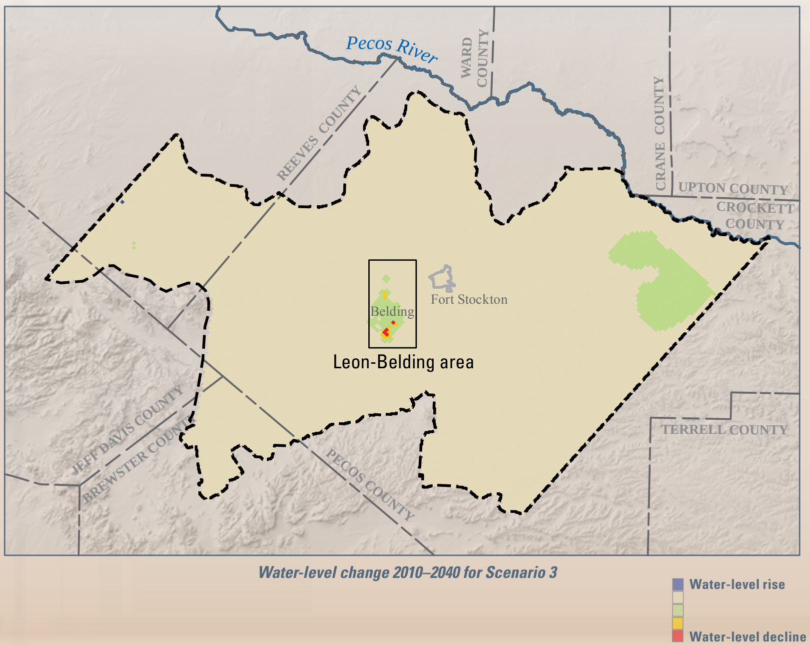
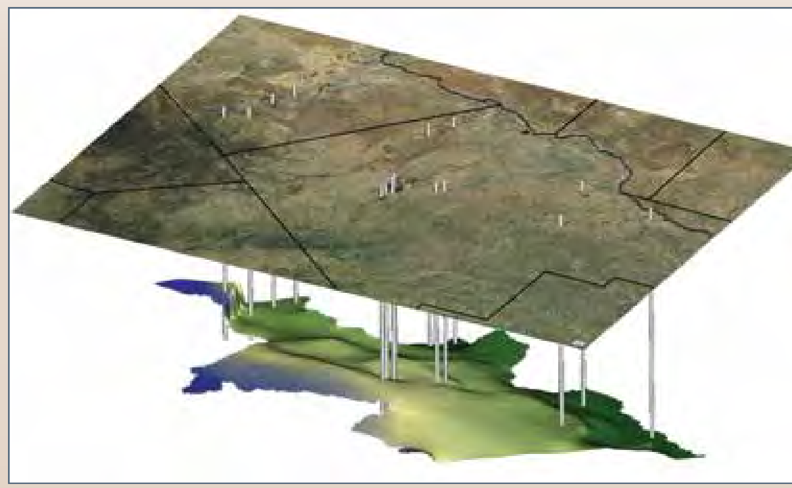
Prepared in cooperation with the Middle Pecos Groundwater Conservation District, Pecos County, City of Fort Stockton, Brewster County, and Pecos County Water Control and Improvement District No. 1

Simulation of Groundwater Flow in the Edwards-Trinity and Related Aquifers in the Pecos County Region, Texas



Water-level change 2010–2040 for Scenario 3



Oblique view of the Pecos County region with selected wells extending into the simulated water table of the Edwards-Trinity aquifer (vertically exaggerated)

Scientific Investigations Report 2013–5228
Version 1.1, August 2014

U.S. Department of the Interior
U.S. Geological Survey

Simulation of Groundwater Flow in the Edwards-Trinity and Related Aquifers in the Pecos County Region, Texas

By Brian R. Clark, Johnathan R. Bumgarner, Natalie A. Houston, and
Adam L. Foster

Prepared in cooperation with the Middle Pecos Groundwater Conservation District, Pecos County, City of Fort Stockton, Brewster County, and Pecos County Water Control and Improvement District No. 1

Scientific Investigations Report 2013–5228
Version 1.1, August 2014

U.S. Department of the Interior
U.S. Geological Survey

U.S. Department of the Interior
SALLY JEWELL, Secretary

U.S. Geological Survey
Suzette M. Kimball, Acting Director

U.S. Geological Survey, Reston, Virginia: 2014
First release: 2014, online
Revised: August 2014 (ver.1.1), online

For more information on the USGS—the Federal source for science about the Earth, its natural and living resources, natural hazards, and the environment, visit http://www.usgs.gov or call 1–888–ASK–USGS.

For an overview of USGS information products, including maps, imagery, and publications, visit http://www.usgs.gov/pubprod

To order this and other USGS information products, visit http://store.usgs.gov

Suggested citation:
Clark, B.R., Bumgarner, J.R., Houston, N.A., and Foster, A.L., 2014, Simulation of groundwater flow in the Edwards-Trinity and related aquifers in the Pecos County region, Texas (ver.1.1, August 2014): U.S. Geological Survey Scientific Investigations Report 2013–5228, 56 p., *http://dx.doi.org/10.3133/sir20135228.*

ISSN 2328-031X (print)
ISSN 2328-0328 (online)
ISBN 978 1 4113 0

Acknowledgments

Jonathan Thomas, Andrew Teeple, and Jason Payne were instrumental in development of the model layers and water level information. Paul Weatherby of the Middle Pecos Groundwater Conservation District provided insightful, detailed knowledge of the area and water-use information. Greg Stanton and George Ozuna provided oversight and conceptual knowledge of the system. Geoff Delin, Randall Hanson, and Mark Kasmarek provided technical reviews of this report.

Contents

Figures

Tables

Conversion Factors

Inch/Pound to SI

Multiply	By	To obtain
	Length	
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square mile (mi^2)	2.590	square kilometer (km^2)
	Flow rate	
foot per day (ft/d)	0.3048	meter per day (m/d)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
gallon per minute (gal/min)	0.06309	liter per second (L/s)
gallon per day (gal/d)	0.003785	cubic meter per day (m^3/d)
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)
inch per year	25.4	millimeter per year (mm/yr)
	Hydraulic conductivity	
foot per day (ft/d)	0.3048	meter per day (m/d)
foot squared per day (ft^2/d)	0.09290	meter squared per day (m^2/d)
gallon per day per foot of drawdown (gal/d/ft)	0.01242	meter squared per day (m^2/d)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

°F=(1.8×°C)+32

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

°C=(°F-32)/1.8

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD88).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD83).

Altitude, as used in this report, refers to distance above the vertical datum.

*Transmissivity: The standard unit for transmissivity is cubic foot per day per square foot times foot of aquifer thickness [($ft^3/d)/ft^2$]ft. In this report, gallon per day per foot of drawdown (gal/d/ft) is used for convenience.

Simulation of Groundwater Flow in the Edwards-Trinity and Related Aquifers in the Pecos County Region, Texas

By Brian R. Clark, Johnathan R. Bumgarner, Natalie A. Houston, and Adam L. Foster

Abstract

The Edwards-Trinity aquifer is a vital groundwater resource for agricultural, industrial, and public supply uses in the Pecos County region of western Texas. The U.S. Geological Survey completed a comprehensive, integrated analysis of available hydrogeologic data to develop a numerical groundwater-flow model of the Edwards-Trinity and related aquifers in the study area in parts of Brewster, Jeff Davis, Pecos, and Reeves Counties. The active model area covers about 3,400 square miles of the Pecos County region of Texas west of the Pecos River, and its boundaries were defined to include the saturated areas of the Edwards-Trinity aquifer. The model is a five-layer representation of the Pecos Valley, Edwards-Trinity, Dockum, and Rustler aquifers. The Pecos Valley aquifer is referred to as the alluvial layer, and the Edwards-Trinity aquifer is divided into layers representing the Edwards part of the Edwards-Trinity aquifer and the Trinity part of the Edwards-Trinity aquifer, respectively. The calibration period of the simulation extends from 1940 to 2010. Simulated hydraulic heads generally were in good agreement with observed values; 1,684 out of 2,860 (59 percent) of the simulated values were within 25 feet of the observed value. The average root mean square error value of hydraulic head for the Edwards-Trinity aquifer was 34.2 feet, which was approximately 4 percent of the average total observed change in groundwater-level altitude (groundwater level). Simulated spring flow representing Comanche Springs exhibits a pattern similar to observed spring flow. Independent geochemical modeling corroborates results of simulated groundwater flow that indicates groundwater in the Edwards-Trinity aquifer in the Leon-Belding and Fort Stockton areas is a mixture of recharge from the Barilla and Davis Mountains and groundwater that has upwelled from the Rustler aquifer.

The model was used to simulate groundwater-level altitudes resulting from prolonged pumping to evaluate sustainability of current and projected water-use demands. Each of three scenarios utilized a continuation of the calibrated model. Scenario 1 extended recent (2008) irrigation and nonirrigation pumping values for a 30-year period from 2010 to 2040. Projected groundwater-level changes in and around the Fort Stockton area under scenario 1 change little from current conditions, indicating that the groundwater system is near equilibrium with respect to recent (2008) pumping stress. Projected groundwater-level declines in the eastern part of the model area ranging from 5.0 to 15.0 feet are likely the result of nonequilibrium conditions associated with recent increases in pumping after a prolonged water-level recovery period of little or no pumping. Projected groundwater-level declines (from 15.0 to 31.0 feet) occurred in localized areas by the end of scenario 1 in the Leon-Belding area. Scenario 2 evaluated the effects of extended recent (2008) pumping rates as assigned in scenario 1 with year-round maximum permitted pumping rates in the Belding area. Results of scenario 2 are similar in water-level decline and extent as those of scenario 1. The extent of the projected groundwater-level decline in the range from 5.0 to 15.0 feet in the Leon-Belding irrigation area expanded slightly (about a 2-percent increase) from that of scenario 1. Maximum projected groundwater-level declines in the Leon-Belding irrigation area were approximately 31.3 feet in small isolated areas. Scenario 3 evaluated the effects of periodic increases in pumping rates over the 30-year extended period. Results of scenario 3 are similar to those of scenario 2 in terms of the areas of groundwater-level decline; however, the maximum projected groundwater-level decline increased to approximately 34.5 feet in the Leon-Belding area, and the extent of the decline was larger in area (about a 17-percent increase) than that of scenario 2. Additionally, the area of projected groundwater-level declines in the eastern part of the model area increased from that of scenario 2—two individual areas of decline coalesced into one larger area. The localized nature of the projected groundwater-level declines is a reflection of the high degree of fractured control on storage and hydraulic conductivity in the Edwards-Trinity aquifer. Additionally, the finding that simulated spring flow is highly dependent on the transient nature of hydraulic heads in the underlying aquifer indicates the importance of adequately understanding and characterizing the entire groundwater system.

Introduction

The Edwards-Trinity aquifer is a vital groundwater resource for agricultural, industrial, and public supply uses in the Pecos County region of western Texas (fig. 1) (Barker and Ardis, 1992; Freese and Nichols, Inc. and LBG-Guyton, Inc., 2010). Resource managers would like to understand the future availability of water in the Edwards-Trinity aquifer in and near Pecos County, Tex., and the effects of the possible increase or temporal redistribution of groundwater withdrawals. To provide

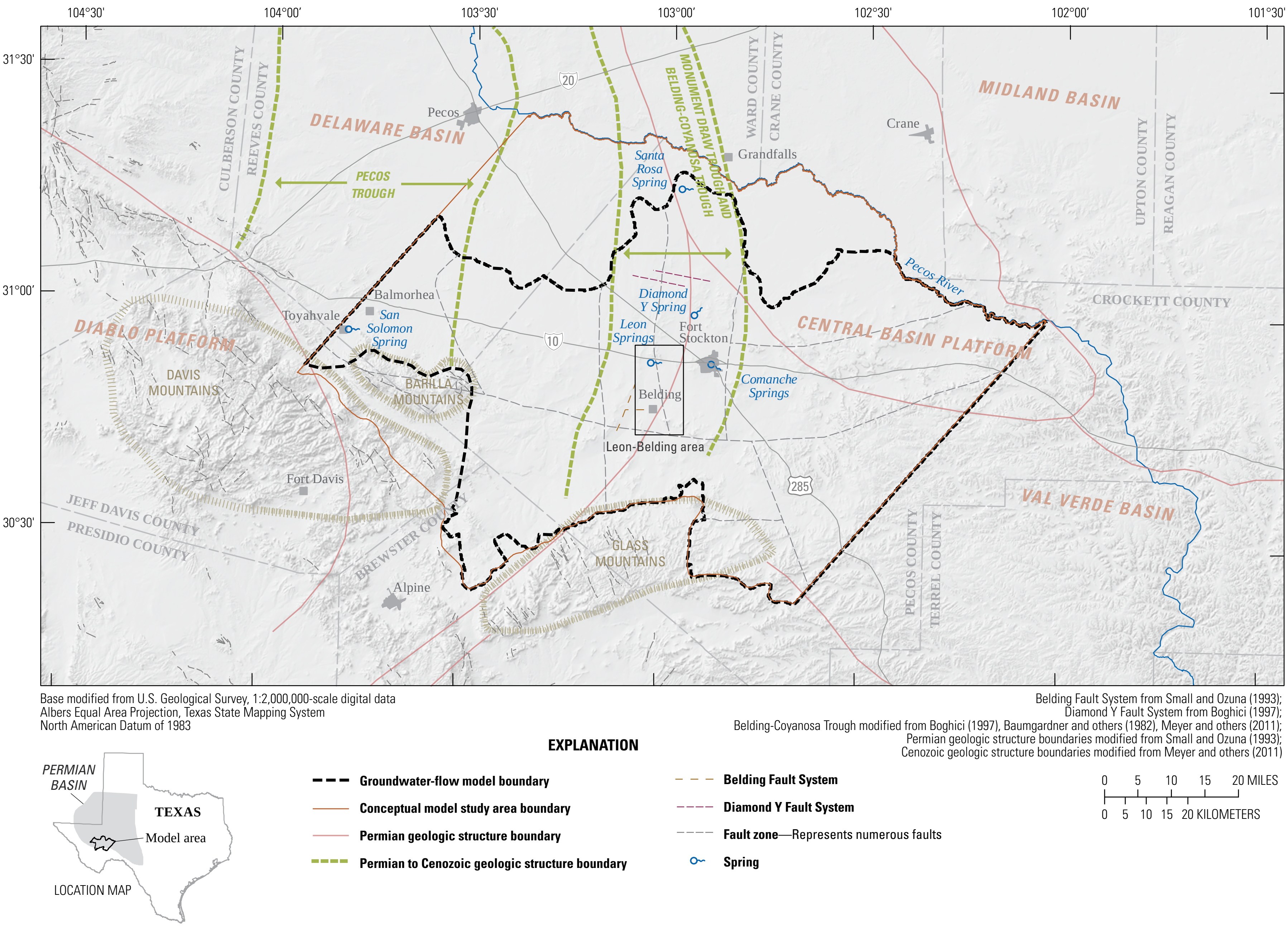


Figure 1. Location and generalized geological structural features of the model area in the Pecos County region of Texas.

resource managers with that information, the U.S. Geological Survey (USGS), in cooperation with the Middle Pecos Groundwater Conservation District (MPGCD), Pecos County, City of Fort Stockton, Brewster County, and Pecos County Water Control and Improvement District No. 1, completed a comprehensive, integrated analysis of available hydrogeologic data to develop a conceptual model of the Edwards-Trinity and related aquifers in parts of Brewster, Jeff Davis, Pecos, and Reeves Counties (fig. 1) (Bumgarner and others, 2012). The Edwards-Trinity and related aquifers (hereinafter referred to as the groundwater system) include the Pecos Valley, Igneous, Edwards-Trinity, Dockum, Rustler, and Capitan Reef aquifers. The Edwards-Trinity aquifer was the focus of the investigation presented in this report, and the related aquifers (with the exception of the Capitan Reef aquifer) were evaluated in terms of how they potentially interact with and affect the Edwards-Trinity aquifer. The Capitan Reef aquifer was not evaluated directly because the Rustler aquifer underlying the Edwards-Trinity aquifer was simulated as a constant head source, which would negate the effects of other underlying hydrogeologic units.

Development of the groundwater-flow model described in this report is the last phase of a three-phase groundwater-availability study being conducted in the Pecos County region by the USGS and its cooperators. The first phase of the study was to collect groundwater, surface-water, geochemical, geophysical, and geologic data in the Pecos County region and develop a geodatabase of historical and collected data (Pearson and others, 2012). The data compiled in the first phase of the study were used in the second phase to develop the conceptual model of the hydrogeologic framework, geochemistry, and groundwater-flow system of the area (Bumgarner and others, 2012).

A groundwater-flow model for the active model area (about 3,400 square-miles [mi^2] of the Pecos County region study area) was developed to simulate groundwater flow under varying pumping conditions. The model incorporates conceptual information provided by Bumgarner and others (2012) and data collected and compiled by Pearson and others (2012) in order to evaluate the sustainability of recent (2008) and projected water-use demands on groundwater resources in the study area. The hydrostratigraphy and structural features of the groundwater system were used to develop hydrologic boundaries and the numerical framework; aquifer-test data were used to estimate aquifer hydraulic properties. Knowledge of groundwater-flow paths inferred from groundwater-quality data (geochemical data) was used to guide model development and calibration. Groundwater-level altitude (groundwater level) and spring-flow data were used as calibration targets to evaluate the goodness of fit of the model simulation.

Purpose and Scope

This report documents the development of a numerical model describing groundwater flow of the Edwards-Trinity and related aquifers in the Pecos County region, Tex., and summarizes potential future pumping scenarios simulated with the model. The sustainability of recent (2008) and projected water-use demands on groundwater resources in the Pecos County region study area were evaluated through the year 2040. The model was developed using data collected by the USGS during 2009–11 as well as historical data from 1930 to 2011 collected by various State and local agencies and compiled by the USGS (Bumgarner and others, 2012; Pearson and others, 2012). The various components of the numerical model are described including the spatial and temporal discretization, initial conditions, hydraulic properties, model calibration, model evaluation, and simulations of groundwater-level changes as a result of changes in groundwater pumping. Inverse geochemical modeling (PHREEQC; Parkhurst and Appelo, 1999) was used to evaluate some of the groundwater-flow model results. The limitations of the model are also described.

Previous Investigations

Several scientific investigations have been done to develop conceptual and numerical groundwater-flow models of the Edwards-Trinity aquifer in the Pecos County region. Thornhill Group, Inc. (2008) and Daniel B. Stephens and Associates (2010) developed conceptual and numerical groundwater-flow models of the Edwards-Trinity aquifer that focused on a 100 mi^2 area near Belding, Tex., referred to hereinafter as the Leon-Belding area (fig. 1). The Leon-Belding area is an agricultural area about 7 miles southwest of Fort Stockton that includes about 30 mi^2 of cultivated land. Water primarily from the Edwards-Trinity aquifer is used for irrigation purposes in the Leon-Belding area. Using the conceptual and numerical groundwater-flow models, simulations to project future aquifer conditions in the Leon-Belding area based on various groundwater-withdrawal scenarios were published (Thornhill Group, Inc., 2008; Daniel B. Stephens and Associates, 2010). Anaya and Jones (2009) developed a 44,000 mi^2 regional groundwater-flow model of the Pecos Valley and Edwards-Trinity aquifers in central and west Texas to determine the availability of groundwater based on projected water demand. Ewing and others (2012) developed a groundwater availability model for the Rustler aquifer to provide a tool to help refine estimates of groundwater availability for the Texas Water Development Board.

Description of the Pecos County Region Model Area[1]

The active model area covers about 3,400 mi^2 of the Pecos County region of Texas west of the Pecos River. The boundaries of the model were defined to include the saturated areas of the Edwards-Trinity aquifer. The model

[1] This section modified from Bumgarner and others (2012).

area is reduced in size from the area described by Bumgarner and others (2012) to focus on groundwater flow within the Edwards-Trinity aquifer. Therefore, areas where the Edwards-Trinity aquifer is absent or where the saturated thickness precludes the use as a viable water source were excluded from the model area. The southwestern and southern boundaries of the model area are rimmed by the Barilla and Davis Mountains, located primarily in northeastern Jeff Davis County as well as southwestern Reeves County, and the Glass Mountains located in northeastern Brewster County and southern Pecos County. The northeastern boundary of the model area is the Pecos River. The western part of the MPGCD management area (Pecos County) is in the model area. Altitude ranges from approximately 4,600 feet (ft) in the southern part of the model area in Pecos County to 2,150 ft in the northeastern part of the model area near the Pecos River in Pecos County. Climate in the model area is arid with average annual rainfall during 1970–2000 at Fort Stockton of approximately 14 inches (National Oceanic and Atmospheric Administration, 2013). Rainfall at Fort Stockton is annually quite variable with 2004 being the wettest year with an annual rainfall of about 26 inches and 2011 being the driest year with an annual rainfall of about 3 inches (National Oceanic and Atmospheric Administration, 2013). Potential annual evaporation of as much as 109 inches has been estimated (Boghici, 1997). Temperatures during 1970–2000 ranged from an average low of about 32 degrees Fahrenheit (ºF) in January to an average high of about 96 ºF in July (National Oceanic and Atmospheric Administration, 2013).

Geologic and Hydrogeological Setting[2]

There were several periods of seawater inundation, deposition, uplift, and erosion during the geologic history of the Pecos County region of west Texas. Sedimentary rocks of Pennsylvanian, Permian, Triassic, and Cretaceous age; Tertiary-age igneous rocks; and Cenozoic-age alluvium are present in the subsurface. Many of the bedrock formations are exposed at the surface in the model area (Texas Water Development Board, 1972). This investigation focuses on subsurface rocks deposited from the Permian to the Quaternary Period (table 1). Dissolution of Permian-age evaporite deposits that began at the time of deposition and continued through the Cretaceous Period caused the Permian beds to collapse and form the north-south Belding-Coyanosa depositional trough (fig. 1) (Armstrong and McMillion, 1961; Boghici, 1997). During the Cenozoic Era, two depositional troughs that roughly trend north-south formed in the central and western parts of the model area because of the continued dissolution of the Permian-age evaporite deposits and subsequent collapse of the overlying sediments (Armstrong and McMillion, 1961). These troughs subsequently filled with Cenozoic-age alluvium and are known as the Monument Draw (central) and Pecos (western) troughs (fig. 1). For simplicity, hereinafter, the name ‘Monument Draw trough’ will be used to represent both the Cenozoic-age Monument Draw and Permian to Cretaceous-age Belding-Coyanosa troughs because the spatial extents and separation of these structural features are not well defined. Additional detail about the geologic and hydrogeologic setting of the model area can be found in Bumgarner and others (2012).

[2] This section modified from Bumgarner and others (2012).

Hydrogeologic Framework

The geologic setting contributed to formation of two major and four minor aquifers in the model area. The Pecos Valley aquifer is a major aquifer composed of Cenozoic-age alluvium consisting of unconsolidated silt, sand, gravel and clay (fig. 2) (Small and Ozuna, 1993). In the northern part of the model area, the Pecos Valley aquifer unconformably overlies the Edwards-Trinity aquifer, the other major (and primary) aquifer in the model area (fig. 2). Minor aquifers include the Igneous, Dockum, Rustler, and Capitan Reef aquifers (table 1). The Edwards-Trinity aquifer is composed of lower Cretaceous-age limestone, marl, and clay of the Washita Group; limestone of the Fredericksburg Group; and sand, limestone, and shale of the Trinity Group (fig. 2, table 1). The Edwards part of the aquifer is composed of upper Cretaceous rocks of the Washita and Fredericksburg Groups, which locally are referred to as the Edwards and Sixshooter Groups (Brand and DeFord, 1958; Small and Ozuna, 1993; Smith and others, 2000). The Trinity Group comprises the Trinity part of the aquifer and is composed of the Maxon Sand, the Glen Rose Formation, and the Basal Cretaceous Sand (Anaya and Jones, 2009). The individual formations in the Trinity Group are not separated for the purposes of this report. Locally the Trinity Group is known as the Trinity Sands (Rees and Buckner, 1980; Small and Ozuna, 1993).

The Dockum aquifer is a minor aquifer and is composed of Triassic-age shale, sand, sandstone, and conglomerate of the Dockum Group (Bradley and Kalaswad, 2003). In Pecos County, a sand unit within the Dockum aquifer is recognizable in some geophysical logs, but the individual formations of the Dockum Group are not separated for the purposes of this report. Because of the shale content within the Dockum aquifer and contrast in aquifer properties in relation to the Edwards-Trinity aquifer, it is treated as a confining unit over much of the model area. Locally, the Dockum aquifer is also known as the Santa Rosa aquifer (Small and Ozuna, 1993).

The Rustler aquifer is composed of Permian-age rocks (table 1) consisting of mostly dolomite, anhydrite, and some limestone of the Rustler Formation. A basal unit of the Rustler aquifer consists of sand, conglomerate, and some shale (Small and Ozuna, 1993; LBG-Guyton, Inc., 2003).

The Capitan Reef aquifer is composed of Permian-age rocks consisting of reef, fore-reef, and back-reef facies of dolomite and limestone of the older Capitan Limestone. Additional detail about the hydrogeologic framework is available in Bumgarner and others (2012).

Table 1. Hydrogeologic section in the Pecos County regional model area, Texas (modified from Bumgarner and others, 2012).

Era	Period	Series or group		Stratigraphic unit			Major and minor aquifers	Model layer
Cenozoic	Quaternary and Tertiary			Alluvium			Pecos valley	Alluvial layer
	Tertiary			Volcanic Rocks, undivided			Igneous	
Mesozoic	Cretaceous	Gulfian Series	Terlingua Group	Boquillas Formation				
		Comanchean Series		Western Pecos County		Eastern Pecos County	Edwards-Trinity	Edwards layer
			Washita Group	Sixshooter Group	Buda Limestone			
					Boracho Formation	Edwards Group: Fort Lancaster Formation		
					University Mesa Marl	Burt Ranch Member		
			Fredericksburg Group		Finlay Formation	Fort Terrett Formation		
			Trinity Group	Trinity Sands	Maxon Sand			Trinity layer
					Glen Rose Formation			
					Basal Cretaceous Sand			
	Triassic	Dockum Group		Middle			Dockum	Dockum layer
				Lower				
Paleozoic	Permian	Ochoan Series						
				Southern Pecos County	Northern Pecos County			
				Tessey Limestone	Rustler Formation		Rustler	Rustler layer
					Salado Formation			
					Castile Formation			
		Guadalupian Series	Whitehorse Group	Gilliam Limestone	Capitan Limestone	Guadalupian Formations; undivided	Capitan Reef	
				Lower Guadalupian Formations; undivided				
				Lower Permian Formations; undivided				
	Pennsylvanian			Pennsylvanian Formations; undivided				

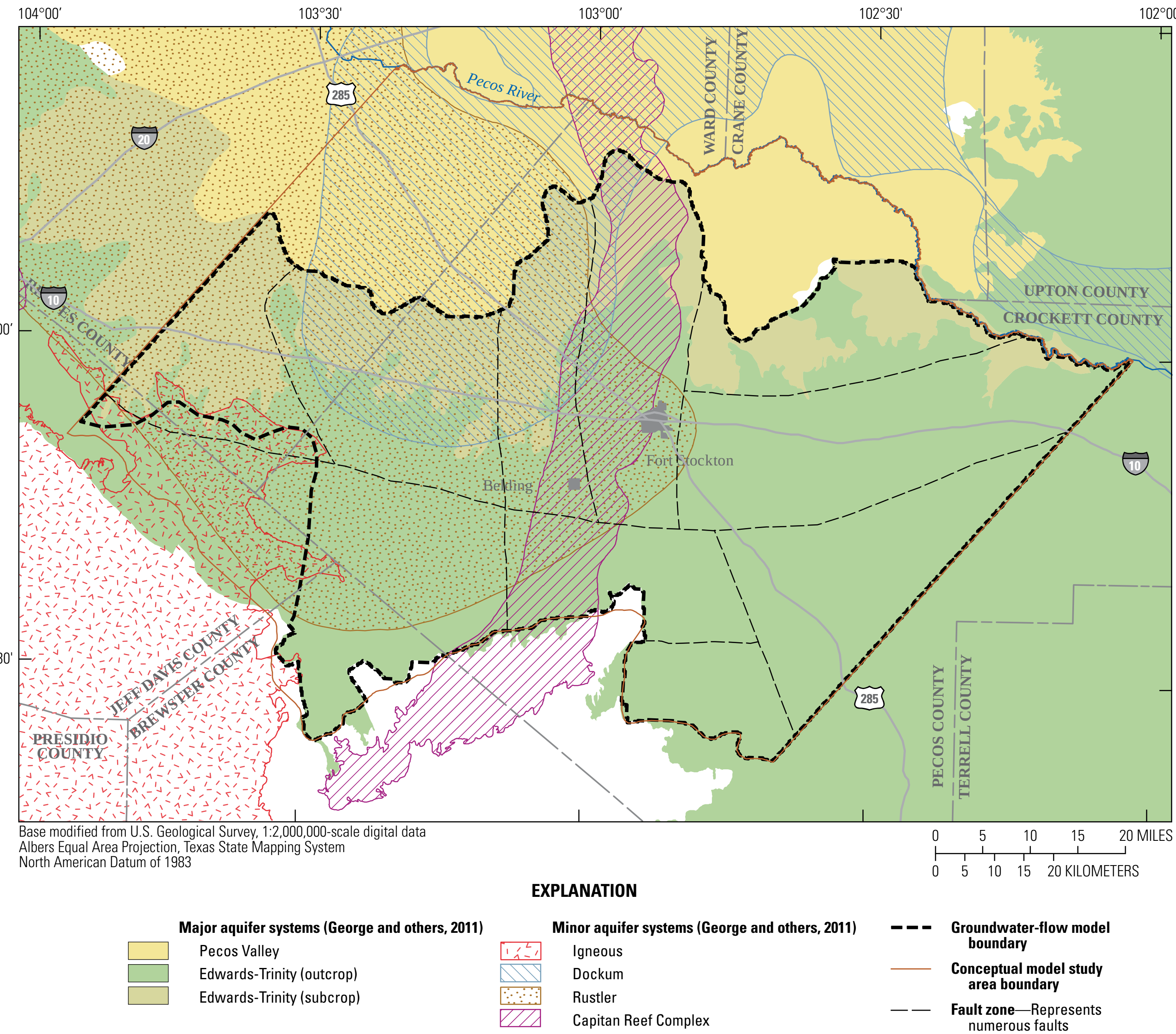


Figure 2. Major aquifers and minor aquifers in the Pecos County region model area, Texas.

Geochemistry

The second phase of this study by Bumgarner and others (2012) indicated that the Edwards-Trinity aquifer in the model area was dominated by mineralized, regional groundwater that most likely recharged during the Pleistocene with variable contributions of recent, local recharge. Four end members were identified to use as part of the qualitative groundwater-flow and mixing analysis. The end members represented: (1) mineralized groundwater that likely recharged northwest of the model area during the Pleistocene; (2) dilute, recent recharge from the Barilla and Davis Mountains; (3) dilute, recent recharge from the Glass Mountains; and (4) mineralized water that is likely a mixture of recharge under recent and Pleistocene climate conditions. Bumgarner also noted that groundwater from the Dockum and Rustler aquifers likely mixes with groundwater compositions of the Edwards-Trinity aquifer. Additional detail about the geochemistry of the groundwater in the model area is available in Bumgarner and others (2012).

Groundwater-Flow System

Groundwater generally flows northward into the downdip extent of the Edwards-Trinity aquifer (corresponding to the northern extent of the Edwards-Trinity subcrop area) or eastward out of the model area (fig. 2). Regional groundwater flow entering the model area from the northwest naturally discharges from springs or flows northward into the Pecos trough where it discharges into the Pecos Valley or Dockum aquifers at the downdip extent of the Edwards-Trinity aquifer. Recharge from the Barilla and Davis Mountains also predominantly flows toward the Pecos trough and most likely discharges to other aquifers of the groundwater system. Groundwater flow in the Edwards-Trinity aquifer in the Monument Draw trough originated as recharge in the Barilla, Davis, and Glass Mountains, agricultural return flow, or upwelling groundwater from lower units. Edwards-Trinity aquifer water generally flows north and northeast in the Monument Draw trough and naturally discharges from springs or to other aquifers of the groundwater system at the downdip extent. Groundwater in the eastern part of the model area likely originated in the Glass Mountains and generally flows northeast and out of the model area. Some groundwater in the eastern part of the model area also naturally discharges from springs to other aquifers of the groundwater system at the downdip extent or to the Pecos River. Additional detail about conceptual groundwater flow in the model area is available in Bumgarner and others (2012).

Simulation of Groundwater Flow

The modular finite-difference code, USGS MODFLOW-2005 (Harbaugh, 2005), was used to approximate the solution of the equations governing three-dimensional groundwater flow. The preconditioned conjugate gradient solver (Hill, 1990) was used for the numerical solution technique.

Groundwater-Flow Model Construction

The groundwater-flow system is represented by a set of grid cells, and within each individual cell the hydraulic properties are the same. Three finite-difference equations describe flow through each cell, which can be solved for steady-state or transient conditions, to simulate groundwater-level changes within the flow system resulting from pumping stress over discrete periods of time. The model was constructed using much of the compiled and field-collected data gathered from Pearson and others (2012). The transient model simulates 70 years (1940–2010) of system response to stress by using 144 stress periods.

Spatial Discretization and Layering

The active model area includes 13,680 active model cells representing the Trinity part of the Edwards-Trinity aquifer. The active model was discretized into a finite-difference grid of 156 rows and 174 columns with uniform cells 0.25 mi^2 in area, a refinement from previous regional modeling and coincident with previous local-scale models. The grid is aligned approximately perpendicular to regional groundwater flow and coincides with the Groundwater Availability Model (GAM) of Anaya and Jones (2009) with the y-coordinate axis at an azimuth of approximately N.48° W.

The layers of the numerical model were developed from the hydrostratigraphy of Bumgarner and others (2012) and Ewing and others (2012). The model has five layers that represent the Pecos Valley aquifer (referred to as the alluvial layer), the Edwards part of the Edwards-Trinity aquifer (referred to as the Edwards layer), the Trinity part of the Edwards-Trinity aquifer (referred to as the Trinity layer), the Dockum aquifer (referred to as the Dockum layer), and the Rustler aquifer (referred to as the Rustler layer) (table 1). In areas that a hydrogeologic unit is thin or nonexistent, such as the Dockum aquifer, the hydraulic properties of the layer are similar to those of the underlying unit.

Temporal Discretization

The model is discretized temporally into 144 stress periods that represent intervals of time with constant stresses (such as pumping) applied throughout. Stress period 1 represents a steady-state period of time prior to 1940 in which water levels were less likely affected by widespread groundwater pumping. Stress period 2 begins the transient period of the simulation starting January 1, 1940. Between stress period 2 (January 1, 1940, to March 31, 1940) and stress period 144 (October 1, 2010, to December 31, 2010), each intervening stress period is 6 months in length to represent irrigation (April through September) and nonirrigation seasons (October through March).

Hydrologic Boundaries

The hydrologic boundaries of the model include areal recharge (Recharge Package), rivers (River Package), no-flow, constant heads (Time-Variant Constant Head Package), and general-head boundaries (General Head Boundary Package). Each boundary was included to represent a specific aspect of the groundwater-flow system and is discussed briefly in the following sections. A complete description of MODFLOW-2005 hydrologic boundaries and model specifications is available in Harbaugh (2005).

Recharge

Because precipitation is generally relatively low and evapotranspiration is relatively high (Anaya and Jones, 2009), net recharge was expected to be low to nonexistent over much of the model area. Therefore, net areal recharge in the model primarily occurs in front of the Barilla, Davis, and Glass Mountains along the western edge of the model domain (fig. 3) (Anaya and Jones, 2009). This mountain-front recharge was simulated using the MODFLOW-2005 Recharge Package in an assumed width of approximately 5 miles along the base of the mountains at an initial rate of 2.0 inches per year (in/yr) based on higher estimates of recharge for the Edwards-Trinity aquifer (Long, 1958; Rees and Buckner, 1980). The recharge rate was further adjusted through model calibration. Additional recharge may be introduced through irrigation return flow (Bumgarner and others, 2012). Return flow recharge was estimated based on streamflow increases and pumping data and varied widely from 0.15 to 0.60 in/yr (Kuniansky and Holligan, 1994). Recharge was specified as 0.2 in/yr in irrigated areas to represent irrigation return flow based on low but detectable concentrations of nutrients and pesticides (Bumgarner and others, 2012). The specified recharge representing irrigation return flow is approximately equal to 2 percent of recent (2008) pumping in the Leon-Belding irrigation area. Because the purpose of the model is an evaluation of projected water use through the year 2040 (long-term demands) rather than seasonal changes in water use and water levels, the above rates of recharge for both mountain-front and irrigation return flow areas were held constant throughout the model simulation.

Discharge

Multiple hydrologic boundaries representing groundwater discharge were included in the model. Springs and groundwater pumping represented in the model serve exclusively as net discharge from the groundwater system. Specified heads representing flow horizontally, vertically, and from the Pecos River may serve as both recharge and discharge at various times and locations within the model. Because the majority of the total flow from specified heads is out of the model (discharge), they are included here in the "Discharge" section of the report.

Springs

Multiple springs exist within the model area, though few discharge records are available to aid model calibration. Until the 1950s, Comanche Springs were the largest in the Pecos County region and sixth largest in the State (Sharp, 2001). Comanche Springs first went dry in 1955, and perennial flow ceased in 1961 (Texas Parks and Wildlife Department, 2012). According to Freese and Nichols, Inc. and LBG-Guyton, Inc. (2010), Comanche Springs have flowed occasionally since 1987. The springs are in faulted areas, and the presence of faults likely contributed to the formation of the springs (Anaya and Jones, 2009; Armstrong and McMillion, 1961; Baumgarner and others, 1982; Boghici, 1997; Sharp and others, 1999; Small and Ozuna, 1993; Texas Water Development Board, 2005; Veni, 1991).

Comanche Springs had usable discharge data to aid in setting boundary conditions and to calibrate the model. Monthly discharge measurements from Comanche Springs corresponding to each 6-month stress period were averaged to represent observed flow. The location and elevation of Comanche Springs were implemented by using the Streamflow Routing Package (SFR) (Niswonger and Prudic, 2005). SFR was designed to simulate the interaction between surface-water features and aquifers as well as to route the flow of water along a linear, downgradient path with the flow system. While SFR is typically used to represent streams, it is analogous to the simulation of springs that have a fracture controlled contributing area. The preferential flow paths that provide flow to Comanche Springs surveyed by Veni (1991) lie along N.60° to N.65° W trending joints. In addition to allowing the user to locate the spring discharge points in the model domain, SFR allows the user to delineate the fracture network that provides flow to the spring discharge point. In this way, the springs can be more accurately represented in model simulations.

Groundwater Pumping

Groundwater-pumping estimates were compiled from multiple sources to develop a pumping record for 1940 to 2010 (Armstrong and McMillion, 1961; Audsley, 1956; Dante 1947; Ogilbee and others, 1962; Paul Weatherby, Middle Pecos Groundwater Conservation District, written commun., 2012; Rees and Buckner, 1980; Small and Ozuna, 1993; Texas Water Development Board, 1986, 2001, 2012a). Site-specific pumping was used when available, though much of the record for irrigation pumping contained only aggregated amounts of withdrawals by county, aquifer, and year. Public supply, manufacturing, mining, and power-generation (industrial) pumping represented actual monthly or annually reported amounts by these water users. All pumping totals were aggregated to annual amounts and assigned to the appropriate stress period of the model. Nonirrigation wells were assigned annual pumping amounts for growing and nongrowing seasons for the corresponding year.

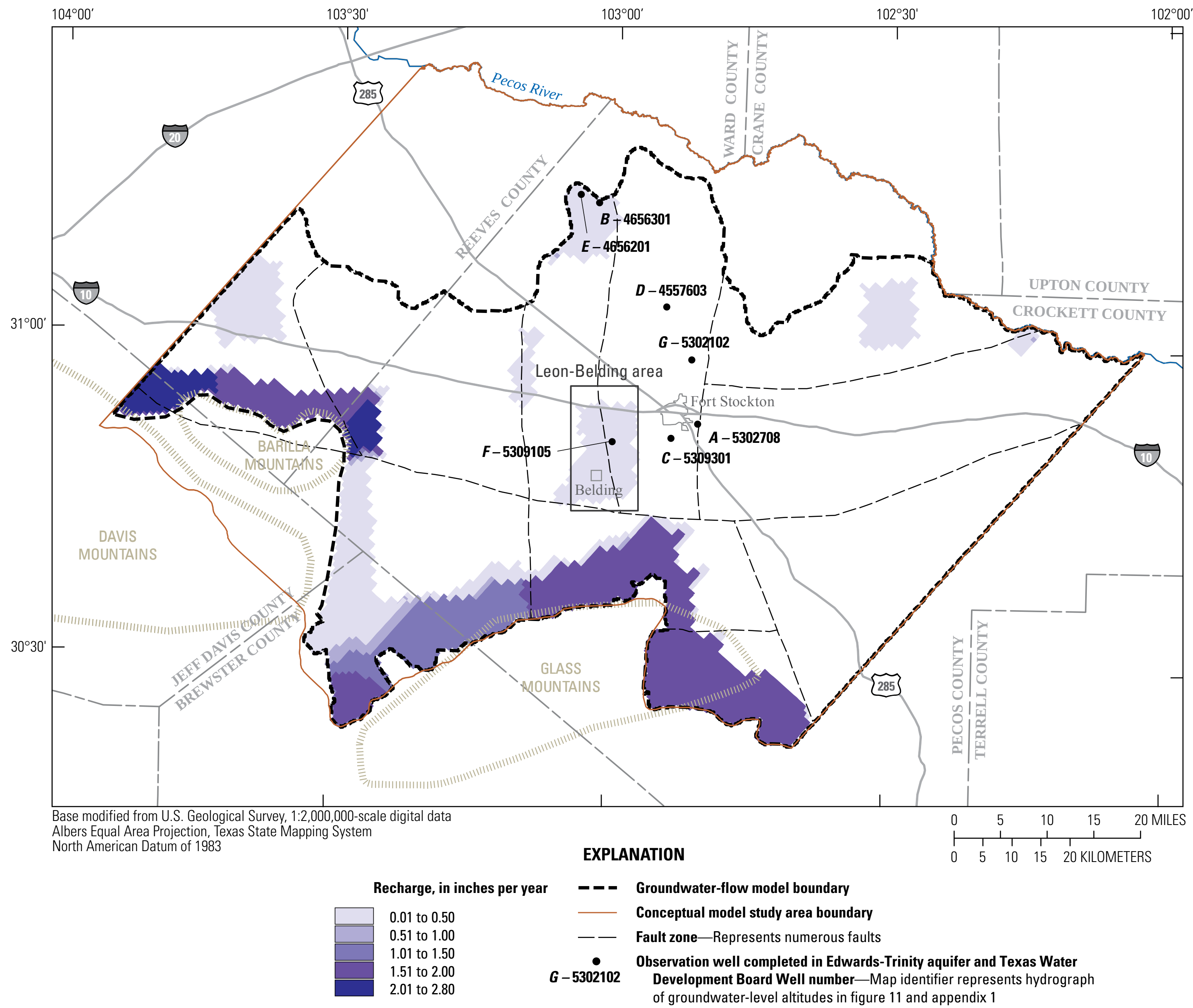


Figure 3. Simulated net recharge in the Pecos County region model area, Texas.

Irrigation wells were assigned total pumping amounts for the growing season months of April through October only, with a pumping amount of zero assigned during nongrowing season months. Nonirrigation pumping data were available for 1955 through 2005. Historical estimates of groundwater pumping from 1955 to 1999 were based on the water-use-survey database used in the Texas Water Development Board's (TWDB) GAM program (Cindy Ridgeway, Texas Water Development Board, written commun., 2001). Groundwater-pumping data from 2000 to 2005 also were obtained from the TWDB water-use-survey database (Kevin Kluge, Texas Water Development Board, written commun., 2012). Pumping amounts then were assigned to wells based on the TWDB groundwater database. The water user in the water-use-survey database was linked to wells in the groundwater database by a unique identifier. If more than one well was referenced for a given water user, the groundwater-pumping amounts were divided evenly among those wells. Wells then were intersected using a Geographic Information System (GIS) (Environmental Systems Research Institute, 2013) with the spatial data representing the tops and bottoms of the aquifers in the model area and based on the latitude, longitude, and well-screen interval. Wells were assigned a model layer if the screen interval of the well was contained within the top and bottom of a given model layer. If a well was screened in multiple aquifers, the well was assigned to multiple model layers; pumping amounts were distributed to each layer using the Multi-Node Well (MNW1) Package (described in the latter part of this section). Pumping amounts for 2006 through 2008 for all categories were obtained from the Middle Pecos Groundwater Conservation District.

Irrigation amounts were obtained using data from the TWDB's historical water-use-information database (Texas Water Development Board, 2012b). Data for 1955, 1958, 1964, 1969, 1974, and 1979 were obtained from the TWDB's Survey of Irrigation studies (Texas Water Development Board, 1986, 2001). Data were obtained for 1980 and 1984 through 2005 from the TWDB historical water-use-information database (Texas Water Development Board, 2012b). Data also were obtained from published reports (Hood and Knowles, 1952; Ogilbee and others, 1962). Based on the assumption that pumping amounts increased every year from the 1940s to the peak reported value in 1964, temporal gaps in the water-use dataset were estimated by linear interpolation between reported pumping values. Irrigation pumping estimates were applied to wells that had available latitude, longitude, documented period of record, and well construction (well depth, well screen) information (Armstrong and McMillion, 1961; Audsley, 1956; Dante, 1947; Ogilbee and others, 1962; Rees and Buckner, 1980; Small and Ozuna, 1993; Texas Water Development Board, 2001, 2012a). Rather than distribute the pumping amounts equally to all irrigation wells, the pumping amount distributed to each irrigation well was based on the percentage of total pumping that each well represented for years that the individual amounts were known or estimated. Groundwater pumping for domestic and livestock uses typically is small compared to public supply, industrial, and irrigation and was not compiled or used in the simulation for 1940 through 2005 (Rees and Buckner, 1980; Small and Ozuna, 1993; Texas Water Development Board 2012a), though some information for domestic and livestock was available after 2005 (appendix 2).

All pumping wells were represented with the MNW1 Package (Halford and Hanson, 2002). The MNW1 allows the simulation of groundwater flow within the well bore and the extraction of groundwater from multiple hydrogeologic units at a single well to better represent pumping from wells open to more than one hydrogeologic unit. Flow into or out of the well bore can be affected by the difference in transmissivity between the formation and the disrupted radius around the well bore, noted by a skin friction coefficient. The skin friction coefficient is derived from the linear well-loss coefficient, which defines head loss from flow through formation damaged during well drilling, the gravel pack, and the well screen. The linear well-loss coefficient can be used directly to define head loss or can be recast in terms of a dimensionless skin friction coefficient (Cooley and Cunningham, 1979; Earlougher, 1977). For all withdrawal wells, a final skin friction coefficient of 4 was used, which results in a contrast of the transmissivity of the formation (T) to transmissivity of the disrupted radius (Tskin) value of 6.77 (T/Tskin). The contrast of T/Tskin allows variation in flow into and out of hydrogeologic units based on the different hydraulic properties of each unit. MNW1 also can be used to limit pumping on the basis of changes to the drawdown constraint; simulated pumping is reduced (possibly to the point of zero pumping) when the water level near a well reaches a specified altitude within the well bore. Approximately 1 percent of the aquifer thickness of the model cell at a given well location was used to specify the altitude of drawdown constraints on all pumping wells.

Specified Head Boundaries

There are three types of MODFLOW-2005 specified head boundary packages represented in the model: General Head, Time-Variant Constant Head, and River (Harbaugh, 2005). The General Head Boundary Package (GHB) was used to represent horizontal flow into or out of the model area (fig. 4). GHBs were placed along the western, northwestern, north, and southeastern perimeters of the model area in layer 3 (Trinity layer). This placement allows for flow between the alluvial, Edwards, and Trinity layers; whereas, the vertical hydraulic conductivity was sufficient to allow groundwater movement vertically and horizontally in the model. The groundwater levels assigned to the GHBs were interpolated using minimum curvature spline that includes input for barriers (with the assumption that features such as faults create a barrier to, or reduction in, horizontal flow) from observation data that represented 1940, 1963, and 2010. The locations of the observation data coincide with most of the locations also used as pilot points described later in the section "Hydraulic Properties." The interpolation of water levels included major faults to act as hydraulic barriers because of large changes in

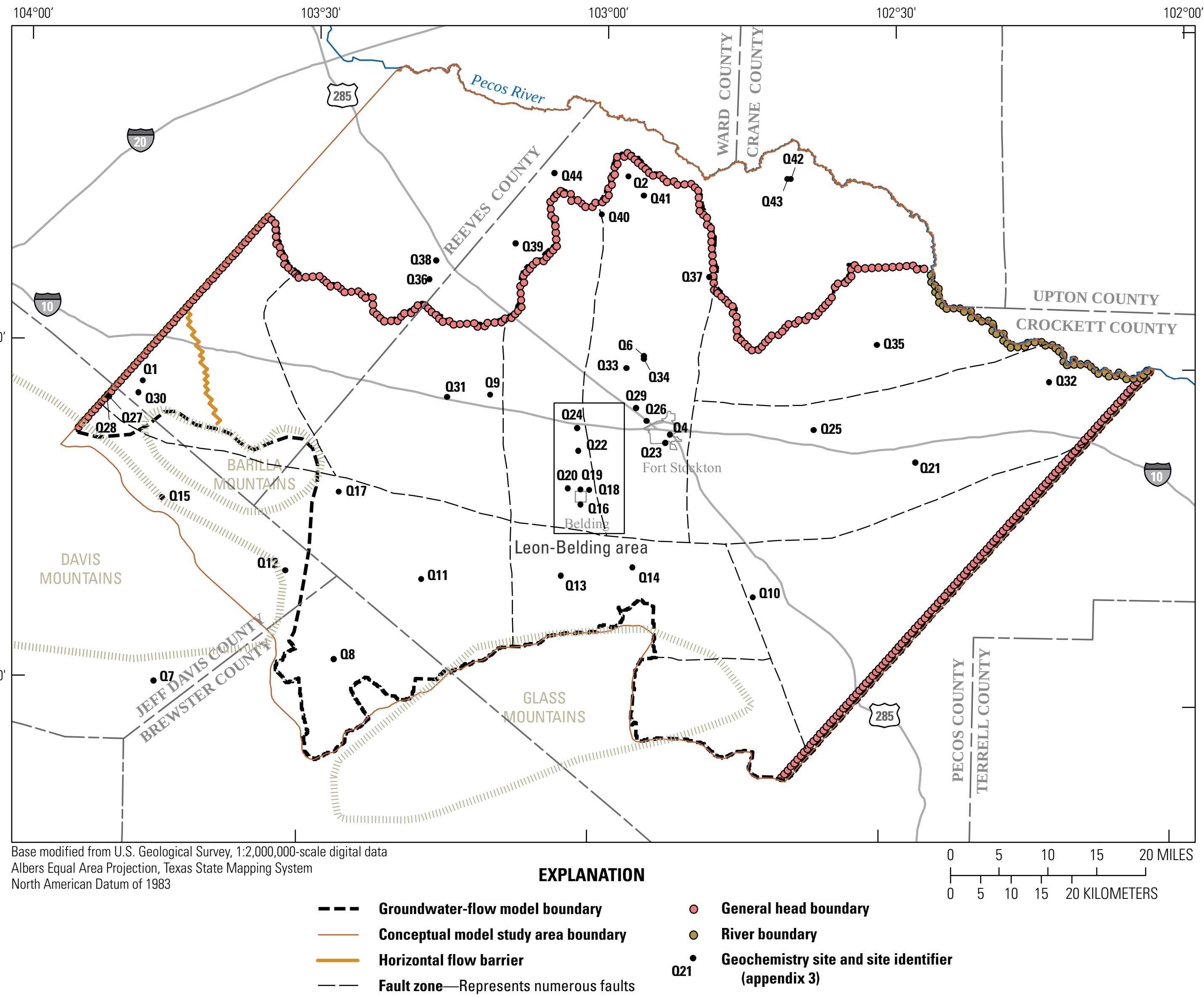


Figure 4. Specified head and horizontal flow (fault) boundaries used in the model simulation (excluding Constant Head Boundary of the Rustler aquifer) and locations of geochemical data collection in the Pecos County region model area, Texas.

hydraulic gradient in the area of the faults. These dates were chosen to depict water levels at the beginning of the model simulation, at the low point of groundwater-level decline, and at the end of the model simulation. The water level at each GHB was linearly interpolated temporally between these three years to allow a smooth transition of groundwater-level decline and recovery during transient model simulation.

Geochemical data from Bumgarner and others (2012) indicate that water from the Rustler aquifer is likely upwelling in some areas of the model domain. Therefore, Time-Variant Constant Heads were used in the model to represent water levels in the Rustler aquifer. Simulated water levels from Ewing and others (2012) were digitized for the 1959, 1970, and 2000 time periods and applied as groundwater-level altitude of the constant heads in the Rustler aquifer. The three time periods were used as endpoints to interpolate constant-head water levels in the transient simulation from 1940 to 1970 (by using the 1959 and 1970 digitized surface) and from 1970 to 2010 (by using the 1970 and 2000 digitized surface). The 1970 and the 2000 digitized surfaces were reduced by 30 ft after model simulations indicated the surfaces were too high relative to water levels for the Rustler aquifer in the Belding and Fort Stockton areas. Groundwater in the Rustler aquifer may be of higher salinity than overlying hydrogeologic units, though salinity differences are probably not great enough to result in variable density-driven flow; thus, the assumption of a constant density simulation is thought to be adequate.

The MODFLOW-2005 River Package was used to represent the Pecos River on the northeastern side of the model area (fig. 4). Estimates of river bottom elevation were calculated as the minimum elevation within each river cell based on a 10-meter digital elevation model. The river stage was set as 5 ft above the river bottom, and the streambed conductance was assigned a value of 8,001 ft^2/d after test simulation indicated values higher or lower than the assigned value would adversely affect the ability to simulate observed conditions.

No-Flow Boundaries

The southwestern perimeter of the model area (fig. 4) and the base of the Rustler aquifer (table 1) are represented as no-flow boundaries. The southwestern perimeter represents an area where the hydrogeologic units do not exist, or flow into or out of the model area is assumed to be negligible. The base of the Rustler aquifer is represented as a no-flow boundary because, while it is underlain by the Capitan Reef Complex aquifer, the hydraulic connection between the two units is unknown. Additionally, Time Variant Constant Head boundaries were applied to the Rustler aquifer as discussed in "Specified Head Boundaries," which could reduce or remove the effects of water levels from underlying units.

Structure

Faulting in the area is widespread and can have a substantial effect on groundwater flow, particularly in areas of large displacement between fault blocks, which can serve as horizontal barriers to groundwater flow if the faulting results in offsets that hydraulically isolate different parts of the same hydrogeologic unit (Bumgarner and others, 2012). The maximum displacement interpreted by Bumgarner and others (2012) was about 1,025 ft in the western part of the model area, which can hydraulically isolate one part of the aquifer from another. While faulting is recognized as typically occurring in wide zones of numerous faults, the delineation of a fault zone was represented as a horizontal flow barrier in the groundwater-flow model (fig. 4) using the Horizontal Flow Barrier (HFB) Package of MODFLOW-2005, which simulates reduced conductance between individual pairs of cells. This particular zone, while not explicitly mapped, appeared to have substantial effects on water levels in the western part of the model area and thus was explicitly included in the simulation.

Initial Conditions

Initial conditions were simulated by using a steady-state stress period (representing conditions prior to January 1, 1940) at the beginning of the simulation. Specified head boundaries of GHB and constant heads for this steady-state stress period were developed using the observation data and previous model simulations (described in the "Specified Head Boundaries" section). Specified heads representing the Pecos River were held at constant altitudes throughout the steady-state and transient simulation periods.

Hydraulic Properties

Hydraulic properties in the model were assigned by using discrete zones (large areas possessing the same property value) and pilot points (Doherty, 2003). Pilot points allow for greater flexibility in the spatial assignment of aquifer properties. Each point at a specified location can be assigned a value of a hydraulic property, which can change throughout the calibration process within specified limits. A hydraulic property value for each model cell is interpolated based on the values of surrounding pilot points, which can serve to spatially vary the properties in a gradational manner, rather than as fixed discrete zones of hydraulic properties. Doherty (2011) provides additional information on pilot points and the geostatistical methods associated with their use. During initial model development, pilot points were distributed uniformly across the model domain at a spacing of approximately 2 miles, but this distribution did not adequately represent hydraulic property heterogeneity in the groundwater system. As a result, the pilot points were reconfigured to locations of existing groundwater-level observations (fig. 5) (288 pilot points in the alluvial layer, 535 in each of the Edwards and Trinity layers, and 480 in the Dockum layer), which allowed for better representation of hydraulic property heterogeneity within the model domain. Pilot points representing recharge remained at the original uniform spacing of 2 miles.

Hydraulic Conductivity

Horizontal hydraulic conductivity values for each hydrogeologic unit were based on available aquifer test information compiled by Bumgarner and others (2012) and Christian and Wuerch (2012), and aquifer properties cited in Anaya and Jones (2009). Information from each data source was used as initial estimates of hydraulic conductivity for the alluvial, Edwards, Trinity, and Rustler layers. Pilot points were used to interpolate the hydraulic conductivity field of the alluvial (fig. 6*A*), Edwards (fig. 6*B*), and Trinity (fig. 6*C*) layers by using ordinary Kriging and a spherical variogram (Doherty, 2011). The hydraulic conductivities for the Dockum and Rustler layers were assigned uniform values of 1.5 and 100 feet per day (ft/d), respectively, to approximate typical values of similar lithology; pilot points were not used to represent hydraulic conductivity in these units.

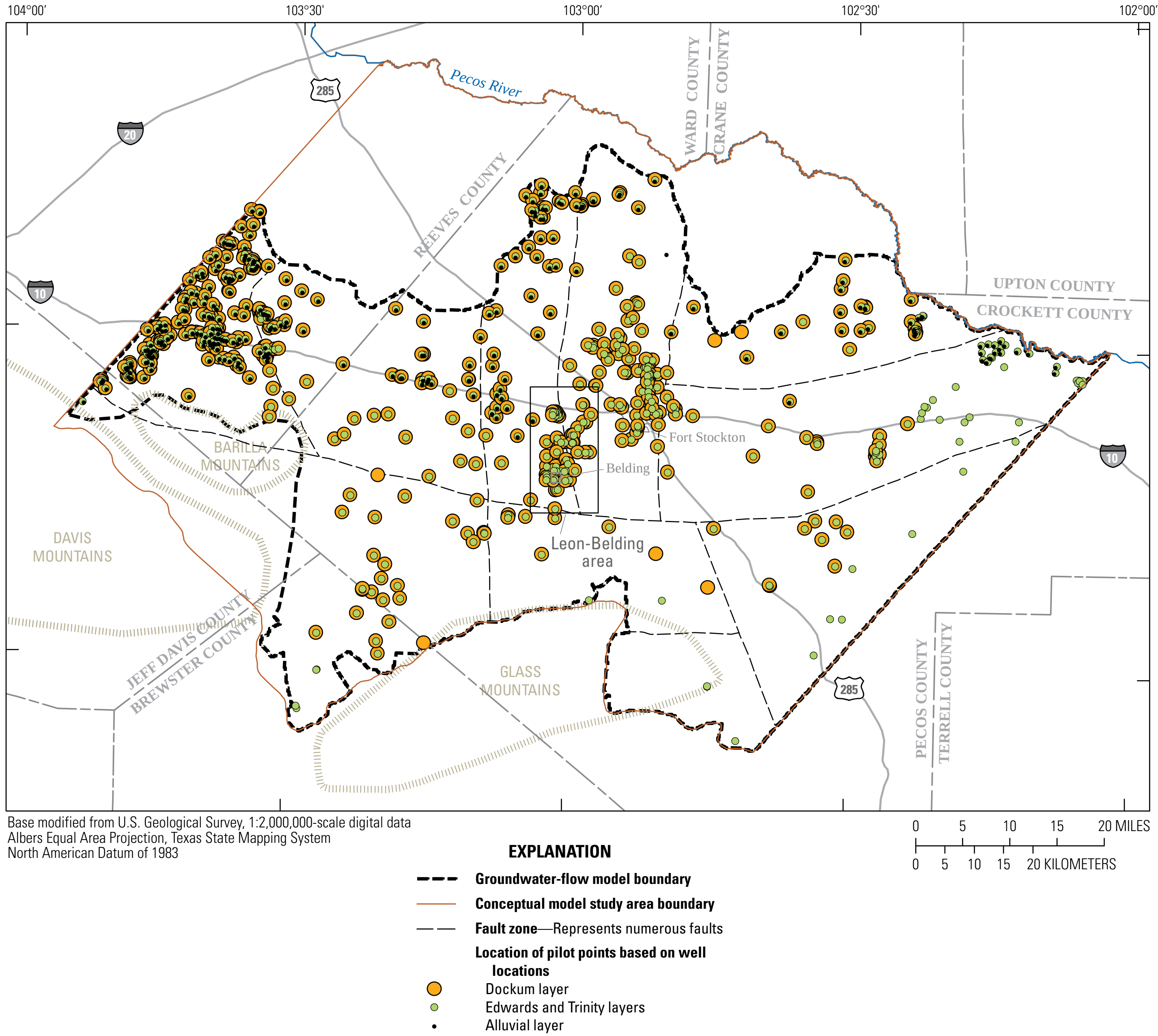


Figure 5. Distribution of pilot points throughout the Pecos County region model area, Texas.

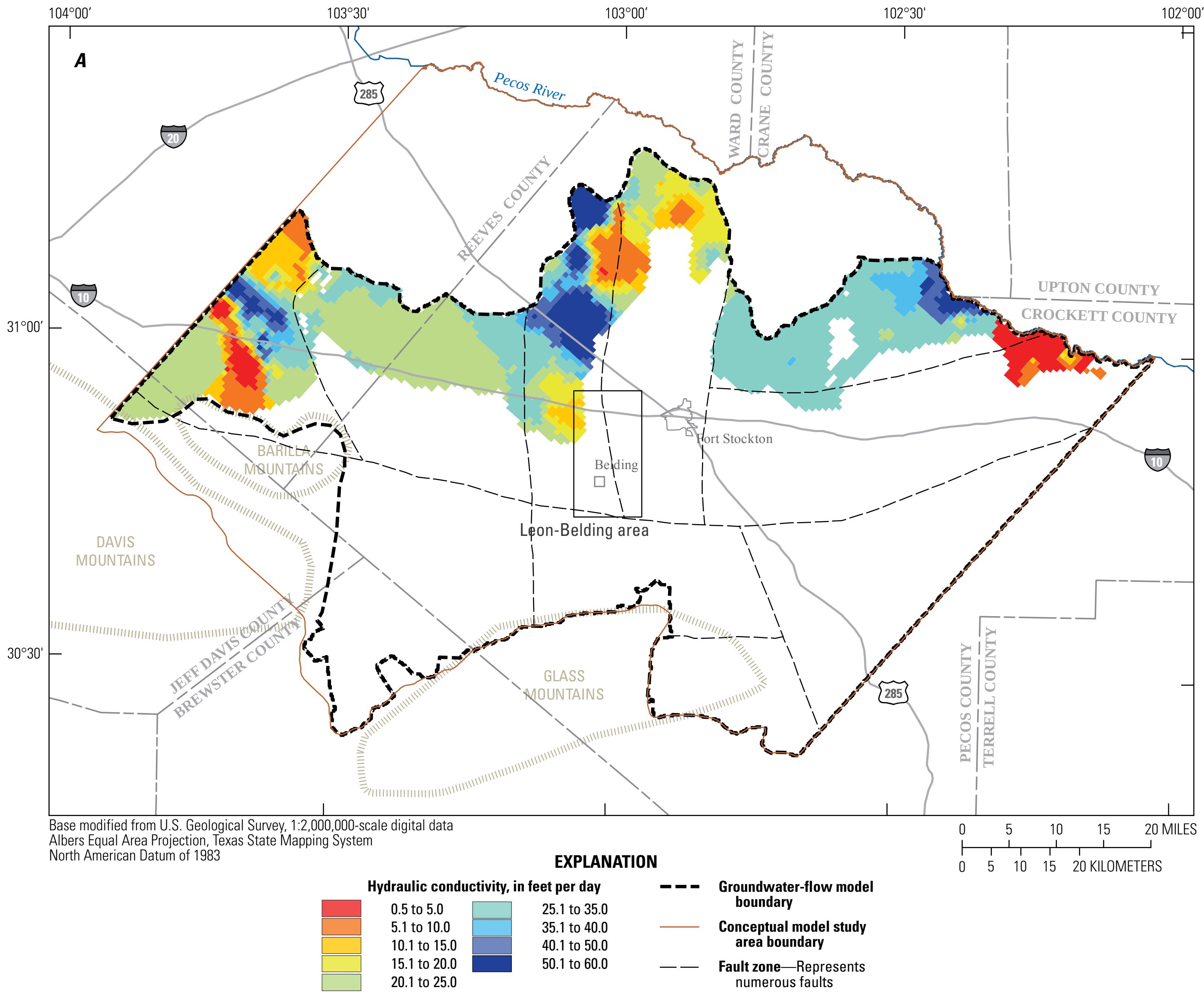


Figure 6A. Calibrated hydraulic conductivity distribution of the Pecos Valley aquifer (alluvial layer) in the Pecos County region model area, Texas.

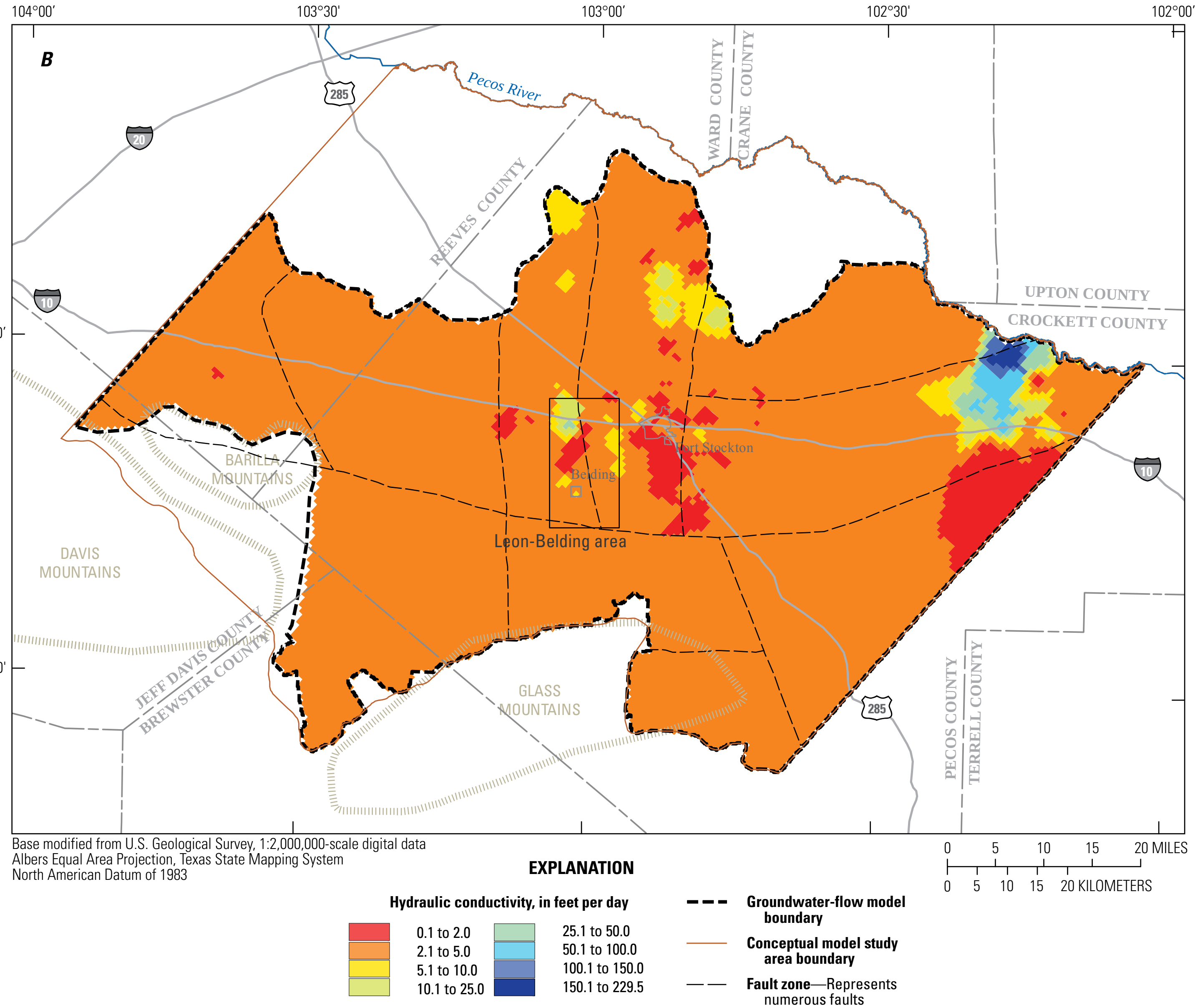


Figure 6*B*. Calibrated hydraulic conductivity distribution of the Edwards part of the Edwards-Trinity aquifer (Edwards layer) in the Pecos County region model area, Texas.

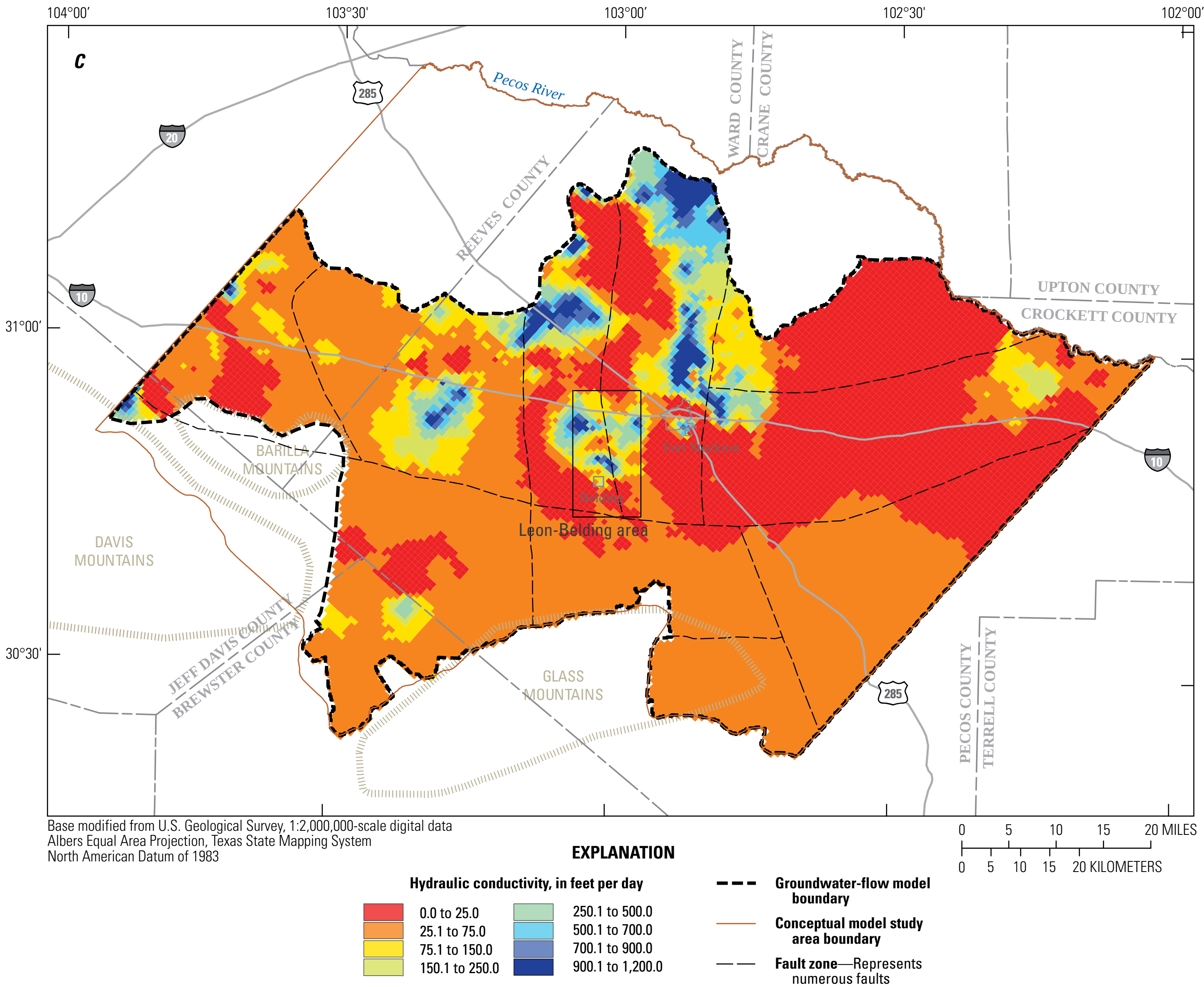


Figure 6*C*. Calibrated hydraulic conductivity distribution of the Trinity part of the Edwards-Trinity aquifer (Trinity layer) in the Pecos County region model area, Texas.

Vertical Hydraulic Conductivity and Storage

Vertical hydraulic conductivity (VK) and storage play a large role in groundwater flow because of the faulted and fractured nature of the geology in the model area. Faults and fractures can act as conduits or barriers to groundwater flow depending on the hydraulic characteristics of the structural feature. For example, conductive faults and fractures that penetrate multiple hydrogeologic units in a groundwater system might allow vertical movement of groundwater between the units, even if a confining unit is present. Conversely, faults that are only marginally conductive or result in an offset that disconnects a unit from itself horizontally can act as barriers to flow in the vertical, horizontal, or both directions (Maclay and Small, 1983). Scant high-resolution information pertaining to VK and storage in the model area was available; VK typically is determined by using laboratory techniques on cores obtained from well bore holes (Dagan, 1986), and the calculation of storage typically requires lengthy pumping tests with multiple observation wells (Heath, 1983). As a result, literature values (Ewing and others, 2008; Anaya and Jones, 2009) were used to assign VK values to pilot points for a given model layer (fig. 5) and modified during calibration. The VK of the alluvial (fig. 7*A*), Trinity (fig. 7*B*), Edwards (fig. 7*C*), and Dockum (fig. 7*D*) layers was represented using pilot points, while the VK of the Rustler layer was assigned a uniform value of 0.49 ft/d to approximate typical values of similar lithology.

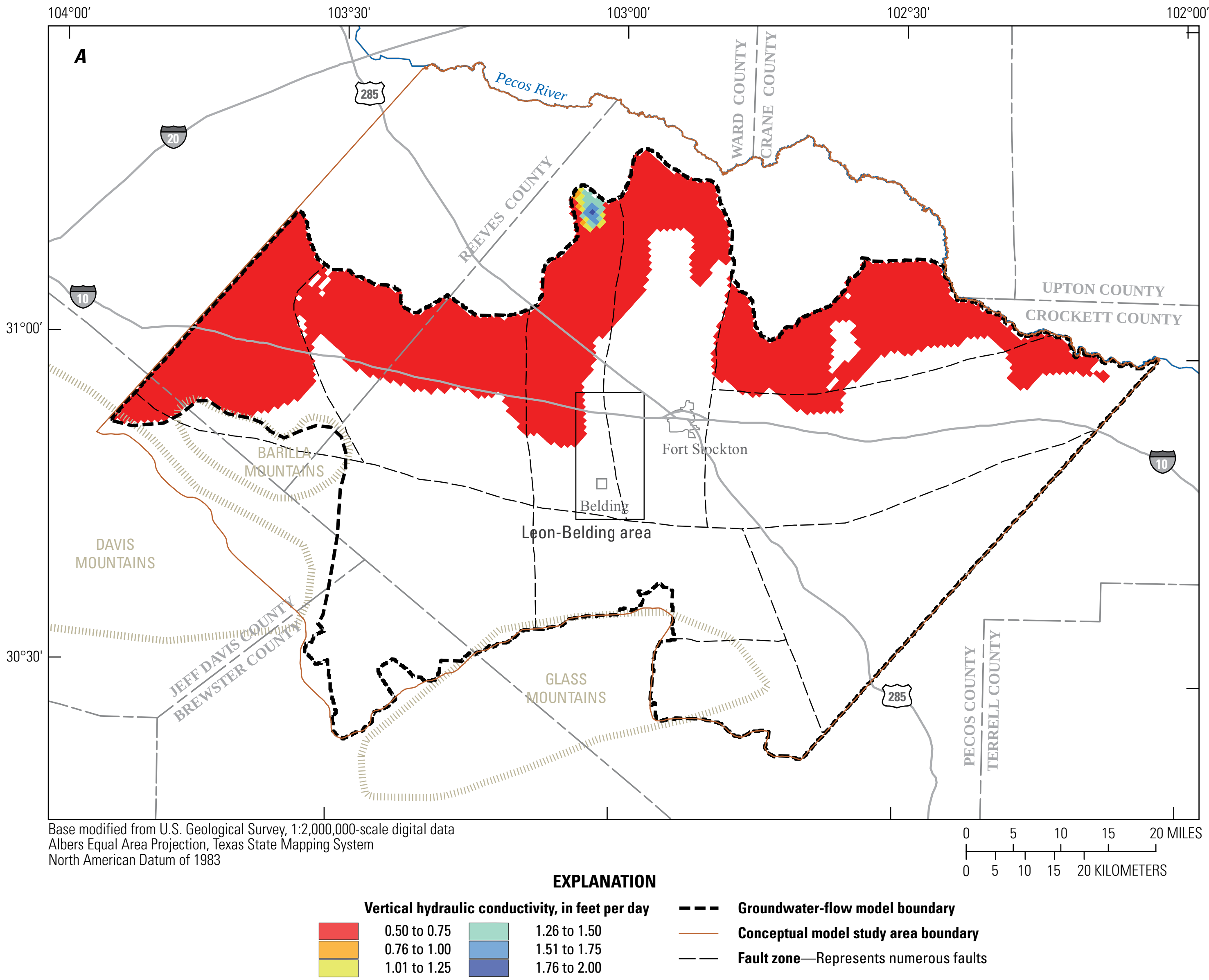


Figure 7*A*. Calibrated vertical hydraulic conductivity distribution of the Pecos Valley aquifer (alluvial layer) in the Pecos County region model area, Texas.

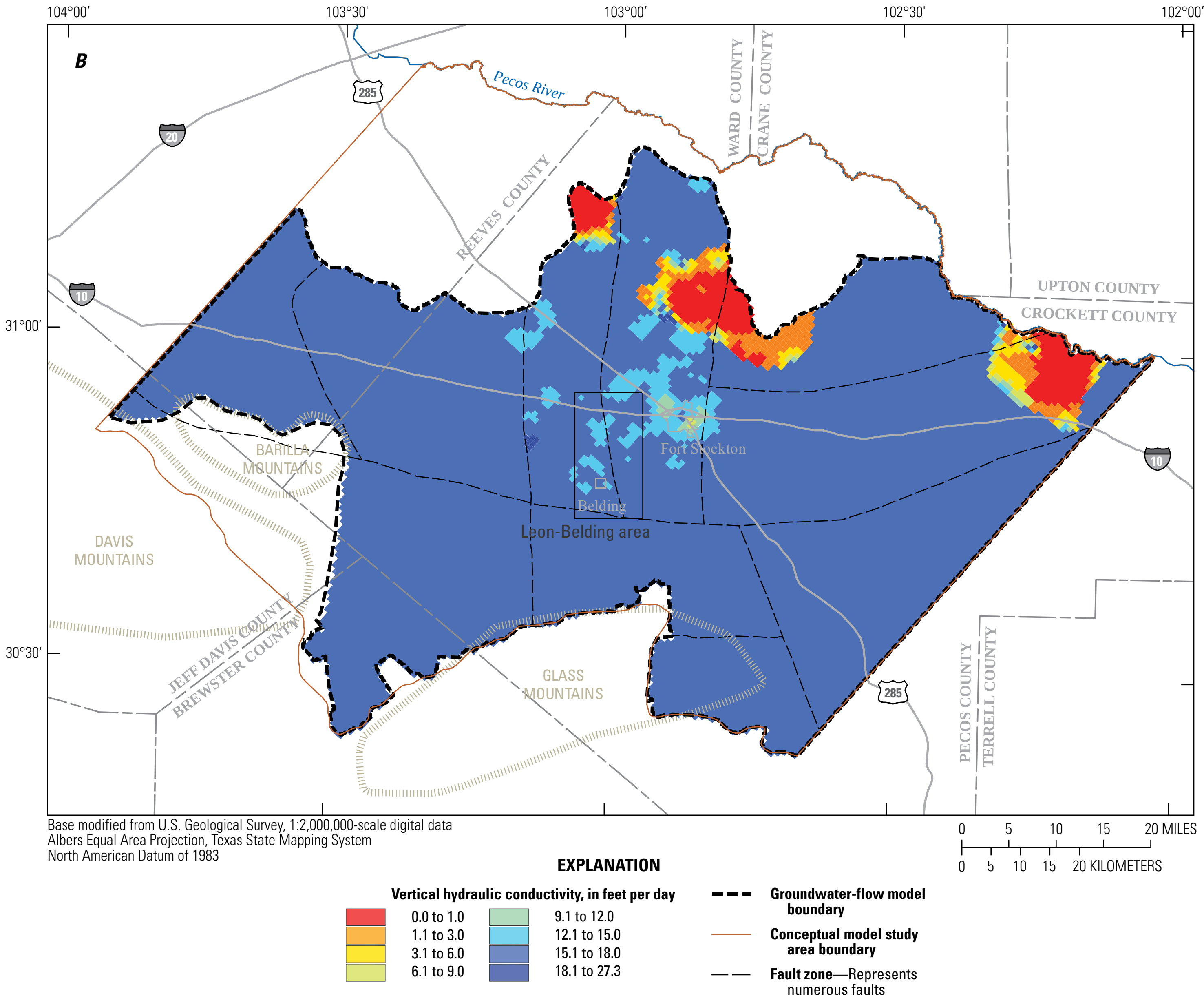


Figure 7*B*. Calibrated vertical hydraulic conductivity distribution of the Edwards part of the Edwards-Trinity aquifer (Edwards layer) in the Pecos County region model area, Texas.

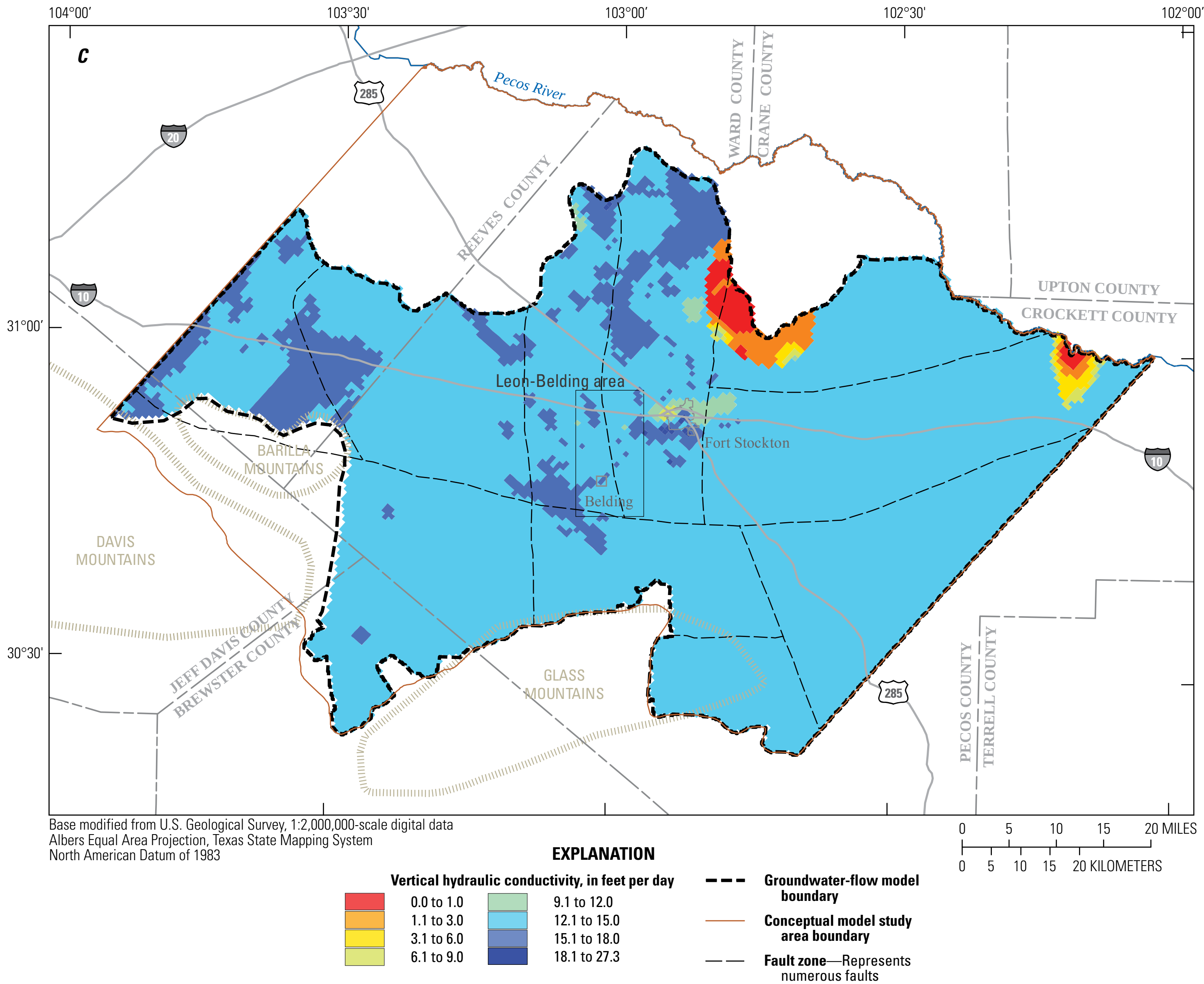


Figure 7*C*. Calibrated vertical hydraulic conductivity distribution of the Trinity part of the Edwards-Trinity aquifer (Trinity layer) in the Pecos County region model area, Texas.

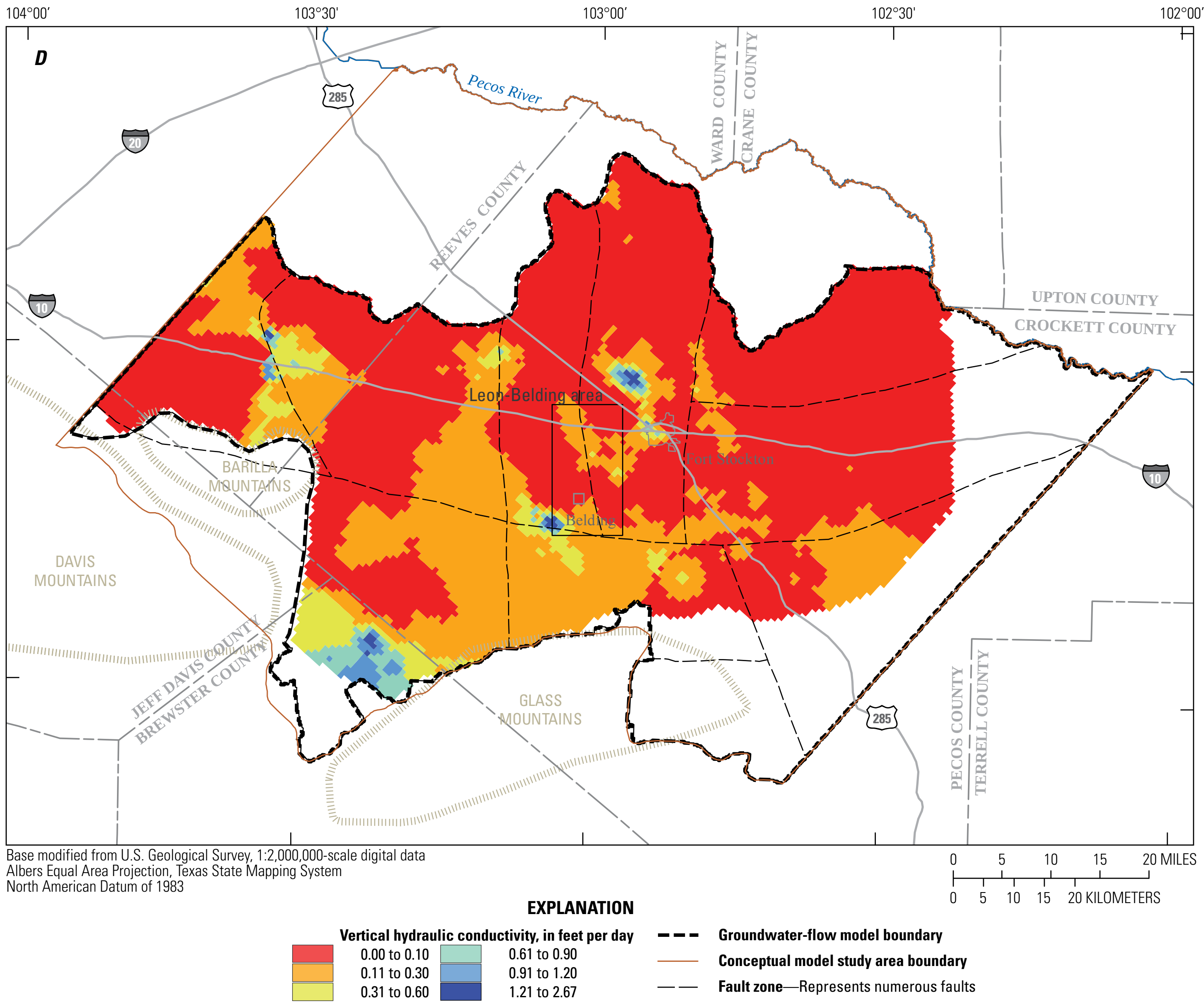


Figure 7*D*. Calibrated vertical hydraulic conductivity distribution of the Dockum layers in the Pecos County region model area, Texas.

Specific storage (confined aquifers) and specific yield (unconfined aquifers) can have a large effect on water levels, particularly in areas of potentially unconfined conditions (Freeze and Cherry, 1979). Specific storage represents the change in storage associated with compressibility of water and the geologic material and when multiplied by thickness provides the storage coefficient for a confined aquifer. Specific yield represents the volume of water that can be drained from a volume of aquifer per unit decline in water-table altitude. Specific storage values were assigned to pilot points within the alluvial (fig. 8*A*) layer and initially to pilot points within the Edwards and Trinity layers. The distribution of points was identical to those used for horizontal hydraulic conductivity in each unit (fig. 5). As noted in the “Model Limitations” section of this report, changing the specific storage of the Edwards and Trinity layers was found to have relatively little effect in many areas of the model. Specific storage values within these layers were then removed from the calibration and were instead calculated by using literature values (Domenico and Mifflin, 1964) of storage coefficient (product of the layer thickness and the specific storage) or specific yield for unconfined conditions and the spatially varying thickness of the layers. The resultant specific storage of the Edwards layer (fig. 8*B*) and the Trinity layer (fig. 8*C*) reflects approximate areas of confined and unconfined conditions in the model area. During the calibration procedure, specific storage of the Dockum and Rustler layers was uniformly calibrated as 8.8×10^{-6} and 5.0×10^{-6} 1/ft, respectively. The alluvial and Edwards layers were represented as convertible layers in the model; meaning that each layer can convert from confined to unconfined in areas where water levels decline below the top of the unit. Because the Trinity layer is specified as a confined layer in the model, the specific storage value may be higher than expected for the lithology because of the representation of potentially unconfined conditions. During the calibration procedure, specific yield of the alluvial layer (fig. 9) was assigned by using pilot points (fig. 5), and the specific yield assigned to the Edwards layer was uniformly 5.0×10^{-2} 1/ft based on model calibration.

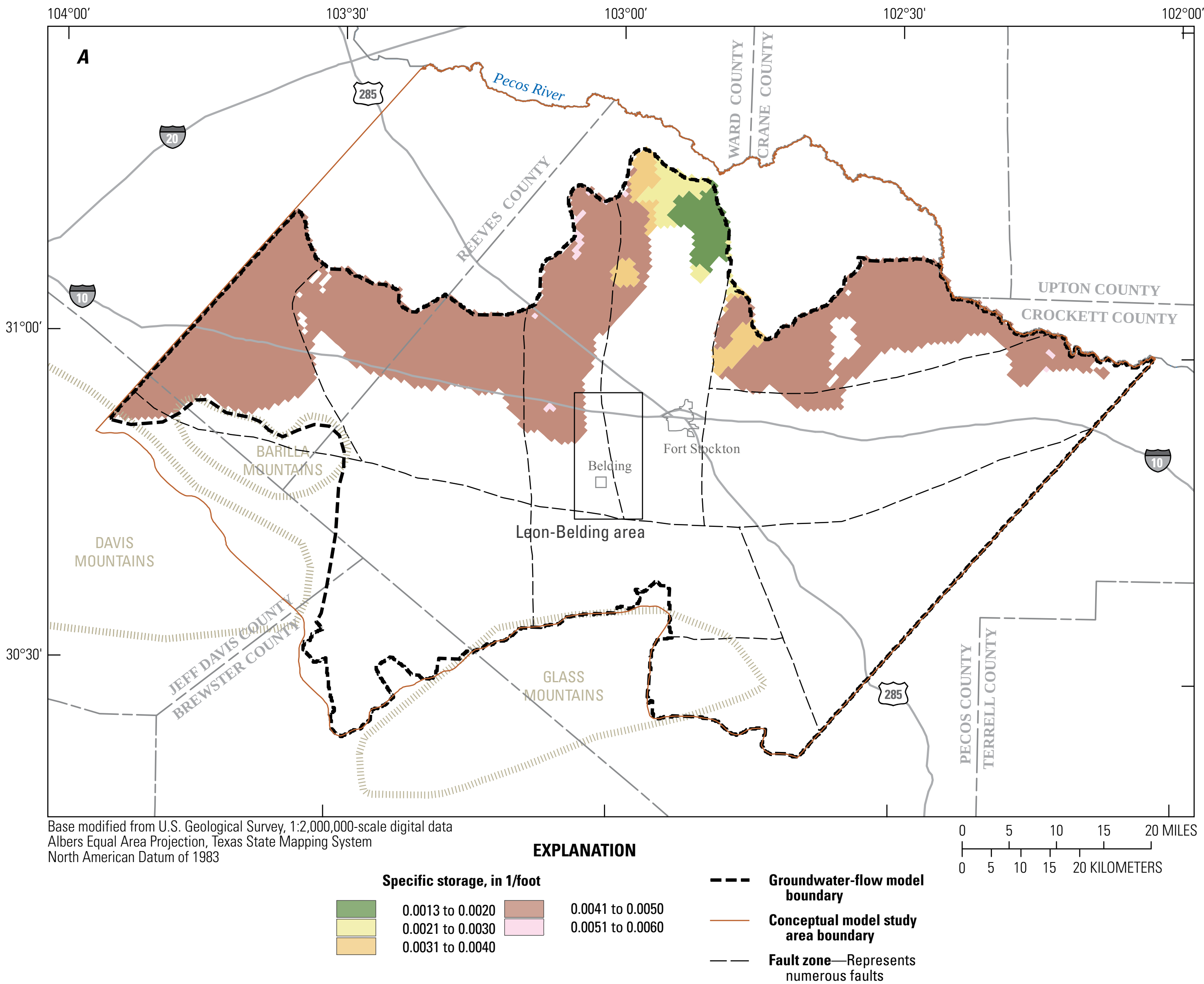


Figure 8*A*. Calibrated specific storage distribution of the Pecos Valley aquifer (alluvial layer) in the Pecos County region model area, Texas.

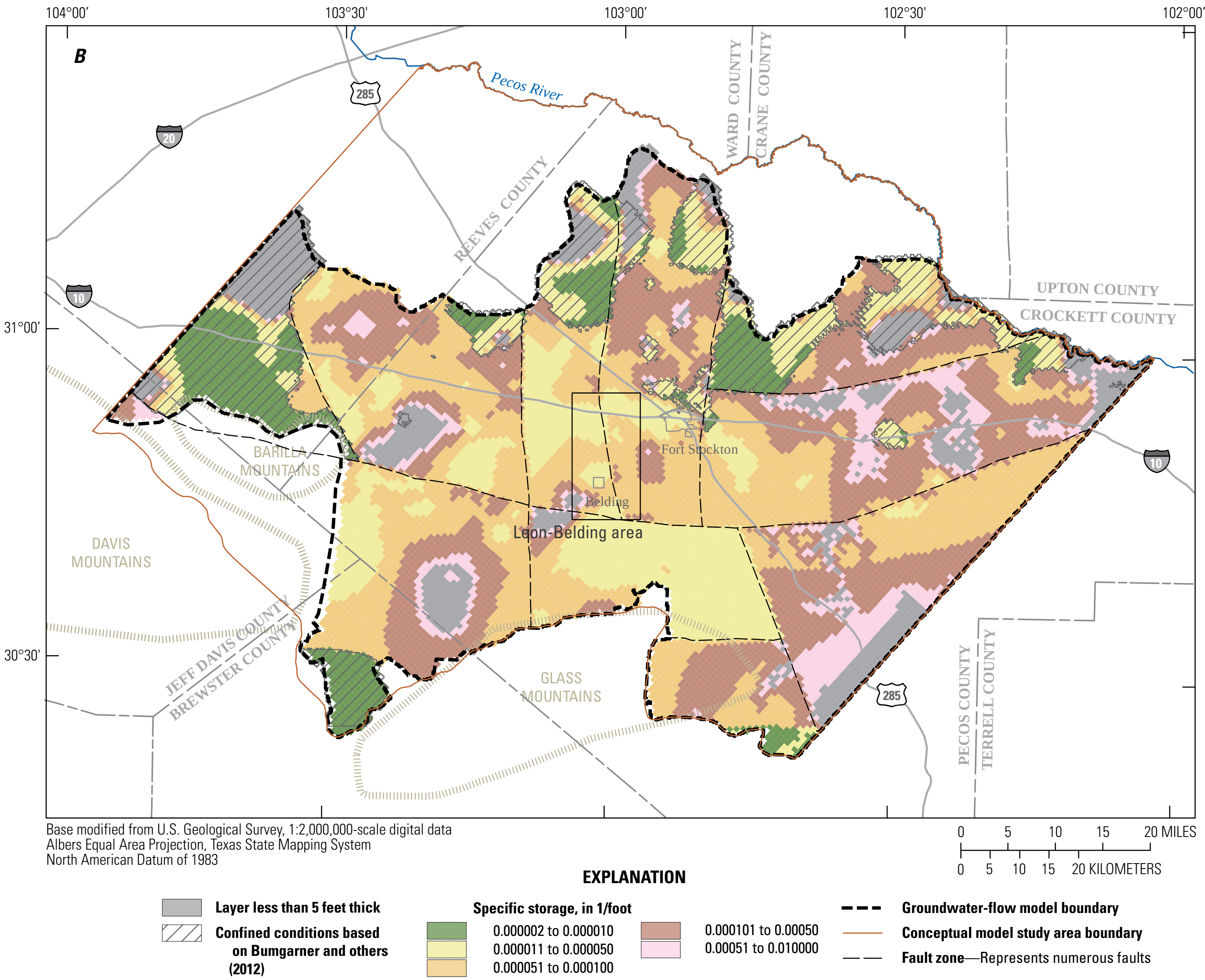


Figure 8*B*. Calibrated specific storage distribution of the Pecos Valley aquifer (alluvial layer) in the Pecos County region model area, Texas.

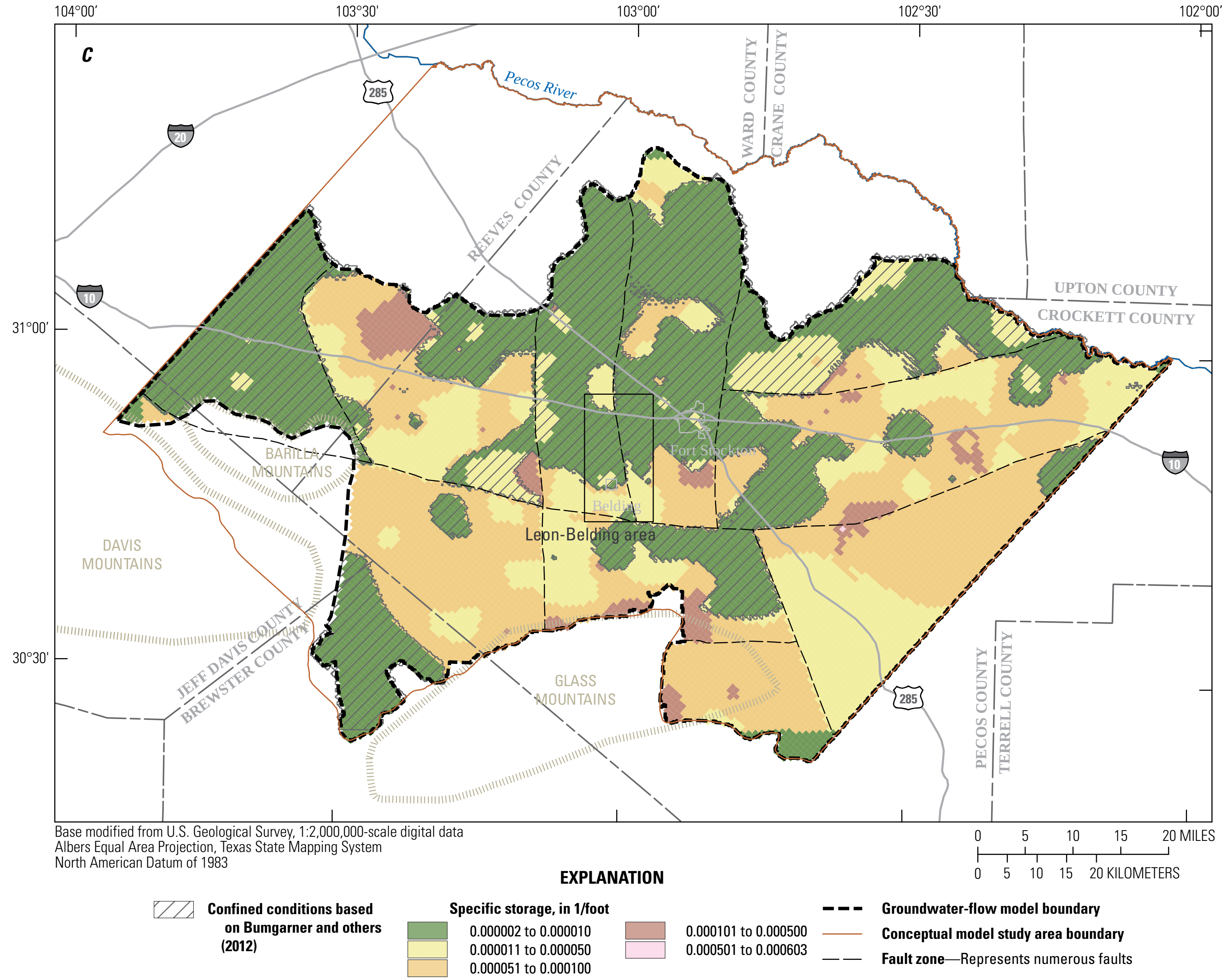


Figure 8*C*. Calibrated specific storage distribution of the Pecos Valley aquifer (alluvial layer) in the Pecos County region model area, Texas.

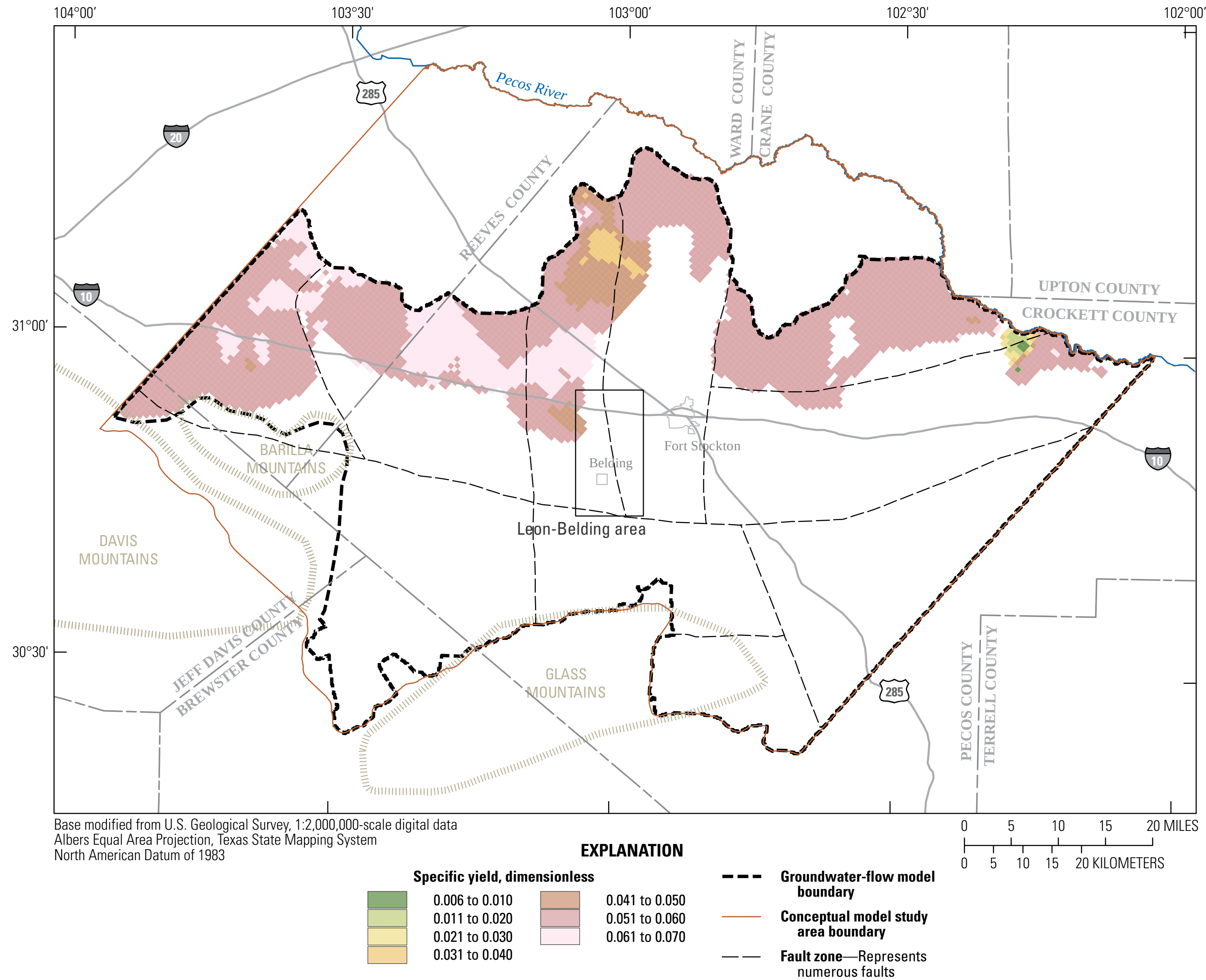


Figure 9. Calibrated specific yield distribution of the Pecos Valley aquifer (alluvial layer) in the Pecos County region model area, Texas.

Model Calibration

The ability of the model to simulate observed conditions was accomplished by a combination of manual changes to input values and automated calibration methods. The value of each pilot point, as well as other discrete zone parameters, was manually and automatically adjusted through the use of the Parameter ESTimation code PEST (Doherty, 2005) and a series of model simulations. The PEST code is an open-source, public domain software suite that allows model-independent parameter estimation analysis. PEST, along with extensive documentation, can be downloaded from http://www.pesthomepage.org. After each model simulation, simulated hydraulic-head (simulated groundwater-level altitude) and spring-flow values were compared to observed values. The iterative simulations continued until a best fit (minimizing the numeric difference) between simulated hydraulic head and spring flow and observed hydraulic head (measured groundwater-level altitude) and spring flow was attained. The calibration approach that was used differs from traditional nonlinear regression parameter estimation by taking advantage of Tikhonov regularization (Doherty, 2003; Fienen and others, 2009; Tikhonov, 1963) and hybrid singular value decomposition (Hunt and others, 2007; Tonkin and Doherty, 2005), also referred to as SVD-Assist (Doherty, 2005). The model was evaluated through a comparison of residuals, or the difference between simulated and observed values of groundwater levels and spring flow at Comanche Springs, as well as the feasibility of estimated parameter values compared to literature values within the model area and of similar lithology (Bumgarner and others, 2012; Freeze and Cherry, 1979; Kunianksy and Holligan, 1994).

Optimal Parameter Estimates

The final calibrated parameter values of the model (table 2) are within the range of reported values and considered reasonable for the type of material and conditions found in the groundwater system (Domineco and Mifflin, 1965; Freeze and Cherry, 1979). The range of horizontal hydraulic conductivity values applied to the Edwards-Trinity aquifer (Edwards and Trinity layers) from 1.0×10^{-3} to 1.2×10^{3} ft/d was within the range of hydraulic conductivities for a fractured rock and karst limestone (Freeze and Cherry, 1979). Specific yield values throughout the model range from 6.0×10^{-3} to 7.0×10^{-2}. Specific storage values range from 2.0×10^{-6} to 1.0×10^{-2} 1/ft. Net recharge values range from 1.0×10^{-8} to 6.2×10^{-4} ft/d (effectively from 0 to 2.7 in/yr) along the western model boundary. Comparatively, investigations by Long (1958), Iglehart (1967), Reeves (1969), and Rees and Buckner (1980) estimated average recharge values ranging from 0.3 to 1.4 in/yr over various parts of the Edwards-Trinity aquifer. The higher end-range value of simulated net recharge likely is a result of finer-scale discretization resulting in greater variability represented in the model, as compared with reported estimated values that are averaged across wide areas, for example countywide averages (Iglehart, 1967; Reeves, 1969).

Model Fit and Model Error

Differences between simulated and observed values of water level and spring flow are referred to as residuals. Residuals for groundwater levels and spring flow were evaluated based on the mean, minimum, maximum, absolute mean, and root mean square error (RMSE). RMSE is determined using the equation:

$$RMSE = \sqrt{\sum((h_s - h_o)^2 / n)}$$

where

h_s is simulated value,
h_0 is observed values, and
n is number of observations.

The mean of residuals indicates model bias depending on the magnitude and direction of the mean from zero. A mean value close to zero indicates a balance between positive and negative residuals, or less model bias. A large positive mean indicates that the model primarily overpredicts (simulated values greater than observed), and a negative mean indicates underprediction (simulated values less than observed). Low values of RMSE indicate better model fit to observed values (Anderson and Woessner, 1992; Reilly and Harbaugh, 2004).

Calibration Targets

Measurements of hydraulic head and spring flow were used as the primary calibration targets to evaluate model fit. Hydraulic head and spring flow were used quantitatively as part of manual and automatic calibration. Qualitative comparisons of hydrographs at selected wells in the model area and a comparison of a simulated potentiometric surface to that produced by Bumgarner and others (2012) are provided in the "Hydrographs" and "Potentiometric Surfaces" sections of the report.

Hydraulic Head Observations and Errors

Simulated hydraulic heads were compared to observed hydraulic heads (2,860 groundwater-level altitude measurements made at 288 wells) in the Edwards-Trinity aquifer (fig. 5). Simulated hydraulic heads generally were in good agreement with observed hydraulic head values, with 1,684 (59 percent) simulated values within 25 ft of the observed value. The RMSE values of most years were within 5 percent of the total observed groundwater-level altitude range in the Edwards-Trinity aquifer (maximum total range of 1,420.5 ft), which was deemed acceptable. The average RMSE value of hydraulic head for the Edwards-Trinity aquifer was 34.2 ft, which was approximately 4 percent of the average total observed groundwater-level change. The RMSE of hydraulic heads ranged from 19.3 ft in 2002 to 55.4 ft in 1987 (table 3).

Table 2. Final calibrated hydraulic parameter values for the Pecos County region model area, Texas.

Parameter group	Parameter description	Parameter name	Final value or range	Units
Hydraulic conductivity in horizontal direction	Pecos Valley aquifer (alluvial layer)	hk_alvm*	0.5 to 60	feet/day
	Edwards part of the Edwards-Trinity aquifer (Edwards layer)	hk_ed*	0.1 to 230	feet/day
	Trinity part of the Edwards-Trinity aquifer (Trinity layer)	hk_trin*	1.0×10^{-3} to 1.2×10^{3}	feet/day
	Dockum aquifer (Dockum layer)	hk_dock	1.5	feet/day
	Rustler aquifer (Rustler layer)	hk_rust	100	feet/day
Vertical hydraulic conductivity	Pecos Valley aquifer (alluvial layer)	vk_alvm*	0.5 to 1.8	feet/day
	Edwards part of the Edwards-Trinity aquifer (Edwards layer)	vk_ed*	1.2×10^{-4} to 27	feet/day
	Trinity part of the Edwards-Trinity aquifer (Trinity layer)	vk_trin*	0.02 to 22	feet/day
	Dockum aquifer (Dockum layer)	vk_dock*	6.2×10^{-6} to 2.7	feet/day
	Rustler aquifer (Rustler layer)	vk_rust	0.49	feet/day
Specific storage	Pecos Valley aquifer (alluvial layer)	ss_alvm*	1.3×10^{-3} to 5.0×10^{-3}	1/foot
	Edwards part of the Edwards-Trinity aquifer (Edwards layer)	ss_ed*	2.0×10^{-6} to 1.0×10^{-2}	1/foot
	Trinity part of the Edwards-Trinity aquifer (Trinity layer)	ss_trin*	2.0×10^{-6} to 6.0×10^{-4}	1/foot
	Dockum aquifer (Dockum layer)	ss_dock	8.8×10^{-6}	1/foot
	Rustler aquifer (Rustler layer)	ss_rust	5.0×10^{-6}	1/foot
Specific yield	Pecos Valley aquifer (alluvial layer)	sy_alvm*	6.0×10^{-3} to 0.07	Dimensionless
	Edwards part of the Edwards-Trinity aquifer (Edwards layer)	sy_ed	5.0×10^{-2}	Dimensionless
Recharge	Recharge	prch*	1.0×10^{-8} to 6.2×10^{-4}	feet/day
Horizontal flow barrier	North/south trending fault within Pecos Trough	westpcstrgh	1.0×10^{-6}	feet/day

* Represented by pilot points, see figure 5.

The mean residual approached zero with an absolute value less than 5 ft for 20 of the 63 years for which residuals were available. Out of the 2,860 observations in the Edwards-Trinity aquifer, 1,536 residuals were greater than or equal to zero (overprediction), and 1,324 residuals were less than zero (underprediction). The maximum and minimum residuals were 149 ft and -286 ft, respectively.

Spring Flow

Simulated spring flow representing Comanche Springs indicates a similar pattern as compared to the observed spring flow (fig. 10). During the calibration process, it was noted that the overall magnitude of spring flow could be controlled by different aquifer properties, such as hydraulic conductivity of the Edwards or Trinity layers. However, each change in this aquifer property did not allow the gradual decline and eventual cessation of simulated spring flow. Only after the addition of the time-variant constant heads in the Rustler layer (described in “Specified Head Boundaries” by Ewing and others [2012]) did the simulated spring flow begin to follow the pattern of the observed data. These findings are corroborated by the geochemical analysis by Bumgarner and others (2012) that indicate upwelling of groundwater from the Rustler aquifer in localized areas. Droughts were common in Texas during the 1940s and 1950s (Thomas and others, 1963), and the preliminary analysis of cumulative below-normal departure from normal precipitation during model calibration followed an almost identical decline as that of spring flow from 1940 to the late 1950s (Sharp, 2001). It is likely that this dry period resulted in the increased pumping to account for the lack of rainfall, resulting in groundwater-level and spring-flow declines; however, specified pumping from the Rustler aquifer would not substantially affect simulated hydraulic heads in the Rustler aquifer because of the time-variant constant heads in the Rustler layer.

Table 3. Summary of hydraulic-head residual statistics for the Edwards-Trinity aquifers in the Pecos County region model area, Texas.

[–, too few observations to compute root mean square error (RMSE)]

Year	Mean residual (feet)	Minimum residual (feet)	Maximum residual (feet)	RMSE (feet)	Mean absolute error (feet)	Number of observations	Range (feet)	Ratio of RMSE to range
1940	-22.1	-61.8	11.2	34.3	27.1	9	501.9	0.07
1941	-66.4	-66.4	-66.4	--	66.4	1	--	--
1942	23.3	-8.06	54.7	--	31.4	2	--	--
1946	9.54	-28.3	42.0	22.6	17.0	14	762.0	0.03
1947	-0.394	-97.3	102	54.1	40.5	21	1,031.5	0.05
1948	-4.57	-86.6	90.1	46.3	37.0	20	870.0	0.05
1949	-15.5	-87.4	28.3	38.1	27.3	18	712.0	0.05
1950	-13.6	-88.1	25.1	36.9	28.5	36	750.8	0.05
1951	-14.9	-85.2	23.0	33.8	27.7	21	751.7	0.04
1952	-4.18	-85.0	52.3	28.6	23.0	51	777.4	0.04
1953	-8.84	-84.0	82.7	38.4	31.2	31	779.2	0.05
1954	-10.6	-77.7	41.1	30.2	25.2	35	781.5	0.04
1955	-12.6	-64.8	61.9	26.8	22.5	61	893.1	0.03
1956	-11.7	-102	80.9	39.8	32.6	44	1,155.3	0.03
1957	1.84	-231	129	32.7	23.0	232	1,063.1	0.03
1958	-9.38	-276	119	41.4	28.3	231	1,199.2	0.03
1959	-7.93	-188	131	50.3	38.2	98	1,080.1	0.05
1960	5.85	-98.0	59.2	46.6	38.1	14	363.4	0.13
1961	-15.0	-286	70.1	51.3	34.6	71	1,420.5	0.04
1962	1.14	-90.6	81.7	36.1	28.6	57	1,132.5	0.03
1963	5.09	-88.5	131	45.4	37.0	61	1,135.9	0.04
1964	14.0	-86.3	112	43.4	34.6	69	1,131.0	0.04
1965	11.8	-83.3	138	40.5	28.8	75	1,134.2	0.04
1966	6.14	-79.1	112	35.4	27.3	75	1,135.4	0.03
1967	10.6	-75.6	115	36.4	26.5	68	1,132.2	0.03
1968	7.27	-75.2	118	35.6	26.2	67	1,128.5	0.03
1969	3.94	-106	110	37.7	26.4	81	1,374.0	0.03
1970	7.16	-84.4	148	39.0	26.2	111	1,124.8	0.03
1971	6.93	-153	115	37.4	26.6	104	1,204.3	0.03
1972	10.9	-70.3	139	41.7	29.6	46	1,119.2	0.04
1973	8.42	-126	145	45.6	31.2	32	961.3	0.05
1974	14.1	-54.5	109	37.9	26.4	24	697.2	0.05
1975	-2.25	-71.8	72.9	35.4	27.9	40	1,102.4	0.03
1976	7.21	-66.3	97.6	39.0	30.9	35	1,102.8	0.04
1977	-2.80	-65.9	66.4	30.8	24.6	25	1,102.5	0.03
1978	1.46	-74.7	75.2	35.1	29.0	23	1,109.3	0.03
1979	0.609	-66.8	53.0	28.1	22.9	24	1,097.5	0.03
1980	6.87	-39.1	66.8	29.0	23.2	18	770.9	0.04
1981	16.1	-38.3	70.8	33.2	25.7	10	733.7	0.05
1982	-11.0	-81.6	13.3	34.0	19.1	6	451.1	0.08
1983	21.5	-39.4	86.3	38.8	28.9	14	738.0	0.05
1984	2.88	-69.4	59.6	33.7	26.8	20	1,111.5	0.03
1985	52.1	-5.51	110	--	57.6	2	--	--
1986	-6.27	-76.4	73.7	36.1	26.6	12	781.6	0.05
1987	-3.76	-140	149	55.4	41.9	51	1,095.6	0.05
1988	7.30	-85.4	63.2	32.0	25.1	52	1,083.7	0.03
1989	7.83	-39.9	54.7	25.5	20.4	31	766.0	0.03
1990	7.39	-67.4	55.9	28.7	22.5	28	1,076.7	0.03
1991	2.39	-68.1	57.7	27.8	21.6	27	1,084.6	0.03
1992	-1.44	-68.9	47.4	27.5	22.1	26	1,087.6	0.03

Table 3. Summary of hydraulic-head residual statistics for the Edwards-Trinity aquifers in the Pecos County region model area, Texas.—Continued

[–, too few observations to compute root mean square error (RMSE)]

Year	Mean residual (feet)	Minimum residual (feet)	Maximum residual (feet)	RMSE (feet)	Mean absolute error (feet)	Number of observations	Range (feet)	Ratio of RMSE to range
1993	13.2	-40.3	115	40.2	27.5	39	724.3	0.06
1994	-5.77	-90.7	35.6	28.0	21.4	27	809.2	0.03
1995	-2.86	-39.8	34.9	19.9	16.7	26	744.4	0.03
1996	2.98	-39.3	79.7	26.1	20.2	23	742.3	0.04
1997	-14.9	-164	35.1	41.3	25.5	26	1,342.7	0.03
1998	-2.74	-42.7	40.1	22.3	19.3	23	762.7	0.03
1999	-1.86	-41.1	56.0	23.1	18.7	26	758.5	0.03
2000	-4.21	-40.9	41.7	21.9	18.3	19	760.5	0.03
2001	-5.53	-154	40.6	34.6	21.8	30	1,332.1	0.03
2002	0.683	-41.2	42.3	19.3	15.6	39	924.1	0.02
2003	-5.42	-34.5	18.5	19.5	17.1	8	118.5	0.16
2004	-11.9	-45.7	39.1	23.6	19.7	24	923.4	0.03
2005	-18.1	-80.4	36.8	31.1	25.8	19	935.4	0.03
2006	-14.5	-54.0	34.4	26.6	23.4	20	931.7	0.03
2007	-8.57	-54.3	33.8	22.2	17.5	48	933.0	0.02
2008	-11.3	-58.0	27.7	19.8	16.2	139	933.0	0.02

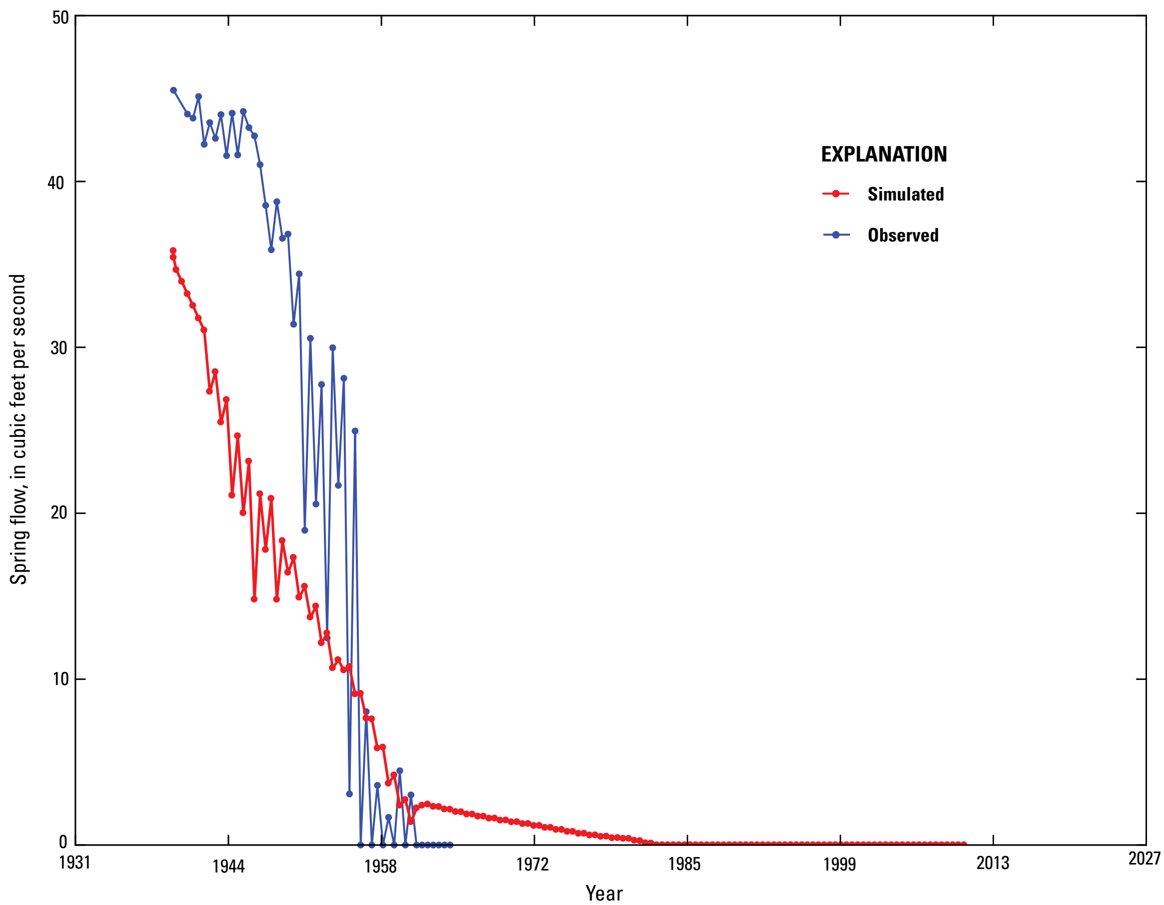


Figure 10. Comparison of simulated and observed spring flow at Comanche Springs in the Pecos County region model area, Texas.

Hydrographs

Hydrographs of simulated and observed hydraulic heads within the Edwards-Trinity aquifer were used to evaluate calibration of the model at selected wells in the model area (fig. 11). The hydrographs generally show good agreement between simulated and observed hydraulic heads for most locations with relatively long periods of record. Simulated hydraulic heads were appreciably larger than observed hydraulic heads at two wells (hydrographs 11*B* and 11*E*) during the midyears of the simulation. Differences between simulated and observed hydraulic heads are caused by uncertainty in hydraulic property values and the placement and timing of pumping wells in the model, which are dependent on the accuracy of the available pumping data.

Potentiometric Surfaces

The observed potentiometric surface for 1980 to 2010 and the simulated potentiometric surface for 2010 of the Edwards-Trinity aquifer generally are in agreement (fig. 12). Although the observed potentiometric surface (fig. 12) was constructed by using the average winter groundwater-level altitude measurements from 1980 to 2010 (Bumgarner and others 2012), the comparison is useful to evaluate regional groundwater-levels and flow directions. The observed and simulated potentiometric surfaces indicate regional groundwater flow from south and southwest to north and northeast in the model area. The simulated surface also coincides roughly with the two groundwater divides in the model area described by Bumgarner and others (2012) (fig. 12).

Sensitivity Analysis

Sensitivity of simulated hydraulic heads to adjustments made to the various model parameters and parameter groups was evaluated using PEST (Doherty, 2005). Sensitivity analysis aids in determining if there is adequate information in the calibration data to estimate a particular parameter. Sensitivity analysis results can also be useful in evaluating where additional data need to be collected to enhance model accuracy. Composite sensitivities (related to the sensitivity of each parameter with respect to all observations [Doherty, 2005]) were calculated for groups of model parameters for each model layer, recharge, and horizontal-flow barrier conductance that serves as the control for the amount of horizontal flow passing through a fault zone (fig. 13). Two parameters, hydraulic conductivity of the Trinity layer (hk_trin) and vertical hydraulic conductivity of the Dockum layer (vk_dock) have the largest composite sensitivity, as might be expected because most groundwater-level observations used in the analysis are within the Trinity layer. Additionally, according to the conceptual model of the groundwater-flow system (Bumgarner and others, 2012), upwelling from the Rustler hydrogeologic unit that underlies the Edwards-Trinity aquifer is a critical component of flow in the Monument Draw trough area of the aquifer. The conceptual model also is corroborated by the most sensitive parameters in the analysis in that simulated groundwater flow is predominately controlled by hydraulic conductivity through the Edwards-Trinity aquifer and vertical hydraulic conductivity that controls upwelling from lower units.

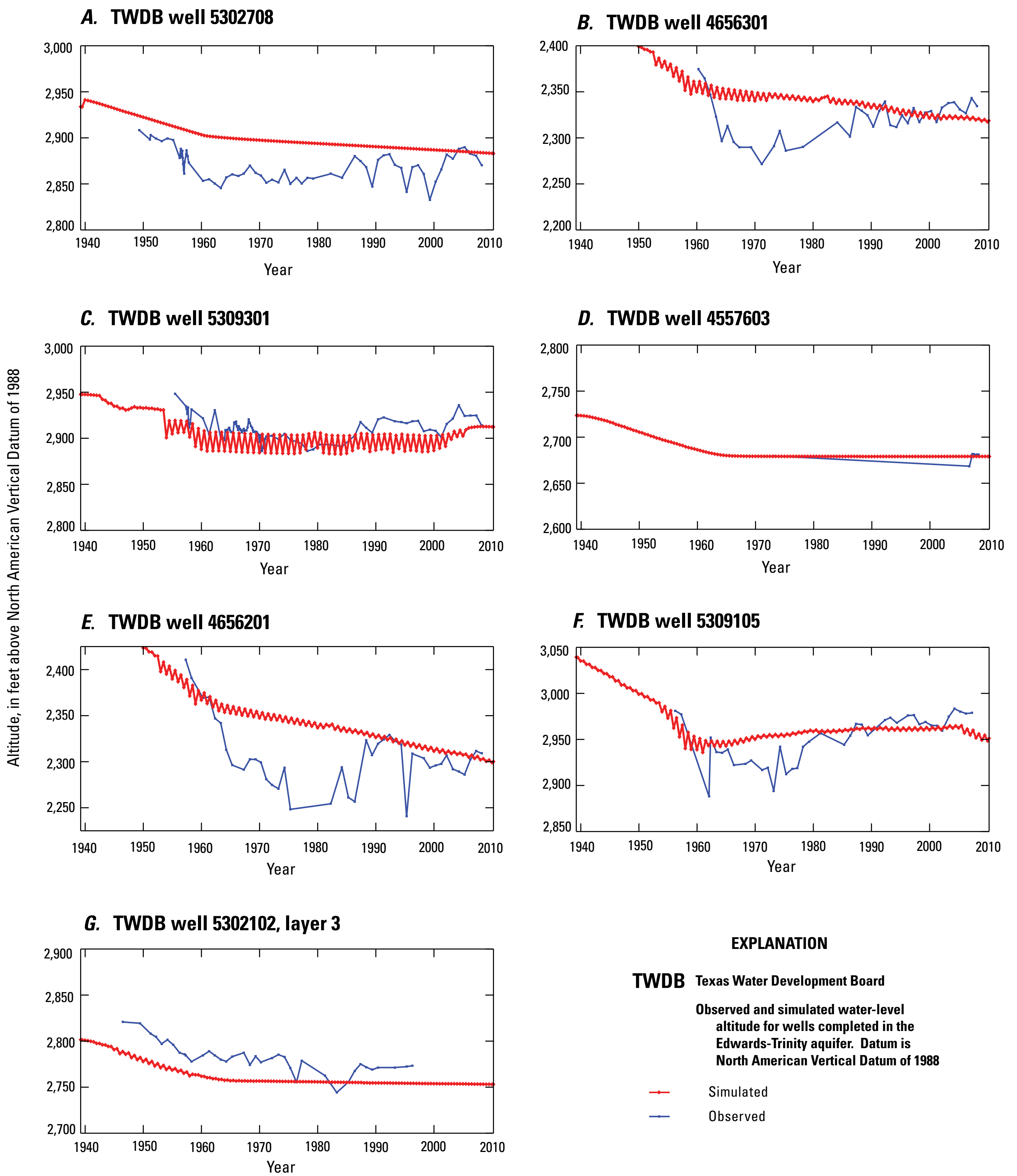


Figure 11. Simulated and observed hydrographs of hydraulic head in selected wells in the Edwards-Trinity aquifer in the Pecos County region model area, Texas.

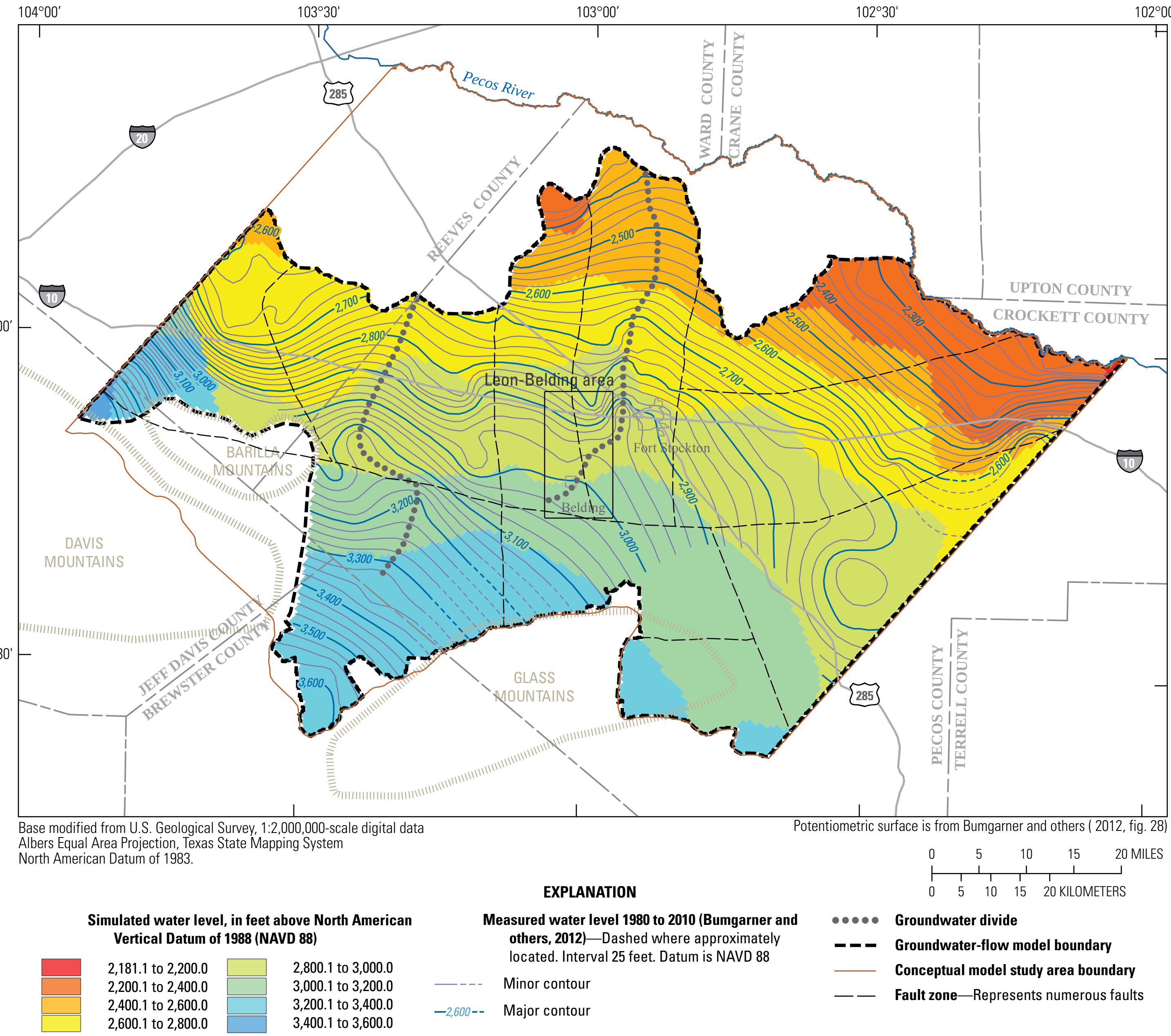


Figure 12. Potentiometric surface (1980–2010) and simulated groundwater-level altitudes for the Edwards-Trinity aquifer in the Pecos County region model area, Texas, 2010.

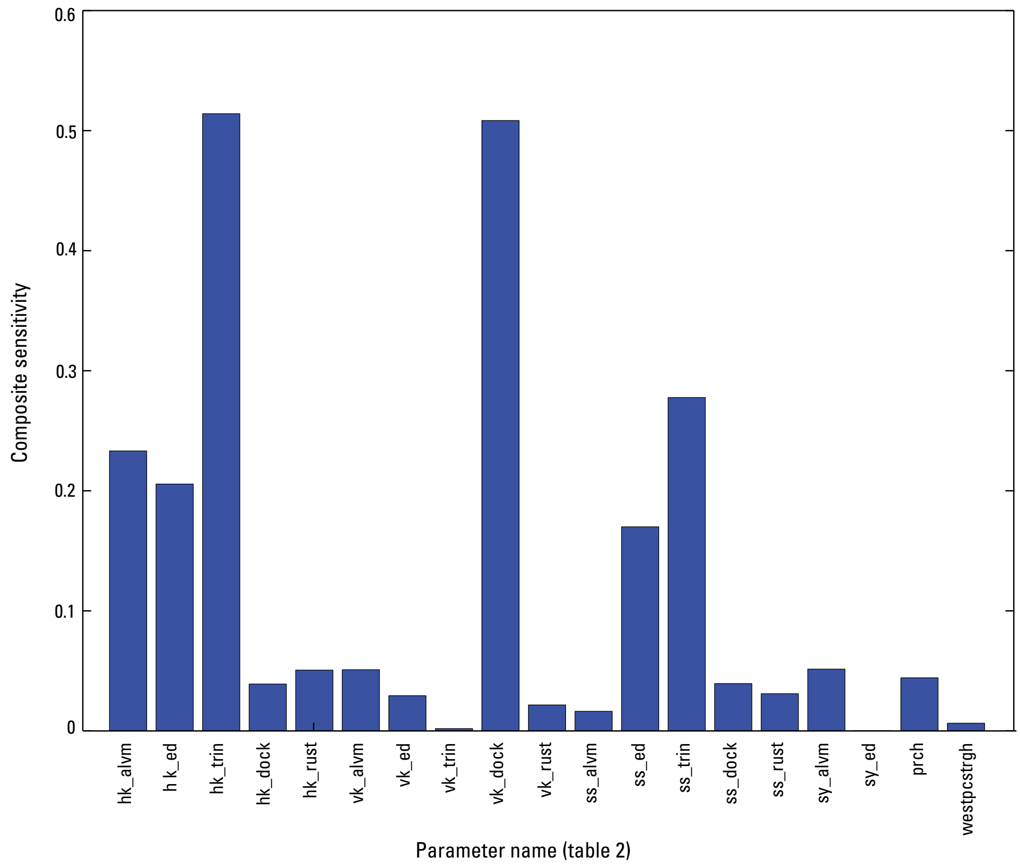


Figure 13. Composite sensitivities of all parameter groups of the groundwater-flow model of the Edwards-Trinity and related aquifers in the Pecos County region model area, Texas.

Normality of Residuals and Goodness of Fit

Normality of residuals is a prerequisite for a valid regression. If the model accurately represents the groundwater-flow system, the residuals are expected to be random, independent, and normally distributed (Hill, 1998). The independence and normality of the residuals can be assessed through use of (1) the summary statistic R_N^2, the correlation coefficient between the weighted residuals ordered from smallest to largest and the order statistics derived from the normal probability distribution function (Brockwell and Davis, 1989; Hill and others, 1998) and (2) a histogram of the residuals. The residuals are thought to be independent and normally distributed if the computed value of R_N^2 for a calibration is greater than the tabulated critical value (Hill and others, 1998; Hill and others, 2000). Hill (1992, p. 64) provides a table of critical values for 35 to 200 observations. The critical value of R_N^2 is 0.987 for a set of 200 observations. The value of R_N^2 for hydraulic heads in the model calibration is 0.99, which is slightly greater than the critical value. A histogram (fig. 14) of the 2,860 Edwards-Trinity residuals shows an approximately normal distribution with the maximum value occurring within the interquartile range (25th to 75th percentile) of -25 to 25 ft.

Graphical analyses of the residuals facilitate assessment of model bias or error and of model fit to the calibration data. These analyses include plots of the observed and simulated values and of the spatial and temporal distribution of the hydraulic-head residuals.

The plot of observed and simulated equivalents for a reasonable calibration effort should approximate a fit to a 1:1 line extending through the data. The model has a reasonable fit to the 1:1 line with a coefficient of determination (R^2) of 0.98 (fig. 15). In the upper range of groundwater-level altitudes of 3,200 ft and larger where data are sparse, the simulated hydraulic heads are appreciably less than the observed hydraulic heads.

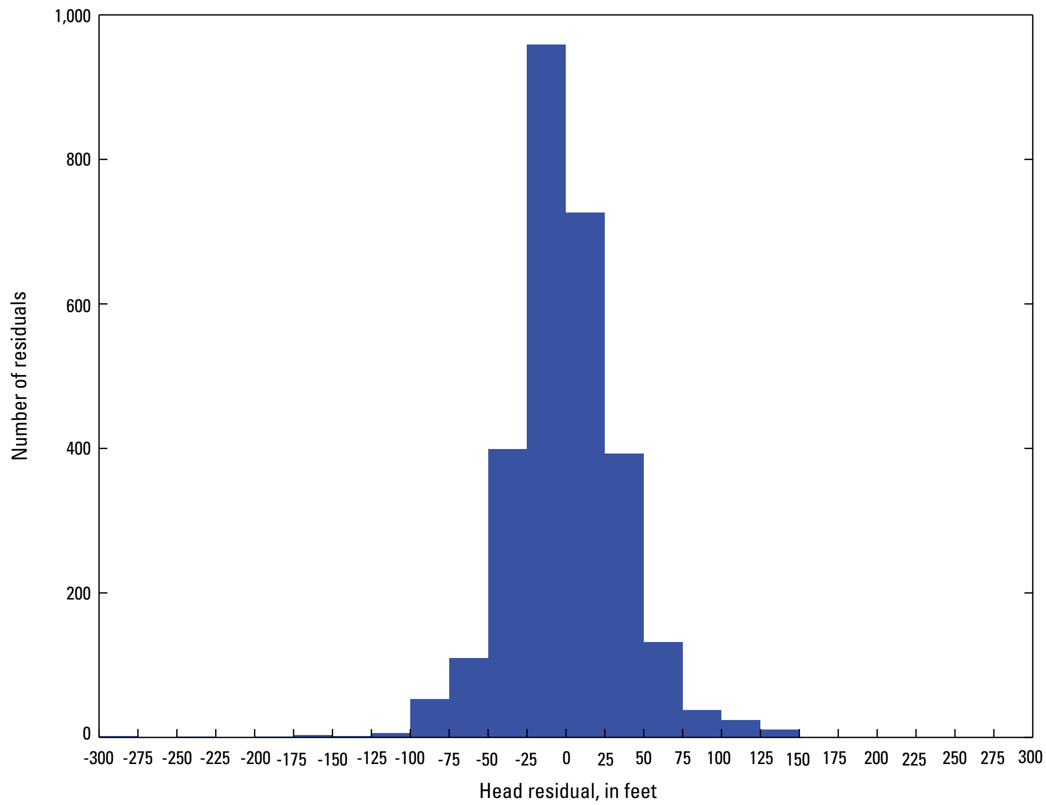


Figure 14. Residuals for the Pecos County region model, Texas.

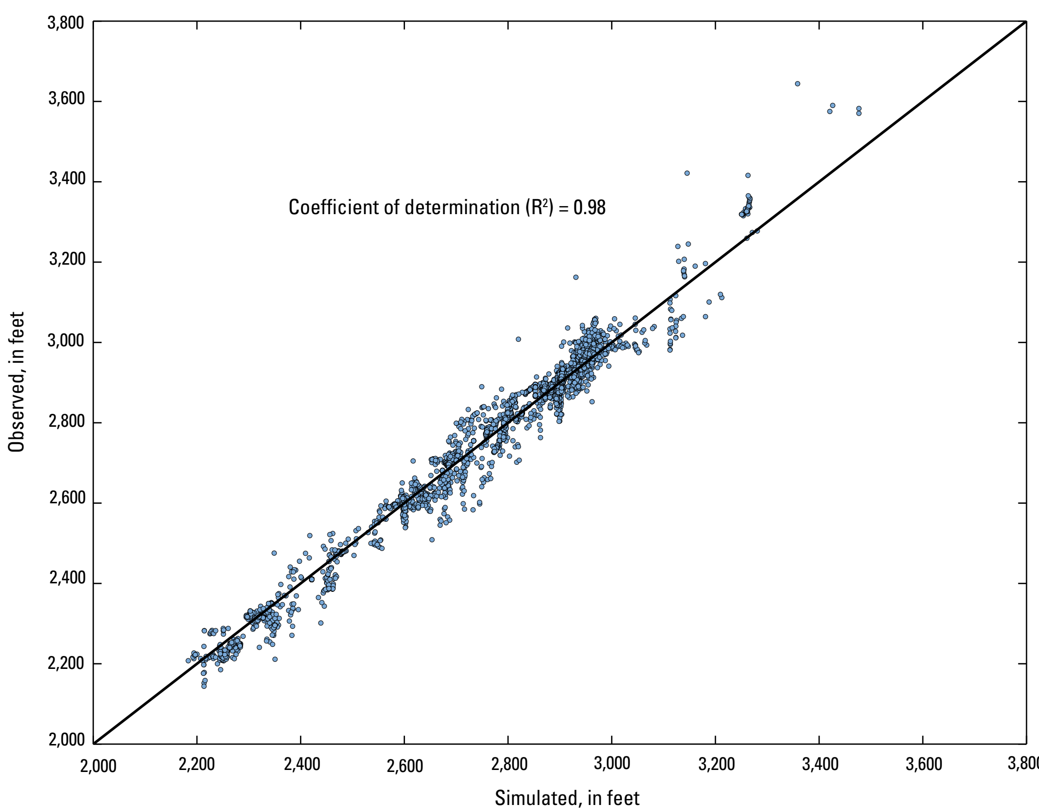


Figure 15. Relation between simulated and observed hydraulic heads for the Pecos County region model, Texas.

Additional assessments of model error were accomplished through analysis of the spatial and temporal distribution of weighted residuals of the Edwards-Trinity aquifer for years after 1940 (fig. 16). Different ranges in residuals represented by a variety of geometric symbols in figure 16 allow for a visual analysis of model bias. Positive residuals, shown in blue, indicate simulated hydraulic heads that are higher than observed, while negative residuals indicate simulated hydraulic heads that are lower than observed.

Ideally, negative and positive weighted residuals should be small and randomly distributed in space. Clustering of residuals with similar magnitudes and signs is indicative of model bias (Reilly and Harbaugh, 2004). Overall, residuals (fig. 16) appear to be evenly distributed in both magnitude and positive or negative sign.

Geochemical Modeling

Geochemical modeling was used independently to evaluate some of the groundwater-flow model results. Results of the geochemical modeling were not used for quantitative comparison during the groundwater-flow model calibration. Because of this, the mixing proportions and source areas of the various types of groundwater may differ slightly between the geochemical and flow models; however, the basic assumptions of the conceptual model of the system were substantiated by the geochemical and flow modeling results.

Bumgarner and others (2012) identified four principal sources of recharge to the Edwards-Trinity aquifer: (1) regional groundwater flow in the Edwards-Trinity aquifer that originated as recharge northwest of the study area and enters the study area near the western corner; (2) runoff from the Barilla, Davis, and Glass Mountains that percolates through underlying rocks and into gravels along the slopes of the mountains; (3) return flow from irrigation; and (4) upwelling from deeper aquifers. Higher specific conductance, chloride, and sulfate values were measured in water-quality samples collected from the Edwards-Trinity aquifer in the Leon-Belding (sites Q16, Q18, Q22, and Q24, fig. 4) and Fort Stockton areas (sites Q23 and Q26, fig. 4) compared to the specific conductance, chloride, and sulfate values measured in water-quality samples collected from the Edwards-Trinity aquifer in other areas. These data indicate that water from the Rustler aquifer is likely upwelling in the Leon-Belding and Fort Stockton areas (Bumgarner and others, 2012).

Inverse geochemical modeling (PHREEQC; Parkhurst and Appelo, 1999) was used to mix upgradient Edwards-Trinity groundwater recharged in the Barilla, Davis, and Glass Mountains (fig. 1) with Rustler groundwater to approximate the composition of groundwater from sites Q16, Q18, Q22, Q23, Q24, and Q26 (fig. 4). The inverse models were constrained by the concentrations of alkalinity, calcium, carbon, chloride, dissolved oxygen, magnesium, sodium, strontium, and sulfur. All models included phases for anhydrite, calcite, celestite, dolomite, halite, carbon dioxide, and dissolved oxygen; anhydrite and halite phases were only allowed to dissolve (no precipitation). The inverse modeling results are valid within the constraints of available thermodynamic, chemical, and mineralogical data. The composition of the sample collected from site Q15 (fig. 4) was used to represent upgradient Edwards-Trinity groundwater recharged in the Barilla and Davis Mountains. Water from site Q15 is a dilute (specific conductance 331 microsiemens per centimeter at 25 degrees Celsius [μS/cm]) calcium-sodium-bicarbonate (Ca-Na-HCO3) type water with a composition indicative of interaction with igneous rocks. The composition of the sample collected from site Q8 (fig. 4) was used to represent upgradient Edwards-Trinity groundwater recharged in the Glass Mountains. Water from site Q8 is a dilute (specific conductance 587 μS/cm) sodium bicarbonate (Na-HCO3) type water with a composition indicative of interaction with carbonate rocks. The composition of the sample collected from site Q19 (located within the Leon-Belding area, fig. 4) was used to represent Rustler groundwater in the Leon-Belding area, and the composition of the sample collected from site Q29 (located within the Fort Stockton area, fig. 4) was used to represent Rustler groundwater in the Fort Stockton area. Sites Q19 and Q29 are hypothesized to be representative of Rustler groundwater in the Leon-Belding and Fort Stockton areas, respectively.

Geochemical model results indicate that Edwards Trinity groundwater in the Leon-Belding and Fort Stockton areas is a mixture of groundwater recharged in the Barilla and Davis Mountains and groundwater that has upwelled from the Rustler aquifer (table 4). In the Leon-Belding area, the proportion of Rustler groundwater in the Edwards-Trinity aquifer increased downgradient from south (site Q16; 0 to 48.8 percent) to north (site Q24; 87.1 to 100 percent) (fig. 4, table 4). Likewise, geochemical modeling indicates that as much as 40.7 percent of the water in the Edwards-Trinity aquifer in the area of Comanche Springs is from the Rustler aquifer. This is similar to groundwater-flow model results that indicate approximately 55 percent of the water in the simulated spring flow in the early part of the simulation period is from the Rustler aquifer, which was determined from the amount of water moving upward through the Dockum layer into model cells containing the SFR.

Bumgarner and others (2012) observed a groundwater divide that originates in the southern part of the Leon-Belding area and extends northward along the center of Monument Draw Trough (figs. 1 and 12) and hypothesized that the divide was related to upwelling of water from deeper aquifers. Results of the geochemical modeling support that hypothesis. Geochemical modeling results also indicate that no proportion of groundwater from the six sites in the Leon-Belding and Fort Stockton areas originated as recharge in the Glass Mountains (table 4). These six sites (fig. 4) are located on or to the west of the groundwater divide (fig. 12); thus, groundwater in the Edwards-Trinity aquifer that originated as recharge in the Glass Mountains flows to the east of this groundwater divide. This geochemical result differs from that of the groundwater-flow model, which simulates that part of the recharge may have originated near the Glass Mountains about halfway between sites Q16 and Q8. The groundwater-flow and geochemical

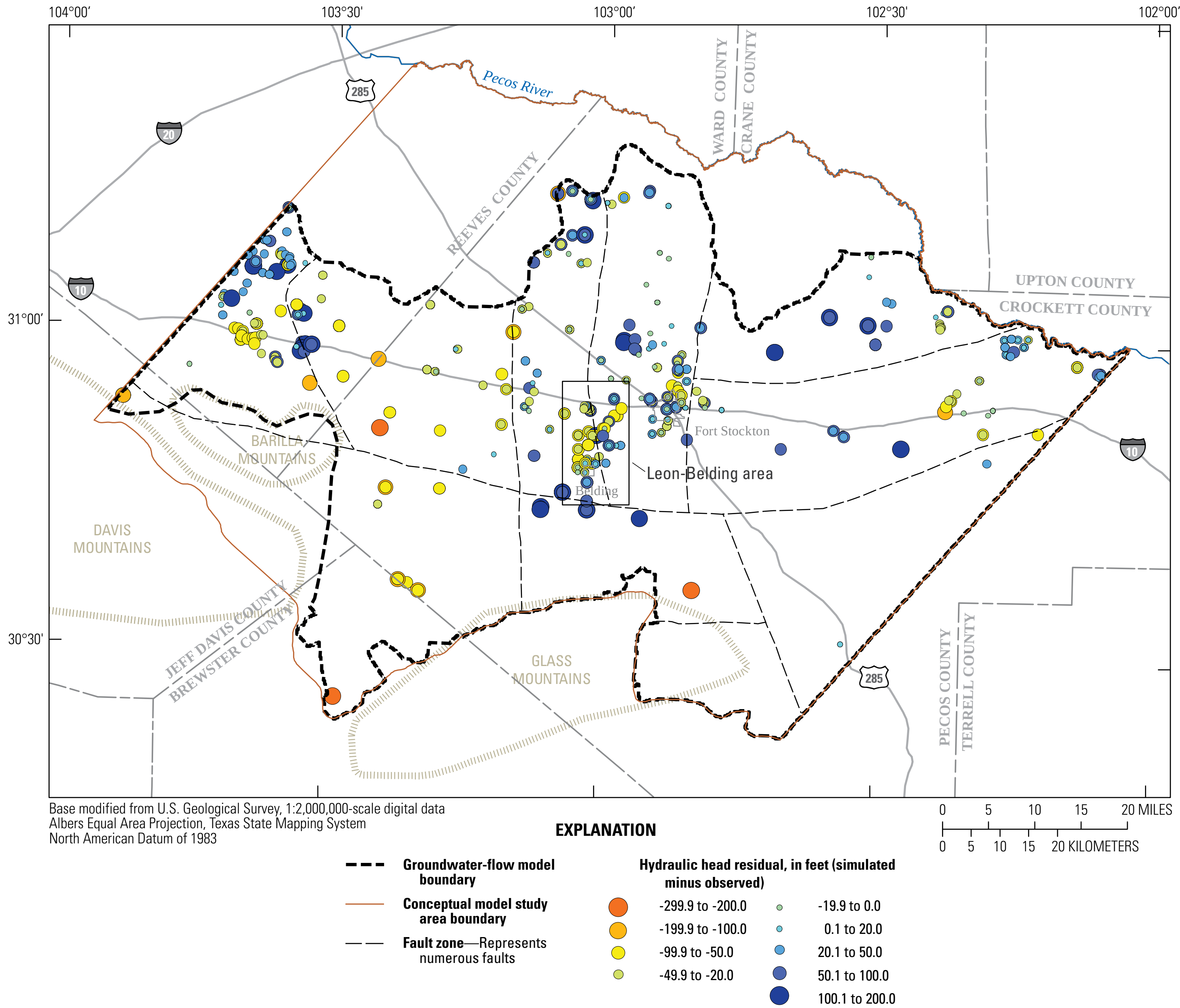


Figure 16. Spatial distribution of hydraulic-head residuals after 1940 in the Edwards-Trinity aquifer in the Pecos County region model area, Texas.

Table 4. Summary of PHREEQC inverse modeling (Parkhurst and Appelo, 1999) results in the Leon-Belding and Fort Stockton areas in the Pecos County region model area, Texas.

[Well locations are shown on figure 4 and described in appendix 3 (modified from Bumgarner and others, 2012)]

Target well	Model results indicating the proportion of groundwater that originated as recharge (percent)		
Site identifier	Site Q15 (Barilla/Davis Mountains)	Site Q8 (Glass Mountains)	Site Q19 (Rustler)
Q16	51.2–100.0	0.0	0.0–48.8
Q18	14.5	0.0	85.5
Q22	10.2	0.0	89.8
Q24	0.0–12.9	0.0	87.1–100.0
	Site Q15 (Barilla/Davis Mountains)	Site Q8 (Glass Mountains)	Site Q29 (Rustler)
Q23	67.3–100.0	0.0	0.0–32.7
Q26	59.3–100.0	0.0	0.0–40.7

models also required similar recharge amounts from the underlying hydrogeologic units. Attempts to exclude this source of recharge from the models resulted in an unsuccessful fit to the observed data.

Groundwater-Flow Budget

The groundwater-flow budget of the Pecos Valley and Edwards-Trinity aquifers indicates changes in flow into (inflows) and out of (outflows) the model area from 1940 to 2010 (fig . 17). Negative rates indicate outflows from the groundwater system, and positive rates indicate inflows to the groundwater system. Total flow (sum of inflows or outflows) through the Pecos Valley and Edwards-Trinity aquifers in the model area ranged from about 613 Mgal/d in predevelopment to over 1,100 Mgal/d during the highest pumping of the 1950s. This increase in simulated flow through the simulated period reflects increases in pumping and inflow compared to the predevelopment condition. Total inflow consists of three primary net inflows to the model listed from smallest to largest: net recharge, storage, and upwelling from the Dockum and Rustler aquifers. Total outflow consists of two primary net discharges or outflows: head dependent boundaries (horizontal flow at the edge of the model perimeter) and pumping. The pumping from wells represents the largest outflow component with a net rate of approximately 600 Mgal/d in the 1950s

Model Limitations

An understanding of model limitations is essential to effectively use groundwater-flow and hydraulic-head simulation results (Reilly and Harbaugh, 2004). The accuracy of a groundwater model is limited by simplification of complexities within the groundwater-flow system (conceptual model), space and time discretization effects, assumptions made in the formulation of the governing flow equations, and simplifications of representations of boundary conditions and discretization and representation of climate. Model accuracy also is affected by cell size, number of layers, accuracy of boundary conditions, accuracy and availability of hydraulic property data, accuracy of withdrawal and areal recharge estimates, historical data for calibration, parameter sensitivity, and the interpolations and extrapolations that are inherent in using data in a model (Reilly and Harbaugh, 2004). The model provides a relatively good fit to groundwater levels in the Leon-Belding and Fort Stockton areas and spring flow from Comanche Springs. However, the finding that simulated spring flow is highly contingent on the transient nature of the underlying hydraulic heads indicates the importance of adequately understanding and characterizing the entire groundwater system.

Although a model might be calibrated, the parameter values likely are not unique in yielding acceptable distributions of hydraulic head. Results of the model must be evaluated while taking into account the resolution of these limitations. The placement and timing of pumping wells in the model, which are dependent on the accuracy of pumping data, play a crucial role in the simulated hydraulic head and flow values. Additionally, data pertaining to wells that are completed through multiple hydrogeologic units are sometimes incomplete. Though the model is capable of simulating wells open to multiple aquifers, assumptions were made regarding skin friction coefficients and the number of model layers through which wells are screened, which may not be accurate. Additionally, wells are simulated as being at the node (center) of a model cell, which likely is not accurate.

Data regarding predevelopment conditions for hydraulic head are sparse to nonexistent, therefore model calibration to predevelopment conditions is not well constrained. With the exception of the pre-1940s steady-state period and initial and final 3-month stress periods in 1940 and 2010, respectively, temporal discretization of the model is based on a 6-month irrigation/nonirrigation period. Each stress period incorporates average input values for pumping and boundary heads for the given time interval. Groundwater flow from underlying or adjacent aquifer systems is not well defined, though geochemical data provide evidence for interaction from underlying units. The model framework, which includes the altitude and thickness of hydrogeologic units, is based on available geophysical information that varies spatially and vertically throughout the model area.

Areas of sparse geophysical information might affect model results through assumptions in the altitude and thickness of these hydrogeologic units and the lack of definition of structural controls such as faults that might affect groundwater movement. The assumptions of a no-flow boundary beneath the Rustler aquifer and constant density of water may not be entirely valid. However, the assumption of constant density is thought to be adequate because salinity differences were probably not great enough to result in variable density-driven flow.

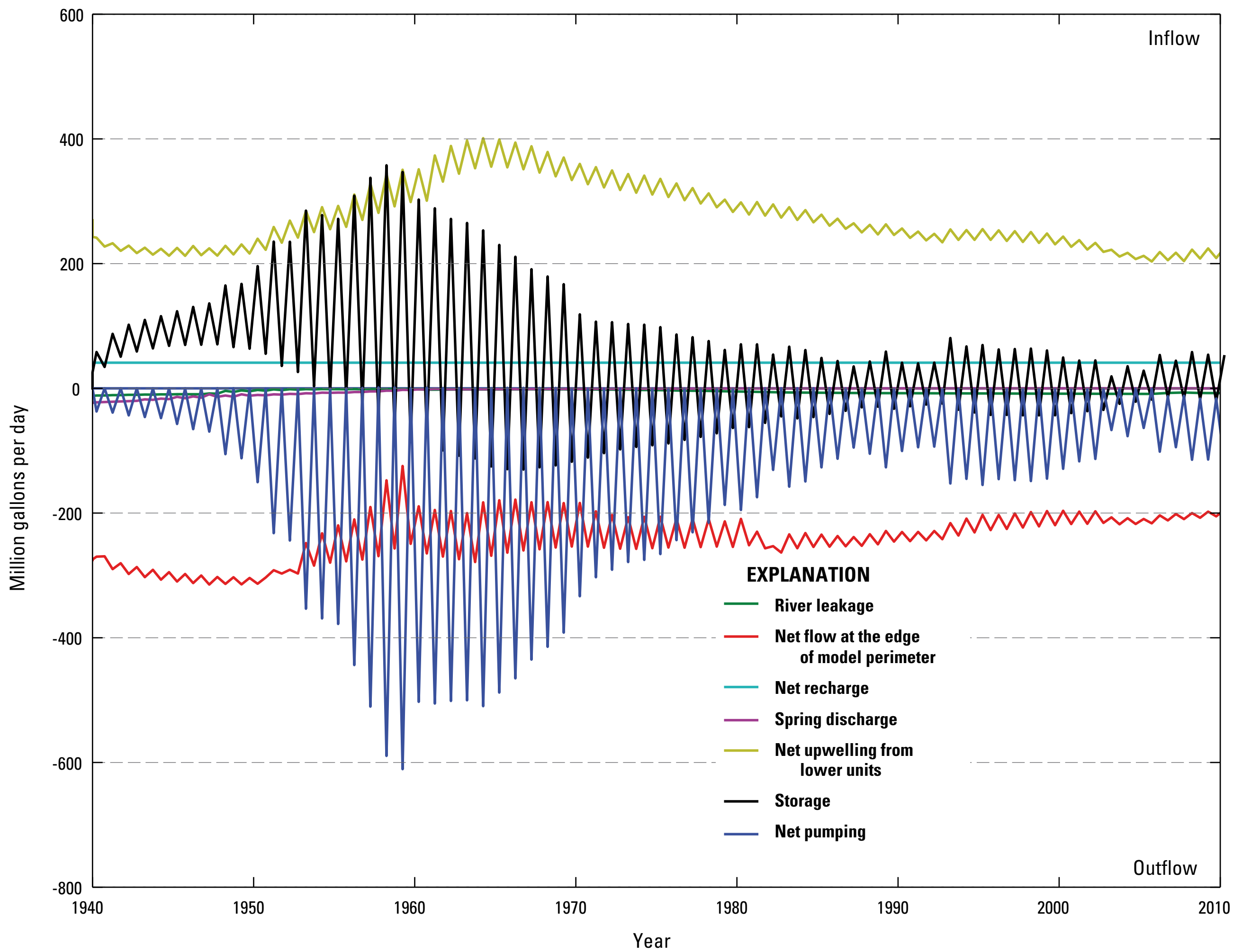


Figure 17. Net simulated groundwater flow from 1940 to 2010 in the Pecos Valley and Edwards-Trinity aquifers in the Pecos County region model area, Texas.

Because of numerical instability, sparse observation data, and little information regarding the connection between the Rustler and Trinity layers, the Trinity layer type was specified as confined in the simulation. This means that regardless of the altitude of the simulated groundwater level in the Trinity layer, it would not become dewatered. Specifying this layer type provided for a more stable numerical simulation because transmissivity was calculated as the product of hydraulic conductivity and the total thickness of the layer for any given model cell rather than a variable transmissivity based on a moving water table. Additionally, the storage term remained fixed for each model cell rather than converting from specific storage to a specific yield value when the groundwater level declined below the top of the layer (unconfined conditions). Because of sparse observation data, unsaturated areas within the Trinity layer were not well known. Some indication of unsaturated conditions may be inferred from the potentiometric map developed by Bumgarner and others (2012), taking into account the map's limitations (contour lines are dashed in most areas and missing in some because of a lack of available data). The degree of hydraulic connection between the Rustler and Trinity layers also was not well known. During test simulations late in the calibration, groundwater levels in the Rustler appeared to have a large effect on groundwater levels in the Trinity layer, particularly in areas where Trinity groundwater levels declined below the bottom of the layer. These test simulations also indicated a relative insensitivity to adjustments in model parameters such as hydraulic conductivity and storage in areas where water-level altitudes are below the base of the Trinity layer. This insensitivity indicated that additional characteristics of the system are not well known or represented in the model such as complex geologic structure or upwelling from lower hydrogeologic units. The geologic structure or upwelling from lower hydrogeologic units may have a greater influence on groundwater levels than hydraulic conductivity and storage.

Most of these insensitive areas are in the southern part of the model area along the base of the Glass Mountains and an area near the Reeves-Pecos County line. Because the specified groundwater levels in the Rustler layer were derived from another groundwater simulation (Ewing and others, 2012), few data were available to constrain the groundwater levels and improve the calibration. Additionally, even though groundwater levels may decline below the base of the Trinity layer in some areas, groundwater continues to flow through these model cells. This is important to provide a continuous hydraulic connection that would not be allowed if the layer was specified as convertible (Harbaugh, 2005).

Development of Groundwater Pumping Scenarios

The model can be used to simulate groundwater levels resulting from hypothetical prolonged pumping to evaluate the sustainability of recent (2008) and projected water use. The following scenarios utilized a continuation of the calibrated model to simulate a 30-year period from 2010 to 2040. This 30-year simulation includes a continuation of input conditions of river stage, net recharge, general-head boundaries (GHBs), constant head boundaries, and the appropriate pumping condition for the scenario under evaluation. For each scenario, the change in groundwater level from 2010 to 2040 was extracted from the model for comparison with regard to effects of changes in pumping. For simplicity, each scenario is summarized as:

- Scenario 1 – Simulation of seasonal 2008 pumping with return flow extended from 2010 to 2040;
- Scenario 2 – Simulation of 2008 pumping extended from 2010 to 2040 with the addition of year-round permitted values in the Leon-Belding area with no return flow; and
- Scenario 3 – Identical pumping as in scenario 2, with increases of 5 percent pumping every 10 years between 2010 and 2040 for every well with no return flow.

Simulations of prolonged pumping provide insight to system response using an extension of recent (2008) pumping (scenario 1), recent pumping with year-round permitted pumping near Leon-Belding (scenario 2), and effects of 5 percent increases in pumping in 10 year increments (scenario 3). While the results of these scenarios are useful in gaining an understanding of the groundwater system as a whole, caution should be used in interpreting the results considering the model limitations described earlier in the "Model Limitations" section.

Scenario 1

Scenario 1 extends recent (2008) irrigation and nonirrigation pumping rates for a 30-year period from 2010 to 2040 represented by 61 stress periods that are each 6 months in length (with the exception of stress period 1). As in the calibration period of the model, the 6-month stress periods continue to represent irrigation (April through September) and nonirrigation (October through March). While recent pumping might not be expected to continue unchanged for the 30-year period, scenario 1 provides a baseline from which to compare additional scenarios where pumping increases in specific areas or increases linearly through time. Return-flow recharge from irrigation is included in scenario 1. Projected groundwater-level changes in and around the Fort Stockton area (fig. 18) indicate little if any change from current conditions indicating that the groundwater system is near equilibrium with respect to recent (2008) pumping stress. Projected groundwater-level declines (from 5.0 to 15.0 ft) in the eastern part of the model area are likely the result of nonequilibrium conditions associated with recent increases in pumping after a prolonged water-level recovery period of little or no pumping. Projected groundwater-level declines (from 15.0 to 31.0 ft) occurred in localized areas by the end of the scenario in the Leon-Belding area. Results of scenario 1 indicate relatively stable water levels ranging from -5.0 to 5.0 ft throughout most of the model area during the 30-year simulation using pumping amounts as specified for the year 2008.

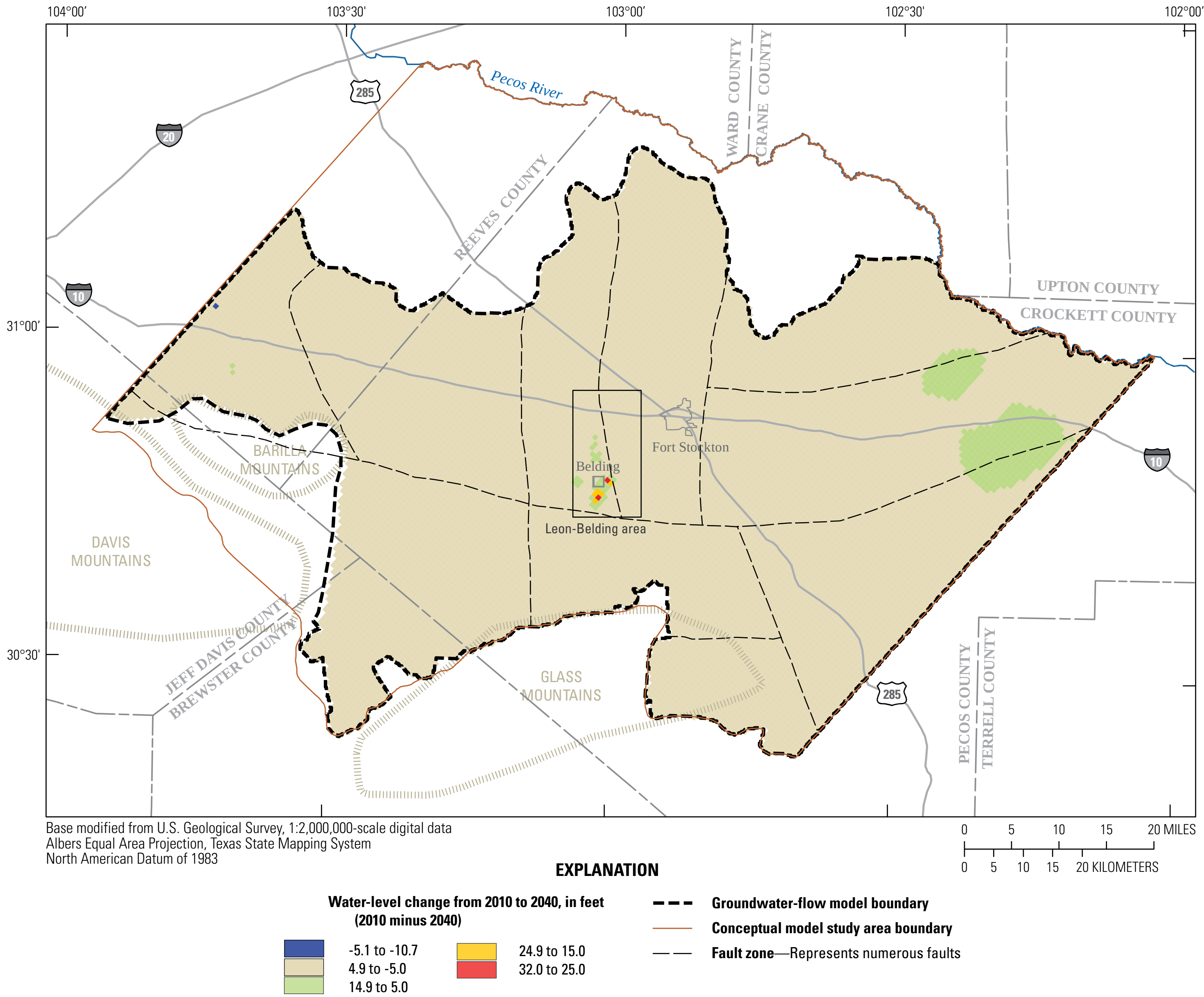


Figure 18. Water-level difference in the Trinity part of the Edwards-Trinity aquifer (Trinity layer) in the Pecos County region model area, Texas, between 2010 and 2040 for scenario 1.

Scenario 2

Scenario 2 evaluates the effects of extended recent (2008) pumping rates as assigned in scenario 1, in addition to year-round maximum permitted pumping rates (about 42 Mgal/d) in the Leon-Belding area. The extended 2008 irrigation and nonirrigation pumping rates are represented as they were in the calibration period reflecting 6-month irrigation and nonirrigation periods, while the recently permitted values were assigned as constant annual pumping for the 30-year period. Return flow recharge from irrigation is not included in scenario 2. Results of scenario 2 (fig. 19) are similar in water-level decline and extent from those of scenario 1 (fig. 18). The extent of the projected groundwater-level decline in the range of 5.0 to 15.0 ft in the Leon-Belding irrigation area expanded slightly (about a 2-percent increase) from that of scenario 1. Maximum projected groundwater-level declines in the Leon-Belding irrigation area were approximately 31.3 ft in small isolated areas, which are depicted as water-level changes ranging from 25.0 to 32.0 in figure 19. The remaining area and magnitude of groundwater-level decline are almost identical to that of scenario 1.

Scenario 3

Scenario 3 evaluates the effects of periodic increases in pumping rates over the 30-year extended period using the same 6-month irrigation and nonirrigation stress periods in scenarios 1 and 2. Groundwater use is predicted to increase approximately 16 percent by 2040 given the projected population growth for Pecos County (Texas Water Development Board, 2013). Based on this projected increase, simulated pumping for all wells was increased by 5 percent every 10 years to account for about a 15-percent increase by the end of the 30-year simulation period. Return-flow recharge from irrigation is not included in scenario 3. Results of scenario 3 are similar to those of scenario 2 in terms of the areas of groundwater-level decline (fig. 20). The maximum projected groundwater-level decline in the Leon-Belding area was greater than scenario 1 or 2 at approximately 34.5 ft, and the extent of the decline is larger in area (about a 17-percent increase) than that of scenario 2. Additionally, the area of projected groundwater-level declines in the eastern part of the model area increased as compared to scenario 2, with two discrete areas of decline coalescing into one larger area. The lack of differences in the remaining areas associated with the results of scenarios 2 and 3 might be attributed to the low magnitude of pumping in 2008 (fig. 17) and the relatively small total increase in water use of about 15 percent over the 30-year period, which together produces small increases in pumping amounts. For example, in 2008, the average pumping rate for wells completed solely in the Trinity layer was approximately 370 gallons per minute (gal/min). After three decades of 5 percent increases, the new average pumping value at the end of the simulation was estimated to be approximately 425 gal/min. This represents an overall increase of 55 gal/min (0.08 million gallons per day), which is a relatively small increase in relation to the total water budget in the simulation of the groundwater system (fig. 17). While projected groundwater-level declines are evident in all scenarios throughout the model area (figs. 18–20), the largest projected groundwater-level declines occurred in localized areas of more intense pumping. The localized nature of the projected groundwater-level declines reflects the secondary porosity of the Edwards-Trinity aquifer. In such a system, groundwater levels that differ by tens or hundreds of feet over relatively short horizontal distances of a few miles are common because of the discontinuity of flow paths and barriers such as faults and fractures. An added complexity is upwelling of groundwater from underlying units, which model results indicate will increase in response to increased pumping in the overlying aquifer units.

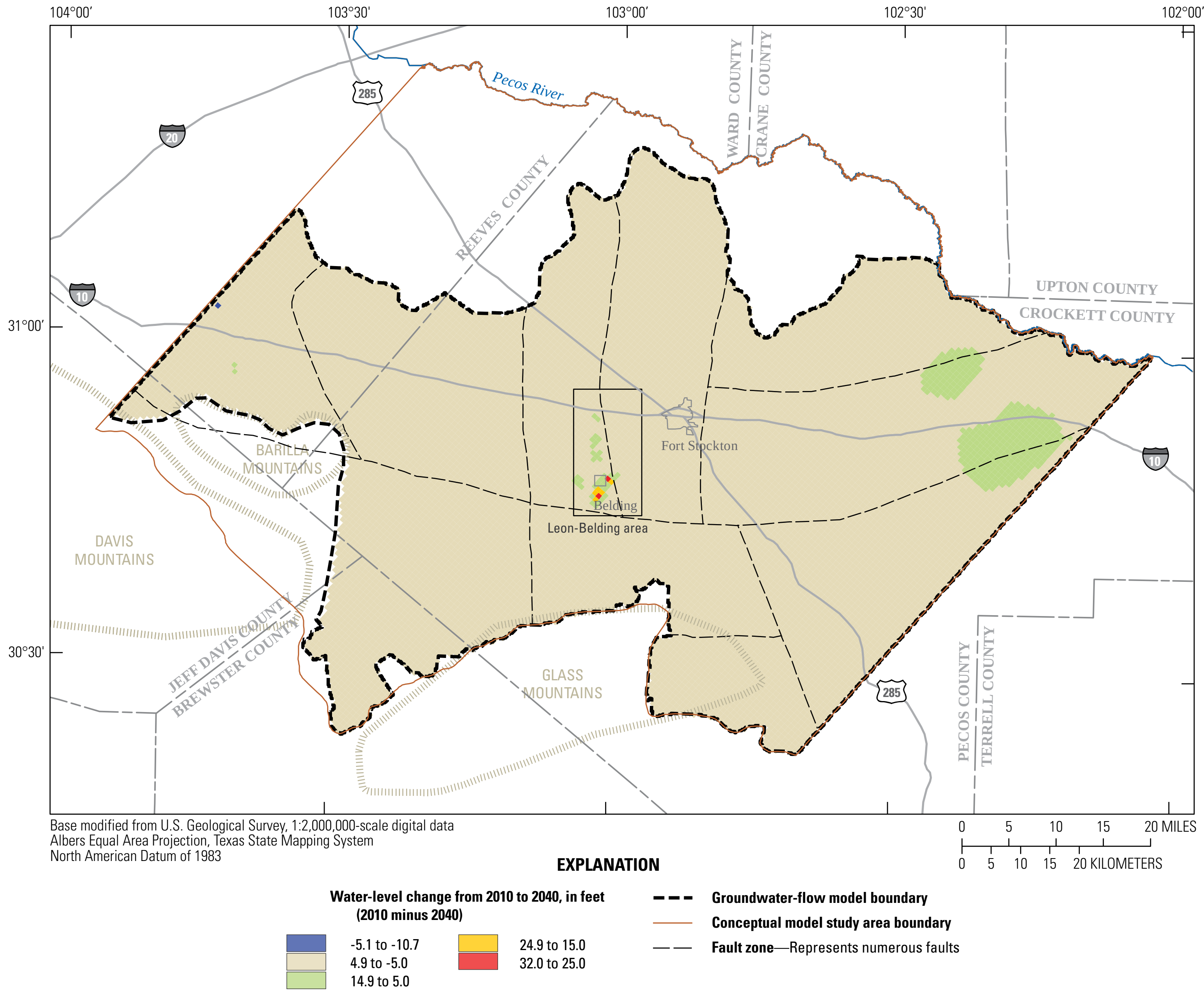


Figure 19. Water-level difference in the Trinity part of the Edwards-Trinity aquifer (Trinity layer) in the Pecos County region model area, Texas, between 2010 and 2040 for scenario 2.

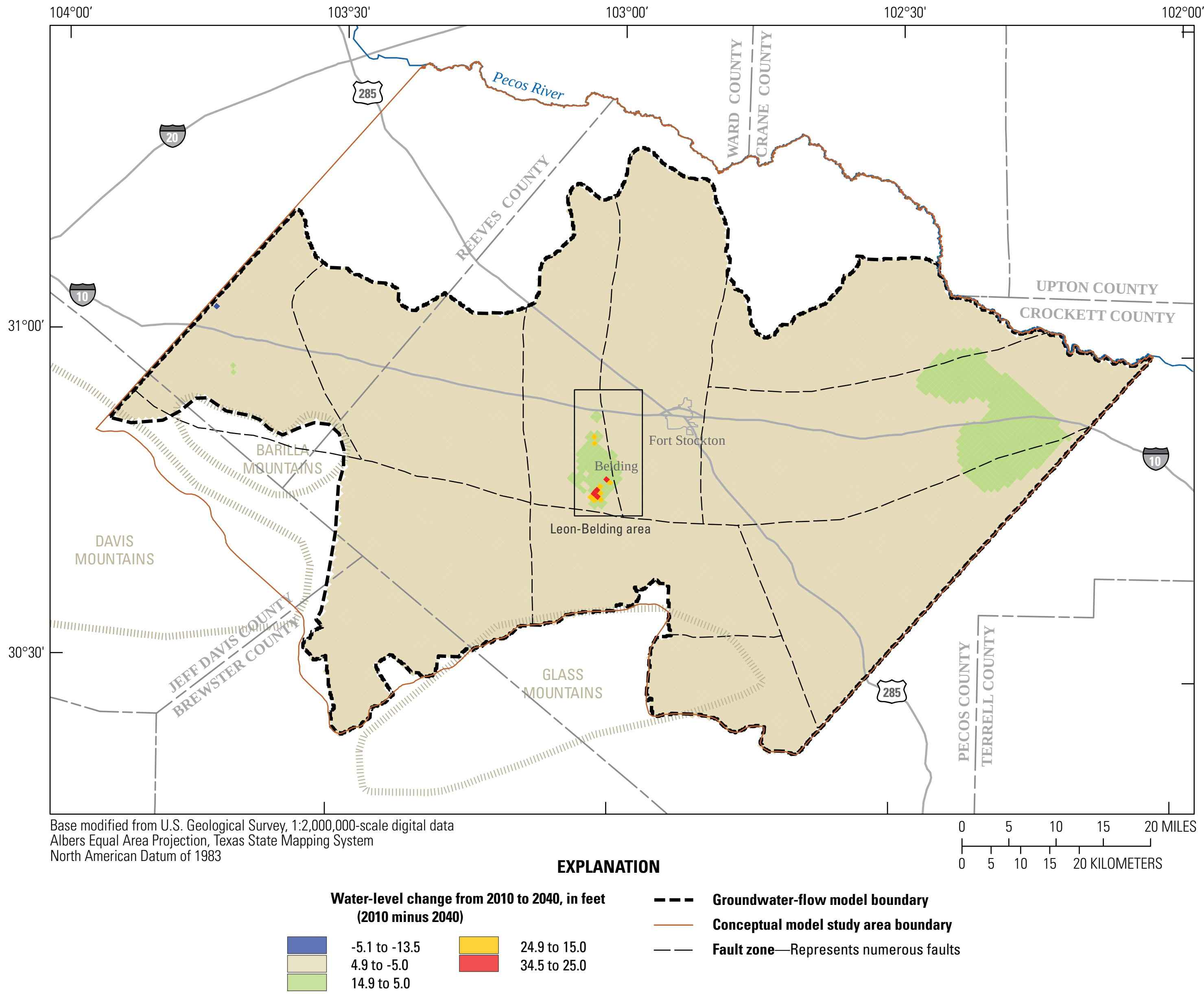


Figure 20. Water-level difference in the Trinity part of the Edwards-Trinity aquifer (Trinity layer) in the Pecos County region model area, Texas, between 2010 and 2040 for scenario 3.

Summary

The Edwards-Trinity aquifer is a vital groundwater resource for agricultural, industrial, and public supply uses in the Pecos County region of west Texas. Resource managers would like to know more about the future availability of water in the aquifer in Pecos County, Texas, and the effects of the possible increase or temporal redistribution of groundwater withdrawals. To provide resource managers with that knowledge, the U.S. Geological Survey, in cooperation with the Middle Pecos Groundwater Conservation District, Pecos County, City of Fort Stockton, Brewster County, and Pecos County Water Control and Improvement District No. 1, completed a comprehensive, integrated analysis of available hydrogeologic data to develop a numerical groundwater-flow model of the Edwards-Trinity and related aquifers in the study area in parts of Brewster, Jeff Davis, Pecos, and Reeves Counties.

The active model area covers about 3,400 square miles of the Pecos County region of Texas west of the Pecos River, and its boundaries were defined to include the saturated areas of the Edwards-Trinity aquifer. The southwestern and southern boundaries of the model area are rimmed by the Barilla and Davis Mountains in northeastern Jeff Davis County and southwestern Reeves County and the Glass Mountains in northeastern Brewster County and southern Pecos County. The northeastern boundary of the model area is the Pecos River.

The modular finite-difference code U.S. Geological Survey MODFLOW-2005 was used to approximate the solution of the equations governing three-dimensional groundwater flow. The model is a five-layer representation of the Pecos Valley aquifer (alluvial layer), the Edwards part of the Edwards-Trinity aquifer (Edwards layer), the Trinity part of the Edwards-Trinity aquifer (Trinity layer), the Dockum aquifer (Dockum layer), and the Rustler aquifer (Rustler layer). The calibration period of the simulation extends from 1940 to 2010 for a total of 70 years and 144 stress periods, each one approximately 6 months in length. The hydrologic boundaries of the model include areal recharge, rivers, no-flow, constant heads, and general-head boundaries. Each boundary was included to represent a specific aspect of the groundwater-flow system. Groundwater pumping in the model represents public supply, manufacturing, mining, and power generation (industrial), and irrigation, with irrigation being the largest water-use category.

Groundwater pumping was compiled from multiple sources to develop a pumping record for the period from 1940 to 2010. Site-specific pumping was used when available, though much of the record for irrigation pumping contained only aggregated amounts of withdrawals by county, aquifer, and year.

Hydraulic properties in the model were assigned through discrete zones (large areas possessing the same property value) and pilot points. The value of each pilot point, as well as other discrete zone parameters, was adjusted through manual and automated methods to achieve a best fit of observed values of hydraulic head and spring flow.

Simulated hydraulic heads were compared to 2,860 measurements from 288 wells in the Edwards-Trinity aquifer within the model area. Simulated hydraulic heads were generally in good agreement with observed hydraulic head values with 1,684 (59 percent) simulated values within 25 feet (ft) of the observed value. The average root mean square error value of hydraulic head for the Edwards-Trinity aquifer for all time periods was 34.2 ft, which was approximately 4 percent of the average total observed changes in groundwater-level altitudes (groundwater levels). Simulated spring flow representing Comanche Springs indicates a similar pattern as compared to the observed spring flow. Independent geochemical modeling corroborates results of simulated groundwater flow that indicates groundwater in the Edwards-Trinity aquifer in the Leon-Belding and Fort Stockton areas is a mixture of recharge from the Barilla and Davis Mountains and groundwater that has upwelled from the Rustler aquifer.

The model was used to simulate groundwater levels resulting from prolonged pumping to evaluate sustainability of current and projected water-use demands. Each of three scenarios utilized a continuation of the calibrated model to simulate a 30-year period from 2010 to 2040.

Scenario 1 extended recent (2008) irrigation and nonirrigation pumping rates for a 30-year period from 2010 to 2040 represented by 61 stress periods that are each approximately 6 months in length. Projected groundwater-level declines (from 5.0 to 15.0 ft) in the eastern part of the model area are likely the result of recent increases in pumping after a prolonged water-level recovery period of little or no pumping. Projected groundwater-level declines (from 15.0 to 31.0 ft) occurred in localized areas by the end of the scenario in the Leon-Belding area. Results of scenario 1 indicate relatively stable water levels ranging from -5.0 to 5.0 ft throughout most of the model area during the 30-year simulation using pumping amounts as specified for the year 2008. Scenario 2 evaluated the effects of extended recent (2008) pumping rates as assigned in scenario 1, with year-round maximum permitted pumping rates in the Leon-Belding area. Results of scenario 2 are similar in water-level decline and extent as those of scenario 1. The extent of the projected groundwater-level decline in the range of 5.0 to 15.0 ft in the Leon-Belding irrigation area expanded slightly from that of scenario 1. Maximum projected groundwater-level declines in the Leon-Belding irrigation area were approximately 31.3 ft in small isolated areas. Scenario 3 evaluated the effects of periodic increases in pumping rates over the 30-year extended period. Results of scenario 3 are similar to scenario 2 in terms of the areas of groundwater-level decline. The maximum projected groundwater-level decline in the Leon-Belding area was greater than scenario 1 or 2 at approximately 34.5 ft, and the extent of the decline is larger in area than that of scenario 2. Additionally, the area of projected groundwater-level declines in the eastern part of the model area increased as compared to scenario 2, with two discrete areas of decline coalescing

into one larger area. While groundwater-level declines are evident in all scenarios throughout the model area, the largest projected groundwater-level declines occur in localized areas of more intense pumping. The localized nature of the projected groundwater-level declines is a reflection of the highly fractured nature of the Edwards-Trinity aquifer. Additionally, the finding that simulated spring flow is highly dependent on the transient nature of the underlying hydraulic heads indicates the importance of adequately understanding and characterizing the entire groundwater system.

References Cited

Anaya, Roberto, and Jones, Ian, 2009, Groundwater availability model for the Edwards-Trinity (Plateau) and Pecos Valley aquifers of Texas: Texas Water Development Board Report 373, 103 p.

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

Armstrong, C.A., and McMillion, L.G., 1961, Geology and ground-water resources of Pecos County, Texas: Texas Board of Water Engineers Bulletin 6106, 536 p.

Audsley, G.L., 1956, Reconnaissance of ground-water development in the Fort Stockton area, Pecos County, Texas: U.S. Geological Survey Open-File Report unnumbered, prepared for the Bureau of Reclamation, U.S. Department of Interior, 68 p.

Barker, R.A., and Ardis, A.F., 1992, Configuration of the base of the Edwards-Trinity aquifer and hydrogeology of the underlying pre-Cretaceous rocks, west-central Texas: U.S. Geological Survey Water-Resources Investigations Report 91–4071, 25 p., 1 pl.

Baumgarner, R.W., Jr., Hoadley, A.D., and Goldstein, A.G., 1982, Formation of the Wink Sink, a salt dissolution and collapse feature, Winkler County, Texas: Bureau of Economic Geology Report of Investigations no. 114, 38 p.

Boghici, Radu, 1997, Hydrogeological investigations at Diamond Y Springs and surrounding area, Pecos County, Texas: Austin, University of Texas, Masters Thesis, 132 p.

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

Brand, J.P., and DeFord, R.K., 1958, Comanchean stratigraphy of Kent quadrangle, Trans-Pecos, Texas: Austin, University of Texas Bulletin 1753, p. 67–172.

Brockwell, P.J., and Davis, R.A., 1989, Time series, Theory and methods: New York, Springer-Verlag, 519 p.

Bumgarner, J.R., Stanton, G.P., Teeple, A.P., Thomas, J.V., Houston, N.A., Payne, J.D., and Musgrove, MaryLynn, 2012, A conceptual model of the hydrogeologic framework, geochemistry, and groundwater-flow system of the Edwards-Trinity and related aquifers in the Pecos County region, Texas: U.S. Geological Survey Scientific Investigations Report 2012–5124, 74 p.

Christian, Brent, and Wuerch, David, 2012, Compilation of results of aquifer tests in Texas: Texas Water Development Board Report 381, 112 p.

Cooley, R.L., and Cunningham, A.B., 1979, Consideration of energy loss in theory of flow to wells: Journal of Hydrology, v. 43, p. 161–184.

Dagan, G., 1986, Statistical theory of groundwater flow and transport—Pore to laboratory to formation, and formation to regional scale: Water Resources Research, v. 22, no. 9, p. 120S–133S.

Daniel B. Stephens and Associates, 2010, City of Fort Stockton groundwater availability analysis—Evaluation of pumping on city wells: Prepared for the City of Fort Stockton, 79 p.

Dante, J.H., 1947, Records of wells and springs in northern Pecos County, Texas: Texas Board of Water Engineers, prepared in cooperation with the U.S. Geological Survey and the Bureau of Reclamation, U.S. Department of the Interior, 90 p.

Doherty, J., 2003, Groundwater model calibration using pilot-points and regularization: Ground Water, v. 41, no. 3, p. 170–177, doi:10.1111/j.1745-6584.2003.tb02580.x.

Doherty, J., 2005, PEST model-independent parameter estimation user manual (5th ed.): Watermark Numerical Computing, accessed March 18, 2013, at http://www.pesthomepage.org/Downloads.php.

Doherty, J., 2011, Groundwater data utilities - Part A: Overview: Watermark Numerical Computing, February 2011, accessed January 21, 2012, at http://www.pesthomepage.org/Downloads.php.

Domenico, P.A., and Mifflin, M.D., 1965, Water from low-permeability sediments and land subsidence: Water Resources Research, v. 1, no. 4, p. 563–576.

Earlougher, R.C., Jr., 1977, Advances in well test analysis: Society of Petroleum Engineers of AIME, Dallas, 264 p.

Environmental Systems Research Institute, 2013, ArcGIS Resources, accessed December 10, 2013, at http://resources.arcgis.com/en/help/main/10.1/index.html#//00qn0000001p00000.

Ewing, J.E., Kelley, V.A., Jones, T.L., Yan, Tingting, Singh, Abhishek, Powers, D.W., Holt, R.M., and Sharp, J.M., 2012, Groundwater availability model report for the Rustler aquifer: Prepared for Texas Water Development Board, March 2012, accessed on August 17, 2012, at http://www.twdb.state.tx.us/groundwater/models/gam/rslr/RSLR_SAF3_Materials.pdf.

Ewing, J.E., Jones, T.L., Yan, T., Vreugdenhil, A.M., Fryar, D.G., Pickens, J.F., Gordon, K., Nicot, J-P., Scanlon, B.R., Ashworth, J.B., and Beach, J., 2008, Groundwater availability model for the Dockum aquifer: Prepared for Texas Water Development Board, 2009, accessed on August 17, 2012, at http://www.twdb.state.tx.us/groundwater/models/gam/dckm/dckm.asp.

Fienen, M.N., Muffles, C.T., and Hunt, R.J., 2009, On constraining pilot point calibration with regularization in PEST: Ground Water, 2009, accessed March 18, 2013, at http://onlinelibrary.wiley.com/doi/10.1111/j.1745-6584.2009.00579.x/full.

Freese and Nichols, Inc., and LBG-Guyton, Inc., 2010, 2011 Region F water plan: Prepared for Region F Water Planning Group, 500 p.

Freeze, R.A., and Cherry, J.A., 1979, Groundwater: Englewood Cliffs, New Jersey, Prentice-Hall, 604 p.

George, P.G., Mace, R.E., and Petrossian, Rima, 2011, Aquifers of Texas: Texas Water Development Board Report 380, 172 p.

Halford, K.J., and Hanson, R.T., 2002, User guide for the drawdown-limited, Multi-Node Well (MNW) package for the U.S. Geological Survey's modular three-dimensional finite-difference ground-water flow model, versions MODFLOW-96 and MODFLOW-2000: U.S. Geological Survey Open-File Report 02–293, 39 p.

Harbaugh, A.W., 2005, MODFLOW-2005, the U.S. Geological Survey modular ground-water model—The ground-water flow process: U.S. Geological Survey Techniques and Methods 6–A16, variously paged.

Heath, R.C., 1983, Basic ground-water hydrology: U.S. Geological Survey Water-Supply Paper 2220, 86 p.

Hill, M.C., 1990, Preconditioned conjugate-gradient 2 (PCG2), a computer program for solving ground-water flow equations: U.S. Geological Survey Water-Resources Investigations Report 90–4048, 43 p.

Hill, M.C., 1992, MODFLOWP, A computer program estimating parameters of a transient, three-dimensional groundwater flow model using nonlinear regression: U.S. Geological Survey Open-File Report 91–484, 358 p.

Hill, M.C., 1998, Methods and guidelines for effective model calibration: U.S. Geological Survey Water-Resources Investigations Report 98–4005, 90 p.

Hill, M.C., Banta, E.R., Harbaugh, A.W., and Anderman, E.R., 2000, MODFLOW-2000, the U.S. Geological Survey modular ground-water model-user guide to the observation, sensitivity, and parameter-estimation processes and three post-processing programs: U.S. Geological Survey Open-File Report 00–184, 209 p.

Hill, M.C., and Tiedeman, C.R., 2007, Effective groundwater model calibration: Hoboken, New Jersey, Wiley, 455 p.

Hood, J.W., and Knowles, D.B., 1952, Summary of groundwater development in the Pecos area, Reeves and Ward Counties, Texas 1947–51: Texas Board of Water Engineers Bulletin 5202, 13 p.

Hunt, R.J., Doherty, J., and Tonkin, M.J., 2007, Are models too simple? Arguments for increased parameterization: Ground Water, v. 45, no. 3, p. 254–262.

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

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, 46 p.

LBG-Guyton, Inc., 2003, Brackish groundwater manual for Texas regional water planning groups: Prepared for the Texas Water Development Board, 188 p.

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

Maclay, R.W., and Small, T.A., 1983, Hydrostratigraphic subdivisions and fault barriers of the Edwards aquifer, south-central Texas, U.S.A.: Journal of Hydrology, v. 61, p. 127–146.

Meyers, J.E., Wise, M.R., and Kalaswad, Sanjeev, 2011, Pecos Valley aquifer, west Texas—Structure and brackish groundwater: Texas Water Development Board Brackish Resources Aquifer Characterization System (BRACS), 92 p.

National Oceanic and Atmospheric Administration, 2013, National Weather Service Forecast Office Midland/Odessa—Fort Stockton Cooperative Precipitation 1940–2013, accessed November 5, 2013, at http://www.srh.weather.gov/maf/?n=cli_maf_coop_annprecip_fort_stockton.

Niswonger, R.G., and Prudic, D.E., 2005, Documentation of the Streamflow-Routing (SFR2) Package to include unsaturated flow beneath streams – A modification to SFR1: U.S. Geological Survey Techniques and Methods 6–A13, 48 p.

Ogilbee, William, Wesselman, J.B., and Irelan, Burdge, 1962, Geology and groundwater resources of Reeves County, Texas: Texas Water Commission Bulletin 6214, v. 1,193 p.

Parkhurst, D.L., and Appelo, C.A.J., 1999, User's guide to PHREEQC (version 2) —A computer program for speciation, batch-reaction, one-dimensional transport, and inverse geochemical calculations: U.S. Geological Survey Water-Resources Investigations Report 99–4259, 312 p.

Pearson, D.K., Bumgarner, J.R., Houston, N.A., Stanton, G.P., Teeple, A.P., and Thomas, J.V., 2012, Data collection and compilation for a geodatabase of groundwater, surface-water, water-quality, geophysical, and geologic data, Pecos County region, Texas, 1930–2011: U.S. Geological Survey Data Series 678, 67 p.

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

Reilly, T.E., and Harbaugh, A.W., 2004, Guidelines for evaluating ground-water flow models: U.S. Geological Survey Scientific Investigations Report 2004–5038, 30 p.

Sharp, J.M., Uliana, M.M., and Boghici, Radu, 1999, Fracture controls on regional groundwater flow in a semiarid environment and implications for long-term maintenance of spring flows: Water 99 Joint Congress, Institution of Engineers, Brisbane, Australia, v. 2, p. 1212–1217.

Sharp, J.R., 2001, Regional groundwater flow systems in Trans-Pecos, Texas, *in* Mace, R.E., Mullican, W.F., III, Angle, E.S., eds., Aquifers of west Texas: Texas Water Development Board Report 356, p. 41–55.

Small, T.A., and Ozuna, G.B., 1993, Ground-water conditions in Pecos County, Texas, 1987: U.S. Geological Survey Water-Resources Investigations Report 92–4190, 68 p.

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: Austin, Texas, Bureau of Economic Geology, The University of Texas at Austin, 39 p.

Texas Parks and Wildlife Department, 2012, Comanche Springs pupfish (*Cyprinodon elegans*): accessed May 10, 2012, at http://www.tpwd.state.tx.us/huntwild/wild/species/comanchespringspupfish/.

Texas Water Development Board, 1972, A survey of the subsurface saline water of Texas: Texas Water Development Board Report 157, 113 p.

Texas Water Development Board, 1986, Surveys of irrigation in Texas, 1958, 1964, 1969, 1974, 1979, and 1984: Texas Water Development Board Report 294, 110 p.

Texas Water Development Board, 2001, Surveys of irrigation in Texas, 1958, 1964, 1969, 1974, 1979, and 1984, 2000: Texas Water Development Board Report 347, 102 p.

Texas Water Development Board, 2005, Diminished spring flows in the San Solomon Springs System, Trans-Pecos, Texas: Report to the Texas Parks and Wildlife Department, Section 6 Endangered Species Grant Number WER69, Study Number 84312, submitted May 2005, 121 p.

Texas Water Development Board, 2012a, Groundwater database reports: Texas Water Development Board, accessed December 2012, at http://www.twdb.state.tx.us/groundwater/data/gwdbrpt.asp.

Texas Water Development Board, 2012b, Historical water-use information database: Texas Water Development Board, accessed September 2012, at http://www.twdb.state.tx.us/waterplanning/waterusesurvey/estimates/index.asp.

Texas Water Development Board, 2013, 2011 regional water plan, accessed June 6, 2013, at http://www.twdb.state.tx.us/waterplanning/data/projections/2012/doc/Population/PopulationByRWPG/4PopulationF.pdf.

Thomas, H.E., and others, 1963, Drought in the Southwest, 1942–56—Effects of drought in central and south Texas: U.S. Geological Survey Professional Paper 372–C, 31 p.

Thornhill Group, Inc., 2008, Edwards-Trinity aquifer study Leon-Belding area: Prepared for Clayton Williams Farms, Inc., 80 p.

Tikhonov, A.N., 1963, Solution of incorrectly formulated problems and the regularization method: Soviet Mathematics, Doklady, v. 4, p. 1035–1038.

Tonkin, M.J., and Doherty, J., 2005, A hybrid regularized inversion methodology for highly parameterized environmental models: Water Resources Research, v. 41, no. 10, p. 1–16.

Veni, George, 1991, Delineation and preliminary hydrogeologic investigations of the Diamond Y Spring, Pecos County, Texas: Report to the Nature Conservancy of Texas, 110 p.

Appendixes 1–3

Appendix 1. Wells completed in the Edwards-Trinity aquifer providing observed hydraulic head data in the Pecos County region model area, Texas, 1940–2010.

[TWDB, Texas Water Development Board]

Map identifier (fig. 3)	TWDB well number	Source station number[1]	Latitude (decimal degrees)	Longitude (decimal degrees)	Period of data collected used for model calibration
A	5302708	305234102504301	30.87618	102.84521	1950–2008
B	5309301	305110102533401	30.85286	102.89278	1956–2008
C	4656301	4656301	31.21583	103.03389	1961–2008
D	4557603	4557603	31.05667	102.90722	1973–2009
E	4656201	311340103040101	31.22792	103.06766	1958–2008
F	5309105	5309105	30.84528	102.99917	1957–2008
G	5302102	5301102	30.99222	102.96583	1947–1997

[1]Bumgarner and others (2012, table 9).

Appendix 2. Amount of pumping in 2008 by county, category, and aquifer in the Pecos County region, Texas.

County	Category	Aquifer	Amount (million gallons per day)	Number of wells
Pecos	Domestic/livestock[1]	Edwards-Trinity	11.28	34
Pecos	Domestic/livestock[1]	Pecos Valley	4.99	9
Pecos	Domestic/livestock[1]	Rustler	1.08	2
Pecos	Irrigation	Edwards-Trinity	46.66	101
Pecos	Irrigation	Pecos Valley	21.18	106
Pecos	Irrigation	Rustler	12.22	18
Pecos	Municipal, industrial, mining	Edwards-Trinity	0.97	31
Pecos	Municipal, industrial, mining	Pecos Valley	0.01	1
Pecos	Municipal, industrial, mining	Rustler	0.18	11
Pecos	Unknown	Edwards-Trinity	20.93	38
Pecos	Unknown	Pecos Valley	4.82	11
Pecos	Unknown	Rustler	0.22	4
Reeves	Irrigation	Edwards-Trinity	0.93	12
Reeves	Irrigation	Pecos Valley	6.62	7

[1]Discrepancy in records indicates values could be largely attributed to irrigation.

Appendix 3. Data-collection sites providing data for the geochemical analysis in the Pecos County region, Texas.

[Modified from Bumgarner and others (2012, table 5). USGS, U.S. Geological Survey; –, not applicable]

Site identifier (fig. 4)	USGS station name	State well number	USGS station number	Latitude (decimal degrees)	Longitude (decimal degrees)	Site type	Contributing aquifer
Q1	San Solomon Spring	–	08427500	30.94292	103.78824	Spring	–
Q2	Santa Rosa Spring	–	08437000	31.26743	102.95828	Spring	–
Q4	Comanche Springs	–	08444500	30.88628	102.87495	Spring	–
Q6	Diamond Y Spring	–	08446600	31.00190	102.92358	Spring	–
Q27	PS-52-02-404	PS-52-02-404	305502103504101	30.91737	103.84518	Well	Pecos Valley
Q36	WD-46-62-201	WD-46-62-201	310625103175201	31.10685	103.29777	Well	Pecos Valley
Q42	US-45-43-807	US-45-43-807	311602102400601	31.26942	102.67609	Well	Pecos Valley
Q43	US-45-43-8xx (PA 1)[1]	US-45-43-8xx	311602102400901	31.26934	102.68214	Well	Pecos Valley
Q15	PS-52-11-702	PS-52-11-702	304605103444601	30.77100	103.74800	Well	Igneous
Q7	PS-52-34-303	–	302955103451101	30.49860	103.75300	Well	Igneous
Q11	US-52-22-8xx (Farm Well 3)[1]	US-52-22-8xx	303941103175001	30.66139	103.29720	Well	Edwards-Trinity
Q12	PS-52-20-601	PS-52-20-601	304006103315601	30.66827	103.53216	Well	Edwards-Trinity
Q14	US-53-17-501	US-53-17-501	304117102560101	30.68806	102.93361	Well	Edwards-Trinity
Q16	US-52-16-910	US-52-16-910	304646103013401	30.77931	103.02615	Well	Edwards-Trinity
Q17	US-52-13-801	US-52-13-801	304715103263501	30.78740	103.44343	Well	Edwards-Trinity
Q18	US-52-16-611	US-52-16-611	304802103003901	30.80088	103.01110	Well	Edwards-Trinity
Q22	US-52-16-3xx (S-21)[1]	US-52-16-3xx	305132103015701	30.85899	103.03244	Well	Edwards-Trinity
Q23	US-53-09-306	US-53-09-306	305140102521101	30.87393	102.88229	Well	Edwards-Trinity
Q24	US-52-08-909	US-52-08-909	305331103020501	30.89210	103.03516	Well	Edwards-Trinity
Q25	US-53-03-9xx	US-53-03-9xx	305354102373501	30.89825	102.62647	Well	Edwards-Trinity
Q26	US-53-01-907	US-53-01-907	305419102545301	30.90560	102.91610	Well	Edwards-Trinity
Q28	PS-52-02-4xx (Balmorhea)[1]	PS-52-02-4xx	305509103510101	30.91911	103.85027	Well	Edwards-Trinity
Q30	WD-52-02-507	WD-52-02-507	305531103474201	30.92539	103.79511	Well	Edwards-Trinity
Q32	US-53-07-105	US-53-07-105	305836102131701	30.97667	102.22139	Well	Edwards-Trinity
Q33	US-53-01-210	US-53-01-210	305859102571001	30.98293	102.95271	Well	Edwards-Trinity
Q35	US-45-60-903	US-45-60-903	310136102311601	31.02670	102.52102	Well	Edwards-Trinity
Q37	US-45-58-2xx	US-45-58-2xx	310718102484801	31.12162	102.81354	Well	Edwards-Trinity
Q40	US-46-56-309	US-46-56-309	311235103000901	31.20974	103.00262	Well	Edwards-Trinity
Q8	BK-52-29-8xx (Brewster County Edwards-Trinity Well)[1]	BK-52-29-8xx	303222103263701	30.53950	103.44346	Well	Edwards-Trinity
Q9	US-52-07-502	US-52-07-502	303342103064001	30.93779	103.18711	Well	Edwards-Trinity
Q21	US-53-13-208	US-53-13-208	305112102265901	30.85341	102.44965	Well	Dockum
Q31	US-52-06-603	US-52-06-603	305559103154101	30.93305	103.26194	Well	Dockum
Q34	US-53-01-208	US-53-01-208	305949102552301	30.99718	102.92291	Well	Dockum
Q39	US-46-55-9xx (Weatherby Ranch)[1]	US-46-55-9xx	310949103090401	31.16341	103.15103	Well	Dockum
Q44	US-46-48-701	US-46-48-701	311610103050901	31.26959	103.08683	Well	Dockum
Q10	US-53-19-7xx (PC QW)[1]	US-53-19-7xx	303852102432902	30.64799	102.72470	Well	Rustler
Q13	US-52-24-501	US-52-24-501	304020103025202	30.67295	103.05601	Well	Rustler
Q19	US-52-16-609	US-52-16-609	304805103013301	30.80129	103.02618	Well	Rustler
Q29	US-53-01-5xx (Apache 3)[1]	US-53-01-5xx	305529102560601	30.92470	102.93490	Well	Rustler
Q38	WD-46-54-901	WD-46-54-901	310806103171901	31.13502	103.28796	Well	Rustler
Q20	US-52-16-504	US-52-16-504	304807103025301	30.80241	103.04844	Well	Capitan Reef
Q41	US-45-49-203	US-45-49-203	311422102555101	31.23974	102.93097	Well	Capitan Reef

[1]Local well name.

Publishing support provided by
Lafayette and Tacoma Publishing Service Centers

Information regarding water resources in Texas is available at
http://tx.usgs.gov/

USGS

Clark and others—**Simulation of Groundwater Flow in the Edwards-Trinity and Related Aquifers in the Pecos County Region, Texas**—SIR 2013–5228 ver. 1.1

ISBN 978-9781-4113-0-4

ISSN 2328-0328 (online)
ISSN 2328-031X (print)
http://doi.dx.org/10.3133/sir20135228

Printed on recycled paper