Hydrogeologic Setting and Groundwater-Flow Simulations of the South-Central Texas Regional Study Area, Texas

By Richard J. Lindgren, Natalie A. Houston, MaryLynn Musgrove,
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Section 3 of

Hydrogeologic Settings and Groundwater-Flow Simulations for Regional Investigations of the Transport of Anthropogenic and Natural Contaminants to Public-Supply Wells— Investigations Begun in 2004

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Abstract

The transport of anthropogenic and natural contaminants to public-supply wells was evaluated for part of the Edwards aquifer in south-central Texas as part of the U.S. Geological Survey National Water-Quality Assessment Program. The Edwards aquifer in the South-Central Texas regional study area is used extensively for public-water supply, is a source of water to major springs, and is susceptible and vulnerable to contamination. The Edwards aquifer is part of an aquifer system developed in thick and regionally extensive Lower Cretaceous carbonates that underlie large areas of Texas. The carbonates in the Edwards aquifer are laterally and vertically heterogeneous. Groundwater flow and aquifer properties of the Edwards aquifer in the study area are appreciably affected by the presence of faults and karst dissolution features.

Existing one-layer, steady-state and transient groundwater-flow models of the Edwards aquifer in the study area were modified to include a finer model grid and one additional layer. The original Edwards aquifer models had been calibrated for two hydraulic conductivity distributions, one representing predominantly conduit flow in the aquifer and the other representing predominantly matrix (diffuse) flow through a network of numerous small fractures and openings. The conduit-flow and diffuse-flow rediscretized regional Edwards aquifer models were recalibrated for steady-state conditions during 2001, a representative year for the recent time period, and transient conditions during 2000–03. The calibrated rediscretized regional Edwards aquifer models and advective particle-tracking simulations were used to compute groundwater-flow paths, areas contributing recharge, and traveltimes from recharge areas for public-supply wells.

Model results from the steady-state simulation indicate recharge from precipitation, about 96 percent of inflow, provides most of the groundwater inflow. The steady-state simulation indicates that about 54 percent of groundwater discharge is to springflow and about 46 percent is to withdrawals by wells. Particle-tracking results indicate minimum computed traveltimes to public-supply wells varied from less than one to 987 years and maximum computed traveltimes ranged from 9 to 5,263 years. The average computed traveltime of 276 years to public-supply wells was greater for the conduit-flow rediscretized regional Edwards aquifer model than the 191 years computed for the diffuse-flow rediscretized regional Edwards aquifer model. For the conduit-flow rediscretized regional Edwards aquifer model, on average, only about 1.3 percent of the flow to a public-supply well was less than 10 years old, about 17 percent of the flow to a public-supply well was less than 50 years old, and about 52 percent of the flow to a public-supply well was less than 200 years old. The corresponding percentages for the diffuse-flow rediscretized regional Edwards aquifer model were greater, 1.9, 24, and 67 percent, respectively. The computed traveltimes are probably much longer than actual traveltimes in the aquifer, because the regional groundwater-flow models do not accurately represent flow through local karst dissolution features.

Introduction

The South-Central Texas regional study area for the transport of anthropogenic and natural contaminants to public-supply wells (TANC) is within the Edwards-Trinity aquifer system (fig. 3.1). The study area overlies the fractured karstic Edwards aquifer in south-central Texas and includes the San Antonio metropolitan area (fig. 3.2). The South-Central Texas regional study area coincides with the San Antonio and Barton Springs segments of the Edwards aquifer (fig. 3.2). The Edwards-Trinity aquifer system underlies a portion of the South-Central Texas study unit of the U.S. Geological Survey (USGS), National Water-Quality Assessment, and much of west-central and south-central Texas. Vulnerability to contamination and the dependence of more than 1.5 million people on the aquifer for public water supply combine to make the water quality of the Edwards aquifer and the streams that recharge it a critical issue for the future of the Greater San Antonio Area, as well as the larger San Antonio region, which for the purposes of this report approximately coincides with the extent of the San Antonio and Barton Springs segments of the Edwards aquifer.

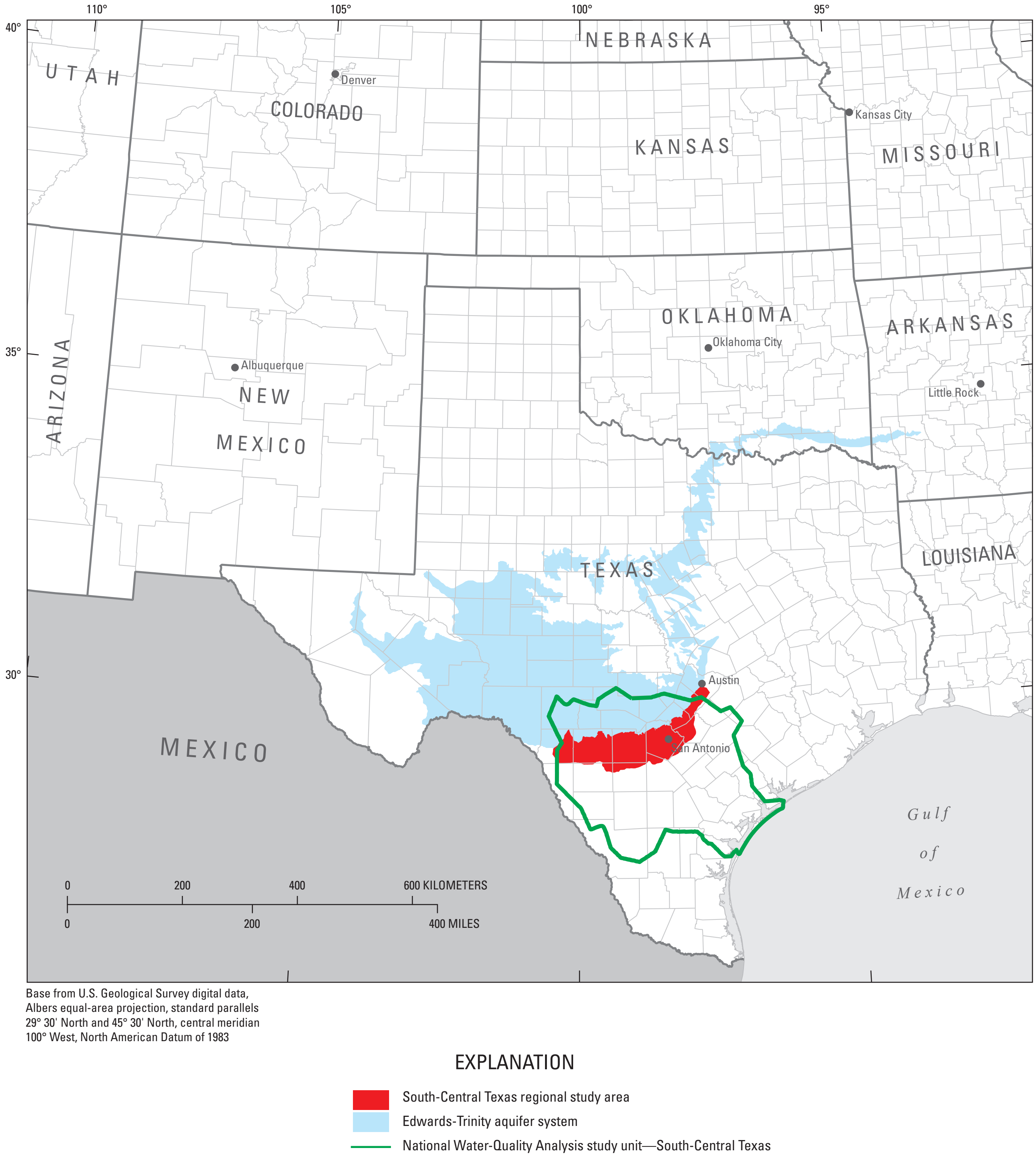
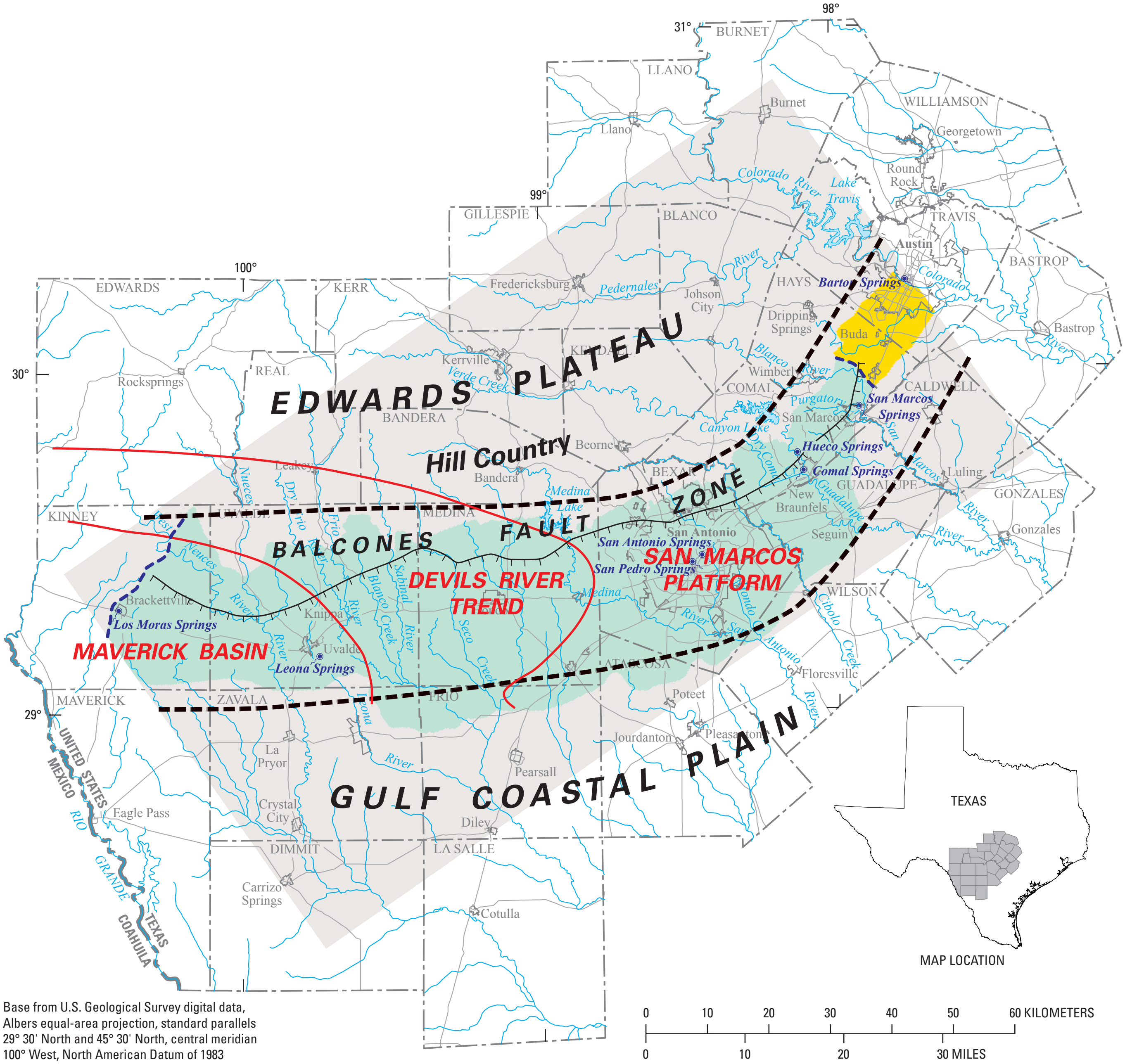


Figure 3.1. Location of the South-Central Texas regional study area within the Edwards-Trinity aquifer system.



EXPLANATION

- South-Central Texas regional study area (coincides with active groundwater-flow model area)
- San Antonio segment
- Barton Springs segment
- Inactive groundwater-flow model area
- Depositional province (modified from Maclay, 1995, fig. 2)
- Boundary of Balcones fault zone
- Balcones escarpment (modified from Abbot and Woodruff, 1986, fig. 1)
- Groundwater divide
- Spring

Figure 3.2. Locations of the groundwater-flow model area for the South-Central Texas regional study, Edwards aquifer segments, and physiographic regions, major groundwater divides and Balcones fault zone, and depositional provinces, San Antonio region, Texas.

Purpose and Scope

The purpose of this Professional Paper section is to present the hydrogeologic setting of the South-Central Texas regional study area. The section also documents the revision and recalibration of regional groundwater-flow models for the study area for steady-state and transient conditions. Groundwater-flow characteristics, pumping-well information, and water-quality data were compiled from existing data to develop a conceptual understanding of groundwater conditions in the study area. Two existing groundwater-flow models of the area with two different horizontal hydraulic-conductivity distributions (Lindgren and others, 2004; Lindgren, 2006) were modified to include a finer model grid and one additional model layer. The models were recalibrated for average conditions during 2001 for the steady-state calibration and were recalibrated for the time period from 2000 to 2003 for the transient calibration. The year 2001 was assumed to be representative of average conditions for the time period from 2000 to 2003, which was the time period selected for data compilation and modeling exercises to facilitate future comparisons between varying TANC regional study areas. The updated groundwater-flow models and associated particle tracking were used to simulate advective groundwater-flow paths and to delineate areas contributing recharge to selected public-supply wells. Groundwater traveltimes from recharge to public-supply wells, oxidation-reduction (redox) conditions along flow paths, and the presence of potential contaminant sources in areas contributing recharge were tabulated into a relational database described in Appendix 1 of Chapter A of this Professional Paper. This section, Section 3 of Chapter B, provides the foundation for future groundwater susceptibility and vulnerability analyses of the study area and comparisons among regional aquifer systems.

Study Area Description

The South-Central Texas regional study area was selected for study because the Edwards aquifer is used extensively for public-water supply and is susceptible and vulnerable to contamination. The aquifer was the first to be designated as a sole source aquifer, defined by the U.S. Environmental Protection Agency (USEPA) as an aquifer that supplies 50 percent or more of the drinking water of an area. The South-Central Texas regional study area also includes a range of hydrogeologic features, including karst features, and land-use conditions within the San Antonio and Barton Springs segments of the Edwards aquifer in south-central Texas (fig. 3.2, table 3.1).

Topography and Climate

The South-Central Texas regional study area includes part of the topographically rugged Edwards Plateau, the eastern part of which locally is called the "Hill Country," and the comparatively flat Gulf Coastal Plain, which are separated by the Balcones escarpment (fig. 3.2). The Balcones escarpment, a surface manifestation of the Balcones fault zone, is a physiographic feature that also separates the Trinity aquifer in the Hill Country from the Edwards aquifer. Land surface altitude ranges from about 137 meters (m) in the eastern part of the study area near the Colorado River to about 594 m in the northwestern part of the study area in the Edwards aquifer recharge zone; topographic relief locally changes dramatically, by hundreds of meters.

The climate in the South-Central Texas regional study area is semiarid in the western part to subtropical humid in the eastern part (Larkin and Bomar, 1983). Average annual rainfall varies from 56 cm at Brackettville in the west to 86 cm at Austin in the east. Months- to years-long droughts that strain water supplies and produce widespread crop failure commonly are followed by wet periods that include torrential rains and flash floods (Bomar, 1994). Storms can produce rapid runoff and recharge to the Edwards aquifer. After many months of drought, in October 1998 more than 381 millimeters of rain fell in a 2-day period on the karstic, unconfined part of the Edwards aquifer (the recharge zone), and even higher rainfall rates were observed in some areas (Slade and Persky, 1999). Groundwater levels in some monitoring wells rose more than 30 m during a 2-week period in response to this storm.

Surface-Water Hydrology

Karst features such as sinkholes, solution enlargement along fractures and bedding planes, caves, and springs are prevalent in the South-Central Texas regional study area. In the recharge zone (outcrop) (fig. 3.3), karst landforms include large shallow, internally drained depressions that are typically tens to hundreds of meters across; depressions of holes in creek bottoms; and small upland features such as sinkholes and solution-enlarged fractures (Hovorka and others, 2004). In addition, more than 400 caves have been inventoried in the Edwards aquifer outcrop (Veni, 1988; Elliott and Veni, 1994).

The South-Central Texas regional study area encompasses the upper parts of the Nueces, San Antonio, and Guadalupe River Basins, as well as part of the Colorado River Basin for the Barton Springs segment (fig. 3.3). Surface water and groundwater in the South-Central Texas regional study area are uniquely interrelated. Springs and seeps discharge

Table 3.1. Summary of hydrogeologic and groundwater-quality characteristics for the Edwards-Trinity aquifer system and the South-Central Texas regional study area, San Antonio region, Texas.

[km, kilometers; m, meters; ºC, degrees Celsius; mm, millimeters; mm/yr, millimeters per year; m/d, meters per day; m^2/d, meters squared per day; m^3/s, cubic meters per second; m^3/d, cubic meters per day; hm^3, cubic hectometers; hm^3/yr, cubic hectometers per year; mg/L, milligrams per liter]

Characteristic	Edwards-Trinity Aquifer System	South-Central Texas regional study area
	Geography	
Topography	Much of the area is characterized by flat to rolling, largely rocky plains that are dissected in places to form steep-walled canyons. Relief locally is tens of meters. Transition from Edwards Plateau to the west and nearly level to gently rolling Gulf Coastal Plain to the east, separated by Balcones escarpment (fig.3.2). Land surface altitude ranges from 1,787 m in west Texas to 64 m in west Arkansas. Karst landforms prevalent in outcrop (recharge zone) (National Hydrography Dataset Plus, 2007).	Topographically rugged and picturesque Edwards Plateau and rolling to hilly Gulf Coastal Plain separated by Balcones escarpment (fig. 3.2); relief locally is hundreds of meters. Land surface altitude ranges from about 137 m in east to 594 m in west. Karst landforms prevalent in outcrop (recharge zone).
Climate	Semiarid in west to subtropical humid in east; average annual precipitation ranges from 279 mm in west Texas to 1,448 mm in western Arkansas. Average annual high temperature ranges from 39.4ºC to 29.4ºC in west Texas. Average annual low temperature ranges from -2.8ºC in west Texas to 5ºC southwest of San Antonio (U.S. Department of Agriculture, 2007).	Semiarid in west to subtropical humid in east; Precipitation 551 mm/yr in west to 851 mm/yr in east.
Surface-water hydrology	In the Edwards plateau region, springs and seeps contribute baseflow to streams that drain the plateau. Major streams that cross the area flow southward and southeastward toward the Gulf Coast. In the southern part of the aquifer system, most of the streams lose their baseflow to the fractured, karstic Edwards formation in the Balcones fault zone (Ryder, 1996).	Includes upper parts of the Nueces, San Antonio, and Guadalupe River Basins, as well as part of the Colorado River Basin for the Barton Springs segment. Most streams lose all of their base flow as recharge to the Edwards aquifer in the Edwards aquifer recharge zone. Comal and San Marcos Springs are the largest springs, with discharges of 10.8 and 7.7 m3/s, respectively (Hamilton and others, 2003).
Land use	Forest and rangeland (81 percent), agriculture (11), urban (6), and water, wetlands, strip mines, and barren (2) (Homer and others, 2004). Major urban cities include San Antonio, Austin, and Dallas-Fort Worth metropolitan areas.	Forest and rangeland (73 percent), agriculture (13), urban (12), and water, wetlands, strip mines, and barren (2) (Homer and others, 2004).
Water use	Total water use in 2000 was estimated to be 2.80 m3/d, of which irrigation was 1.07, public-supply was 1.55, and self-supplied industrial was 0.18. Of the total, 2.76 m3/d was used in Texas, 0.015 in Oklahoma, and 0.025 in Arkansas (Maupin and Barber, 2005).	In 2003, water use from the Edwards aquifer in Atascosa, Bexar, Comal, Hays, Kinney, Medina, Travis and Uvalde Counties was estimated to be 460.7 hm3 (Texas Water Development Board, 2008). Municipal withdrawals accounted for about 70 percent and irrigation accounts for 27 percent; the remaining 3 percent included manufacturing, steam electric, mining and livestock.

Table 3.1. Summary of hydrogeologic and groundwater-quality characteristics for the Edwards-Trinity aquifer system and the South-Central Texas regional study area, San Antonio region, Texas.—Continued

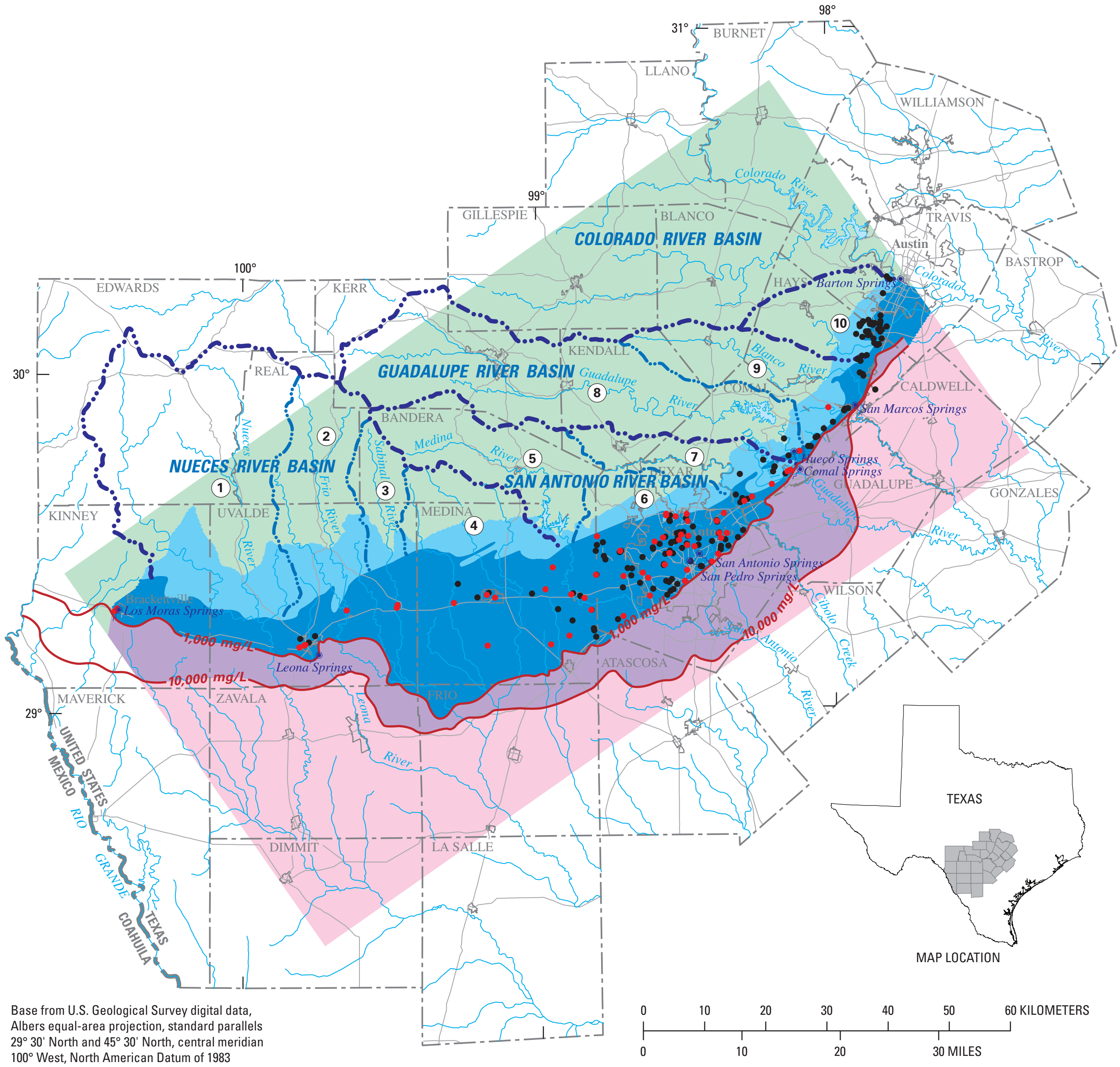
[km, kilometers; m, meters; ºC, degrees Celsius; mm, millimeters; mm/yr, millimeters per year; m/d, meters per day; m^2/d, meters squared per day; m^3/s, cubic meters per second; m^3/d, cubic meters per day; hm^3, cubic hectometers; hm^3/yr, cubic hectometers per year; mg/L, milligrams per liter]

Characteristic	Edwards-Trinity Aquifer System	South-Central Texas regional study area
	Geology	
Surficial deposits	Limestone and dolostone in outcrop area (recharge zone); limestone, chalk, shale, clay, and gravel in confined zone.	Limestone and dolostone in outcrop area (recharge zone); limestone, chalk, shale, clay, and gravel in confined zone.
Bedrock geologic units	Cretaceous, generally carbonate in the upper part and clastic sandstone in the lower part, relatively flat lying to north and west, more steeply dipping toward the coast. Rocks are exposed in updip areas, and dip and thicken east- and southward below overlying confining units (Ryder, 1996; Renken, 1998).	Carbonate sequence from 0 m (at updip boundary of outcrop area (recharge zone)) to 335 m (in western part of confined zone) thick; fractured with many dissolution features, especially in outcrop areas (recharge zone).
	Groundwater hydrology	
Aquifer conditions	Unconfined in outcrop area (recharge zone); confined downdip of outcrop area.	Unconfined in outcrop area (recharge zone); confined downdip of outcrop area (recharge zone).
Hydraulic properties	Transmissivity=18,580-185,800 m^2/d Storage coefficient=$1x10^{-5}$ to $1x10^{-4}$ Specific yield= average 0.02–0.04 (Ryder 1996).	Transmissivity=39,947 to 204,380 m^2/d Horizontal hydraulic conductivity= $3.05x10^{-4}$ to $3.05x10^{4}$ m/d Storage coefficient=$1x10^{-5}$ to $8x10^{-4}$ (San Antonio segment); Specific storage=$3.28x10^{-6}$ to $9.51x10^{-2}$ m^{-1} (Barton Springs segment); Specific yield=0.005 to 0.20; porosity =0.04 to 0.42 (Hovorka and others, 1996; Hovorka and others, 1998; Maclay and Land, 1988; Maclay and Rettman, 1973; Maclay and Small, 1984; Senger and Kreitler, 1984; Sieh, 1975; Slade and others, 1985; Scanlon and others, 2002).
Water budget	Recharge is generally as precipitation that falls on aquifer outcrop areas and as seepage from streams and ponds where the head gradient is downward. Discharge is by evapotranspiration, spring discharge, diffuse lateral or upward leakage into shallower aquifers, and withdrawals from wells. Much of the natural discharge from the aquifer is as spring flows along the southeastern edge of the Edwards Plateau where erosion has cut the rocks of the Edwards Group down to the water table (Ryder, 1996).	For the San Antonio segment, recharge from seepage losses from streams and infiltration of rainfall 862.2 hm^3/yr; subsurface inflow from Trinity aquifer about 2 to 9 percent of total recharge. Discharge to springs about 53 percent or 459.2 hm^3/yr; withdrawals by wells about 43 percent or 370.8 hm^3/yr; unknown amount discharges to Leona River floodplain and subsequently leaves study area (Hamilton and others, 2003). For the Barton segment, recharge from seepage losses from streams and infiltration of rainfall 53.6 hm^3/yr; subsurface inflow from Trinity aquifer minimal. Discharge to springs about 91 percent or 49.0 hm^3/yr; withdrawals by wells about 9 percent or 4.6 hm^3/yr (Scanlon and others, 2001).

Table 3.1. Summary of hydrogeologic and groundwater-quality characteristics for the Edwards-Trinity aquifer system and the South-Central Texas regional study area, San Antonio region, Texas.—Continued

[km, kilometers; m, meters; ºC, degrees Celsius; mm, millimeters; mm/yr, millimeters per year; m/d, meters per day; m^2/d, meters squared per day; m^3/s, cubic meters per second; m^3/d, cubic meters per day; hm^3, cubic hectometers; hm^3/yr, cubic hectometers per year; mg/L, milligrams per liter]

Characteristic	Edwards-Trinity Aquifer System	South-Central Texas regional study area
	Groundwater hydrology—Continued	
Groundwater residence times	Unknown	As short as a few days for rapid-response system (conduits) (Tomasko and others, 2001; Worthington, 2004). Generally less than 200 years (Leon Kauffman, U.S. Geological Survey, written commun., 2008). MODPATH results inconclusive because of karst terrain.
Lengths of groundwater travel paths	Unknown	Generally less than 160 km; median of about 40 km (Leon Kauffman, U.S. Geological Survey, written commun., 2008). Generally shorter in the Barton segment.
	Groundwater quality	
Water chemistry (dissolved solids, pH, reduction-oxidation conditions, major water types)	Dissolved solids range from 280 to 1500 mg/L in the freshwater part, increasing in concentration from the recharge area to downdip area. Saline water exists downdip of the freshwater zone.	Dissolved solids range from 280 to 560 mg/L with a median of 380 mg/L; pH ranges from 6.5 to 7.4 with a median of 7.0; reduction-oxidation conditions are predominantly oxidizing; Calcium and bicarbonate are dominant dissolved ions (Marylynn Musgrove, USGS, written commun., 2007).
Major contaminants (natural and anthropogenic)	Nitrate; radon; pesticides including atrazine and deethylatrazine; volatile organic compounds including trichloromethane, bromodichloromethane, chlorodibromomethane, perchloroethylene, and solvents (Bush and others, 2000; Fahlquist and Ardis, 2004).	Nitrate; radon; pesticides including atrazine and deethylatrazine; volatile organic compounds including trichloromethane, bromodichloromethane, chlorodibromomethane, perchloroethylene, and solvents (Bush and others, 2000; Fahlquist and Ardis, 2004).



EXPLANATION

South-Central Texas regional study area (coincides with active groundwater-flow model area) and adjacent hydrogeologic zones

- Recharge zone (outcrop) (modified from Puente, 1978)
- Freshwater zone
- Freshwater/saline-water transition zone

Inactive groundwater-flow model area hydrogeologic zones

- Catchment zone
- Saline zone

Line of equal dissolved solids concentration, in milligrams per liter (A.L. Schultz, consultant, written commun., 2000)

Catchment area

- Major river basin boundary
- Stream basin or contributing area boundary
- Public supply well sampled by NAWQA
- Public supply well
- Spring

Stream basin or contributing area

1. Nueces-West Nueces River Basin
2. Frio-Dry Frio River Basin
3. Sabinal River Basin
4. Area between Sabinal and Medina River Basins (includes Hondo and Seco Creeks)
5. Medina River Basin
6. Area between Medina River Basin and Cibolo-Dry Comal Creek Basins (includes Saludo Creek)
7. Cibolo and Dry Comal Creek Basins
8. Guadalupe River Basin (includes Guadelupe River and Verde Creek)
9. Blanco River Basin (includes Blanco River andPurgatory Creek)
10. Barton Springs segment contributing area (includes Barton, Williamson, Slaughter, Bear, and Onion Creeks)

Figure 3.3. Hydrogeologic zones and catchment area (upper parts of stream basins that contribute recharge) of the Edwards aquifer and locations of public-supply wells, San Antonio region, Texas.

along impermeable zones of the Trinity aquifer in the deeply incised stream channels of the Edwards Plateau (fig. 3.2). These springs provide base flow to streams that flow southward and eastward from the plateau. As they flow across the highly permeable, fractured and faulted carbonate rocks of the Edwards aquifer in the Balcones fault zone, most streams lose all of their base flow as recharge to the Edwards aquifer in the Edwards aquifer recharge zone (fig. 3.4). Six large springs (from west to east Los Moras, San Pedro, San Antonio, Comal, San Marcos, and Barton), important to the local recreational economy as well as to downstream users, issue from the confined part of the Edwards aquifer. Two additional springs, Leona Springs and Hueco Springs, occur in the study area, but all or part of their discharge is derived from sources other than the confined part of the Edwards aquifer. Comal and San Marcos Springs are the largest springs, with total discharges of 339.0 and 241.7 cubic hectometers (hm^3), respectively, in 2002, which translates to flow rates of 10.8 and 7.7 cubic meters per second (m^3/s), respectively (Hamilton and others, 2003). The springs of the Edwards aquifer provide unique habitat for about 90 plant and animal species, about one-half of which are subterranean and include such organisms as blind shrimp, salamanders, and catfish (Bush and others, 2000). Some species have been federally listed as endangered or threatened.

Over most semiarid regions of the Edwards Plateau and Hill Country, soil development is poor and generally less than 0.3 m thick. In the Edwards Plateau, soils tend to be calcareous stony clays vegetated by desert shrubs in the west and juniper, oak, and mesquite in the east. The Hill Country soils and vegetation are similar to those of the Edwards Plateau. In the northeastern part of the Balcones fault zone, soils are calcareous clay, clayey loam, and sandy loam with some prairie vegetation. West of San Antonio in the southwestern part of the Balcones fault zone, vegetation is predominantly juniper, oak, and mesquite (Kier and others, 1977).

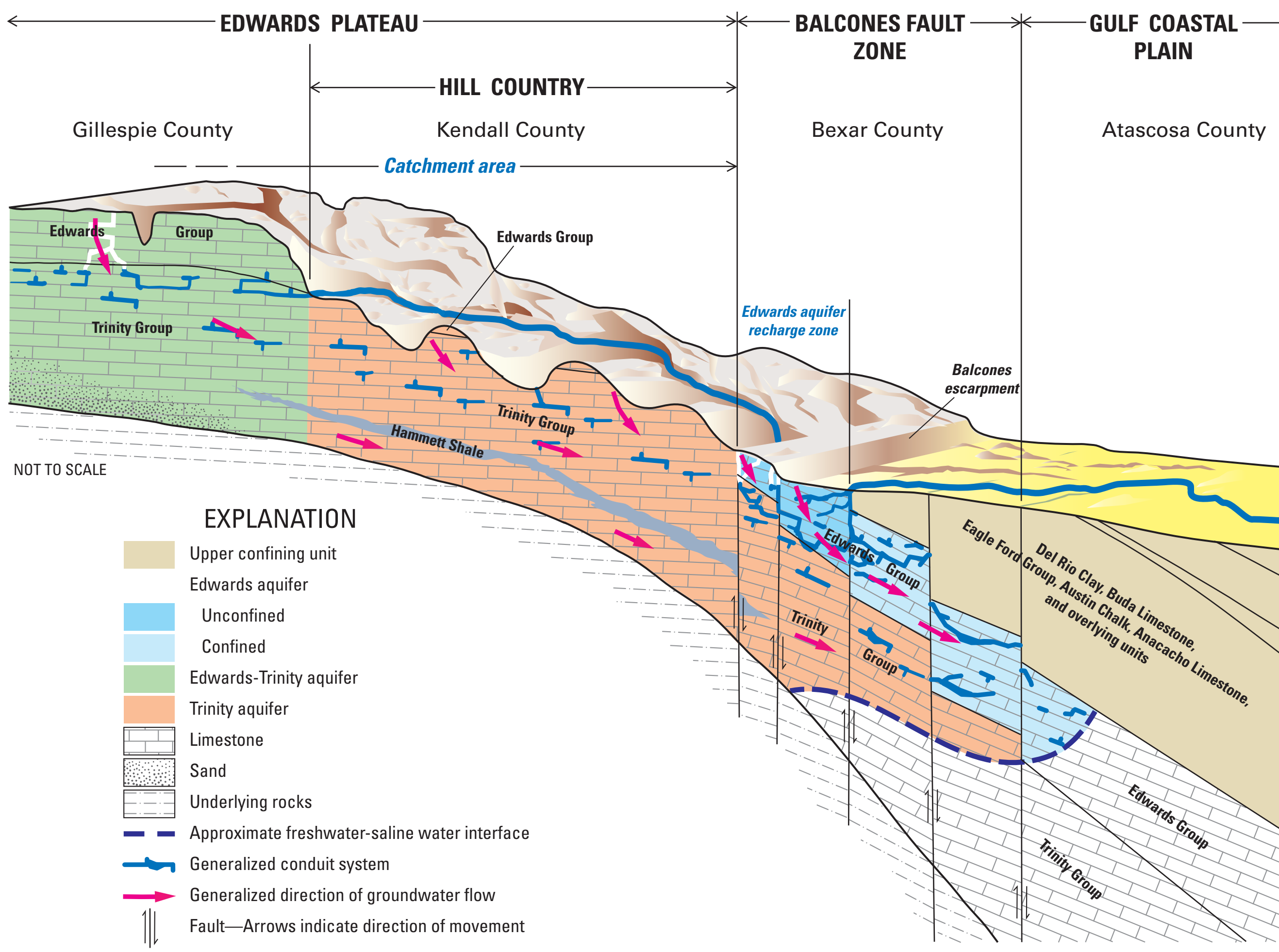


Figure 3.4. Diagrammatic north-northwest-to-south-southeast section showing hydrogeologic framework and generalized groundwater-flow directions, Edwards Plateau to Gulf Coastal Plain, San Antonio region, Texas.

Land Use

Land use in the South-Central Texas regional study area correlates with physiography. The rugged, thin-soiled terrain of the Edwards Plateau is largely undeveloped and rangeland predominates. The flatter, thicker-soiled terrain of the Gulf Coastal Plain is better suited to growing crops—primarily hay, sorghum, wheat, corn, and oats. In 2001, land use (Homer and others, 2004) in the South-Central Texas regional study area was quantified as 13 percent agriculture; 12 percent urban; 73 percent forest, shrub, and grassland; and 2 percent was water, wetlands, strip mines, or barren land. San Antonio is the principal urban area and includes much of Bexar County in the central part of the South-Central Texas regional study area (fig. 3.2).

Water Use

Groundwater accounts for nearly all of the water supply in the South-Central Texas regional study area, and the Edwards aquifer, one of the most productive aquifers in the world, is the principal source. Withdrawals from the Edwards aquifer meet the water-supply needs of more than 1.5 million people in the San Antonio region and support farming and ranching west of San Antonio. In 2003, water use from the Edwards aquifer in Atascosa, Bexar, Comal, Hays, Kinney, Medina, Travis and Uvalde Counties was estimated to be 460.7 hm^3 (Texas Water Development Board, 2008). Municipal withdrawals accounted for about 70 percent and irrigation accounts for 27 percent of water use; the remaining 3 percent included manufacturing, steam electric, mining, and livestock. An estimate for domestic use was not available. Bexar and Uvalde Counties are the largest producers of groundwater from the Edwards aquifer in the South-Central Texas regional study area; use in Bexar County is mostly municipal, and use in Uvalde County is mostly irrigation.

Conceptual Understanding of the Groundwater System

The Edwards aquifer is part of an aquifer system developed in thick and regionally extensive Lower Cretaceous carbonates that underlie large areas of Texas. The conceptualization of the Edwards aquifer includes a description of the geologic and hydrologic setting within which the aquifer functions. Groundwater flow and aquifer properties are appreciably affected by the presence of faults and karst dissolution features. The Balcones fault zone is a system of high-angle normal faults with net displacement toward the Gulf of Mexico and constitutes the principal structural deformation affecting aquifer development. Karst features in the Edwards aquifer include caves and solution-enlarged fractures (conduits). The Edwards aquifer is recharged predominantly through seepage losses from surface streams that flow onto the outcrop of the aquifer. Discharge from the aquifer is primarily from withdrawals by wells and springflow.

Hydrogeology

The Cretaceous strata of south-central Texas regionally include two aquifers, the Edwards aquifer in the Balcones fault zone and the Trinity aquifer in the Hill Country (fig. 3.4). The correlation chart (table 3.2) summarizes the relation among time-stratigraphic, rock-stratigraphic, and hydrogeologic units. The upper zone of the Trinity aquifer generally has lower permeability than the Edwards aquifer and, because of shaley interbeds, has a much lower vertical than horizontal permeability (Mace and others, 2000). Conventionally, the lower boundary of the Edwards aquifer is defined as the top of the Glen Rose Limestone (table 3.2). Cross-formational interconnection across the boundary between the two aquifers regionally is probable, however. Both units are karstic limestones, and large caves that cross the contact are interpreted as evidence that cross-formational flow occurs through karst systems in at least parts of the San Antonio segment of the Edwards aquifer (Veni, 1988; Vauter, 1992).

The carbonates in the Edwards aquifer are laterally and vertically heterogeneous. Maclay and Small (1976, table 1) defined eight “hydrostratigraphic” units within the Kainer, Person, and Georgetown Formations that compose the Edwards aquifer in the San Marcos platform of the Balcones fault zone (table 3.2). Groschen (1996) indicated that aquifer subdivisions III, VI, and VII transmit most of the groundwater within the San Antonio region. However, high-permeability dissolution features have been observed in all of the hydrostratigraphic units. The Edwards aquifer contains carbonates that have numerous intervals of intercrystalline high porosity, as well as petrophysical properties that make the carbonates subject to development of karst conduits (Hovorka and others, 1998). The Georgetown Formation, commonly included within the Edwards aquifer (table 3.2), consists of stratigraphically distinct limestone that overlies and is generally of lower porosity and permeability than the Edwards Group. The thick and regionally extensive shale of the Del Rio Clay directly overlies and confines the Edwards aquifer.

The altitude of the top of the Edwards aquifer ranges from about 305 m above NGVD 29 near the recharge zone in the western part of the San Antonio segment to about 1,219 m below NGVD 29 near the downdip limit of the aquifer in Frio County. The aquifer thickness ranges from 0 m at the updip boundary of the oucrop area (recharge zone) to about 335 m in the confined part of the aquifer in Kinney County (fig. 3.5).

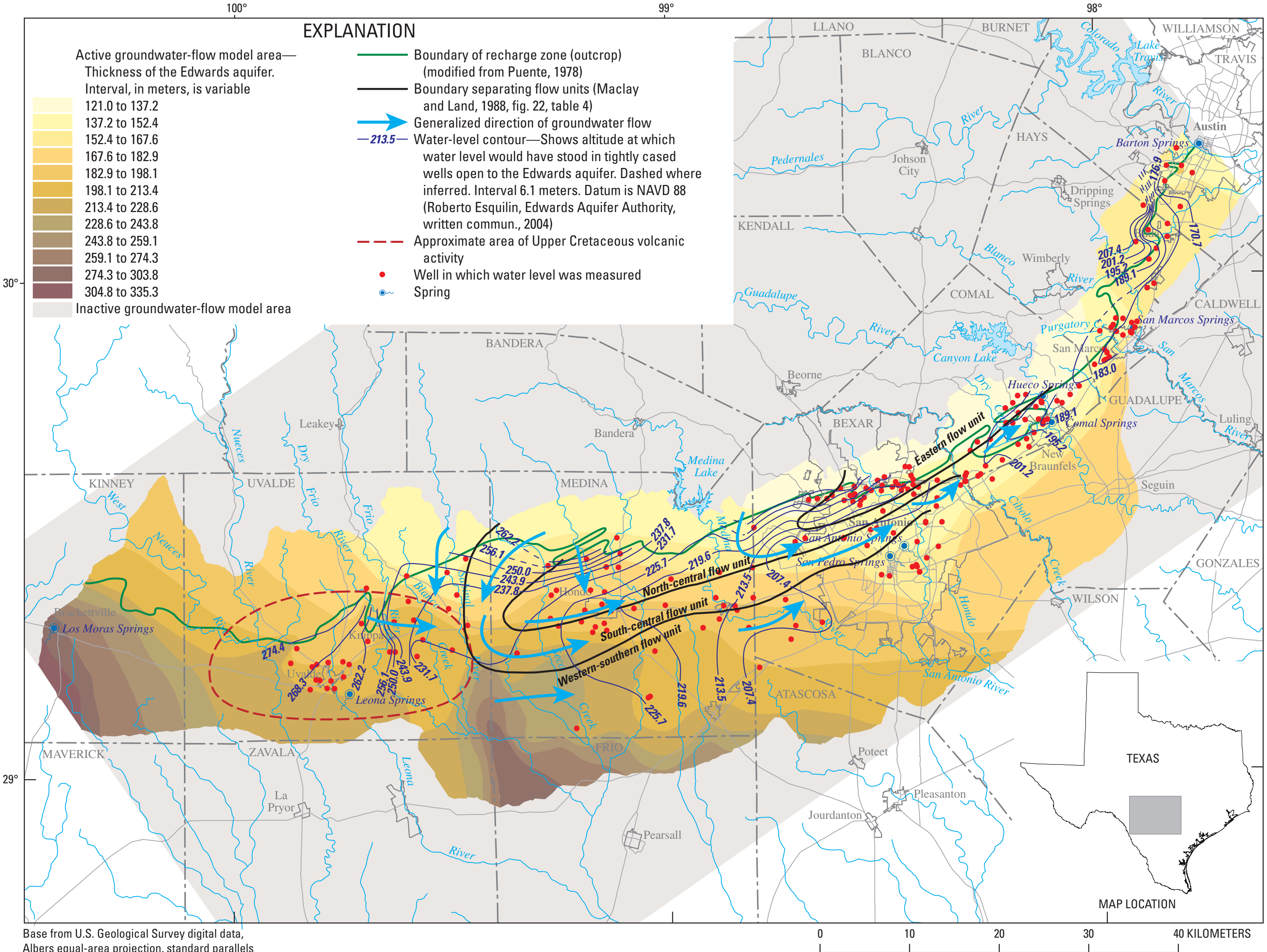
Fractures, solution-enlarged fractures, and caves make up 1 to 3 percent of the outcrop area in the San Antonio segment of the Edwards aquifer (Hovorka and others, 1998). More than 400 caves have been inventoried in the Edwards aquifer outcrop (Veni, 1988; Elliott and Veni, 1994). Maclay and Small (1984) hypothesized that solution channels within the Edwards

Table 3.2. Correlation of Cretaceous stratigraphic units and hydrogeologic units, and relative permeabilities in the rediscretized regional Edwards aquifer models area, San Antonio region, Texas (modified from Maclay, 1995, fig. 11).

[The descriptors "very small," "moderate," and "large" refer to the relative permeability of stratigraphic units, and arrows indicate an interval of uniform relative permeability, by depth, in a stratigraphic unit.]

STRATIGRAPHIC UNITS — DEPOSITIONAL PROVINCE: SYSTEM	[4] MAVERICK BASIN	[4] DEVILS RIVER TREND	[4] SAN MARCOS PLATFORM		HYDROGEOLOGIC UNITS	
UPPER CRETACEOUS	ANACACHO LIMESTONE Very small / AUSTIN CHALK Moderate	ANACACHO LIMESTONE Very small / AUSTIN CHALK Moderate	ANACACHO LIMESTONE Very small / AUSTIN CHALK Moderate		UPPER CONFINING UNIT	
UPPER CRETACEOUS	EAGLE FORD GROUP Very small	EAGLE FORD GROUP Very small	EAGLE FORD GROUP Very small		UPPER CONFINING UNIT	
UPPER CRETACEOUS	BUDA LIMESTONE Small	BUDA LIMESTONE Small	BUDA LIMESTONE Small		UPPER CONFINING UNIT	
UPPER CRETACEOUS	DEL RIO CLAY Very small	DEL RIO CLAY Very small	DEL RIO CLAY Very small		UPPER CONFINING UNIT	
LOWER CRETACEOUS	[1] SALMON PEAK FORMATION: Very small	[1] DEVILS RIVER LIMESTONE: Large	GEORGETOWN FORMATION Very small		I ([2] Aquifer subdivision in the San Marcos platform area)	EDWARDS AQUIFER
LOWER CRETACEOUS	[1] SALMON PEAK FORMATION: Large	[1] DEVILS RIVER LIMESTONE: Large	Erosional hiatus			EDWARDS AQUIFER
LOWER CRETACEOUS	[1] SALMON PEAK FORMATION: Small to moderate	[1] DEVILS RIVER LIMESTONE: Large	EDWARDS GROUP — [3] PERSON FORMATION	Cyclic and Marine Members (undivided) Moderate to large	II	EDWARDS AQUIFER
LOWER CRETACEOUS	[1] SALMON PEAK FORMATION: Small to moderate	[1] DEVILS RIVER LIMESTONE: Moderate	EDWARDS GROUP — [3] PERSON FORMATION	Leached Member Moderate to large	III	EDWARDS AQUIFER
LOWER CRETACEOUS	[1] SALMON PEAK FORMATION: Moderate	[1] DEVILS RIVER LIMESTONE: Moderate	EDWARDS GROUP — [3] PERSON FORMATION	Collapsed Member Moderate to large	III	EDWARDS AQUIFER
LOWER CRETACEOUS	[1] MCKNIGHT FORMATION Verysmall	[1] DEVILS RIVER LIMESTONE: Moderate	EDWARDS GROUP — [3] PERSON FORMATION	Regional Dense Member Very small	IV	EDWARDS AQUIFER
LOWER CRETACEOUS	[1] MCKNIGHT FORMATION Verysmall	[1] DEVILS RIVER LIMESTONE: Moderate	EDWARDS GROUP — [3] KAINER FORMATION	Grainstone Member Moderate	V	EDWARDS AQUIFER
LOWER CRETACEOUS	[1] WEST NUECES FORMATION Samll	[1] DEVILS RIVER LIMESTONE: Small	EDWARDS GROUP — [3] KAINER FORMATION	Kirschberg Evaporite Member Large	VI	EDWARDS AQUIFER
LOWER CRETACEOUS	[1] WEST NUECES FORMATION Samll	[1] DEVILS RIVER LIMESTONE: Small	EDWARDS GROUP — [3] KAINER FORMATION	Dolomitic Member Moderate	VII	EDWARDS AQUIFER
LOWER CRETACEOUS	[1] WEST NUECES FORMATION Samll	[1] DEVILS RIVER LIMESTONE: Small	EDWARDS GROUP — [3] KAINER FORMATION	Basal Nodular Member Very small	VIII	EDWARDS AQUIFER
LOWER CRETACEOUS	GLEN ROSE LIMESTONE	GLEN ROSE LIMESTONE	GLEN ROSE LIMESTONE	UPPER MEMBER OF THE GLEN ROSE LIMESTONE Very small	TRINITY AQUIFER	UPPER ZONE
LOWER CRETACEOUS	GLEN ROSE LIMESTONE	GLEN ROSE LIMESTONE	GLEN ROSE LIMESTONE	LOWER MEMBER OF THE GLEN ROSE LIMESTONE	TRINITY AQUIFER	LOWER ZONE

1 Lozo and Smith (1964).
2 Maclay and Small (1984).
3 Modified from Rose (1972).
4 Location shown in figure 3.2.



Base from U.S. Geological Survey digital data, Albers equal-area projection, standard parallels 29° 30' North and 45° 30' North, central meridian 100° West, North American Datum of 1983

Figure 3.5. Thickness and potentiometric surface and inferred regional groundwater-flow pattern in the Edwards aquifer, October 27–November 2, 2001, South-Central Texas regional study area, San Antonio region, Texas.

aquifer might be oriented parallel to the courses of streams recharging the Edwards aquifer and that vertical solution channels are well developed below segments of stream courses in the recharge zone. Worthington (2004) conceptualized a dendritic pattern of conduit connection from the recharge zone to the confined zone. A regionally extensive system of high-permeability zones is defined by broad troughs in the potentiometric surface, which indicate the potential for development or the presence of conduits, in the confined zone of the Edwards aquifer. A wide trough extends westward from central Bexar County to western Medina County and also further westward to Uvalde County (Hovorka and others, 2004, figs. 7, 8, 9, and 10). Relatively high porosity and permeability in the deepest parts of the aquifer near the freshwater/saline-water interface, anomalously high well yields, and sharp chemical gradients indicate that flow might be focused in this area (Maclay and Small, 1984; Hovorka and others, 1998). Large-scale structural troughs, grabens and synclines, with increased flow occur in the Edwards aquifer, and conduit development in these is favored. Worthington (2004, fig. 17) identified nine major structural troughs in the San Antonio segment of the Edwards aquifer. The locations of conduits in the Edwards aquifer were inferred by Worthington (2004, fig. 21) and Hovorka and others (2004).

The principal evidence of flow through karst is the heterogeneous and rapidly responsive nature of water-level variation. Using data from single storms, Worthington (2004) demonstrated two distinct responses in the Edwards aquifer, corresponding to conduit flow and matrix and small fracture flow. Wells close together can have different responses to a single recharge pulse (Johnson and others, 2002). The response of springs to rainfall is rapid. The maximum lag between rainfall and peak springflow was 11 days or less at Comal Springs and 9 days or less at San Marcos Springs following an intense storm October 17–19, 1998, centered in Comal County (Tomasko and others, 2001). In addition, tracer testing in the San Antonio segment of the Edwards aquifer has shown rapid flow (velocities of 180 to 800 meters per day (m/d) over distances of 0.8 to 4.0 kilometers (km)) from wells to the nearby high-flow springs (Ogden and others, 1986; Rothermel and others, 1987; Schindel and others, 2002).

Groundwater Occurrence and Flow

The northern Edwards aquifer boundary is defined by the updip limit of contiguous, outcropping rocks of the Edwards Group, Georgetown Formation, and their westward stratigraphic equivalents (Edwards rocks) and the southern boundary by the 10,000-milligrams per liter (mg/L) dissolved-solids concentration line, which is the downdip boundary of the freshwater/saline-water transition zone (fig. 3.3). The San Antonio segment of the aquifer (fig. 3.2) contains the most productive and transmissive parts of the aquifer. The San Antonio segment of the aquifer discharges primarily to Comal and San Marcos Springs, whereas the Barton Springs segment discharges primarily to Barton Springs (fig. 3.2).The Edwards aquifer is unconfined adjacent to and in the recharge zone (outcrop), where recharge occurs (fig. 3.3). The water table is at depths generally greater than 30 m below the streambeds. The Edwards aquifer is confined in downdip parts of the Balcones fault zone, including the freshwater zone and the freshwater/saline-water transition zone (fig. 3.3).

The groundwater-flow system of the Edwards aquifer in the San Antonio region includes (1) the catchment area in the Edwards Plateau, where the rocks of the Edwards-Trinity and Trinity aquifers are exposed and receive direct recharge to the water table; (2) the recharge zone, where streams lose flow directly into the unconfined Edwards aquifer and the aquifer receives direct recharge to the water table; and (3) the confined zone, which comprises the freshwater zone and the freshwater/saline-water transition zone (figs. 3.3 and 3.4). Water that enters the catchment area and recharge zone moves from unconfined to confined parts of the aquifer through generally southeasterly flow paths (fig. 3.5). In the confined zone, the water moves under low hydraulic gradients through fractured, highly transmissive, cavernous strata toward the east and northeast, where it is discharged through springs and wells. The freshwater zone and the freshwater/saline-water transition zone are hydraulically interconnected, but the aquifer transmits water in the freshwater zone at a much greater rate than in the transition zone (Schultz, 1992). Geochemical interpretation of water compositions (Clement, 1989; Oetting, 1995) documents slow movement of freshwater into the transition zone.

Conduits are major contributors to flow in the Edwards aquifer (Hovorka and others, 2004; Worthington, 2004). The multimodal permeability distribution of the Edwards aquifer (Hovorka and others, 1998) implies that the fastest-moving water, in fractures and conduits, can travel many times faster than the largest volume of water, in the matrix. Based on comparisons between mean matrix permeability and mean hydraulic conductivities estimated from aquifer tests, the contribution of matrix permeability to regional-scale hydraulic conductivity likely is minor, and most Edwards aquifer water flows through fractures and conduits (Hovorka and others, 1998). The absence of major known saline-water discharge areas might limit flow and conduit development in the freshwater/saline-water transition zone.

Faults can either increase or decrease total transmissivity (Hovorka and others, 1998). Some of the abundant, interconnected fractures in intensely fractured zones adjacent to faults have been enlarged, and they might focus flow parallel to faults. Where calcite cement fills breccia, cross-fault flow might be decreased. Stratigraphic offset of permeable zones along faults might also decrease the cross-fault flow (Maclay and Small, 1983, 1984). Holt (1959) observed nearly 30 m of head difference across faults in northern Medina County, and George (1952) reported head differences of 1.8 to 7.9 m across segments of major faults in unconfined, less-transmissive parts of the aquifer in Comal County. Maclay (1995) and Groschen (1996) characterized flow in the Edwards aquifer as being controlled laterally by barrier faults that locally compartmentalize the aquifer, especially toward the eastern part of the San Antonio segment. Maclay and Land (1988) hypothesized that large-throw faults in Medina County act as barriers and divert flow to the west before flow is redirected back toward the east (fig. 3.5). Water entering the recharge zone flows on relay ramps—transfer zone accommodating deformation between normal fault segments with similar dip directions (Peacock and Sanderson, 1994)—to the west and southwest before resuming the eastward regional flow direction.

Aquifer Hydraulic Properties

The hydraulic properties of primary interest include permeability, hydraulic conductivity, transmissivity, anisotropy, and storativity. Qualitative estimates of relative permeability for stratigraphic and hydrogeologic units are shown in table 3.2. Matrix, fracture, and conduit permeability occur in the Edwards aquifer. The carbonate matrix of the Edwards aquifer is very permeable; however, in many intervals, the very high permeabilities resulting from conduits and fractures dwarf the matrix contribution. Outcrops, which are at the highest altitudes, show abundant dissolution features and additional karst features that have developed in near-surface settings; however, matrix porosity and permeability of outcrop rocks are low relative to those in the aquifer. Geochemical processes that favor dissolution might account for greater development of conduit and matrix permeability in the deeper, downdip parts of the aquifer (Hovorka and others, 1998).

Transmissivity and hydraulic conductivity of the Edwards aquifer each vary over several orders of magnitude. On the basis of numerical modeling results, Maclay and Land (1988) estimated transmissivities of more than 399,470 meters squared per day (m^2/d) in Comal County near Comal Springs in the freshwater confined zone of the aquifer; their smallest estimated transmissivity was 12 m^2/d in the freshwater/saline-water transition zone. The transmissivity for most of the freshwater zone of the confined aquifer ranges from 39,947 to 204,380 m^2/d and in the recharge area generally is less than 39,947 m^2/d (Maclay and Land, 1988). Hovorka and others (1998) reported that transmissivity ranges from $9.29x10^{-3}$ to $9.29x10^{5}$ m^2/d, and hydraulic conductivity ranges from $3.05x10^{-4}$ to $3.05x10^{4}$ m/d, on the basis of specific-capacity and other aquifer tests. Painter and others (2002) estimated hydraulic conductivity for the Edwards aquifer in the San Antonio region ranging from 0.3 to 2,239 m/d, based on a combination of spatial statistical methods and model calibration for hydraulic conductivity using a Bayesian updating procedure (Woodbury and Ulrych, 1998, 2000).

Hovorka and others (1998, table 10) reported mean hydraulic conductivities, computed from specific capacity, for the recharge zone (outcrop) and confined zone of the San Antonio segment of the Edwards aquifer of 0.085 and 10.4 m/d, respectively, and 3.4 m/d for the aquifer as a whole. A mean of 0.03 m/d was reported for the hydraulic conductivity of the matrix. Structurally influenced cave systems contribute the highest hydraulic conductivities (3.05 to $3.05x10^{5}$ m/d), solution-enhanced fractures and stratigraphicallycontrolled karst features contribute intermediate values, and the porous carbonate matrix contributes hydraulic conductivities of $3.05x10^{-4}$ to 3.05 m/d (Hovorka and others, 1998).

The quantitative magnitude of anisotropy of the Edwards aquifer is largely unknown. Factors that might influence anisotropy in the aquifer include the presence of barrier faults with large vertical displacements and the development of conduits. Water circulation might cause focused dissolution and the development of conduits along the main flow paths in carbonate aquifers. Because faults are most abundant across northern Medina, central Bexar, southern Comal, southern Hays, and central Travis Counties (Maclay and Small, 1984, fig. 3; Baker and others, 1986, fig. 2), the strongest anisotropy exists east of Uvalde County. The ratio of anisotropy, which is the ratio of y-direction transmissivity to x-direction transmissivity, derived from past digital-model analysis ranges from 0:1 to 1:1 (Maclay and Land, 1988). The regional maximum directional transmissivity is generally aligned from the west-southwest to the east-northeast, parallel with structural features and prevailing groundwater flow paths.

The amount and distribution of water in the Edwards aquifer are related to the development of porosity and the storage characteristics of the aquifer. Hovorka and others (1996) estimated that Edwards aquifer porosity varies vertically from lows of 4 to 12 percent to highs of 20 to 42 percent, and the average for the entire aquifer is 18 percent. The effective porosity generally ranges from 2 to 14 percent (Maclay and Small, 1976); 6 percent is considered to be average (Maclay, 1995). Reported estimates of specific yield for the San Antonio segment of the Edwards aquifer range from 0.025 to 0.20, and reported estimates of storage coefficient range from $1x10^{-5}$ to $8x10^{-4}$ (Maclay and Rettman, 1973; Sieh, 1975; Klemt and others, 1979; Maclay and Small, 1984; Maclay and Land, 1988; Hovorka and others, 1993). Reported estimates of specific yield for the Barton Springs segment range from 0.005 to 0.06, and reported specific storage ranges from $3.28x10^{-6}$ to $9.51x10^{-2}$ m^{-1} (Brune and Duffin, 1983; Senger and Kreitler, 1984; Slade and others, 1985; Scanlon and others, 2002).

Water Budget

Water-level fluctuations reflect changes in the amount of water in storage in the Edwards aquifer. The aquifer is dynamic, and water levels generally respond to temporal and spatial variations in recharge and groundwater withdrawals. During periods of drought, water levels decline but recover rapidly in response to recharge. Although recurring droughts and floods have caused appreciable short-term fluctuations in water levels, long-term hydrographs from about 80 years of record indicate no net decline—or rise—of water levels in the San Antonio area.

The total amount of stored water in the Edwards aquifer represents the long-term accumulation of the volumetric difference between recharge and discharge. Hovorka and others (1996) estimated the total amount of water-filled pore space within the San Antonio segment of the Edwards aquifer to be 213,420.6 hm^3. Of this, 193,682.3 hm^3 of water is stored in the confined zone and 19,738.3 hm^3 is stored in the unconfined zone. Maclay (1989) estimated that 30,841.1 to 67,850.5 hm^3 of water in the Edwards aquifer is circulating in pore space or drainable by gravity.

Estimates for the major sources of water to and discharges from the San Antonio segment of the Edwards aquifer are shown in table 3.3. Similar estimates for the Barton Springs segment of the aquifer are incomplete and not readily available. Estimated average annual flow rates are given for 1993–2002, a relatively wet period, and for 1934–2002. Recharge from leakage through streambeds and infiltration of precipitation in interstream areas was about 14 percent greater during 1993–2002 compared to the long-term average for 1934–2002. Total discharge was also greater during 1993–2002than the 1934–2002 long-term average, due to greater springflowresulting from greater recharge and greater withdrawals resulting from increased demands for groundwater. The sources of water to and discharges from the Edwards aquifer in the South-Central Texas regional study area are discussed in more detail in the following sections of the report.

Recharge

The Edwards aquifer is recharged through (1) seepage losses from surface streams that drain the Hill Country, where the streams flow onto the outcrop of the Edwards aquifer; (2) infiltration of rainfall on the outcrop; (3) subsurface inflow across the updip margin of the Balcones fault zone, where the Trinity aquifer is laterally adjacent to the downfaulted Edwards aquifer (LBG-Guyton Associates, 1995); and (4) movement of water from the Trinity aquifer, where it underlies the Edwards aquifer, into the Edwards aquifer (fig. 3.4). The primary source of recharge is seepage from streams crossing the outcrop; hence, the outcrop is synonymous with the recharge zone. The headwater stream basins compose the catchment area and recharge zone (fig. 3.3). All of the base flow and some of the storm runoff of streams crossing the recharge zone, other than the Guadalupe River, infiltrate to the unconfined aquifer and are losing streams. Reported percentages of the total recharge that occurs as infiltration in interstream areas, rather than in streambeds, are (1) 15 percent for the Barton Springs segment of the Edwards aquifer (Slade and others, 1985; Scanlon and others, 2002) and (2) 20 percent (Klemt and others, 1979; Thorkildsen and McElhaney, 1992) and 40 percent (Maclay and Land, 1988) for the San Antonio segment.

Estimates of the combined recharge to the San Antonio segment of the Edwards aquifer from stream seepage and infiltration of rainfall range from a low of 53.9 hm^3 during 1956 to a high of 3,066.8 hm^3 during 1992 (Hamilton and others, 2003). The long-term (1934–2002) mean annual recharge to the Edwards aquifer is 862.2 hm^3 (median 688.1 hm^3) and for 1993–2002, is 979.6 hm^3 (median 710.9 hm^3) (Hamilton and others, 2003). Monthly rates of recharge for the San Antonio segment of the Edwards aquifer from seepage losses from streams and infiltration of rainfall in the recharge zone are computed from records of streamflow-gaging stations near upstream and downstream limits of the recharge area and from estimated runoff in the recharge area (Puente, 1978; Slattery, 2004). Recent unpublished work indicates that 50 to 60

Table 3.3. Estimated water budget components for the San Antonio segment of the Edwards aquifer for 1993–2002 and 1934–2002, San Antonio region, Texas.

[Recharge includes leakage from streams through streambeds and infiltration of precipitation in interstream areas. Estimates of recharge, withdrawals (pumpage), and springflow are from Hamilton and others (2003). Estimates of inflow from Trinity aquifer are from Mace and others (2000). hm3/yr, cubic hectometers per year]

Budget component	1993–2002		1934–2002	
	Flow rate (hm^3/yr)	Percentage of total sources or discharges	Flow rate (hm^3/yr)	Percentage of total sources or discharges
Source				
Recharge	980	93	862	92
Inflow from Trinity aquifer	79	7	79	8
Total sources	1,059	100	941	100
Discharge				
Withdrawals (pumpage)	512	49	375	45
Springflow	535	51	459	55
Total discharges	1,046	100	835	100

percent of the stream channel for Cibolo Creek between the streamflow-gaging stations, which was used to estimate the leakage from Cibolo Creek to the Edwards aquifer, lies within the Trinity aquifer outcrop area (Darwin Ockerman, U.S. Geological Survey, written commun., 2002).

The Edwards aquifer in much of the Balcones fault zone is juxtaposed against the Trinity aquifer both at the surface and at depth, and the Trinity aquifer likely discharges directly into the Edwards aquifer. The volume of flow from the Trinity aquifer into the Edwards aquifer can only be estimated. The available estimates vary. Woodruff and Abbott (1986) reported that recharge from Trinity aquifer inflow is 6 percent of total recharge, or about 50.6 hectometers per year (hm^3/yr) on average, to the Edwards aquifer. LBG-Guyton Associates (1995) estimated an approximate range of Trinity aquifer underflow to the Edwards aquifer in the San Antonio region, excluding the Cibolo Creek contribution, of about 3.3 to 14.1 hm^3/yr, representing about 2 percent of total average annual recharge to the Edwards aquifer. A flow of about 79.0 hm^3/yr from the upper and middle zones of the Trinity aquifer in the direction of the Edwards aquifer, representing about 9 percent of the average estimated annual recharge to the Edwards aquifer, was simulated by Mace and others (2000).

Discharge

Most discharge from the Edwards aquifer occurs as (1) withdrawals by industrial, irrigation, and public-supply wells, and (2) springflow. Groundwater withdrawals by wells have increased with increasing population. From 1934 through 2002, the lowest estimated annual pumpage (withdrawals) was 125.7 hm^3 in 1934 and the highest was 669.1 hm^3 in 1989 (Hamilton and others, 2003). Springflow from the San Antonio segment averaged 459.2 hm^3/yr (median 463.6 hm^3/yr) for 1934–2002 (Hamilton and others, 2003). Total annual springflow from the Edwards aquifer has varied as much as an order of magnitude over the period of record. Springflow totaled 86.1 hm^3 in 1956 during the 1950s drought and reached a record high of 990.4 hm^3 in 1992 (Hamilton and others, 2003). Water also discharges from the Edwards aquifer to the Leona River floodplain in south-central Uvalde County. Green (2004) estimated that as much as 123.4 hm^3/yr is discharged from the Edwards aquifer to the Leona River floodplain, about 13 percent of which becomes surface flow in the Leona River and about 87 percent becomes subsurface flow in the sand and gravel deposits. Part of the subsurface flow ultimately discharges to Leona Springs.

Thousands of water wells tap the Edwards aquifer in the San Antonio region. Annual discharge by wells increased steadily at an average annual rate of about 5.6 hm^3/yr, more than tripling between 1939 and 2000. Municipal, irrigation, and industrial water use make up more than 95 percent of annual withdrawals from the Edwards aquifer in each county except for Comal County, where mining by rock quarries also accounts for appreciable withdrawals. In Bexar, Hays, Kinney, and Travis Counties, municipal water withdrawals account for more than 85 percent of annual withdrawals. Irrigation accounts for more than 60 percent of withdrawals in Uvalde County and more than 80 percent in Medina County. Bexar and Uvalde Counties are the largest producers of groundwater from the Edwards aquifer in the San Antonio region. Pumpage is concentrated in the confined part of the Edwards aquifer, and the largest withdrawals are in and around San Antonio. Yields of more than 3.5 cubic meters per minute (m^3/min) are common for wells in the confined freshwater zone of the Edwards aquifer. The density of wells in the unconfined recharge zone of the aquifer is substantially less than that in the confined zone, and typically the yields are smaller.

Springs and seeps are the major natural discharge outlets for the Edwards aquifer, accounting for nearly all natural discharge from the aquifer. Comal and San Marcos Springs are the largest springs, with total discharges of 339.0 and 241.7 hm^3, respectively, in 2002, which translates to flow rates of 10.76 and 7.67 cubic meters per second (m^3/s), respectively (Hamilton and others, 2003). Groschen (1996) postulated that the locations of most major springs in the Edwards aquifer are structurally controlled. Groundwater flow is diverted along barrier faults, with vertical openings at a few places along faults where springs can emerge. Faults that intersect the aquifer at depth provide a pathway for water to rise to the land surface. Leona Springs consists of a number of seeps emerging from permeable gravel of the Leona Formation within the channel of the Leona River in Uvalde County. The average annual discharge estimated by the USGS for Leona Springs was about 16.0 hm^3 (0.51 m^3/s) for 1939–2000. However, the discharge from Leona Springs estimated by the USGS might appreciably underestimate the actual discharge because of unmeasured discharge from the Edwards aquifer to the overlying Leona gravels (Green, 2004).

Increases in pumpage upgradient from the springs have, at times, appreciably reduced the discharge at Comal Springs. The only period of zero flow at Comal Springs was from June 13, 1956, to November 4, 1956, near the end of the severe drought of the 1950s. Maclay (1995) concluded that most of the San Marcos Springs discharge might be derived from water entering the aquifer in the Cibolo Creek and Dry Comal Creek, Guadalupe River, and Blanco River Basins (fig. 3.2). Hueco Springs is the only large spring in the Edwards aquifer outcrop area—its 1945–73 average annual flow was about 1.0 m^3/s—and it is believed to have a much smaller contributing area than any of the other major springs. An unknown percentage of the Hueco Springs flow might be derived from the Trinity aquifer (LBG-Guyton Associates, 1995). Increased pumpage, primarily from wells in San Antonio, has resulted in frequent periods of zero discharge from San Antonio and San Pedro Springs (Brune, 1975). San Antonio Springs has a larger discharge capacity and higher spring orifice altitude than San Pedro Springs.

Groundwater Quality

The groundwater chemistry of the Edwards aquifer in the San Antonio segment is relatively homogeneous and typical of a well-buffered carbonate aquifer system. Water-chemistry data collected for the USGS NAWQA Program during 1996–2006 include results from domestic, public, monitoring, and other wells located in both unconfined (recharge zone) and confined parts of the aquifer. Calcium and bicarbonate are the dominant dissolved ions, reflecting the carbonate lithology of the aquifer. Dissolved-solids concentrations of the unconfined and confined parts of the aquifer are similar, with a median value of 380 milligrams per liter (mg/L) and a range from 280 mg/L to 560 mg/L. The pH values range from 6.5 to 7.4 standard units, with a median of 7.0.

Oxidation-reduction (redox) conditions in the Edwards aquifer are characterized by predominantly oxidizing conditions. A few isolated wells that have higher dissolved-solids concentrations, or less oxidizing conditions, may be influenced by water from the underlying Trinity aquifer or saline water in the Edwards aquifer. Oxygen-reducing conditions generally occur upgradient of the 1,000 mg/L dissolved-solids concentration line, which is the updip boundary of the freshwater/saline-water transition zone (fig. 3.6). Variably-reducing conditions typically occur downgradient of this boundary.

The water chemistry of groundwater samples from the unconfined part of the Edwards aquifer is not significantly different from that of samples from the confined part of the aquifer, including spring samples. Nonetheless, as groundwater-residence times increase along flow paths from shallow unconfined parts of the aquifer to deep confined parts, geochemical evolution processes may affect the proportions of dissolved ions. Water samples from wells completed in the confined part of the aquifer generally have slightly lower bicarbonate, calcium, and dissolved oxygen and slightly higher sodium, sulfate, chloride, and strontium concentrations compared to water samples from wells completed in the unconfined part.

The USGS defined a national background threshold of 2.0 mg/L as nitrogen for nitrate (U.S. Geological Survey, 1999). Samples with nitrate concentrations greater than 2.0 mg/L as nitrogen might contain nitrogen derived from anthropogenic sources, for example, from human or industrial waste, fertilizer use, or livestock operations. Nitrate concentrations in water samples collected for the USGS NAWQA Program during 1996–2006 ranged from nondetection, defined as less than 0.05mg/L, to 8.23 mg/L, with a median of 1.68 mg/L. Nitrate nitrogen concentrations did not exceed the public drinking-water standard of 10 mg/L (U.S. Environmental Protection Agency, 2006).

Radon activities in water samples from the unconfined Edwards aquifer ranged from 80 to 776 picocuries per liter (pCi/L), and radon in 10 samples exceeded a proposed public drinking-water standard of 300 pCi/L. The source of radon in the Edwards aquifer is unknown (Bush and others, 2000). Most water samples from the Edwards aquifer contained tritium (^3H) at concentrations indicating that the water was derived from recharge within the last decade, including five water samples from springs that issue from the confined part of the Edwards aquifer (Fahlquist and Ardis, 2004).

Organic compounds have been found throughout the Edwards aquifer, mostly at very low concentrations of much less than 1 microgram per liter (µg/L) (Musgrove and others, 2010). Pesticide compounds were widely measured in water samples from the Edwards aquifer collected for the USGS NAWQA Program during 1996–2006, albeit at very low concentrations (much less than 1 µg/L). Atrazine and its breakdown product deethylatrazine were the most frequently detected compounds; they were detected in greater than 50 percent of the wells, similar to the results observed for other USGS NAWQA major aquifer studies across the Nation (Bush and others, 2000; U.S. Geological Survey, 1999; Fahlquist and Ardis, 2004). Frequency of detection and range of concentration were 55 percent and less than 0.001 to 0.132 µg/L, respectively, for atrazine and 68 percent and less than 0.002 to 0.053 µg/L, respectively, for deethylatrazine. Other pesticide compounds also were detected, but less frequently. Some water samples from the Edwards aquifer contained more than one pesticide compound. Moran and others (2002) reported that the most commonly detected volatile organic carbon compounds (VOCs) in USGS NAWQA major aquifer studies across the Nation, regardless of well type, are trihalomethanes (THMs) and solvents. Similar results were observed for NAWQA samples collected from the Edwards aquifer. Most VOCs were measured at small concentrations, which were much less than 1 µg/L; however, some were measured at concentrations greater than 1 µg/L. The most frequently detected VOCs in water samples from the Edwards aquifer, which were detected in greater than 50 percent of water samples, were trichloromethane (chloroform), and tetrachloroethene (PCE). Frequency of detection and range of concentration were 66 percent and less than 0.024 to 5.88 µg/L, respectively, for trichloromethane and 43 percent and less than 0.027 to 0.95 µg/L, respectively, for tetrachloroethene.

Groundwater-Flow Simulations

Existing numerical models of groundwater flow developed in MODFLOW-2000 (Harbaugh and others, 2000) for the Edwards aquifer (Lindgren and others, 2004; Lindgren, 2006) (hereinafter, the original Edwards aquifer models) were modified to simulate groundwater flow in the South-Central Texas regional study area. The original Edwards aquifer models were calibrated for steady-state and transient conditions. The steady-state calibration period was 1939–46, representing average conditions for a near-predevelopment interval when irrigation development was minimal. The transient calibration period, which includes changes in groundwater storage over time, was 1947–2000, including 648 monthly stress periods.

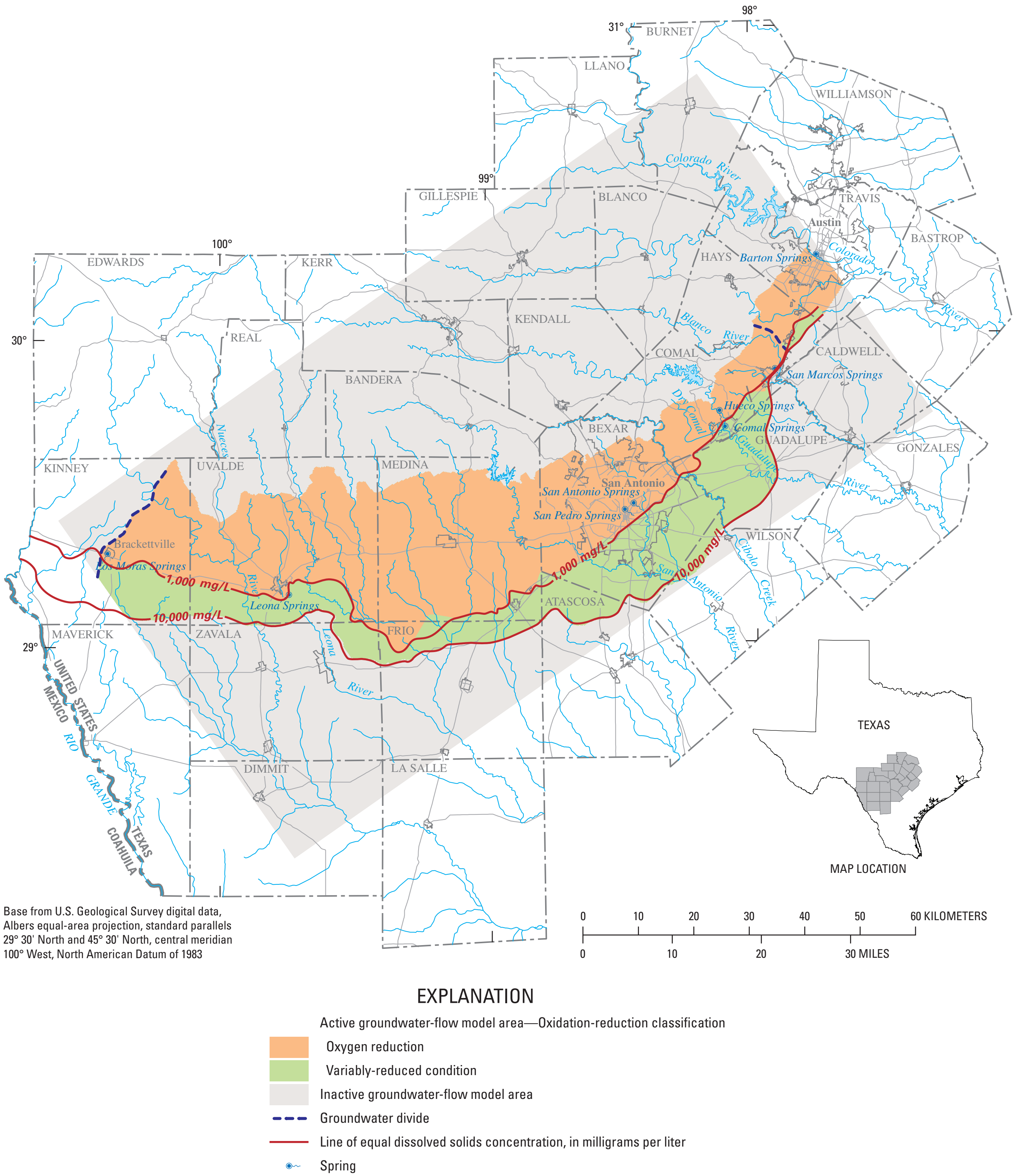


Figure 3.6. Oxidation-reduction classification zones for the Edwards aquifer in the South-Central Texas regional study area, San Antonio region, Texas.

The original Edwards aquifer models were calibrated for two hydraulic-conductivity distributions. A numerical groundwater-flow model (hereinafter, the conduit-flow Edwards aquifer model) of the karstic Edwards aquifer in south-central Texas was developed for a study conducted during 2000–03 on the basis of a conceptualization emphasizing conduit development and conduit flow (Lindgren and others, 2004). Uncertainties regarding the degree to which conduits pervade the Edwards aquifer and influence groundwater flow, as well as other uncertainties inherent in simulating conduits, raised the question of whether or not a model based on the conduit-flow conceptualization was the optimum model for the Edwards aquifer. Accordingly, a model with an alternative hydraulic-conductivity distribution without conduits was developed in a study conducted during 2004–05 (Lindgren, 2006). The hydraulic-conductivity distribution for the modified Edwards aquifer model (hereinafter, the diffuse-flow Edwards aquifer model) is based primarily on a conceptualization in which flow in the aquifer predominantly is through a network of numerous small fractures and openings.

The original Edwards aquifer models were modified for the South-Central Texas regional study to a finer discretization, both horizontally and vertically, and updated to include the 2001–2003 time period. The rediscretized Edwards aquifer models (hereinafter, the rediscretized regional Edwards aquifer models) were calibrated using two different hydraulic-conductivity distributions, based on conduit flow or diffuse flow, as for the original Edwards aquifer models. The two rediscretized regional Edwards aquifer models are hereinafter referred to as the conduit-flow rediscretized regional Edwards aquifer model and the diffuse-flow rediscretized regional Edwards aquifer model. The initial boundary conditions and hydraulic properties used in the rediscretized regional Edwards aquifer models were the same as those used in the original Edwards aquifer models, but they were adjusted to conform to the smaller grid size in the rediscretized regional Edwards aquifer models.

Model Area and Spatial Discretization

The uniformly spaced finite-difference grid used to spatially discretize the model area for the rediscretized regional Edwards aquifer models has 740 rows and 1,400 columns and is rotated 35 degrees counterclockwise from horizontal (fig. 3.7). The dimensions of the grid cells are uniformly 201.2 m along rows and columns, half the dimensions of those for the original Edwards aquifer models (Lindgren and others, 2004; Lindgren, 2006). Two model layers were used to represent the multiple hydrogeologic zones that comprise the Edwards aquifer, compared to the one model layer for the original Edwards aquifer models. Model layer 1 represents the hydrostratigrahic units of the Edwards aquifer above the Regional Dense Member (table 3.2). Model layer 2 represents the hydrostratigrahic units of the Edwards aquifer below, and including, the Regional Dense Member (table 3.2). The layer thickness for model layer 1 ranges from 0 to 218.2 m and for model layer 2 ranges from 2.74 to 358.1 m. The Edwards aquifer was not discretized more finely in the vertical dimension because of a lack of hydrogeologic data sufficient to spatially define additional individual zones within the aquifer. The extent of layer 2 for the rediscretized regional Edwards aquifer models is the same as the extent of the single layer for the original Edwards aquifer models (Lindgren and others, 2004, fig. 2). The extent of layer 1 for the rediscretized regional Edwards aquifer model (fig. 3.7) coincides approximately with the areas where the hydrostratigraphic units of the Edwards aquifer above the Regional Dense Member are present.

Boundary Conditions

The boundary conditions for model layers 1 and 2 of the rediscretized regional Edwards aquifer models (fig. 3.7) are generally the same as for the original Edwards aquifer models (Lindgren and others, 2004, fig. 18). The interested reader is referred to Lindgren and others (2004) and Lindgren (2006) for further discussion of boundary conditions in the original Edwards aquifer models. The MODFLOW well package was used to simulate a constant flux through the northern model boundary and the northern part of the western model boundary for layer 2 for all stress periods. The northern boundary for layer 1 of the rediscretized regional Edwards aquifer models corresponds approximately with the physical limits of the hydrostratigraphic units that the layer represents; therefore, a no-flow boundary condition was imposed.

The eastern model boundary and the southern part of the western model boundary for layers 1 and 2 of the rediscretized regional Edwards aquifer models were assigned a no-flow boundary condition (fig. 3.7). The northern part of the eastern model boundary is defined by the location of the Colorado River, which is a regional sink for the Edwards aquifer. The southern part of the western model boundary coincides with the location of a groundwater divide near Brackettville in Kinney County (LBG-Guyton Associates, 1995). A no-flow boundary condition was also imposed for layers 1 and 2 for the southern model boundary coinciding with the 10,000-mg/L dissolved solids concentration line, assuming minimal downdip flow of freshwater from the Edwards aquifer.

Aquifer Structure

Model aquifer structure considerations include assigning top and bottom altitudes of the Edwards aquifer to model cells and the simulation of faults and conduits. The altitude of the top of model layer 1 for the rediscretized regional Edwards aquifer models is the same as the altitude of the top of the single model layer simulated in the original Edwards aquifer models (Lindgren and others, 2004; Lindgren, 2006). However, model layer 1 is absent in the rediscretized regional Edwards aquifer models in areas where the hydrostratigrahic units above the Regional Dense Member are absent. These areas where model layer 1 is absent are limited to the Edwards aquifer outcrop area (recharge zone). The altitude of the

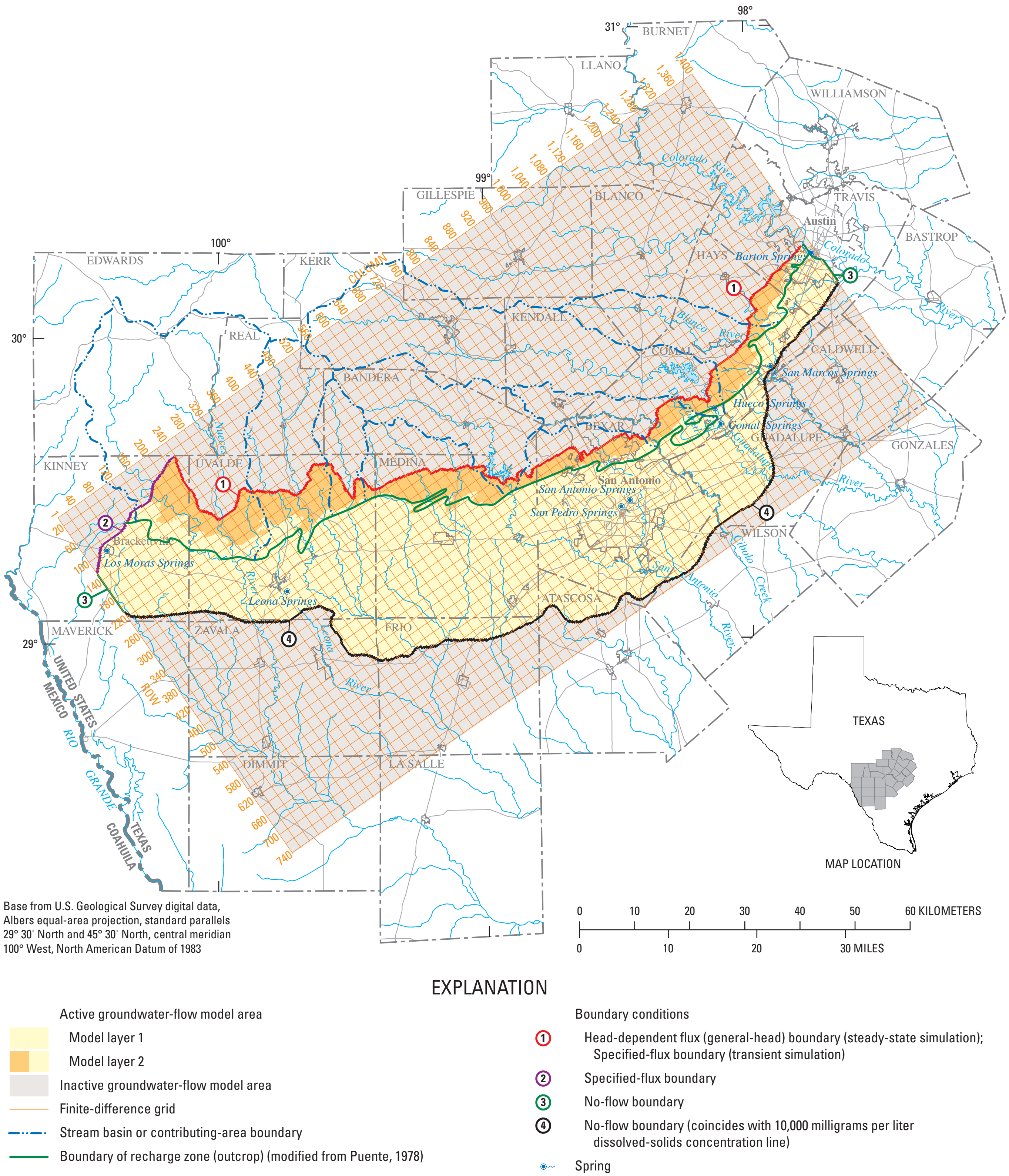


Figure 3.7. Model grid, extent of model layers, and boundary conditions for the rediscretized regional Edwards aquifer models, San Antonio region, Texas.

bottom of model layer 1 coincides with the altitude of the top of the Regional Dense Member. The altitude of the top of model layer 2 for the rediscretized regional Edwards aquifer models coincides with the land-surface altitude in those areas where model layer 1 is absent. The altitude of the bottom of model layer 2 coincides with the altitude of the top of the Glen Rose Limestone, except where it is modified in the recharge zone (Lindgren and others, 2004).

The anisotropy of the Edwards aquifer is largely unknown, except for that attributable to the presence of faults. The anisotropic effects of faults were incorporated in the original and the rediscretized regional Edwards aquifer models by using the MODFLOW Horizontal Flow Barrier package (Harbaugh and others, 2000). Conduits are simulated in the conduit-flow Edwards aquifer models (original and rediscretized regional models) by narrow (0.40-km wide), initially continuously connected zones with large hydraulic-conductivity values. The locations of conduit zones in the conduit-flow Edwards aquifer model were assigned on the basis of the conduit locations inferred by Worthington (2004) (Lindgren and others, 2004, fig. 7) and modified during model calibration (Lindgren and others, 2004, fig. 7). The interested reader is referred to Lindgren and others (2004) for further discussion of the simulation of faults and conduits.

Aquifer Hydraulic Properties

The aquifer hydraulic properties specified in the Edwards aquifer models (original and rediscretized regional models) are hydraulic conductivity and storativity. The horizontal hydraulic-conductivity distribution for the conduit-flow Edwards aquifer model (Lindgren and others, 2004) includes two components. The first component is the hydraulic-conductivity distribution developed by Painter and others (2002), with values ranging from 0.3 to 2,239 m/d. An approach based on nonparametric geostatistics, stochastic simulation, and numerical flow simulation was used to upscale and interpolate hydraulic-conductivity estimates to the Edwards aquifer model grid. The second component is the network of conduits, as mapped by Worthington (2004, fig. 21) (Lindgren and others, 2004, fig. 7). For the Barton Springs segment of the aquifer, the hydraulic-conductivity distribution from Scanlon and others (2002), rather than that of Painter and others (2002), was used.

The horizontal hydraulic-conductivity distribution for the diffuse-flow Edwards aquifer model (Lindgren, 2006) is based primarily on a diffuse-flow conceptualization of groundwater flow. The preliminary diffuse-flow hydraulic-conductivity distribution included a total of 24 zones—8 for the recharge zone, 15 for the confined freshwater zone, and 1 for the freshwater/saline-water transition zone. The initial model simulation results for the diffuse-flow Edwards aquifer model indicated that the simulated springflows for Comal and San Marcos Springs were much lower than the measured springflows, and further upscaling of hydraulic conductivity was required to simulate the high measured springflows. The required upscaling of the hydraulic conductivity was accomplished by the insertion of broad high hydraulic conductivity (HHC) zones within the model domain. The widths of the delineated HHC zones vary from as narrow as 1.2 km near the freshwater/saline-water interface and San Marcos Springs to as wide as approximately 8 to 16 km.

The initial hydraulic-conductivity distributions for the conduit-flow rediscretized regional Edwards aquifer model and the diffuse-flow rediscretized regional Edwards aquifer model were the same as for the conduit-flow Edwards aquifer model and the diffuse-flow Edwards aquifer model, respectively. The initial horizontal hydraulic-conductivity distributions for layers 1 and 2 in the rediscretized regional Edwards aquifer models (conduit-flow and diffuse-flow) were the same.

Because the rediscretized regional Edwards aquifer models include two model layers, vertical hydraulic conductivity also needed to be specified. Isotropic conditions were assumed, with the vertical hydraulic conductivity for each model cell being the same as the horizontal hydraulic conductivity. Although hydrogeologic units with differing relative permeabilities ranging from very small to large comprise the Edwards aquifer (table 3.2), (1) vertical variations in hydraulic conductivity in the aquifer indicate that the entire aquifer is highly permeable as well as highly variable (Hovorka and others, 1998) and (2) the Regional Dense Member, which has a very small permeability (table 3.2), is generally not considered a regional confining unit. Unrestricted vertical flow and mixing in the aquifer is also indicated by the relatively uniform quality and temperature of water throughout the aquifer (Maclay, 1995). A sensitivity analysis done for vertical hydraulic conductivity indicated that reducing vertical hydraulic conductivity by factors of 0.1, 0.01, and 0.001 for the steady-state simulations had minimal effects on the residuals for hydraulic heads for the rediscretized regional Edwards aquifer models (conduit-flow and diffuse-flow models). The reductions in the mean absolute error of the residuals for hydraulic heads resulting from the variations in vertical hydraulic conductivity were less than 0.03 m. The changes in the residuals for springflows were generally less than 6 percent, except for as much as 23 percent for Comal Springs for the diffuse-flow model, as much as 27 percent for San Marcos Springs for the conduit-flow model, and as much as 46 percent for San Antonio Springs for both models. A reduction in the vertical hydraulic conductivity resulted in both increases and decreases in the residuals for springflows. For the conduit-flow model, reducing the vertical hydraulic conductivity resulted in a decrease in the residuals for all of the springs except San Antonio Springs. For the diffuse-flow model, reducing the vertical hydraulic conductivity resulted in a decrease in the residuals for San Marcos and Leona Springs and an increase in the residuals for Comal, San Antonio, and San Pedro Springs.

The initial storativity values were varied during model calibration for the conduit-flow Edwards aquifer model, resulting in a zonation of values (Lindgren and others, 2004). The storativity distribution for the diffuse-flow Edwards aquifer model and for the rediscretized regional Edwards aquifer models (conduit-flow and diffuse-flow models) are the same as the final calibrated storativity distribution for the conduit-flow Edwards aquifer model (Lindgren and others, 2004). The storativity distribution for model layers 1 and 2 of the rediscretized regional Edwards aquifer models is the same. The interested reader is referred to Lindgren and others (2004) and Lindgren (2006) for further discussion of the simulation of hydraulic properties in the original Edwards aquifer models.

Model Stresses

Stresses include recharge to and discharge from the Edwards aquifer. Recharge to the Edwards aquifer occurs primarily by seepage from streams to the aquifer in the recharge zone. Discharge from the Edwards aquifer includes withdrawals by wells and springflow.

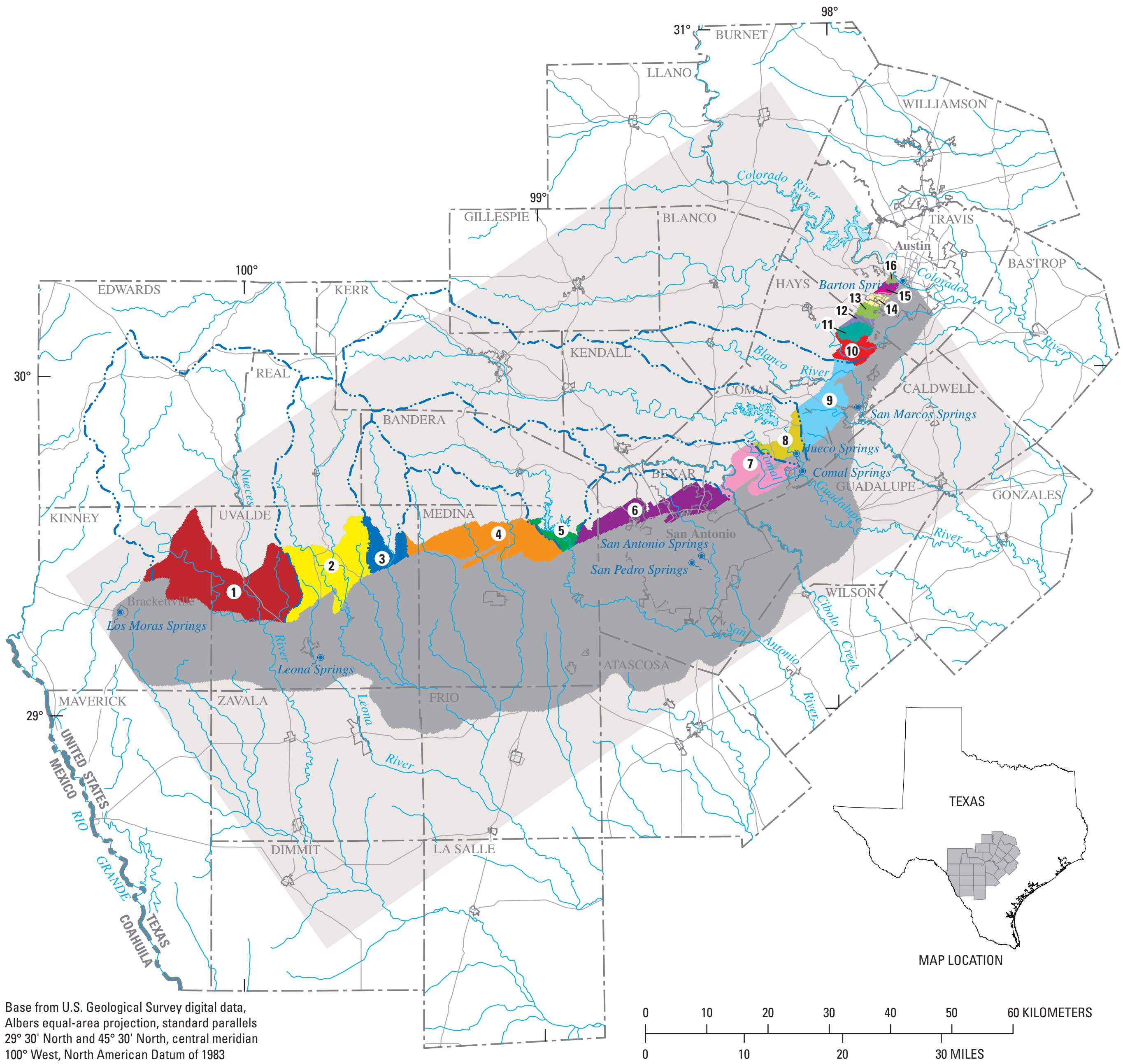
Recharge

Recharge to the Edwards aquifer occurs primarily by seepage from streams to the aquifer in the recharge zone (fig. 3.3). Additional recharge is from infiltration of rainfall in the interstream areas of the recharge zone. Recharge in the San Antonio segment of the aquifer by seepage from streams and infiltration of rainfall was assigned to eight major recharging streams and their interstream areas (hereinafter referred to as recharge subzones) in the recharge zone (fig. 3.8), on the basis of monthly recharge rates to the Edwards aquifer for 2000–2003 computed by the USGS and published, as annual totals, by the Edwards Aquifer Authority (EAA). Recharge rates for the Guadalupe River recharge subzone, not computed by the USGS, were calculated as the average of the recharge rates for the adjacent Cibolo Creek and Dry Comal Creek and Blanco River recharge subzones. Annual and monthly recharge rates for six recharge basins in the Barton Springs segment of the aquifer (fig. 3.8) were estimated using the methods described by Barrett and Charbeneau (1996) and Scanlon and others (2002). Recharge rates for the Colorado River recharge subzone were assumed to be the same as for the adjacent Barton Creek subzone. Monthly recharge rates for the recharge subzones simulated in the rediscretized regional Edwards aquifer models (conduit-flow and diffuse-flow models) are shown in table 3.4. For both the San Antonio and Barton Springs segments of the Edwards aquifer, 85 percent of the recharge was applied to streambed cells and the remaining 15 percent was applied to the interstream cells. A specified-flux boundary, simulated using the MODFLOW recharge package, was used to represent recharge to the aquifer in the recharge zone in the original and rediscretized regional Edwards aquifer models. No recharge was applied to cells outside the recharge zone.

Discharge

Discharge from the Edwards aquifer includes withdrawals by wells and springflow. Withdrawals by wells for 2000–03 were compiled and distributed spatially and temporally within the model grid for the rediscretized regional Edwards aquifer models (conduit-flow and diffuse-flow models). The vertical assignment of pumpage to a layer was done based on the percentage of the screened interval in each of the two layers. Withdrawals were separated into four categories based on water use: municipal, irrigation, industrial, which includes manufacturing, mining, and power generation, and livestock. Municipal withdrawals were provided (1) by well by EAA, Bexar Metropolitan Water District, and Fort Clark Municipal Utility District and (2) by entry point by the San Antonio Water System (SAWS) for each of their 36 well fields. Irrigation, industrial, and livestock withdrawals were provided by well for most of the model area, with the exception of Kinney County, where irrigation withdrawals were spatially distributed for the land-use categories of row crops, small grains, and orchard/vineyards. Industrial and livestock withdrawals for Kinney County are minimal and were not simulated in the models. All municipal and irrigation withdrawals for the years 2000 through 2003 were distributed to stress periods (months) based on factors developed for the original Edwards aquifer model (Lindgren and others, 2004). All industrial and livestock withdrawals were distributed to stress periods (months) based on factors provided by the reporting agency or developed by the Texas Water Development Board.

Discharge from the Edwards aquifer also includes springflow. Comal, San Marcos, Leona, San Antonio, and San Pedro Springs were simulated in the original and the rediscretized regional (layer 1) Edwards aquifer models and used for model calibration (fig. 3.7). The springs were simulated in the models using the MODFLOW drain package (Harbaugh and others, 2000). The MODFLOW drain package simulates the effects of features that remove water from the aquifer at a rate proportional to (1) the difference between the hydraulic head in the aquifer and the drain elevation and (2) the hydraulic conductance. The hydraulic conductance depends on the characteristics of the convergent flow pattern toward the drain, as well as on the characteristics of the drain itself and its immediate environment (Harbaugh and others, 2000). Conductance was adjusted during model calibration for the original Edwards aquifer model to match measured values of discharge to simulated values (Lindgren and others, 2004).



EXPLANATION

Recharge subzones, San Antonio segment
- 1 Nueces-West Nueces River
- 2 Frio-Dry Frio River
- 3 Sabinal River
- 4 Area between Sabinal and Medina Rivers
- 5 Medina River
- 6 Area between Medina River and Cibolo-Dry Comal Creeks
- 7 Cibolo Creek and Dry Comal Creek
- 8 Guadalupe River
- 9 Blanco River

Recharge subzones, Barton Springs segment
- 10 Onion Creek
- 11 Little Bear Creek
- 12 Bear Creek
- 13 Slaughter Creek
- 14 Williamson Creek
- 15 Barton Springs

Recharge subzones, Colorado River segment
- 16 Colorado River

Active groundwater-flow model area

Inactive groundwater-flow model area

Stream basin or contributing-area boundary

Spring

Figure 3.8. Simulated subzones of the recharge zone of the Edwards aquifer in the South-Central Texas regional study area, San Antonio region, Texas.

Table 3.4. Estimated recharge rates, by recharge subzone, in the rediscretized regional Edwards aquifer models area, 2000—2003, San Antonio region, Texas.

[Monthly recharge rates have been estimated by the U.S. Geological Survey for the San Antonio segment of the Edwards aquifer since 1934. For the Guadalupe River Basin, recharge is assumed to be negligible and is not estimated by the U.S. Geological Survey. Monthly recharge rates for the Barton Springs segment of the Edwards aquifer for 2000-2003 were estimated using the methods described by Barrett and Charbeneau (1996) and Scanlon and others (2002). The Barton Springs segment other than Onion Creek includes the Little Bear Creek, Bear Creek, Slaughter Creek, Williamson Creek, and Barton Creek recharge basins]

	Estimated recharge rate (cubic meters per month)									
	Recharge subzone									
	San Antonio segment								Barton Springs segment	
Month-Year	Nueces-West Nueces River	Frio-Dry Frio River	Sabinal River	Area between Sabinal and Medina River	Medina River	Area between Medina River and Cibolo Creek	Cibolo Creek and Dry Comal Creek	Blanco River	Onion Creek	Barton Springs segment other than Onion Creek
January-00	3,108,341	4,090,296	422,855	635,760	5,515,626	717,009	396,835	1,503,290	1,035,934	1,266,142
February-00	3,326,852	3,828,719	416,566	591,494	5,023,402	719,641	581,080	1,619,181	839,464	1,026,011
March-00	3,456,589	3,799,355	403,548	475,256	5,798,131	1,079,651	850,361	1,802,104	968,876	1,184,182
April-00	3,107,460	2,655,413	304,888	290,819	5,551,402	744,379	651,944	1,678,744	881,007	1,076,786
May-00	2,561,451	2,214,916	165,780	360,878	5,061,645	503,578	573,994	3,151,378	921,473	1,126,244
June-00	14,547,044	9,618,531	2,185,168	1,080,956	4,996,262	0	745,559	2,227,198	1,688,018	2,063,133
July-00	2,536,199	2,091,640	348,174	291,896	4,811,215	0	64,150	1,090,142	1,358,507	1,660,398
August-00	1,314,444	1,070,876	105,047	115,738	4,564,486	0	20,972	873,556	949,221	1,160,159
September-00	1,001,212	924,912	0	20,823	4,317,757	0	4,071	637,182	730,704	893,082
October-00	98,709,050	37,986,089	6,465,855	10,636,809	5,785,794	0	3,545,420	1,795,782	1,290,293	1,577,025
November-00	144,573,669	62,389,651	22,748,241	45,083,184	7,310,579	20,793,331	37,036,127	22,000,458	2,747,076	3,357,537
December-00	15,900,646	21,108,690	7,234,918	8,520,574	7,151,439	10,752,751	15,448,965	3,713,977	3,082,367	3,767,337
January-01	7,563,057	19,103,695	8,933,703	22,049,663	7,278,505	12,321,082	27,667,425	13,149,913	3,344,985	4,088,315
February-01	10,778,119	17,146,472	9,975,088	14,655,916	7,895,327	16,144,433	28,916,416	8,435,487	3,221,268	3,937,105
March-01	9,622,916	19,596,636	11,855,628	26,396,742	8,758,879	19,130,769	41,789,230	14,966,137	3,627,106	4,433,130
April-01	5,285,868	11,359,214	8,178,627	11,414,995	10,732,710	12,162,446	18,916,484	4,772,110	3,566,982	4,359,644
May-01	44,303,070	23,325,397	10,781,344	26,862,121	11,317,458	10,095,747	19,747,380	7,185,585	3,682,605	4,500,962
June-01	3,695,930	5,861,876	3,717,628	6,232,285	8,882,243	2,066,055	6,594,393	3,704,480	3,319,548	4,057,225
July-01	12,975,348	3,409,048	2,884,248	3,512,334	8,082,841	1,727,872	1,424,355	2,859,523	3,156,519	3,857,967
August-01	14,226,194	8,757,100	2,259,657	5,317,368	7,158,841	0	1,173,196	4,194,492	2,714,837	3,318,135
September-01	5,442,796	15,214,727	4,909,774	8,392,232	10,177,570	9,334,879	8,602,380	6,388,982	2,674,369	3,268,673
October-01	5,150,615	4,701,557	2,328,823	3,516,039	7,895,327	10,162,679	12,313,573	5,141,441	2,426,935	2,966,254
November-01	217,713,043	20,814,424	12,788,212	21,031,773	11,164,486	16,064,404	18,890,449	29,205,818	2,773,805	3,390,207
December-01	30,226,533	7,008,897	3,026,228	3,756,792	11,624,636	16,029,961	28,235,130	10,662,579	3,787,823	4,629,561

Table 3.4. Estimated recharge rates, by recharge subzone, in the rediscretized regional Edwards aquifer models area, 2000—2003, San Antonio region, Texas.—Continued

[Monthly recharge rates have been estimated by the U.S. Geological Survey for the San Antonio segment of the Edwards aquifer since 1934. For the Guadalupe River Basin, recharge is assumed to be negligible and is not estimated by the U.S. Geological Survey. Monthly recharge rates for the Barton Springs segment of the Edwards aquifer for 2000-2003 were estimated using the methods described by Barrett and Charbeneau (1996) and Scanlon and others (2002). The Barton Springs segment other than Onion Creek includes the Little Bear Creek, Bear Creek, Slaughter Creek, Williamson Creek, and Barton Creek recharge basins]

Month-Year	Estimated recharge rate (cubic meters per month)									
	Recharge subzone									
	San Antonio segment								Barton Springs segment	
	Nueces-West Nueces River	Frio-Dry Frio River	Sabinal River	Area between Sabinal and Medina River	Medina River	Area between Medina River and Cibolo Creek	Cibolo Creek and Dry Comal Creek	Blanco River	Onion Creek	Barton Springs segment other than Onion Creek
January-02	11,806,244	5,423,141	4,233,931	5,071,488	9,054,953	9,755,560	13,715,385	3,129,298	4,006,351	4,896,651
February-02	5,224,695	4,221,452	2,813,975	2,435,091	8,943,925	5,626,580	5,484,832	2,013,671	3,513,795	4,294,638
March-02	3,345,938	3,567,386	2,286,660	1,585,642	8,709,533	4,321,384	4,166,771	3,339,609	3,642,137	4,451,501
April-02	3,574,604	3,807,186	2,472,872	1,532,867	8,487,477	655,241	3,349,558	3,790,173	3,398,172	4,153,321
May-02	3,241,283	4,866,987	2,625,515	1,555,020	7,957,009	1,767,118	1,544,823	3,298,125	3,245,549	3,966,782
June-02	6,142,292	2,747,478	1,628,680	1,173,494	7,266,168	0	6,803,089	8,704,268	2,765,712	3,380,314
July-02	22,397,820	173,499,971	28,719,089	274,569,715	12,953,271	146,651,517	270,495,169	56,132,948	3,466,390	4,236,698
August-02	3,364,633	6,116,427	2,755,490	7,309,614	9,091,963	16,379,860	97,549,416	22,009,741	3,608,606	4,410,519
September-02	2,271,343	11,368,225	11,229,759	44,847,685	12,459,813	5,463,426	90,383,767	22,984,136	3,190,050	3,898,949
October-02	37,244,749	22,500,865	14,651,846	54,988,343	12,459,813	3,244,664	8,584,846	14,170,155	3,076,739	3,760,458
November-02	3,556,296	9,649,260	6,954,286	20,185,646	9,128,972	12,332,298	34,378,942	27,218,324	3,406,265	4,163,213
December-02	1,024,018	7,935,409	6,688,451	10,660,362	9,116,636	10,260,587	15,927,800	18,277,137	3,816,728	4,664,890
January-03	3,737,497	11,711,029	5,324,285	6,023,293	9,496,598	9,888,058	22,141,792	7,770,641	3,901,133	4,768,052
February-03	3,297,489	8,571,612	3,574,971	5,715,180	9,496,598	12,193,561	22,394,062	22,727,332	3,683,761	4,502,375
March-03	3,327,317	8,116,482	3,124,246	7,942,040	9,957,981	13,966,733	14,555,354	3,178,416	4,134,693	5,053,513
April-03	3,168,071	6,508,846	2,544,323	5,008,101	9,227,664	8,145,198	16,793,872	4,546,807	3,720,761	4,547,597
May-03	2,182,029	5,186,767	1,753,718	2,874,761	8,758,879	5,783,097	9,875,477	4,252,251	3,591,263	4,389,321
June-03	17,290,343	19,368,633	6,593,602	12,569,792	9,816,112	7,332,075	13,138,732	6,455,332	3,324,173	4,062,878
July-03	5,144,288	10,331,499	5,809,213	29,623,078	9,816,112	2,260,968	9,800,558	6,322,755	3,196,987	3,907,429
August-03	3,250,875	6,314,498	2,168,718	3,768,349	8,450,467	2,160,599	5,428,349	5,446,454	2,936,834	3,589,464
September-03	57,392,439	21,652,124	2,171,165	2,787,663	8,475,140	1,009,528	5,156,996	3,884,392	2,445,435	2,988,865
October-03	77,559,058	21,482,481	2,801,281	2,822,970	8,276,523	1,883,196	1,346,406	2,913,304	2,030,347	2,481,535
November-03	4,476,422	11,735,280	1,737,813	2,231,154	7,833,645	2,454,163	1,962,918	2,801,731	1,492,698	1,824,409
December-03	3,919,304	7,482,726	1,501,219	1,778,986	7,414,206	2,277,308	6,880,718	3,653,293	1,431,418	1,749,510

Model Calibration and Sensitivity

The rediscretized regional Edwards aquifer models (conduit-flow and diffuse-flow models) were calibrated for steady-state and transient conditions. Average stresses (recharge and pumpage) during 2001, a representative year for the recent time period (2000–03), were used to simulate steady-state conditions. The transient simulation period for the rediscretized regional Edwards aquifer models was 2000–2003, including 48 monthly stress periods. The calibrated parameter values from the conduit-flow and diffuse-flow Edwards aquifer models were used as the initial parameter values for the conduit-flow and diffuse-flow rediscretized regional Edwards aquifer models, respectively. The interested reader is referred to Lindgren and others (2004) and Lindgren (2006) for further discussion of the calibration of the original Edwards aquifer models.

The steady-state and transient simulations for the rediscretized regional Edwards aquifer models were calibrated to 2000–2003 conditions, primarily using a trial-and-error approach, by varying the simulated recharge rates and hydraulic conductivities. The use of parameter estimation to determine optimized parameters for the steady-state simulation was investigated, but it was of limited usefulness due to correlation between the parameters. The initial average recharge rates for year 2001 and the initial monthly recharge rates for 2000–03 for the recharge subzones were adjusted during model calibration for the rediscretized regional Edwards aquifer models until the differences between model-computed and measured hydraulic heads and springflows were minimized. As a result of the calibration, the calibrated recharge rates were reduced by 10 percent for most of the recharge subzones and as much as 50 percent for the Cibolo Creek and Dry Comal Creek subzone, compared to the simulated initial rates. In addition, the hydraulic conductivities for some zones were adjusted for both the conduit-flow and diffuse-flow models, and the drain conductance for Leona Springs was reduced from 18,580 m^2/d to 9,290 m^2/d. The final calibrated distribution of horizontal hydraulic conductivity for the conduit-flow and diffuse-flow rediscretized regional Edwards aquifer models is shown in figures 3.9*A* and 3.9*B*, respectively. The distribution of storativity for the calibrated rediscretized regional Edwards aquifer models is the same as for the original Edwards aquifer models (Lindgren and others, 2004; Lindgren, 2006) and is shown in figure 3.10.

A series of sensitivity tests was made for the conduit-flow Edwards aquifer model (Lindgren and others, 2004) to ascertain how the model results were affected by variations greater than and less than the calibrated values of input data. Simulated hydraulic heads and springflows in the model were most sensitive to recharge, withdrawals, hydraulic conductivity of the conduit segments, and specific yield and relatively insensitive to spring-orifice conductance, northern boundary inflow, and specific storage (Lindgren and others, 2004). Larger values of hydraulic conductivity result in increased springflow if the reduced recharge, due to model cells going dry, is accounted for. Moving the simulated southern no-flow model boundary northward from the 10,000-mg/L dissolved-solids concentration line to the 1,000-mg/L dissolved-solids concentration line resulted in minimal changes in simulated hydraulic heads and springflows. The effect of lowering the simulated spring-orifice altitudes for Comal and San Marcos Springs was to appreciably lower hydraulic heads in the aquifer, because the spring-orifice altitudes serve as a controlling base level for hydraulic heads in the aquifer.

The overall goodness of fit of the original and rediscretized regional Edwards aquifer models to the observation data was evaluated using summary statistics and graphical analyses. The goodness of fit between simulated and measured hydraulic heads and springflows was quantified using the mean absolute difference, mean algebraic difference, and root mean square (RMS) error. If the ratio of the RMS error to the total head change in the modeled area is small, then the error in the head calculations is a small part of the overall model response (Anderson and Woessner, 1992).

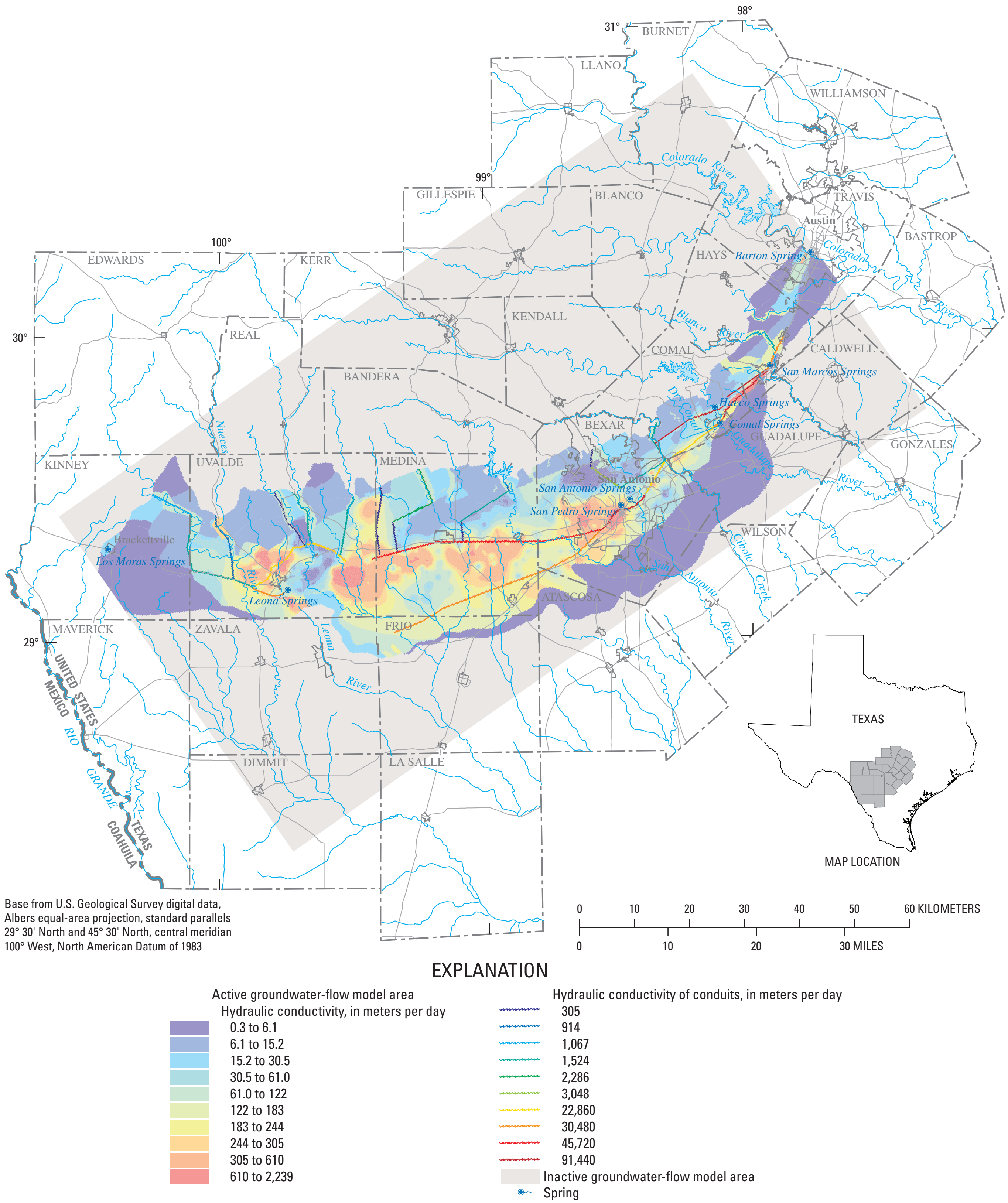


Figure 3.9*A*. Simulated distribution of horizontal hydraulic conductivity for the calibrated conduit-flow rediscretized regional Edwards aquifer model, San Antonio region, Texas.

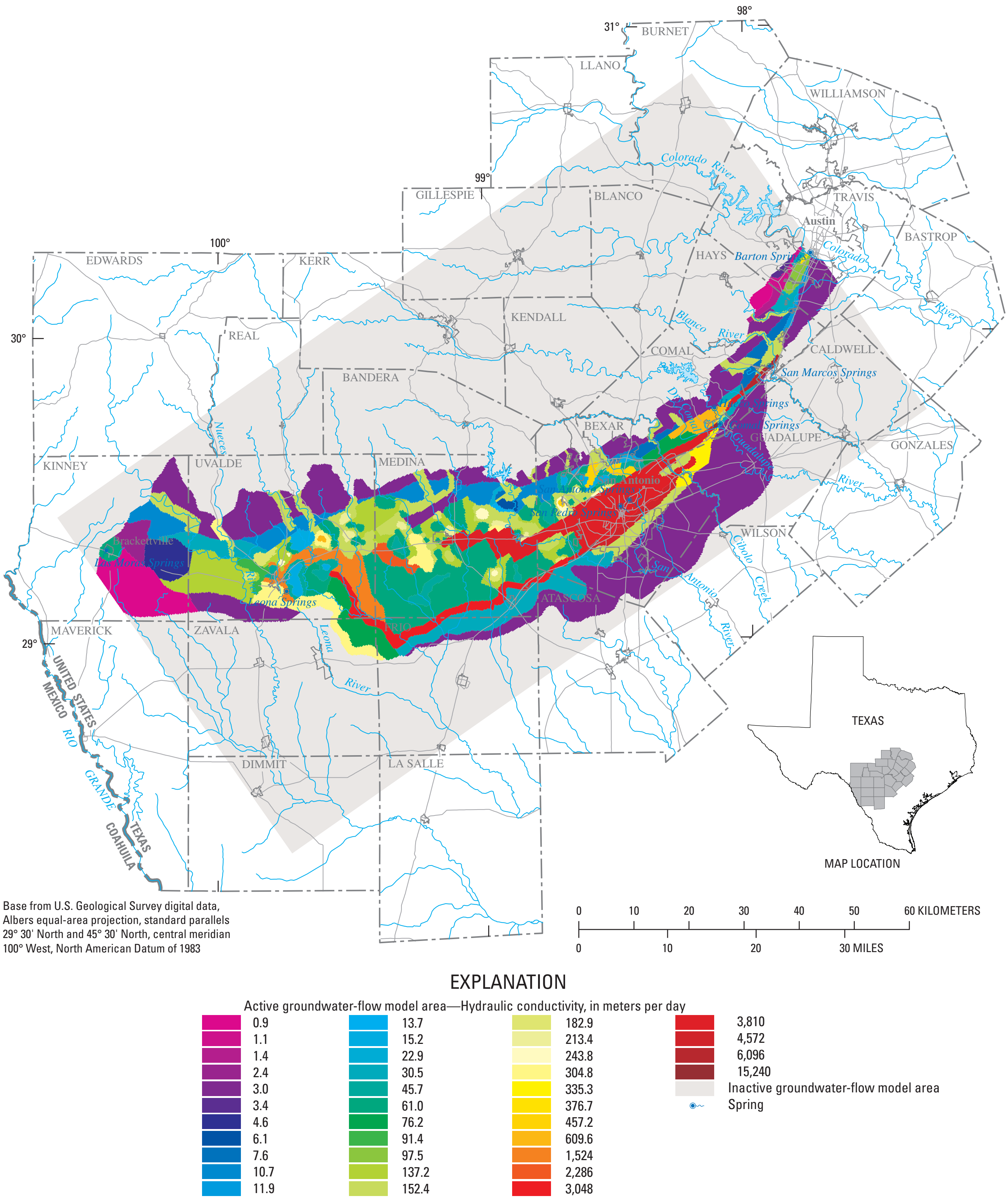


Figure 3.9*B*. Simulated distribution of horizontal hydraulic conductivity for the calibrated diffuse-flow rediscretized regional Edwards aquifer model, San Antonio region, Texas.

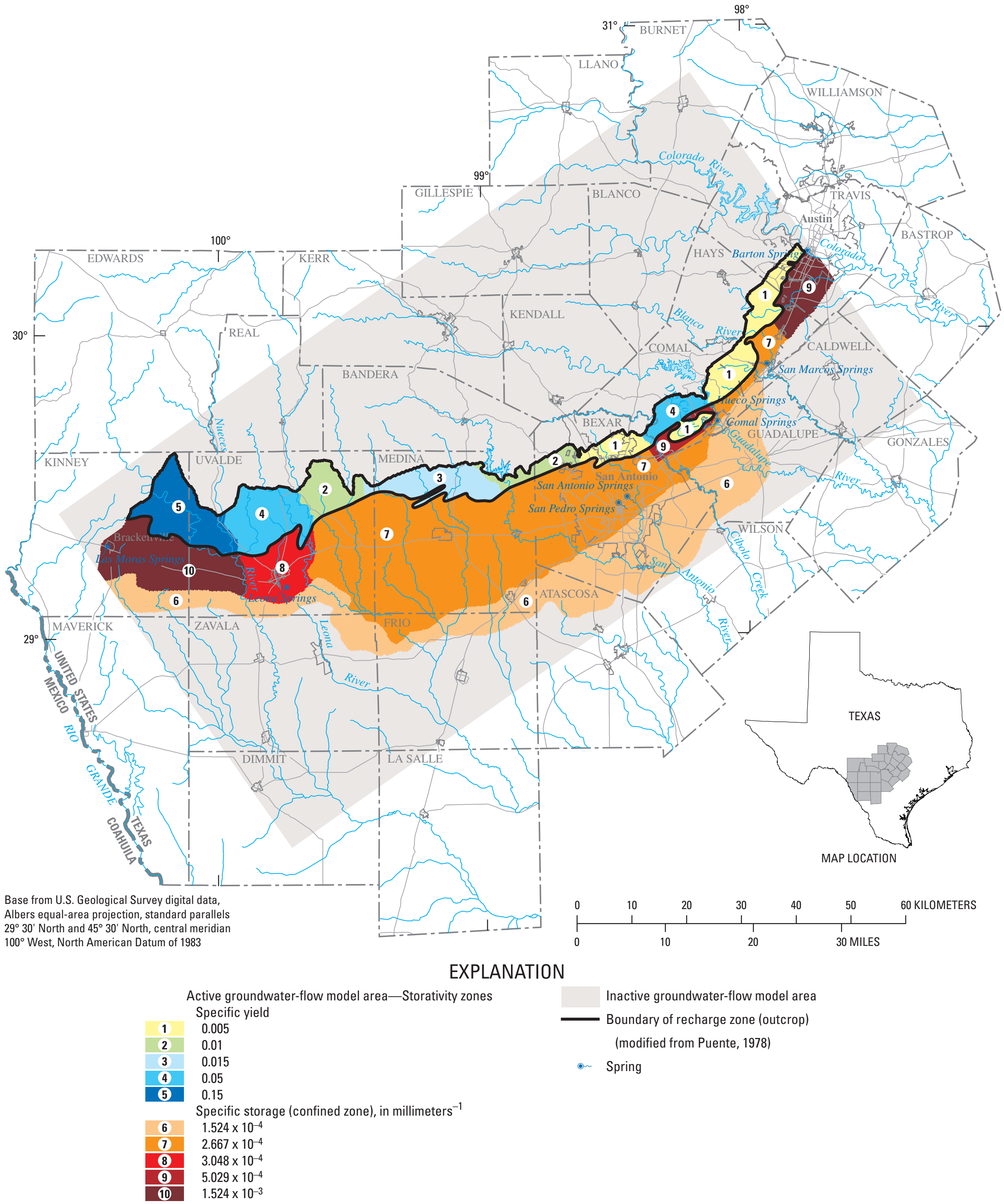


Figure 3.10. Simulated storativity zones for the calibrated rediscretized regional Edwards aquifer models, San Antonio region, Texas.

Model-Computed Hydraulic Heads

The steady-state simulation calibration results for the rediscretized regional Edwards aquifer models (conduit-flow and diffuse-flow models) include a comparison of simulated hydraulic heads to average measured water levels for 2001. Simulated hydraulic heads were within 9.0 m of measured water levels at 177 of the 229 wells used as targets for the conduit-flow rediscretized regional Edwards aquifer model for the calibrated steady-state simulation (fig. 3.11*A*). The difference was less than 6.0 m at 129 of the 229 wells. The mean absolute difference between simulated and measured hydraulic heads is 7.4 m (table 3.5). The RMS error is 10.5 m, which represents about 5 percent of the total head difference across the model area. For the diffuse-flow rediscretized regional Edwards aquifer model, simulated hydraulic heads were within 9.0 m of measured water levels at 185 of the 229 wells used as calibration targets for the steady-state simulation (fig. 3.11*B*). The difference was less than 6.0 m at 159 of the 229 wells. The mean absolute difference between simulated and measured hydraulic heads is 6.3 m (table 3.5). The RMS error is 11.0 m, which represents about 5 percent of the total head difference across the model area. The graphs of simulated relative to measured hydraulic heads indicate little spatial bias in the steady-state simulation results for the conduit-flow and diffuse-flow models (fig. 3.12*A*).

The transient simulation results for the rediscretized regional Edwards aquifer models (conduit-flow and diffuse-flow models) include a comparison of simulated hydraulic heads with synoptic sets of water levels in multiple wells during 2000–03. Eight synoptic sets of water-level measurements during January or February and July of each year were used for model calibration, (table 3.5). The mean absolute difference between simulated and measured hydraulic heads for the calibrated transient simulation for the conduit-flow rediscretized regional Edwards aquifer model ranged from 6.4 to 8.7 m for the eight time periods (table 3.5). The RMS error ranged from 9.8 to 10.6 m for seven of the eight time periods, but it was comparatively large (15.6 m) for July 2002, coincident with the large recharge to the Edwards aquifer that occurred during July 2002 (871.5 hm^3). These errors represent 4.4 to 4.8 percent of the total head difference across the model for seven of the eight time periods, compared with 7.0 percent for July 2002.

The mean absolute difference between simulated and measured hydraulic heads for the calibrated transient simulation for the diffuse-flow rediscretized regional Edwards aquifer model ranged from 6.0 to 8.7 m for the eight time periods (table 3.5), with the largest difference being for July 2002, as for the conduit-flow model. The RMS error ranged from 9.7 to 11.9 m for seven of the eight time periods, but it was somewhat larger (13.4 m) for July 2002. These errors represent 4.3 to 4.8 percent of the total measured head difference across the model area for the first five time periods (January 2000 through January 2002), compared to 5.2 to 6.0 percent for the last three time periods (July 2002 through July 2003). The graphs of simulated relative to measured hydraulic heads indicate little spatial bias in the transient simulation results for the conduit-flow and diffuse-flow models (figs. 3.12*B* and 3.12*C*).

Model-Computed Springflow

The steady-state simulation calibration results for the rediscretized regional Edwards aquifer models (conduit-flow and diffuse-flow models) include a comparison of simulated springflows with median springflows for 2001. The simulated springflows for Comal and San Marcos Springs for the calibrated steady-state simulation for the conduit-flow rediscretized regional Edwards aquifer model were within 1.3 and 0.3 percent of the median springflows for the two springs, respectively (table 3.5). The simulated springflows for San Antonio and San Pedro Springs were 17.6 and 37.5 percent greater than the median measured springflows, respectively. However, their discharges probably reflect local hydrogeologic conditions. The simulated springflow for Leona Springs was 63.6 percent greater than the median measured springflow. However, this discrepancy probably is reasonable because the reported discharge for Leona Springs might not account for all of the discharge from the Edwards aquifer to the Leona gravels (Green, 2004). The simulated springflows for Comal, San Marcos, and San Pedro Springs for the calibrated steady-state simulation for the diffuse-flow rediscretized regional Edwards aquifer model were within 1.2 percent of the median measured springflows for the three springs (table 3.5).

The transient calibration results for the rediscretized regional Edwards aquifer models (conduit-flow and diffuse-flow models) include a comparison of simulated springflows with a series of measurements of springflow during the 2000–03 period. The RMS errors for the conduit-flow rediscretized regional Edwards aquifer model for Comal, San Marcos, Leona, San Antonio, and San Pedro Springs ranged from 0.11 cubic meters per second (m^3/s) for San Pedro Springs to 1.44 m^3/s for Comal Springs (table 3.5). The RMS errors for the five springs, as a percentage of the range of springflow fluctuations measured at the springs, varied from 15.5 percent for San Antonio Springs to 27.0 percent for Leona Springs and were 17.7 percent or less for all but Leona Springs. The RMS errors for the diffuse-flow rediscretized regional Edwards aquifer model for Comal, San Marcos, Leona, San Antonio, and San Pedro Springs ranged from 0.17 m^3/s for San Pedro Springs to 2.47 m^3/s for San Antonio Springs (table 3.5). The RMS errors for the five springs, as a percentage of the range of discharge fluctuations measured at the springs, varied from 9.3 percent for Comal Springs and 16.7 percent for San Marcos Springs to 49.3 percent for San Antonio Springs.

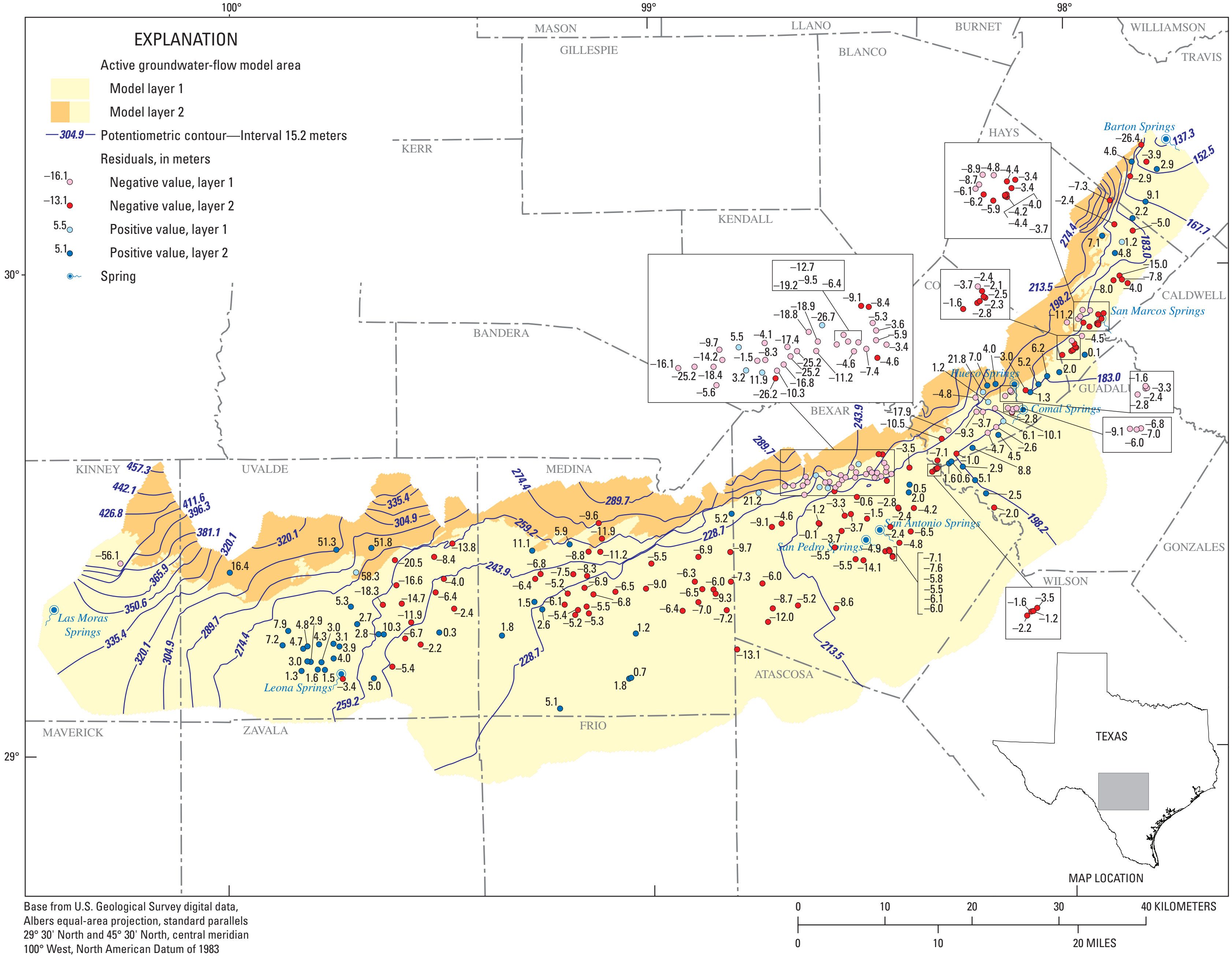
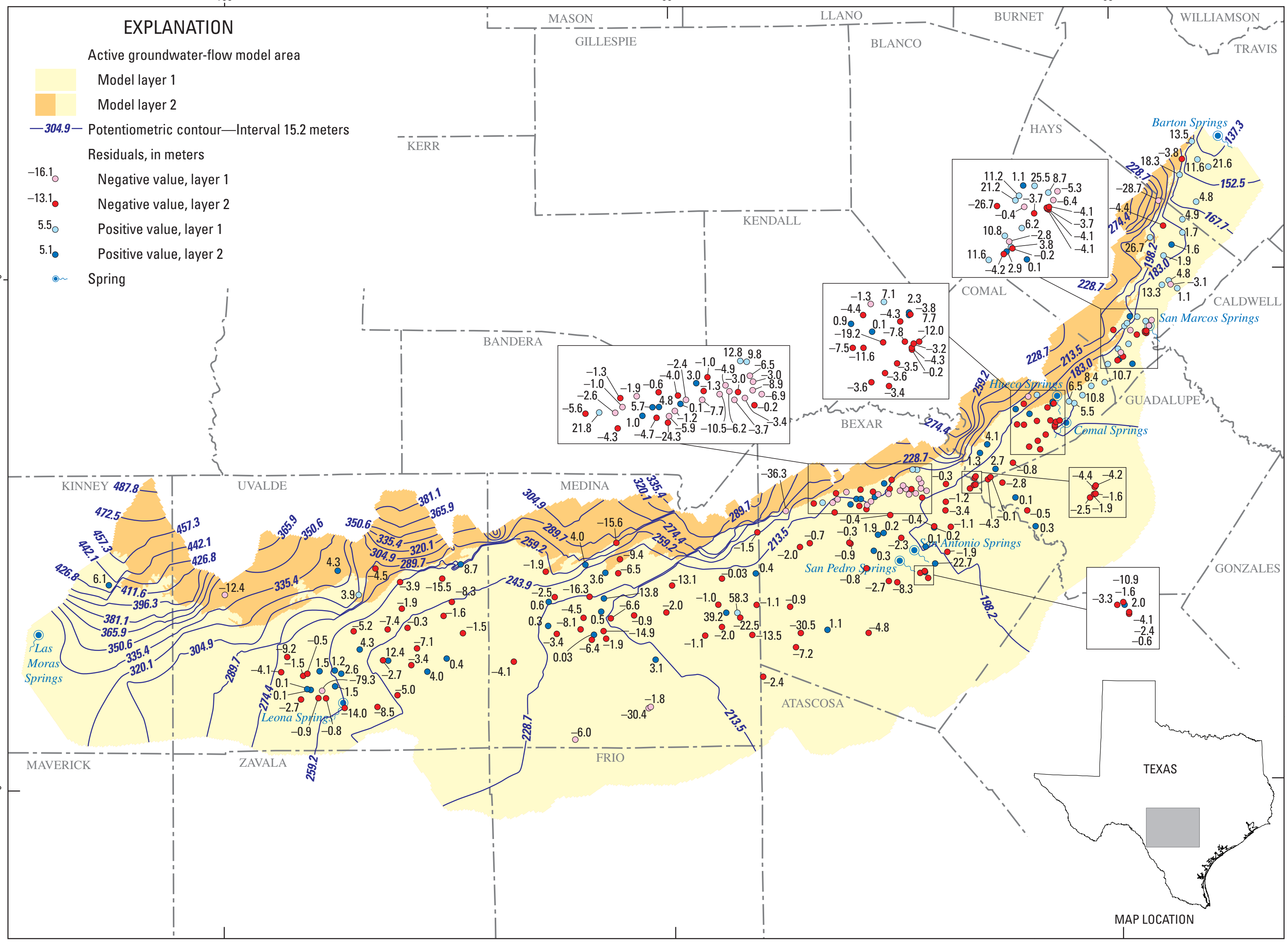


Figure 3.11*A*. Simulated potentiometric surface in model layer 2 and hydraulic head residuals in model layers 1 and 2 for the conduit-flow rediscretized regional Edwards aquifer model, steady-state simulation, San Antonio region, Texas.



Base from U.S. Geological Survey digital data,
Albers equal-area projection, standard parallels
29° 30' North and 45° 30' North, central meridian
100° West, North American Datum of 1983

Figure 3.11*B*. Simulated potentiometric surface in model layer 2 and hydraulic head residuals in model layers 1 and 2 for the diffuse-flow rediscretized regional Edwards aquifer model, steady-state simulation, San Antonio region, Texas.

Table 3.5. Comparison of residuals for hydraulic heads and springflows for the conduit-flow and diffuse-flow rediscretized regional Edwards aquifer models, San Antonio region, Texas.

[Mean algebraic difference is the algebraic sum of the residuals, which is simulated water level or springflow minus the measured water level or springflow, divided by the number of wells. Mean absolute difference is the sum of the absolute values of the residuals divided by the number of measurements. m^3/s, cubic meters per second; NA, not applicable]

			Hydraulic head residuals (meters)					
			Conduit-flow rediscretized regional Edwards aquifer model			Diffuse-flow rediscretized regional Edwards aquifer model		
Time of measurements	Stress period	Number of wells	Mean algebraic difference	Mean absolute difference	Root mean square	Mean algebraic difference	Mean absolute difference	Root mean square
Steady-state	NA	229	3.4	7.6	11.2	1.4	6.3	11.0
January-00	1	235	1.8	6.8	10.3	0.0	6.0	9.7
July-00	7	221	0.7	6.7	10.5	0.0	6.9	10.6
February-01	14	218	-0.1	6.6	10.5	-0.5	6.7	10.5
July-01	19	221	1.9	6.8	9.9	0.5	6.4	10.1
January-02	25	222	1.1	6.4	9.8	-0.8	6.5	10.4
July-02	31	205	3.5	8.7	15.6	1.6	8.7	13.4
February-03	38	207	4.5	7.9	10.5	-0.8	7.2	11.9
July-03	43	229	2.8	7.0	10.1	-0.9	7.7	11.5

				Springflow residuals (cubic meters per second)							
				Conduit-flow rediscretized regional Edwards aquifer model				Diffuse-flow rediscretized regional Edwards aquifer model			
Spring name	Median 2001 springflow (m^3/s)	Period of measurements	County	Steady-state residual	Mean algebraic difference	Mean absolute difference	Root mean square	Steady-state residual	Mean algebraic difference	Mean absolute difference	Root mean square
Comal	9.69	Steady-state	Comal	0.15				0.08			
		2000–03			0.17	1.15	1.44		-0.16	0.64	0.76
San Marcos	6.57	Steady-state	Hays	0.03				-0.07			
		2000–03			-0.07	0.84	0.99		-0.14	0.83	1.03
Leona	0.33	Steady-state	Uvalde	0.21				0.21			
		2000–03			0.15	0.32	0.40		0.07	0.29	0.34
San Antonio	0.91	Steady-state	Bexar	0.14				0.01			
		2000–03			-0.26	0.56	0.78		1.45	1.60	2.47
San Pedro	0.24	Steady-state	Bexar	0.09				-0.09			
		2000–03			0.07	0.08	0.11		-0.12	0.13	0.17

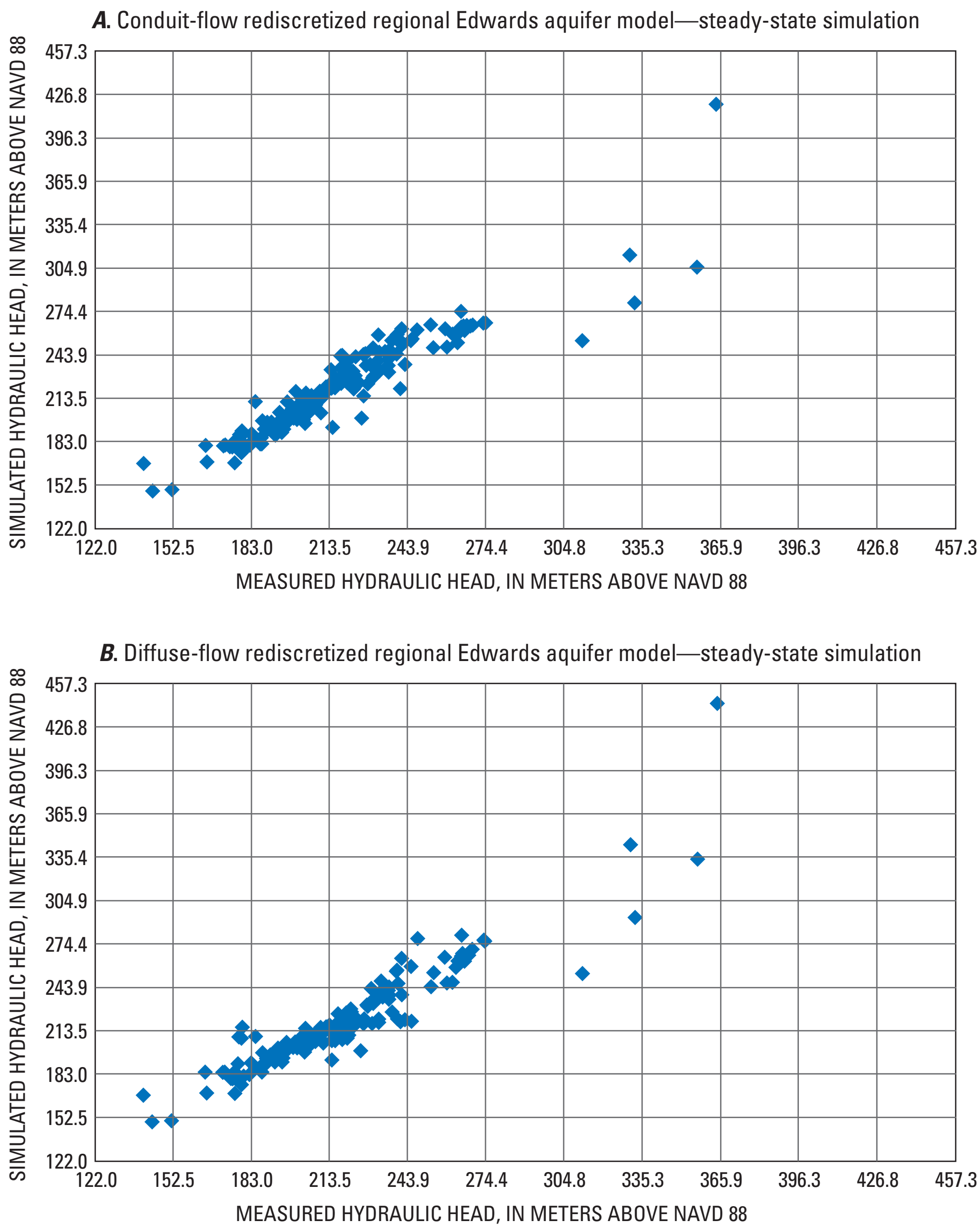


Figure 3.12*A*. Simulated relative to measured hydraulic heads for (*A*) conduit-flow and (*B*) diffuse-flow rediscretized regional Edwards aquifer models, steady-state simulation, San Antonio region, Texas.

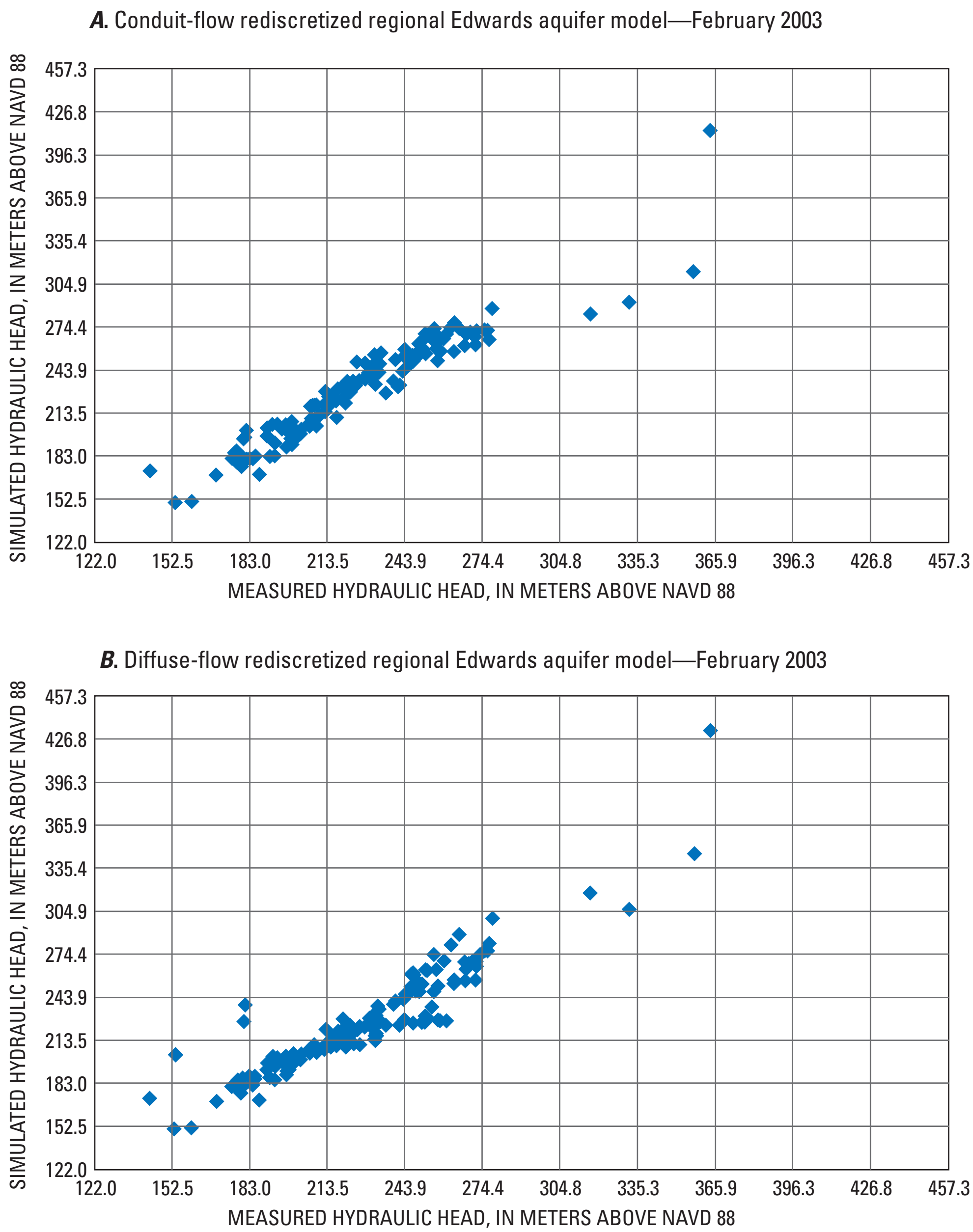
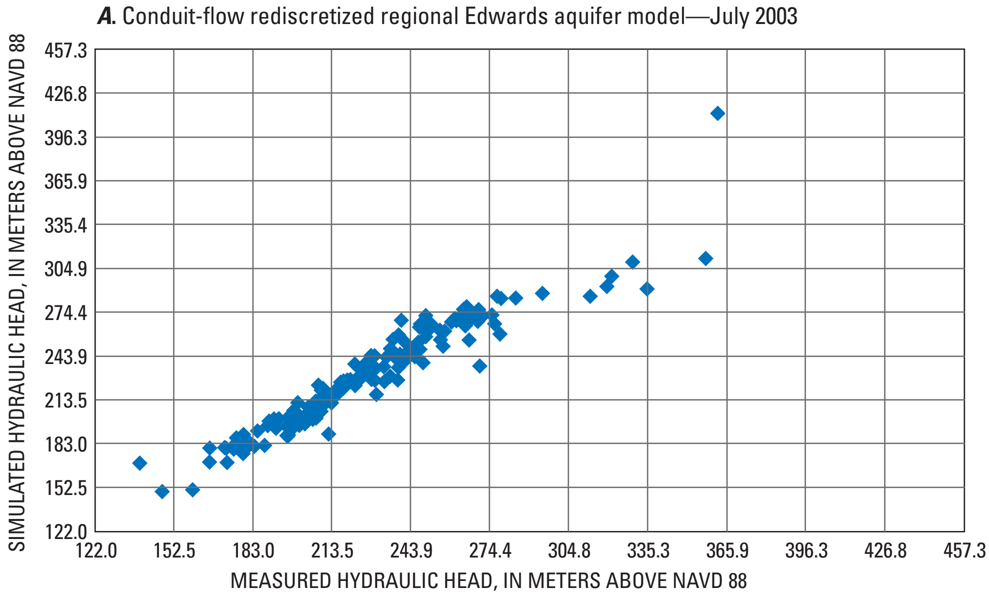


Figure 3.12*B*. Simulated relative to measured hydraulic heads for (*A*) conduit-flow and (B) diffuse-flow rediscretized regional Edwards aquifer models for February 2003, which was a period of average recharge and comparatively small groundwater withdrawals by wells, San Antonio region, Texas.



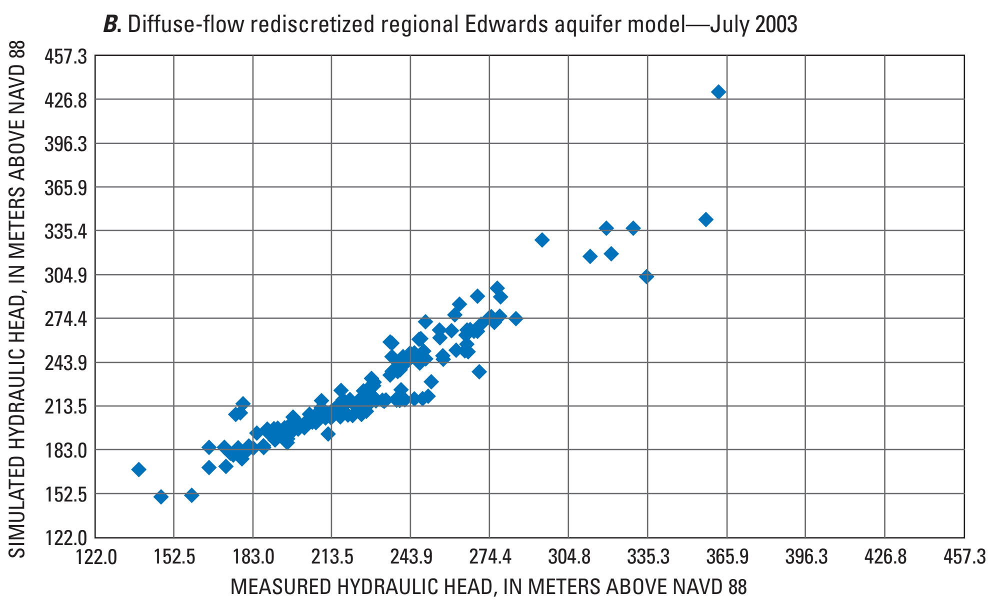


Figure 3.12*C*. Simulated relative to measured hydraulic heads for (*A*) conduit-flow and (*B*) diffuse-flow rediscretized regional Edwards aquifer models for July 2003,which was a period of average recharge and comparatively large groundwater withdrawals by wells,
San Antonio region, Texas.

Model-Computed Water Budget

The water budgets for the rediscretized regional Edwards aquifer models (conduit-flow and diffuse-flow models) for the steady-state simulation and for year 2003 of thetransient simulation are shown in figure 3.13 and table 3.6. The steady-state simulation water budget for the conduit-flow rediscretized regional Edwards aquifer model indicates that recharge accounts for 95.9 percent of the sources of water to the Edwards aquifer and inflow through the northern and northwestern model boundaries contributes 4.1 percent (fig. 3.13*A*; table 3.6). Most of the simulated recharge, 91.3 percent, is applied in layer 2, because layer 1 is absent for much of the recharge zone (fig. 3.7). The largest discharges from the Edwards aquifer in the steady-state simulation water budget are springflow, 54.2 percent, and withdrawals by wells, 45.8 percent (fig. 3.13*A*; table 3.6). The groundwater withdrawals are greater for layer 1,which accounts for 63.9 percent of total withdrawals, than for layer 2,which accounts for 36.1 percent of total withdrawals. The steady-state simulation water budget for the diffuse-flow rediscretized regional Edwards aquifer model (fig. 3.13*B*; table 3.6) is similar to the simulated water budget for the conduit-flow rediscretized regional Edwards aquifer model.

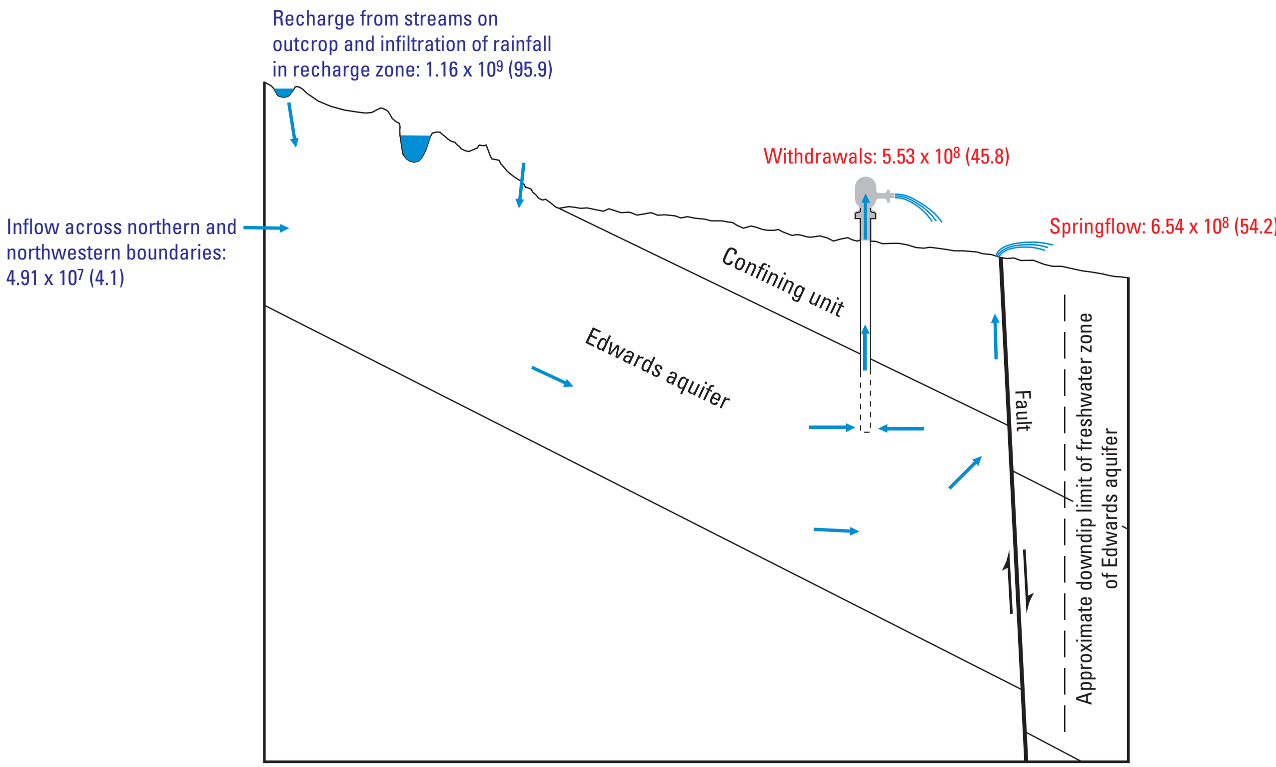
The principal source of water to the Edwards aquifer, excluding change in storage, for the conduit-flow rediscretized regional Edwards aquifer model for the transient simulation is recharge, constituting 94.2 percent of the sources of water to the Edwards aquifer during 2003 (fig. 3.13*A*; table 3.6). Inflow through the northern and northwestern model boundaries contributed a relatively small amount of water, 5.8 percent. During 2003, recharge constituted 64.8 percent of the total sources to the aquifer, including change in storage, compared to 31.2 percent for the net annual change in storage, expressed as net release of water from storage or net gain of water to the aquifer (fig. 3.13*A*; table 3.6). Most of the net release of water from storage (83.3 percent) was derived from layer 2. The aquifer was being depleted of water—water was released from storage—for 10 of the 12 months during 2003. The principal discharges from the Edwards aquifer for the conduit-flow rediscretized regional Edwards aquifer model for the transient simulation during 2003 are springflow, 65.7 percent, and withdrawals by wells, 34.3 percent (fig. 3.13*A*; table 3.6). Net addition to storage,or discharge from the aquifer, occurred in September and October during 2003. The transient simulation water budget for the diffuse-flow rediscretized regional Edwards aquifer model (fig. 3.13*B*; table 3.6) is similar to the simulated water budget for the conduit-flow rediscretized regional Edwards aquifer model.

Simulation of Areas Contributing Recharge to Public-Supply Wells

The calibrated steady-state rediscretized regional Edwards aquifer models (conduit-flow and diffuse-flow models) were used to estimate water particle traveltimes and areas contributing recharge for 68 public-supply wells from the four quartiles of pumping rates using the MODPATH (Pollock, 1994) particle-tracking post processor and methods outlined in Chapter A, Section 1 of this Professional Paper. Use of the steady-state simulations, rather than the transient simulations, simplified and facilitated the simulation of areas contributing recharge and traveltimes to public-supply wells, especially with respect to dealing with weak sinks (Leon Kauffman, U.S. Geological Survey, written commun., 2008). Reilly and Pollack (1995) showed that when the mean traveltime is much greater than the cyclical nature of the stresses on a system, the steady-state results do not differ appreciably from a transient analysis. This conclusion can be expected to hold true for the steady-state results presented here. However, there are likely fast flow paths that are not represented in the models, and this can cause more variation in the traveltime distributions and locations of areas contributing recharge than would be computed by either the transient simulations or the steady-state simulations. The effects of storage, not accounted for in steady-state simulations, on traveltimes are likely to be minimal because the water released from storage is ultimately derived from recharge and is not a different source of water (Leon Kauffman, U.S. Geological Survey, written commun., 2008). The water released from storage is derived from recharge, is of an age corresponding to the time that recharge occurred, and is not a new source of water that would have a different age. The model-computed areas contributing recharge represent advective groundwater flow and do not account for mechanical dispersion. Advection-dispersion transport simulations would likely yield larger areas contributing recharge than advective particle-tracking simulations, because the effects of dispersion caused by aquifer heterogeneity would be included.

In addition to output from the groundwater-flow models, the MODPATH simulations require effective porosity values to calculate groundwater-flow velocities. For the rediscretized regional Edwards aquifer models (conduit-flow and diffuse-flow models), porosity values were assumed uniform within each layer based on typical regional values. A porosity of 0.18,the average for the Edwards aquifer reported by Hovorka and others (1996), was used for both layers (model layers 1 and 2) in the models. Because of the karst nature of groundwater flow in the study area, the porosity values used for this regional simulation would not be applicable to local karst conditions.

A.



Units are cubic meters per year; numbers in parentheses are percentages of total sources or discharges.

A. Steady-state simulation

EXPLANATION

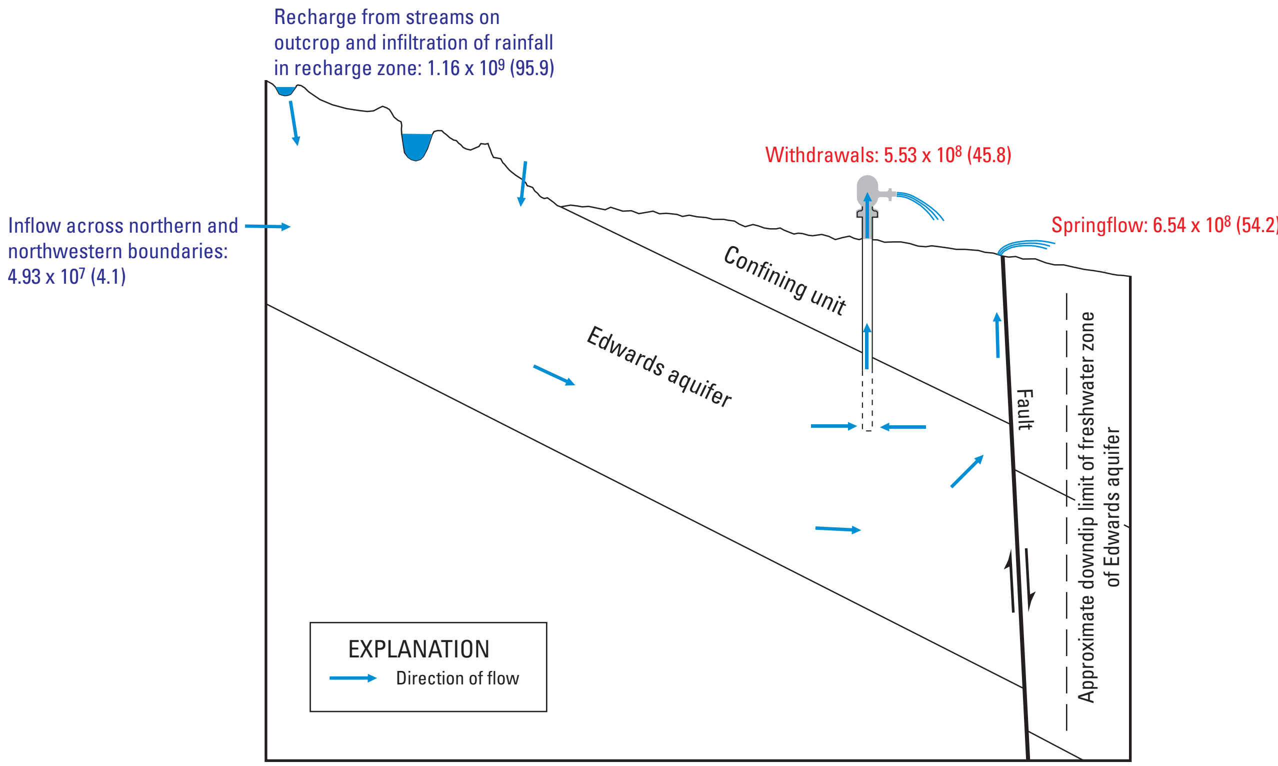
Direction of flow

	2003
Recharge	+7.98 x 10^8 (64.8)
Boundary inflow	+4.89 x 10^7 (4.0)
Springflow	–8.10 x 10^8 (65.7)
Withdrawals	–4.22 x 10^8 (34.3)
Net change in storage	+3.85 x 10^8 (31.2)

Units are cubic meters; + is source of water to aquifer, including release of water from storage; – is discharge of water from aquifer, including addition of water to storage; numbers in parentheses are percentages of total sources or discharges.

Figure 3.13*A*. Schematic diagram showing simulated water-budget components for (*A*) steady-state simulation and (*B*) year 2003 of the transient simulation for the conduit-flow rediscretized regional Edwards aquifer model, San Antonio region, Texas..

B.



Units are cubic meters per year; numbers in parentheses are percentages of total sources or discharges.

A. Steady-state simulation

	2003
Recharge	+7.98 x 10^8 (62.8)
Boundary inflow	+4.93 x 10^7 (3.9)
Springflow	–8.48 x 10^8 (66.7)
Withdrawals	–4.23 x 10^8 (33.3)
Net change in storage	+4.22 x 10^8 (33.3)

Units are cubic meters; + is source of water to aquifer, including release of water from storage; – is discharge of water from aquifer, including addition of water to storage; numbers in parentheses are percentages of total sources or discharges.

B. Transient simulation

Figure 3.13*B*. Schematic diagram showing simulated water-budget components for (*A*) steady-state simulation and (*B*) year 2003 of the transient simulation for the diffuse-flow rediscretized regional Edwards aquifer model, San Antonio region, Texas.

Table 3.6. Simulated annual water budget for steady-state simulation and for year 2003 of the transient simulation for the conduit-flow and diffuse-flow rediscretized regional Edwards aquifer models, San Antonio region, Texas.

[Recharge includes leakage from streams through streambeds and infiltration of precipitation in interstream areas. Boundary inflow includes inflow through specified-flow boundary condition cells at the northern and northwestern model boundaries. Subtotal includes source or discharge components exclusive of changes in storage. Total includes changes in storage. Negative net change in storage indicates a net loss of water from storage (storage is included as a source). hm^3/yr, cubic hectometers per year; NA, not applicable]

	Source								
	Conduit-flow rediscretized regional Edwards aquifer model				Diffuse-flow rediscretized regional Edwards aquifer model				
Budget component and time period	Flow rate (hm^3/yr)	Percent of budget component	Percent of subtotal for sources or discharges	Percent of total sources or discharges	Flow rate (hm^3/yr)	Percent of budget component	Percent of subtotal for sources or discharges	Percent of total sources or discharges	Change in percent of total sources
Recharge									
Steady-state									
Layer 1	101	8.7	NA	8.3	101	8.7	NA	8.3	0.0
Layer 2	1,058	91.3	NA	87.6	1,058	91.3	NA	87.6	0.0
Subtotal	1,158	100.0	NA	95.9	1,158	100.0	NA	95.9	0.0
2003									
Layer 1	80	10.0	9.4	6.5	80	10.0	9.5	6.3	0.2
Layer2	719	90.0	84.8	58.3	719	90.0	84.7	56.5	1.8
Subtotal	799	100.0	94.2	64.8	799	100.0	94.2	62.8	2.0
Boundary inflow (layer 2)									
Steady-state	49	NA	NA	4.1	49	NA	NA	4.1	0.0
2003	49	NA	5.8	4.0	49	NA	5.8	3.9	0.1
Subtotal									
2003	848	NA	100.0	68.8	848	NA	100.0	66.7	2.1
Total sources									
Steady-state	1,207	NA	NA	100.0	1,208	NA	NA	100.0	0.0
2003	1,233	NA	NA	100.0	1,271	NA	NA	100.0	0.0
	Discharge								
Withdrawals (pumpage)									
Steady-state									
Layer 1	353	63.9	NA	29.3	353	63.9	NA	29.3	0.0
Layer2	200	36.1	NA	16.5	200	36.1	NA	16.5	0.0
Subtotal	553	100.0	NA	45.8	553	100.0	NA	45.8	0.0
2003									
Layer 1	262	62.0	21.2	21.2	262	62.0	20.6	20.6	0.6
Layer2	161	38.0	13.1	13.1	161	38.0	12.7	12.7	0.4
Subtotal	423	100.0	34.3	34.3	423	100.0	33.3	33.3	1.0

Table 3.6. Simulated annual water budget for steady-state simulation and for year 2003 of the transient simulation for the conduit-flow and diffuse-flow rediscretized regional Edwards aquifer models, San Antonio region, Texas.—Continued

[Recharge includes leakage from streams through streambeds and infiltration of precipitation in interstream areas. Boundary inflow includes inflow through specified-flow boundary condition cells at the northern and northwestern model boundaries. Subtotal includes source or discharge components exclusive of changes in storage. Total includes changes in storage. Negative net change in storage indicates a net loss of water from storage (storage is included as a source). hm^3/yr, cubic hectometers per year; NA, not applicable]

	Source								
	Conduit-flow rediscretized regional Edwards aquifer model				Diffuse-flow rediscretized regional Edwards aquifer model				
Budget component and time period	Flow rate (hm^3/yr)	Percent of budget component	Percent of subtotal for sources or discharges	Percent of total sources or discharges	Flow rate (hm^3/yr)	Percent of budget component	Percent of subtotal for sources or discharges	Percent of total sources or discharges	Change in percent of total sources
Discharge—Continued									
Springflow (layer 1)									
Steady-state	654	NA	NA	54.2	655	NA	NA	54.2	0.0
2003	810	NA	65.7	65.7	848	NA	66.7	66.7	1.0
Subtotal									
2003	1,233	NA	100.0	100.0	1,271	NA	100.0	100.0	0.0
Total discharges									
Steady-state	1,207	NA	NA	100.0	1,208	NA	NA	100.0	0.0
2003	1,233	NA	100.0	100.0	1,271	NA	100.0	100.0	0.0
Net change in storage									
2003									
Layer 1	-64	16.7	NA	5.2	-89	21.1	NA	7.0	1.8
Layer 2	-321	83.3	NA	26.0	-333	78.9	NA	26.3	0.3
Subtotal	-385	100.0	NA	31.2	-423	100.0	NA	33.3	2.1

The MODPATH simulations were used to delineate areas contributing recharge to 68 public-supply wells. The contributing areas and pathlines for selected wells are shown on figures 3.14 and 3.15. Although only selected contributing areas and pathlines are presented on the figures in this report, contributing area statistics, as described in the database data dictionary in Appendix 1 of Chapter A, have been stored for all 65 public-supply wells to support further analysis, including comparison with other regional aquifer systems described elsewhere in this Professional Paper. In general, the pathlines outlining zones of contribution to public-supply wells extend upgradient to the north and northwest toward the recharge zone. For some wells, these pathlines initially trend upgradient to the west before extending to the north and northwest toward the recharge zone. The areas contributing recharge to the public-supply wells are restricted to the recharge zone because, as discussed previously in this report, no recharge occurs in the confined part of the aquifer. Figures 3.14 and 3.15 indicate that the areas contributing recharge and the pathlines outlining the zones of contribution computed by the rediscretized regional Edwards aquifer models (conduit-flow and diffuse-flow models)differ appreciably for many of the wells. The differences in the contributing areas and pathlines are because of differences in the hydraulic-conductivity distributions of the conduit-flow and diffuse-flow models (fig. 3.9). The computed pathlines outlining zones of contribution to selected public-supply wells tend to be aligned with the simulated zones of high hydraulic conductivity, representing a continuously connected network of conduits in the conduit-flow model (fig. 3.9*A*) and generally wider zones in the diffuse-flow model (fig. 3.9*B*). The distribution and extents of the high hydraulic conductivity zones differ

A.

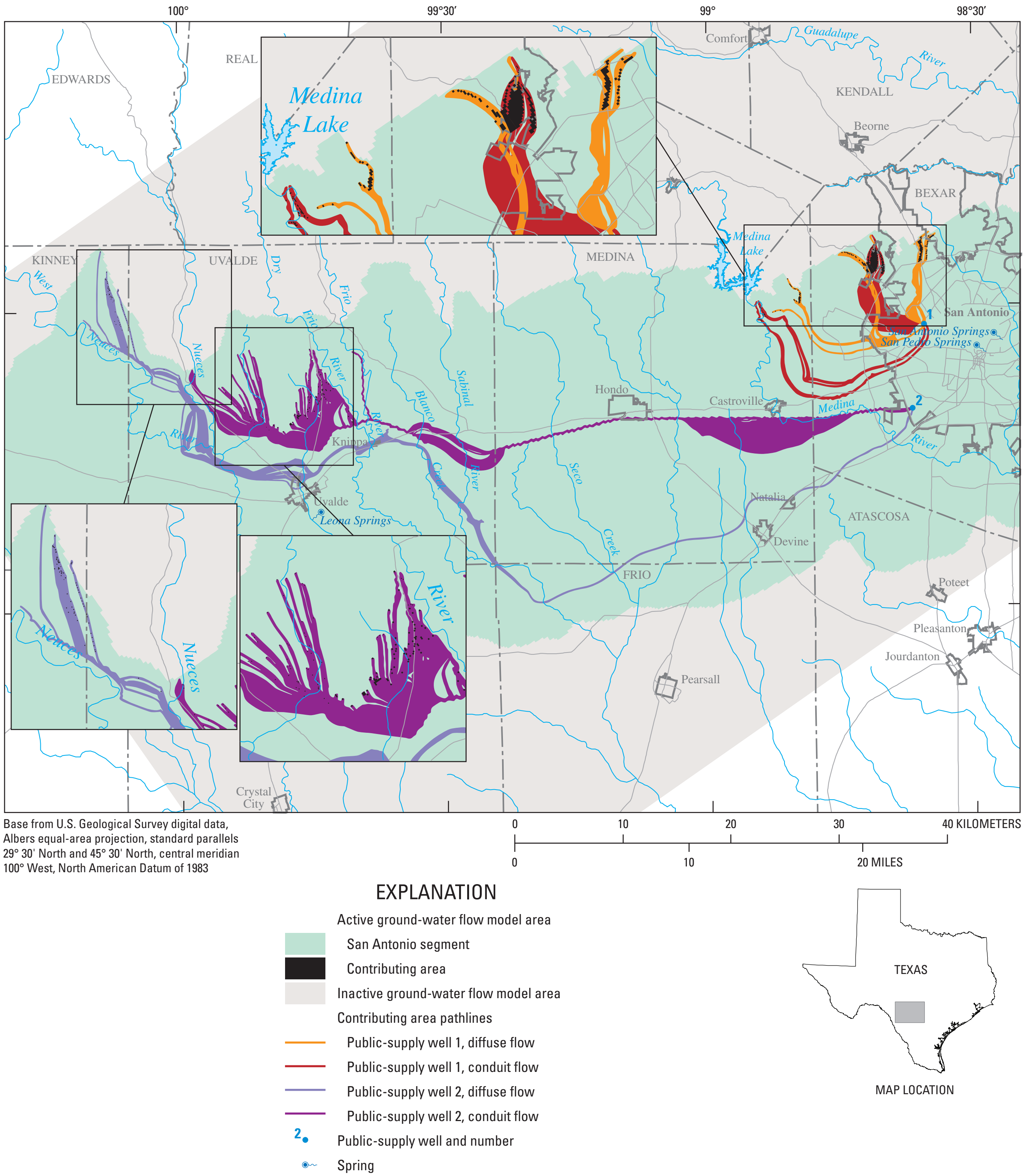


Figure 3.14*A*. Areas contributing recharge and zones of contribution for selected public-supply wells in Bexar County in the South-Central Texas regional study area simulated by the conduit-flow and diffuse-flow rediscretized regional Edwards aquifer models, San Antonio region, Texas.

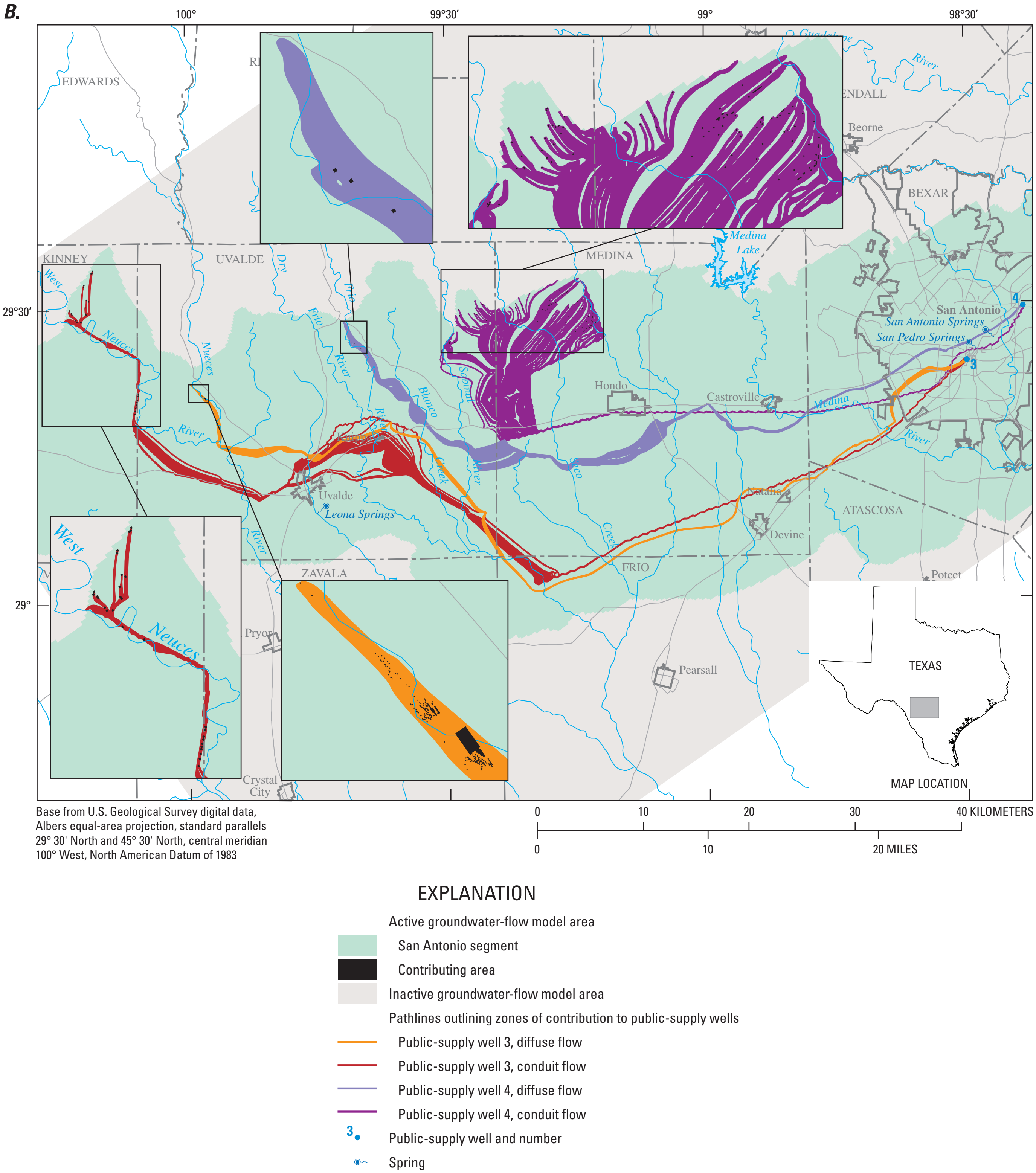
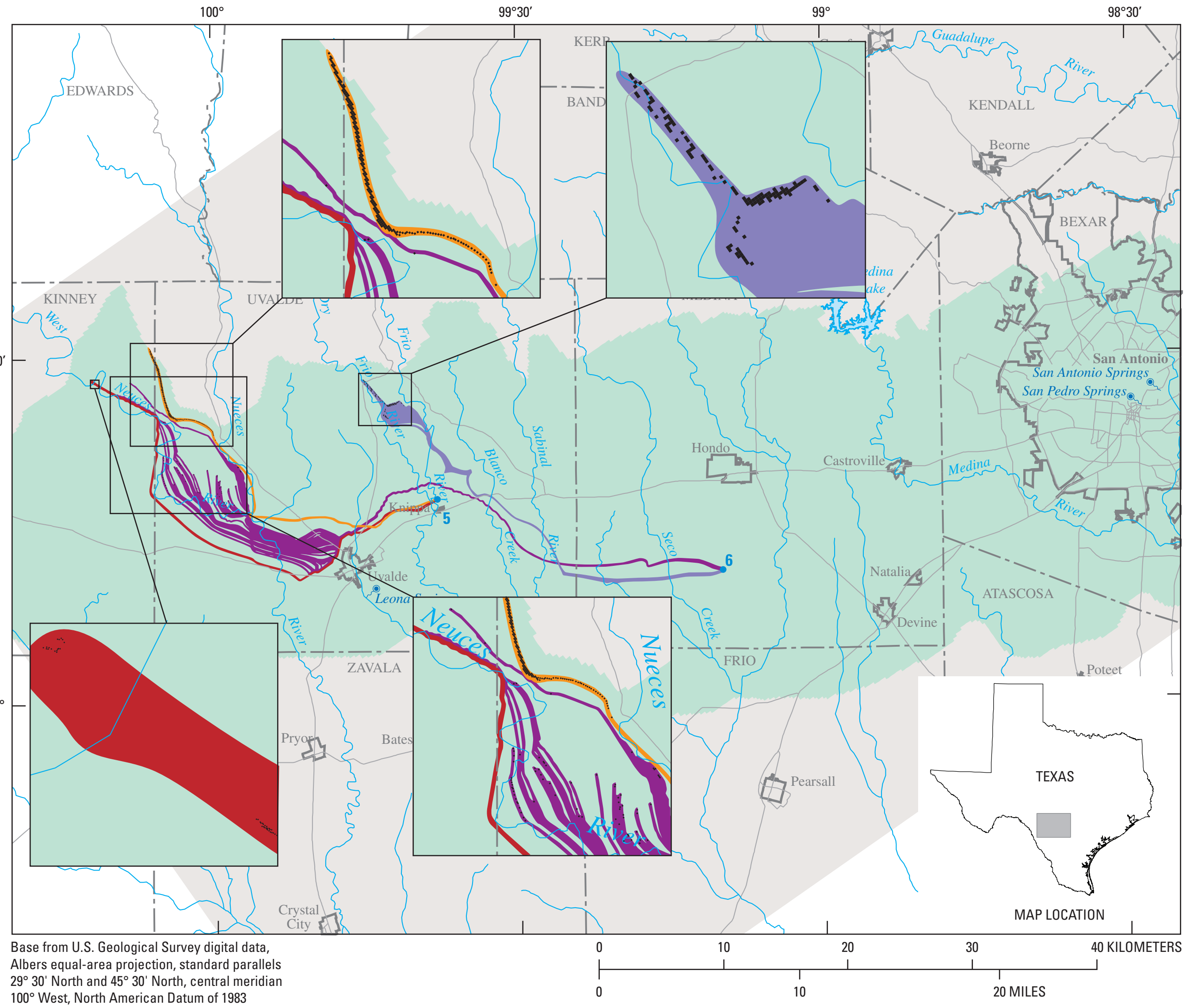


Figure 3.14*B*. Areas contributing recharge and zones of contribution for selected public-supply wells in Bexar County in the South-Central Texas regional study area simulated by the conduit-flow and diffuse-flow rediscretized regional Edwards aquifer models, San Antonio region, Texas.

A.



Base from U.S. Geological Survey digital data,
Albers equal-area projection, standard parallels
29° 30′ North and 45° 30′ North, central meridian
100° West, North American Datum of 1983

EXPLANATION

Active groundwater-flow model area
- San Antonio segment
- Contributing area

Inactive groundwater-flow model area

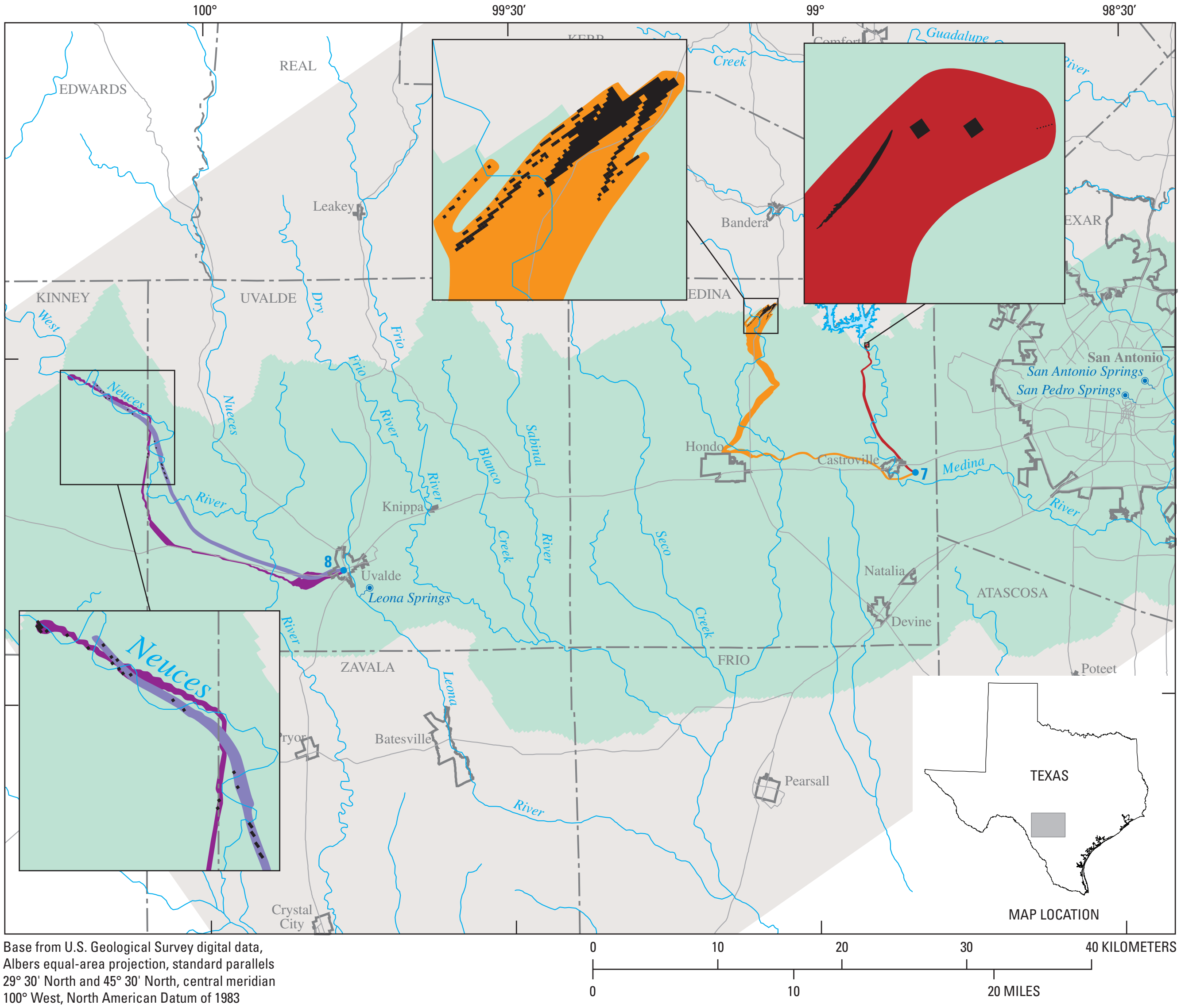
Pathlines outlining zones of contribution to public-supply wells
- Public-supply well 5, diffuse flow
- Public-supply well 5, conduit flow
- Public-supply well 6, diffuse flow
- Public-supply well 6, conduit flow

6 Public-supply well and number

Spring

Figure 3.15*A*. Areas contributing recharge and zones of contribution for selected public-supply wells in Medina and Uvalde Counties in the South-Central Texas regional study area simulated by the conduit-flow and diffuse-flow rediscretized regional Edwards aquifer models, San Antonio region, Texas.

B.



Base from U.S. Geological Survey digital data,
Albers equal-area projection, standard parallels
29° 30′ North and 45° 30′ North, central meridian
100° West, North American Datum of 1983

EXPLANATION

Active groundwater-flow model area
- San Antonio segment
- Contributing area

Inactive groundwater-flow model area

Pathlines outlining zones of contribution to public-supply wells
- Public-supply well 7, diffuse flow
- Public-supply well 7, conduit flow
- Public-supply well 8, diffuse flow
- Public-supply well 8, conduit flow

7 Public-supply well and number

Spring

Figure 3.15*B*. Areas contributing recharge and zones of contribution for selected public-supply wells in Medina and Uvalde Counties in the South-Central Texas regional study area simulated by the conduit-flow and diffuse-flow rediscretized regional Edwards aquifer models, San Antonio region, Texas.

between the two models, resulting in the observed differences in the computed contributing areas and pathlines.

Summary statistics for computed particle traveltimes and flow and the size of areas contributing recharge to the public-supply wells are shown in table 3.7. The average area contributing recharge to the public-supply wells was approximately 340 and 230 hectares for the conduit-flow and diffuse-flow rediscretized regional Edwards aquifer models, respectively. The minimum area contributing recharge to the public-supply wells was less than 0.02 hectare for both models, but the maximum for the diffuse-flow rediscretized regional Edwards aquifer model (3,459 hectares) was about 1.4 times that for the conduit-flow rediscretized regional Edwards aquifer model (2,503 hectares).

Minimum computed traveltimes for the public-supply wells for the conduit-flow rediscretized regional Edwards aquifer model ranged from less than one to 817 years and for the diffuse-flow rediscretized regional Edwards aquifer model ranged from 5 to 987 years. Maximum computed traveltimes for the public-supply wells for the conduit-flow rediscretized regional Edwards aquifer model ranged from 13 to 5,263 years and for the diffuse-flow rediscretized regional Edwards aquifer model ranged from 9 to 1,491 years. The average computed traveltime to public-supply wells was greater for the conduit-flow rediscretized regional Edwards aquifer model (276 years) than for the diffuse-flow rediscretized regional Edwards aquifer model (191 years) (table 3.7). For the conduit-flow rediscretized regional Edwards aquifer model, on average, only about 1.3 percent of the flow to a public-supply well was less than 10 years old, about 17 percent of the flow to a public-supply well was less than 50 years old, and about 52 percent of the flow to a public-supply well was less than 200 years old (table 3.7). The corresponding percentages for the diffuse-flow rediscretized regional Edwards aquifer model were greater (1.9, 24, and 67 percent, respectively) (table 3.7) and are consistent with the lower average computed traveltime. Conversely, the percentage of the flow to a public-supply well that was greater than 500 years old was greater for the conduit-flow rediscretized regional Edwards aquifer model, about 11 percent,than for the diffuse-flow rediscretized regional Edwards aquifer model, about 8 percent. As for the model-computed contributing areas and pathlines, the model-computed traveltimes differ for the conduit-flow and diffuse-flow rediscretized regional Edwards aquifer models because of the differences in the hydraulic-conductivity distributions of the two models.

The computed traveltimes are probably much longer than actual traveltimes in the aquifer because (1) an average porosity value for the Edwards aquifer of 0.18 was used for the simulations, and (2) the regional groundwater-flow models do not accurately represent flow through local karst dissolution features. An analysis was done for this study comparing available data for groundwater-age tracers with estimates for groundwater-age tracers derived from simulations using the rediscretized regional Edwards aquifer models (Leon Kauffman, U.S. Geological Survey, written commun., 2008). The measured concentrations for the tracers tritium (^3H) and sulfur hexafluoride (SF_6) were compared to concentrations computed

Table 3.7. Summary statistics for computed particle traveltimes and flow and size of areas contributing recharge to public-supply wells in the South-Central Texas regional study area for the conduit-flow and diffuse-flow rediscretized regional Edwards aquifer models, San Antonio region, Texas.

[Average, average minimum, and average maximum of particle travel time to public-supply wells are the sum of the average values for the public-supply wells divided by the number of public-supply wells. Average percentage of flow to public-supply wells is based on the average flow-weighted age of water particles contributing recharge to the simulated public-supply wells. <, less than; >, greater than]

Particle travel time and flow to public-supply wells								
	Particle travel time to public-supply wells (years)			Average percentage of flow to public-supply wells				
Model	Average	Average minimum	Average maximum	<10 years old	<50 years old	<100 years old	<200 years old	<500 years old
Conduit-flow	219	151	497	0.3	17	35	56	91
Diffuse-flow	181	133	328	1.5	22	36	66	94

Area contributing recharge to public-supply wells									
	Size of area contributing recharge to public-supply wells (hectares)			Percentage of public-supply wells with contributing area of specified extent					
Model	Average	Minimum	Maximum	<4.0 hectares	<20.2 hectares	<40.5 hectares	<202.4 hectares	<404.7 hectares	>404.7 hectares
Conduit-flow	204	0.07	1,758	21.1	40.4	49.1	75.4	87.7	12.3
Diffuse-flow	277	0.03	3,452	44.1	54.2	61.0	71.2	79.7	20.3

using output from the conduit-flow and diffuse-flow rediscretized regional Edwards aquifer models. The median ^3H concentration for 154 groundwater samples was 3.3 tritium units (TU), whereas median ^3H concentrations derived from the model simulations were 1.2 TU for the conduit-flow rediscretized regional Edwards aquifer model and 0.1 TU for the diffuse-flow rediscretized regional Edwards aquifer model. The median SF_6 concentration for 43 groundwater samples was 4.1 parts per trillion by volume (pptv), whereas median SF_6 concentrations derived from the model simulations were 2.4 pptv for both rediscretized regional Edwards aquifer models. The lower median ^3H and SF_6 concentrations derived from the rediscretized regional Edwards aquifer models compared to the measured concentrations indicate that the model-derived groundwater ages tend to be older and the model-derived particle traveltimes tend to be longer than the actual groundwater ages and traveltimes in the aquifer. However, the model-derived concentrations for ^3H were greater than the measured concentrations, indicating a younger groundwater age and shorter traveltimes, for 14.8 and 29.2 percent of the model-derived concentrations for the conduit-flow and diffuse-flow rediscretized regional Edwards aquifer models, respectively. Similarly, the model-derived concentrations for SF_6 were greater than the measured concentrations, indicating a younger groundwater age and shorter traveltimes, for 34.2 and 23.7 percent of the model-derived concentrations for the conduit-flow and diffuse-flow rediscretized regional Edwards aquifer models, respectively.

Limitations and Appropriate Use of the Model

All numerical groundwater-flow models are simplifications of the real system and, therefore, have limitations. Limitations generally result from assumptions used to develop the conceptual and numerical models, limitations in the quality and quantity of the input data, and the scale at which the model can be applied. Use of a distributed, porous media model to simulate flow in a karst system is a simplification, and the original and rediscretized regional Edwards aquifer models will not be able to simulate some aspects of flow accurately in this system, particularly the effects of rapid and potentially turbulent flow in conduits. Further model limitations include the discretization of the model grid and the temporal discretization for the transient simulations. In addition, a combination of input to the models different from that used in the calibrated simulations could produce the same result; the solution is nonunique.

Model limitations also are associated with input data. The input datasets for the original and rediscretized regional Edwards aquifer models are based on scanty information in some areas and for some parameters, in particular the storativity distribution. Hydrogeologic data is relatively meager for the recharge zone, for the Kinney County area, and for areas south of the 1,000-mg/L dissolved-solids concentration line. Secondary porosity created by karst dissolution features contributes to uncertainty in values of hydraulic conductivity, which can vary by up to eight orders of magnitude (3.05×10^{-4} to 3.05×10^{4} m/d) in the Edwards aquifer (Hovorka and others, 1998). A fully accurate representation of groundwater flow in the models also is constrained by lack of knowledge of the location and characteristics of high-permeability zones or conduits. Conduit locations, as well as the physical dimensions, connectivity, and hydraulic properties of conduits, are subject to considerable uncertainty. The original and rediscretized regional Edwards aquifer models are regional in nature and, therefore, best suited for the evaluation of variations in spring discharge, regional water-level changes, and the relative comparison of regional water-management scenarios. Accuracy and applicability of the models decrease when changing from the regional to the local scale.

Computed areas contributing recharge and groundwater traveltimes to public-supply wells for this study are based on calibrated steady-state models and an estimated average effective porosity value of 0.18. In a steady-state model, changes to input porosity values do not change the area contributing recharge to a given well. Changes to input porosity values, however, will change computed traveltimes from recharge areas to discharge areas (public-supply wells) in direct proportion to changes of effective porosity, because there is an inverse linear relation between groundwater flow velocity and effective porosity and a direct linear relation between traveltime and effective porosity. For example, a 1-percent decrease in porosity will result in a 1-percent increase in velocity and a 1-percent decrease in particle traveltime.

The rediscretized regional Edwards aquifer models were designed to delineate areas contributing recharge to public-supply wells, to help guide data collection, and to support future local modeling efforts. For karst terrains, where an appreciable amount of flow occurs through a series of discrete openings, conduits, and fractures, a porous-media approach at a regional scale cannot accurately predict zones of contribution, areas contributing recharge, and traveltimes to public-supply wells. Kuniansky and others (2001) found that an effective porosity of 1 to 3 percent was needed for the karst Edwards aquifer system in Texas to match estimated traveltimes derived from geochemical mixing models. Therefore, the computed areas contributing recharge and traveltimes to public-supply wells presented in this report, using an average porosity for the Edwards aquifer of 0.18 (Hovorka and other, 1996), are only one possible scenario of groundwater transport to public-supply wells. A detailed sensitivity analysis of porosity distributions was beyond the scope of this study, although comparisons of simulated groundwater traveltimes to groundwater ages would provide a more thorough evaluation of effective porosity values, and, thus, refine the conceptual model. Future work in the study area will include development of a local model and simulation of discrete karst features.

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