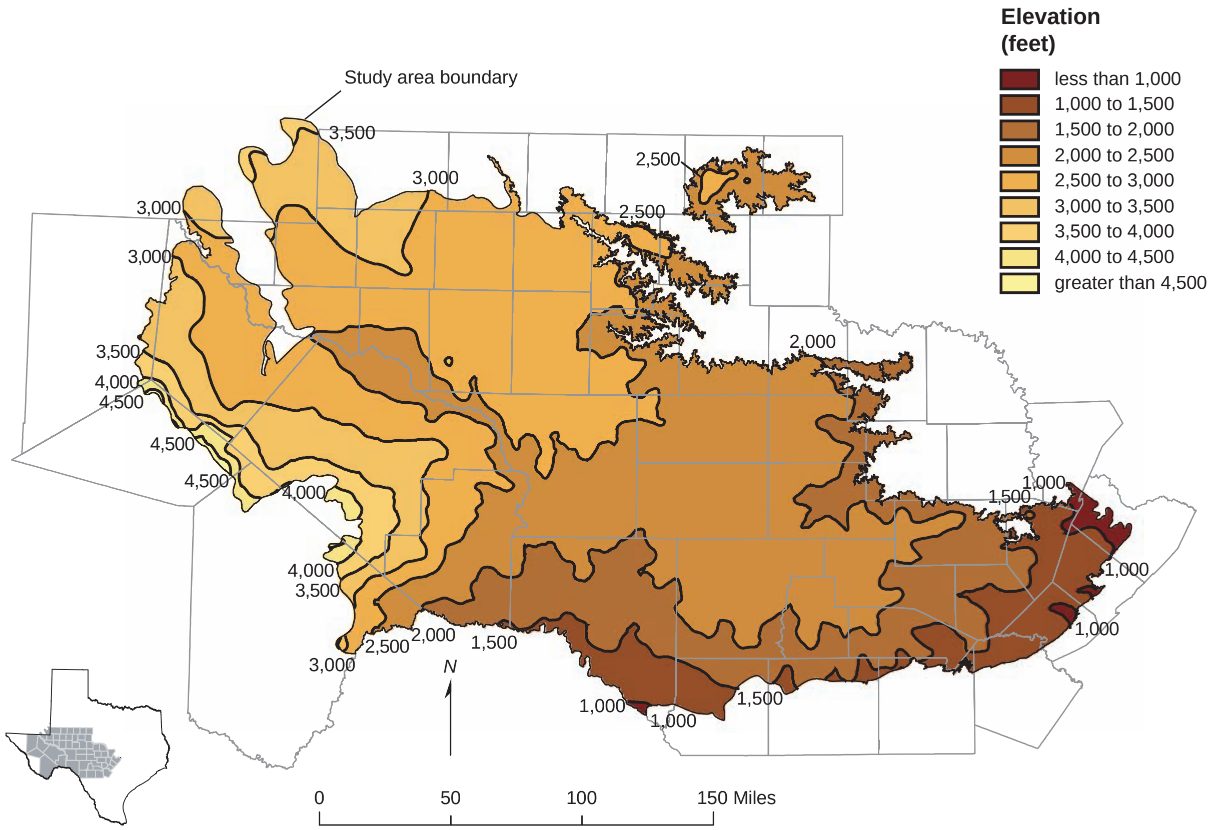

Figure 3-7. Land surface elevations of the study area.

Alluvial stream deposits form the Lipan Flats where the Concho River has cut and filled its way onto the northern plateau. Older Precambrian and Paleozoic rocks to the northeast are exposed in the Central Mineral Region, often referred to as the Llano Uplift. A thin layer of remnant Quaternary sand sediments, with playa lakes characteristic of the Llano Estacado (Staked Plains) region of the High Plains, extends down into the study area to cover a small area of the northeastern Edwards Plateau. These remnant sand sediments and the underlying Edwards-Trinity (Plateau) Aquifer sediments terminate to the southwest along the southeast trend of the Mescalero Escarpment. The eastern flanks of the Rustler Hills (east of the Delaware Mountains), and the Apache, Davis, Glass, and Santiago mountains of the Basin and Range form the far western boundary of the Edwards Plateau within the area traditionally known as the Trans-Pecos. The Edwards-Trinity (Plateau) Aquifer sediments extend beneath the Stockton Plateau, located east of the Glass and Santiago mountains and just west of the Pecos River Canyon, and continue south into the Big Bend region and across the Rio Grande into the northern region of the Mexican Chihuahua Desert.

The Pecos Valley Aquifer consists of a thick accumulation of alluvial and eolian (windblown) sediments between the westernmost plateau margin and the Mescalero Escarpment. The Pecos River flows from northwest to southeast along a broad valley, with gentle slopes rising in the northeast toward the Mescalero Escarpment and steeper slopes rising in the southwest into the mountains of the Trans-Pecos region. Bands of migrating sand dunes approximately 5 miles wide and rising as much as 50 feet above the surrounding land surface (Ashworth, 1990) occur with a northwest-to-southeast trending pattern

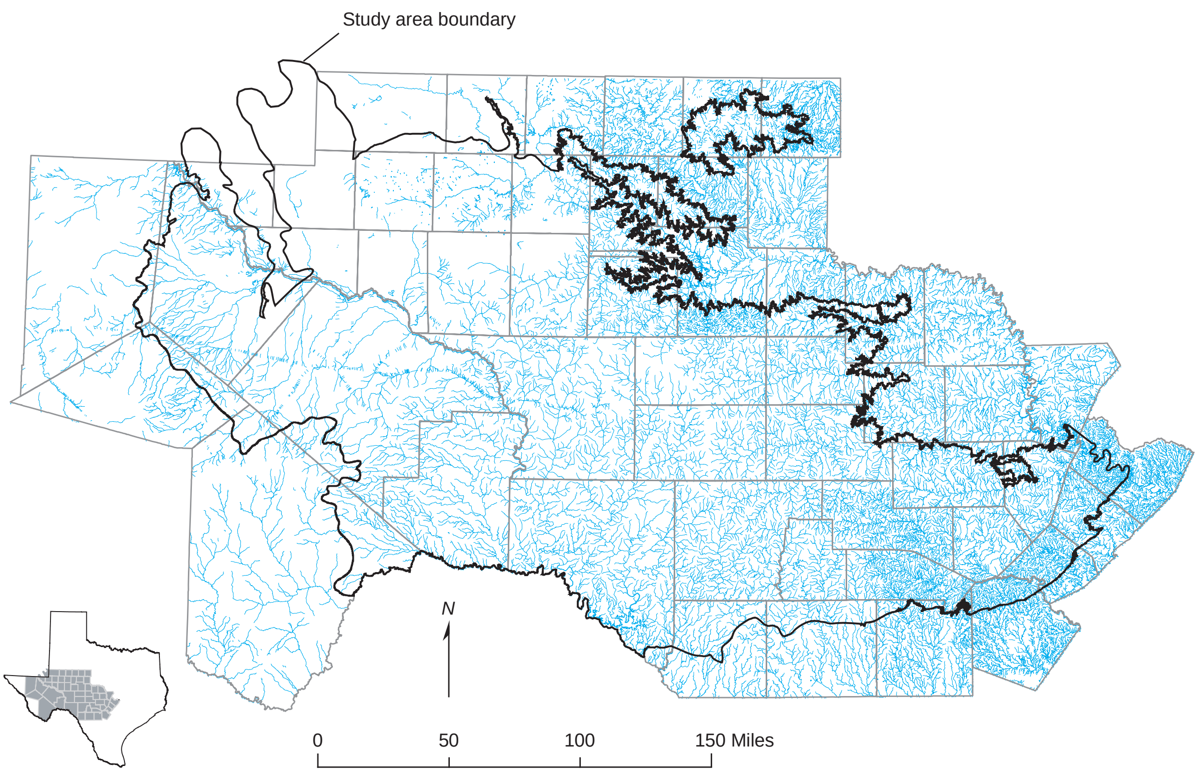

Figure 3-8. Drainage density and dendritic pattern of surface water drainage in the study area.

between the Pecos River and the Mescalero Escarpment. Alluvial fans emerge from the Trans-Pecos uplands and spread out northeastward onto the Pecos River Valley, capping the underlying Edwards-Trinity sediments, as well as Paleozoic sediments. A shallow drainage area between the Davis Mountains and the Pecos River is commonly referred to as the Toyah Basin. The Pecos River drops about 500 feet in elevation along a reach from the Texas-New Mexico border to the entrance of the Pecos Canyon in northwestern Crockett County. The river then drops another 1,100 feet as it cuts through the Pecos Canyon (with some walls reaching over 300 feet above the riverbed) to its confluence with the Rio Grande.

3.1.2
Surface drainage

Surface drainage is closely tied to geologic and climatic characteristics as well as to groundwater recharge and discharge of the aquifer. Perennial surface water is sparse to nonexistent on the Edwards Plateau but occurs along the spring-fed headwater tributaries that dissect the northern, eastern, and southern plateau margins. Streams draining the Edwards Plateau have a very dendritic (branch-like) pattern characteristic of drainage patterns for flat-lying rock strata (Figure 3-8). Stream density (stream channel length per unit area) on the Edwards Plateau is mostly influenced by local and regional surface water gradients. Stream density generally increases with increasing surface water gradients and approaches zero as the topography becomes flat where playa lakes may be the more dominant surface drainage features. However, there is also a distinct increase in stream density toward the east, which may be attributed to both the eastward-increasing average annual precipitation (Walker, 1979) and

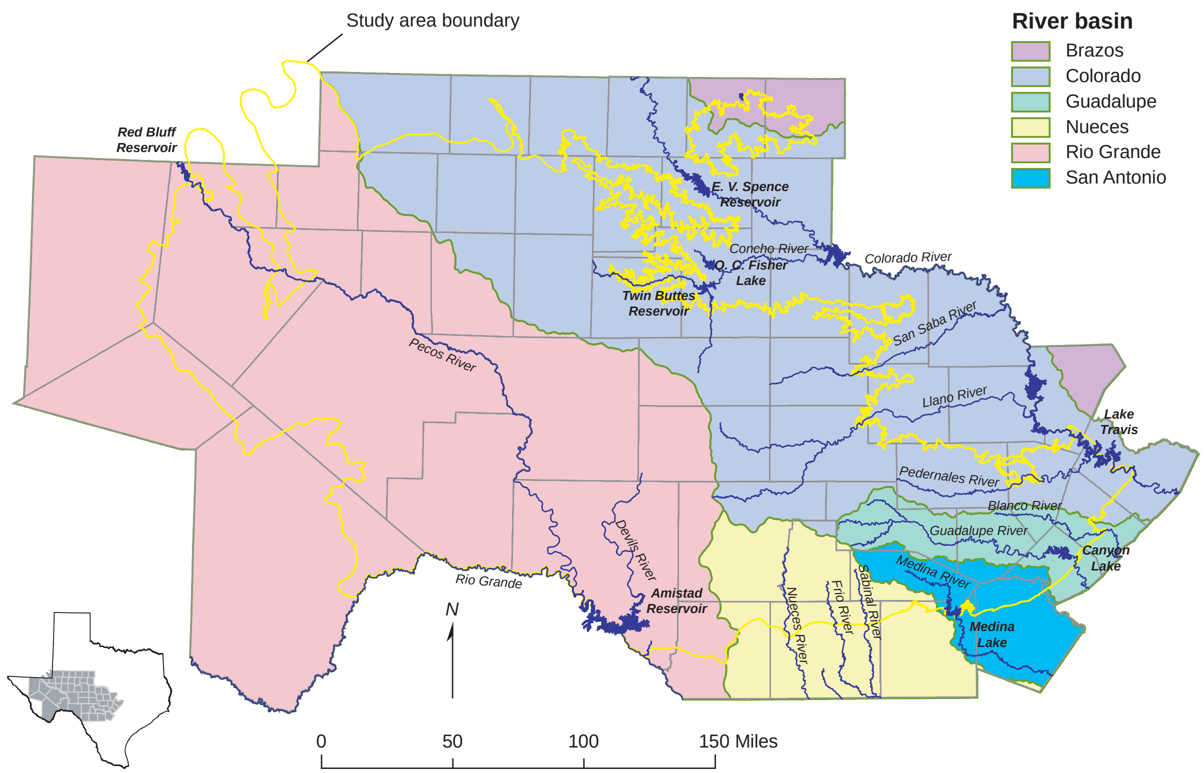

Figure 3-9. Major streams and drainage basins of the study area.

the southeastward regional outflow of groundwater to springs of the Edwards-Trinity (Plateau) Aquifer.

Tributary streams of the Colorado River, such as the Concho, San Saba, Llano, and Pedernales rivers, drain the northeastern portion of the Edwards Plateau into the Lipan Flats and the Llano Uplift. The Blanco, Guadalupe, Medina, Sabinal, Frio, and Nueces rivers drain the southeastern and southern portion of the plateau through the Texas Hill Country and across the Balcones Escarpment (Figure 3-9). The Pecos River and Devils River, both major tributaries to the Rio Grande, drain the entire southwestern half of the study area. Except for short and steep arroyos along the Mescalero Escarpment and Landreth Draw in eastern Crane County, drainage features between the Pecos River and the Mescalero Escarpment consist mainly of desert flats, evaporation pans, and small playas. Although surface water flows rarely contribute to the Pecos River flow (Ashworth, 1990), the southwestern half of the Pecos Valley is drained by numerous draws dissecting the alluvial fans off of the Trans-Pecos uplands, with Toyah Creek as the primary tributary to the Pecos River.

Although there are some small surface water bodies (less than 1 square mile) in the central region of the Edwards Plateau, the only noteworthy water bodies on the plateau include Big Lake (more recently a dry lakebed) in Reagan County, Orient Reservoir in Pecos County, and Balmorhea Lake in Reeves County. Other much larger water bodies along the edge of the Edwards Plateau include International Amistad Reservoir in Val Verde County, Twin Buttes and San Angelo reservoirs in Tom Green County, and E.V. Spence Reservoir in Coke County. Red Bluff Lake in Loving County is located along the northwestern margin of the Pecos Valley Aquifer, and Medina Lake, Canyon Lake, Lake Travis, and Lake Austin are situated in the Texas Hill Country.

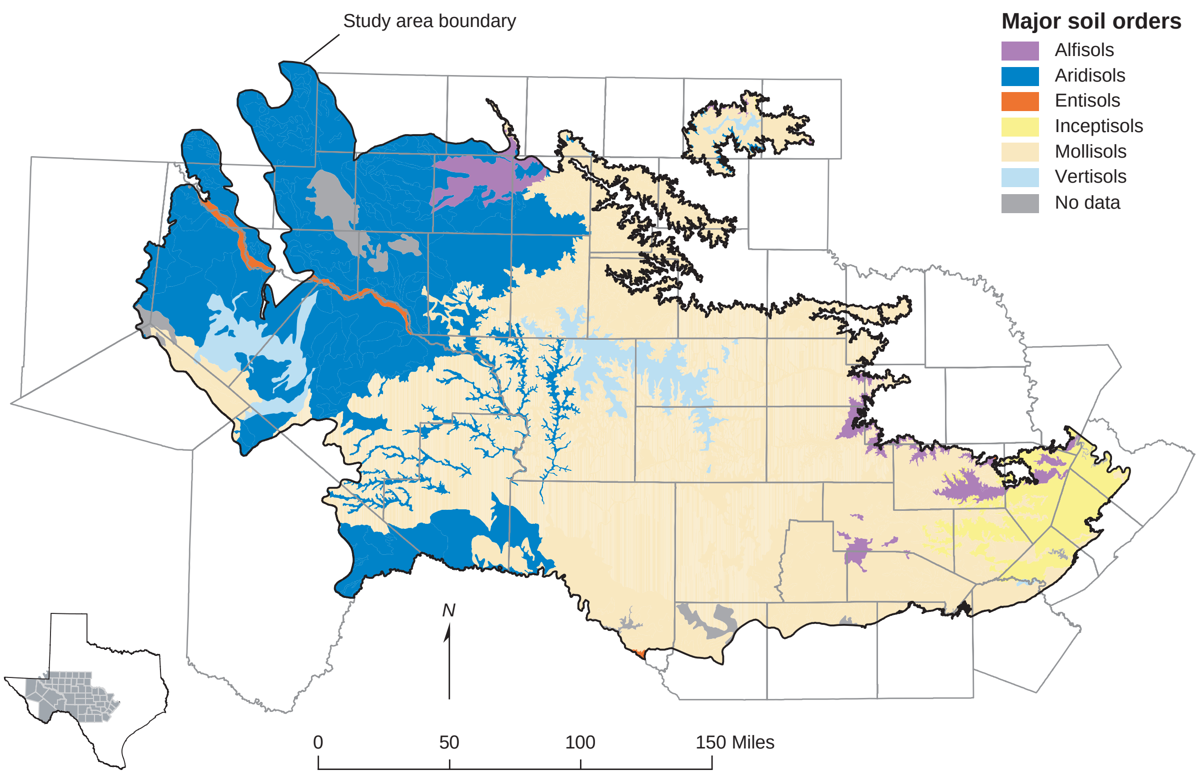

Figure 3-10. Spatial distribution of major soil order types.

3.1.3
Soil development

Soil development is influenced by geologic and climatic characteristics and affects vegetation type as well as infiltration and runoff qualities of the landscape. The predominant soil group (Figure 3-10) for most of the Edwards Plateau is classified as ustolls, a suborder of mollisols that drain easily and develop under grass or savanna-type vegetation in subhumid to semiarid climates (USDA, 1999). In the northwesternmost portion of the Edwards Plateau, relic soils thicken into more sandy, loamy soils characteristic of the Llano Estacado. These soils are classified as aridisols and are characterized by the limited availability of soil moisture to sustain plant growth (USDA, 1999). The aridisols also extend westward across the Pecos Valley into the Trans-Pecos region, cover the southern portion of the Stockton Plateau, and continue south into the Big Bend region. In the eastern portion of the Edwards Plateau where the Edwards Group sediments have been removed to expose the underlying Trinity Group sediments, soils have minimal soil horizon development and form on steep slopes of young geomorphic surfaces in a humid to subhumid climate (USDA, 1999; University of Idaho, undated). These soils of the eastern Texas Hill Country are classified as inceptisols. Another soil order found on the plateau includes the vertisols, which are clay-rich and have a high shrink and swell potential and very low permeability. Vertisols are located in a small central portion of the plateau along the northwest-to-southeast trending, relatively flat topographic divide between the Colorado River and Rio Grande and in the Trans-Pecos uplands of the Pecos Valley. Entisols also occur within the Pecos Valley, coinciding with migrating sand dunes, and along the Pecos River bed. Entisols are poorly developed soils

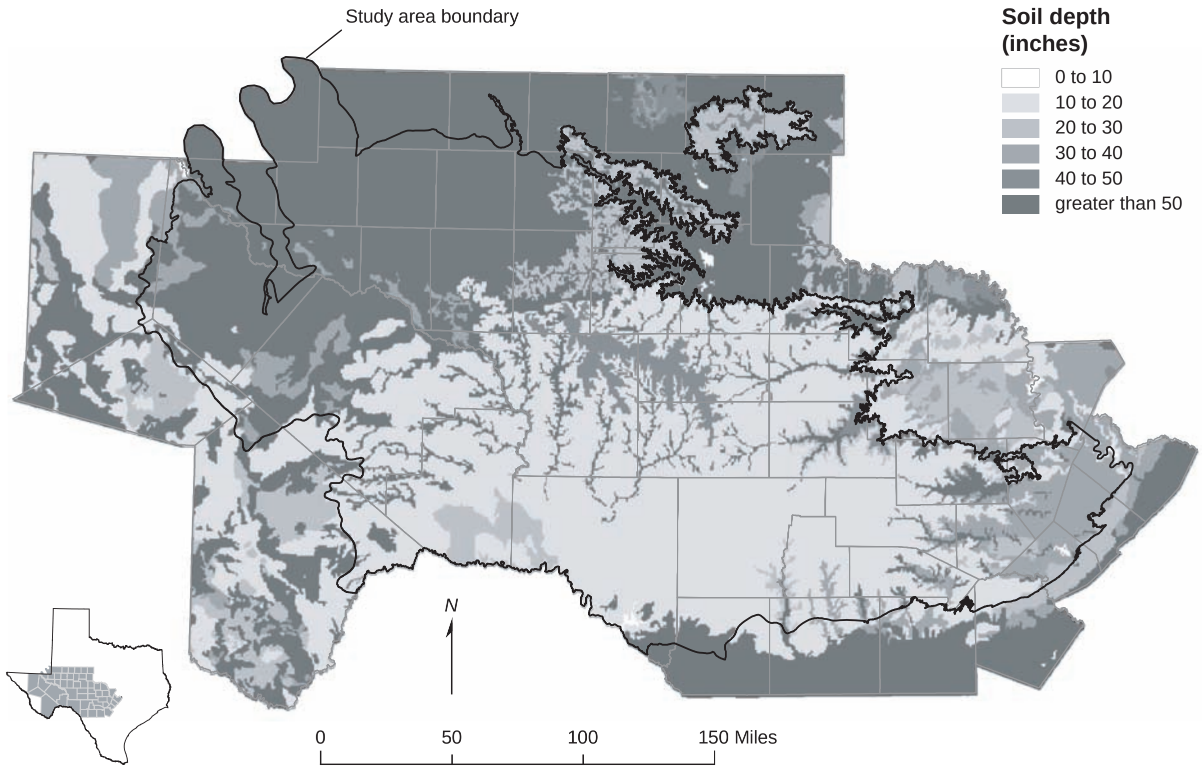

Figure 3-11. Spatial distribution of soil thickness.

that form from recent unconsolidated parent materials and do not fit into any of the other 11 soil orders.

Pleistocene paleosoils, typically called "terra rossas," formed between one and two million years ago and are found scattered throughout the Edwards Plateau, usually within caves and sinkholes where they have been protected from erosion (Young, 1986). Following the last glacial maximum of the Late Pleistocene, the rate of soil erosion on the plateau is thought to have increased due to an increase in both aridity and variability of seasonal precipitation. However, the more recent human-induced rate of soil erosion from the plateau is an order of magnitude greater than the Pleistocene climate-driven rate (Cooke and others, 2003). Heavy grazing and the suppression of natural grass fires during the past 150 years of European settlement have augmented the erosional state of the plateau and allowed the soils to develop thin, stony characteristics (Riskind and Diamond, 1986; Mecke, 1996). Consequently, the thin characteristic nature of the soils for most of the Edwards Plateau is the most extreme in the state (Figure 3-11).

3.1.4
Vegetation and land use

Similar to soil development, vegetation and land use affect the infiltration and runoff qualities of the landscape. Early Spanish explorers described the vegetation on most of the Edwards Plateau as being open grasslands dominated by short grasses covering the more arid western regions and a diversity of mid to tall grasses in the eastern areas suitable for roaming bison (Riskind and Diamond, 1986; Mecke, 1996). The steep slopes along the southeastern plateau margins provided fire proof breaks, which confined the woody evergreen brush species to canyon walls (Taylor and Smeins, 1994). The cooler and wetter bottomlands supported mixed forest hardwood species of pecan, ash, cypress, walnut, maple, willow, sycamore, and cottonwood (Riskind and Diamond,

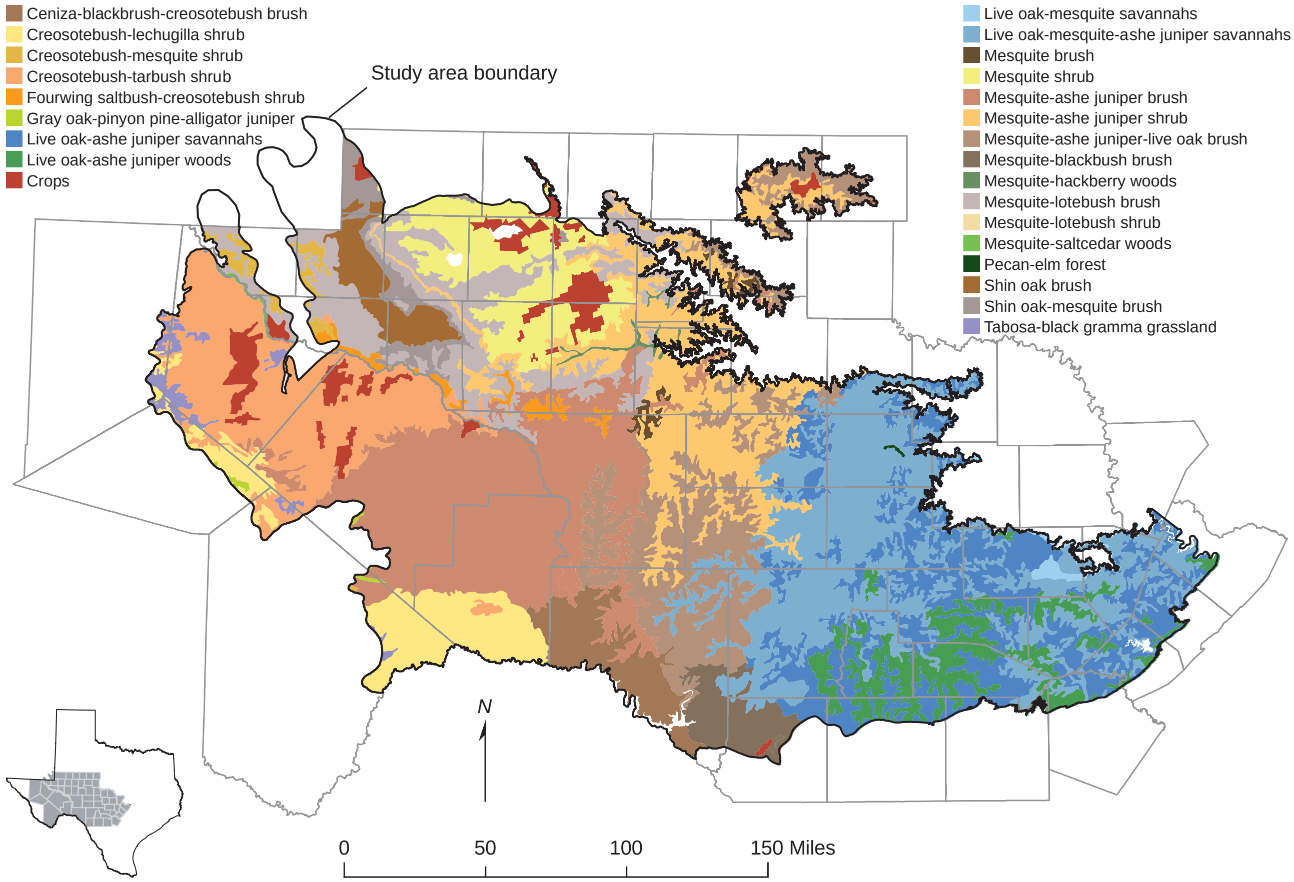

Figure 3-12. Spatial distribution of vegetation types.

1986; Mecke, 1996). Today, oak forests and oak-juniper woodlands are still common on the steeper canyon walls (Riskind and Diamond, 1986). However, the open grassland savannas have since been transformed by unsustainable land use (Mecke, 1996) into a stunted, scrubby savanna of oak, juniper, and grass in the north and east and desert shrub and woody mesquite brush in the southwest (Figure 3-12).

The combined effects of overgrazing and inhibiting the natural regeneration of grasses by fire has allowed invasive woody species such as mesquite, ashe juniper (locally referred to as cedar), and both live oak and shin oak to change the landscape (Riskind and Diamond, 1986; Taylor and Smeins, 1994; Mecke, 1996). Loss of the grasslands has increased soil erosion and rainfall runoff, consequently reducing the amount of effective rainfall available for groundwater recharge (Mecke, 1996). Since the invasive woody vegetation also consumes more of the effective rainfall through evapotranspiration, historical natural springs have ceased to flow, and perennial streams have become intermittent (Mecke, 1996). The invasion of saltcedar has also occurred in some stream valleys and contributes to significant amounts of evapotranspiration, especially along the Pecos River.

Cattle, sheep, and goat ranching, along with wild game hunting (deer, antelope, turkey, javelina, quail, and a few exotic species), is the current primary form of land use for most of the Edwards Plateau (Figure 3-13). However, in the northern portion of the plateau, cotton and grain sorghum crops irrigated with groundwater are the more dominant land use. Oil and gas production from the deep underlying Midland portion of the Permian Basin sediments is also common in

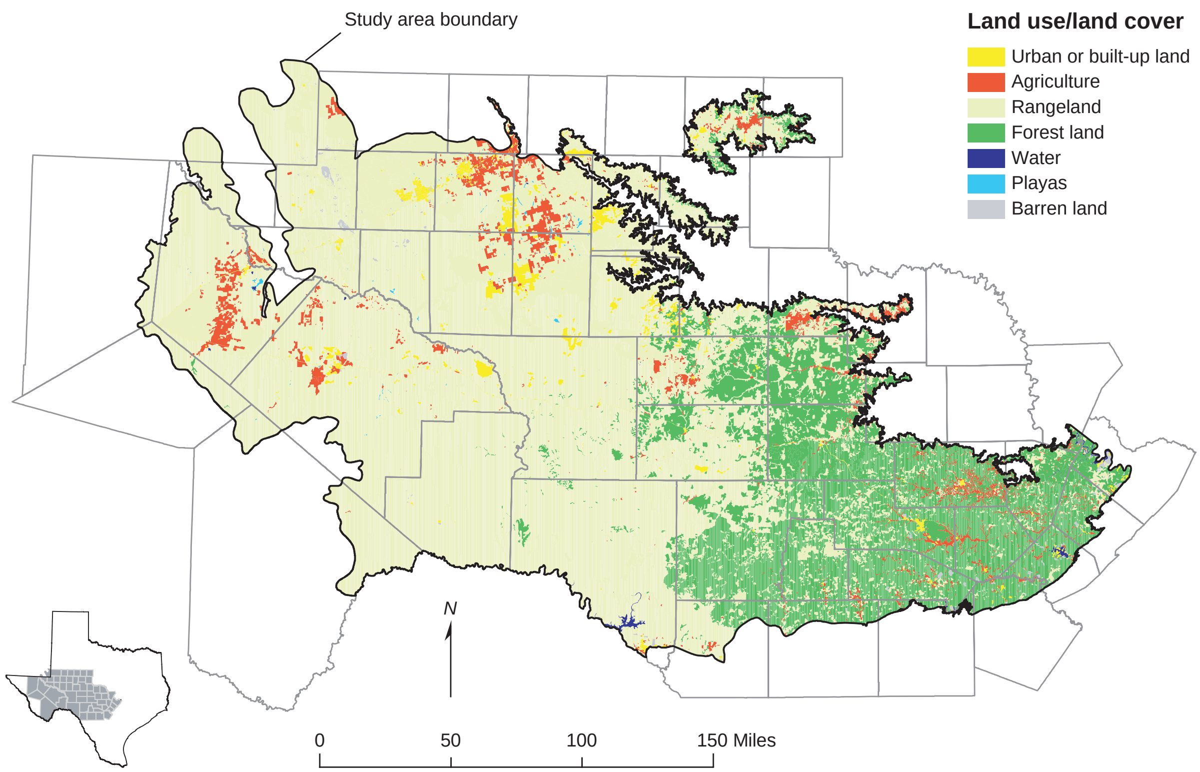

Figure 3-13. Spatial distribution of land use and land cover.

the northern and western portions of the plateau. Hay, pasture grasses, and small grains are grown in some of the valleys along the southern and eastern margins of the plateau where surface water and rainfall are more readily available. The dominant type of ranching in the Pecos Valley consists of low density cattle grazing. Irrigated agriculture in the Pecos Valley consists of a variety of fruits and vegetables, pecans, alfalfa, grains, sorghums, and a declining production of cotton (Hayter, 2004). Oil and gas production is also common from the Delaware portion of the Permian Basin sediments in the eastern areas of the Pecos Valley.

3.2 CLIMATIC SETTING

The climatic setting provides insights into the water sources of an aquifer and the physiography of the landscape. Climate is typically described by statistical interpretations of precipitation, temperature, evaporation, and drought observations with respect to time and space.

The climate of the Edwards Plateau was twice as wet during the Pleistocene Epoch, about 10,000 years ago, as it is today according to studies of the "terra rossas" found in Central Texas (Young, 1986). At some point after the last major ice age, the climate became more arid and variable (Cooke and others, 2003). The more recent climate (Figure 3-14 and Figure 3-15) of the Edwards Plateau is mostly subtropical, dominated by the northwestward onshore flow of tropical air from the Gulf of Mexico (Larkin and Bomar, 1983). The only exception is for a small area in the Llano Estacado region of the northwestern Edwards Plateau, typified as a continental-steppe climate (variable daily temperature and precipitation extremes and semiarid with mild winters) similar to the High Plains (Larkin and Bomar, 1983). The subtropical climate ranges from subhumid (hot summers and dry winters) in the eastern Edwards Plateau, to steppe (semiarid to arid conditions) in the western Edwards Plateau, to arid in the Pecos

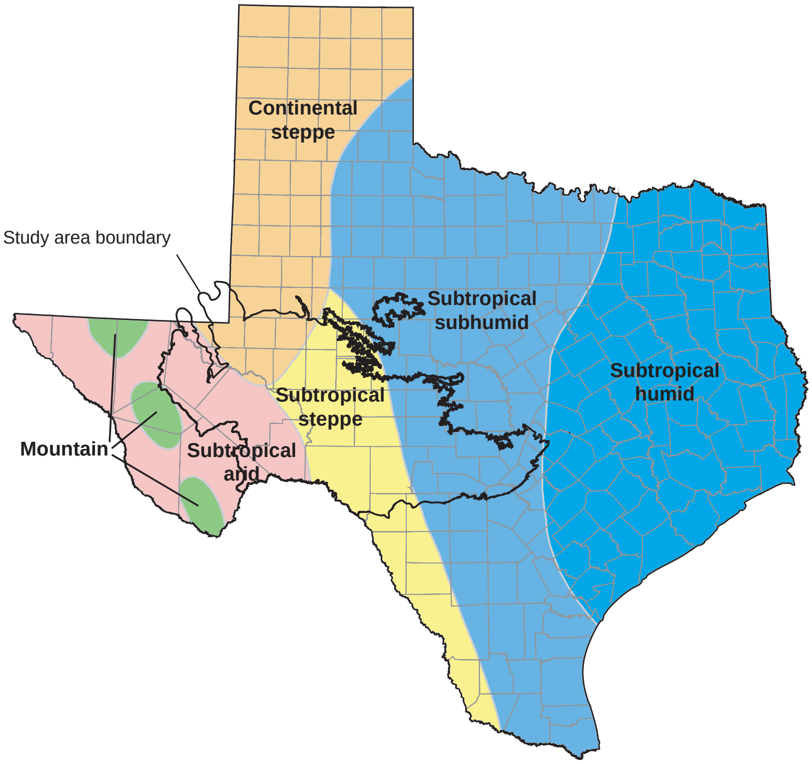

Figure 3-14. Climate regions of Texas (modified from Larkin and Bomar, 1983).

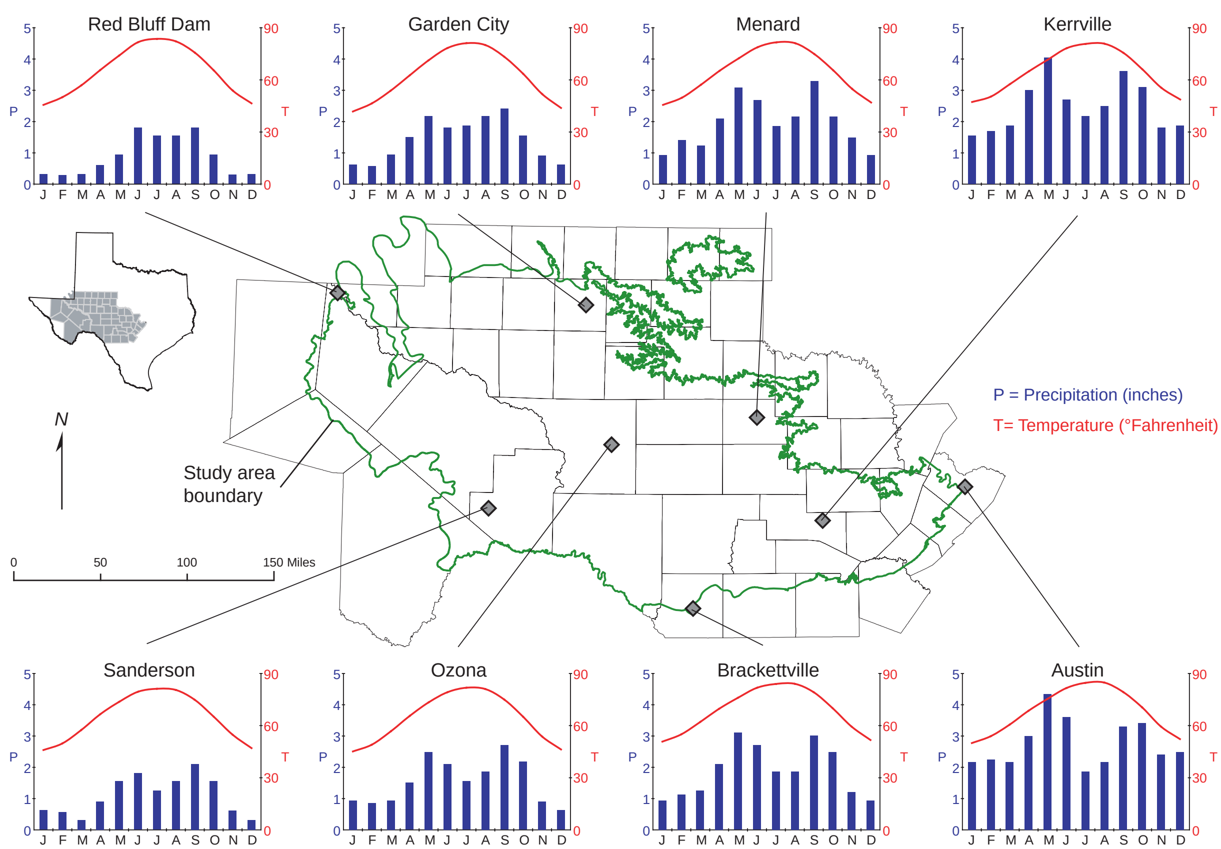

Figure 3-15. Climographs showing average monthly precipitation (vertical bars) and temperature (curved line) for selected stations in the study area having a minimum of 50 years monitoring data.

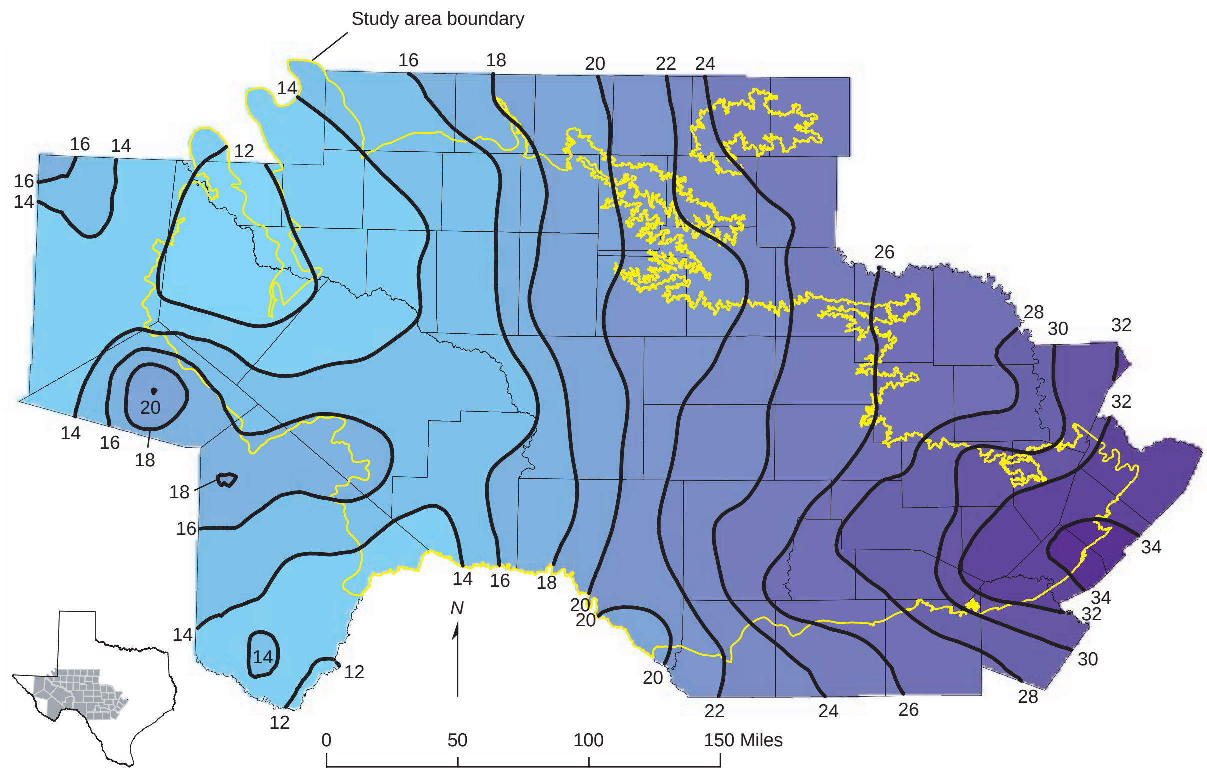

Figure 3-16. Average annual precipitation for 1961–1990 in inches.

Valley and Trans-Pecos region (Bomar, 1983; Larkin and Bomar, 1983).

3.2.1 Precipitation

Precipitation refers to rainfall and various forms of ice and snow. The long-term (1961–1990) average annual precipitation for the study area ranges from about 34 inches in the east to about 12 inches in the west (Figure 3-16). For the eastern two-thirds of the Edwards Plateau, precipitation occurs mostly during late spring and early fall as cool northern frontal air masses collide with warm southern moist air masses from the Gulf of Mexico (Carr, 1967; Bomar, 1983; Larkin and Bomar, 1983). On the western third of the Edwards Plateau and in the Pecos Valley, most of the precipitation occurs as scattered thunderstorms resulting from the convection of air masses off of the heated land surface during July, August, and September (Carr, 1967; Bomar, 1983; Larkin and Bomar, 1983; Kuniansky and Holligan, 1994). Mountains in the Trans-Pecos region contribute to anomalous orographic precipitation from the remaining moisture of eastward-moving Pacific air masses lifted up over the mountains (Carr, 1967; Bomar, 1983; Larkin and Bomar, 1983). This precipitation occurs on the windward side of the mountains rather than the leeward side of the dry and mostly barren Stockton Plateau and Pecos Valley. Orographic precipitation also occurs along the Balcones Escarpment. The northwestward flow of moist air from the Gulf of Mexico is lifted up over the escarpment, producing locally anomalous precipitation totals along the southern and southeastern margin of the plateau (Caran and Baker, 1986).

The variation of monthly precipitation totals (Figure 3-17) is greatest for the month of September and is attributed to tropical disturbances that occasionally find their way onto the plateau from the warm late summer waters of the Gulf of Mexico (Carr, 1967; Bomar,

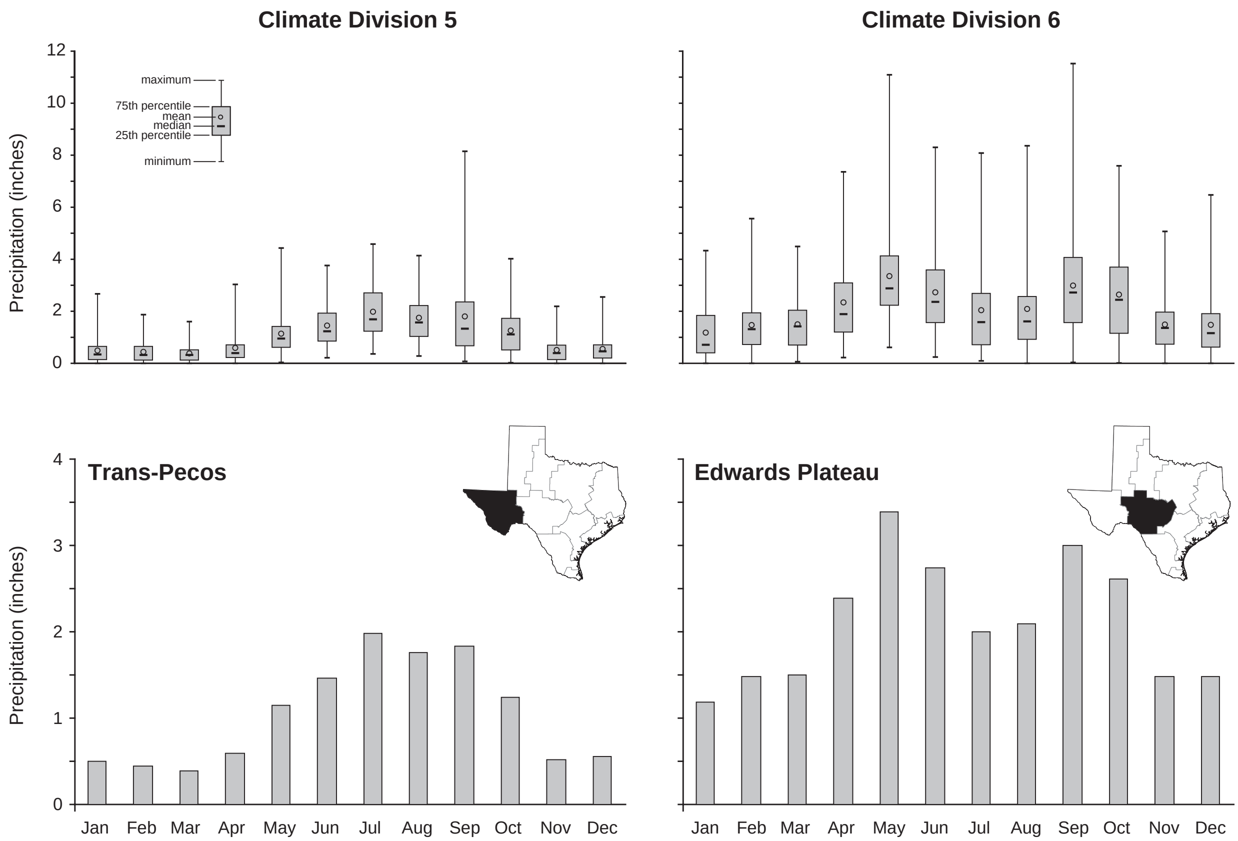

Figure 3-17. Monthly precipitation statistics for 1895–2003 in the Trans-Pecos and Edwards Plateau climate divisions.

1983; Larkin and Bomar, 1983). Kuniansky and Holligan (1994) noted that the spatial variability of annual precipitation increases from east to west from year to year, whereas the frequency of precipitation storm events increases from west to east. However, variability in the frequency of precipitation storm events generally increases toward the arid west (Bomar, 1983; Larkin and Bomar, 1983), whereas the variability of annual precipitation totals tends to increase toward the more humid east. Other variations in the average annual precipitation of the study area may be attributed to the cyclic interaction between the Pacific Ocean and the atmosphere, known as the El Niño Southern Oscillation (NOAA, 2004). Average annual precipitation usually increases during the El Niño phase and decreases during the La Niña phase, with the greatest variations in precipitation totals occurring during the fall and winter periods (Slade, 2001; NOAA, 2004). In addition, statistical data analysis of long-term streamflow and precipitation records suggests a slight apparent increasing trend in the variability of precipitation events over time (Slade, 2001).

3.2.2
Temperature, evaporation, and drought

The maximum average annual temperature for the study area ranges from about 73°F in the Trans-Pecos uplands to about 79°F in southern Val Verde County (Figure 3-18). Rates of evaporation are high throughout the study area, with an average annual lake evaporation ranging from about 88 inches in the southwest to about 64 inches in the east (Figure 3-19). Droughts are common throughout the state, with about 10 moderate to severe droughts during the last 100 years. Based on the percent departure from long-term (1895–2000) average annual precipitation, the

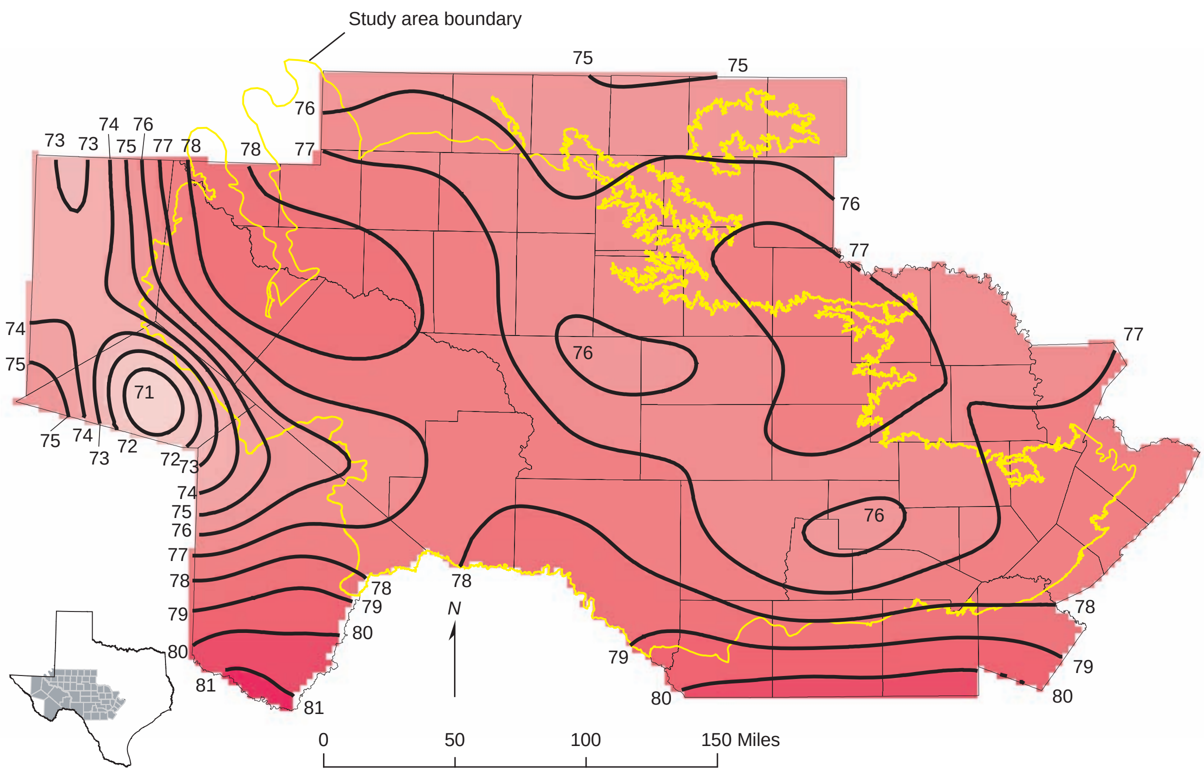

Figure 3-18. Average annual maximum temperature for 1961–1990 in degrees Fahrenheit.

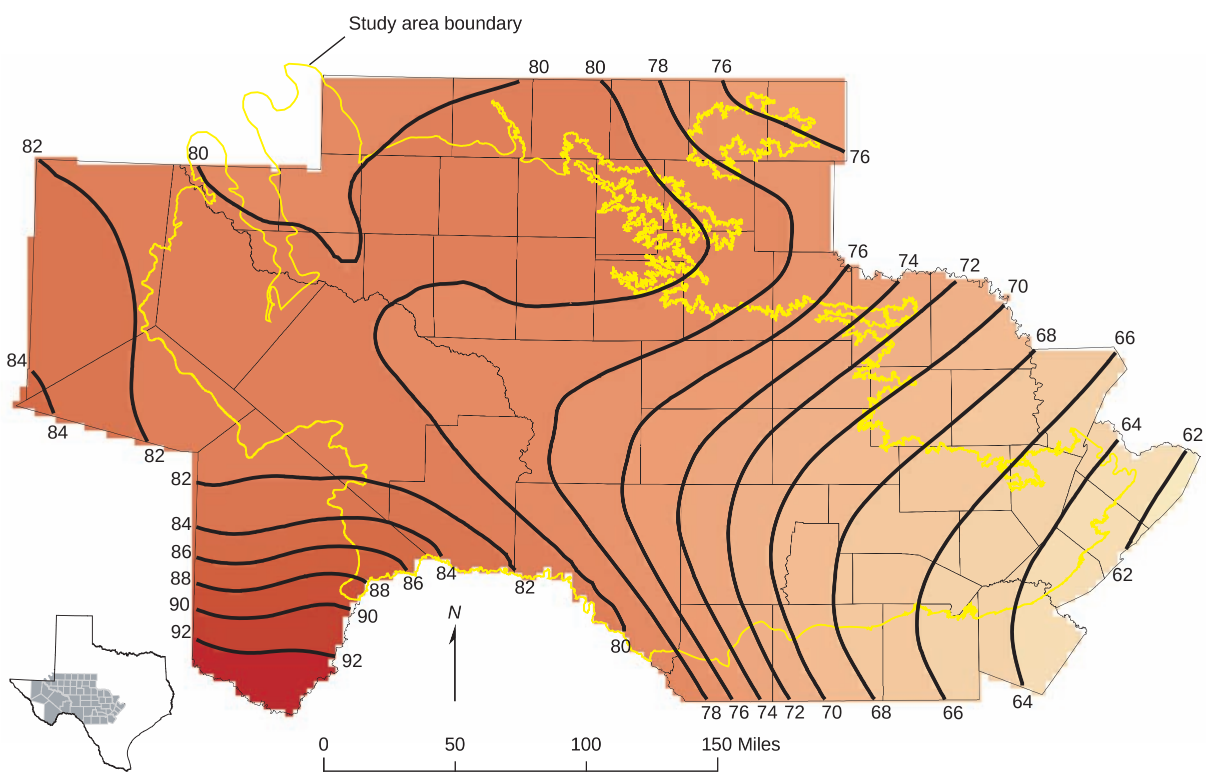

Figure 3-19. Average annual lake evaporation for 1950–1979 in inches.

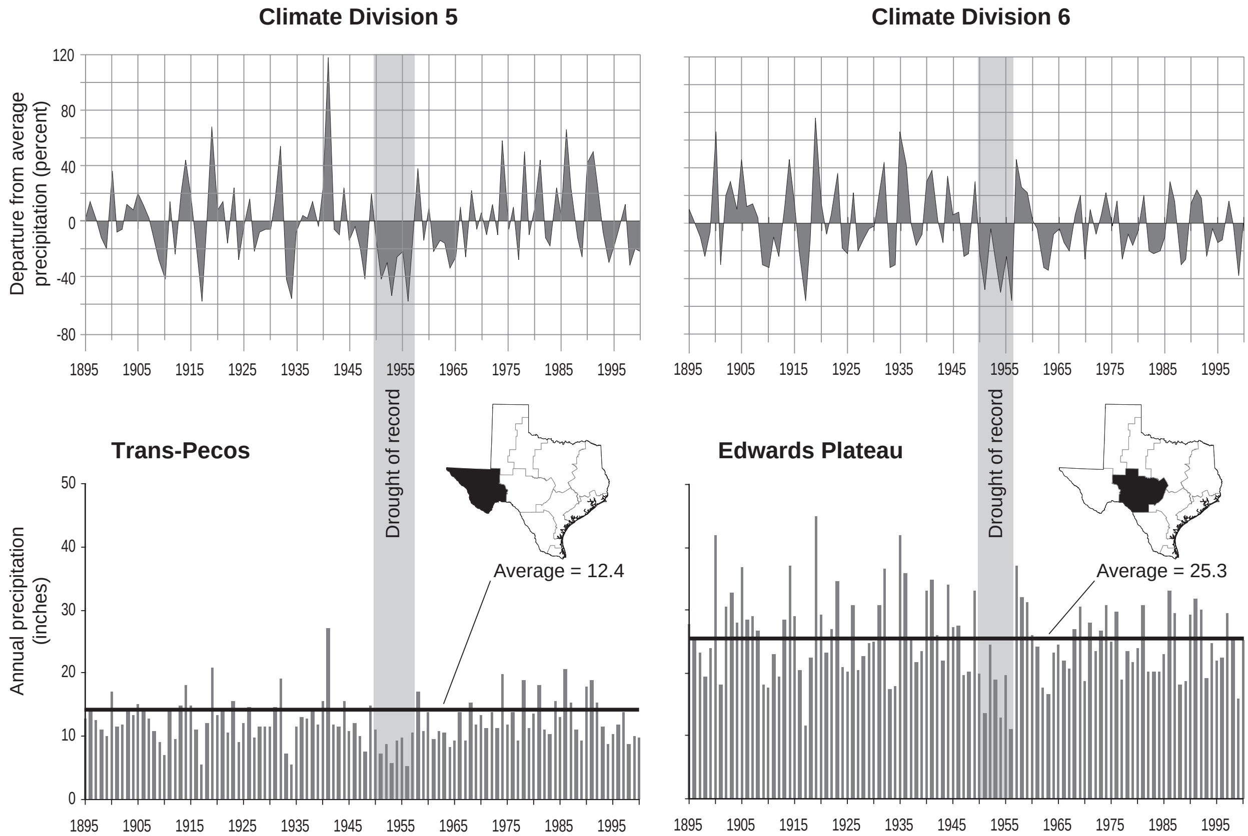

Figure 3-20. Annual precipitation and departure from average annual precipitation for 1895–2003 in the Trans-Pecos and Edwards Plateau climate divisions.

drought of record for the entire study area with respect to duration and intensity occurred during the period between October 1950 and February 1957 (Bradley and Malstaff, 2004), consistent with most of the state (Figure 3-20). However, when based on other drought indices or for more localized areas, the drought of record may fall outside the historic 1950s drought.

3.3 GEOLOGIC HISTORY

The geologic history is a reconstruction of significant events and processes that shaped the surface and subsurface rock materials of the landscape over the course of geologic time. The Edwards-Trinity (Plateau) Aquifer consists of Early Cretaceous age shallow marine rock sediments belonging to the lithostratigraphic units of the Trinity, Fredericksburg, and Lower Washita groups (Figure 3-21). The Trinity Group sediments form the lower aquifer unit of the Edwards-Trinity (Plateau) Aquifer, and the Fredericksburg and Lower Washita group sediments form the upper aquifer unit and are typically referred to as the Edwards Group sediments. The Pecos Valley Aquifer is composed of Cenozoic age terrigenous rock sediments. In the eastern third of the study area, the Edwards-Trinity sediments rest unconformably on top of a smooth to gently rolling erosional surface of folded and faulted Early to Late Paleozoic age sediments. In the western two-thirds of the study area, both the Edwards-Trinity (Plateau) Aquifer and Pecos Valley Aquifer sediments rest unconformably over an erosional surface of folded and faulted Permian and Triassic age sediments. The following subsections briefly summarize the geologic history for the study area.

Era	Period	Epoch	Age	M yr BP	GROUP
Cenozoic	Quaternary	Holocene		0.01	
		Pleistocene		1.6	
	Tertiary	Pliocene		5.3	
		Miocene		23.7	
		Oligocene		36.6	
		Eocene		57.8	
		Paleocene		66.4	
Mesozoic	Cretaceous	Late	Maastrichtian	74.5	
			Campanian	84.0	
			Santonian	87.5	
			Coniacian	88.5	
			Turonian	91.0	
			Cenomanian	97.5	
		Early	Albian	113	WASHITA FREDERICKSBURG
			Aptian	119	TRINITY
			Neocomian	144	
	Jurassic			208	
	Triassic			245	
Paleozoic	Permian			286	
	Pennsylvanian			320	
	Mississippian			360	
	Devonian			408	
	Silurian			438	
	Ordovician			505	
	Cambrian			570	
	Precambrian				

Figure 3-21. Geologic time chart and the Edwards and Trinity group sediments.
M yr BP = million years before present time

3.3.1
Paleozoic Era

The period prior to the Paleozoic Era was dominated by uplift and erosion of igneous and metamorphic rocks of the ancient Llano Uplift rather than by depositional processes (Walker, 1979; Barker and Ardis, 1996). A low, north-south trending arch formed during the Late Precambrian that extended from Nolan County to Sutton County (Walker, 1979). A mostly depositional phase prevailed between the Cambrian and Mississippian periods. During the Pennsylvanian Period, a tectonic plate collision occurred between the North American, European, and African-South American continental plates, increasing the rate of both uplift and depositional processes (Barker and Ardis, 1992). This tectonic event, known as the Ouachita Orogeny, uplifted, faulted, and folded the Paleozoic landscape into a mountain range that extended across Texas from northern Mexico, east, then northeast along the present day Balcones Escarpment up to the Ouachita Mountains of Oklahoma and Arkansas (Barker and Ardis, 1996). Prior to a final uplift at the end of the Paleozoic Era, deposition of a Late Permian age carbonate reef, followed by evaporite deposition, occurred within a shallow inland sea north of the Ouachita Fold Belt in an area now known as the Texas Permian Basin (Barker and Ardis, 1992).

3.3.2
Triassic and Jurassic periods

The first half of the Mesozoic Era represents a period dominated by a terrigenous landscape emerging from Permian seas and erosion of the Paleozoic sediments (Barker and Ardis, 1992). The end of the Ouachita Tectonic Cycle initiated the Gulfian Tectonic Cycle, as the North American-South American continental plates began to rift and separate from the European-African plates to form the ancestral Atlantic Ocean. This rifting changed the previous drainage direction from northwest into the Permian inland seas to the southeast into the developing Gulf of Mexico. During the Triassic Period, terrigenous clastic red beds were deposited over Paleozoic rocks as the Triassic age Dockum Group sediments in West Texas. By the Jurassic Period, the study area was completely exposed to erosion and transformed into a rolling peneplain known as the Wichita Paleoplain (Barker and Ardis, 1996). By the end of the Jurassic Period, the Gulf of Mexico had formed, and tilting of the peneplain toward the southeast provided the structural foundation for the new continental shelf deposits of Cretaceous age Trinity and Edwards group sediments.

3.3.3
Cretaceous Period

As the Gulf of Mexico continued to develop and the Cretaceous seas advanced from the southeast, a broad continental shelf known as the Comanche Shelf began to form (Figure 3-22). The Llano Uplift, a tectonically active structural feature since the Precambrian, became a prominent structural shelf element for the deposition of the Trinity Group sediments (Barker and Ardis, 1996). The Early Cretaceous seas advanced across the Pre-Cretaceous structural base in three cycles of transgressive-regressive stages to deposit the Trinity Group sediments (Barker and others, 1994). The Stuart City Reef Trend began to form parallel to the ancestral Gulf of Mexico about 150 miles inland from the present Texas Gulf Coast, enabling the carbonate platform deposits of the Edwards Group sediments to accumulate to the northwest behind the protection of the reef. Other structural shelf elements that formed behind the Stuart City Reef Trend and controlled the depositional environments and lithologic characteristics of the Edwards Group formations include the Central Texas Platform, the San Marcos Arch, the Devils River Reef Trend on the edge of the Maverick Basin, and the Fort Stockton Basin (Figure 3-22). Prior to the deposition of Upper Cretaceous Del Rio Clay, Buda Limestone, Boquillas Formation, and Austin Group sediments, much of the Central Texas Platform was subaerially exposed (Figure 3-23), allowing for an initial dissolution and karstification of the Lower Cretaceous carbonate sediments (Barker and others, 1994).

3.3.4
Tertiary and Quaternary periods

Toward the end of the Cretaceous and beginning of the Tertiary Period, the

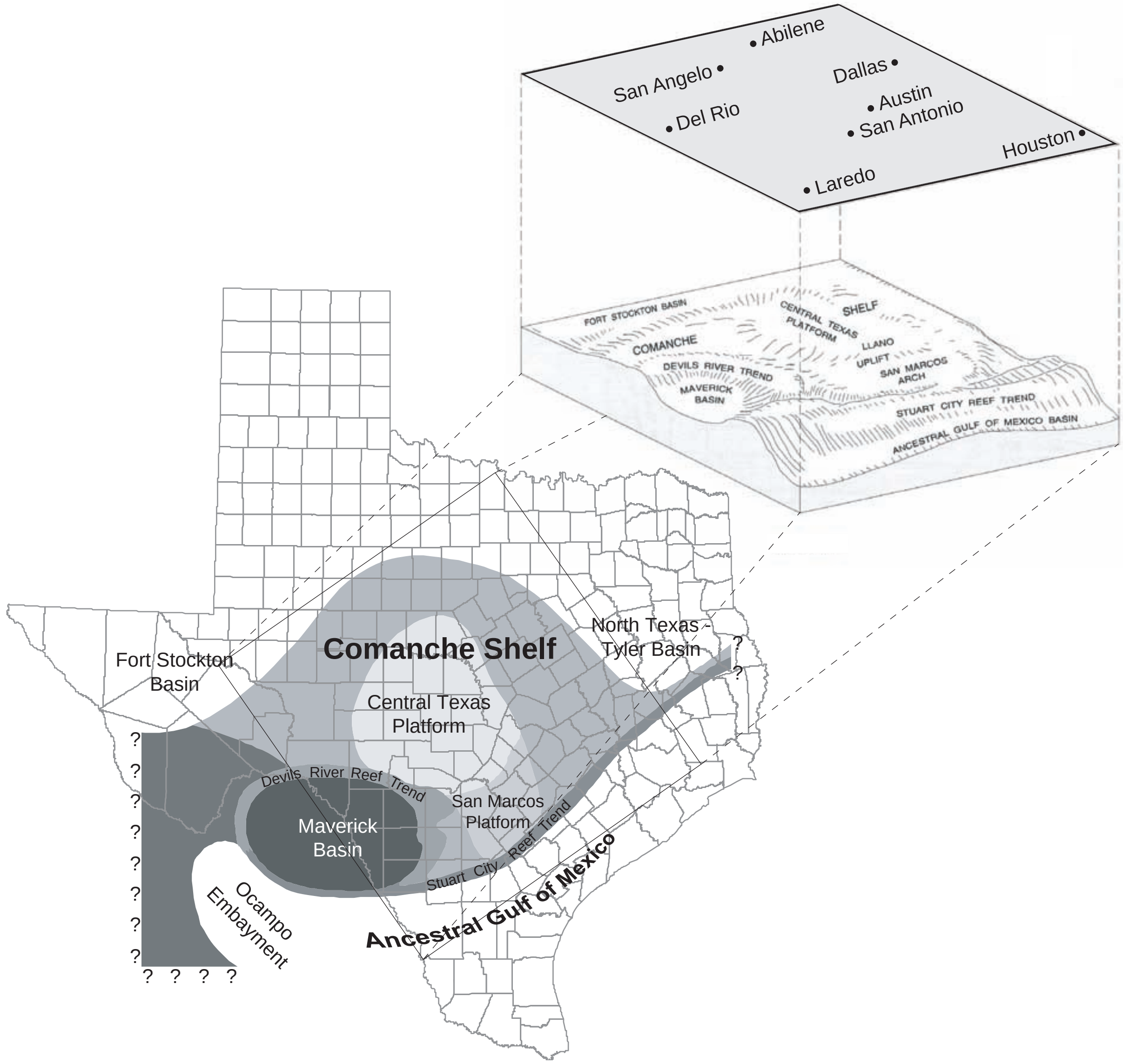

Figure 3-22. Paleogeographic elements affecting the depositional environments of the Edwards Group sediments.

Laramide orogenic cycle began. In conjunction with Laramide folding and faulting, the dissolution of Upper Permian evaporite sediments resulted in the formation of elongated solution cavities along the Pecos River Valley (Barker and others, 1994). As a result, a slow structural collapse and erosion of the overlying Triassic and Cretaceous sediments occurred. These sediments were then deposited into two main troughs along the Pecos Valley throughout the Tertiary Period, and the deposition was further enhanced by the Basin and Range tectonic cycle later during the Quaternary Period.

During the mid-Tertiary Period, regional uplifting and the accumulation of basin sediments into the Gulf of Mexico produced tensional stresses along the ancient hinge-line of the Ouachita Fold Belt. Consequently, the Balcones Fault Zone was formed as Lower Tertiary, Cretaceous, and older sediments were displaced by 900 to 1,200 feet (Barker and others, 1994) along a narrow zone

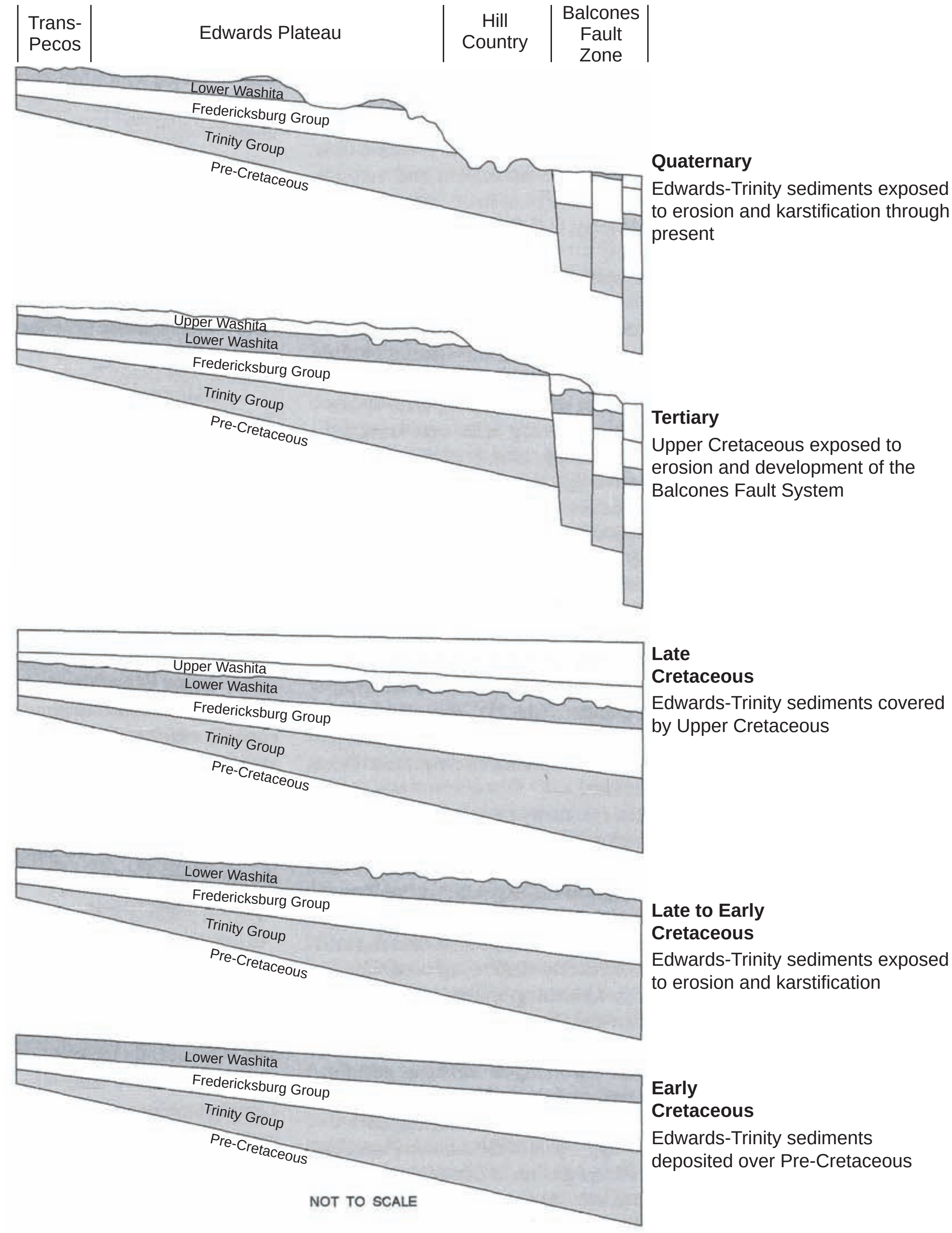

Figure 3-23. Evolutionary development of the Edwards-Trinity (Plateau) Aquifer system (modified from Barker and Ardis, 1996).

of faults stair-stepped down toward the Texas Gulf Coast.

During the Late Tertiary Period, sediments of the Ogallala Formation began to cover over a portion of the Edwards-Trinity sediments in the northern region of the plateau. The natural processes of geologic weathering and the headward erosion of streams have shaped the study area into its current landscape throughout the Quaternary Period.

4 *Previous aquifer investigations*

Previous studies of the Edwards-Trinity (Plateau) and Pecos Valley aquifers began with countywide studies by the Texas Board of Water Engineers, Texas Water Commission, Texas Department of Water Resources, Texas Water Development Board, and U.S. Geological Survey. The Texas Department of Water Resources was the first to publish regional study reports on the Trans-Pecos (Rees and Buckner, 1980) and Edwards Plateau (Walker, 1979) portions of the Edward-Trinity (Plateau) Aquifer. TWDB published a regional study report of the Pecos Valley Aquifer (Ashworth, 1990). During the late 1980s, the U.S. Geological Survey began a Regional Aquifer Systems Analysis program for the Edwards-Trinity (Plateau) Aquifer that resulted in the publication of some of the more recent and comprehensive reports on the aquifer system (Bush, 1986; Kuniansky, 1989; Kuniansky, 1990; Barker and Ardis, 1992; Ardis and Barker, 1993; Bush and others, 1993; Barker and others, 1994; Bush and others, 1994; Barker and Ardis, 1996). The U.S. Geological Survey has also published a groundwater atlas for Oklahoma and Texas (Ryder, 1996) consisting of executive summaries of the Edwards-Trinity (Plateau) and Pecos Valley aquifers.

The U.S. Geological Survey developed a finite-element numerical groundwater flow model to simulate two-dimensional steady-state flow for the Edwards-Trinity (Plateau) Aquifer and contiguous hydraulically connected units (Kuniansky and Holligan, 1994). The single layer model included the Edwards-Trinity (Plateau) Aquifer, Hill Country part of the Trinity Aquifer, and Edwards (Balcones Fault Zone) Aquifer, as well as the contiguous, hydraulically connected units of the Pecos Valley, Dockum, Ogallala, Lipan, Hickory, Ellenburger-San Saba, and Marble Falls aquifers. The model suggested that simulated regional groundwater flow within the model boundary was about 3 million acre-feet per year, flowing mostly toward springs and streams within the region. Transmissivity values used in the model ranged from less than 1,000 to 100,000 feet-squared per day for the Edwards-Trinity (Plateau) Aquifer, Hill Country part of the Trinity Aquifer, and Pecos Valley Aquifer. Recharge estimates for the model simulations ranged from less than 0.5 to about 1 inch per year for the Edwards-Trinity (Plateau) and Pecos Valley aquifers and increased to as much as 4 inches per year for the Hill Country part of the Trinity Aquifer. This finite element model is inadequate for TWDB's groundwater availability modeling because of its limitation in modeling the complexity of the study area as a single layer and also because it is limited to steady-state conditions.

TWDB developed a finite-difference numerical groundwater flow model to simulate three-dimensional steady-state and transient flow for the Hill Country part of the Trinity Aquifer (Mace and others, 2000). The model used one layer to represent the Edwards Group and two layers to represent the Upper and Middle Trinity Aquifer units, respectively. The Lower Trinity Aquifer unit was not modeled. The hydraulic conductivity was calibrated to a uniformly distributed conductivity field of 7 feet per day for the Edwards layer and 5 feet per day for the Upper Trinity layer. The Middle Trinity layer was calibrated with a variable conductivity field having an average of 7.5 feet per day. Recharge estimates for the model were calibrated to an average of about 4 percent of average annual rainfall (about 1.2 inches per year). The model also simulated the movement of about 64,000 acre-feet per year of cross-formational flow from the Hill Country part of the Trinity Aquifer into the Edwards (Balcones Fault Zone) Aquifer.

5 *Hydrogeologic setting*

The hydrogeologic setting provides an understanding of the aquifer by characterizing (1) the aquifer framework, which describes three-dimensional properties such as the hydrostratigraphy, structural geometry, predevelopment water levels, regional groundwater flow, and hydraulic properties; (2) the aquifer stresses, which affect the state of groundwater storage and flows over time, such as the recharge, pumping discharge, and natural interactions between groundwater and surface water features such as springs, streams, and lakes; and (3) the aquifer chemistry, which affects the quality of the groundwater.

5.1 HYDROSTRATIGRAPHY

Stratigraphy refers to the vertical and lateral organization of the various geologic units and is usually depicted in a diagram with one or more stratigraphic charts (Figure 5-1 and Figure 5-2). Geologists typically use a hierarchical classification system of stratigraphic units for correlating lithostratigraphic units (based on rock characteristics) with chronostratigraphic units (based on time-rock or age of rock) and/or geochronologic units (based on geologic time). We developed a hydrostratigraphy to further organize the stratigraphic units of the Edwards-Trinity (Plateau) and Pecos Valley aquifers into hydrostratigraphic units based upon similar aquifer characteristics.

The Edwards-Trinity (Plateau) Aquifer is composed of sediments from the stratigraphic time-rock unit known as the Lower Cretaceous Series or the equivalent provincial (or regional) series known as the Comanchean Series (Smith and others, 2000). The Edwards-Trinity

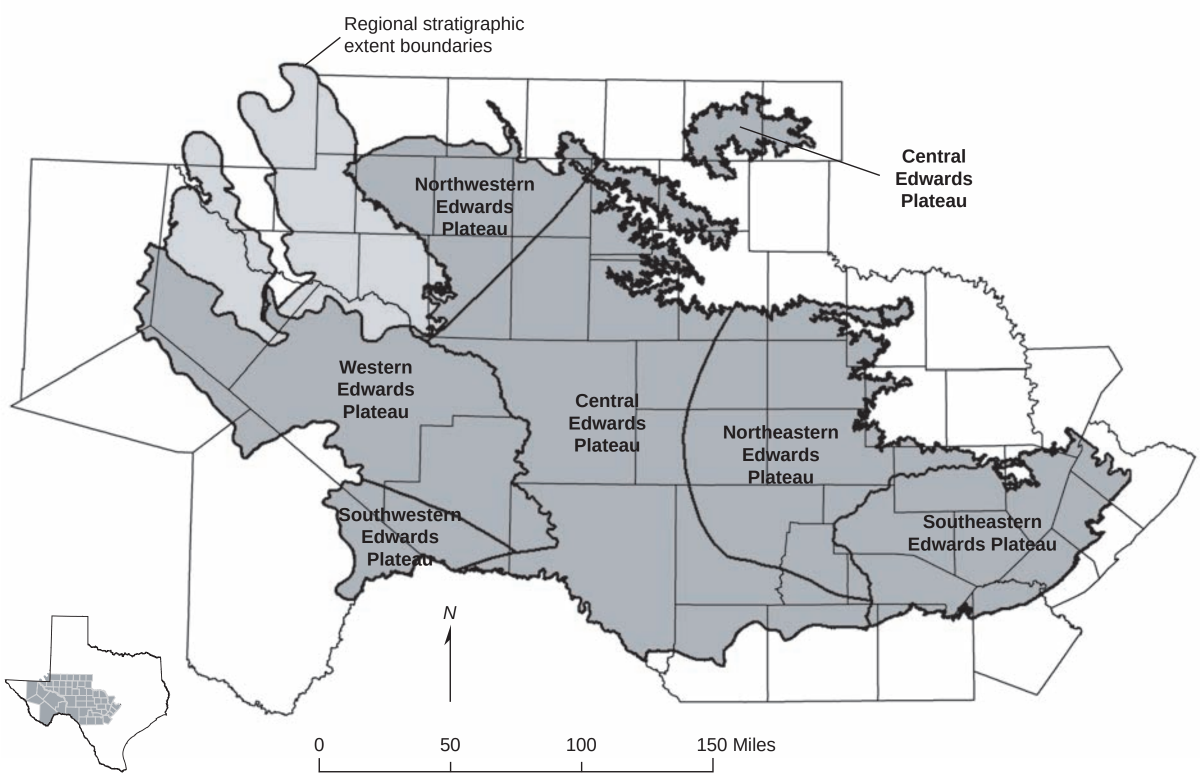

Figure 5-1. Regional extents of stratigraphic nomenclature for the Edwards-Trinity (Plateau), Pecos Valley, and Trinity (Hill Country) aquifer systems.

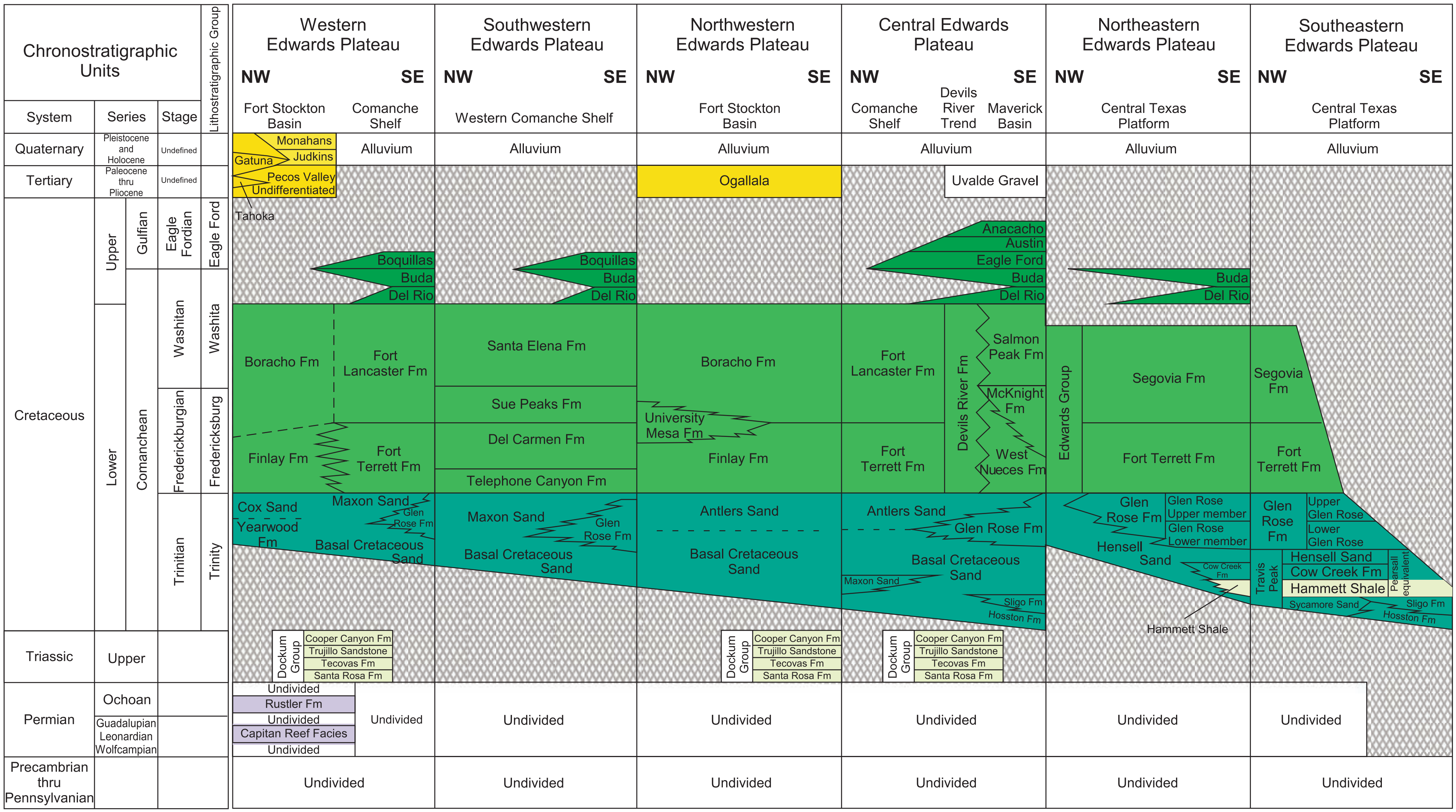

Figure 5-2. Stratigraphic chart of the Edwards-Trinity (Plateau) and Pecos Valley aquifers and the Hill Country part of the Trinity Aquifer (modified from Barker and Ardis, 1996).
Fm= formation

(Plateau) Aquifer sediments were deposited throughout the Albian Age of the Early Cretaceous Epoch. The Pecos Valley Aquifer consists of sediments of the Cenozoic Erathem and were deposited during both the Tertiary and Quaternary periods. As a consequence of the vast geographic extent of the Edwards-Trinity (Plateau) Aquifer, the stratigraphy for this aquifer is relatively complex and variable within the study area. The hydrostratigraphy is, therefore, discussed in the following subsections according to geographic regions (Figure 5-3 through Figure 5-8).

5.1.1 Southeastern Edwards Plateau (Hill Country)

In general, most of the underlying Paleozoic rocks provide for a relatively impermeable base for the Edwards-Trinity (Plateau) Aquifer sediments (Barker and Ardis, 1992). However, along the northeastern margin of the Hill Country, covering the southern bounds of the Llano Uplift, the Hickory Aquifer (Precambrian age Hickory Sand), the Ellenburger-San Saba Aquifer (Cambrian age San Saba Member of the Wilberns Formation; the Ordovician age Honeycut, Gorman, and Tanyard formations of the Ellenburger Group), and, to a much lesser degree, the Marble Falls Aquifer (Pennsylvanian age Marble Falls Limestone) are hydraulically connected to the Edwards-Trinity (Plateau) Aquifer (Figure 5-3).

In the Hill Country, the Trinity hydrostratigraphic unit of the Edwards-Trinity (Plateau) Aquifer is subdivided into Lower, Middle, and Upper Trinity aquifer units, which are composed of the Trinity Group sediments (Ashworth, 1983). The Lower Trinity Aquifer unit consists of the Hosston Sand (known as the Sycamore Sand when exposed as surface outcrop) and the overlying Sligo Formation. The Hammett Shale is a lower confining unit for the Middle Trinity Aquifer unit and an upper confining unit for the Lower Trinity Aquifer. The Middle Trinity Aquifer unit consists of the Cow Creek Limestone, Hensell Sand, and the lower member of the Glen Rose Limestone. The Upper Trinity Aquifer unit consists of the upper member of the Glen Rose Limestone (Ashworth, 1983; Mace and others, 2000).

The Fort Terrett Formation of the Fredericksburg Group and the Segovia Formation of the Washita Group form the Edwards hydrostratigraphic unit of the Edwards-Trinity (Plateau) Aquifer. The Edwards hydrostratigraphic unit, often referred to as the Edwards Group Limestones, is generally found capping the higher ridges of the Hill Country.

5.1.2 Northeastern Edwards Plateau (Llano Uplift)

In general, most of the underlying Paleozoic rocks provide for a relatively impermeable base for the Edwards-Trinity (Plateau) Aquifer sediments (Barker and Ardis, 1992). However, along the eastern part of the plateau overlying the western margin of the Llano Uplift, the Hickory Aquifer (Precambrian age Hickory Sand); the Ellenburger-San Saba Aquifer (Cambrian age San Saba Member of the Wilberns Formation; and the Ordovician age Honeycut, Gorman, and Tanyard formations of the Ellenburger Group); and, to a much lesser degree, the Marble Falls Aquifer (Pennsylvanian age Marble Falls Limestone) are hydraulically connected to the Edwards-Trinity (Plateau) Aquifer (Figure 5-4).

As in the Hill Country, the Trinity Group forms the Lower, Middle, and Upper Trinity Aquifer units within the Trinity hydrostratigraphic unit. The Lower Trinity Aquifer unit consists of the Hosston Sand (Sycamore Sand in the outcrop), Sligo Formation, and the confining Hammett Shale. The Middle Trinity Aquifer unit consists of the Cow Creek Limestone, Hensell Sand, and the lower member of the Glen Rose Limestone.

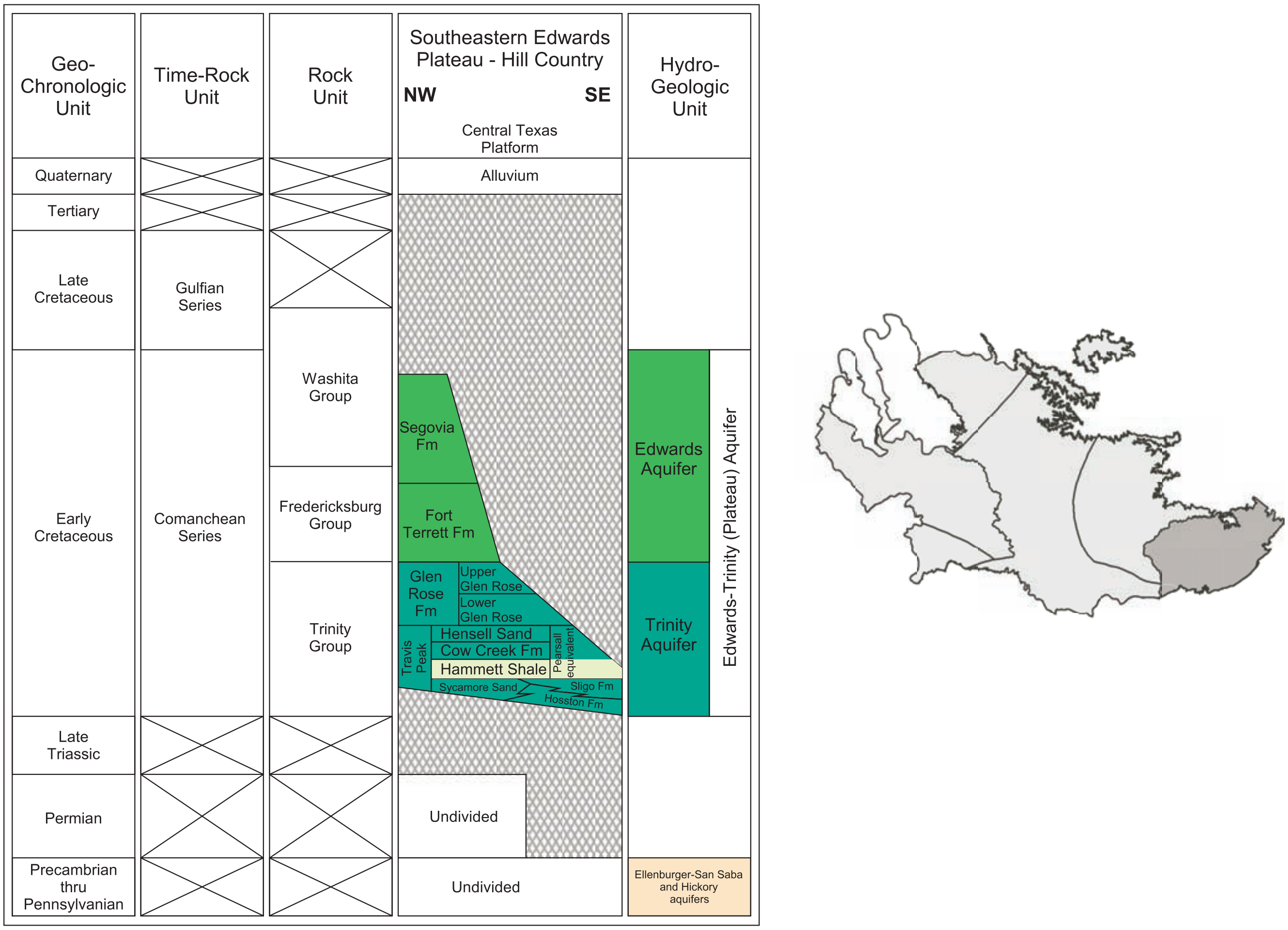

Figure 5-3. Hydrostratigraphic chart of the southeastern Edwards Plateau, Hill Country region. Fm=formation

The Upper Trinity Aquifer unit consists of the upper member of the Glen Rose Limestone (Ashworth, 1983; Mace and others, 2000). Additionally, the Fort Terrett Formation of the Fredericksburg Group and the Segovia Formation of the Washita Group, are together locally referred to as the Edwards Group Limestones that form the Edwards hydrostratigraphic unit of the Edwards-Trinity (Plateau) Aquifer.

The Upper Cretaceous sediments include the uppermost section of the Washita Group sediments (Del Rio Clay and the Buda Limestone). The Upper Cretaceous sediments are generally considered confining units to the underlying Edwards hydrostratigraphic unit of the Edwards-Trinity (Plateau) Aquifer.

5.1.3 Central Edwards Plateau (Plateau)

The underlying Paleozoic rocks provide a relatively impermeable base for much of the Edwards-Trinity (Plateau) Aquifer (Barker and Ardis, 1992). In the north, the Edwards-Trinity (Plateau) Aquifer overlies Late Triassic age rocks of the Dockum Group (Figure 5-5). The Dockum Group consists of the Santa Rosa, Tecovas, Trujillo, and Cooper Canyon formations that form the Dockum Aquifer (Bradley and Kalaswad, 2003). Hydraulic communication between the Dockum Aquifer and the Trinity hydrostratigraphic unit of the Edwards-Trinity (Plateau) Aquifer is insignificant except where the Trinity Group lies directly over the Santa Rosa Formation (Walker, 1979).

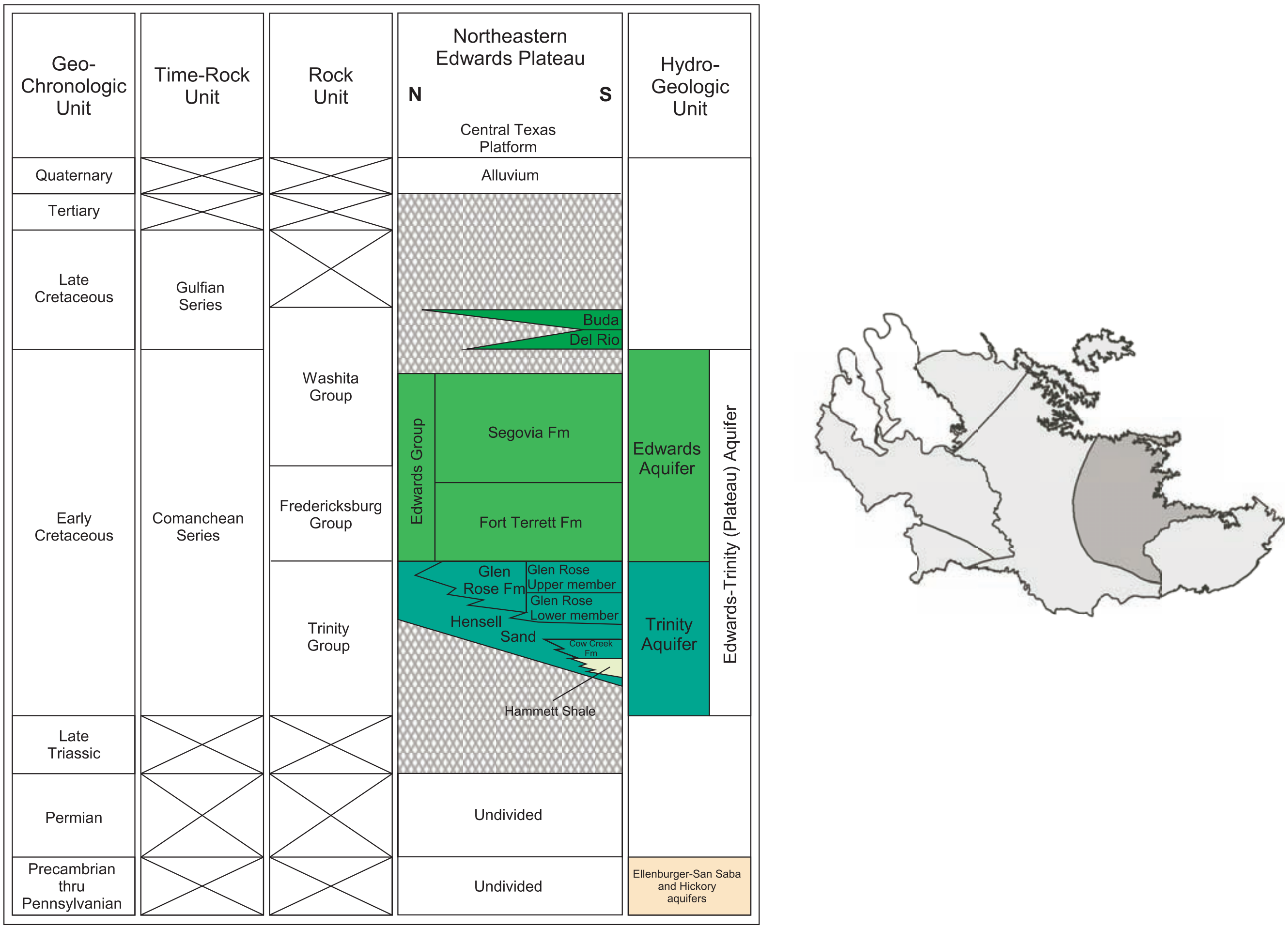

Figure 5-4. Hydrostratigraphic chart of the northeastern Edwards Plateau, Llano Uplift region. Fm=formation

The Trinity hydrostratigraphic unit is composed of the Trinity Group, which consists of the Basal Cretaceous Sand, the Glen Rose Limestone, the Antlers Sand, and the Maxon Sand. The Basal Cretaceous and Maxon sands are sometimes grouped together and are laterally equivalent to the Antlers Sand (sometimes also referred to as Trinity Sands) in the northern plateau area where the Glen Rose Limestone is absent.

The Fredericksburg Group consists of the Fort Terrett Formation and the lower part of the Fort Lancaster Formation, the Devils River Formation within the Devils River Reef Trend, and the West Nueces and McKnight formations within the Maverick Basin. The Lower Washita Group is composed of the Fort Lancaster Formation, the Devils River Formation within the Devils River Reef Trend, and the McKnight and Salmon Peak formations within the Maverick Basin. Locally, these units are combined and referred to as the Edwards Group Limestones (Rose, 1972) and form the Edwards hydrostratigraphic unit of the Edwards-Trinity (Plateau) Aquifer.

The Upper Cretaceous sediments include the uppermost section of the Washita Group sediments (Del Rio Clay and the Buda Limestone). The Boquillas Formation of the Eagle Ford Group and the Austin Chalk Formation of the Austin Group sediments are present only within Val Verde and Terrell counties. The Upper Cretaceous sediments are generally considered confining units to the underlying Edwards hydrostratigraphic unit of the Edwards-Trinity (Plateau) Aquifer.

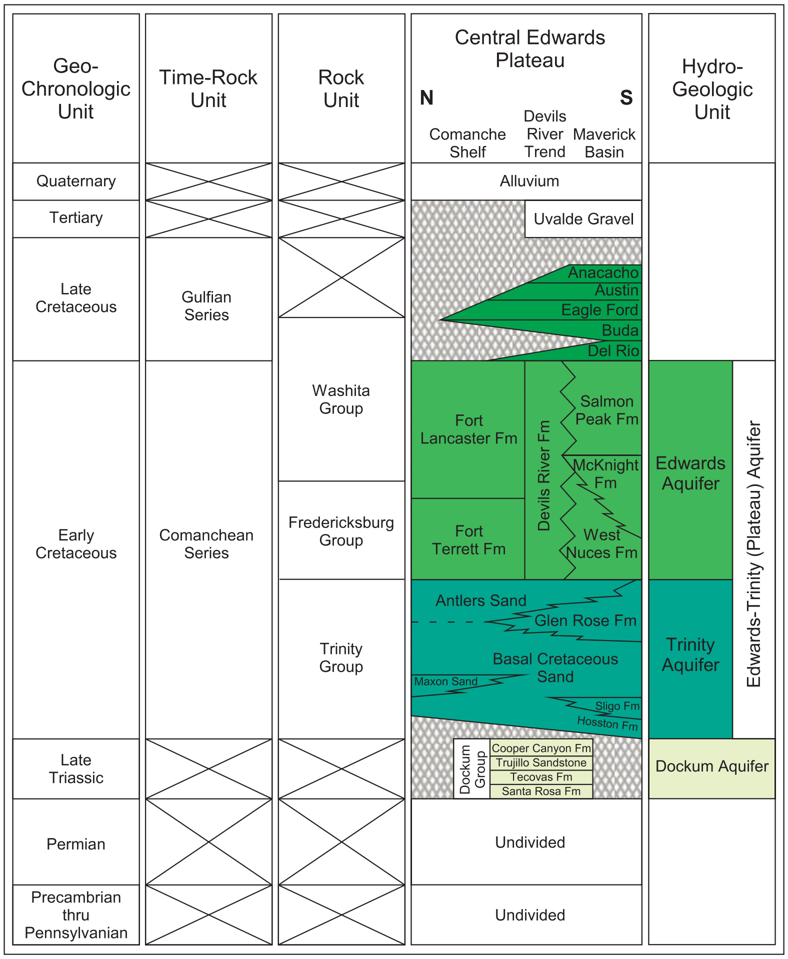

Figure 5-5. Hydrostratigraphic chart of the central Edwards Plateau region.
Fm=formation

5.1.4
Northwestern Edwards Plateau (Llano Estacado)

Late Triassic age rocks of the Dockum Group underlie the Edwards-Trinity (Plateau) Aquifer sediments throughout the Llano Estacado region (Figure 5-6). The Dockum Group consists of the Santa Rosa, Tecovas, Trujillo, and Cooper Canyon formations and form the Dockum Aquifer. Except where the Trinity Group sediments lie directly over the Santa Rosa Formation, there is insignificant hydraulic communication between the Trinity hydrostratigraphic unit of the Edwards-Trinity (Plateau) Aquifer and the Dockum Aquifer (Walker, 1979). The Trinity Group sediments are composed of the Basal Cretaceous Sand and the Antlers Sand, which are sometimes grouped together and referred to as the Trinity Sands.

The Fredericksburg Group is composed of the Finlay Formation, the University Mesa Formation, and the lower part of the Boracho Formation. The Washita Group sediments consist of the upper part of the Boracho Formation. Locally, these units are combined and referred to as the Edwards Group Limestones, which form the Edwards hydrostratigraphic unit of the Edwards-Trinity (Plateau) Aquifer. Where the Edwards Group Limestones are overlain by the Late Tertiary age Ogallala Formation, the Ogallala Aquifer is hydraulically connected to the underlying Edwards-Trinity (Plateau) Aquifer.

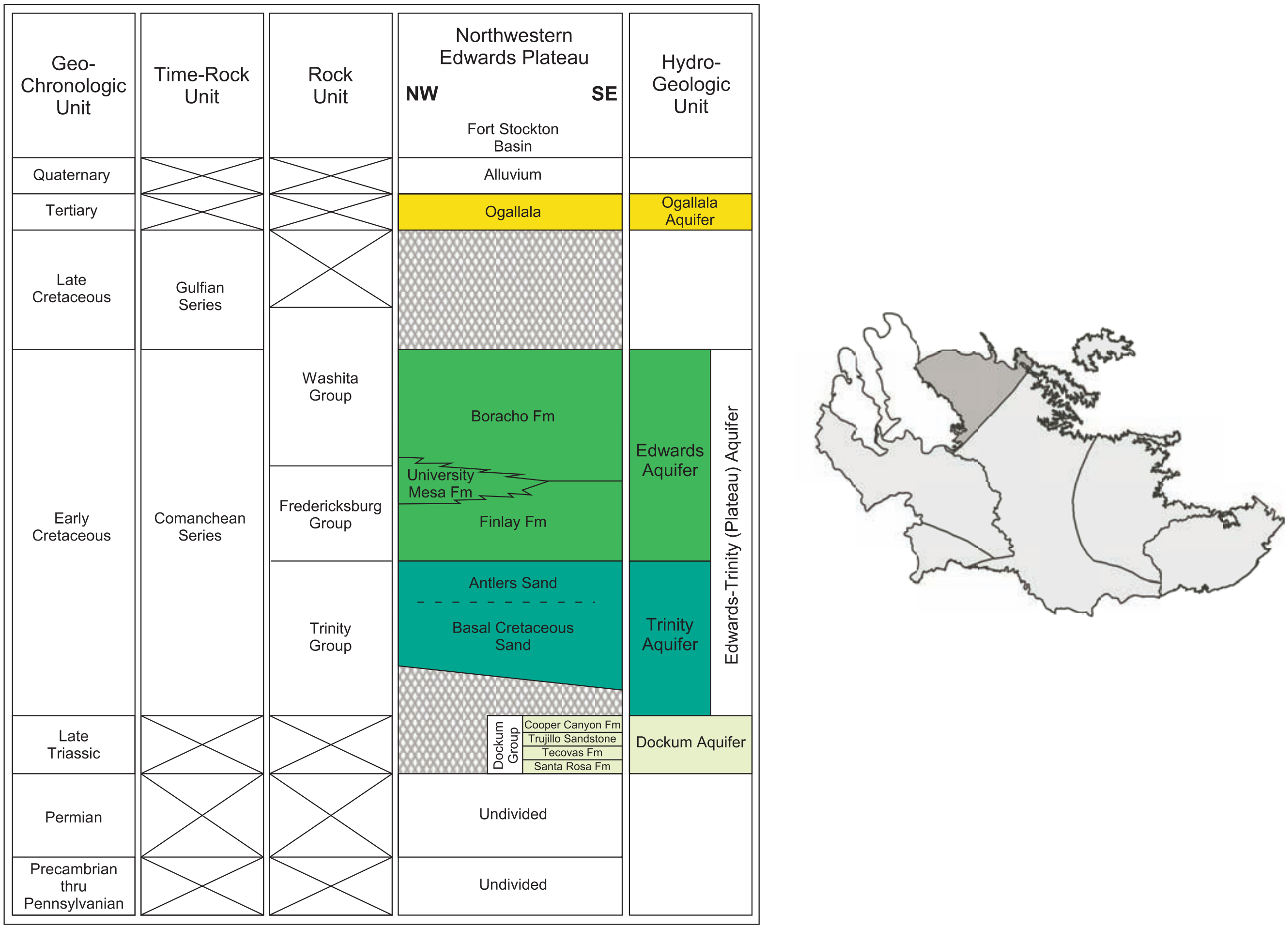

Figure 5-6. Hydrostratigraphic chart of the northwestern Edwards Plateau, Llano Estacado region.
Fm=formation

5.1.5
Southwestern Edwards Plateau (Stockton Plateau)

In general, most of the underlying Paleozoic rocks provide for a relatively impermeable base for the Edwards-Trinity (Plateau) Aquifer sediments (Barker and Ardis, 1992).

The Trinity Group is composed of the Basal Cretaceous Sand, the Glen Rose Limestone, and the Maxon Sand. The Trinity Group forms the Trinity hydrostratigraphic unit of the Edwards-Trinity (Plateau) Aquifer (Figure 5-7).

The Fredericksburg Group consists of the Telephone Canyon, Del Carmen, and lower part of the Sue Peaks formations. The Lower Washita Group is composed of the upper part of the Sue Peaks Formation in addition to the Santa Elena Formation. Locally, these units are combined and referred to as the Edwards Group Limestones, which form the Edwards hydrostratigraphic unit of the Edwards-Trinity (Plateau) Aquifer.

The Upper Cretaceous sediments include the uppermost section of the Washita Group (Del Rio Clay and the Buda Limestone) and also the Boquillas Formation of the Eagle Ford Group. The Upper Cretaceous sediments are generally considered confining units to the underlying Edwards hydrostratigraphic unit of the Edwards-Trinity (Plateau) Aquifer.

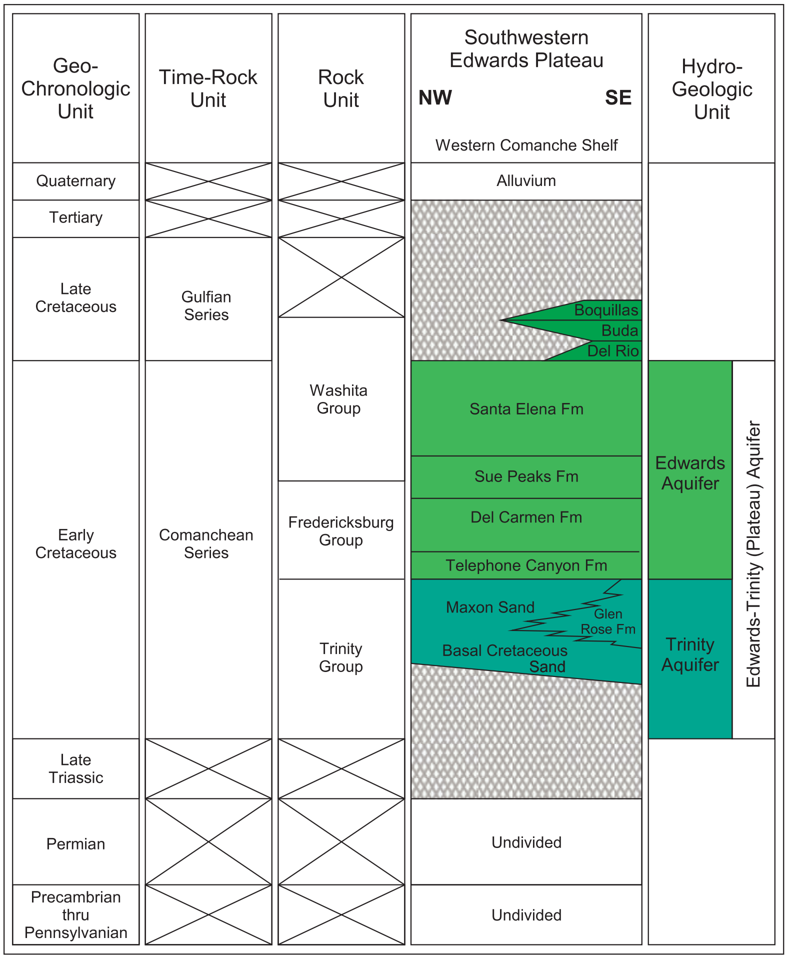

Figure 5-7. Hydrostratigraphic chart of the southwestern Edwards Plateau, Stockton Plateau region. Fm=formation

5.1.6 Western Edwards Plateau (Trans-Pecos)

The Permian age sediments of the Capitan Reef Complex and Rustler aquifers are hydraulically connected to the Edwards-Trinity (Plateau) Aquifer in the Trans-Pecos region (Bush and others, 1994) (Figure 5-8). The Dockum Group sediments of the Dockum Aquifer, which consist of the Santa Rosa, Tecovas, Trujillo, and Cooper Canyon formations (Bradley and Kalaswad, 2003), underlie parts of the Edwards-Trinity (Plateau) Aquifer. A hydraulic connection between the Edwards-Trinity (Plateau) Aquifer and the Dockum Aquifer exists where the Santa Rosa Formation is overlain by the Trinity Group (Walker, 1979).

The Trinity Group is composed of the Basal Cretaceous Sand, the Glen Rose Limestone, and the Maxon Sand. The Basal Cretaceous Sand and Maxon Sand are sometimes grouped together and referred to as the Trinity Sands where the Glen Rose Limestone is absent. In the far northwestern Trans-Pecos region, the Trinity Group is composed of the Yearwood Formation and the Cox Sandstone. The Trinity Group forms the Trinity hydrostratigraphic unit of the Edwards-Trinity (Plateau) Aquifer.

The Fredericksburg Group consists of the Fort Terrett Formation and the lower portion of the Fort Lancaster Formation within the Comanche Shelf carbonate depositional environment. It also includes the Finlay Formation and

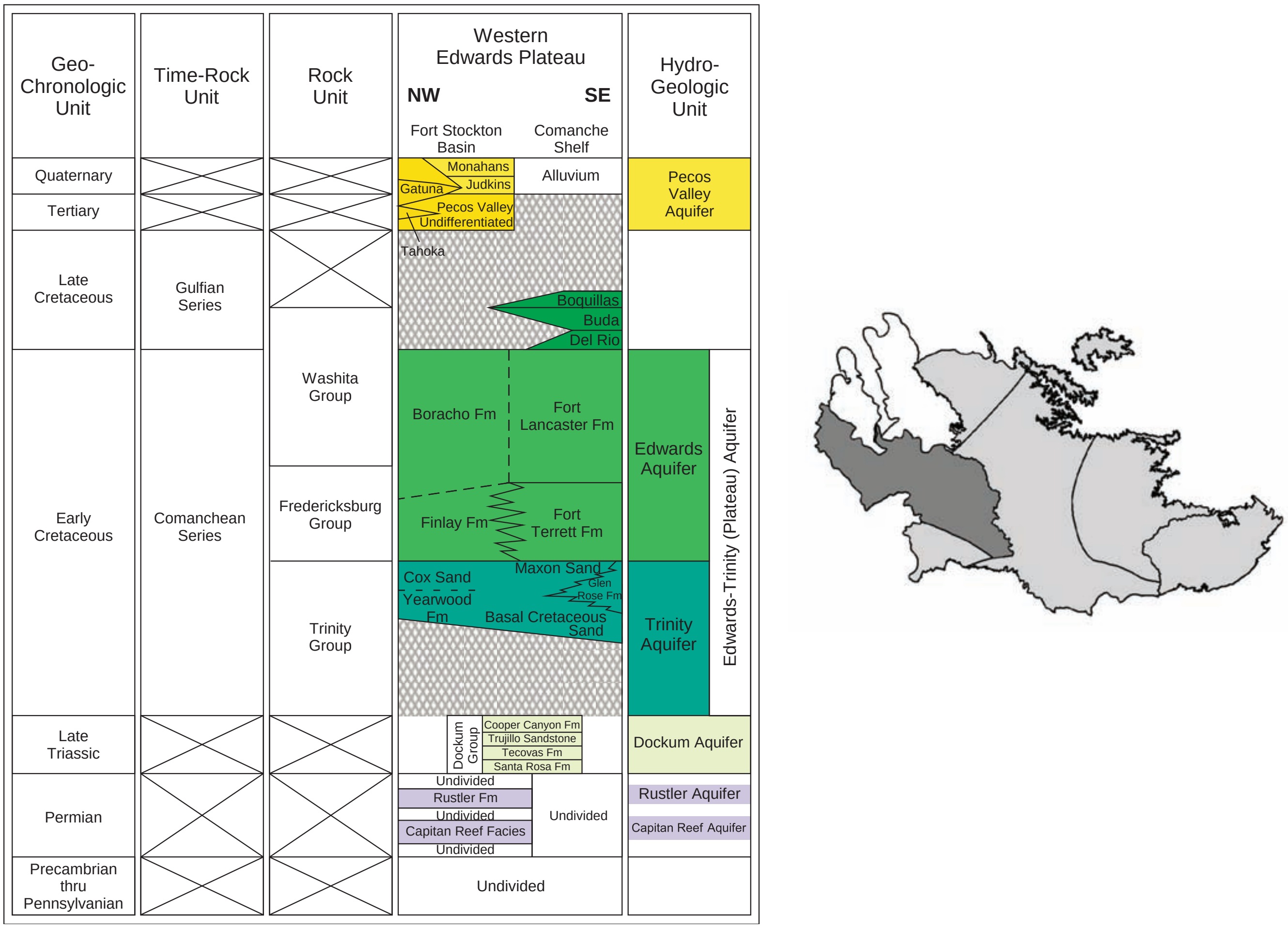

Figure 5-8. Hydrostratigraphic chart of the western Edwards Plateau, Trans-Pecos region. Fm=formation

the lower part of the Boracho Formation within the Fort Stockton Basin depositional environment. The Lower Washita Group is composed of the Fort Lancaster Formation within the Comanche Shelf and the Boracho Formation within the Fort Stockton Basin. Locally, all of these units are combined and referred to as the Edwards Group Limestones, which form the Edwards hydrostratigraphic unit of the Edwards-Trinity (Plateau) Aquifer.

The Upper Cretaceous sediments include the Buda Limestone of the uppermost section of the Washita Group and the Boquillas Formation of the Eagle Ford Group. The Upper Cretaceous sediments are generally considered confining units to the underlying Edwards hydrostratigraphic unit of the Edwards-Trinity (Plateau) Aquifer.

The Tertiary and Quaternary age sediments of the Pecos Valley consist of discontinuous alluvium, lacustrine, eolian, and valley fill deposits. Hawley, Bachman and Manley (1976) suggest that some of the valley fill deposits may be correlated to the Ogalalla Formation. The Pliocen age Tahoka Formation consists of lacustrine depostis (BEG, 1976b). The Pliocene to Mid Pleistocene age Gatuna Formation consists of an assemblage of mudstone, siltstone, conglomerate, limestone, shale, and gypsum as well as the most dominant rock type, sand (Kelley, 1971; Kelley 1980). Eolian dune deposits of the late Pleistocene to Holocene aged Judkins and Monahans formations lie uncomformably over older alluvium and valley fill deposits primarily north of the of the Pecos River and along the

Mescalero Escarpment (Huffington and Albritton, 1941; Green, 1961; Reeves, 1972; Machenberg, 1984). These Tertiary and Quaternary age sediments are all undifferentiated and grouped into a single hydrostratigraphic unit for the Pecos Valley Aquifer.

5.2 STRUCTURAL GEOMETRY

The structural geometry refers to the three-dimensional framework of the hydrostratigraphic units delineated for the aquifers. Developing the structural geometry requires achieving a preliminary understanding of the regional tectonic and geologic controls responsible for the three-dimensional distribution of each of the hydrostratigraphic units. It also requires extensive data collection and analysis. We collected vast amounts of data from various sources, including information from paper sources that we carefully digitized. We then organized and geo-referenced the data to a common coordinate system within a geographic information system for quality control, spatial analysis, and visualization. By using geostatistical techniques within the geographic information system environment, we developed structural surfaces for the tops and bottoms of both the Edwards and Trinity hydrostratigraphic units, as well as for the Pecos Valley Aquifer.

5.2.1 Regional tectonics and geologic controls

Regional tectonics and geologic processes control the depositional environment and subsequent structural deformation of the rock sediments composing the aquifer units. Tectonics refers to the deformation of the earth's crust, which results in folding, faulting, and forming mountains and seas. As a result, changes in the geography and, consequently, the depositional and erosional environment occur—affecting the composition, lateral distribution, and thickness of the rock sediments being deposited. Additionally, the rock sediments may later be faulted and/or folded, changing the three-dimensional character of their distribution.

The initial surface upon which the Cretaceous sediments were deposited was generally flat to gently rolling and slightly tilted toward the Gulf of Mexico except for the area of the Llano Uplift, a tectonic structural high that has persisted throughout much of the geologic history of Central Texas. Consequently, both the Edwards and Trinity group sediments were deposited over the Comanche Shelf (a broad Cretaceous age continental shelf) as wedges that thicken from the north and northwest toward the Gulf of Mexico, thinning up against the more local structural high of the Llano Uplift. Although the Edwards Group was initially deposited over the Llano Uplift and later removed by erosion, the Early Cretaceous seas only rose high enough to deposit the Trinity Group sediments around the flanks of the paleogeographic Llano Islands. Other more localized structures of the Comanche Shelf, such as the San Marcos Arch, Edwards Arch, Maverick Basin, Fort Stockton Basin, East Texas-Tyler Basin, and Rio Grande Embayment, influenced the depositional composition and initial structural character of the Edwards sediments (Figure 3-22).

Throughout the Tertiary Period, dissolution of Upper Permian evaporite sediments in tandem with Laramide tectonic folding, faulting, and uplifting caused overlying Upper Triassic and Cretaceous sediments to lose structural integrity and subside into the Pecos Valley. The subsidence formed two main deep, elongated subparallel basins trending roughly north-south known as the Pecos Trough and Monument Draw Trough. Alluvial sediments filled in the two structural basins throughout the Tertiary and Quaternary Periods. (Sediments from the western Trans-Pecos uplands, as well as wind-blown sediments from east of the Pecos River, continue to fill in these two basins today.) During the latter part of the Tertiary Period, uplifting of the Central Texas region and accumulating basin sediments in the Gulf of Mexico created tensional forces that formed a narrow system of stair-stepped faults known as the Balcones Fault Zone ("balcones" is Spanish for stairs), displacing sediments down toward the Gulf.

Upper Cretaceous sediments cap the top of the Edwards sediments along a topographic divide between the Colorado River and the Rio Grande. Ultimately controlled by tectonic and geologic evolution, the current surface topography of the study area is a result of the erosional processes of streams draining the landscape toward the Gulf of Mexico.

5.2.2
Structural data collection and analysis

TWDB acquired digital source data from the U.S. Geological Survey developed for the Source Water Assessment and Protection program, consisting of digitized structural contour maps and point locations attributed with interpretations from well logs and cross sections. We also incorporated previously used digital source data from the groundwater availability model for the Hill Country part of the Trinity Aquifer. We digitized data from published reports, such as structural maps and cross sections from Walker (1979) and Rees and Buckner (1980) and cross sections from Barker and Ardis (1996). We added additional control data for our structural surface database by digitizing selected boundaries between geologic rock units and land surface elevations from the Bureau of Economic Geology's Geologic Atlas of Texas quadrangle sheets (BEG, 1974a, 1974b, 1976a, 1976b, 1977, 1979a, 1979b, 1981a, 1981b, 1982, 1986a, 1986b, 1994).

The data were geo-referenced into an Albers Equal Area projection optimized for Texas. Prior to developing structural surfaces, the data were analyzed for outliers with an ordinary kriging method, a geostatistical technique. Our structural surfaces were generalized as smooth, curved surfaces along fault displacements rather than the abrupt surface displacements of actual faults.

5.2.3
Trinity hydrostratigraphic unit structural base and top

The base of the Trinity hydrostratigraphic unit of the Edwards-Trinity (Plateau) Aquifer rests on a surface of Precambrian and Paleozoic (Cambrian through Pennsylvanian) sediments in the eastern third of the of the study area. In the central third of the study area, the Trinity hydrostratigraphic unit overlies mostly Permian sediments, and in the western third, it overlies Upper Permian and Upper Triassic sediments. A paleovalley is expressed within the base of the Trinity hydrostratigraphic unit coinciding with the lower Pecos River (Figure 5-9). The sloped surface of the base of the Trinity hydrostratigraphic unit increases toward the south along the Balcones Fault Zone. In addition, the base of the Trinity hydrostratigraphic unit has a localized structural high, known as the Roosevelt High (Barker and Ardis, 1992), trending mostly north-south along an axis separating Concho, Menard, and Kimble counties from Tom Green, Schleicher, and Sutton counties. The base of the Trinity hydrostratigraphic unit also rises steeply along the flanks of the Trans-Pecos uplands.

The top of the Trinity hydrostratigraphic unit is the same as the base of the Edwards hydrostratigraphic unit of the Edwards-Trinity (Plateau) Aquifer except where the Edwards Group sediments have been completely eroded away exposing Trinity Group sediments at land surface. This exposure occurs primarily within the Hill Country area and to a much lesser extent along the fringes of the plateau. In Andrews, Martin, Ector, Midland, and Glasscock counties, some of the Edwards Group sediments have

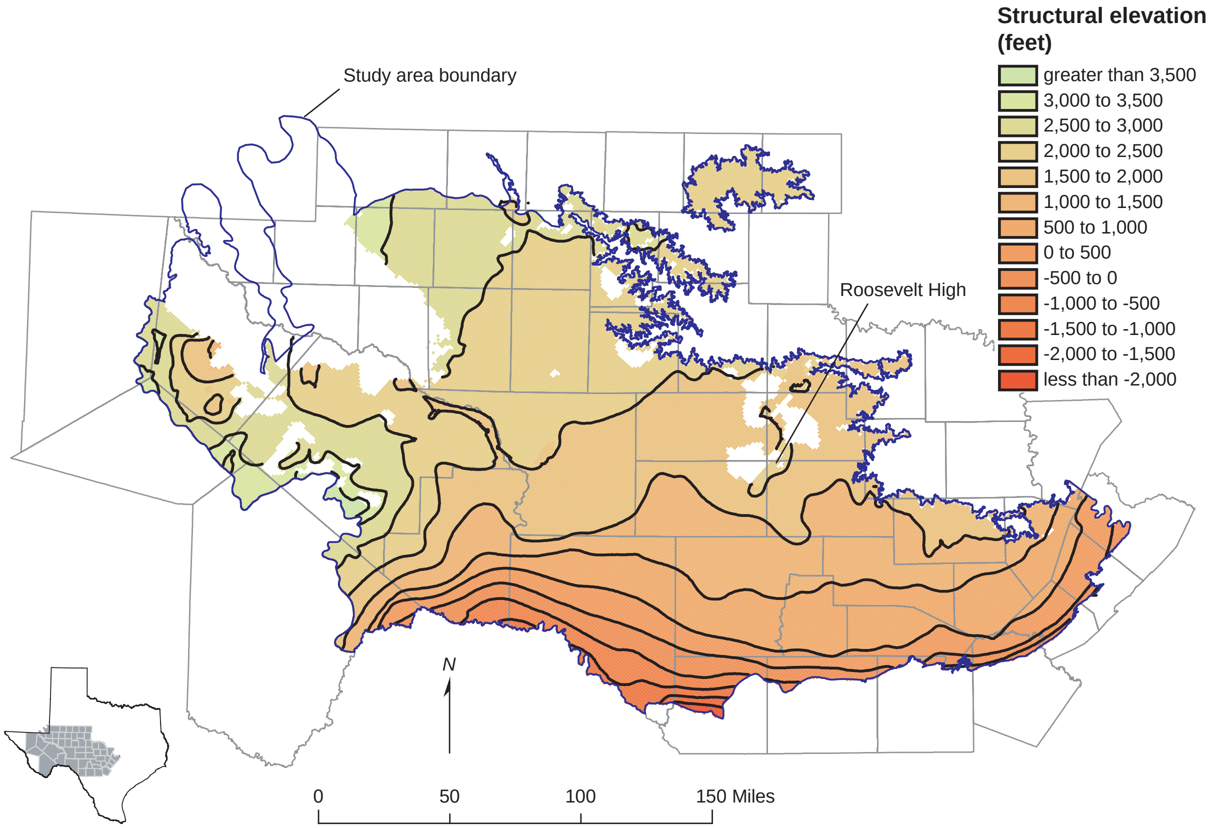

Figure 5-9. Structural base of the Trinity Group.

been removed by erosion and the Trinity hydrostratigraphic unit was subsequently overlain by Ogallala sediments along northwest-southeast trending paleochannels. The base of the Ogallala sediments serves as the top of the Trinity hydrostratigraphic unit in these channels.

5.2.4
Edwards hydrostratigraphic unit structural base and top

The base of the Edwards hydrostratigraphic unit of the Edwards-Trinity (Plateau) Aquifer coincides with the top of the Trinity hydrostratigraphic unit except where Trinity Group sediments have been completely removed by erosion or were never deposited. These windows of missing Trinity sediments expose Permian sediments to the base of the Edwards hydrostratigraphic unit in parts of eastern Schleicher, western Menard, northeastern Sutton, and southern Pecos counties. Trinity windows also reveal Upper Triassic sediments in south central Reagan and northeastern Midland counties for the base of the Edwards hydrostratigraphic unit. The base of the Edwards hydrostratigraphic unit displays the same localized structural high associated with the Roosevelt High as the underlying Trinity hydrostratigraphic unit (Figure 5-10). Additionally, a structural low along the northeastern margin of the Maverick Basin is expressed parallel to the Rio Grande in southeastern Terrell, southwestern Val Verde, and eastern Kinney counties.

The top of the Edwards hydrostratigraphic unit is equivalent to the land surface except where overlain by Ogallala sediments in the northwesternmost portion of the plateau and to a lesser extent where the Pecos Valley sediments cover them within the Trans-Pecos area. In the northwesternmost portion of the plateau,

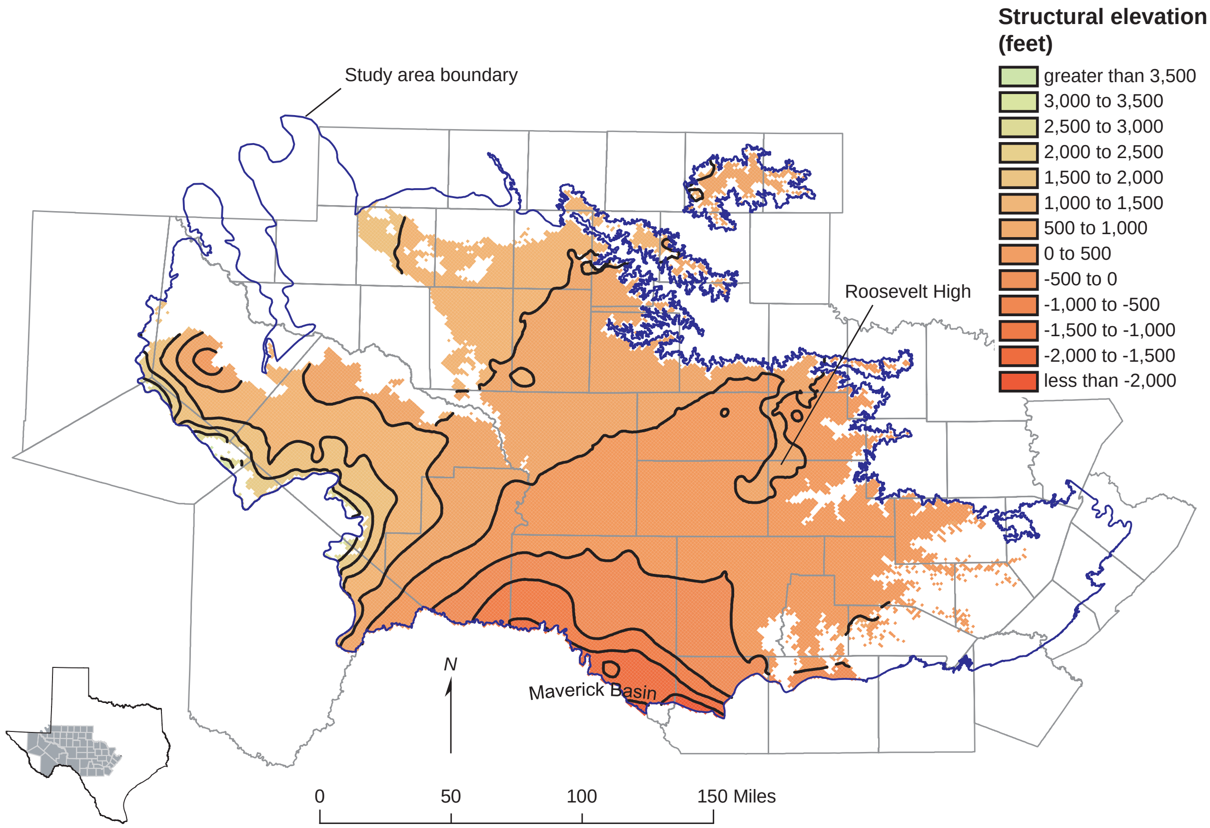

Figure 5-10. Structural base of the Edwards Group.

some of the Edwards Group sediments have been removed by erosion and subsequently overlain by Ogallala sediments along northwest-southeast trending paleochannels.

5.2.5
Pecos Valley Aquifer structural base and top

The Pecos Valley Aquifer is composed of sediments that fill two main subparallel basins known as the Pecos Trough (within Pecos and Loving counties) and the Monument Draw Trough (mostly in Winkler and Ward counties). The base of the Pecos Valley Aquifer consists of Triassic sediments in the northeast, Triassic and Permian sediments in the northwestern and central Pecos Valley, and Edwards and Trinity sediments in the southern portion of the Pecos Valley (Figure 5-11). The top of the Pecos Valley sediments coincides with their exposure at the land surface.

5.3
WATER LEVELS, SATURATED THICKNESS, AND REGIONAL FLOW

Water level data are used in conjunction with the structural geometry to calculate the aquifer's saturated thickness. The saturated thickness of an aquifer is determined by subtracting the structural base elevation of the aquifer from the elevation of the water table for any given geographical point or area. Water level analysis provides an essential understanding of the regional groundwater flow directions within an aquifer. We analyzed water levels for the Trinity and Edwards hydrostratigraphic units of the Edwards-Trinity (Plateau) Aquifer and the Pecos Valley Aquifer as represented by long-term average conditions to calculate the saturated thickness and gain an understanding of the regional groundwater flow patterns.

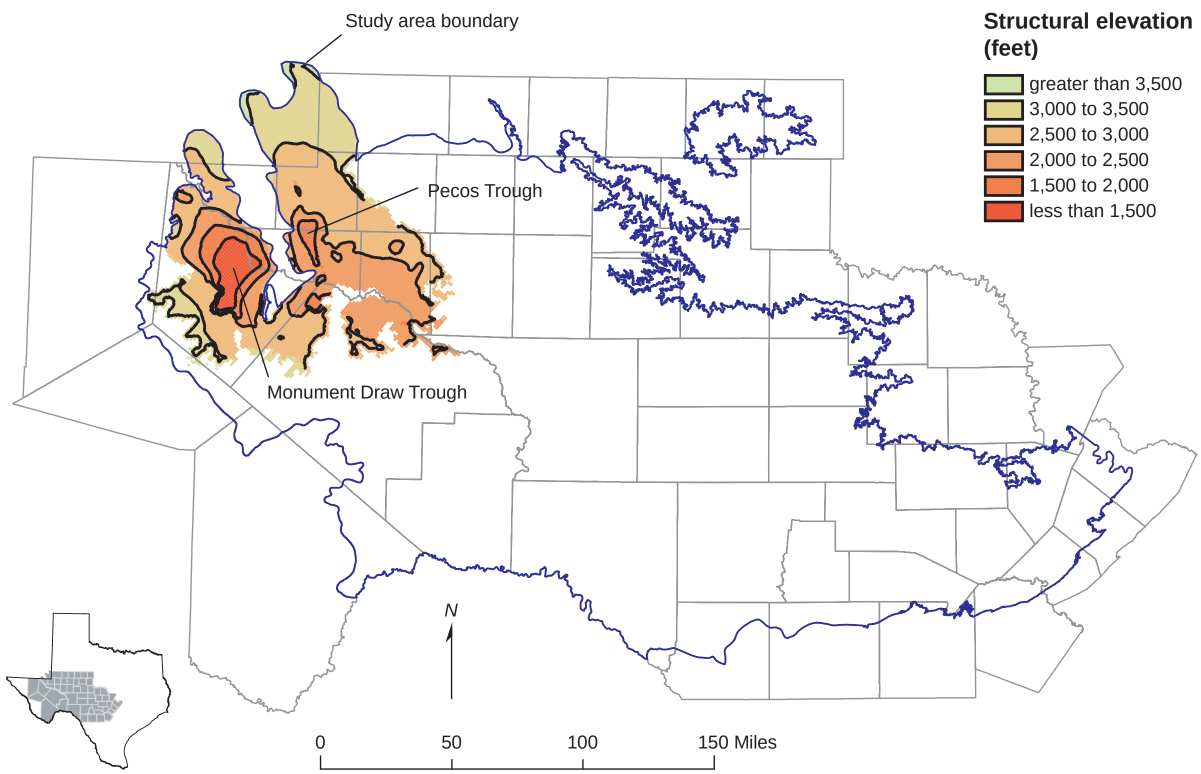

Figure 5-11. Structural base of the Pecos Valley.

5.3.1 *Water level data collection and analysis*

We queried water level data for the study area from the TWDB groundwater database, selecting the first winter measurements of each available well record and excluding measurements taken during the 1930s and 1950s drought years. We queried the selection with the assumption that the water level data represented ambient aquifer conditions with minimal influence from climate extremes and pumpage discharge. Based on our hydrograph analysis, we selected the year 1980 as a good overall representation of a steady-state condition for all of the Trinity and Edwards hydrostratigraphic units of the Edwards-Trinity (Plateau) Aquifer and the Pecos Valley Aquifer. We entered the water level data into a geographic information system and inspected it against the structural surfaces of their respective aquifer units. We accessed the data for quality assurance and interpolated it into water level or potentiometric surfaces for the Trinity and Edwards hydrostratigraphic units of the Edwards-Trinity (Plateau) and Pecos Valley aquifers, using an ordinary kriging geostatistical technique.

5.3.2 *Trinity hydrostratigraphic unit water levels, saturated thickness, and regional flow*

The Trinity hydrostratigraphic unit of the Edwards-Trinity (Plateau) Aquifer may be confined to semiconfined locally where relatively impermeable sediments of the overlying basal member of the Edwards Group exist. Although agricultural pumping has caused water level declines within the Trinity hydrostratigraphic unit in areas of Glasscock, Upton, Midland, and Reagan counties, water levels have historically remained fairly constant for most of the Edwards Plateau since 1980 (Ashworth and Hopkins, 1995). In the Hill Country, water levels of the Trinity hydrostratigraphic unit have declined over the

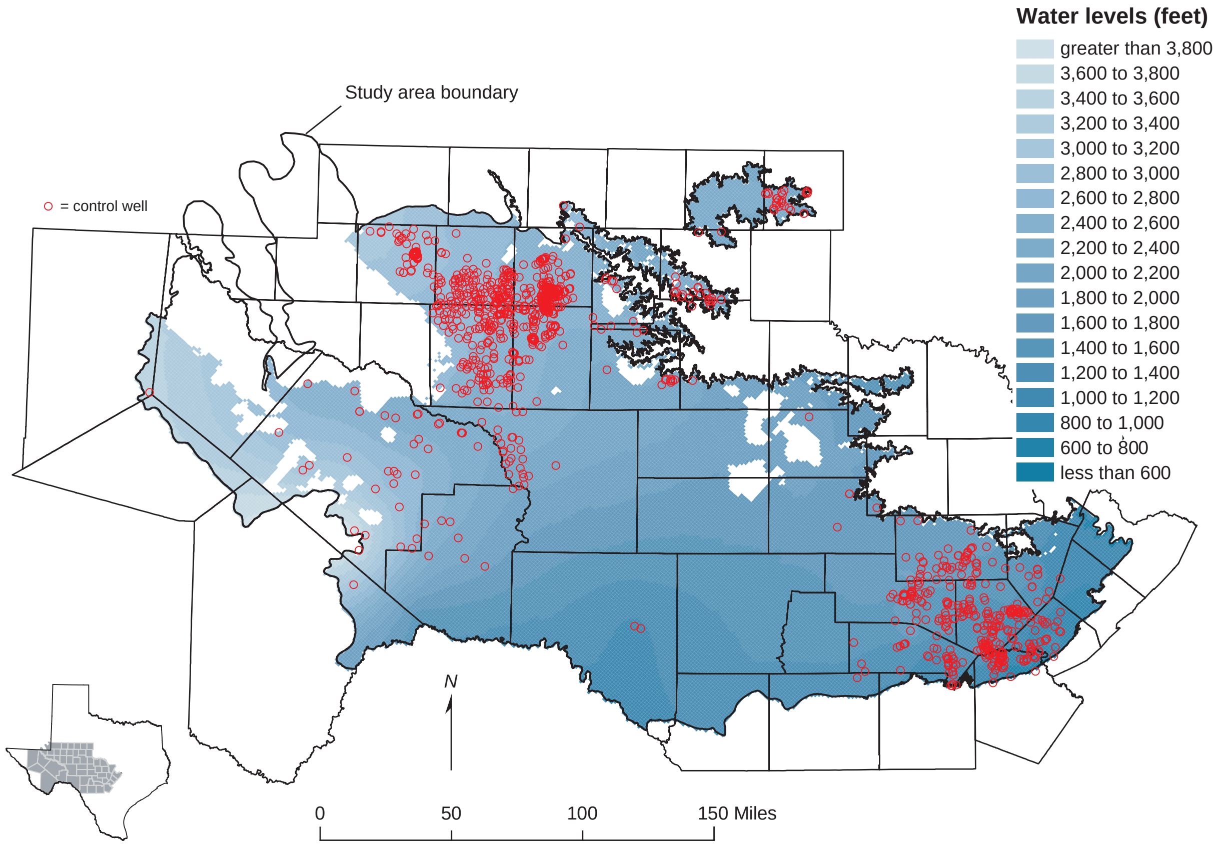

Figure 5-12. Average winter water levels for the Trinity hydrostratigraphic unit of the Edwards-Trinity (Plateau) Aquifer.

past 25 years in areas of Kerr, Kendall, Bandera, Bexar, and Hays counties due to significant population growth and development (Mace and others, 2000). In addition, water levels are also sensitive to climate variations where the Trinity hydrostratigraphic unit is less than about 100 feet thick.

Trinity water levels in the Trans-Pecos region show a steep gradient toward the Pecos River and the Rio Grande (Figure 5-12). The water level pattern suggests that the Trinity hydrostratigraphic unit provides water to the lower reaches of the Devils River and to Amistad Reservoir in southern Val Verde County. A cone of depression is expressed in the central part of the Reagan-Glasscock County boundary, historically an area of concentrated groundwater irrigation. Anomalous low water levels also exist within an area of concentrated oil production in the west central part of Midland County. To the north and east of the Pecos River, the water levels have a more gentle and subdued surface. Water levels for the Trinity hydrostratigraphic unit continue with the gentle surface gradient south toward the Balcones Fault Zone and southeast into the Hill Country. The Medina River and Medina Lake appear to provide a primary outlet for the Trinity hydrostratigraphic unit within the Hill Country.

Gentle north-south trending ridges and troughs of the folded Paleozoic base depositional surface, combined with the topographic influence on the water table, control the variability in saturated thickness for the Edwards-Trinity (Plateau) Aquifer (Barker and Ardis, 1996). The saturated thickness of the Trinity hydrostratigraphic unit is thinnest in the northern area of its extent and has a maximum saturated thickness of over 3,500 feet in central Kinney County. In southern Terrell County near the Val Verde County line, the saturated thickness is about 2,300 feet (Figure 5-13).

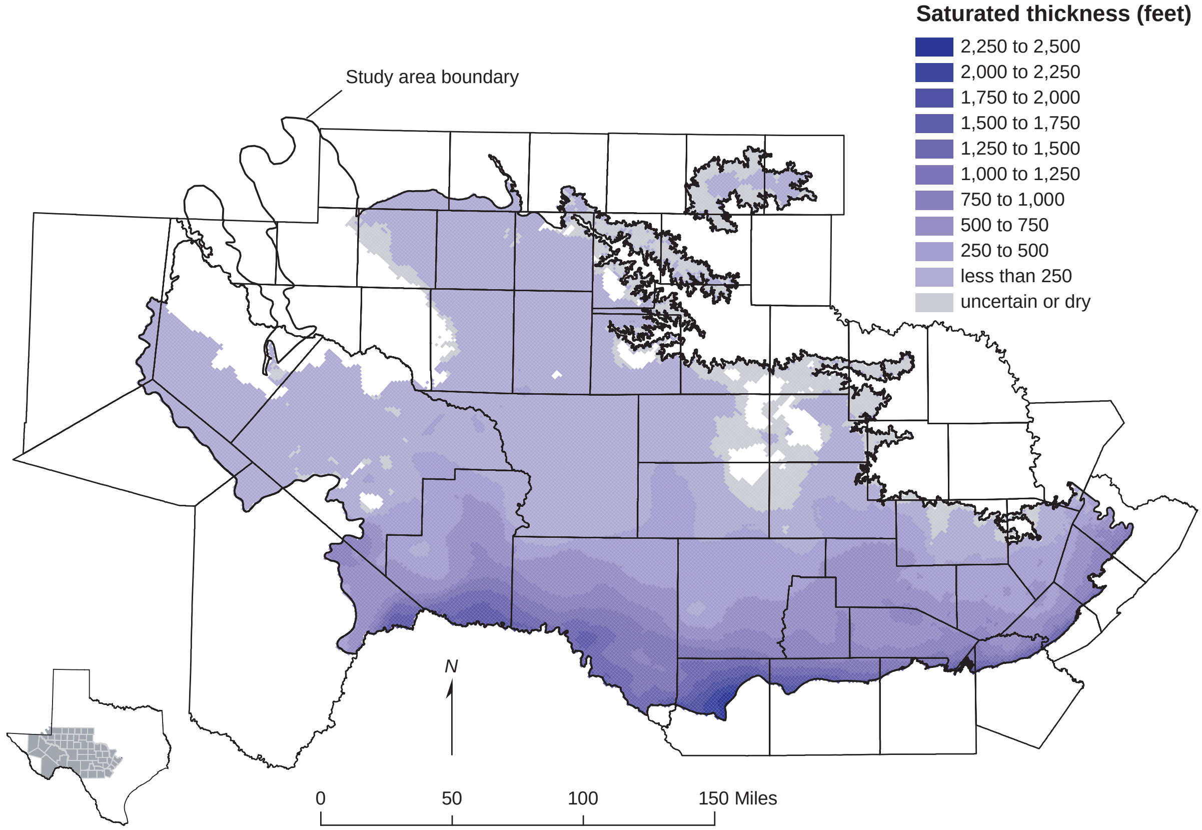

Figure 5-13. Saturated thickness of the Trinity hydrostratigraphic unit of the Edwards-Trinity (Plateau) Aquifer.

5.3.3 Edwards hydrostratigraphic unit water levels, saturated thickness, and regional flow

The Edwards hydrostratigraphic unit of the Edwards-Trinity (Plateau) Aquifer is unconfined throughout most of the study area. Water levels in the Edwards hydrostratigraphic unit fluctuate very little and only in response to variations in climate. Consequently, water levels have remained fairly constant throughout history.

Water levels for the Edwards hydrostratigraphic unit show a steep gradient toward the Rio Grande in Terrell County, as well as in the southern part of the aquifer just to the north of the Balcones Fault Zone in Val Verde, Edwards, and Kinney counties (Figure 5-14). A small anomaly of low water levels appears in southern Reagan County near Big Lake. The middle reach of the Devils River affects Edwards water levels in the southeastern corner of Crockett County. A mounding of the water level surface is visible in southwestern Kerr and northeastern Real counties, forming a southwest-northeast trending, saddle-shaped valley through northern Edwards and southeastern Kimble counties. A regional groundwater divide coinciding with the surface topography trends from Ector County in the northwest toward the southeast and terminates in the saddle-shaped valley. The groundwater divide separates groundwater flowing toward the Colorado River from groundwater flowing toward the Pecos River and Rio Grande. On the southeast side of the Kerr-Real water level mound, groundwater flows toward the Balcones Escarpment and into the Guadalupe, San Antonio, and Nueces river basins.

The saturated thickness of the Edwards hydrostratigraphic unit is thinnest in the northern area of its extent

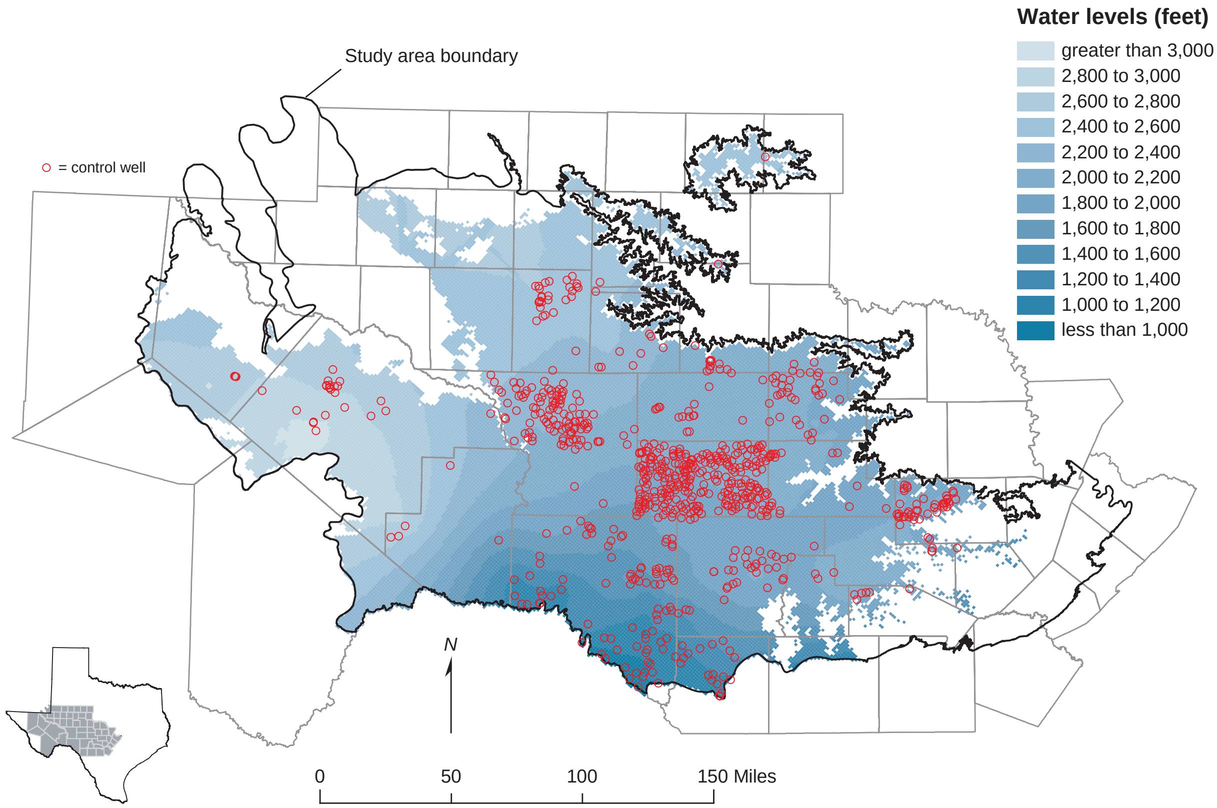

Figure 5-14. Average winter water levels for the Edwards hydrostratigraphic unit of the Edwards-Trinity (Plateau) Aquifer.

between the Llano Estacado and the Llano Uplift. It has a maximum saturated thickness along the Balcones Escarpment, with over 1,500 feet of thickness in central Kinney County (Figure 5-15). The Edwards hydrostratigraphic unit is generally dry in the Trans-Pecos and Llano Estacado in the western and northwestern parts of the study area, respectively.

5.3.4
Pecos Valley Aquifer water levels, saturated thickness, and regional flow

The Pecos Valley Aquifer is an unconfined aquifer. A general trend of declining water levels occurred during the 1940s and 1950s and peaked during the 1960s due to intense irrigation pumpage within areas of Reeves and Pecos counties (Ashworth, 1990; Jones, 2004). However, both of these areas have shown a slight recovery in their water levels since the mid-1970s (Ashworth and Hopkins, 1995).

The Pecos Valley Aquifer water levels show a steep gradient toward the Pecos Trough from the Trans-Pecos uplands to the west (Figure 5-16). Anomalously low water levels are visible in northern Pecos and central Reeves counties where intense irrigation pumpage has formed cones of depression and diverted natural groundwater flow away from the Pecos River. Northeast of the Pecos River, the water level surface is much less steep toward the Monument Draw Trough. The Pecos River influences groundwater flow in the western part of the aquifer and serves as the primary sink for the western third of the study area. Some groundwater flow in this part of the aquifer occurs as cross-formational flow from the Edwards-Trinity (Plateau) Aquifer off the eastern flanks of the Trans-Pecos mountains into the Pecos Valley Aquifer. Groundwater flow within the Pecos Valley Aquifer and east of the Pecos River is generally from the north and northwest toward the Pecos River.

The saturated thickness of the Pecos

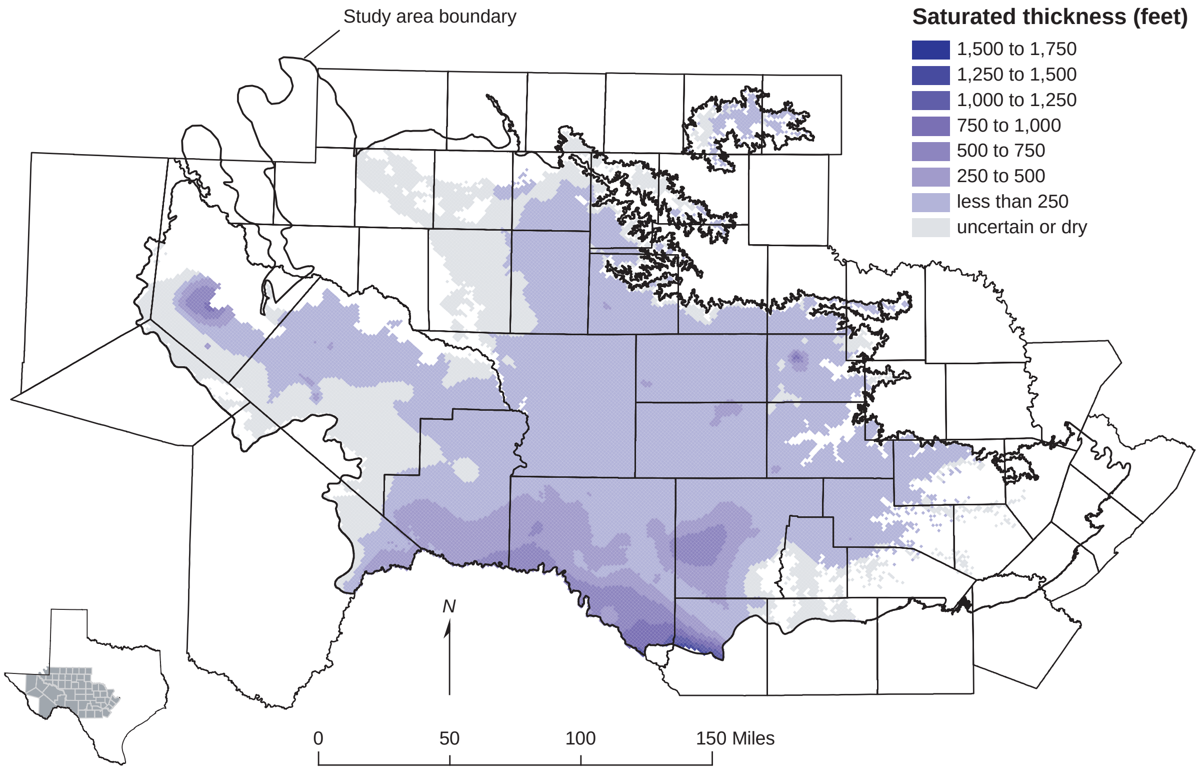

Figure 5-15. Saturated thickness of the Edwards hydrostratigraphic unit of the Edwards-Trinity (Plateau) Aquifer.

Valley Aquifer varies from less than 100 feet to over 1,400 feet (Figure 5-17). The northern part of the Monument Draw Trough in Winkler County has a saturated thickness of about 800 feet, although it is much smaller than the area of more than 1,400 feet of saturated thickness occurring in the Pecos Trough, a few miles west of the town of Pecos in Reeves County.

5.4 HYDRAULIC PROPERTIES

The hydraulic properties refer to the characteristics of an aquifer that enable groundwater to flow through the aquifer. Hydraulic properties generally consist of hydraulic conductivity, transmissivity, and storativity. The lithologic composition of an aquifer unit is the principal control on its hydraulic properties, although groundwater chemistry, faulting, and fracturing may also have a significant influence.

5.4.1 Hydraulic data collection and analysis

Hydraulic conductivity describes the ease with which water can flow through the aquifer sediments. Except for areas of significant karst-enhanced conductivity, the average hydraulic conductivity for the combined Edwards-Trinity (Plateau) and Pecos Valley aquifers is about 10 feet per day based on transmissivity and saturated thickness distributions calculated by Barker and Ardis (1996). We queried the TWDB groundwater database for specific-capacity test data measured at geographically defined well locations and used it to calculate hydraulic conductivity values (Mace, 2001) for the Edwards and Trinity hydrostratigraphic units and the Pecos Valley Aquifer. We also collected specific-capacity test data from the Texas Commission on Environmental Quality and analyzed it to calculate hydraulic conductivity values for both

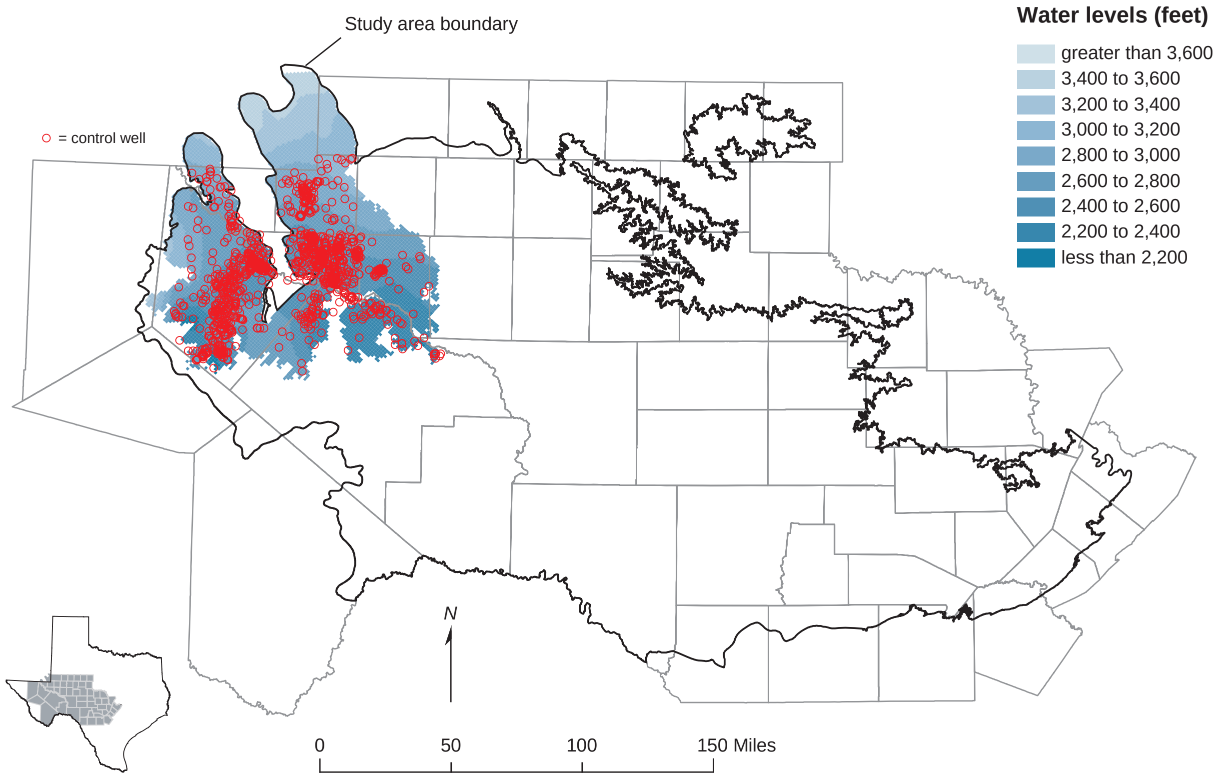

Figure 5-16. Average 1940 water levels for the Pecos Valley Aquifer.

the Edwards and Trinity hydrostratigraphic units. The specific-capacity test data lacked geographical coordinates and were spatially referenced only to standard two and one-half minute quadrangles. Consequently, for our analysis, we located the specific-capacity data at the center of their respective quadrangles. We then collected pumping test data from the TWDB groundwater database and analyzed it to calculate hydraulic conductivity for both the Edwards and Trinity hydrostratigraphic units. In addition, we conducted one or more pumping tests specifically for this modeling study in almost every county of the Edwards-Trinity (Plateau) Aquifer during the year 2000. We also used hydraulic properties data incorporated into the Source Water Assessment and Protection geographic information system database developed by the U.S. Geological Survey. We included conductivity data from the groundwater availability model study of the Hill Country part of the Trinity Aquifer (Mace and others, 2000). In total, we used about 190 conductivity values for the Edwards hydrostratigraphic unit, about 655 conductivity values for the Trinity hydrostratigraphic unit, and about 56 conductivity values for the Pecos Valley Aquifer. We spatially interpolated the calculated conductivity data using an ordinary kriging geostatistical technique for visualization and then analyzed the data with traditional exploratory statistics (Figure 5-18, Figure 5-19, and Figure 5-20).

Transmissivity is the multiplication product of the hydraulic conductivity and the saturated thickness of the aquifer sediments. Transmissivity values in the Edwards-Trinity (Plateau) and the Pecos Valley aquifers are less than 5,000 feet-squared per day in the thinner portions of the aquifers and between 5,000 and 50,000 feet-squared per day in the

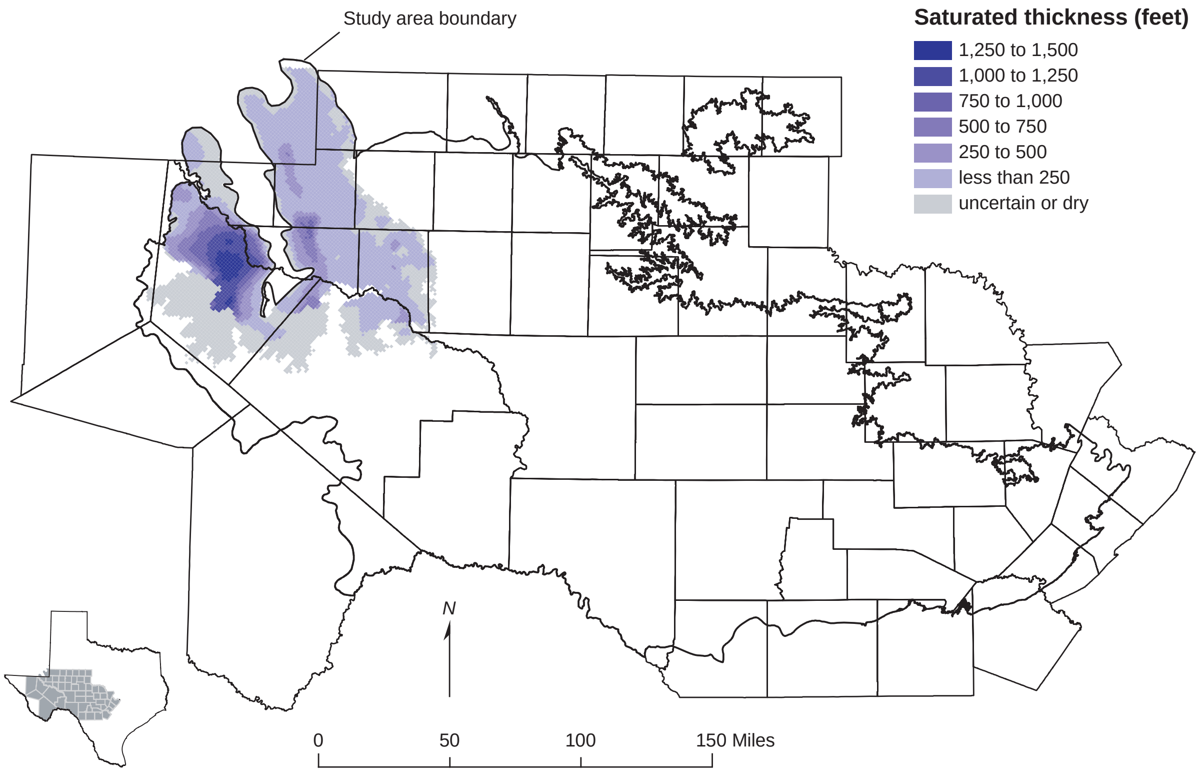

Figure 5-17. Saturated thickness of the Pecos Valley Aquifer.

thicker portions, with an average of less than 10,000 feet-squared per day (Barker and Ardis, 1996). We calculated transmissivity values for the Edwards and Trinity hydrostratigraphic units and the Pecos Valley Aquifer by multiplying their saturated thickness by the calculated geometric means of their hydraulic conductivities.

Storativity is a hydraulic property that describes the amount of water released from or taken into aquifer sediments due to a change in hydraulic head. Storativity is often expressed as a storage parameter, such as specific storage, storativity, or specific yield. Specific storage is a measure of the volume of water released from aquifer storage per unit volume of aquifer sediments per unit decline in water level. The storativity is analogous to transmissivity in that it is the multiplication product of the specific storage and the saturated thickness and measures the volume of water released from aquifer storage per unit "area" of aquifer sediments per unit decline in water level. The specific yield measures the volume of water released as drainage under gravity from aquifer storage per unit volume of aquifer sediments per unit decline in water level. Storage parameters must be determined from aquifer or pumping tests and are commonly subject to error; therefore, these data are usually very limited (Anderson and Woessner, 1992). We calculated average storativity values for the Edwards and Trinity hydrostratigraphic units and the Pecos Valley Aquifer based on available pumping tests and evaluated them against those found in published studies.

5.4.2 Trinity hydrostratigraphic unit hydraulic properties

The Trinity hydrostratigraphic unit has a regionally variable lithologic composition. The thin, northern part is composed only of the Trinity Sands, whereas the thicker southern part is composed of

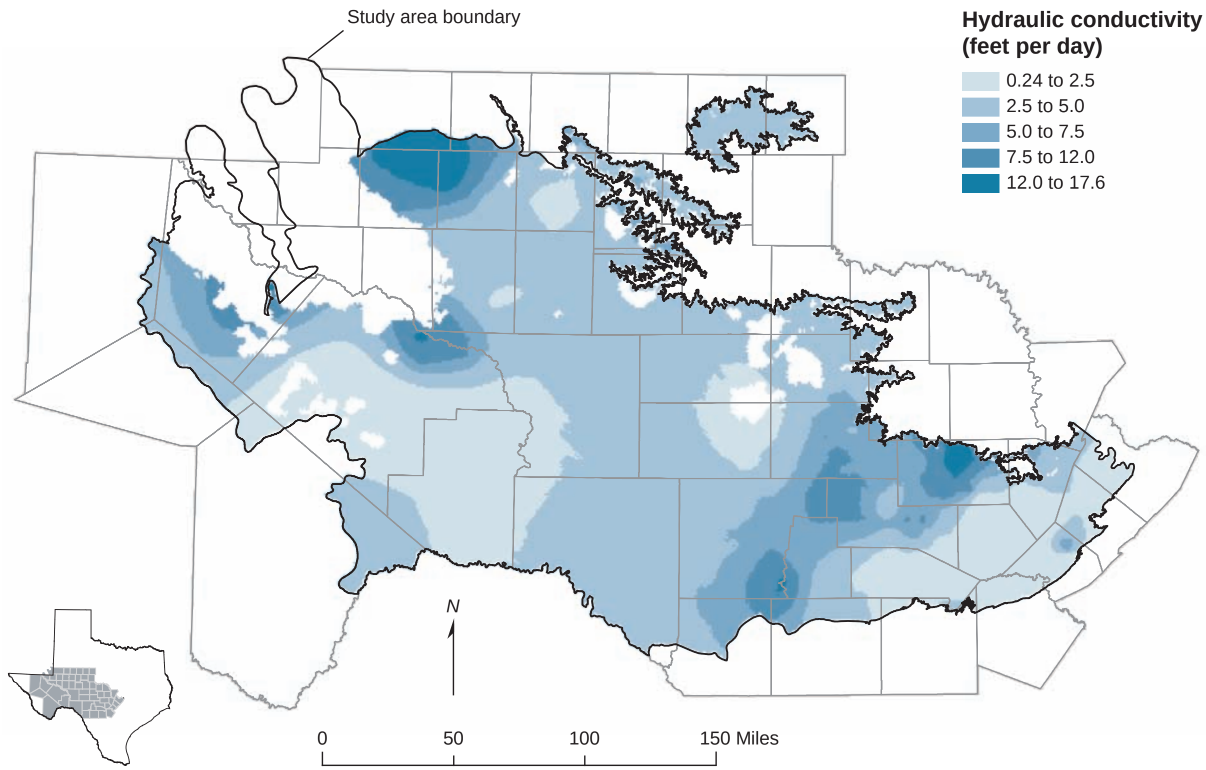

Figure 5-18. Interpolated hydraulic conductivity for the Trinity hydrostratigraphic unit of the Edwards-Trinity (Plateau) Aquifer.

a shale, sand, and limestone transgressive-regressive sequence representing the Lower, Middle, and Upper Trinity sediments. Consequently, the northern part of the Trinity hydrostratigraphic unit has a higher and more homogeneous hydraulic conductivity, and the southern part has a significant vertical anisotropy (much lower vertical hydraulic conductivity than horizontal hydraulic conductivity) expressed by the stratification of the Trinity Group sediment sequence. We used the northern updip limit of the Glen Rose Limestone to delineate the northern region of the Trinity hydrostratigraphic unit from the southern region (Figure 5-21). We calculated the geometric mean of the hydraulic conductivity for the northern part of the Trinity hydrostratigraphic unit to be about 4.5 feet per day and for the southern part to be about 2.5 feet per day. Based on the geometric mean, we calculated that transmissivity values range from less than 1 feet-squared per day to about 7,000 feet-squared per day.

Walker (1979) reported an average storativity value of 7.4×10^{-2} for the northern region of the Trinity hydrostratigraphic unit, and Ashworth (1983) reported a range in storativity values from 2×10^{-5} to 7.4 × 10-4 for the southern region of the Trinity hydrostratigraphic unit. We obtained a total of 22 storativity values, ranging from 8×10^{-6} to 6×10^{-3}, with the semiconfined and confined portions of the Trinity hydrostratigraphic unit tending toward the lower values and the unconfined portions tending toward the higher values.

5.4.3 Edwards hydrostratigraphic unit hydraulic properties

The Edwards hydrostratigraphic unit has a relatively high hydraulic conductivity because of the mostly massive limestone composition of the Edwards Group sediments. Furthermore, the karst dissolution of these sediments

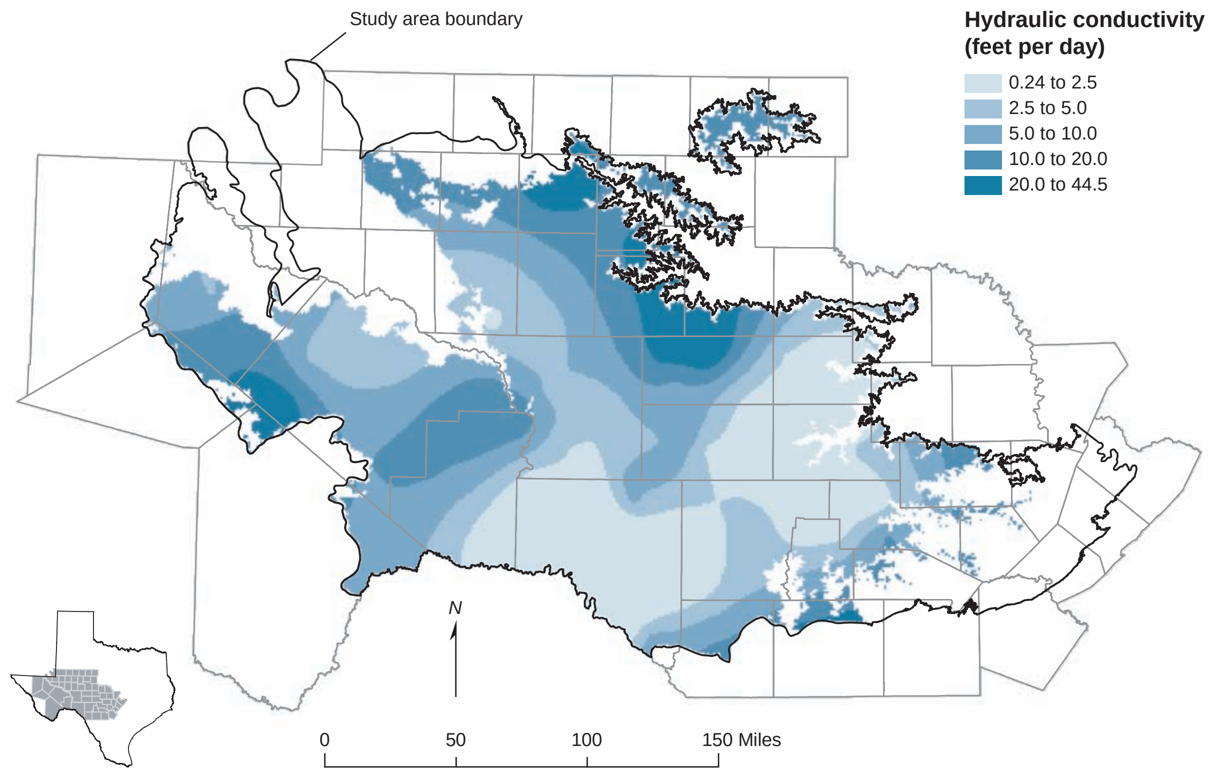

Figure 5-19. Interpolated hydraulic conductivity for the Edwards hydrostratigraphic unit of the Edwards-Trinity (Plateau) Aquifer.

has enhanced the local variability of the hydraulic conductivity within the Edwards hydrostratigraphic unit, especially where the upper, more karst-soluble formations of the Edwards Group exist. We calculated the geometric mean of the hydraulic conductivity for the Edwards hydrostratigraphic unit to be about 6.7 feet per day. Based on the geometric mean, our calculated transmissivity values range from less than 1 feet-squared per day to about 8,000 feet-squared per day. Only two specific yield values were available for the Edwards hydrostratigraphic unit, 4×10^{-3} in Terrell County and 5×10^{-3} in Sutton County.

5.4.4 Pecos Valley Aquifer hydraulic properties

The Pecos Valley Aquifer is composed of mostly alluvial sediments with a relatively high hydraulic conductivity. The geometric mean of the hydraulic conductivity for the Pecos Valley Aquifer was calculated at about 8.6 feet per day. Based on the geometric mean, our calculated transmissivity values range from less than 1 feet-squared per day to about 14,000 feet-squared per day. Storativity values were not available for the Pecos Valley Aquifer, although specific yields for sand and gravel alluvium commonly range from 0.1 to 0.25 (Fetter, 1988; Domenico and Schwartz, 1990; Anderson and Woessner, 1992).

5.5 RECHARGE

Recharge rates vary with climate conditions, surface geology, surface topography, soils, vegetation, and land use. The high evaporation rates characteristic of the semiarid to arid climate of the region suggest that large and/or frequent storm events are needed to generate effective recharge to the

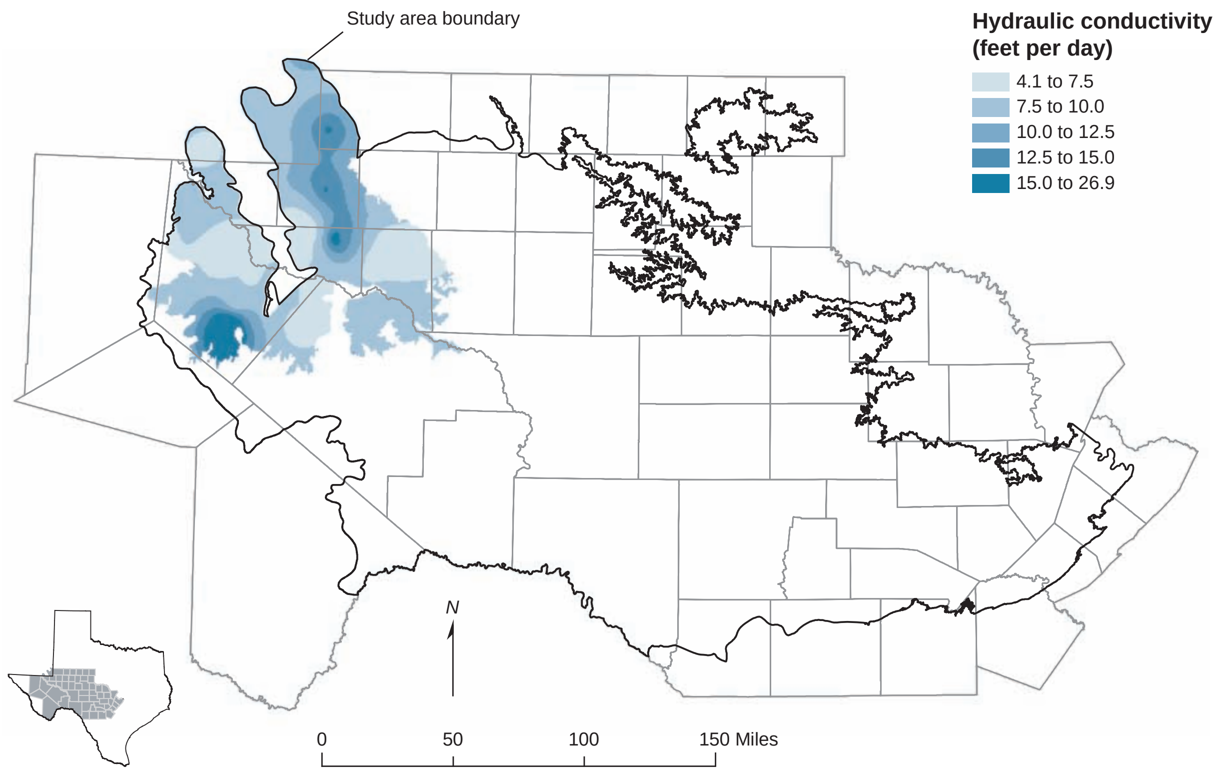

Figure 5-20. Interpolated hydraulic conductivity for the Pecos Valley Aquifer.

aquifers within the study area. Natural recharge to the Edwards-Trinity (Plateau) Aquifer occurs from the diffuse recharge from precipitation over the aquifer's outcrop, direct recharge from surface runoff into sinkholes, and direct recharge from stream losses by numerous intermittent streams. In the northwestern portion of the aquifer, a relatively small amount of groundwater from the Ogallala Aquifer enters the Edwards-Trinity (Plateau) Aquifer as cross-formational flow (Blandford and Blazer, 2004). Cross-formational flow also occurs in the Trans-Pecos region from the Edwards-Trinity (Plateau) Aquifer to the Pecos Valley Aquifer. In addition, irrigation diversions from the Pecos River are estimated to be over 50 percent of the recharge to the Pecos Valley Aquifer as seepage from irrigation fields (Ashworth, 1990). Induced recharge is believed to occur in Pecos and Reeves counties as a result of localized water level declines due to irrigation pumpage from the Pecos Valley Aquifer (Barker and Ardis, 1996).

Long (1958) estimated recharge for Real County to be about 2.0 inches per year. Iglehart (1967) estimated recharge in Crockett County to be about 0.3 inches per year, and Reeves (1969) estimated recharge in Kerr County to be about 1.0 inches per year. Rees and Buckner (1980) estimated recharge over the Trans-Pecos region of the plateau west of the Pecos River to be between about 0.3 and 0.4 inches per year. Using base flow analysis, Kuniansky (1989) estimated recharge over the eastern portion of the Edwards-Trinity (Plateau) Aquifer to range between 0.1 and 2.2 inches per year. Recharge to the Pecos Valley Aquifer is estimated at about 67,800 acre-feet per year (Ashworth, 1990). Mace and others (2000) estimated recharge in the Hill Country part of the Trinity area to be about 1.5 inches per year. Mace and

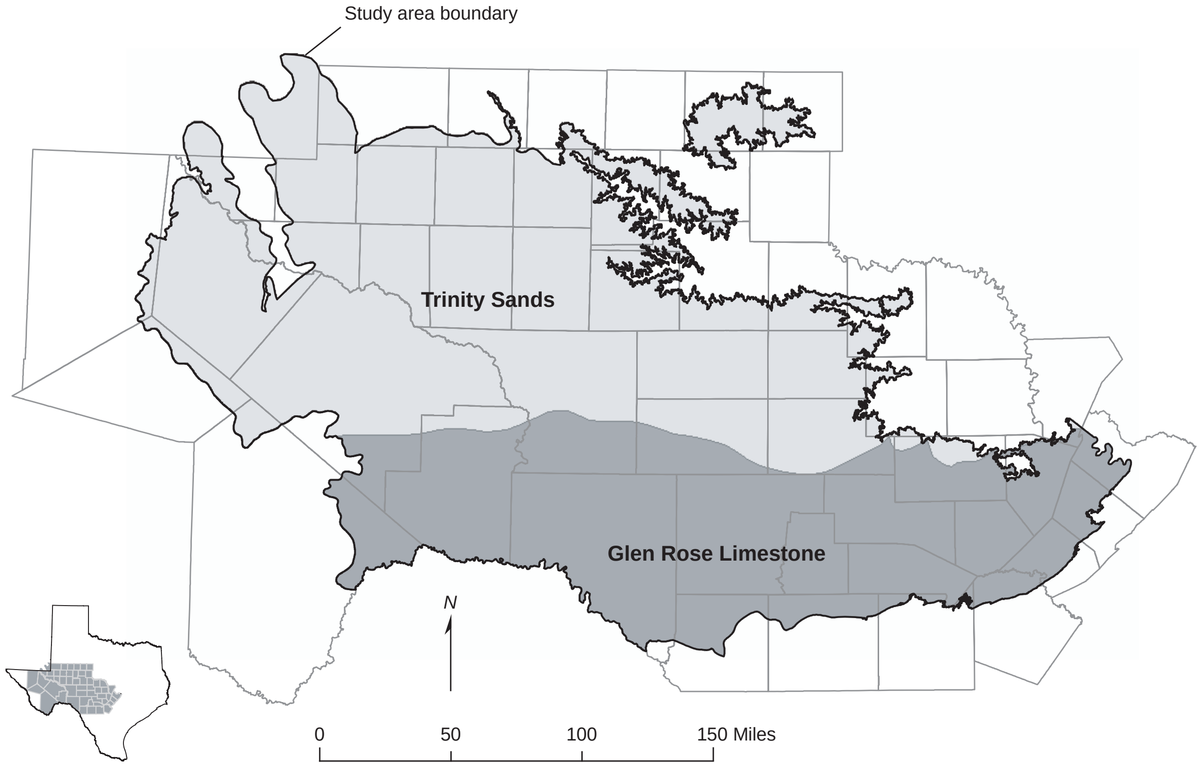

Figure 5-21. Delineation between the Trinity Sands and Glen Rose Limestone extents of the Trinity hydrostratigraphic unit of the Edwards-Trinity (Plateau) Aquifer.

Anaya (2004) estimated a long-term mean annual recharge of about 2.5 inches per year (or about 10.5 percent of long-term average annual rainfall) for northern Kinney County.

5.6 PUMPAGE DISCHARGE

The Edwards hydrostratigraphic unit provides most of the water in the central, southern, and eastern portions of the plateau, and the Trinity hydrostratigraphic unit provides much of the water for the northern and western areas of the plateau and the Hill Country region (Barker and Ardis, 1996). Over three-fourths of the total groundwater pumpage from the Edwards-Trinity (Plateau) Aquifer is used for irrigation, primarily in the northern and western portions of the aquifer (Figure 5-22). Municipal water suppliers account for the second largest groundwater use, followed by industrial, mining, livestock, and rural domestic uses. Climate has a significant effect on the amount of groundwater pumpage from the Edwards-Trinity (Plateau) Aquifer because of increased irrigation pumpage during times of drought.

5.7 INTERACTIONS OF GROUNDWATER AND SURFACE WATER

Natural discharge from the Edwards-Trinity (Plateau) Aquifer occurs mostly along the margins of the aquifer from springs and seeps where the water table intersects the land surface to provide base flow to streams. Springs also discharge groundwater along the eastern flanks of the Trans-Pecos mountains and the lower Pecos River canyons. As water levels decline in the western portion of the aquifer due to increased irrigation pumpage, springflows within those areas have also declined. Many small springs that once flowed throughout the

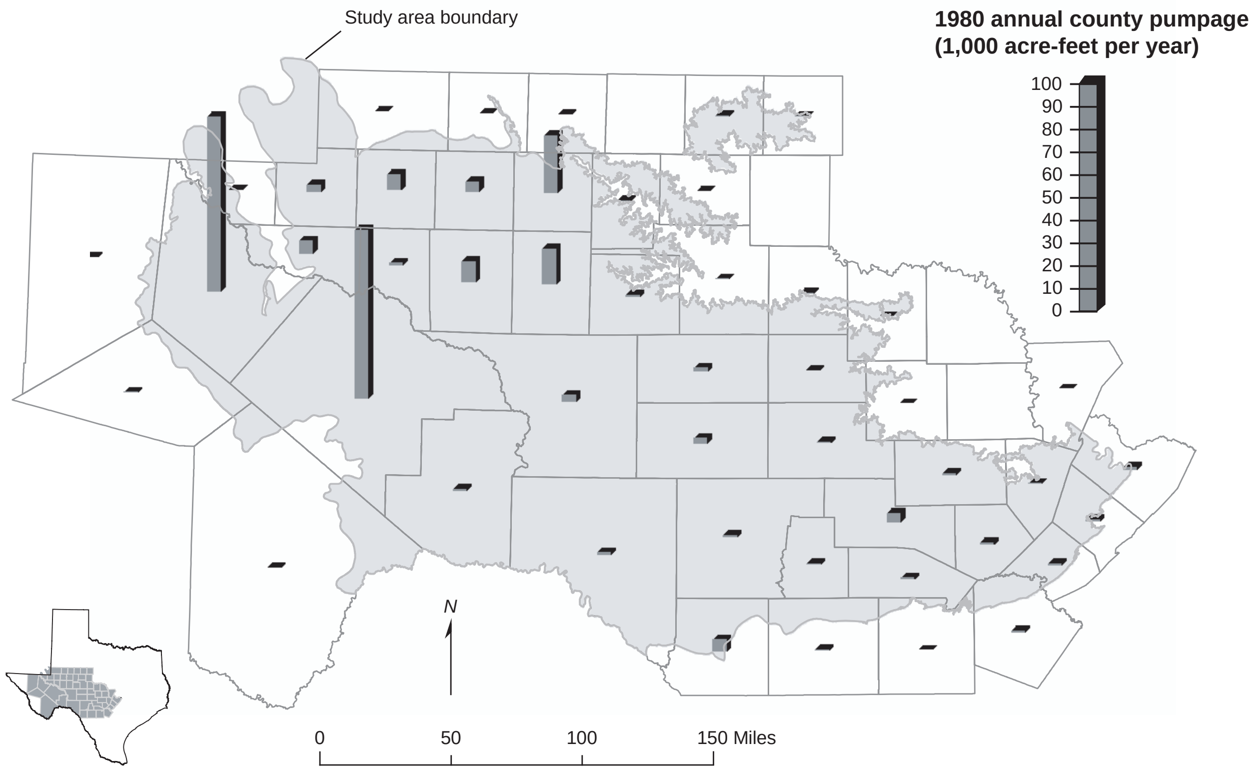

Figure 5-22. Annual groundwater pumpage for 1980 from the Edwards-Trinity (Plateau) and Pecos Valley aquifers and Hill Country part of the Trinity Aquifer by county.

plateau have ceased to flow as diminishing native grasslands have effectively reduced the recharge potential.

Most of the smaller intermittent streams high on the Edwards Plateau lose their flow to the underlying Edwards hydrostratigraphic unit. The lower reaches of major perennial streams along the northern, eastern, and southern margins of the Edwards Plateau then become gaining streams, usually where their stream channel elevation falls below the base of the Edwards hydrostratigraphic unit. These perennial streams have flashy hydrographs resulting from episodic rainfall-runoff events, and the base of the hydrograph peaks reflect base flow from the underlying aquifer (Figure 5-23). Phreatophytes (vegetation that obtains most of its water from the saturated zone of an aquifer), mostly along major stream valleys, discharge groundwater naturally through evapotranspiration where the water table is shallow enough for the root networks. Some reaches along the Pecos River are prime examples of extreme evapotranspiration by invasive saltcedar.

The Edwards-Trinity (Plateau) Aquifer interacts with reservoirs or lakes only along the southern margin of the aquifer. These manmade water bodies initially lost water to the aquifers and raised water levels in their vicinity but have all reached a fairly steady-state condition since the late 1970s. The largest of these lakes is the International Amistad Reservoir just below the confluence of the Devils River with the Rio Grande in Val Verde County (Figure 3-9). The remaining lakes are located in the Hill Country just north of the Balcones Escarpment and include Medina Lake on the Medina River in northern Medina County, Canyon Lake on the Guadalupe River in Northern Comal County, and Lake Travis and Lake Austin on the Colorado River in Travis County.

5.8
Water Quality

Although water quality is typically hard, it is generally fresh except for areas in the Trans-Pecos region where groundwater from Permian evaporite sediments and/or oil field brines is able to mix with groundwater from the Edwards-Trinity (Plateau) Aquifer (Rees and Buckner, 1980). Cross-formational flow from underlying saline Permian aquifers is also enhanced due to increasing municipal and industrial pumpage in the Monument Draw Trough portion of the Pecos Valley Aquifer (Jones, 2004). Water quality is also affected by induced recharge from Pecos River stream losses (Barker and Ardis, 1996). East of the Pecos River, oil field brines and agricultural runoff have a significant effect on the groundwater quality of the northern portion of the Edwards-Trinity (Plateau) Aquifer (Walker, 1979) as well as for the Pecos Valley Aquifer (Ashworth, 1990). The water quality is generally better within the Monument Draw Trough of the Pecos Valley (Jones, 2001).

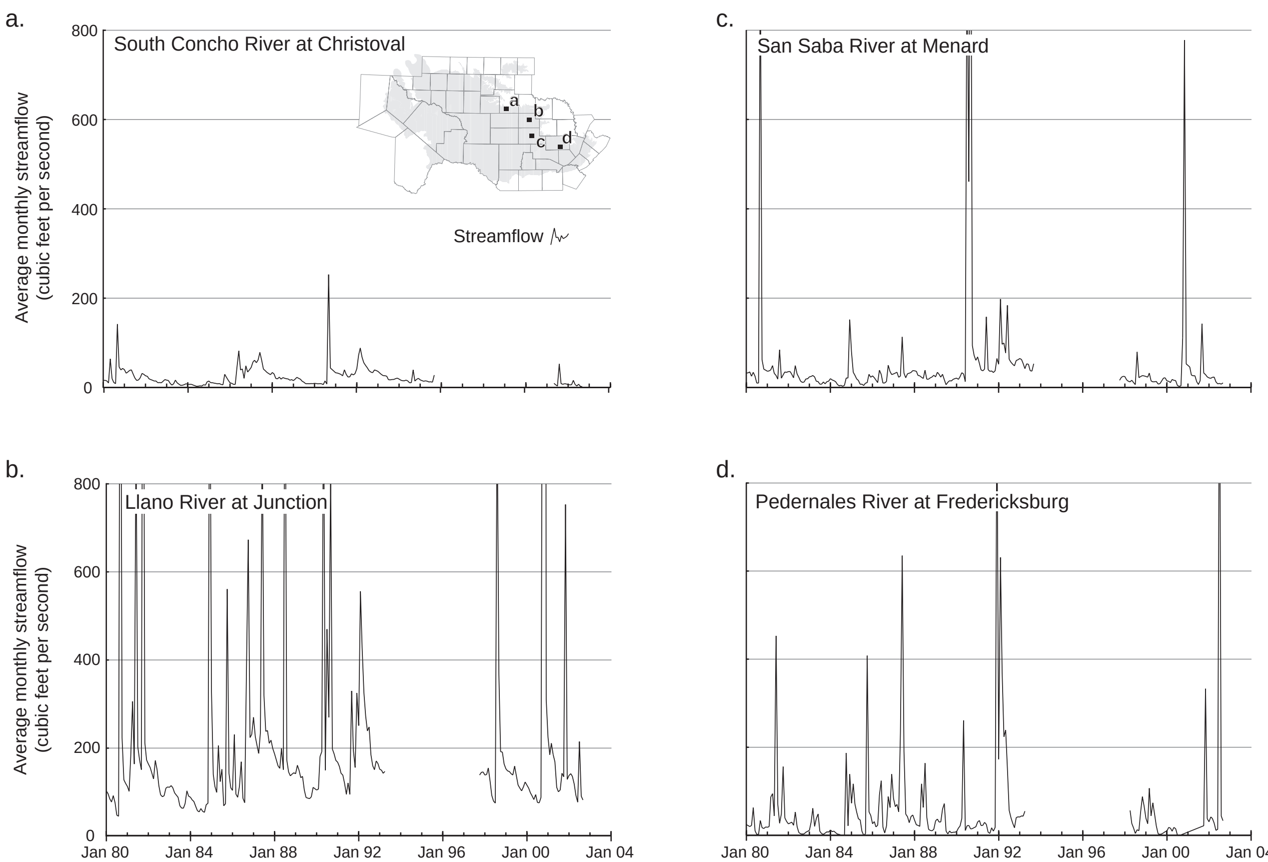

Figure 5-23. Streamflow hydrographs for major perennial streams over the Edwards-Trinity (Plateau) and Pecos Valley aquifers and Hill Country part of the Trinity Aquifer.

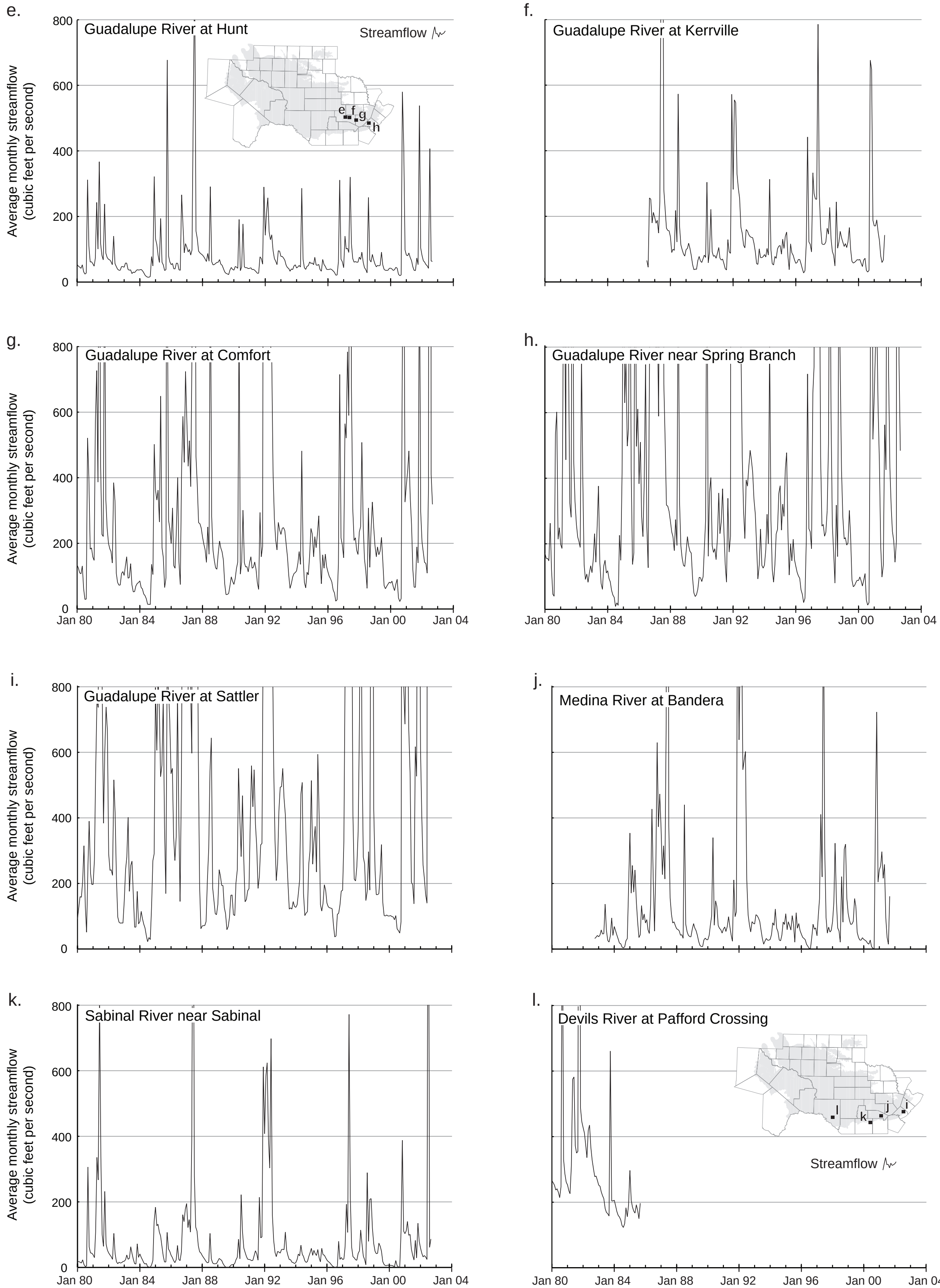

Figure 5-23 (continued).

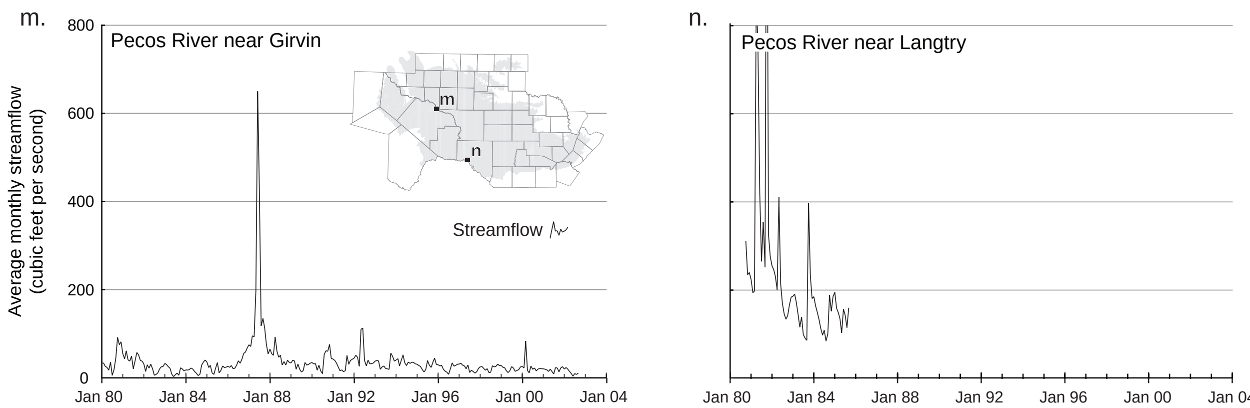

Figure 5-23 (continued).

6 *Conceptual model of the aquifers*

A conceptual model is a generalized description of the aquifer that describes the water budget; defines the hydrostratigraphic units, hydrostratigraphic aquifer boundaries and parameters, and hydrologic stress variables; and illustrates the flow system (Anderson and Woessner, 1992). The conceptual model facilitates the compilation and organization of field data and allows us to simplify the real-world aquifer flow system into a representative diagram while retaining the complexity needed to reproduce the system behavior adequately (Anderson and Woessner, 1992). The first step in developing a conceptual model is to delineate the study area and form an understanding of its physical landscape with regard to the physiography, climate, and geology. Additional tasks in developing a conceptual model must also include researching and investigating previous aquifer studies and, if possible, collecting additional field data. All of the information is then reviewed and analyzed to establish a hydrogeologic setting for the aquifer.

The conceptual model for the Edwards-Trinity (Plateau) and the Pecos Valley aquifers defines two basic hydrostratigraphic units (Figure 6-1 and Figure 6-2). The lower unit represents the partially confined Trinity hydrostratigraphic unit and is contiguously extended to the southeast to include the Hill Country part of the Trinity Aquifer. The upper

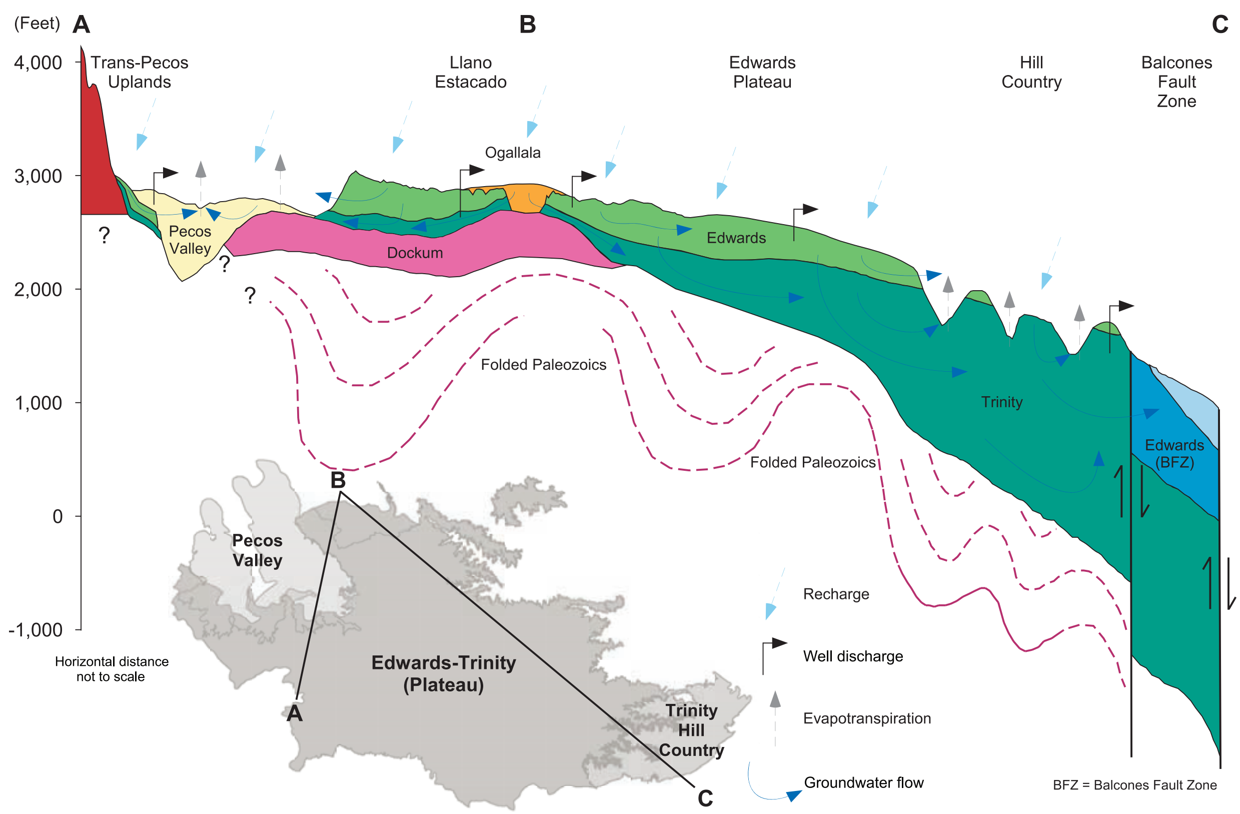

Figure 6-1. Conceptual model of the Edwards-Trinity (Plateau) and Pecos Valley aquifers and Hill Country part of the Trinity Aquifer.

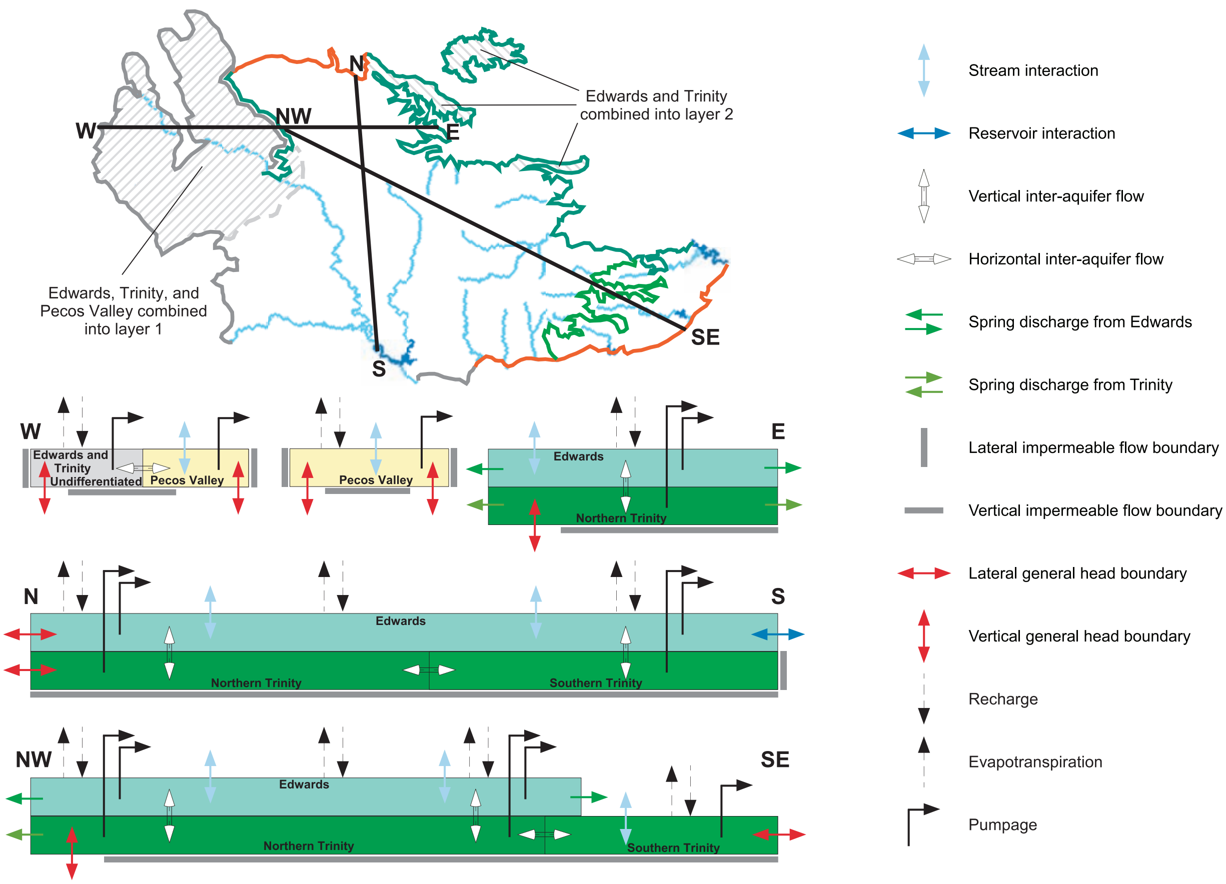

Figure 6-2. Block diagram of the Edwards-Trinity (Plateau), Trinity (Hill Country), and Pecos Valley aquifers.

unit represents the mostly unconfined Edwards hydrostratigraphic unit and Pecos Valley Aquifer.

The water budget incorporates recharge from precipitation as the primary input into the Edwards hydrostratigraphic unit. However, most of the precipitation returns to the atmosphere through evapotranspiration or exits from the study area as runoff before it can recharge the hydrostratigraphic unit. Up to 4 percent of the annual precipitation enters the aquifer as diffuse recharge over aquifer outcrops or as direct recharge from losing streams over the aquifer's outcrop. Some of the recharge that occurs over the Edwards hydrostratigraphic unit outcrop flows downward into the underlying Trinity hydrostratigraphic unit. The remaining recharge eventually exits the aquifer unit as (1) evapotranspiration where vegetation is able to tap into the water table; (2) seeps, springs, and base flow that feed the headwaters and tributaries of major streams; or (3) pumping from wells.

The Trinity hydrostratigraphic unit has few outcrops exposed for diffuse or direct recharge and, consequently, receives much of its water from the overlying Edwards hydrostratigraphic unit except in the Hill Country where the Edwards Group sediments have been removed by erosion. In the Hill Country area, recharge over the Trinity hydrostratigraphic unit is about 4 to 6 percent of annual precipitation. The Trinity hydrostratigraphic unit loses its water to pumping wells mostly in the Llano Estacado and Hill Country areas. In the Hill Country, groundwater also flows out of the Trinity hydrostratigraphic unit as springs and base flow to gaining streams and as cross-formational flow to the Edwards (Balcones Fault Zone) Aquifer. In the Trans-Pecos region, groundwater exits both the Edwards and Trinity hydrostratigraphic units as cross-formational flow into the Pecos Valley Aquifer. Groundwater also flows from the Edwards-Trinity (Plateau) Aquifer into reservoirs and lakes.

The Pecos Valley Aquifer receives diffuse recharge from precipitation over the aquifer and cross-formational flow from the Edwards-Trinity (Plateau) Aquifer. The Pecos Valley Aquifer is discharged through evapotranspiration from the riparian reaches of the Pecos River where the water table is near the surface, as base flow to the Pecos River, and by pumpage from irrigation wells. Except for local cones of depression caused by intense pumping, groundwater flow through the Pecos Valley Aquifer is generally toward the Pecos River (Jones, 2004).

The Edwards-Trinity (Plateau) Aquifer is hydraulically connected to four major aquifers: the Pecos Valley, the Ogallala, the Trinity, and the Edwards (Balcones Fault Zone). A relatively small amount of groundwater moves laterally from the Ogallala Aquifer into the Edwards-Trinity (Plateau) Aquifer (Blandford and Blazer, 2004). Groundwater generally flows from the Edwards-Trinity (Plateau) Aquifer into the Edwards (Balcones Fault Zone) and Pecos Valley aquifers. The Edwards-Trinity (Plateau) Aquifer is also hydraulically connected to several minor aquifers: Dockum, Capitan Reef Complex, Rustler, Hickory, Ellenburger-San Saba, Marble Falls, and Lipan. Groundwater flow between the Edwards-Trinity (Plateau) Aquifer and the minor aquifers is assumed to be insignificant. The Pecos Valley Aquifer is hydraulically connected to the underlying minor aquifers—Dockum, Capitan Reef Complex, and Rustler aquifers. Groundwater flow between the Pecos Valley Aquifer and the minor aquifers is also assumed to be insignificant.

7 Model design

Model design includes (1) the selection of a computer code and processor, (2) the discretization of the aquifer into layers and cells, (3) the assignment of model parameters, and (4) the assignment of boundary and initial conditions. It is essential that the model design be compatible with and representative of the conceptual model of an aquifer as much as possible.

7.1 CODE AND PROCESSOR

Groundwater flow through the Edwards-Trinity (Plateau) and Pecos Valley aquifers was modeled on an IBM-compatible personal computer consisting of a Dell Optiplex GX150 with a 930 megahertz Pentium III processor and 256 megabytes of random access memory on a Microsoft Windows operating system. We used 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 Edwards-Trinity (Plateau) and Pecos Valley aquifers, (2) its documentation and wide use (McDonald and Harbaugh, 1988; Anderson and Woessner, 1992), (3) the availability of a number of third-party pre- and post-processors for facilitating easy use of the modeling software, and (4) its easy availability as public domain software. Processing MODFLOW Pro (PMWIN) version 7.0.18 (Chiang and Kinzelbach, 2001) aided in loading data into the model and viewing model outputs.

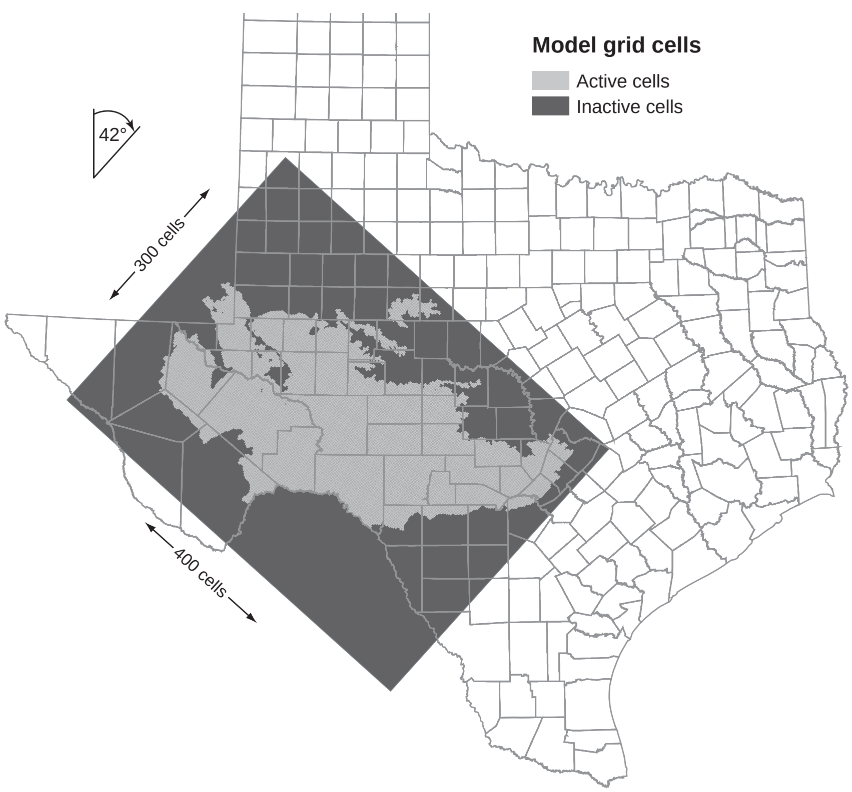

Figure 7-1. Model grid location and orientation showing active and inactive cells.

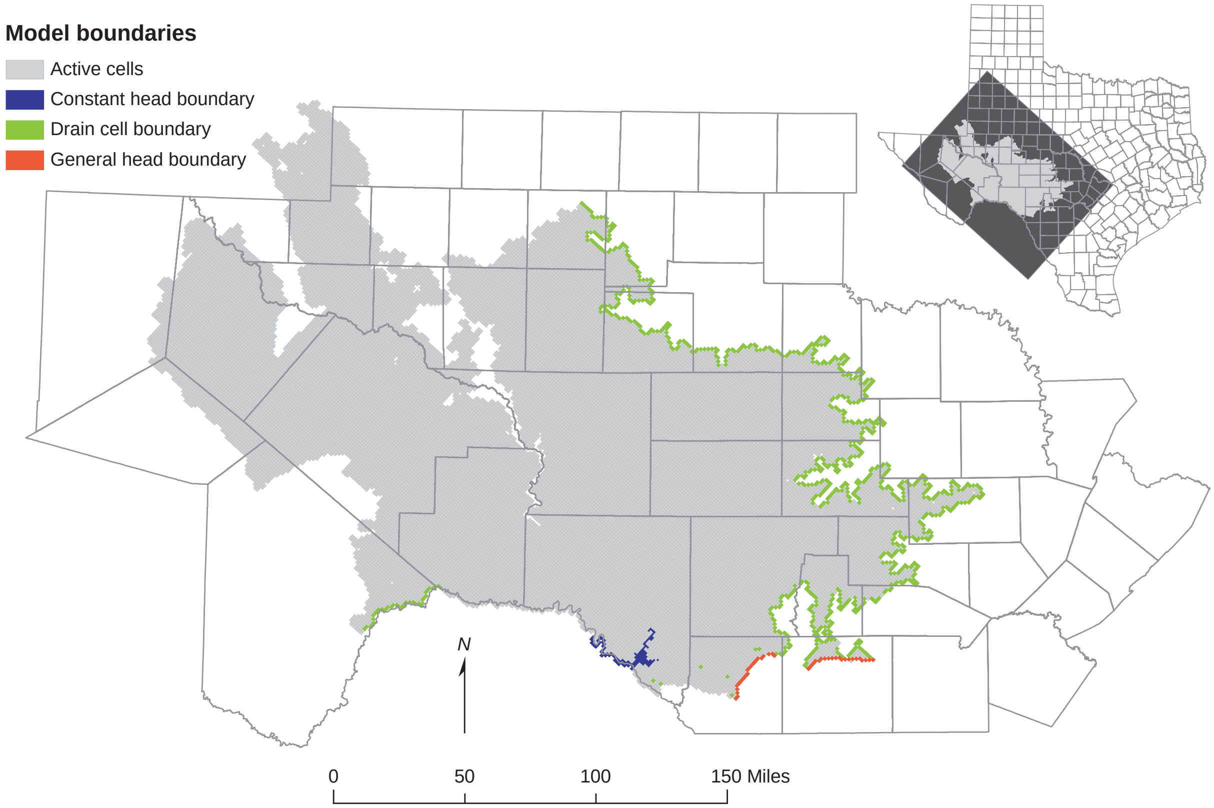

Figure 7-2. Boundary conditions for layer 1 used within model.

7.2 MODEL GRID AND LAYERS

The model grid has 400 columns and 300 rows (Figure 7-1). It uses a coordinate system based on an Albers Equal Area projection with parameters suited for Texas (Table 7-1). The x-y origin of the model grid or the x-y location of the centroid of the upper leftmost grid cell in Row 1, Column 1, is 4223291.90207 feet, 20776712.21495 feet. The grid is oriented 42° east of north so that it is approximately perpendicular to regional groundwater flows and parallel to the groundwater and surface water divides between the Colorado River and Rio Grande. We selected a uniform grid cell size of 5,280 feet by 5,280 feet to reflect the density of input data while providing adequate output resolution.

This model has three layers. The upper layer, layer 1, is composed of 32,066 active cells to model the Pecos Valley Aquifer and the Edwards hydrostratigraphic unit (Figure 7-2). Layer 2 is composed of 31,332 active cells to model the Trinity hydrostratigraphic unit (Figure 7-3). Where the aquifers were too thin and,

Table 7-1. Model coordinate system and parameters.

Projection	Albers equal area conic
Datum	North American datum 1983
Spheroid	Geodetic reference system 1980
Longitude of origin	-100.00 degrees west
Latitude of origin	31.25 degrees north
Lower standard parallel	27.50 degrees north
Upper standard parallel	35.00 degrees north
False easting	4921250.00000 feet
False northing	19685000.00000 feet
Unit of linear measure	U.S. survey feet

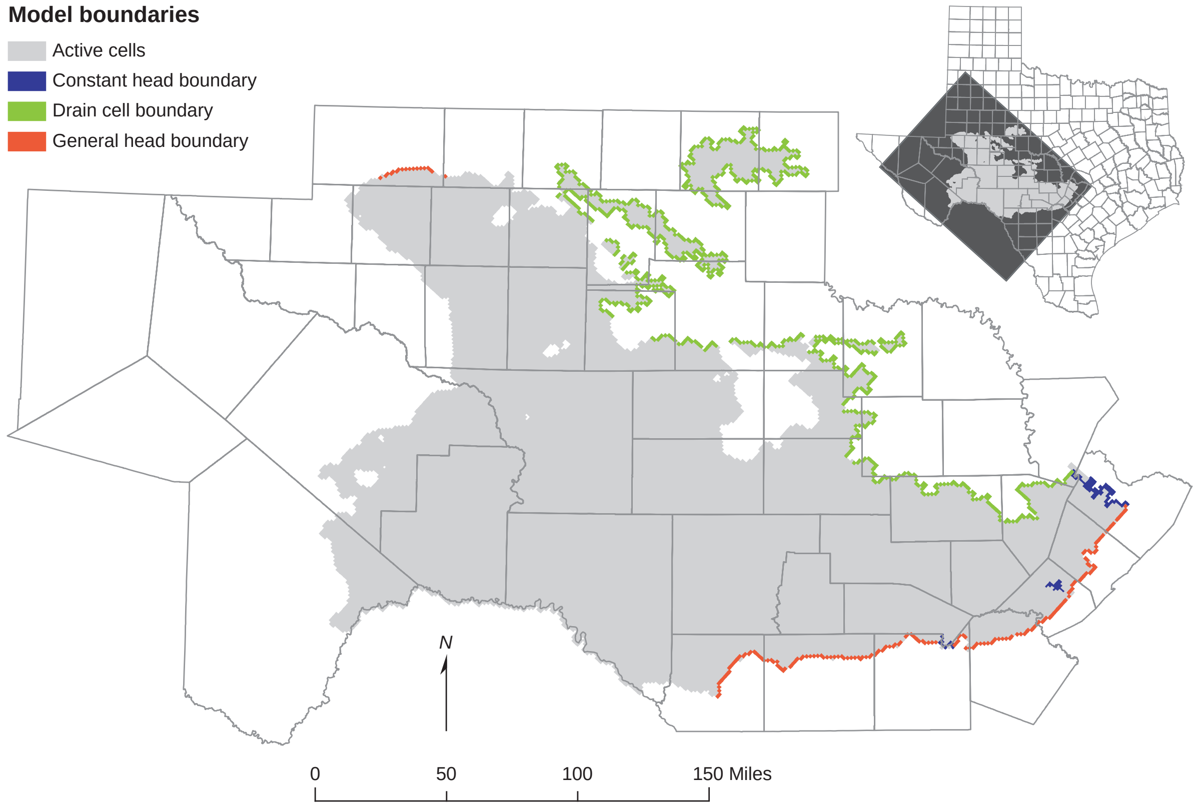

Figure 7-3. Boundary conditions for layer 2 used within model.

therefore, too difficult to simulate at the regional scale, the model was simplified by deactivating cells or by merging cells from both layers into either layer 1 or layer 2. In the Trans-Pecos region, the Trinity hydrostratigraphic unit was merged with the Pecos Valley Aquifer and the Edwards hydrostratigraphic unit within layer 1. In the northern part of the study area, the Edwards hydrostratigraphic unit was merged with the Trinity hydrostratigraphic unit within layer 2. The lowermost layer, layer 3, is an inactive layer that may be used to model interactions with underlying aquifers if more data becomes available in the future. Layer 3 is hereafter not discussed again.

7.3 MODEL PARAMETERS

We assigned the model layers as confined/unconfined layer types, allowing MODFLOW to calculate storativity from simulated saturated thickness and assigned specific storage values. The length and time units used in this model were feet and days, respectively. We used geographic information system procedures to spatially distribute model parameters for the model grid cells, such as aquifer base and top elevations, hydraulic conductivity zones, transmissivity, specific yield, and specific storage.

We based the top and base of each layer on structural data from the Bureau of Economic Geology, U.S. Geological Survey, and Texas Water Development Board (Barker and Ardis, 1992, 1996; Barker and others, 1994; BEG, 1974a, 1974b, 1976a, 1976b, 1977, 1979a, 1979b, 1981a, 1981b, 1982, 1986a, 1986b, 1994; Cartright, 1932; Rees and Buckner, 1980; Walker, 1979). We compiled this data, interpolated it using ordinary kriging, and then evaluated it to remove outliers and ensure accuracy (Figure 5-9, Figure 5-10, and Figure 5-11).

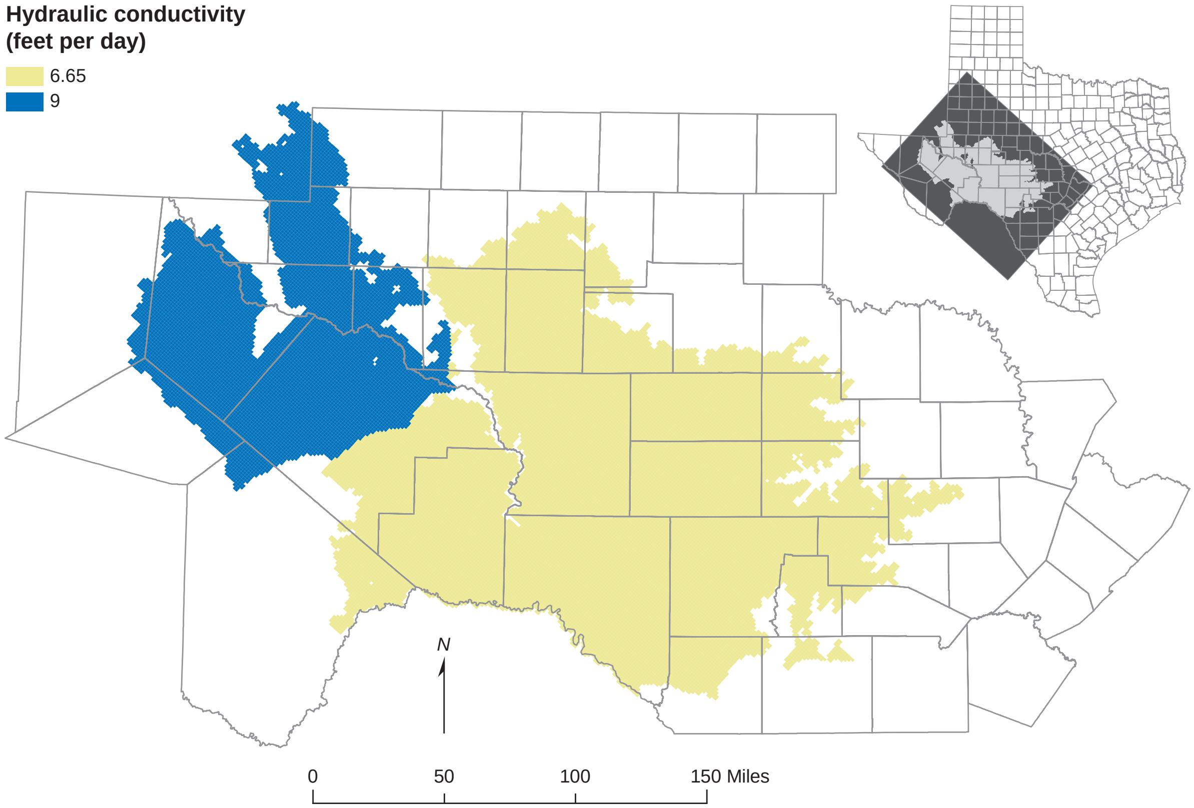

Figure 7-4. Zoned hydraulic conductivity for layer 1 used within model.

Horizontal hydraulic conductivity zones were delineated for the model layers based on geology (Figure 7-4 and Figure 7-5). These zones represented the Pecos Valley Aquifer and Edwards hydrostratigraphic unit of the Edwards-Trinity (Plateau) Aquifer in layer 1. In layer 2 the Trinity hydrostratigraphic unit is divided into northern and southern zones where the Glen Rose Formation is absent and present, respectively. Each zone was assigned an initial hydraulic conductivity value representing the geometric mean of hydraulic conductivity data for the respective zone. We assigned the initial hydraulic conductivity values of 6.65 feet per day and 9.0 feet per day to layer 1, representing the Edwards hydrostratigraphic unit and the Pecos Valley Aquifer, respectively. In layer 2, we assigned initial hydraulic conductivity values as 2.5, 5.0, and 15 feet per day, representing the southern part of the Trinity hydrostratigraphic unit where the Glen Rose Formation is present, the northern part of the Trinity hydrostratigraphic unit where the Glen Rose Formation is absent, and an Edwards-Trinity (Plateau) Aquifer outlier in Nolan and Taylor counties, respectively. The vertical hydraulic conductivity used to simulate flow between the Edwards and Trinity hydrostratigraphic units was assigned an initial value of 0.67 feet per day or 10 percent of the horizontal hydraulic conductivity assigned to the Edwards hydrostratigraphic unit.

We assigned transmissivity values based on estimated aquifer thickness and our delineated hydraulic conductivity zones (Figure 7-6 and Figure 7-7). Transmissivity values for this model ranged between 5 to 19,000 feet-squared per day and 20 to 8,400 feet-squared per day for layers 1 and 2, respectively. We increased the general head boundary conductance in the calibrated model from an initial value of 10 feet-squared per day to 1,500

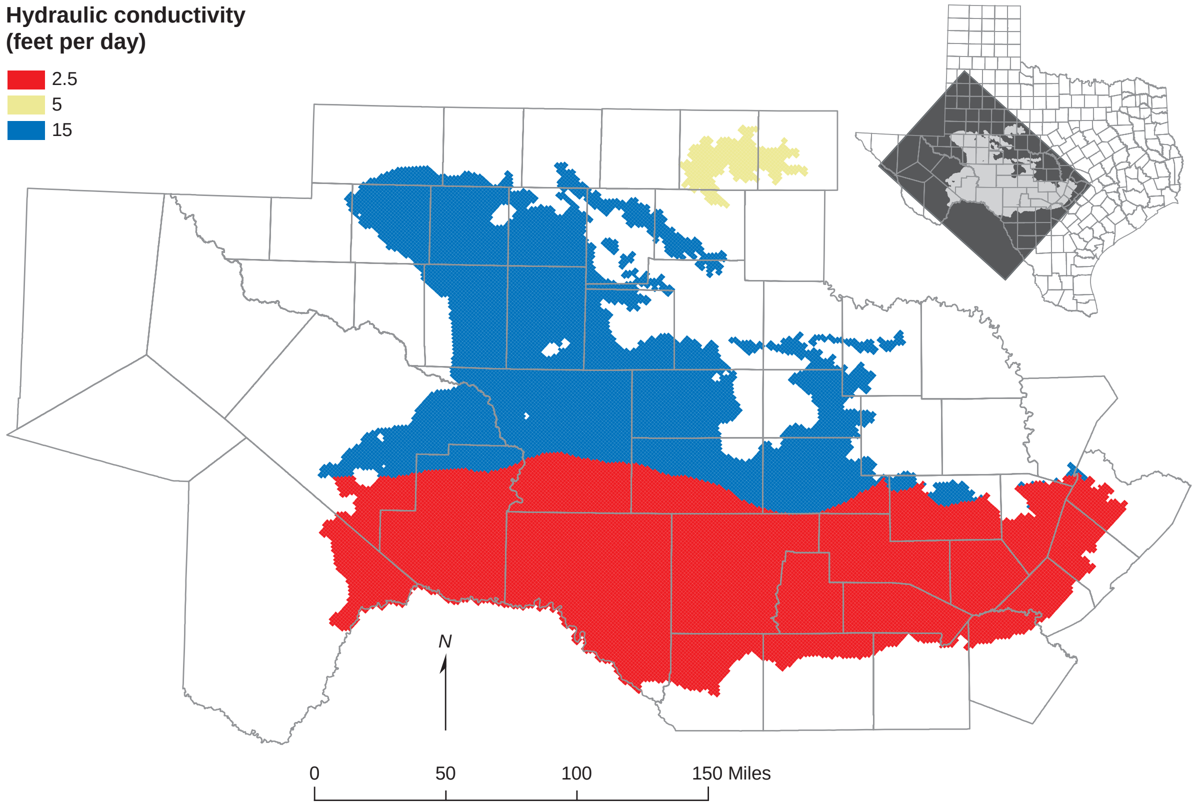

Figure 7-5. Zoned hydraulic conductivity for layer 2 used within model.

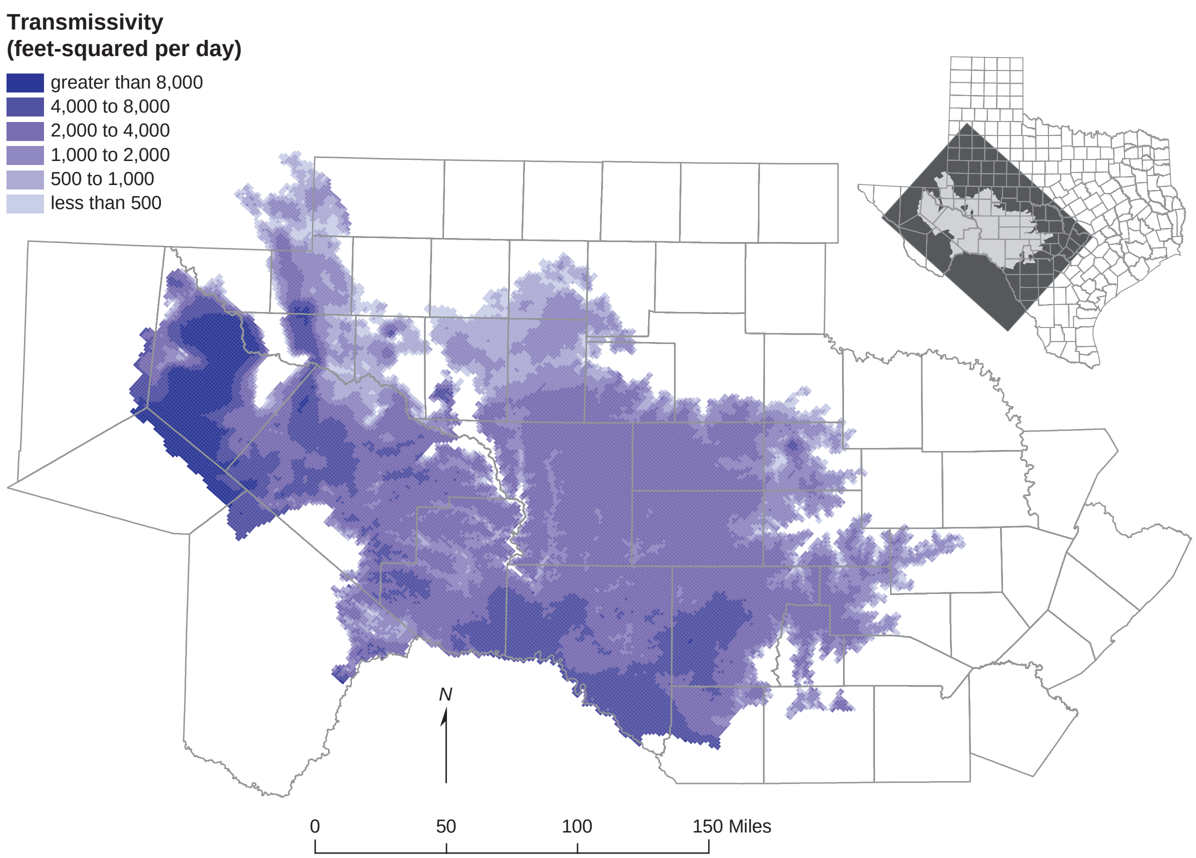

Figure 7-6. Transmissivity for layer 1 used within model.

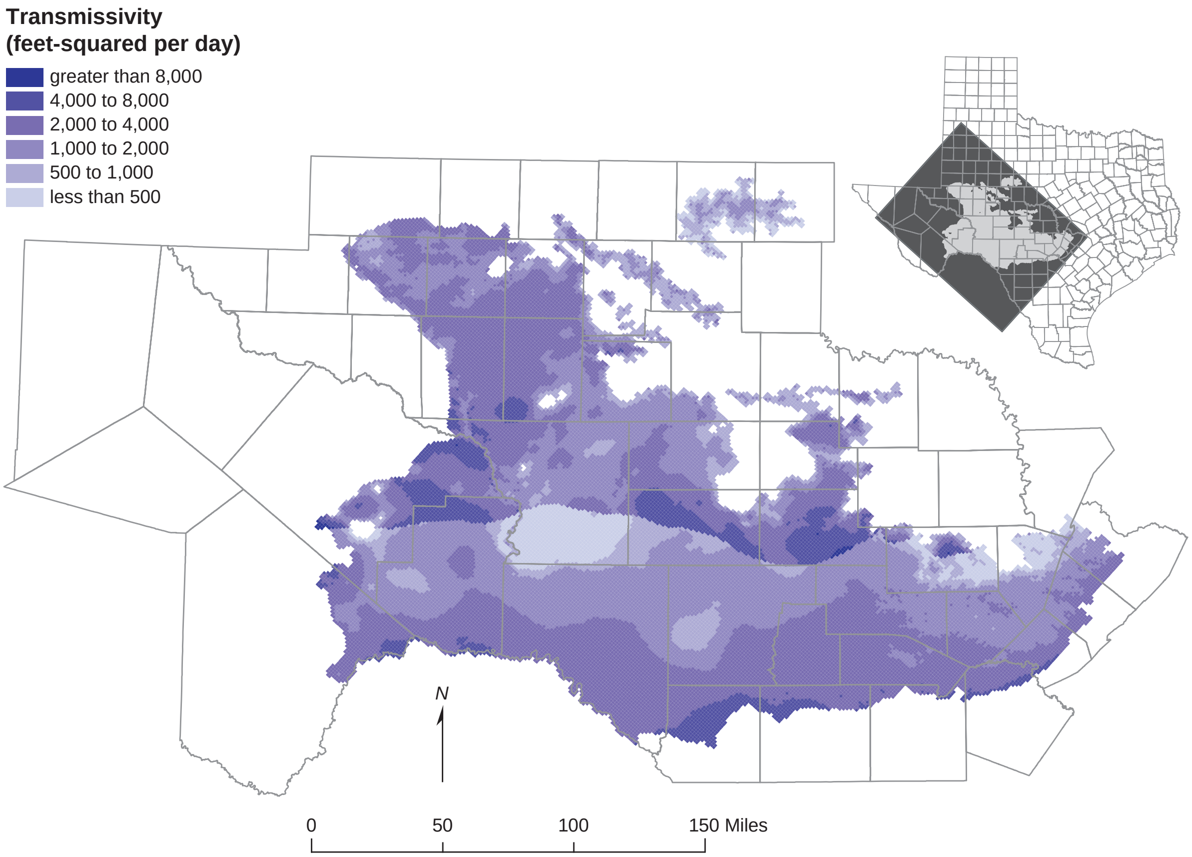

Figure 7-7. Transmissivity for layer 2 used within model.

feet-squared per day, which lies within the range of values for the groundwater availability model of the Hill Country part of the Trinity Aquifer (Mace and others, 2000). Although the higher conductance value is probably more realistic, overall the model was unaffected by the change.

Specific yield and storage values were assigned uniformly over each aquifer in the model. We assigned initial specific yield values of 0.2, 0.005, and 0.003 to the Pecos Valley Aquifer and Edwards and Trinity hydrostratigraphic units, respectively. We assigned initial specific storage values of 2×10^{-4}, 5×10^{-6}, and 10^{-6} per foot to the Pecos Valley Aquifer, Edwards hydrostratigraphic unit, and Trinity hydrostratigraphic unit, respectively. We took the initial specific yield and storage values assigned to the Edwards and Trinity hydrostratigraphic units from the previous groundwater availability model for the Hill Country part of the Trinity Aquifer (Mace and others, 2000). The initial specific yield and storage values assigned to the Pecos Valley Aquifer were taken from the literature as values typical of fine to coarse sand (Fetter, 1988; Domenico and Schwartz, 1990).

We used the Preconditioned Conjugate Gradient package to solve the groundwater flow equation. We set the convergence criterion for iterations at 1 foot in order to overcome water level oscillations during model runs. Despite the relatively large convergence criterion, model water budget discrepancies were generally less than 0.1 percent.

7.4 MODEL BOUNDARIES

Model boundaries were assigned for (1) initial conditions, (2) streams and springs, (3) recharge, and (4) pumping. We used geographic information system procedures to spatially distribute the model boundaries for recharge, pumping, stream reaches, drains, and general head boundaries.

We assigned initial water level elevations 10 feet above land surface over the model except where constant-head cells were used to simulate lakes or reservoirs. The initial water level elevations in the model were set above land surface in order to prevent the occurrence of dry cells during the first iterations of a model run when large water level oscillation may occur. We set constant-head levels in the model at 1,081; 669; 492; 908; and 1,063 feet above mean sea level, the conservation pool elevations for the International Amistad Reservoir, Lake Travis, Lake Austin, Canyon Lake, and Medina Lake, respectively.

The drain package in MODFLOW simulates groundwater discharge to seeps and springs along the margins of the aquifer. Discharge from the aquifer takes place only when simulated water levels in the drain cells exceed set elevations that represent spring orifice elevations. Discharge through drains is also a function of hydraulic conductance. In this model, we set initial drain hydraulic conductance at 1,000 feet-squared per day.

The General-Head Boundary package simulates cross-formational groundwater flow between the Edwards-Trinity (Plateau) and Pecos Valley aquifers and the adjacent Ogallala and Edwards (Balcones Fault Zone) aquifers. Groundwater flow across the general head boundary is head dependent, influenced by the elevation difference between simulated hydraulic heads of the modeled aquifer relative to hydraulic heads for the general head boundary. The general head boundary represents hydraulic heads in an adjacent aquifer based on observed water level measurements. If simulated hydraulic heads for the modeled aquifer exceed the hydraulic heads for the general head boundary, groundwater flows out of the aquifer. Otherwise, cross-formational flow enters the aquifer. In addition to relative hydraulic heads, cross-formational flow is also influenced by the hydraulic conductance across the general head boundary, initially set at 10 feet-squared per day.

The MODFLOW Recharge package simulates aquifer recharge. Recharge to the Edwards-Trinity (Plateau) and Pecos Valley aquifers occurs both as diffuse recharge from the infiltration of precipitation and as direct recharge from losing intermittent streams. Estimating recharge is simplified by generalizing recharge processes in both space and time domains. Therefore, infiltration from precipitation averaged annually and intermittent stream channels generalized into 1 square-mile areas allowed us to use a simple linear relationship to estimate recharge from annual precipitation. The initial recharge for the model was assigned a uniform 4 percent of annual precipitation.

The Streamflow-Routing package in MODFLOW simulates interaction between the modeled aquifers and perennial streams that flow over the aquifer outcrop (Figure 7-8). Groundwater-surface water interaction is head dependent, influenced by the relative hydraulic heads in the aquifer and stream. If hydraulic heads in the aquifer exceed stream heads (stage), groundwater flows out of the aquifer into the stream. The Streamflow-Routing package uses stream data, including stream stage, streambed hydraulic conductance, elevation of streambed top and bottom, width and slope of stream channel, and Manning's Roughness Coefficient. We determined the streambed top elevation data from the minimum elevation in each cell based on a 90-meter digital elevation model obtained from the U.S. Geological Survey. We assumed streambeds were 1 foot thick and set the initial stream stage at 1 foot above the top of the streambed. Consequently, the streambed bottom elevation and initial stream stage data represent elevations 1 foot below and above the digital elevation model elevation, respectively. We obtained the stream channel width and slope

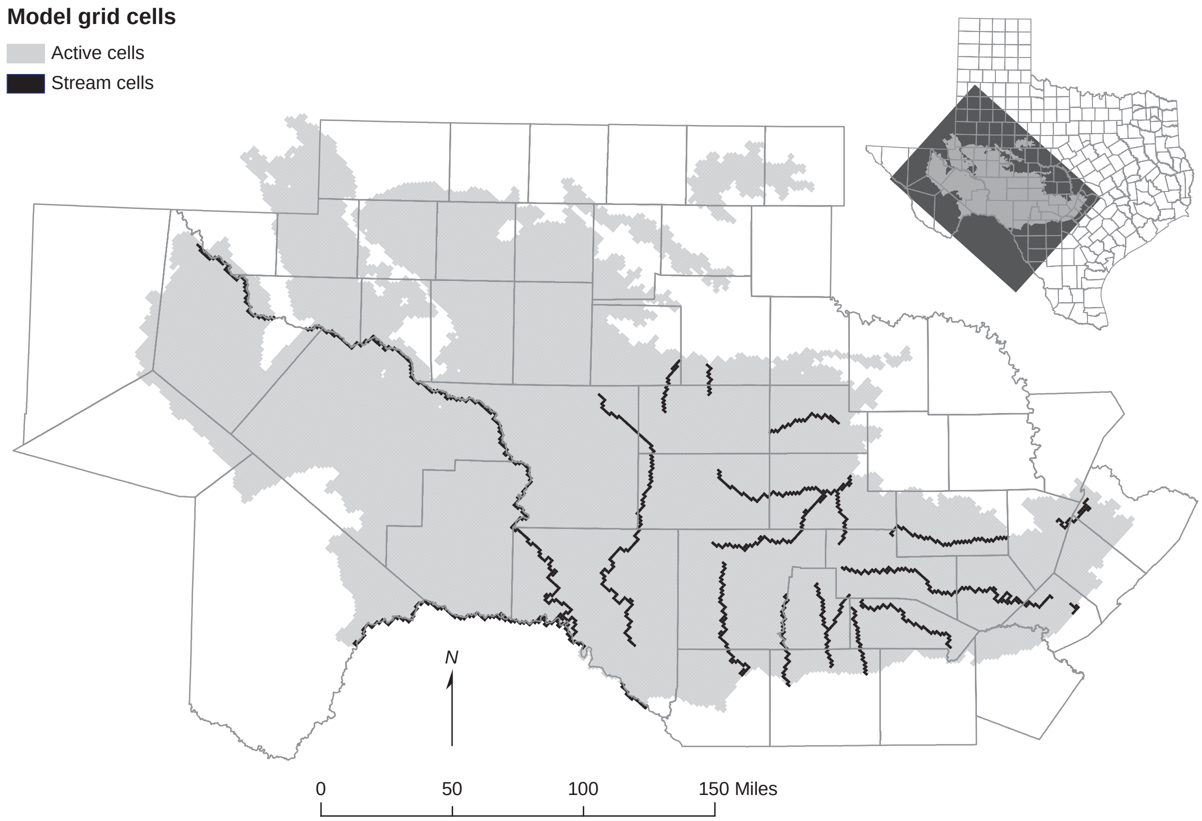

Figure 7-8. Stream cells used within model.

and Manning's Roughness Coefficient data from the River Reach Files (version 1.0) developed by the U.S. Environmental Protection Agency (www.epa.gov/waters/doc/rf1_meta.html). We determined streambed hydraulic conductance by the calibration process.

This model simulates the regional effects of pumping for rural domestic, municipal, irrigation, industrial, and livestock uses (Table 7-2 and Table 7-3). We based the spatial distribution of municipal pumping on known well locations and pumping data from the TWDB Water Use Survey (Figure 7-9). We distributed irrigation pumping for each model cell based on irrigated acreage derived from the U.S. Geological Survey 1:250,000-scale land use and land cover data (Figure 7-10). We assumed irrigation occurred on all land classified as orchards, row crops, or small grains. We also distributed livestock pumping based on the land use and land cover data from the U.S. Geological Survey (Figure 7-11). We assumed livestock pumping occurred on all land classified as rangeland. Rural domestic pumping was distributed based on population density (Figure 7-12), and we excluded major cities and urban areas as well as lake and reservoir areas that lie within the model grid. We based population density on block-level data from the 1990 and 2000 U.S. Census. Because of the difficulty in obtaining the exact locations for industrial pumping (manufacturing, mining, and power), we used the U.S. Geological Survey land use and land cover data on land classified as industrial or mining to distribute industrial pumping.

Table 7-2. Rate of total withdrawal from the Edwards-Trinity (Plateau) and Pecos Valley aquifers (values expressed in acre-feet).

County name	1980	1981	1982	1983	1984	1985	1986
Andrews	120	141	151	149	151	121	92
Bandera	1,278	1,277	1,320	1,331	1,388	1,399	1,407
Bexar	1,377	1,595	1,793	1,936	2,268	1,311	1,602
Blanco	496	497	495	500	506	502	571
Brewster	422	440	459	477	496	783	847
Burnet	157	201	245	290	335	547	350
Coke	45	38	30	23	16	17	14
Comal	1,541	1,544	1,519	1,538	1,562	1,618	1,718
Concho	311	302	291	282	271	218	214
Crane	1,805	1,780	1,883	1,794	1,737	1,153	1,178
Crockett	4,258	3,609	3,249	3,143	2,645	2,595	2,488
Culberson	43	40	37	34	31	34	28
Ector	10,576	10,590	9,472	9,571	9,178	9,194	8,134
Edwards	1,301	1,101	1,022	915	815	775	683
Gillespie	1,518	1,516	1,518	1,538	1,560	1,546	1,607
Glasscock	37,931	38,794	39,657	40,516	41,377	24,152	47,166
Hays	1,418	1,467	1,540	1,655	1,894	1,791	1,888
Howard	177	168	192	204	209	204	223
Irion	1,202	1,042	895	755	622	512	586
Jeff Davis	162	151	140	130	120	127	95
Kendall	1,818	1,863	1,904	2,007	2,240	1,986	1,941
Kerr	6,048	3,597	3,312	3,170	3,723	3,781	3,309
Kimble	1,070	980	917	908	827	814	923
Kinney	8,145	8,086	8,030	7,974	7,918	4,107	4,461
Loving	52	45	38	32	26	28	30
Martin	71	72	75	77	79	78	76
Mason	3	3	3	3	3	3	3
McCullouch	33	33	32	31	29	31	27
Medina	64	62	59	57	55	50	51
Menard	593	540	487	439	391	392	519
Midland	6,708	7,753	8,755	9,569	10,348	9,725	8,538
Nolan	394	375	358	341	324	343	246
Pecos	110,610	106,920	103,766	100,494	96,981	85,648	71,182
Reagan	23,656	25,562	27,771	29,978	32,579	22,325	23,768
Real	678	562	624	640	435	419	425
Reeves	114,560	105,470	96,084	88,276	80,946	62,971	60,069
Schleicher	2,178	2,112	2,219	2,220	2,251	2,259	2,156
Sterling	772	735	686	637	589	661	515
Sutton	3,654	3,206	2,995	2,755	2,879	3,095	2,705
Taylor	345	298	250	201	153	145	141
Terrell	1,361	1,238	1,160	1,009	990	1,136	1,184
Tom Green	362	321	286	248	211	183	194
Travis	1,956	2,081	2,121	2,283	2,459	2,486	2,131
Upton	14,147	13,677	13,213	12,750	12,287	8,570	8,742
Uvalde	617	610	604	600	595	570	416
Val Verde	1,611	1,420	4,594	4,120	5,757	2,653	5,655
Ward	8,524	8,681	8,349	8,242	7,684	8,000	7,384
Winkler	4,845	3,770	2,856	1,838	850	1,304	1,299

Sources: Data for 1980–2000 from TWDB Water Use Survey; data for 2001–2050 based on 2002 State Water Plan.

Table 7-2 (continued).

County name	1987	1988	1989	1990	1991	1992	1993
Andrews	45	25	85	55	62	85	85
Bandera	1,552	1,644	1,741	1,776	1,841	1,777	2,028
Bexar	1,688	1,810	1,858	1,892	1,869	1,921	1,961
Blanco	578	608	615	646	657	697	713
Brewster	904	940	500	530	537	443	458
Burnet	348	353	217	231	235	232	202
Coke	14	16	15	15	16	21	19
Comal	1,857	1,828	1,945	2,121	2,229	2,304	2,450
Concho	238	202	202	242	249	314	328
Crane	1,027	1,297	1,265	1,182	1,029	626	686
Crockett	2,266	2,677	2,807	2,568	2,527	2,277	2,640
Culberson	45	48	47	46	47	31	29
Ector	8,336	8,416	8,720	8,684	9,090	8,836	9,675
Edwards	712	773	845	851	850	877	1,020
Gillespie	1,454	1,436	1,843	1,906	1,972	2,094	2,211
Glasscock	39,357	29,677	30,948	26,972	35,404	24,621	39,141
Hays	2,037	2,024	2,122	1,980	2,006	1,996	2,203
Howard	191	183	249	266	257	270	197
Irion	646	627	702	1,008	1,014	999	1,147
Jeff Davis	75	85	131	129	132	131	115
Kendall	1,904	2,416	2,421	2,309	2,145	2,176	2,800
Kerr	2,990	3,277	3,788	3,418	3,414	3,901	4,260
Kimble	888	900	749	748	783	790	761
Kinney	2,101	2,633	9,052	5,943	5,957	4,900	7,736
Loving	31	33	29	30	31	43	42
Martin	74	74	71	84	85	88	90
Mason	3	3	3	3	3	3	3
McCullouch	25	27	26	27	26	33	32
Medina	55	54	60	58	58	63	73
Menard	488	470	431	465	501	638	609
Midland	5,529	9,494	10,360	11,698	7,784	9,846	11,292
Nolan	227	255	347	305	268	234	379
Pecos	65,121	63,981	71,012	67,868	64,838	63,780	78,193
Reagan	20,085	22,245	32,893	36,646	31,463	24,103	23,775
Real	436	444	823	721	732	443	571
Reeves	41,304	49,839	71,287	39,250	34,410	34,194	380,364
Schleicher	1,450	1,646	2,442	1,922	1,982	2,160	2,398
Sterling	405	432	558	548	557	616	550
Sutton	2,582	2,706	2,687	2,503	2,563	2,367	2,838
Taylor	141	126	137	111	119	187	151
Terrell	1,096	1,350	1,113	1,080	1,106	1,054	1,110
Tom Green	184	182	195	228	227	270	311
Travis	2,137	2,271	2,554	2,245	2,269	2,259	2,330
Upton	7,063	10,609	11,664	11,397	13,538	12,929	11,738
Uvalde	436	417	424	445	458	615	593
Val Verde	5,031	7,947	5,863	4,236	7,475	6,271	8,015
Ward	6,731	6,261	6,202	6,125	5,999	6,201	7,242
Winkler	1,399	1,513	478	416	1,896	1,914	510

Table 7-2 (continued).

County name	1994	1995	1996	1997	1998	1999	2000
Andrews	85	94	91	95	86	67	512
Bandera	1,991	2,020	2,106	2,142	2,255	2,330	3,605
Bexar	2,045	2,174	2,053	2,055	2,296	2,398	550
Blanco	698	748	712	735	723	743	554
Brewster	719	678	623	631	631	671	534
Burnet	167	178	176	169	179	189	147
Coke	19	21	19	18	16	16	136
Comal	2,584	2,700	2,766	2,869	2,914	3,057	1,170
Concho	266	277	254	271	264	265	349
Crane	812	793	758	665	768	557	1,856
Crockett	2,844	2,616	2,551	2,570	3,262	3,068	3,125
Culberson	26	21	23	25	34	37	36
Ector	5,592	5,535	5,593	3,725	2,991	3,422	3,891
Edwards	1,049	1,006	946	875	941	1,004	1,131
Gillespie	3,463	3,479	3,968	3,393	3,338	2,304	1,994
Glasscock	50,092	59,244	47,620	45,288	53,742	21,325	17,099
Hays	2,367	2,529	2,718	2,653	3,149	2,816	1,024
Howard	267	337	345	481	364	585	789
Irion	408	432	369	417	362	367	593
Jeff Davis	111	95	95	90	134	141	126
Kendall	2,856	3,056	3,301	3,375	3,373	3,513	1,365
Kerr	4,040	3,970	4,592	4,207	4,205	4,179	9,817
Kimble	790	843	805	745	747	793	915
Kinney	6,355	5,095	6,828	5,926	5,373	3,835	5,036
Loving	55	53	42	53	45	32	72
Martin	89	92	88	90	95	94	0
Mason	3	3	3	3	3	3	0
McCullouch	31	31	29	31	30	29	18
Medina	67	73	74	72	66	69	729
Menard	967	916	826	812	757	921	2,587
Midland	14,512	21,127	17,474	12,808	16,401	18,152	13,484
Nolan	105	120	151	116	105	89	524
Pecos	74,549	85,461	79,161	81,112	83,000	81,684	86,631
Reagan	30,956	41,634	42,470	45,071	61,779	19,939	28,050
Real	598	595	589	497	488	501	430
Reeves	103,821	108,121	101,437	102,328	101,136	94,965	59,170
Schleicher	2,721	2,351	2,539	2,504	3,328	3,729	2,702
Sterling	421	375	320	359	351	339	1,141
Sutton	2,875	2,931	3,432	3,442	1,927	3,443	3,574
Taylor	112	117	114	97	54	98	643
Terrell	1,109	1,014	982	935	1,017	1,028	1,037
Tom Green	642	741	507	702	484	397	1,229
Travis	2,277	2,378	2,639	2,171	2,132	1,744	249
Upton	15,236	16,235	15,103	12,729	20,590	6,069	12,313
Uvalde	570	568	742	559	573	563	3,249
Val Verde	7,312	6,358	7,380	7,280	12,147	14,553	7,214
Ward	6,749	6,555	6,242	6,131	6,423	5,820	10,924
Winkler	508	497	504	468	601	559	573

Table 7-2 (continued).

County name	2010	2020	2030	2040	2050
Andrews	430	319	288	273	277
Bandera	5,233	5,128	5,564	6,087	6,667
Bexar	553	494	566	570	444
Blanco	614	678	735	757	707
Brewster	535	535	527	534	526
Burnet	164	189	178	180	154
Coke	136	136	136	136	136
Comal	1,383	1,492	1,330	1,224	1,022
Concho	383	382	381	379	382
Crane	1,673	1,615	1,620	1,635	1,671
Crockett	3,117	3,110	3,122	3,124	3,137
Culberson	36	36	36	36	35
Ector	5,607	5,564	5,621	5,657	5,613
Edwards	1,139	1,135	1,138	1,137	1,141
Gillespie	2,005	2,028	2,046	2,127	2,175
Glasscock	17,099	17,100	17,100	17,102	17,102
Hays	1,162	1,240	1,403	1,579	1,371
Howard	814	826	823	848	898
Irion	591	580	574	570	568
Jeff Davis	126	126	126	126	126
Kendall	1,626	1,823	2,199	2,465	2,468
Kerr	10,763	11,653	12,795	13,918	15,266
Kimble	2,042	2,080	2,108	2,206	2,309
Kinney	4,845	4,661	4,509	4,349	4,207
Loving	71	71	70	70	69
Martin	0	0	0	0	0
Mason	0	0	0	0	0
McCullouch	18	18	18	18	18
Medina	739	744	742	756	785
Menard	2,566	2,545	2,524	2,506	2,488
Midland	13,486	13,493	13,489	13,486	13,503
Nolan	510	496	483	470	458
Pecos	87,941	86,719	85,466	84,173	82,902
Reagan	29,534	29,507	29,465	29,192	28,813
Real	421	408	403	394	386
Reeves	59,299	59,282	59,279	59,278	59,281
Schleicher	2,670	2,622	2,584	2,545	2,516
Sterling	1,012	987	970	954	939
Sutton	3,630	3,629	3,597	3,556	3,521
Taylor	627	610	607	605	608
Terrell	1,028	1,014	998	981	972
Tom Green	1,221	1,228	1,229	1,222	1,225
Travis	252	323	573	588	502
Upton	12,254	11,754	11,581	11,414	11,265
Uvalde	3,200	3,170	3,134	3,115	2,988
Val Verde	7,437	7,555	7,669	8,263	8,906
Ward	9,035	9,300	9,927	10,640	11,511
Winkler	3,459	4,040	4,727	5,539	6,504

Table 7-3. Rate of irrigation, rural domestic, municipal, industrial, and livestock pumping from the Edwards-Trinity (Plateau) and Pecos Valley aquifers (values expressed in acre-feet).

Year	Irrigation	Rural	Municipal	Industrial	Livestock
1980	312,888	14,061	21,606	13,655	16,353
1981	303,679	14,997	17,604	11,782	15,393
1982	294,470	15,779	21,608	8,139	14,422
1983	285,260	16,148	21,734	7,701	13,452
1984	276,051	16,531	24,156	7,810	12,482
1985	213,912	16,731	19,973	6,148	11,762
1986	220,433	16,366	22,388	5,044	11,089
1987	177,517	16,353	19,282	4,969	11,707
1988	185,360	15,932	24,575	5,357	11,180
1989	234,326	18,542	22,531	4,432	11,357
1990	196,662	18,341	19,185	4,085	11,596
1991	192,515	18,822	21,090	4,037	12,048
1992	173,271	19,033	19,807	3,487	12,880
1993	552,921	19,409	24,019	2,864	12,644
1994	291,580	19,864	24,286	3,301	12,893
1995	333,560	20,422	22,373	3,359	12,402
1996	307,150	21,140	24,588	2,728	12,495
1997	302,567	18,847	24,240	2,863	11,864
1998	339,907	19,260	30,368	2,313	10,080
1999	245,297	19,394	31,292	2,290	11,049
2000	219,721	20,475	25,136	12,135	13,368
2010	218,133	22,507	26,877	19,102	13,368
2020	216,133	22,600	27,871	19,645	13,368
2030	213,870	23,386	29,351	20,845	13,367
2040	211,768	25,151	30,745	22,517	13,367
2050	209,650	26,589	31,820	24,681	13,357

Sources: Data for 1980–2000 from the TWDB Water Use Survey; data for 2001–2050 based on 2002 State Water Plan.

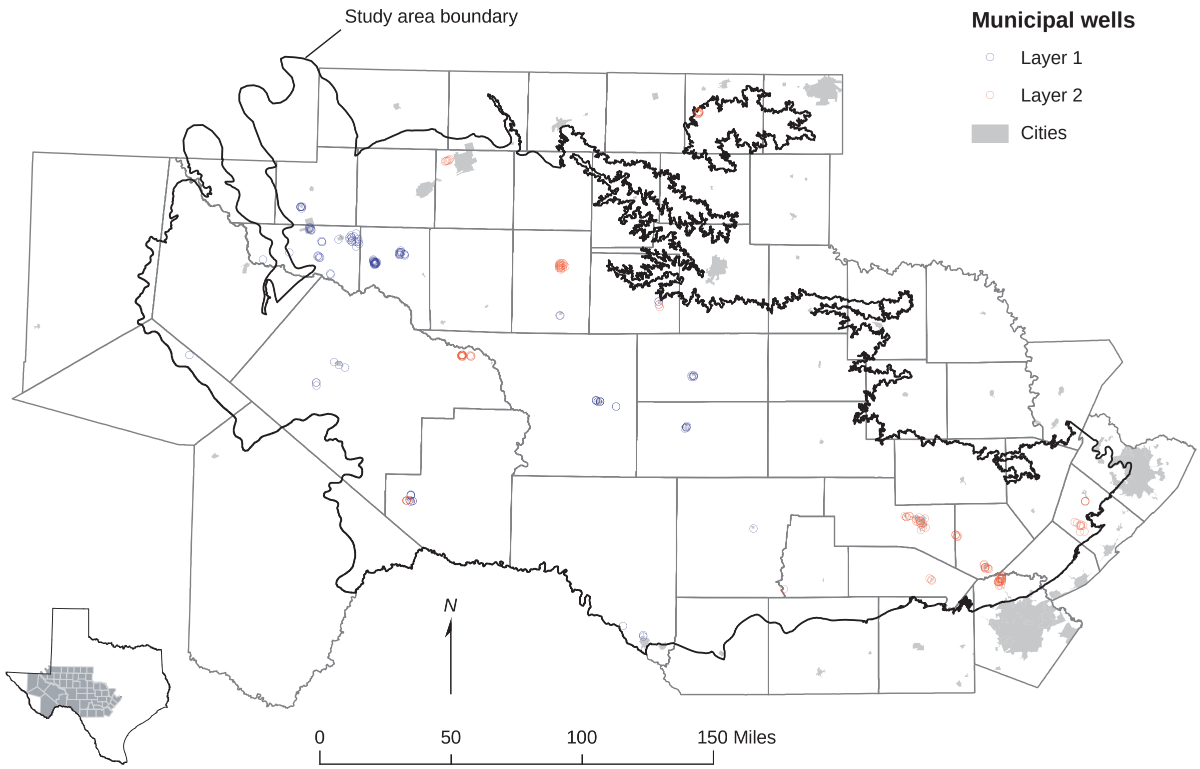

Figure 7-9. Location of municipal well fields used within the model.

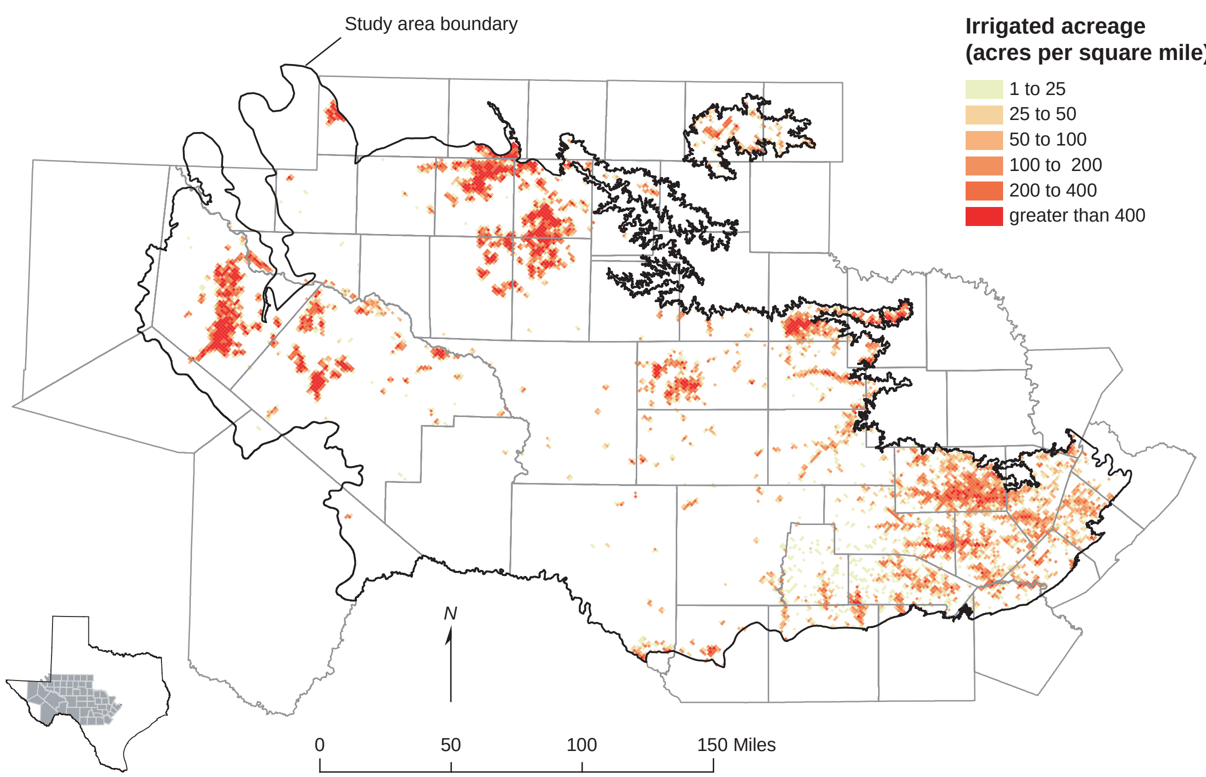

Figure 7-10. Agricultural acreage density distributed within the model grid.

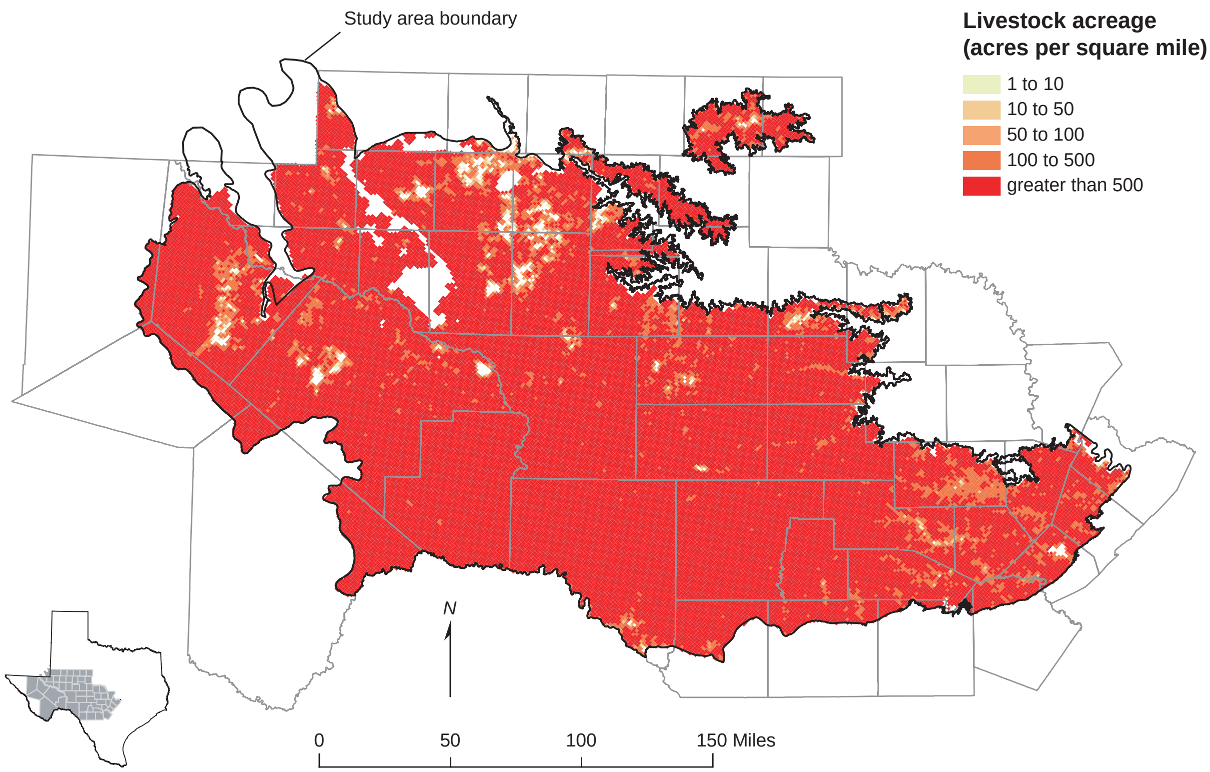

Figure 7-11. Livestock acreage density distributed within the model grid.

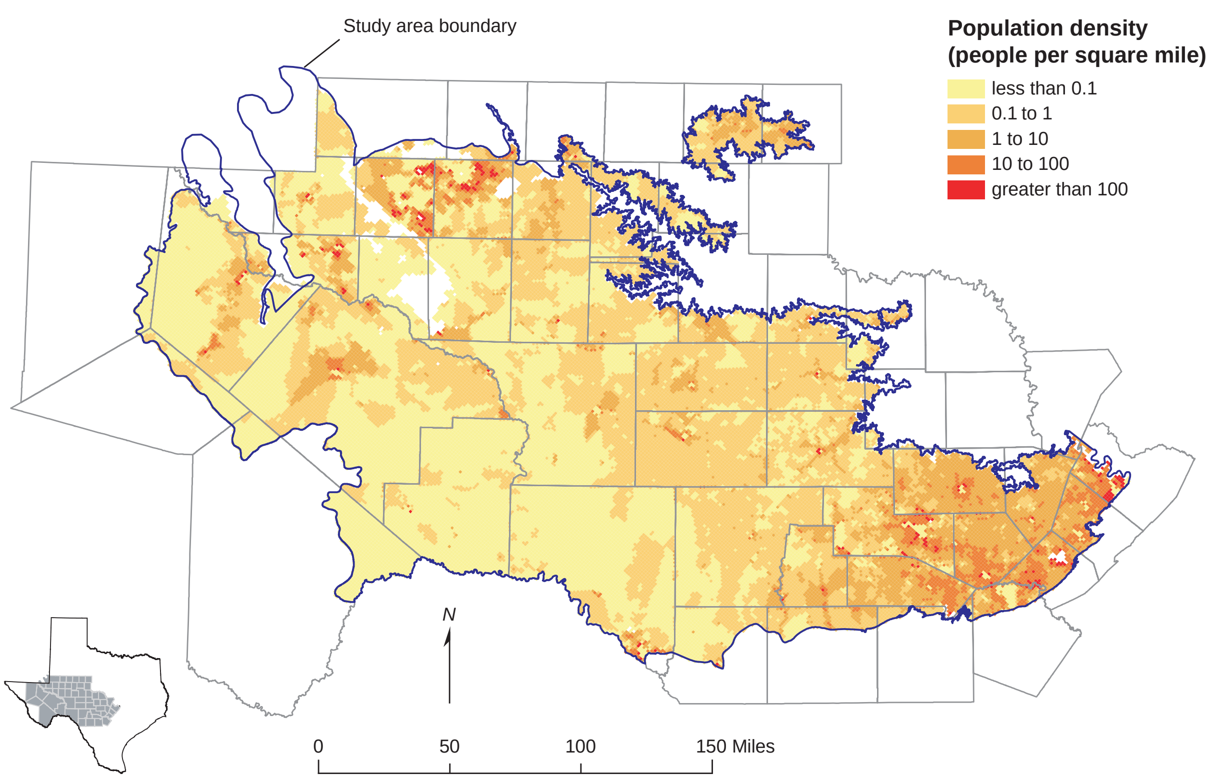

Figure 7-12. Population density distributed within the model grid.

8 *Modeling approach*

The process of modeling the Edwards-Trinity (Plateau) and Pecos Valley aquifers included steady-state model calibration, historical transient model calibration (1980–1989), and verification (1990 to 2000). The steady-state model calibration facilitates the modeling process because some parameters, such as aquifer storage that influences water level fluctuations over time, are not considered. In the steady-state model, calibration requires consideration only of spatial variations of hydraulic properties in the aquifer.

We calibrated the steady-state model to reproduce water levels for 1980. The steady-state model was used to investigate (1) recharge rates, (2) hydraulic properties, (3) boundary conditions, and (4) the flow budget. Model calibration in the steady-state model involved matching simulated water levels and streamflow with available measurement data. We quantified steady-state calibration using the root mean square error between measured and simulated water levels,

$$\text{Root mean square error} = \left[\frac{1}{n}\sum_{i=1}^{n}\left(h_m - h_s\right)_i^2\right]^{0.5}$$

where n is the number of calibration points and h_m and h_s are measured and simulated water level elevations, respectively, at point i. The calibration process for the steady-state model is designed to minimize the root mean square error of the model with a target root mean square error less than 10 percent of the range of measured water level values.

Once we achieved steady-state calibration, the resulting model was the basis for the initial conditions of the transient model. In the historical transient model, calibration involved matching water level and streamflow fluctuations with available measurements. After we calibrated and verified the historical transient model, we analyzed the sensitivity of selected parameters.

9 *Steady-state model*

After assembling input data and constructing the model framework, we calibrated the steady-state model to fit measured parameters. After successful calibration, we assessed model sensitivity to selected input parameters.

9.1 Steady-state model calibration

We initially began calibrating the steady-state model by adjusting recharge, horizontal hydraulic conductivity, vertical hydraulic conductivity, and the general head boundary conductance. However, because the geometry of the model layers along the northern and western aquifer margins, which thin out over short distances and/or consist of steep slopes, dry cells resulted in model instability and prevented the model from converging. We were, therefore, required to use fixed transmissivity instead of horizontal hydraulic conductivity to allow the model to converge and complete the model calibration. Using fixed transmissivity also has the adverse effect of decoupling the simulated water levels from the model layers. The decoupling resulted in simulated water levels occurring below the base of the aquifer layers in certain parts of the study area.

We considered cross-formational flow to or from the Dockum, Capitan Reef Complex, Rustler, and Hickory aquifers. However, the model calibration process, as well as evaluation of groundwater geochemistry, indicated little interaction between these aquifers and the Edwards-Trinity (Plateau) and Pecos Valley aquifers (Jones, 2004). Vertical hydraulic conductivity was calibrated to 0.0001 and 0.00001 feet per day distributed in zones delineated by the presence or absence of the underlying Glen Rose Formation. We assumed estimated pumping to be a known and did not adjust it. We used estimated pumping for 1980 in the steady-state model (Figure 9-1, Figure 9-2, and Figure 9-3).

Recharge adjustments during the calibration process resulted in creating recharge zones within the model that correlated with surface geology. We calibrated recharge values for each zone by a different percentage of annual precipitation (Figure 9-4): (1) 1 percent for the Pecos Valley outcrop north the Pecos River; (2) 5 percent for the Pecos Valley outcrop south of the Pecos River; (3) 2 percent for the Edwards Group outcrop on the Edwards Plateau; (4) 4.7 percent for the Trinity Group outcrop in the Hill Country; (5) 1 percent for the Edwards Group outcrop where overlain by the Buda and/or Del Rio Formation(s); (6) 8 percent for the Edwards Group outcrop on the Stockton Plateau; (7) 6 percent for the Edwards Group, Trinity Group, and/or the Pecos Valley outcrops along the steeper mountain slopes of the Trans-Pecos uplands; (8) 5 percent for the Devils River Formation outcrop; (9) 10.9 percent for the Edwards Group outcrop within the Maverick Basin; and (10) 3 percent for the Edwards-Trinity outcrop where overlain by Ogallala sediments. The range of recharge in the steady-state model is 0 to 2.7 inches per year, or 0 to 10.9 percent of 1980 annual precipitation. Our calibrated recharge expressed as a percentage of 1961 to 1990 average annual precipitation matched well with previous recharge studies (Table 9-1).

Simulated water levels from the calibrated steady-state model are fairly close to measured water levels for a modeled area of this extent (Figure 9-5 and Figure 9-6). The root mean square error of the calibrated model is 134 feet, which is approximately 6 percent of the approximately 2,200-foot range of measured water levels (Figure 9-7). This indicates

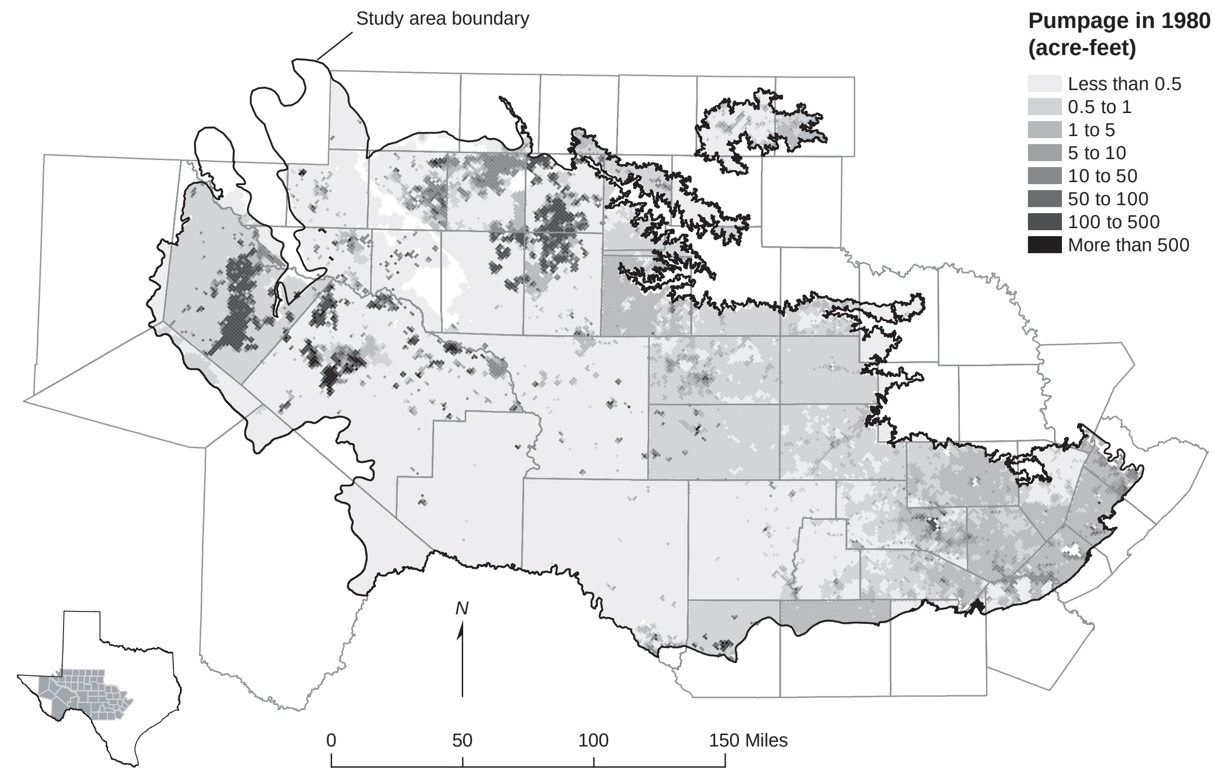

Figure 9-1. Total 1980 pumping volumes for both layers 1 and 2 distributed within the model grid.

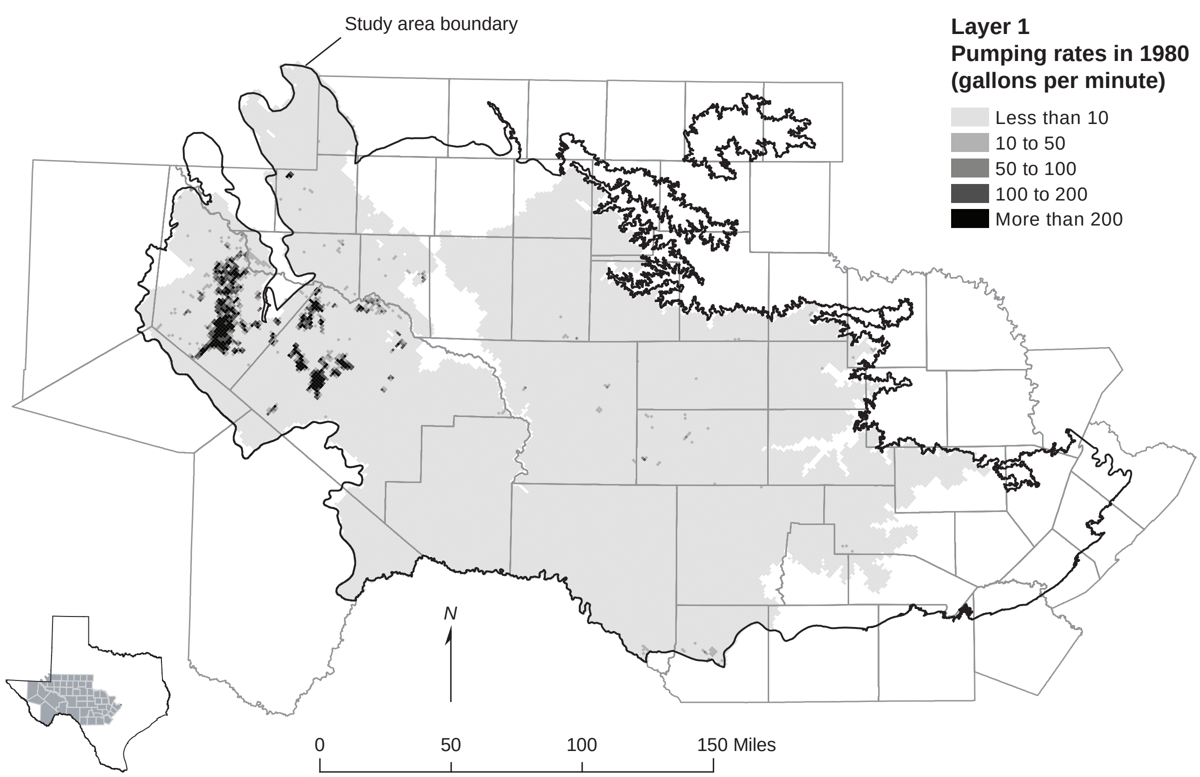

Figure 9-2. Total 1980 pumping volumes for layer 1 distributed within the model grid.

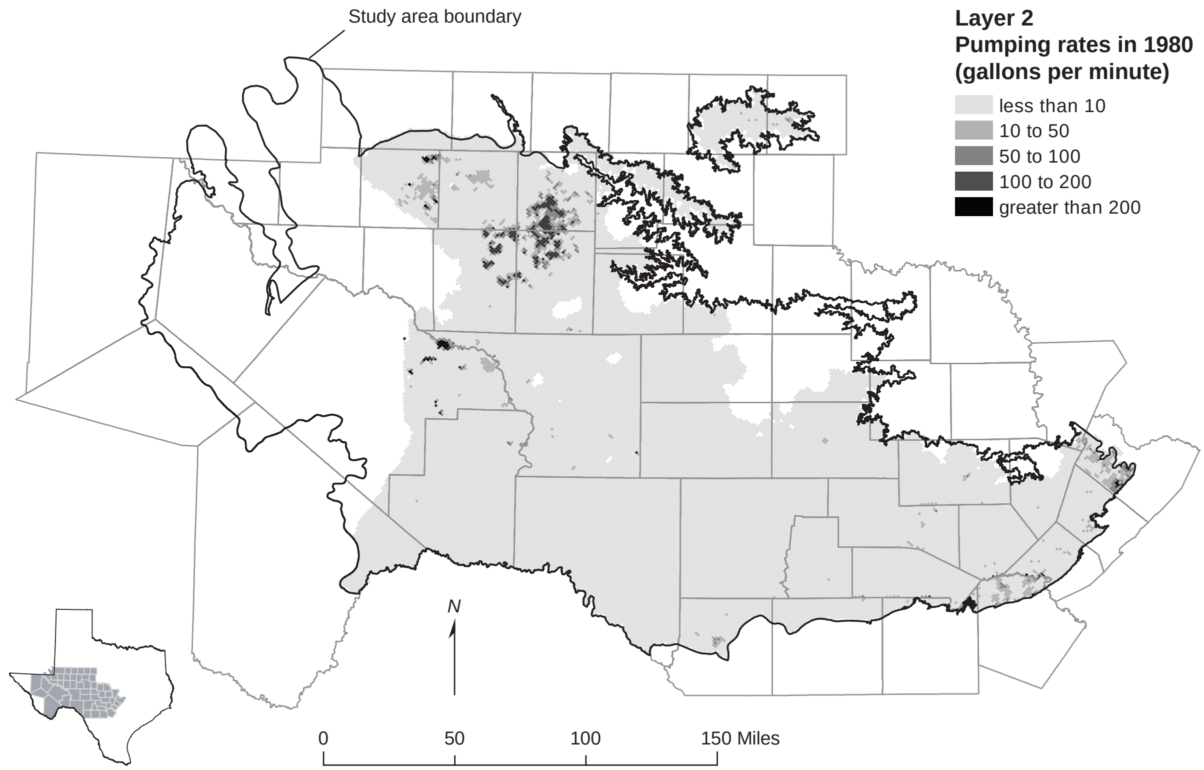

Figure 9-3. Total 1980 pumping volumes for layer 2 distributed within the model grid.

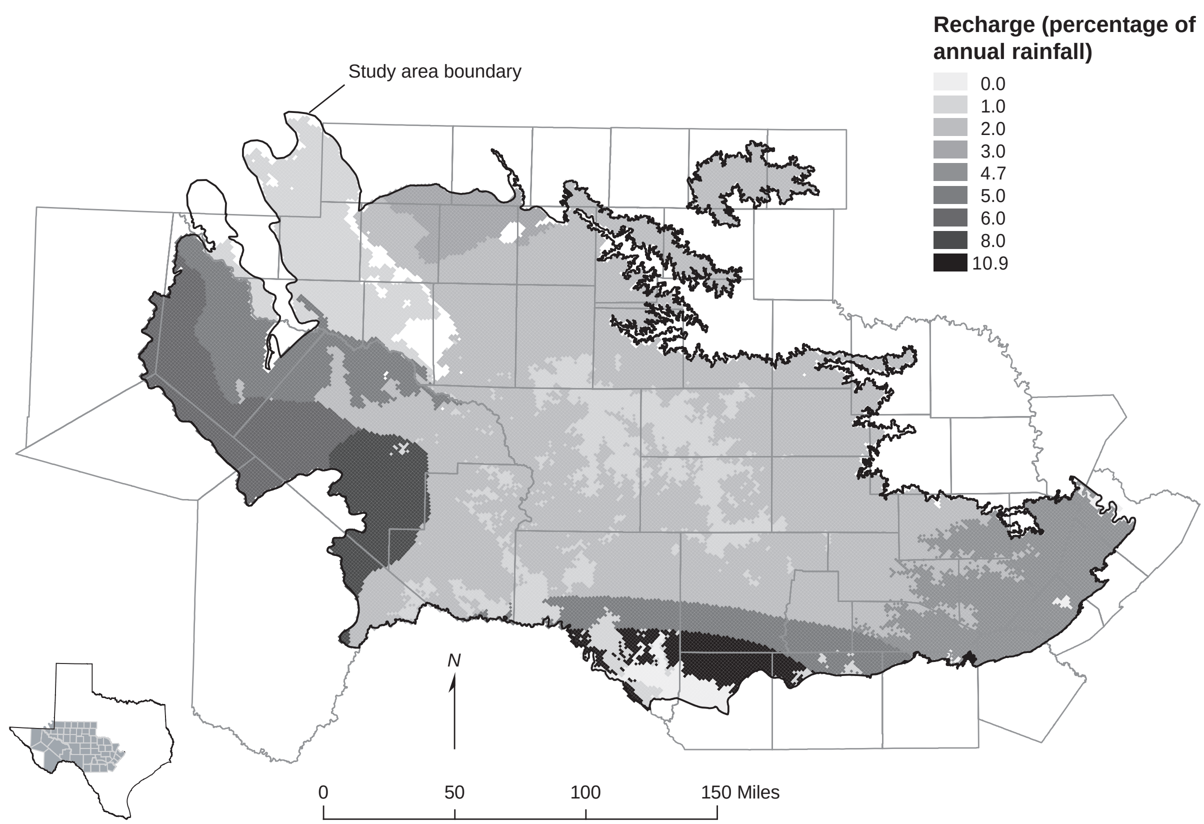

Figure 9-4. Model calibrated zones of recharge expressed as a percentage of annual rainfall.

Table 9-1. Comparison of average annual recharge from the calibrated model and recharge estimates from previous studies.

Recharge area	Average annual recharge		Previous study reference
	This study	Previous study	
Real County	0.9 inches	2 inches	Long (1958)
Crockett County	0.3 inches	0.3 inches	Iglehart (1967)
Kerr County	0.8 inches	1 inch	Reeves (1969)
Kinney County	2.6 inches	2.5 inches	Mace and Anaya (2004)
Hill Country	1.5 inches	1.5 inches	Mace and others (2000)
Trans-Pecos Region	0.6 inches	0.35 inches	Rees and Buckner (1980)
Eastern Edwards Plateau	0.1 to 2.9 inches	0.1 to 2.2 inches	Kuniansky (1989)
Pecos Valley Aquifer	89,800 acre-feet	67,800 acre-feet	Ashworth (1990)

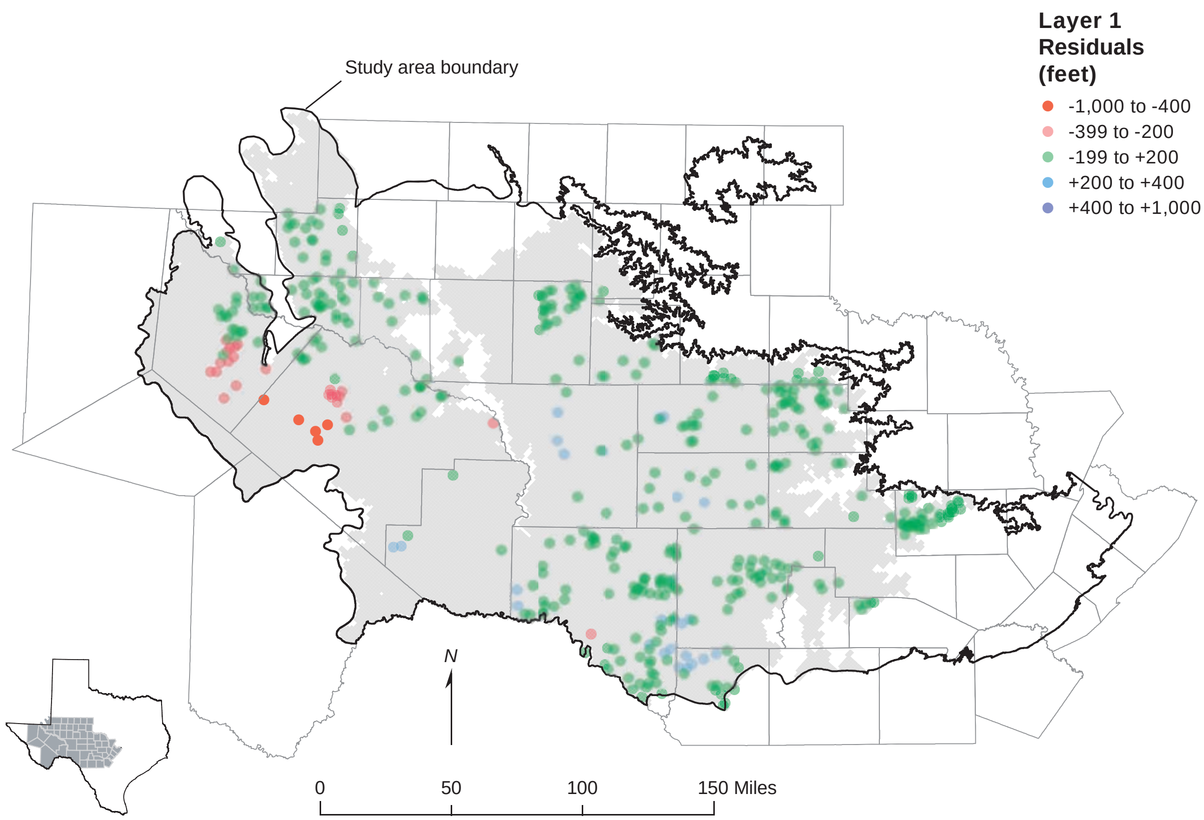

Figure 9-5. Spatial comparison of simulated and measured water levels in layer 1 for the 1980 steady-state model. Residuals are the difference between simulated and measured water levels.

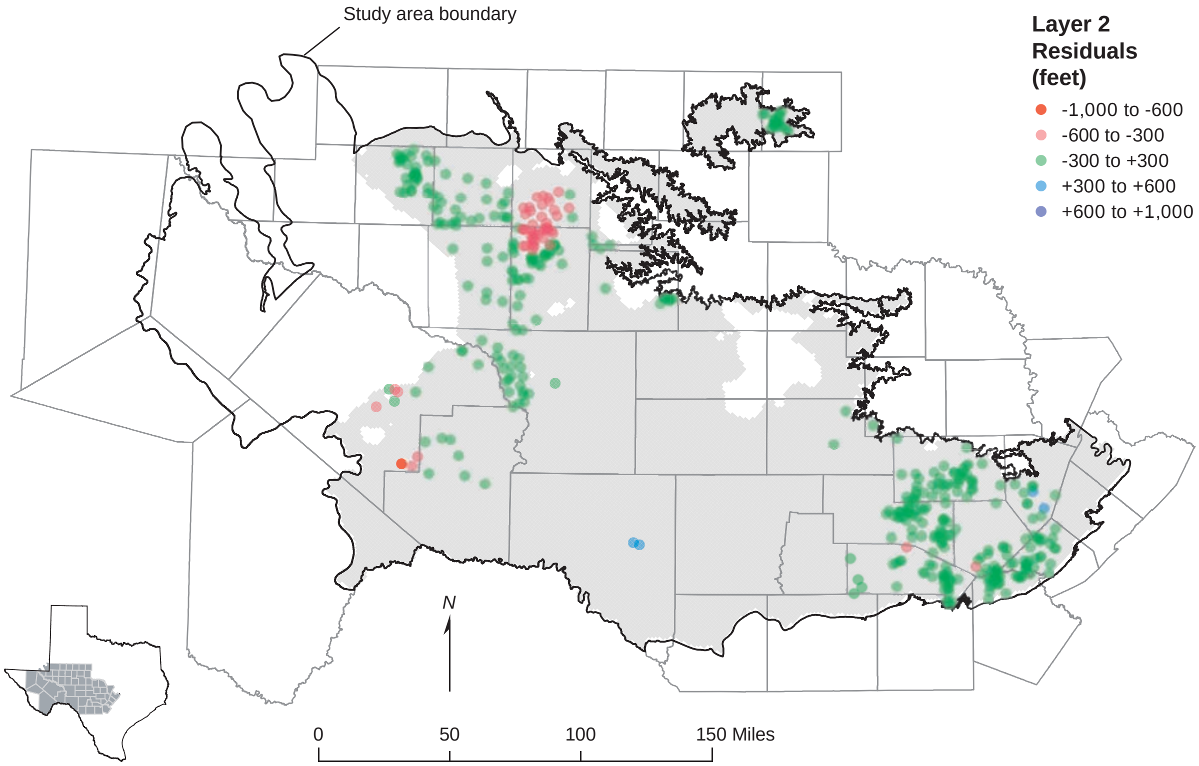

Figure 9-6. Spatial comparison of simulated and measured water levels in layer 2 for the 1980 steady-state model. Residuals are the difference between simulated and measured water levels.

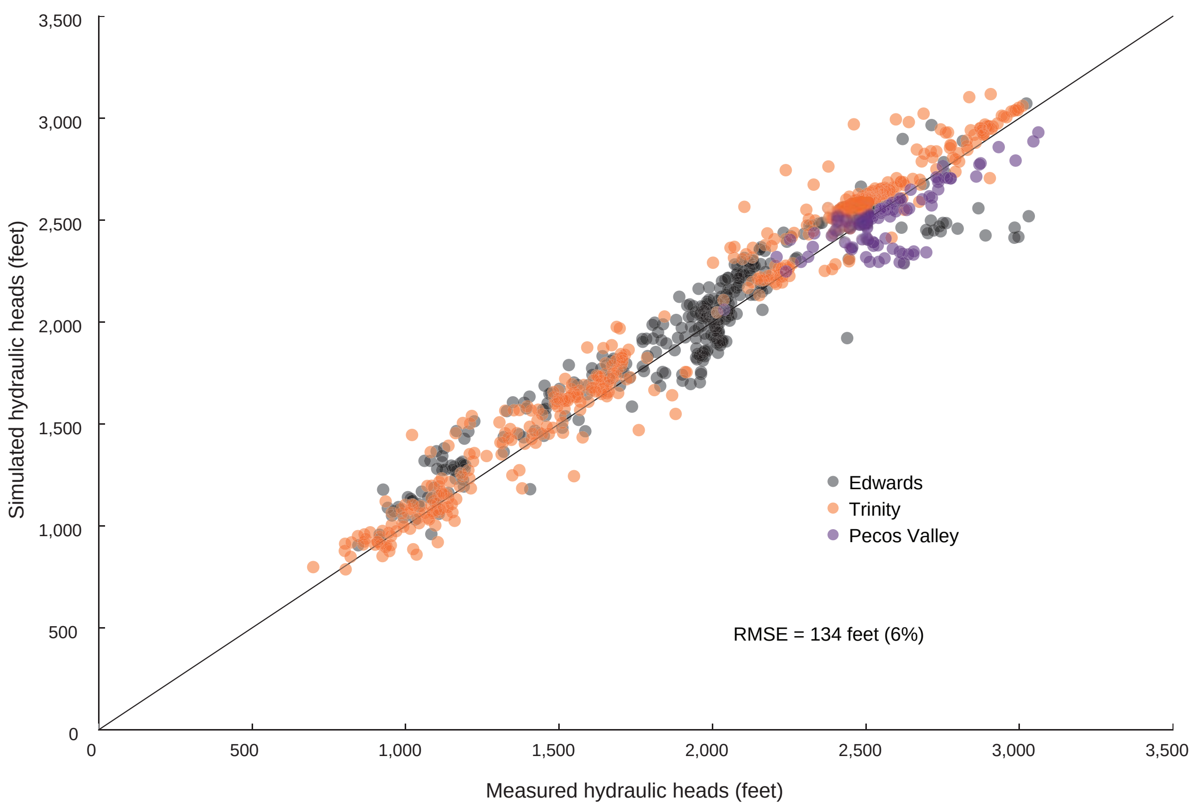

Figure 9-7. Cross plot comparison of simulated and measured water levels for layers 1 and 2 for the 1980 steady-state model.
RMSE=root mean square error.

that the average difference between measured and simulated water levels in the model is ±134 feet, which lies within our 10 percent target for model calibration. Although the root mean square error is within our modeling standards, it may be too high for certain groundwater management needs. In comparison, the one-layer finite-element model constructed by Kuniansky and Holligan (1994) that included the Edwards-Trinity (Plateau) and Pecos Valley aquifers had a root mean square error of 96 feet.

In addition to comparing measured and simulated water levels, comparing the bottoms of the rise and fall in the stream hydrograph curves (or base flow) and simulated groundwater discharge to streams indicates how well the model reproduces groundwater discharge to major streams and springs in the study area (Figure 9-8). There is general agreement between measured streamflow of the South Concho, San Saba, Llano, Pedernales, Guadalupe, Medina, Sabinal, Devils, and Pecos rivers, indicating that the steady-state model reproduces the base flow component of the stream hydrographs for the major perennial streams.

The water budget of the steady-state model indicates that total groundwater flow through the model is approximately 1,600,000 acre-feet per year (Table 9-2). Of this flow, roughly 40 percent discharges to rivers, 15 percent discharges to springs and seeps along the aquifer margins, 15 percent discharges through cross-formational flow to adjacent aquifers, 5 percent discharges to reservoirs, and 25 percent is pumped mostly for irrigation uses (Figure 9-9 and Figure 9-10).

Recharge rates and discharge to streams in the model by Kuniansky and Holligan (1994) is similar to steady-state model results for our model. In the model by Kuniansky and Holligan (1994), recharge is 7 percent of average annual precipitation, compared to 0 to 10.9 percent in our model. Discharge to streams is almost equal at approximately 410,000 acre-feet per year in both models. Cross-formational flow from the Edwards-Trinity (Plateau) Aquifer to the Edwards (Balcones Fault Zone) Aquifer is 120,000 acre-feet per year in our model, which is significantly less than the 360,000 acre-feet per year in the Kuniansky and Holligan (1994) model, and about double the flow in the model of the Hill Country portion of the Trinity Aquifer by Mace and others (2000), which indicates a cross-formational flow of 64,000 acre-feet per year.

9.2 STEADY-STATE MODEL SENSITIVITY ANALYSIS

After calibration of the steady-state model was completed, we assessed the sensitivity of model results to input parameters, that is, transmissivity; vertical hydraulic conductivity; streambed, drain, and general head boundary conductance; 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, 1992). 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 relatively small small changes in model output. Insensitivity results in more uncertainties because the model will calibrate over a large range of input parameter values.

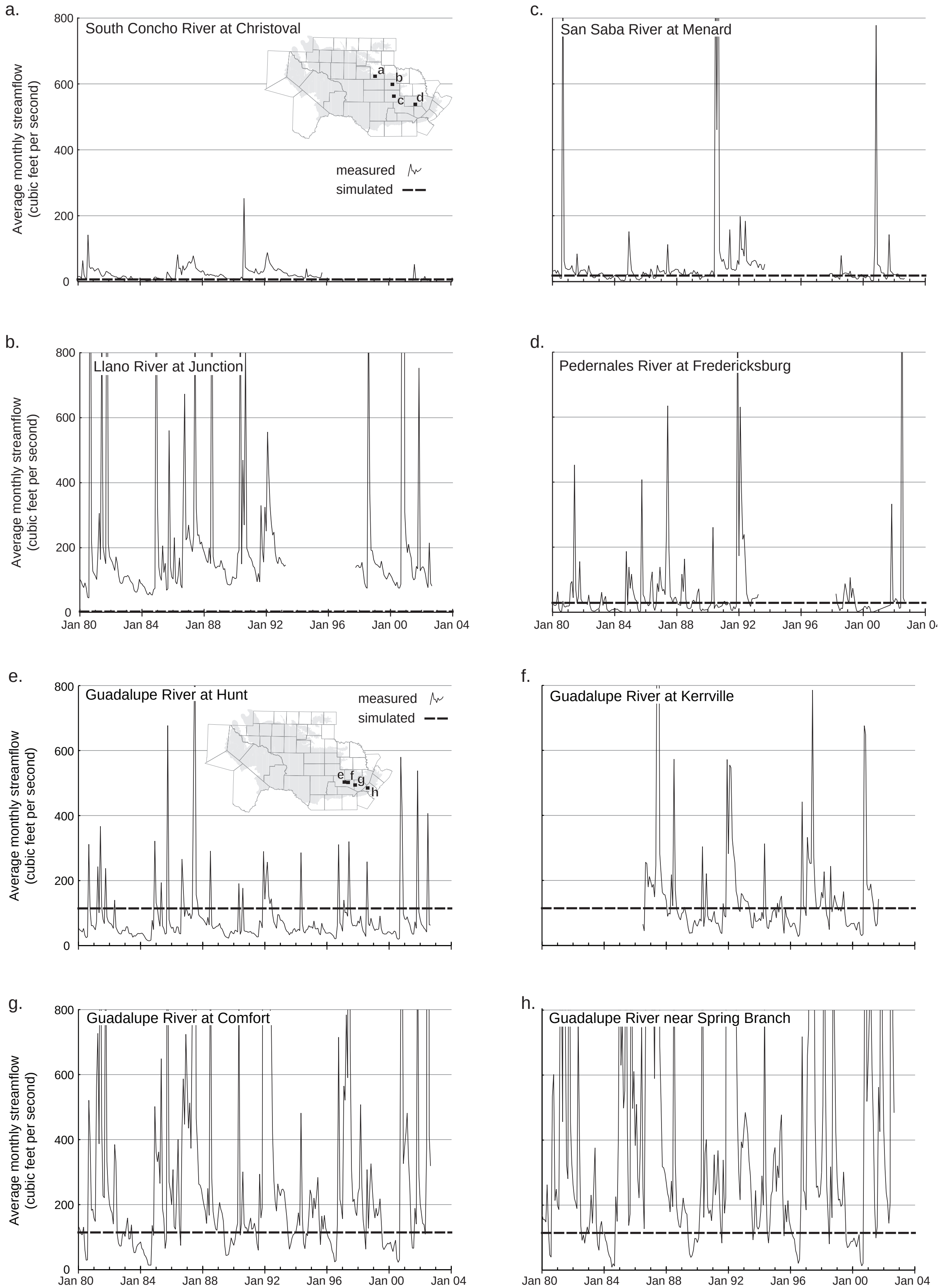

Figure 9-8. Comparison of simulated groundwater discharge to perennial streams for the 1980 steady-state model (dashed line) and measured streamflow.

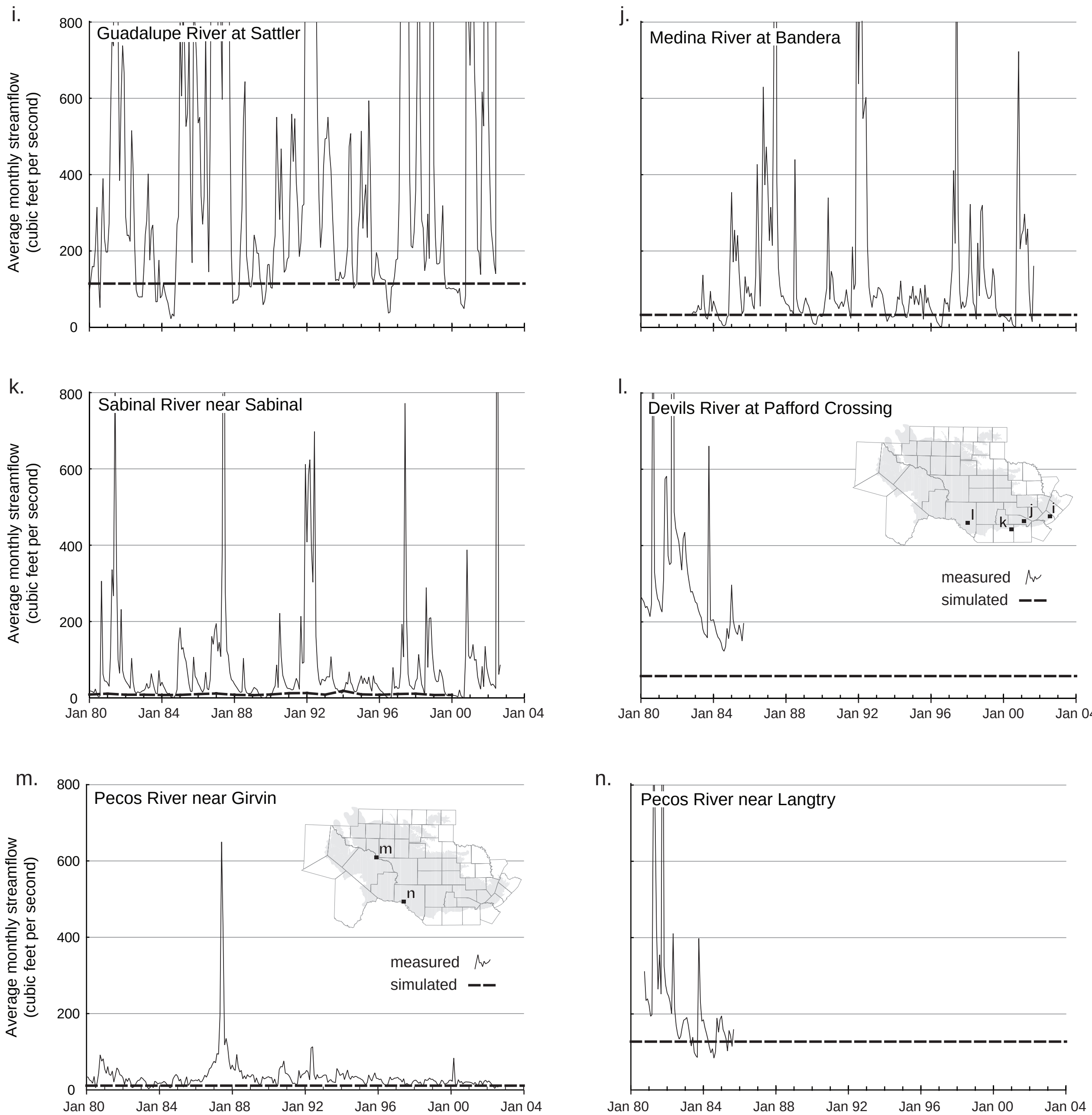

Figure 9-8 (continued).

Table 9-2. Water budget for the calibrated steady-state model for 1980. Values expressed in acre-feet per year.

	Layer 1			Layer 2		
	In	**Out**	**Net**	**In**	**Out**	**Net**
Reservoir	14,200	48,300	-34,100	10,900	41,100	-30,200
Inter-layer exchange	9,640	150,000	-140,000	150,000	9,640	140,000
Wells	0	257,000	-257,000	0	119,000	-119,000
Springs/seeps	0	130,000	-130,000	0	80,000	-80,000
Recharge	776,000	0	776,000	433,000	0	433,000
Adjacent aquifers	2,840	33,900	-31,100	28,700	144,000	-115,000
Rivers	105,000	289,000	-184,000	33,400	262,000	-228,000
% Difference			-0.02			0.00

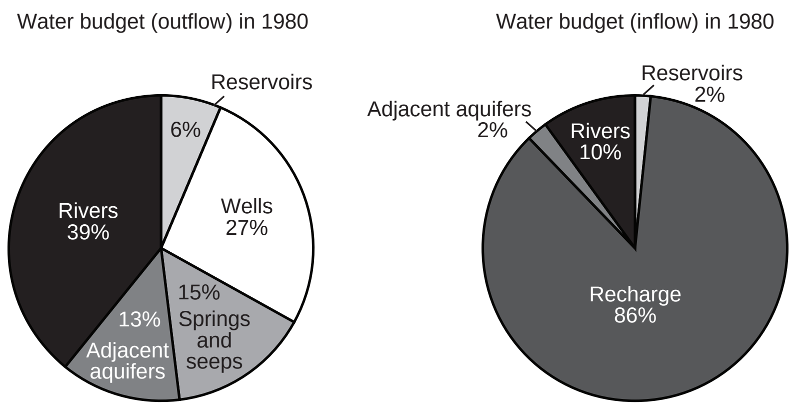

Figure 9-9. Groundwater inflows and outflows of the water budget for the 1980 steady-state model.

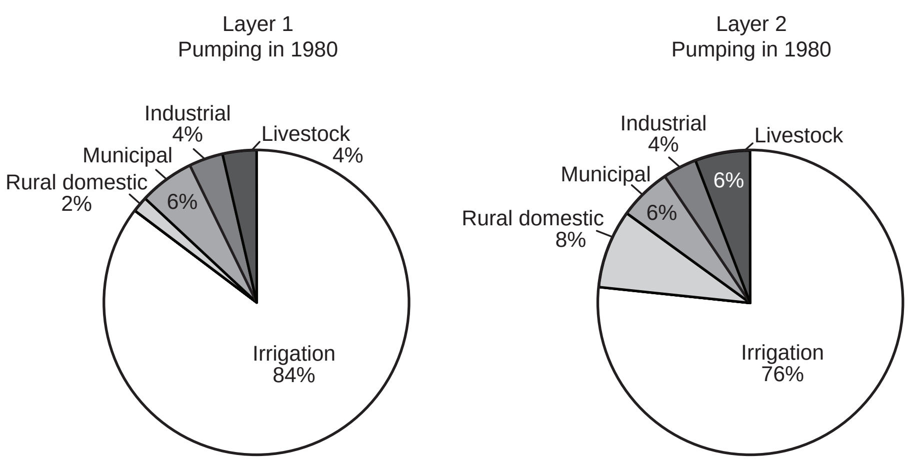

Figure 9-10. Pumping categories for 1980 steady-state model.

Sensitivity is analyzed by systematically varying a parameter value and noting changes in water levels at the well locations used to calibrate the model. The parameters that we varied were vertical hydraulic conductivity, streambed conductance, drain conductance, recharge, and transmissivity. We varied each of these parameters by the following factors: 0.5, 0.75, 1.25, and 1.5. We quantified water level changes by calculating the mean difference as follows:

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

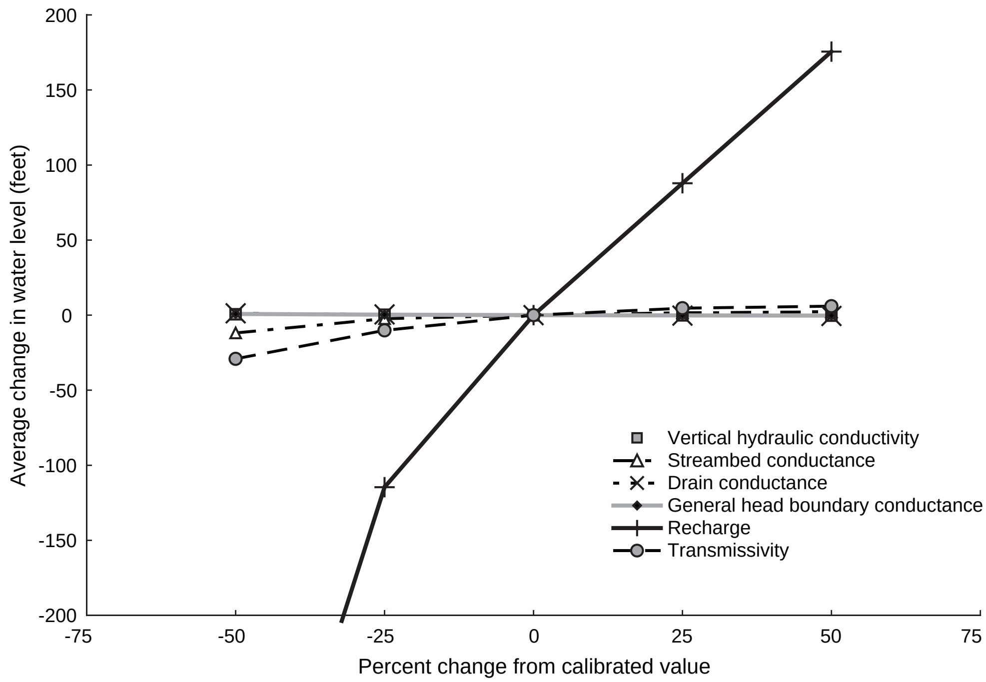

Figure 9-11. Sensitivity of numerically predicted water levels for 1980.

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 for the Edwards-Trinity (Plateau) Aquifer and Pecos Valley Aquifer are most sensitive to recharge, and, to a lesser extent, to streambed conductance and transmissivity (Figure 9-11). The model is insensitive to vertical hydraulic conductivity and drain and general head boundary conductance. This insensitivity can be explained by the spatial distribution of drains and general head boundaries, which occur along the margins of the aquifer. Consequently, the effects of varying both drain and general head boundary conductance are most likely restricted to the margins and have little effect in the interior of the aquifer. Additionally, as head-dependent boundaries, drains and especially general head boundaries tend to buffer adjacent water levels in the aquifer because there is a tendency for the model to try to equalize water levels on both sides of the boundary. The model is most sensitive to recharge because recharge is the primary source of inflow, accounting for 85 and 66 percent of inflow in layers 1 and 2, respectively, and 86 percent of total inflows. The model is sensitive to streambed conductance because discharge to streams is the primary outflow from the model, especially in layer 1. Kuniansky and Holligan (1994) found their model to be most sensitive to recharge, transmissivity, and discharge.

10 *Transient model*

After calibrating the steady-state model to conditions in 1980, we then calibrated the model to simulate transient conditions from 1980 through 2000.

10.1 TRANSIENT MODEL CALIBRATION

Because of variations in pumping and recharge, we simulated water level fluctuations during the period 1980 through 2000 using annual stress periods (Figure 10-1 and Figure 10-2). We achieved calibration by adjusting storage parameter values, specific yield, and specific storage until the model responses approximated water level fluctuations observed in wells in the model area. Specific yield is applicable to the unconfined part of the aquifer, and specific storage is applicable to the confined part of the aquifer. Specific yield and storage are important factors in transient calibration because they influence water level responses to changes in recharge and discharge. Low specific storage or yield values result in water level fluctuations that are larger and more rapid than those of higher values. This difference occurs because less water is required to produce a given water level change.

During the calibration process, we calibrated specific yield and storage in zones based on observed water level fluctuation responses. For example, we assigned higher specific yields and storage values for zones where water level fluctuations over the modeling period (1980–2000) were smaller than zones with greater water level fluctuations. The values for specific yield and specific storage calibrated for this model were 0.0005 to 0.2 and 5×10^{-7} to 2×10^{-4} per foot, respectively (Figure 10-3, Figure 10-4, Figure 10-5, and Figure 10-6). MODFLOW uses the assigned specific yield values where the aquifer is unconfined and the assigned specific storage values where the aquifer is under confined conditions. Overall, the transient model matched reasonably well to hydrograph trends observed in annual water levels (Figure 10-7). Differences between simulated and observed water level fluctuations can be attributed to the influence of local-scale conditions that are not represented in this regional-scale model. Over the calibration period, water level fluctuations

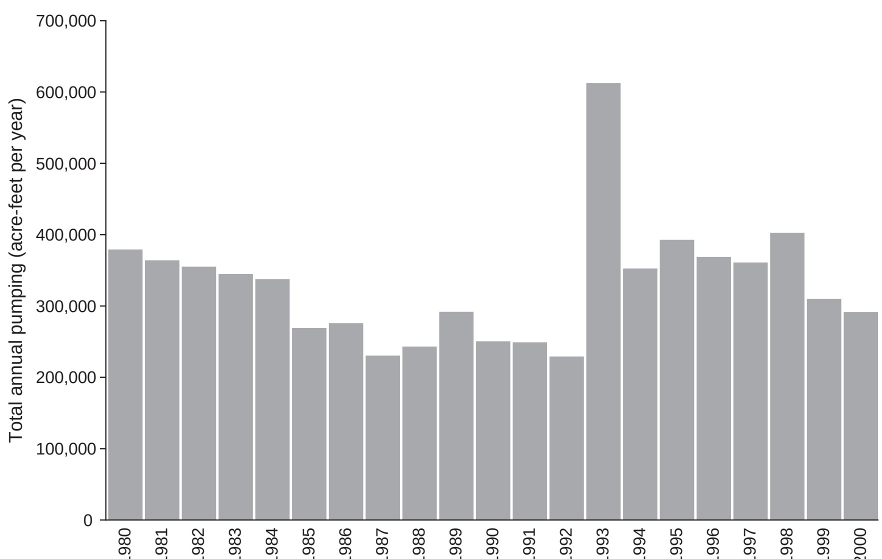

Figure 10-1. Historical annual pumping in the study area.

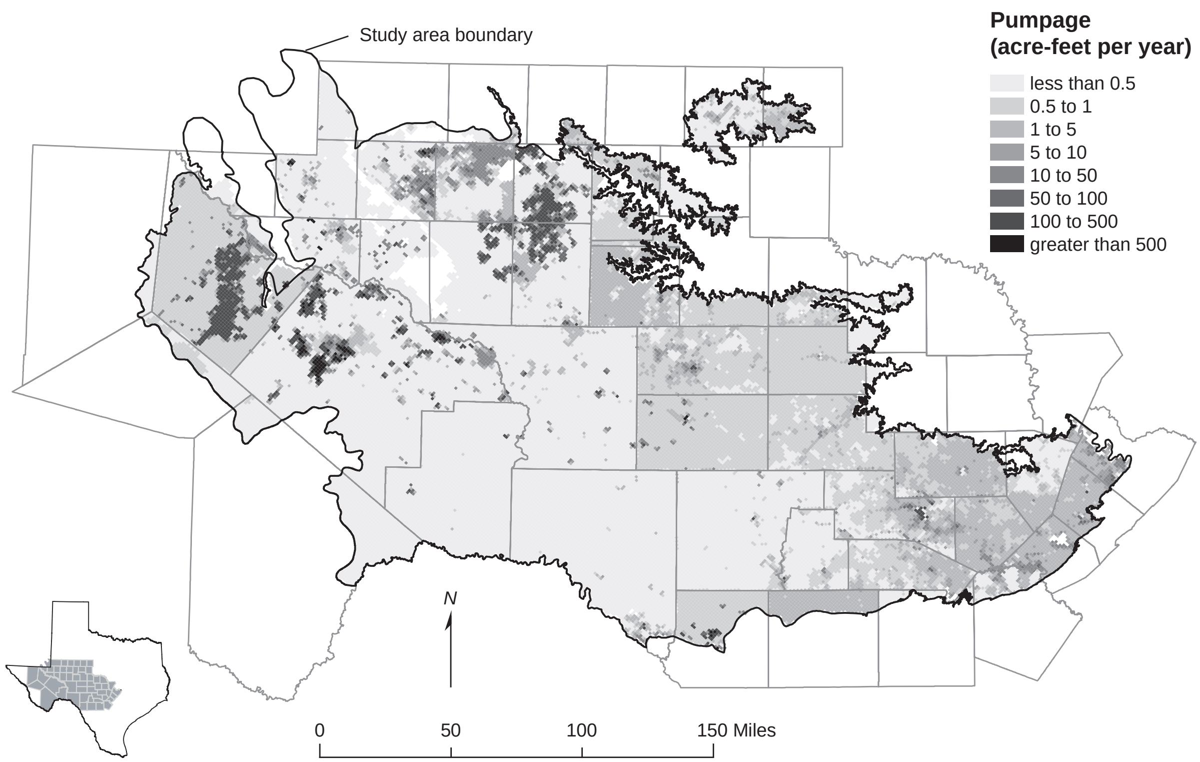

Figure 10-2. Total pumping volumes assigned per grid cell for 2000.

were generally greater in northern and eastern parts of the Edwards and Trinity hydrostratigraphic units of the Edwards-Trinity (Plateau) Aquifer. Elsewhere in the Edwards-Trinity (Plateau) and Pecos Valley aquifers, water levels remained almost constant. The simulated base flow trends from the model also matched fairly well to the base flow component of streamflow hydrographs for major streams in the study area (Figure 10-8). However, our model used annual time steps, which may not reflect the true seasonal variability of base flow conditions.

The simulated water levels for our model meets TWDB's groundwater availability modeling error standards for matching measured water levels throughout the model area (Figure 10-9 and Figure 10-10). The difference between measured and simulated water level elevations is less than 200 feet at most measured well locations. Comparing measured and simulated water levels for the period 1990 and 2000 indicates an overall root mean square error of 143 feet, or 6 percent of the range of measured water levels (Figure 10-11). However, although our model meets TWDB's groundwater availability modeling error standards, the model may not be appropriate for use in all groundwater management decisions or for certain regions within the modeling study area.

10.2 TRANSIENT MODEL SENSITIVITY ANALYSIS

Upon completing the transient model calibration, we adjusted storage parameters to determine the sensitivity of the model to specific yield and specific storage. We analyzed sensitivity by systematically varying specific yield and storage to determine associated changes in aquifer response over the transient model run.

We varied calibrated specific yield and storage values by ± 1 order of magnitude resulting in values ranging from 0.00003 to 2.0 and 5×10^{-8} to 2×10^{-3} per foot, respectively. Sensitivity analysis indicates that the overall model is more sensitive to variation of specific yield than specific storage (Figure 10-12).

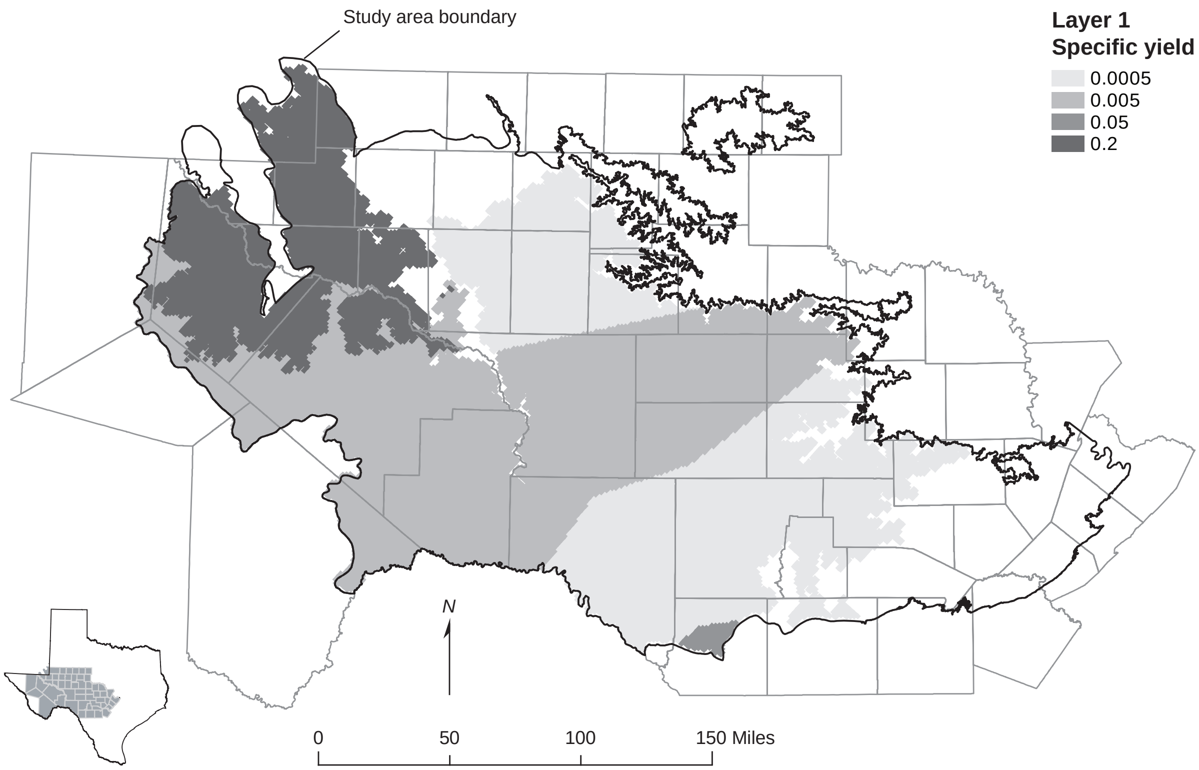

Figure 10-3. Specific yield for layer 1 used within model.

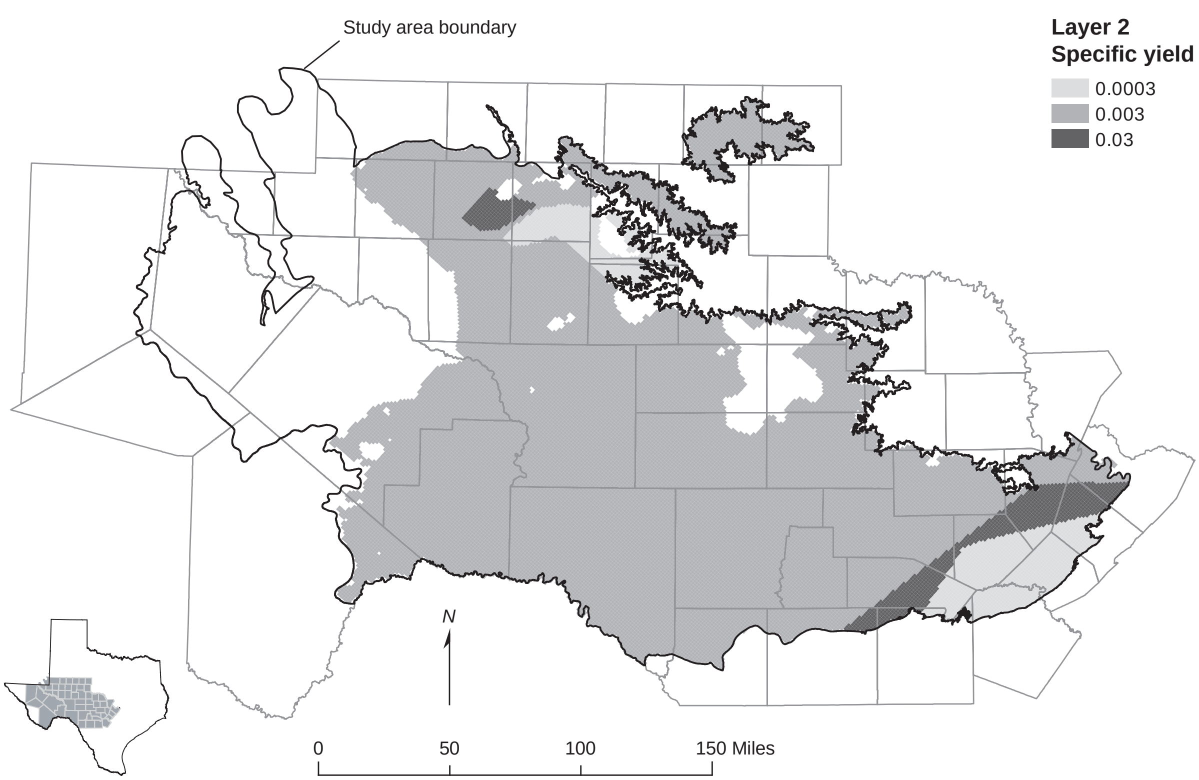

Figure 10-4. Specific yield for layer 2 used within model.

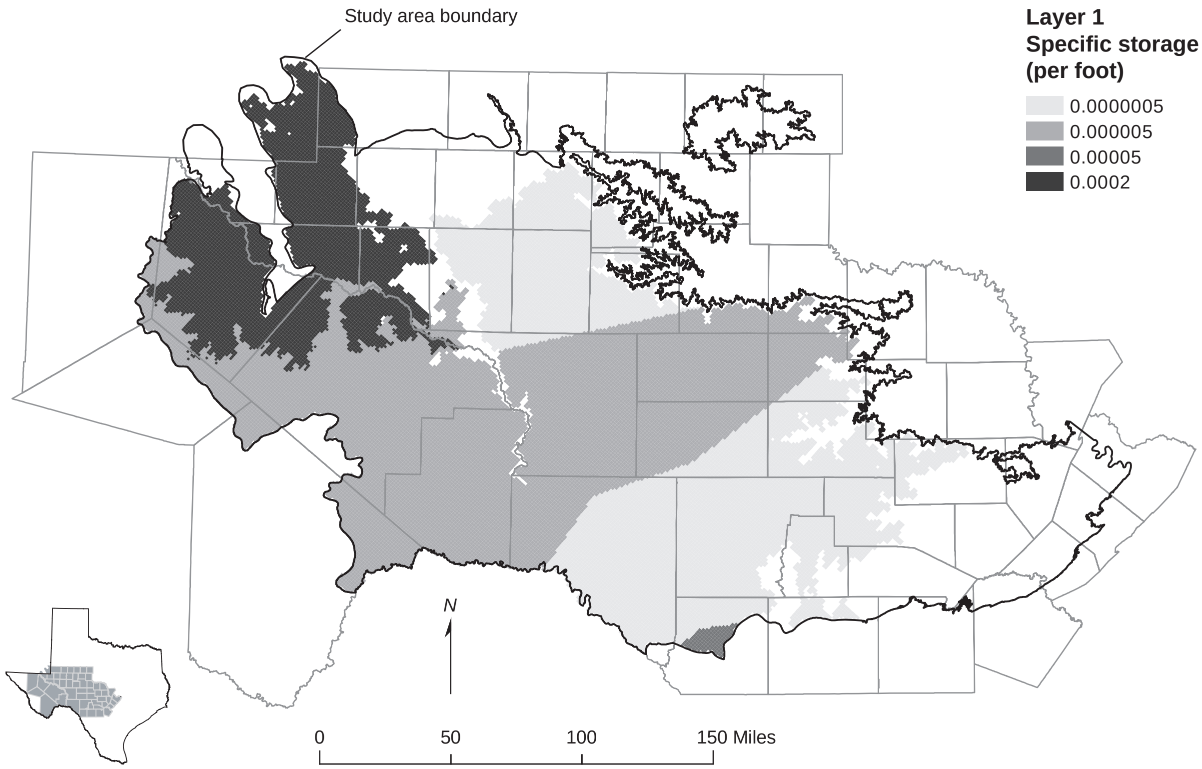

Figure 10-5. Specific storage for layer 1 used within model.

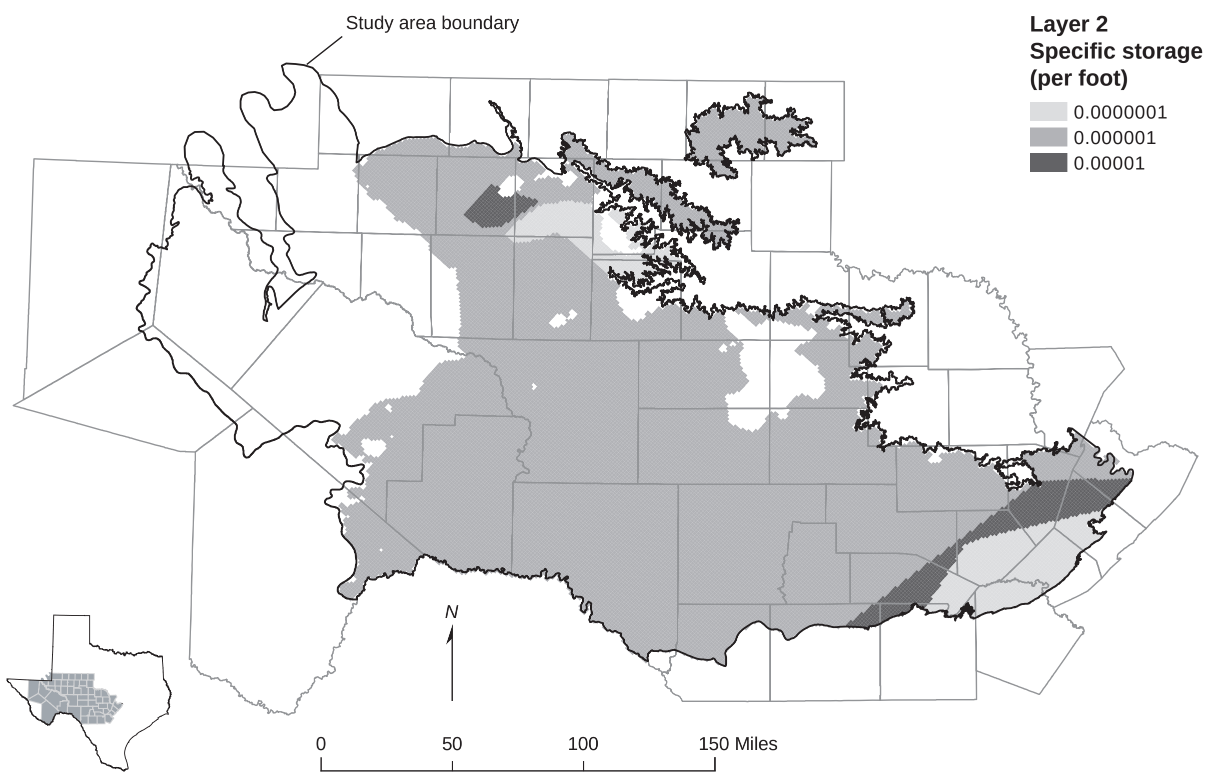

Figure 10-6. Specific storage for layer 2 used within model.

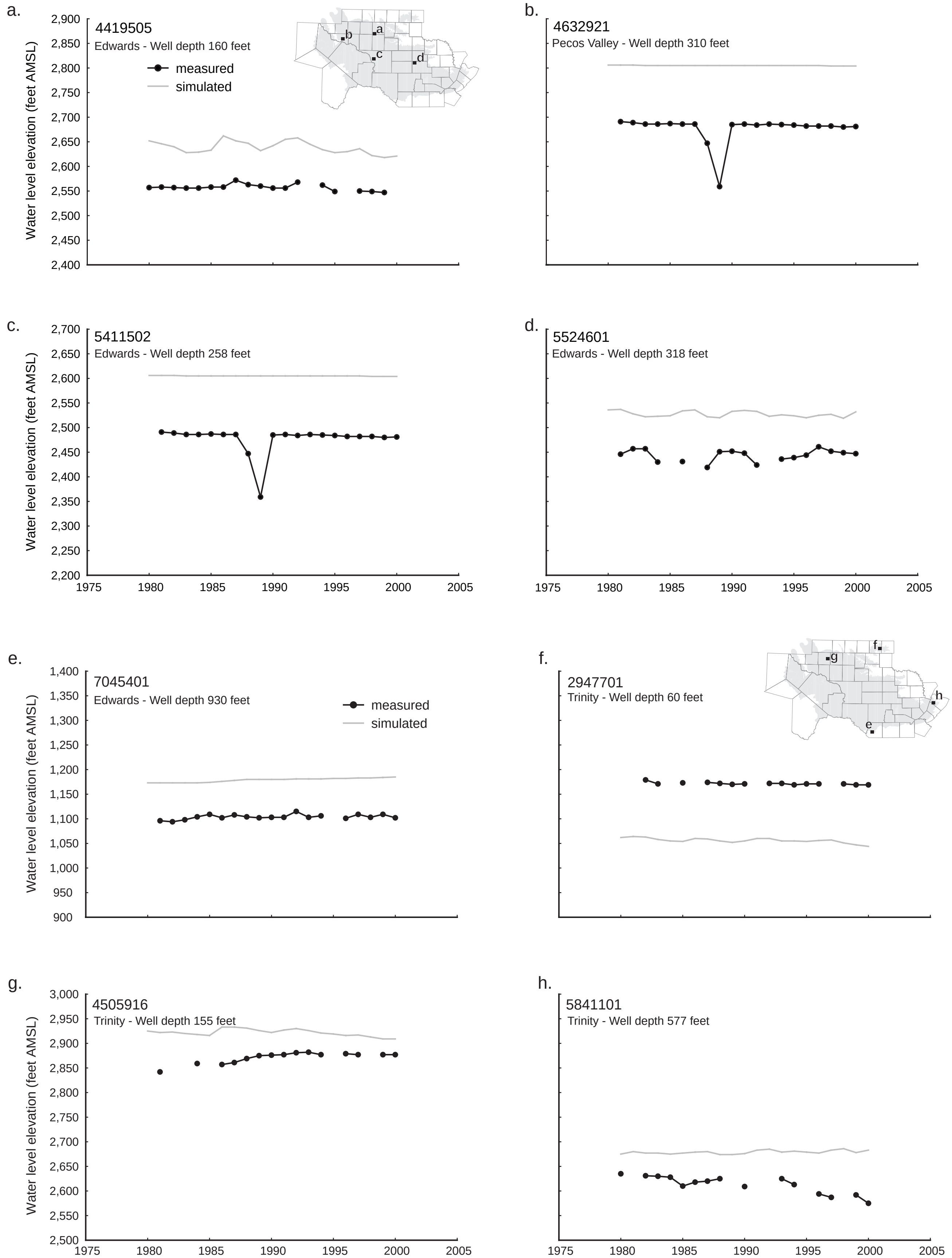

Figure 10-7. Measured and simulated water level fluctuations for the period 1980–2000.
AMSL=above mean sea level

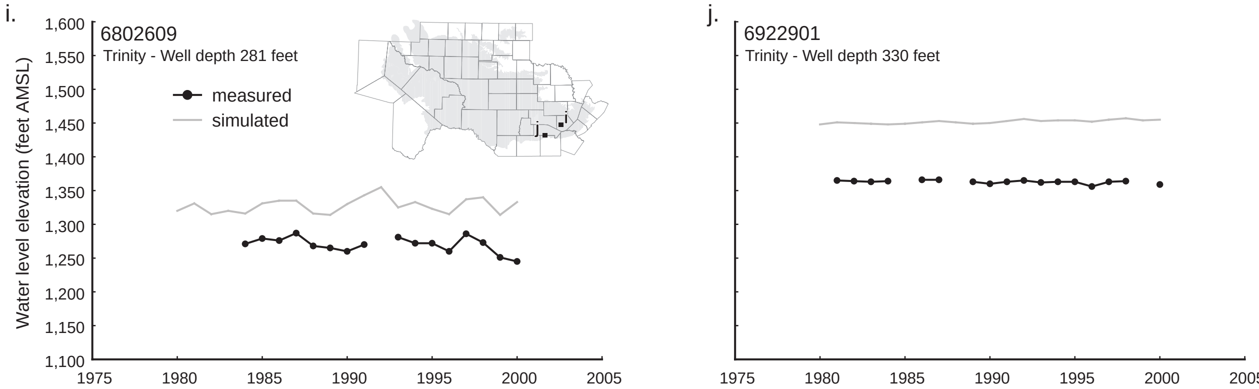

Figure 10-7 (continued).

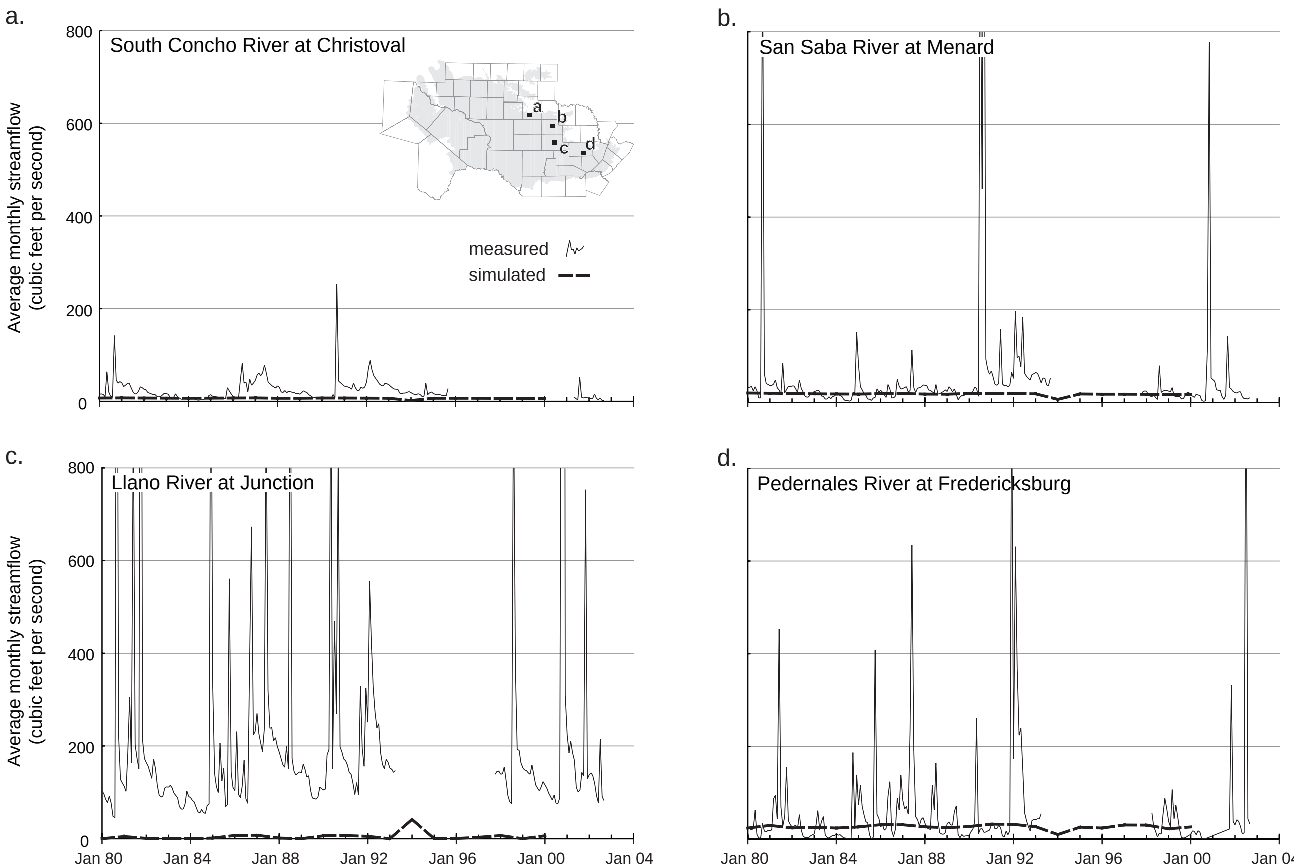

Figure 10-8. Comparison of simulated groundwater discharge to perennial streams for the 1980–2000 transient model (dashed line) and measured streamflow.

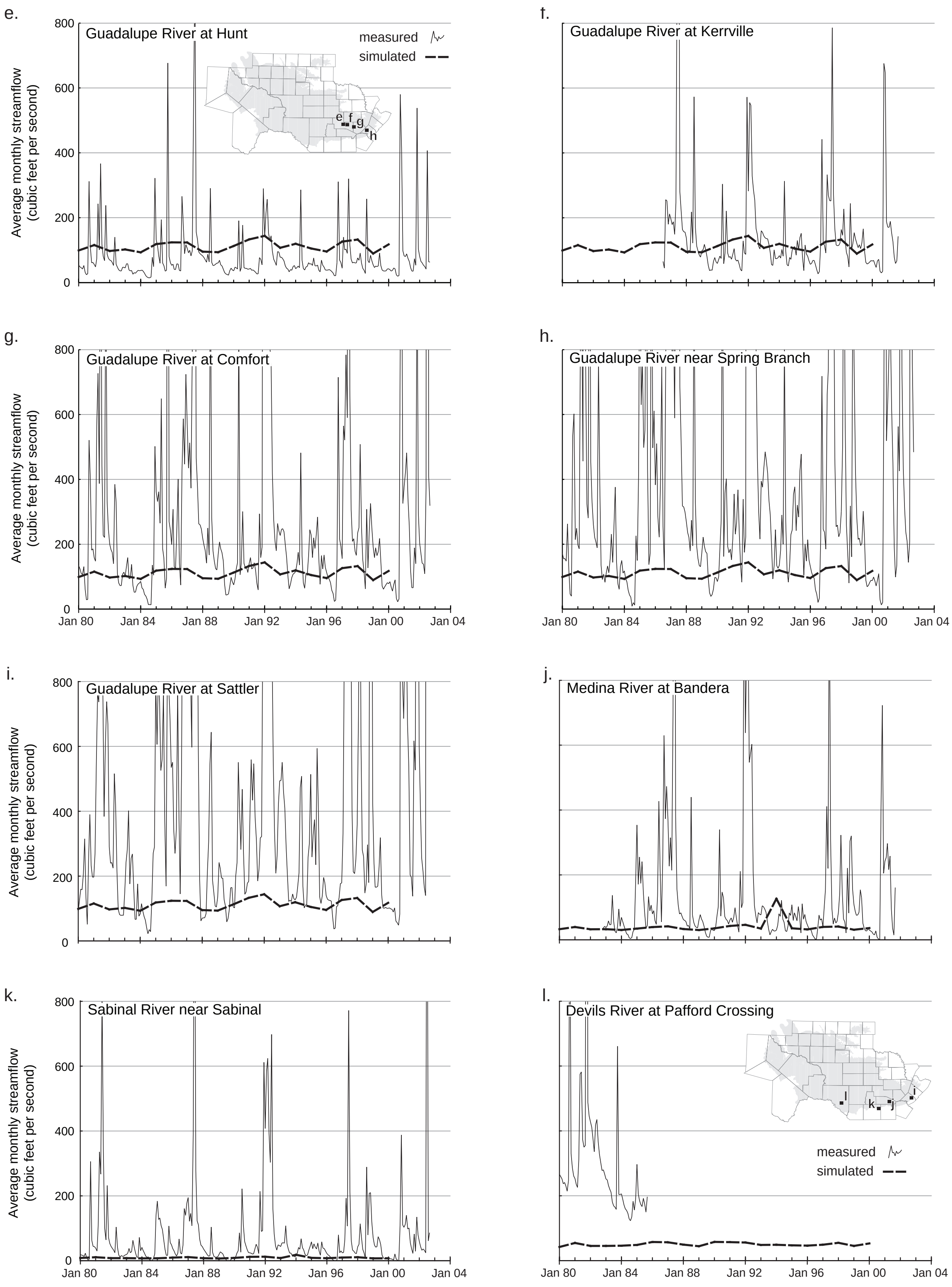

Figure 10-8 (continued).

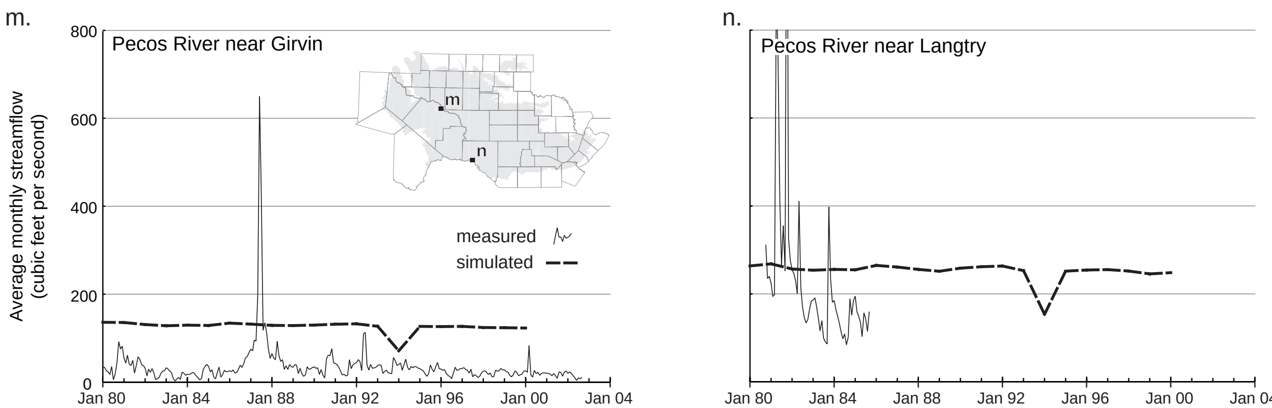

Figure 10-8 (continued).

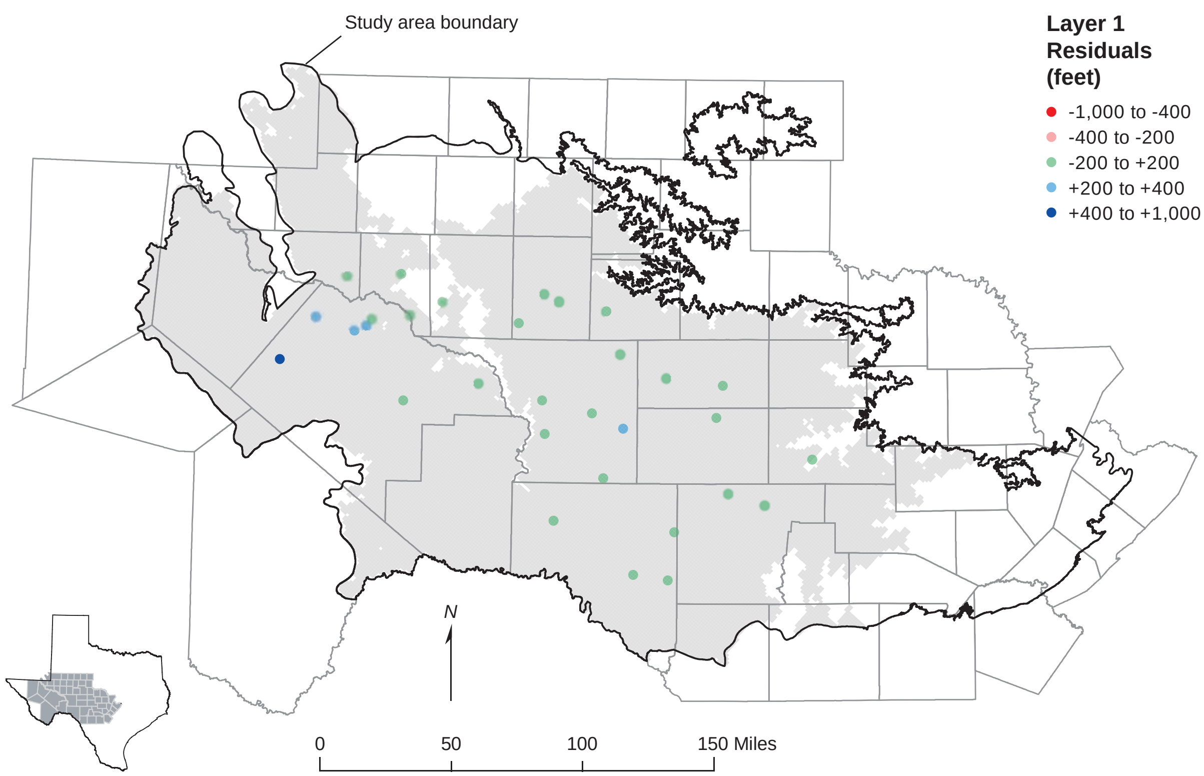

Figure 10-9. Spatial comparison of simulated and measured water levels in layer 1 of the transient model for the 2000 annual stress period. Residuals are the difference between simulated and measured water levels.

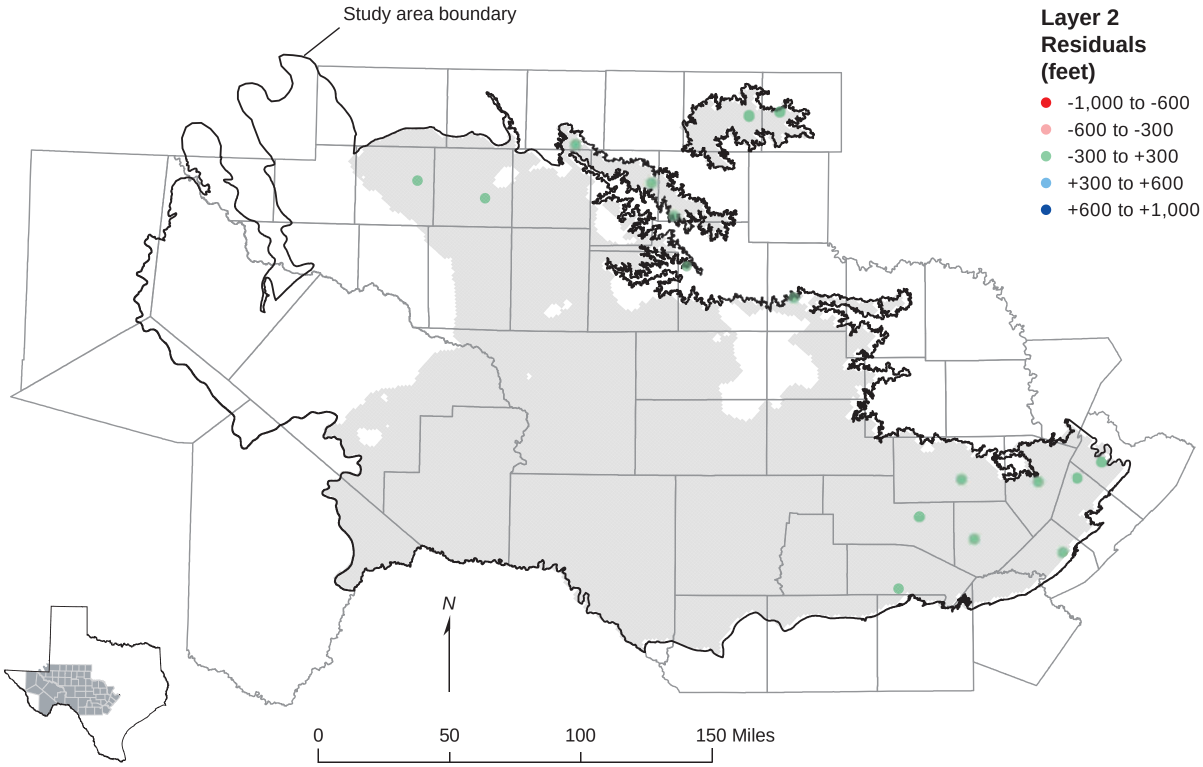

Figure 10-10. Spatial comparison of simulated and measured water levels in layer 2 of the transient model for the 2000 annual stress period. Residuals are the difference between simulated and measured water levels.

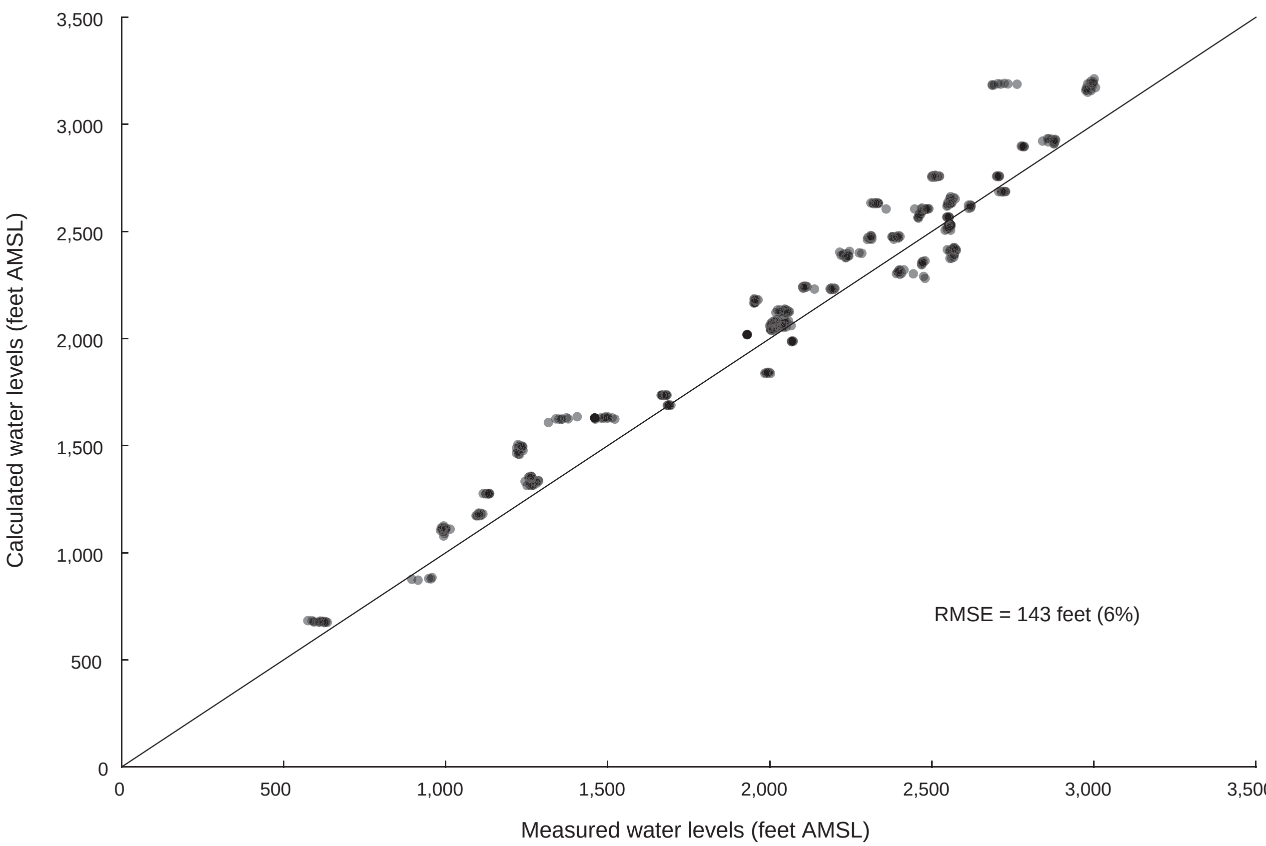

Figure 10-11. Cross plot comparison of simulated and measured water levels for both layers 1 and 2 of the (1980–2000) transient model.

RMSE=room mean square error; AMSL=above mean sea level

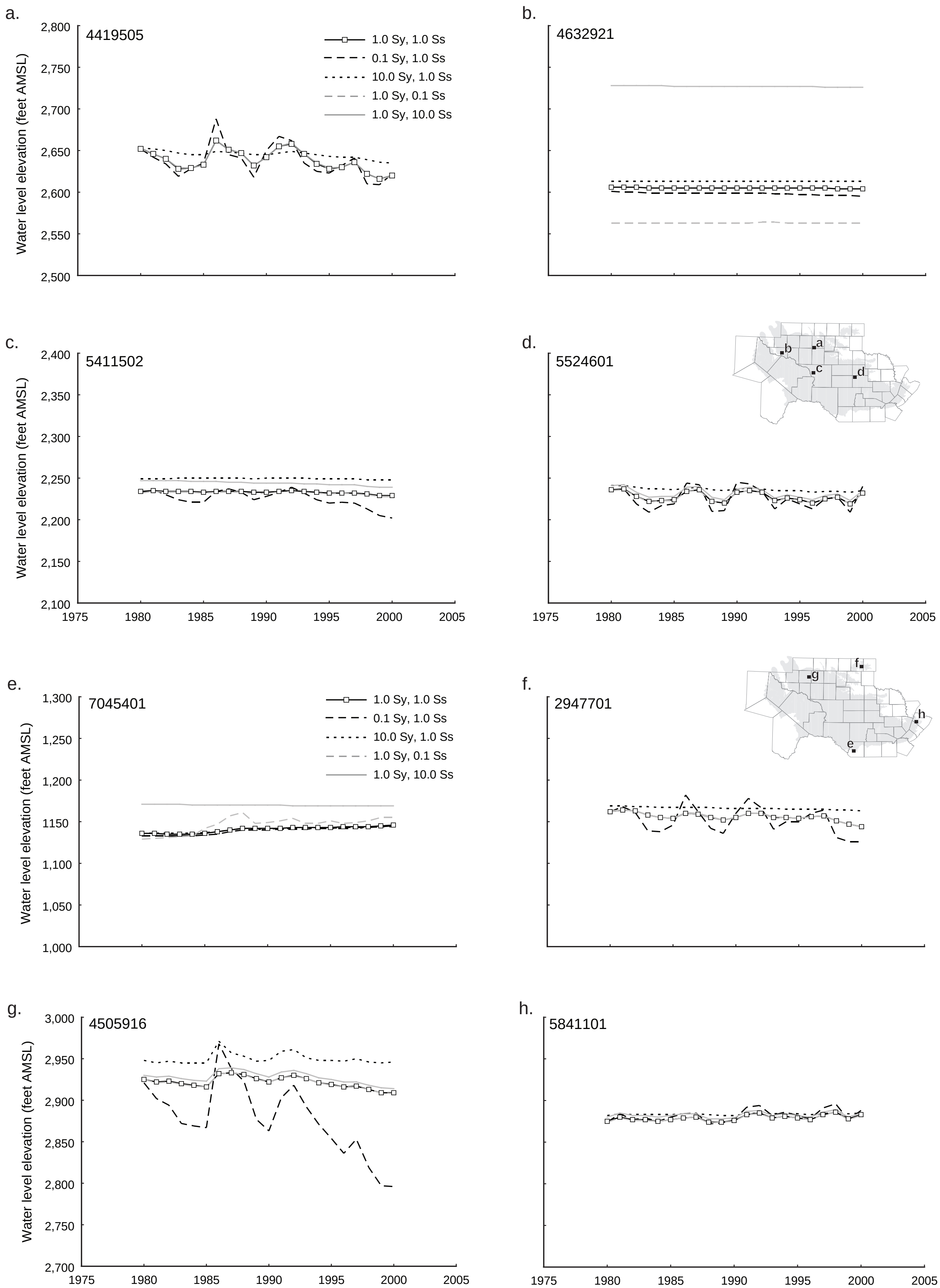

Figure 10-12. Sensitivity of model to specific yield and specific storage.

AMSL=above mean sea level

Sy=specific yield

Ss=specific storage

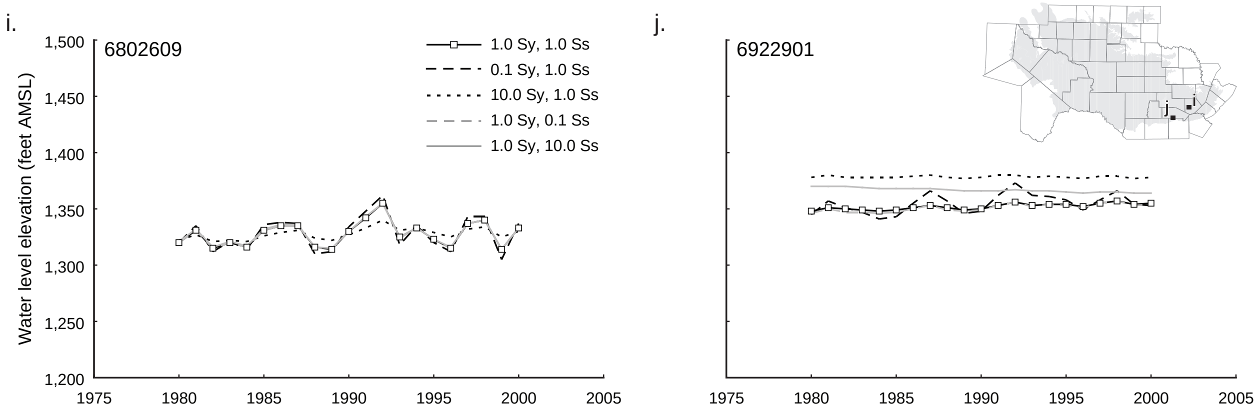

Figure 10-12 (continued).

11 *Limits of the model*

All numerical groundwater flow models have limitations. These limitations are usually associated with the (1) extent of current understanding of the workings of the aquifer, (2) availability and accuracy of input data, and (3) assumptions and simplifications used in developing the conceptual and numerical models. 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 input parameter data sets for the model are based on limited information. These include structural geology, recharge, water level and streamflow data, hydraulic conductivity, specific storage, and specific yield.

There is a paucity of information on the structural geology of the model area along the western margin of the Edwards-Trinity (Plateau) Aquifer. Consequently, the elevations of the aquifer tops and bottoms along the western margin of the model are less reliable than the structural information in the other parts of the model.

No information on the spatial or seasonal distribution of recharge to the Pecos Valley Aquifer has been published. We obtained calibrated recharge rates by trial and error. Applying these recharge rates to the transient model assumes that a linear relationship exists between precipitation and recharge and no threshold 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 recharge uncertainties, the model water budget approximates the aquifer water budget.

Information on the spatial distribution of water levels in the Edwards-Trinity (Plateau) and Pecos Valley aquifers is limited. There is little to no water level data for the Trinity hydrostratigraphic unit in the central portion of the model area and few water level data for the Edwards hydrostratigraphic unit in Terrell and Pecos counties. There is also model uncertainty associated with annual stress periods used in the model. The use of annual stress periods results in the model not simulating seasonal effects of recharge and pumping. However, attempts to successfully simulate seasonal effects would be impractical due to the paucity of wells with frequent water level measurements needed for calibration and the fact that seasonal fluctuations may be too small to simulate with certainty at the regional scale.

There is also uncertainty with simulating base flow from the spatial and temporal scale of this model. Actual discharge to streams occurs within small areas averaging 50 feet wide, compared to the 1 square mile of the model cells, and base flow is more variable than the annual time steps of the model. Uncertainty occurs because calculated discharge to streams is averaged over a 1-year stress period and 1 square-mile cell.

Available transmissivity and hydraulic conductivity data for the Edwards-Trinity (Plateau) and Pecos Valley aquifers is derived primarily from specific-capacity data obtained from wells scattered throughout the model area. However, these data are not located close enough to indicate more localized heterogeneity within the zones used in the model. The same is true in the assignment of specific storage and specific yield values for the model. The scarcity of measured specific storage and yield values is addressed by calibrating the model based on observed water level responses to wells with time series measurements of annual water levels (Figure 9-5).

11.2 ASSUMPTIONS

We made several assumptions in constructing this model. The most important assumptions were that (1) no groundwater flows between the Edwards-Trinity (Plateau) and Pecos Valley aquifers and the underlying Rustler, Capitan Reef Complex, Dockum, and Ellenberger-San Saba aquifers; (2) some components of recharge are modeled by stream-aquifer interactions; (3) the General-Head Boundary package of MODFLOW can be used to simulate cross-formational flow between the Edwards-Trinity (Plateau) Aquifer and adjacent units, such as the Ogallala and Edwards (Balcones Fault Zone) aquifers; and (4) transmissivity is fixed for this model and not allowed to vary according to saturated thickness.

Groundwater flow between the Edwards-Trinity (Plateau) and Pecos Valley aquifers and the underlying aquifers is assumed to be negligible. This assumption is based partially on successfully calibrating the model without the need to factor in the underlying aquifers. It was difficult for us to consider this inter-aquifer groundwater flow because of the paucity of water level and hydraulic property data to constrain such flow. Additionally, groundwater geochemistry studies in the Pecos Valley Aquifer, which would potentially be impacted the most by groundwater interaction with underlying aquifers, indicate only minor amounts of groundwater flow from underlying saline aquifers.

Recharge generally takes the form of diffuse infiltration from precipitation through aquifer material exposed at land surface. This recharge differs from direct recharge, such as streamflow losses from streams and rivers or along other specific discrete recharge features. These alternative mechanisms are simulated in MODFLOW using the Streamflow-Routing package.

The General-Head Boundary package is used to simulate cross-formational flow between the Edwards-Trinity (Plateau) Aquifer and the adjacent Ogallala and Edwards (Balcones Fault Zone) aquifers. We based the construction of the general head boundary on interpolated Ogallala and Edwards (Balcones Fault Zone) Aquifer hydraulic heads and calibrated hydraulic conductance. Even though the model is insensitive to general head boundary conductance, net general head boundary outflow from the Edwards-Trinity (Plateau) Aquifer to the Edwards (Balcones Fault Zone) Aquifer is 91,000 acre-feet per year, a value within the range estimated for the groundwater availability model of the Hill Country part of the Trinity Aquifer (Mace and others, 2000). Additionally, general head boundaries are used to simulate cross-formational flow between the Edwards-Trinity (Plateau) and Pecos Valley aquifers and adjacent minor aquifers, the Rustler, Dockum, and Capitan Reef Complex aquifers, as well as the aquifers of the Llano Uplift. However, we assume this cross-formational flow is insignificant.

Because transmissivity in the model is fixed and not allowed to change with changes in water levels, it is important to note that (1) model cells will not go dry when simulated water levels fall below the base of the aquifer, (2) saturated thickness must be carefully monitored, and (3) fixed transmissivity values are not valid in cases of extreme drawdown. Saturated thickness data from this model must be used carefully, especially in parts of Glasscock, Midland, Reagan, and Upton counties where saturated thickness is less than the root mean square error of the model. This often results in negative calculated saturated thickness because the simulated water levels lie below the base of the aquifer.

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. This model is most accurate in assessing larger regional-scale groundwater issues, such as predicting aquifer-wide water level changes and trends over the next 50 years that may result from different proposed water management strategies. Accuracy and applicability of the model decreases when using it for more 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 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 distributed over many square miles. The model predicts changes in ambient water levels rather than actual water level changes at a specific location, such as an individual well.

12 *Future model improvements*

TWDB plans to periodically update and thus improve groundwater availability models. This model can be improved by incorporating greater complexity or hydrologic information that was not available initially. Model uncertainty can be reduced with additional information on base flow, hydraulic properties, water level elevations, and recharge.

The model can be improved by using hydraulic conductivity and allowing the model to calculate transmissivity instead of using the current model's fixed transmissivity. The advantage of using fixed transmissivity is that it overcomes model instability issues associated with the steeply sloping base of the Edwards hydrostratigraphic unit along the western margin of the aquifer. The disadvantage of using constant transmissivity values is that it introduces error into the model because model cells do not go dry. They continue producing water when water levels fall below the base of the aquifer.

The use of shorter stress periods are required to better determine the seasonal and spatial distribution of stream discharge gain and loss. Additional hydraulic head measurements and aquifer test data are required for the Edwards-Trinity (Plateau) and Pecos Valley aquifers. This information can be used to improve calibration of the model by increasing the number and spatial distribution of sites for comparing measured and simulated water levels. Aquifer tests will facilitate determining whether improving the model by more complex spatial distribution of hydraulic conductivity, specific storage, and specific yield can be justified.

This model can also be improved by investigating the spatial and temporal distribution of recharge. Determining the hydrologic conditions required for recharge to the Edwards-Trinity (Plateau) and Pecos Valley aquifers will facilitate better constraints on the annual and seasonal distribution of recharge to the aquifer.

Model results could be improved by using a smaller grid interval of 1,320 feet instead of the larger 5,280 feet interval used in this model. A smaller grid interval would not have been practical in the Edwards-Trinity (Plateau)/Pecos Valley model because (1) it is not justified by the density of input data and (2) the resultant number of cells in the model grid would cause difficulties with computer run times, required computer memory, and manipulation of input and output data. Creating separate, more detailed groundwater flow models may be useful to simulate groundwater flow in selected parts of the Edwards-Trinity (Plateau) Aquifer because of complex boundary conditions. The southern parts of Kinney and Val Verde counties and the areas with significant irrigation use in the northern part of the Edwards-Trinity (Plateau) Aquifer would benefit from such separate sub-regional models. The Pecos Valley Aquifer would also benefit from decoupling it into its own separate groundwater flow model. The use of smaller model grid intervals will allow a model to better use detailed input data, if available, and thus address local-scale issues of groundwater hydrology that may not be adequately addressed in a regional model.

The model covers a very large area with a variable hydrogeologic framework. We believe that the modeling study area should be subdivided into smaller regional models based on natural boundary conditions, such as major streams and groundwater divides. This would allow for improved calibration errors in simulated water levels.

13 *Conclusions*

TWDB constructed a numerical groundwater flow model to simulate groundwater flow through the Edwards-Trinity (Plateau) and Pecos Valley aquifers. The model was a challenge to develop because of the vast study area and complexity of the aquifer systems. The model should be used with some caution depending on the groundwater management solution desired. We based the conceptualization of the model on available hydrologic and geologic data for the Edwards and Trinity hydrostratigraphic units of the Edwards-Trinity (Plateau) Aquifer and for the Pecos Valley Aquifer. The model is composed of two layers, with a model grid of 300 rows and 400 columns, of which 32,066 and 31,354 are active in layers 1 and 2, respectively. We assigned the model boundary conditions, initial conditions, and input parameters and variable stresses incorporated into the model design based on the conceptual model. The modeling approach included construction and calibration of steady-state (1980) and historical transient (1980 through 2000) models.

The calibrated model meets TWDB's groundwater availability standards for errors in matching water level distribution and fluctuations in the aquifer and discharge to major perennial streams. The root mean square errors for the steady-state and transient models are 134 feet and 143 feet, respectively, or 6 percent of the range of measured water levels in the respective models. Calibrating the steady-state and transient models resulted in (1) a recharge rate ranging from 1 to 8 percent of mean annual precipitation, (2) specific yields of 0.003 to 0.2, and (3) specific storage of 10^{-6} to 2×10^{-4} per foot. The model is most sensitive to changes in specific yield, recharge, and streambed conductance. The model indicates that under steady-state conditions approximately 60 percent of the groundwater flows through the unconfined Edwards hydrostratigraphic unit and Pecos Valley Aquifer. Discharge to rivers, springs, and reservoirs accounts for approximately 60 percent of discharge from the aquifers. Pumping, mostly for irrigation, accounts for approximately 25 percent of groundwater discharge; the remaining 15 percent is discharged mostly to the Edwards (Balcones Fault Zone) Aquifer. Calibrating the transient model indicates that it is able to reproduce historical water level fluctuations. In most parts of the Edwards-Trinity (Plateau) and Pecos Valley aquifers, these fluctuations are relatively small over the modeling period.

Limitations to the model include limited availability of data from certain parts of the study area, assumptions made within the conceptual model, and the scale of application. We made interpolations and extrapolations from available data for areas lacking data. Major assumptions we made include the following: (1) the hydraulic connection between the Edwards-Trinity (Plateau) and Pecos Valley aquifers and the underlying and or adjacent Rustler, Capitan Reef Complex, Dockum, Hickory, Ellenburger-San Saba, and Marble Falls aquifers are insignificant to the overall groundwater flow of the Edwards-Trinity (Plateau) Aquifer and Pecos Valley Aquifers; (2) recharge occurs only as diffuse infiltration over the aquifer outcrops and has a linear relationship with precipitation; (3) the hydraulic connection between the Edwards-Trinity (Plateau) and Pecos Valley aquifers and the Ogallala and Edwards (Balcones Fault Zone) aquifers can be accurately modeled by the General-Head Boundary package of MODFLOW; and (4) transmissivity remains constant and independent of the actual fluctuating saturated thickness. The model should only be used for assessing groundwater availability on a regional scale and not for specific locations or wells. The root mean square error of 134 feet is quite good when compared to the total drop in hydraulic head (or water level elevation) across the aquifers and suggests that the model performs well for regional simulations.

Future improvements to consider include the collection of additional data to reduce uncertainties in hydraulic properties, groundwater and surface water interactions, and recharge. More work is needed to improve calibration in the thinner parts of the Edwards-Trinity (Plateau) Aquifer in the northern areas and along the western margin of the aquifer. Constructing a separate groundwater flow model for the Pecos Valley Aquifer and sub-regional models for the Edwards-Trinity (Plateau) Aquifer and also reducing the grid cell size of the models would improve model simulation of groundwater flow between the aquifer and streams and the calibration of difficult areas of the model such as the steep hydraulic gradients of the Trans-Pecos region.

14 *Acknowledgments*

As authors of this report, we would like to offer our thanks to the other members of the TWDB groundwater availability modeling staff for their contributions to this study, specifically to Shirley Wade, Scott Hamlin, Richard Smith, and Ali Chowdhury for data processing and technical assistance and to Doug Coker and Brent Christian for their field data collection efforts. Additionally, we are grateful to all of the members and participants of the stakeholder advisory forums for their support and comments, and specifically to Dennis Clark of the Emerald Underground Water Conservation District, Cindy Cawley of the Sutton County Underground Water Conservation District, and Cindy Weatherby of the Santa Rita Underground Water Conservation District for hosting the forums. We wish to acknowledge the staff at the U.S. Geological Survey Austin District office and the Texas Commission on Environmental Quality for their assistance in making available to us some of the many data sets used in this study. Finally, we are appreciative of the technical and editorial comments provided for this report by Cindy Ridgeway, Edward Angle, Merry Klonower, and Robert Mace; the design assistance of JoAnn Estrada; and the management support of Bill Mullican and Kevin Ward.

15 *References*

Anderson, M.P., and Woessner, W.W., 1992, Applied groundwater modeling—Simulation of flow and advective transport: San Diego, Academic Press, Inc., 381 p.

Ardis, A.F., and Barker, R.A., 1993, Historical saturated thickness of the Edwards-Trinity aquifer system and selected contiguous hydraulically connected units, West-Central Texas: U.S. Geological Survey Water-Resources Investigation Report 92-4125, 2 plates.

Ashworth, J.B., 1983, Ground-water availability of the Lower Cretaceous formations in the Hill Country of south-central Texas: Texas Department of Water Resources Report 273, 173 p.

Ashworth, J.B., 1990, Evaluation of ground-water resources in parts of Loving, Pecos, Reeves, Ward, and Winkler Counties, Texas: Texas Water Development Board Report 317, 51 p.

Ashworth, J.B., and Hopkins, J., 1995, Aquifers of Texas: Texas Water Development Board Report 345, 69 p.

Barker, R.A., and Ardis, A.F., 1992, Configuration of the base of the Edwards-Trinity aquifer system and hydrogeology of the underlying pre-Cretaceous rocks, West-Central Texas: U.S. Geological Survey Water Resources Investigation Report 91-4071, 25 p.

Barker, R.A., and Ardis, A.F., 1996, Hydrogeologic framework of the Edwards-Trinity aquifer system, West-Central Texas: U.S. Geological Survey Professional Paper 1421-B, 61 p. with plates.

Barker, R.A., Bush, P.W., and Baker, E.T., Jr., 1994, Geologic history and hydrogeologic setting of the Edwards-Trinity aquifer system, West-Central Texas: U.S. Geological Survey Water Resources Investigation Report 94-4039, 50 p.

BEG (Bureau of Economic Geology), 1974a, Big Spring Sheet: Geologic Atlas of Texas, scale 1:250,000, 1 sheet.

BEG (Bureau of Economic Geology), 1974b, San Angelo Sheet: Geologic Atlas of Texas, scale 1:250,000, 1 sheet.

BEG (Bureau of Economic Geology), 1976a, Hobbs Sheet: Geologic Atlas of Texas, scale 1:250,000, 1 sheet.

BEG (Bureau of Economic Geology), 1976b, Pecos Sheet: Geologic Atlas of Texas, scale 1:250,000, 1 sheet.

BEG (Bureau of Economic Geology), 1977, Del Rio Sheet: Geologic Atlas of Texas, scale 1:250,000, 1 sheet.

BEG (Bureau of Economic Geology), 1979a, Emory Peak-Presidio Sheet: Geologic Atlas of Texas, scale 1:250,000, 1 sheet.

BEG (Bureau of Economic Geology), 1979b, Seguin Sheet: Geologic Atlas of Texas, scale 1:250,000, 1 sheet.

BEG (Bureau of Economic Geology), 1981a, Austin Sheet: Geologic Atlas of Texas, scale 1:250,000, 1 sheet.

BEG (Bureau of Economic Geology), 1981b, Sonora Sheet: Geologic Atlas of Texas, scale 1:250,000, 1 sheet.

BEG (Bureau of Economic Geology), 1982, San Antonio Sheet: Geologic Atlas of Texas, scale 1:250,000, 1 sheet.

BEG (Bureau of Economic Geology), 1986a, Brownwood Sheet: Geologic Atlas of Texas, scale 1:250,000, 1 sheet.

BEG (Bureau of Economic Geology), 1986b, Llano Sheet: Geologic Atlas of Texas, scale 1:250,000, 1 sheet.

BEG (Bureau of Economic Geology), 1994, Fort Stockton Sheet: Geologic Atlas of Texas, scale 1:250,000, 1 sheet.

Blandford, T.N. and Blazer, D.J., 2004, Hydrologic relationships and numerical simulations of the exchange of water between the southern Ogallala and the Edwards-Trinity aquifers in Southwest Texas, *in* Mace, R.M., Angle, E.S., and Mullican, W.F., III, eds., Aquifers of the Edwards Plateau: Texas Water Development Board Report 360, p. 115–131.

Bomar, G.W., 1983, Texas Weather: Austin, University of Texas Press, 256 p.

Bradley, R.G. and Kalaswad, S., 2003, The groundwater resources of the Dockum Aquifer in Texas: Texas Water Development Board Report 359, 73 p.

Bradley, R.G. and Malstaff, G., 2004, Dry periods and drought events of the Edwards Plateau, Texas, *in* Mace, R.M., Angle, E.S., and Mullican, W.F., III, eds., Aquifers of the Edwards Plateau: Texas Water Development Board Report 360, p. 201–210.

Bush, P.W, 1986, Planning report for the Edwards-Trinity regional aquifer-system analysis in Central Texas, Southeast Oklahoma, and Southwest Arkansas: U.S. Geological Survey Water-Resources Investigations Report 86-4343, 15 p.

Bush, P.W., Ardis, A.F., and Wynn, K.H., 1993, Historical potentiometric surface of the Edwards-Trinity aquifer system and contiguous hydraulically connected units, West-Central Texas: U.S. Geological Survey Water-Resources Investigations Report 92-4055, 3 sheets.

Bush, P.W., Ulery, R.L., and Rittmaster, R.L., 1994. Dissolved-solids concentrations and hydrochemical facies in water of the Edwards-Trinity aquifer system, West-Central Texas: U.S. Geological Survey Water-Resources Investigations Report 94-4126, 29 p.

Caran, S.C., and Baker, V.R., 1986, Flooding along the Balcones Escapment, Central Texas, *in* Abbott, P.L. and Woodruff, C.M., Jr., eds., The Balcones Escarpment: Geological Society of America Meeting, San Antonio, Texas, November, 1986, p. 1–14.

Carr, J.T., Jr., 1967, The climate and physiography of Texas: Texas Water Development Board Report 53, 27 p.

Cartright, L.D., Jr., 1932, Regional structure of Cretaceous on Edwards Plateau of Southwest Texas: Bulletin of the American Association of Petroleum Geologists, v. 16, no. 7, p. 691–700, 3 figs.

Chiang, W., and Kinzelbach, W., 2001, 3D-groundwater modeling with PMWIN: New York, Springer-Verlag, 2nd ed., 346 p.

Cooke, M.J., Stern, L.A., Banner, J.L., Lawrence, E.M., Stafford, T.W., Jr., and Toomey, R.S., III, 2003, Precise timing and rate of massive late Quaternary soil denudation: Geology, v. 31, no. 10, p. 853–856.

Domenico, P.A., and Schwartz, F.W., 1990, Physical and chemical hydrogeology: New York, John Wiley & Sons, 824 p.

Fenneman, N.M., 1931, Physiography of Western United States (1st ed.): New York, McGraw-Hill, 534 p.

Fenneman, N.M. and Johnson, D.W., 1946, Physical divisions of the United States: U.S. Geological Survey special map series, scale 1:7,000,000.

Fetter, C.W., 1988, Applied hydrogeology: Columbus, Ohio, Merrill Publishing, 2nd ed., 592 p.

Green, F.E., 1961, The Monahans Dunes area, *in* Wendorf, F., ed., Paleoecology of the Llano Estacado, No. 1: Museum of New Mexico Press, p. 23–47.

Harbaugh, A. W., and McDonald, M.G., 1996, User's documentation for MODFLOW-96, an update to the U.S. Geological Survey modular finite-difference ground-water flow model: U.S. Geological Survey Open-File Report 96–485, 56 p.

Hawley, J.W., Bachman, G.O., and Manley, K., 1976, Quaternary stratigraphy in the Basin and Range and Great Plains provinces, New Mexico and western Texas, *in* Mahaney, W.C., ed., Quaternary stratigraphy of North America: Stroudsburg, Pa, Dowden, Hutchison, and Ross, Inc., p. 235–274.

Hayter, D.J., 2004, The handbook of Texas online—Pecos River: The General Libraries at the University of Texas at Austin and the State Historical Association: www.tshsa.utexas.edu/handbook/online/articles/view/PP/rnp2.html, accessed April 2004.

Huffington, R.M. and Albritton C.C., Jr., 1941, Quaternary Sands of the Southern High Plains of western Texas: American Journal of Science, v. 239, no. 5, p. 325–338, 3 figs.

Iglehart, H.H., 1967, Occurance and quality of ground water in Crockett County, Texas: Texas Department of Water Resources Report 47, 150 p.

Jones, I.C., 2001, Cenozoic Pecos Alluvium Aquifer, *in* Mace, R.E., Mullican, W.F., III, and Angle, E.S., eds., Aquifers of West Texas: Texas Water Development Board Report 356, p. 120–134.

Jones, I.C., 2004, Cenozoic Pecos Alluvium Aquifer, *in* Mace, R.E., Angle, E.S., and Mullican, W.F., III, eds., Aquifers of the Edwards Plateau: Texas Water Development Board Report 360, p. 133–148.

Kastning, E.H., Jr., 1984, Hydrogeomorphic evolution of karsted plateaus in response to regional tectonism, *in* LaFleur, R.G., ed., Groundwater as a geomorphic agent–Proceedings of the Thirteenth Annual Geomorphology Symposium, Troy, New York: London, George Allen and Unwin, p. 351–382.

Kelley, V.C., 1971, Geology of the Pecos Country, Southeastern New Mexico: New Mexico Institute of Mining and Technology Memoir 24, 60 p.

Kelley, V.C., 1980, Gatuna Formation (Late Cenozoic), Pecos Valley, New Mexico and Trans-Pecos Texas, *in* Guidebook 13, Souteastern New Mexico and West Texas, 21st Field Conference: Socorro, New Mexico, New Mexico Geological Society, p. 213–217.

Kier, R.S., Garner, L.E., and Brown, L.F, Jr., 1977, Land resources of Texas: The University of Texas at Austin, Bureau of Economic Geology, 42 p., scale 1:250,000, 4 sheets.

Kuniansky, E.L., 1989, Precipitation, streamflow, and baseflow, in West-Central Texas, December 1974 through March 1977: U.S. Geological Survey Water-Resources Investigations Report 89-4208, 2 sheets.

Kuniansky, E.L., 1990, Potentiometric surface of the Edwards-Trinity aquifer system and contiguous hydraulically connected units, West-Central Texas, winter 1974–75: U.S. Geological Survey Water-Resources Report 89-4208, 2 sheets.

Kuniansky, E.L., and Holligan, K.Q., 1994, Simulations of flow in the Edwards-Trinity aquifer system and contiguous hydraulically connected units, West-Central Texas: U.S. Geological Survey Water-Resources Investigations Report 93-4039, 40 p.

Larkin, T.J., and Bomar, G.W., 1983, Climatic atlas of Texas: Texas Department of Water Resources Report LP-192, 151 p.

LBJ School of Public Affairs, 1978, Preserving Texas' natural heritage, Research Project Report 31: The University of Texas at Austin, p.17.

Long, A.T., 1958, Ground-water geology of Edwards County, Texas: Texas Water Commission Bulletin 6208, 128 p.

Mace, R.E., 2001, Estimating transmissivity using specific-capacity data: The University of Texas at Austin, Bureau of Economic Geology Geological Circular No. 01-2, 44 p.

Mace, R.E., and Anaya, R., 2004, Estimate of recharge to the Edwards (Balcones Fault Zone) and Edwards-Trinity (Plateau) aquifers in Kinney County, Texas, *in* Mace, R.E., Angle, E.S., and Mullican, W.F., III, eds., Aquifers of the Edwards Plateau: Texas Water Development Board Report 360, p. 345–366.

Mace, R.E., Chowdhury, A.H., Anaya, R., and Way, S.C., 2000, Groundwater availability of the Trinity Aquifer, Hill Country Area, Texas—numerical simulations through 2050: Texas Water Development Board Report 353, 117 p.

Machenberg, M.D., 1984, Sand dune migration in Monahans Sandhills State Park, Texas: The University of Texas at Austin, Bureau of Economic Geology Guidebook No. 21, 39 p.

McDonald, M.G., and Harbaugh, A.W., 1988, A modular three-dimensional finite-difference ground-water flow model: U.S. Geological Survey Techniques of Water-Resources Investigations Book 6: Model Techniques, Chapter A1.

Mecke, M.B., 1996, Historical vegetation changes on the Edwards Plateau of Texas and the effects upon watersheds: Watershed '96, EPA Conference—Moving Ahead Together, Technical Conference and Exposition, Baltimore, Maryland, Session 26, p. 281–285. www.epa.gov/owow/watershed/Proceed/mecke.html, accessed May 2004.

NOAA, (National Oceanic and Atmospheric Administration), 2004, El Niño Theme Page: National Oceanic and Atmospheric Administration Web site, www.pmel.noaa.gov/tao/elnino/nino-home.html.

Raisz, E., 1957, Landforms of the United States: Brookline, Mass., Raisz Landform Maps.

Rees, R., and Buckner, A.W., 1980, Occurrence and quality of ground water in the Edwards-Trinity (Plateau) aquifer in the Trans-Pecos Region of Texas: Texas Department of Water Resources Report 255, 41 p.

Reeves, C.C., Jr., 1972, Tertiary-Quaternary stratigraphy and geomorphology of west Texas and southeastern New Mexico, *in* New Mexico Geological Society Guidebook, East-central New Mexico, 23rd Field Conference: Socorro, New Mexico, New Mexico Geological Society, p. 108–117.

Reeves, R.D., 1969, Ground-water resources of Kerr County, Texas: Texas Department of Water Resources Report 102, 58 p.

Riskind, D.H., and Diamond, D.D., 1986, Plant communities of the Edwards Plateau, *in* Abbott, P.L., and Woodruff, C.M., Jr., eds., The Balcones Escarpment–Geology, hydrology, ecology, and social development of Central Texas: Geological Society of America Annual Meeting, San Antonio, Texas, November 1986, p. 63–70.

Rose, P.R., 1972, Edwards Group, surface and subsurface, Central Texas: The University of Texas at Austin, Bureau of Economic Geology Report of Investigations No. 74, 198 p.

Ryder, P.D., 1996, Groundwater atlas of the United States, Segment 4-Oklahoma, Texas: U.S. Geological Survey Hydrologic Investigations Atlas 730-E, p. E19–E25.

Slade, R.M., Jr., 2001, Temporal trends in the precipitation and related hydrologic characteristics for Central Texas, *in* Woodruff, C.M., Jr., and Collins, E.W., trip coordinators: Guidebook 21, Austin, Texas, Austin Geological Society, April 2001, p. 55–61.

Smith, C.I., Brown, J.B., and Lozo, F.E., 2000, Regional stratigraphic cross sections, Comanche Cretaceous (Fredericksburg-Washita Division), Edwards and Stockton Plateaus, West Texas—Interpretation of sedimentary facies, depositional cycles, and tectonics: The University of Texas at Austin, Bureau of Economic Geology, 37 p. with plates.

Taylor, C.A., and Smeins, F.E., 1994, A history of land use of the Edwards plateau and its effect on the native vegetation, *in* Taylor, C.A., ed., Juniper Symposium 1994: Texas A&M University Research Station, Sonora, Texas, Technical Report 94-2, p. 1–8.

Thornberry, W.D., 1965, Regional geomorphology of the United States: New York, John Wiley and Sons, 609 p.

TWDB (Texas Water Development Board), 2007, Water for Texas, Vol. 2: Texas Water Development Board, 392 p.

University of Idaho, undated, The twelve soil orders: University of Idaho Soil and Land Resources Division Web site, soils.ag.uidaho.edu/soilorders/index.htm.

USDA (U.S. Department of Agriculture), 1999, Soil Taxonomy—A basic system of soil classification for making and interpreting soil surveys: U.S. Department of Agriculture, Natural Resources Conservation Service, Agriculture Handbook Number 436, 871 p., ftp://ftp-fc.sc.egov.usda.gov/NSSC/Soil_Taxonomy/tax.pdf.

Walker, L.E., 1979, Occurrence, availability, and chemical quality of ground water in the Edwards Plateau Region of Texas: Texas Department of Water Resources Report 235, 337 p.

Wermund, E.G., 1996, Physiographic Map of Texas: The University of Texas at Austin, Bureau of Economic Geology, 1 p., 1 map plate.

Young, K., 1986, The Pleistocene terra rossa of Central Texas, *in* Abbott, P.L., and Woodruff, C.M., Jr., eds., The Balcones Escarpment—Geology, Hydrology, Ecology, and Social Development of Central Texas: Geological Society of America Annual Meeting, San Antonio, Texas, November 1986, p. 63–7.

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Texas Water Development Board
P.O. Box 13231, Capitol Station
Austin, Texas 78711-3231