Hydrogeologic Setting and Ground-Water Flow Simulations of the Northern Tampa Bay Regional Study Area, Florida

By Christy Crandall

Section 5 of

Hydrogeologic Settings and Ground-Water Flow Simulations for Regional Studies of the Transport of Anthropogenic and Natural Contaminants to Public-Supply Wells—Studies Begun in 2001

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Hydrogeologic Setting and Ground-Water Flow Simulations of the Northern Tampa Bay Regional Study Area, Florida

By Christy Crandall

Abstract

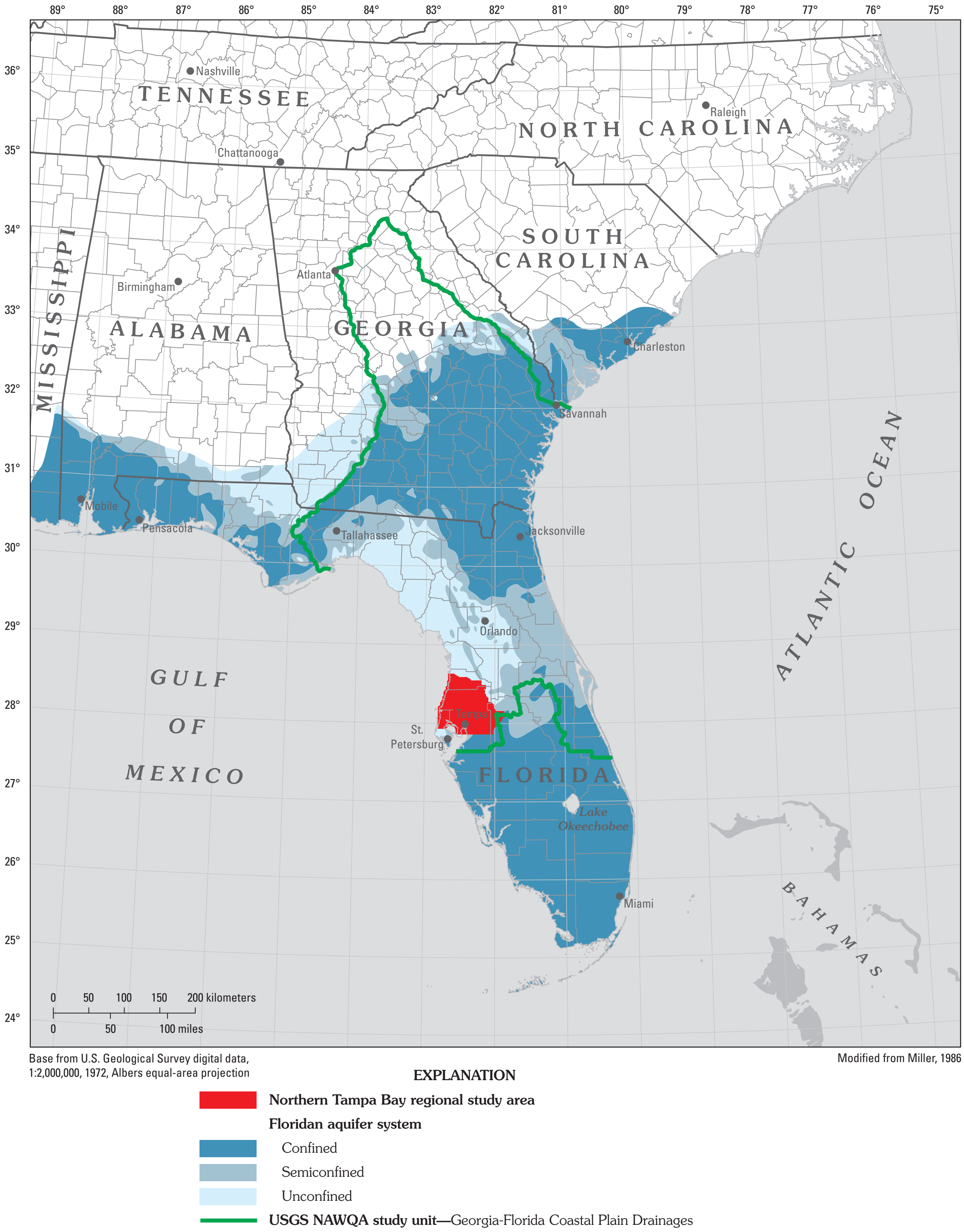
The transport of anthropogenic and natural contaminants to public-supply wells was evaluated for part of the Floridan aquifer system in the vicinity of Tampa Bay, Florida, as part of the U.S. Geological Survey National Water-Quality Assessment Program. The aquifer system in the Northern Tampa Bay regional study area is representative of the karst Floridan aquifer system throughout the Southeastern United States, is used extensively for public water supply, and is susceptible and vulnerable to contamination. The aquifer system in the study area is composed of an unconfined surficial aquifer of sandy deposits underlain by the karst limestone of the Floridan aquifer system. The two aquifers are separated by an intermediate confining zone in some parts of the study area creating confined and unconfined conditions in the Floridan aquifer system. An existing two-layer, steady-state ground-water flow model of the study area was modified to include a finer model grid, two additional layers, and additional boundary conditions and was recalibrated to year-2000 conditions. The calibrated ground-water flow model and advective particle-tracking simulations were used to compute ground-water flow paths, areas contributing recharge, and traveltimes from recharge areas to public-supply wells. Model results indicate precipitation recharge (55.4 percent of inflow) and lateral ground-water flow (35.1 percent of inflow) provide most of the ground-water inflow. Ground-water discharge is to the Gulf of Mexico and Tampa Bay (38 percent of outflow), wells (29.1 percent of outflow), and springs and streams (32.7 percent of outflow). Particle-tracking results indicate minimum traveltimes to public-supply wells ranged from 0.7 to 233 years with an average minimum traveltime of 19 years. Maximum computed traveltimes ranged from 32 to 1,875 years and averaged 600 years. On average, only 3 percent of the flow to a public-supply well was less than 10 years old, about 36 percent of the flow to a public-supply well was less than 50 years old, and about 80 percent of the flow to a public-supply well was less than 200 years old. Simulated traveltimes are probably much longer than actual travel times in the aquifer because the regional ground-water flow model does not accurately represent flow through local karst dissolution features.

Introduction

The Northern Tampa Bay regional study area for the transport of anthropogenic and natural contaminants (TANC) study overlies the karst Floridan aquifer system in west-central peninsular Florida in the Tampa Bay metropolitan area (fig. 5.1). The Floridan aquifer system underlies the Georgia-Florida Coastal Plain drainages National Water-Quality Assessment (NAWQA) study unit and much of the southeastern coast of the United States (fig. 5.1)

Purpose and Scope

The purpose of this Professional Paper section is to present the hydrogeologic setting of the Northern Tampa Bay TANC regional study area. The section also documents the setup and recalibration of a steady-state regional ground-water flow model for the study area. Ground-water flow characteristics, pumping-well information, and water-quality data were compiled from existing data to develop a conceptual understanding of ground-water conditions in the study area. An existing ground-water flow model of the area (Yobbi, 2000) was modified to include a finer model grid, two additional layers, and additional boundary conditions and was recalibrated to year-2000 conditions. The year 2000 was assumed to represent average conditions for the period from 1997 to 2001. The 5-year period 1997–2001 was selected for data compilation and modeling exercises for all TANC regional study areas to facilitate future comparisons between study areas. The updated ground-water flow model and associated particle tracking were used to simulate advective ground-water flow paths and to delineate areas contributing recharge to selected public-supply wells. Ground-water traveltimes from recharge to public-supply wells and presence of potential contaminant sources



Base from U.S. Geological Survey digital data, 1:2,000,000, 1972, Albers equal-area projection

Modified from Miller, 1986

Figure 5.1. Location of the Northern Tampa Bay regional study area within the Floridan aquifer system.

in areas contributing recharge were tabulated into a relational database as described in Section 1 of this Professional Paper. This section provides the foundation for future ground-water susceptibility and vulnerability analyses of the study area and comparisons among regional aquifer systems.

Study Area Description

The Northern Tampa Bay regional study area was chosen because the Floridan aquifer system is used extensively for public water supply and is susceptible and vulnerable to contamination. The area also represents the range of hydrogeologic and land-use conditions throughout areas overlying the Floridan aquifer system (table 5.1). For example, variable hydrologic confining conditions and karst features are prevalent in both the Floridan aquifer system and the Northern Tampa Bay regional study area (Miller, 1986).

Topography and Climate

The Northern Tampa Bay regional study area is characterized by relatively flat, marshy lowlands along the coast (Coastal Swamps region), rolling hills of intermediate relief throughout parts of central Pasco County with elevations as high as 30 m above NAVD88 (Gulf Coastal Lowlands), and sand terraces to the northeast and southeast (Brooksville Ridge and Western Highlands, respectively) (White, 1970). The most prominent topographic feature in the study area is the Brooksville Ridge, located in central Hernando and eastern Pasco Counties. Land surface altitudes range from sea level to approximately 90 m above NAVD88 along the Brooksville Ridge (fig. 5.2).

The climate of the study area is subtropical with warm, wet summers and relatively dry, mild winters. Rainfall varies seasonally with more than one-half the total annual rainfall usually occurring between June and September, the result of convective storms. Average annual rainfall in the study area ranges from 125 to 140 cm per year (Metz and Sacks, 2002). Pan evaporation rates are high and average 125 to 150 cm per year (Farnsworth and others, 1982).

Surface-Water Hydrology

Karst features such as sinkholes and springs are prevalent throughout the study area (fig 5.2). Ancient, shallow, stable sinkhole depressions 5 to 8 m below land surface usually contain swamps and cypress domes, whereas deeper depressions infill with water and contain sinkhole lakes. At least 17 major springs are located in the study area. Springs usually discharge to rivers or directly to the Gulf of Mexico. The two largest springs are the Weeki Wachee Springs complex in western Hernando County and Crystal Springs, located along the northern reaches of the Hillsborough River. Weeki Wachee and Crystal Springs provide base flow to the Weeki Wachee and Hillsborough Rivers, respectively (Yobbi, 2000).

Six major rivers and their tributaries are located in the study area (fig. 5.2). The two rivers with the largest discharge are the Hillsborough and Withlacoochee Rivers. Hundreds of lakes, swampy plains, and intermittent ponds ranging in size from 0.001 to 10 km^2 also are dispersed throughout the study area.

Soils covering the Brooksville Ridge and the sand hills (the eastern edge of the study area) are very well drained and have relatively deep water tables, rapid percolation, internal drainage, and high recharge potential (HydroGeoLogic, Inc., 1997). Soils in the lower Gulf Coast Lowlands and Coastal Swamp regions (along river channels and the coast) are moderately to poorly drained with shallow water tables; numerous perched lakes, ephemeral ponds, and wetlands; and high organic contents (Soil Conservation Service, 1976, 1981, 1989). Recharge is relatively low in these areas except in areas with sinkholes and other karst features (HydroGeoLogic, Inc., 1997).

Land Use

Land use in the study area includes urban, residential, new-commercial, suburban, agriculture, wetland, and forests. Land-use change from agriculture and rural forests to residential and commercial is typical of areas overlying the Floridan aquifer system as a whole and the study area. The largest components of land use in the study area are agriculture (28 percent), urban (22 percent), and wetlands (21 percent) (Hitt, 2004). Within these categories, cropland (74 percent) and citrus groves (20 percent) dominate agricultural land uses, whereas residential (77 percent) and commercial (10 percent) land uses account for most of urban land uses. Wetlands are 86 percent forested in the study area. Rangeland (7 percent), forests (10 percent), and waterways (6 percent) account for the remainder of land uses in the study area.

Water Use

Ground-water withdrawals from the entire Floridan aquifer system are 15.4 million cubic meters per day (Mm^3/d) and from the Floridan aquifer system within the study area they are 1.8 Mm^3/d (Marella and Berndt, 2005). The Tampa Metropolitan area relies heavily on the Floridan aquifer system as a drinking-water source. In 2000, Tampa Bay Water, the largest user of the Floridan aquifer system in the study area, withdrew about 0.7 Mm^3/d from the Floridan aquifer system and served 1.2 million people. In addition to public supply, the Floridan aquifer system is the primary source for domestic, irrigation, and industrial wells in the study area. Within the Northern Tampa Bay regional study area, public-supply wells are the basis of community water systems for the cities of Tampa, St. Petersburg, and Clearwater, Florida, and numerous smaller cities.

Table 5.1. Summary of hydrogeologic and ground-water-quality characteristics for the Floridan aquifer system and the Northern Tampa Bay regional study area, Florida.

[m, meters; km, kilometers, cm/yr, centimeters per year; m^3/d, cubic meters per day; m/d, meters per day; Kh, horizontal hydraulic conductivity; Kv, vertical hydraulic conductivity; Sy, specific yield; n, porosity; Mm^3/d, million of cubic meters per day; mg/L, milligrams per liter; O_2, dissolved oxygen; CH_4 methane; Ca, calcium; Mg, magnesium; HCO_3, bicarbonate; SO_4, sulfate; Na, sodium; Cl, chloride]

Characteristic	Floridan aquifer system	Northern Tampa Bay regional study area
	Geography	
Topography	Rolling hills below the Fall Line Hills of Central Georgia (fig. 1); elevations range from 100 to 250 m; sandy terraces with elevations ranging from about 25 to 100 m; Coastal Plains and Wetlands from near sea level to about 25 m. Karst topography, in north through central Florida (Krause and Randolph, 1989).	Sandy hills in the Brooksville Ridge upland (fig. 2); relief generally less than 60 m; eolian deposits and sandy terraces less than 25 m; Coastal Plain and Swamps generally less than 3 m. Karst topography evident (Metz and Sacks, 2002; Ryder, 1985; Yobbi, 2000).
Climate	Temperate to subtropical; humid; precipitation 115 to165 cm/yr; evapotranspiration 115 to165 cm/yr (Bush and Johnston, 1988).	Subtropical; humid; precipitation 125 to150 cm/yr; evapotranspiration 125 to140 cm/yr (Metz and Sacks, 2002).
Land use	Urban, suburban, water, wetland, rural residential/ commercial, woodlands, farmland (Hitt, 2004).	Urban, suburban, rural, water, wetland, residential/ commercial, woodlands, farmland (Hitt, 2004).
	Geology	
Surficial deposits	Eolian sands and clays, gravel, and limestone; more fine-grained deposits further north, sand uplands (Miller, 1986).	Sand and clays; limited clay, mostly fine sand, unconsolidated limestone. Eolian sands discontinuous (Yobbi, 2000).
Bedrock geologic units	Thick carbonate sequence ranging from 30 to 1,000 m in thickness from north to south Florida; fractured with many dissolution features especially in unconfined and semiconfined areas of south Georgia and Peninsular Florida.	Thick carbonate sequence from 200 to 400 m thick; fractured with many dissolution features especially in unconfined and semiconfined areas.
	Ground-water hydrology	
Aquifer conditions	Unconfined; semiconfined; confined (Miller, 1986).	Unconfined; semi-confined, confined (Miller, 1986; Yobbi, 2000).
Hydraulic properties	Floridan: Kh=0.1 to 3,000 m/d; Kv=0.00006 m/d to 0.10 m/d; n=0.02 to 0.50 (Bush and Johnston, 1988; Knochenmus and Robinson, 1996).	Surficial: Kh=0.3 to 5 m/d; n=0.25 Floridan: Kh=0.2 to 2,000 m/d; Kv=0.02 to 2 X 10^{-5} m/d; n=0.15 (Knochenmus and Robinson, 1996; SDI, Inc., 1997)
Ground-water budget	Recharge from precipitation: 12.7 cm/yr or 12.1 Mm^3/d; evaporation: 92 to 102 cm/yr; discharge to springs: approximately 7.8 Mm^3/d; river discharge, offshore springs, and diffuse leakage: 0.73 Mm^3/d; wells: 3.6 Mm^3/d (Bush and Johnston, 1988; Ryder, 1985)	Recharge from precipitation: 23 cm/yr or 3.44 Mm^3/d; recharge from streams: 0.59 Mm^3/d; discharge to springs and rivers: 2.04 Mm^3/d; pumping: 1.8 Mm^3/d. Loss to head-dependent boundaries: 0.30 Mm^3/d (this study).
Lengths of ground-water travel paths	Generally thought short (less than 40 km) (Bush and Johnston, 1988; Knochenmus and Robinson, 1996)	Generally less than 15 km; usually less than 7 km.

Table 5.1. Summary of hydrogeologic and ground-water-quality characteristics for the Floridan aquifer system and the Northern Tampa Bay regional study area, Florida.—Continued

[m, meters; km, kilometers, cm/yr, centimeters per year; m^3/d, cubic meters per day; m/d, meters per day; Kh, horizontal hydraulic conductivity; Kv, vertical hydraulic conductivity; Sy, specific yield; n, porosity; Mm^3/d, million of cubic meters per day; mg/L, milligrams per liter; O_2, dissolved oxygen; CH_4 methane; Ca, calcium; Mg, magnesium; HCO_3, bicarbonate; SO_4, sulfate; Na, sodium; Cl, chloride]

Characteristic	Floridan aquifer system	Northern Tampa Bay regional study area
	Ground-water quality	
Water chemistry (dissolved solids, pH, redox, major water types)	Dissolved solids less than 25 to greater than 1,000 mg/L along the coast and in S. Florida; pH 6.0 to 8.0; varies from O_2 to CH_4 reducing; Ca, and Ca,Mg-HCO_3, Ca-SO_4, and Na-Cl along the coast (Sprinkle,1989)	Dissolved solids less than 200 to greater than 1,000 mg/L along the coast; pH 6.0 to 8.0; varies from O_2 to Fe and SO_4 reducing; Ca, and Ca,Mg-HCO_3, Ca-SO_4, and Na-Cl in Pinellas County (Ryder, 1985).
Contaminants	Nutrients, uranium, radon, arsenic, halogenated volatile organic compounds, including some gasoline and drycleaner free product, triazine and bromated herbicides. Saline water in areas with large pumping wells near the coast (Sprinkle, 1989).	Nutrients, uranium, radon, arsenic, halogenated volatile organic compounds including some gasoline and drycleaner free product, triazine and bromiated herbicides. Saline water in areas with large pumping wells near the coast (Ryder, 1985)

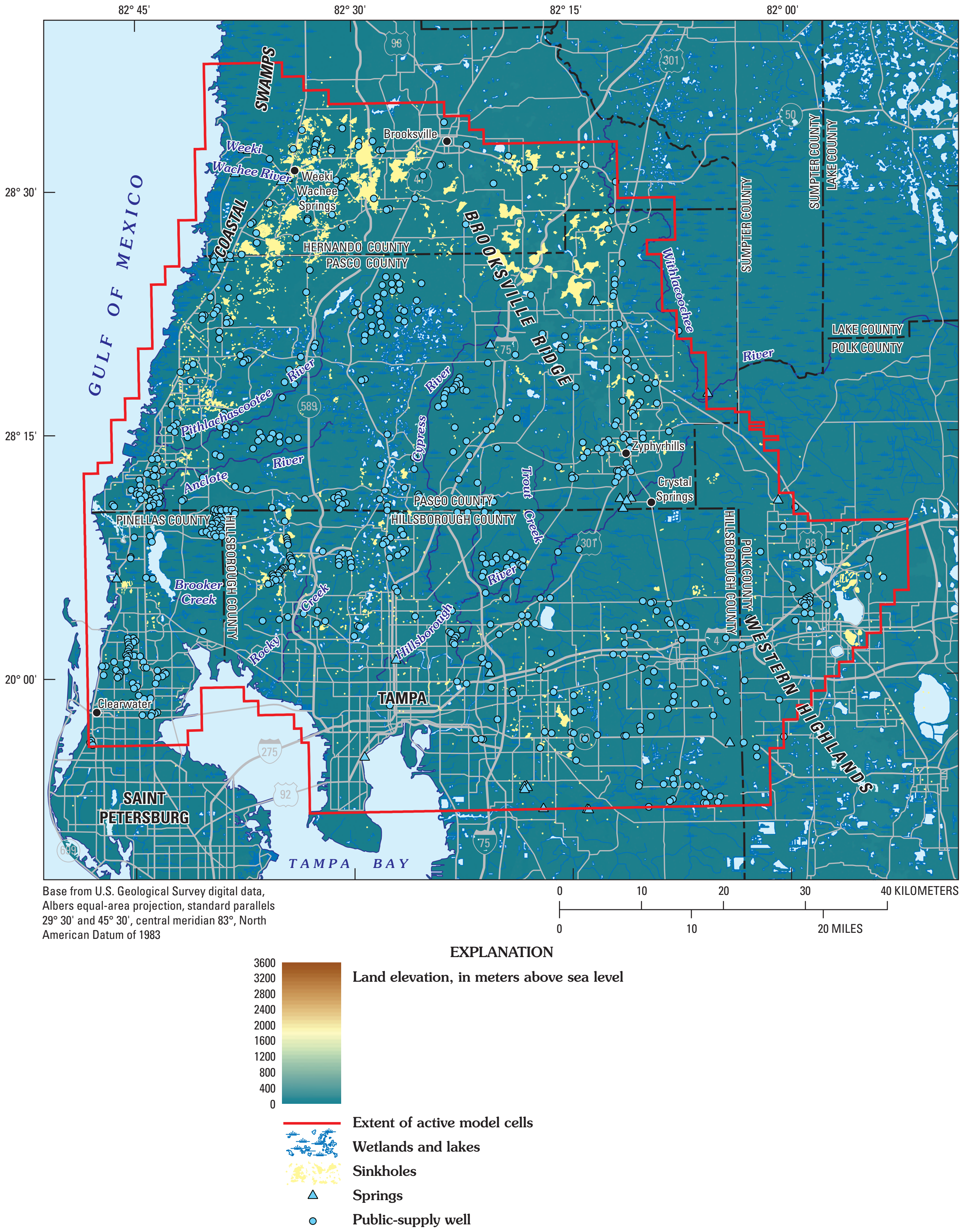


Figure 5.2. Topography, hydrologic features, and locations of public-supply wells, Northern Tampa Bay regional study area, Florida.

Conceptual Understanding of the Ground-Water System

The study area is underlain by a sequence of Paleocene to Miocene carbonate rocks. Karst dissolution features control the ground-water flow, aquifer hydraulic properties, and to a lesser extent, ground-water chemistry (fig. 5.3). Ground-water recharge is greatest where karst sinkholes are present at the land surface. Ground-water discharge occurs to streams by way of karst springs. Aquifer hydraulic properties such as porosity and permeability are greatest where solution-enlarged fissures are present in the subsurface. Ground-water chemistry is controlled by ground-water flow paths and residence time in the carbonate rock aquifer, which are in turn controlled by the presence and location of karst features.

Geology

The ground-water flow system beneath the study area consists of a thick sequence of layered carbonate rocks overlain by surficial clastic deposits (table 5.2). The surficial deposits and carbonate rocks are subdivided into a hydrogeologic framework of two aquifers and one confining unit. The framework includes the unconfined surficial aquifer system, the intermediate confining unit that separates the surficial aquifer system from the Floridan aquifer system, and the Floridan aquifer system. The surficial aquifer system is composed of Pliocene to Holocene undifferentiated sands, clays, and marls. The intermediate confining unit is part of the late Miocene Hawthorn Group sediments and is composed of dense, plastic, green-grey clay, interbedded with varying amounts of chert, sand, clay, marl, shell, and phosphate. The intermediate confining unit is not present or is breached in parts of the study area where the Floridan aquifer system is semiconfined or unconfined (fig. 5.1). The Floridan aquifer system is composed of a thick sequence of limestone, dolomite, and evaporitic dolomite. The formational components of the Floridan aquifer system in the regional study area are as follows (in order of youngest to oldest): the Tampa Member of the Arcadia Formation and Hawthorn Group of early Miocene age, the Suwannee Limestone of Oligocene age, the Ocala Limestone of Oligocene to Eocene age, the Avon Park Formation of middle Eocene age, and the Oldsmar and Cedar Keys Formations of Eocene to Paleocene age (table 5.2) (Miller, 1986; Southeastern Geological Society, 1986). A relatively impermeable layer composed of evaporitic limestone located at the base of the Avon Park Formation forms the middle confining unit at the base of the upper Floridan aquifer system and is considered the base of the freshwater flow system in the study area (Yobbi, 2000; Miller, 1986).

Ground-Water Occurrence and Flow

In general, unconfined ground-water conditions occur in the surficial aquifer system, and confined ground-water conditions occur in the Floridan aquifer system. Ground-water occurrence and flow for each of these aquifer systems are discussed in the following sections.

Surficial Aquifer System

The surficial aquifer system exists throughout most of the study area except where the Floridan aquifer system is exposed at land surface and unconfined (fig. 5.1) (Miller, 1986; Berndt and Katz, 1992). The term surficial aquifer system refers to any permeable material exposed at land surface that contains ground water under water-table conditions and is

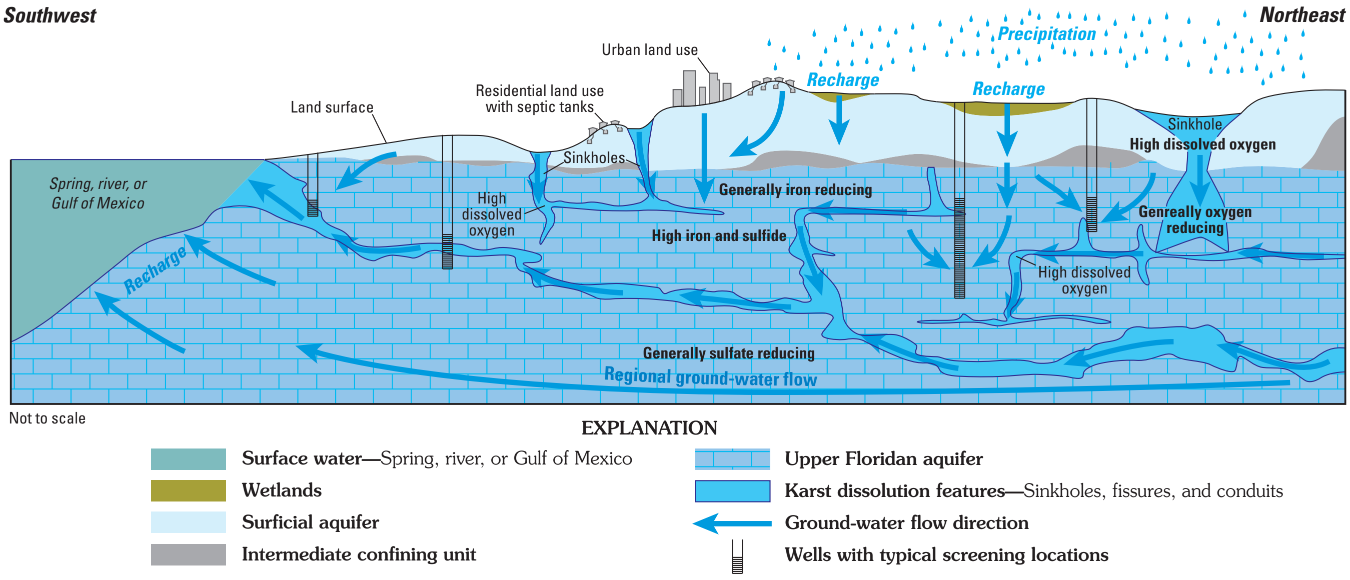


Figure 5.3. Conceptual ground-water flow and geochemical conditions, Northern Tampa Bay regional study area, Florida.

Table 5.2. Geology, hydrogeology, and water-use characteristics of the Northern Tampa Bay regional study area, Florida [adapted from Ryder (1985) and Metz and Sacks (2002)].

[m, meters; SAS, surficial aquifer system; FAS, Floridan aquifer system; m^3/d, cubic meters per day]

Age	Stratigraphic unit	Lithologic descriptions	Range in thickness (m)	Hydrogeologic unit	Aquifer characteristics
Holocene to Pliocene	Undifferentiated surficial deposits, terrace sand, phosphorite	Predominantly fine sand; interbedded clay, marl, shell, limestone, sandy clay.	8 to 15	SAS	Limited use; lawn irrigation; yields less than 27 m^3/d; high iron content.
Miocene	Undifferentiated deposits of the Hawthorn Group	Dense plastic green-grey clay, contains varying amounts of chert, sand; clay, marl, shell, phosphate.	0 to 6	Intermediate Confining bed if present	Semiconfining unit retards downward percolation from the SAS; breaches in clay unit preferentially transmit recharge to the Upper FAS.
	Tampa Member of the Arcadia Formation of the Hawthorn Group	Weathered limestone surface, white to light tan, soft sandy, fossiliferous; clays in lower part in some areas.	6 to 75	FAS—Upper FAS	Many domestic and public-supply wells tap this unit; poor to fair producer of water; yields from a few to 1,100 m^3/d.
Oligocene	Suwannee Limestone	Soft to hard limestone, vuggy, granular, fossiliferous limestone.	30 to 60		Domestic and large capacity public-supply wells tap these units; yields from a 1,100 m^3/d to 11,000 m^3/d.
Oligocene to Eocene	Ocala Limestone	Limestone, chalky, foraminferal, dolomitic near bottom.	50 to 60		
Eocene	Avon Park Formation	Hard brown dolomite and limestone, with intergranular evaporite in lower part.	120 to 200	Middle confining unit at the bottom of the Avon Park Formation	
Eocene to Paleocene	Oldsmar and Cedar Keys Formations	Dolomite and limestone with beds of anhydrite.	180 to 200	Lower FAS	Not used for domestic or public supply—highly mineralized.

not part of the Floridan aquifer system. The surficial aquifer system may be in direct hydraulic contact with the Floridan aquifer system or be separated by confining beds. The base of the surficial aquifer system has been designated as “the top of the laterally extensive and vertically persistent beds of much lower permeability” (Southeastern Geological Society, 1986)—the Hawthorn Group in the study area. The Floridan aquifer system underlies the surficial aquifer system directly where the intermediate confining unit is absent (Berndt and Katz, 1992).

The surficial aquifer system is recharged by rainfall, irrigation, and septic effluent (fig. 5.3). Rainfall easily infiltrates the surficial aquifer system and percolates downward to recharge the Floridan aquifer system by way of downward leakage through the intermediate confining unit. Ground water discharges from the surficial aquifer system through lakes, ditches, streams, evaporatranspiration, pumping, and downward leakage to the Floridan aquifer system (Tibbals and others, 1980). Water levels in the surficial aquifer system fluctuate widely and rapidly in response to rainfall and evaporation (Miller, 1986). The configuration of the top of the water table in the surficial aquifer system is a subdued reflection of the land surface and is generally within 0.1 to 3 m of the land-surface. The surficial aquifer system is not used for water supply (table 5.2) because of low yields (less than 27 m^3/d), high iron content, and its vulnerability to contamination from overlying land use (Metz and Sacks, 2002).

Floridan Aquifer System

The Floridan aquifer system consists of a thick sequence of hydraulically connected carbonate rocks and covers a land area of more than 260,000 km^2. The aquifer underlies coastal regions of southern Mississippi, Alabama, Georgia, and South Carolina and the entire Florida peninsula (fig. 5.1) (Miller, 1986). The Floridan aquifer system is composed of limestones and dolomites of late Paleocene to early Miocene age; however, neither the aquifer boundaries nor its high- and low-permeability zones necessarily conform to either formational boundaries or time-stratigraphic units. Solution-enlarged fissures (channel porosity) in combination with diffuse flow through more uniformly distributed interconnected pores (rock porosity) contribute to flow in the study area. The aquifer ranges in thickness from about 61 m in the north to over 1,000 m in areas of central and south Florida (Miller, 1986). Units that compose the Floridan aquifer system outcrop in west-central-southern Georgia and along the north- to south-central Gulf Coast of Florida (fig. 5.1). The Floridan aquifer system is considered unconfined or semiconfined where it outcrops and the intermediate confining unit is absent or less than 30 m thick and(or) breached. The Floridan aquifer system is considered confined where the intermediate confining unit is present and greater than 30 m thick (Miller, 1986).

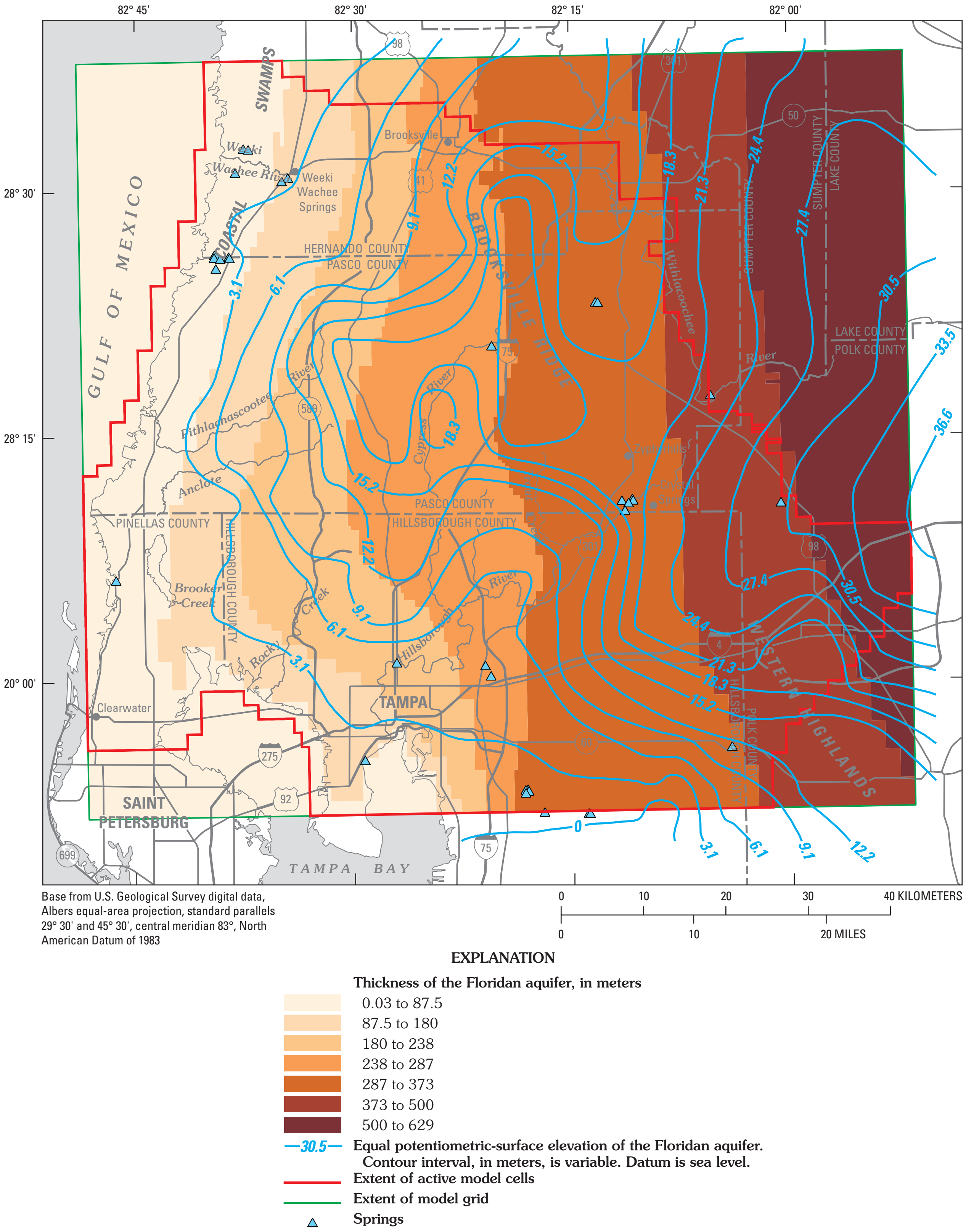
Ground-water recharge to and discharge from the Floridan aquifer system are controlled by the prominent karst features and aquifer confinement. Precipitation recharge, which provides most of the recharge to the Floridan aquifer system in the study area, ranges from 25 to 55 cm/yr and occurs primarily in areas considered unconfined and semiconfined (fig. 5.1) (Aucott, 1988). Karst features such as springs, conduits, and sinkholes are common in the study area and elsewhere where the aquifer is unconfined or semiconfined and provide direct pathways for contaminants to travel from land surface to the aquifer (Miller, 1986). Ground-water discharge from the Floridan aquifer system occurs through springs, rivers, and coastal seeps and springs with approximately 75 percent of all Floridan aquifer system discharge flowing to springs (Bush and Johnston, 1988). The Floridan aquifer system in the study area supplies base flow to the Withlacoochee, Hillsborough, and other rivers, which are important water-supply and recreational resources (Bush and Johnston, 1988).

The Floridan aquifer system potentiometric surface is controlled by seasonally influenced recharge and local pumping. The regional ground-water flow direction is from east to west with a slightly southern component (fig. 5.4). Flow is convergent toward springs, rivers, and the Gulf of Mexico, and flow is transmitted vertically and laterally through karst conduits and enlarged fracture planes. The regional potentiometric surface exhibits highs and lows that generally correspond to topographic highs and lows. River and spring discharge features are topographic and potentiometric lows. In the study area, the potentiometric surface ranges from 0 to approximately 40 m in elevation (fig. 5.4).

Aquifer Hydraulic Properties

Hydraulic conductivity of the surficial aquifer system generally ranges from 0.1 to 5 m/d and averages 3 m/d in the modeled area (SDI Environmental Services Inc., 1997; Knochenmus and Robinson, 1996), although hydraulic conductivity may be as large as 30 m/d in some areas (Ryder, 1985). The surficial aquifer system thickness ranges from approximately 0 in the northern part of the study area to more than 30 m in the southeastern part of the study area and averages between 8 and 25 m in the study area (Miller, 1986; Berndt and Katz, 1992). Effective porosity measurements for the surficial aquifer system vary, but an average value of 0.25 based on geophysical measurements has been used in various models (SDI Environmental Services Inc., 1997; Knochenmus and Robinson, 1996).

Horizontal hydraulic conductivity of the Floridan aquifer system in the study area generally is reported to range from 0.2 to 2000 m/d in the literature (Bush and Johnston, 1988; Knochenmus and Robinson, 1996), but it can vary by up to five orders of magnitude where karst features create secondary porosity in the aquifer (Langevin, 1998). Storage coefficients reported in the literature for the Floridan aquifer system range from 1×10^{-5} to 2×10^{-2} (Bush and Johnston, 1988). An average storage coefficient of 2.5×10^{-4} is reported for the study area (Tibbals and Grubb, 1982), and vertical hydraulic conductivity of the Floridan aquifer system ranges from 0.02



Base from U.S. Geological Survey digital data, Albers equal-area projection, standard parallels 29° 30' and 45° 30', central meridian 83°, North American Datum of 1983

Figure 5.4. Year-2000 potentiometric surface and thickness of the Floridan aquifer, Northern Tampa Bay regional study area, Florida.

to 2 X 10^{-5} m/d in the study area (Bush and Johnston, 1988; Knochenmus and Robinson, 1996).

Water Budget

Estimates of the water budget in the modeled area for the year 1987 (a representative year) are provided in Yobbi (2000) and are reported here. Recharge estimates for the modeled area vary greatly. A net recharge rate of 23.1 cm/yr from precipitation is considered reasonable, although site-specific values likely vary from 0 to more than 30 cm/yr because of the karst topography. An estimated net discharge rate of 1.05 Mm^3/d was calculated from the total average annual ground-water discharge to 13 major springs in the modeled area. Total base flow to rivers from ground water, determined from hydrograph separation techniques for 21 sites in the modeled area, was 1.37 Mm^3/d. Discharge to wells estimated from year-2000 pumping data is approximately 1.8 Mm^3/d as discussed in the "Model Stresses" section.

Ground-Water Quality

Concentrations of major ions in any aquifer reflect the quality of recharge water, lithology and mineralogy of geologic deposits, residence time of water, and proximity to the coast and(or) other contaminant sources. The most commonly occurring water types in the surficial aquifer system in the study area are mixed and calcium-bicarbonate. Precipitation, which provides most of the recharge to the surficial aquifer system, is generally a sodium-chloride type water; however, water quality rapidly evolves to calcium-bicarbonate or mixed type water owing to water-rock interaction with the carbonate rocks (Berndt and Katz, 1992). Dissolved-solids concentrations are generally low (less than 100 mg/L) (Berndt and Katz, 1992), pH is normally less than 5, and water entering the aquifer through recharge is normally oxic.

The intermediate confining unit overlying the Floridan aquifer system contains many minerals including magnesium-rich clay sediments, uranium, pyrite, and phosphatic minerals (Katz, 1992). Arsenic, uranium, radon, and radium are present as trace elements in the phosphatic and(or) pyrite minerals, and these constituents may leach into the Floridan aquifer system when conditions are favorable. The dominant water type for the intermediate confining unit is mixed, and the pH and dissolved-solids concentration in the intermediate confining unit are generally greater than those of water from the surficial aquifer system.

Ground water in the Floridan aquifer system has a predominantly calcium-bicarbonate to calcium-sulfate, or calcium-magnesium-bicarbonate-sulfate chemical signature (Katz, 1992), although water-chemistry conditions in the Floridan aquifer system can be highly variable because karst features can cause variable residence times. Ground-water pH of the Floridan aquifer system in the study area is generally between 6.0 and 8.0 pH units. Dissolved-solids concentrations range from 10 to 30,000 mg/L and average approximately 250 mg/L depending on the degree of confinement, depth in the aquifer, and mixing with seawater. Calcium concentrations generally increase with depth in the Floridan aquifer system within the study area because aquifer residence times tend to increase with depth. The dissolution of gypsum may also contribute to high concentrations of calcium and sulfate. Pyrite dissolution from the Suwannee Limestone, and possibly the overlying Hawthorn Group, may contribute iron and arsenic to the Florida aquifer (Thomas Pichler, University of South Florida, Tampa, oral commun., 2002). Ground water in discharge areas is commonly mixed or of sodium-chloride type indicating mixing with or evolving to seawater (Katz, 1992).

Oxidation-reduction (redox) conditions in the Floridan aquifer system were difficult to generalize, but several observations came from analysis of retrospective data. Conditions consistent with oxygen reduction generally occurred in ground water from shallow sediments and in the Floridan aquifer system in areas where sinkhole density is highest and(or) the aquifer is unconfined or semiconfined (figs. 5.3, 5.5). Conditions consistent with oxygen reduction in deeper wells were observed almost exclusively in waters from large-capacity public-supply wells and may be the result of high pumping rates oxidizing ground water near the well. Reduced conditions, represented by iron-reducing waters, were more often present in proximity to wetlands, discharge areas, and at greater aquifer depths (fig. 5.3). Iron and sulfate concentrations are high in waters from shallower wells because of the iron- and magnesium-rich clay minerals, pyrite and dolomite dissolution from the Hawthorn Group intermediate confining unit, and gypsum dissolution in the deeper Floridan aquifer system.

Because of the complex karst ground-water flow system within the Floridan aquifer system and the various types of wells used to evaluate redox conditions (public-supply wells with large open intervals compared to monitoring wells with short open intervals), delineation of spatial or vertical redox zones is not possible with the available water-quality data. The ability to delineate redox zones in the Floridan aquifer system may be improved by defining a quantifiable link between the total area of wetlands and/or number of sinkholes (and other karst features) in the contributing areas of wells and the redox conditions of the aquifer.

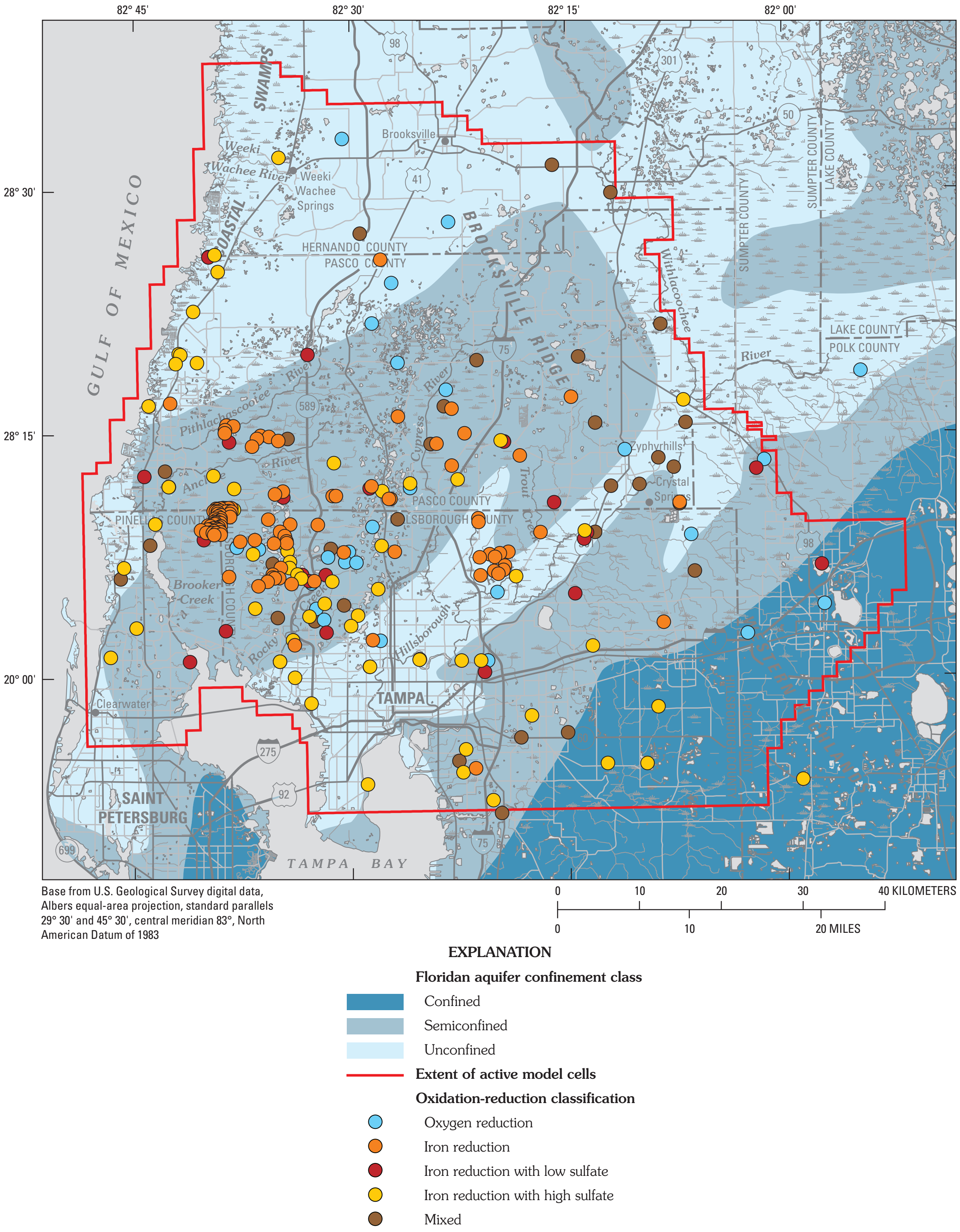


Figure 5.5. Oxidation-reduction classification, Northern Tampa Bay regional study area, Florida.

Ground-Water Flow Simulations

Ground-water flow of the Northern Tampa Bay regional study area was simulated by modifying an existing steady-state ground-water flow model, developed in MODFLOW88 (McDonald and Harbaugh, 1988) of the Central-Northern Tampa Bay area (SDI Environmental Services, Inc., 1997). The Central-Northern Tampa Bay model was originally developed as a tool to evaluate the effects of ground-water withdrawal from specific well fields on aquifer and lake water levels. The Central-Northern Tampa Bay model was a transient, coupled surface-water/ground-water flow model with a simulation period of 1971 through 1993 (SDI Environmental Services, Inc., 1997). In the late 1990's, the ground-water component of the Central-Northern Tampa Bay model was split from the coupled model, converted to a steady-state model, and the hydraulic parameters of the ground-water model were optimized by Yobbi (2000).

The optimized steady-state ground-water flow model of Yobbi (2000) was updated by this study to reflect withdrawal rates for year 2000, rediscretized, converted to MODFLOW-2000 (Harbaugh and others, 2000), and recalibrated. The year 2000 was selected for the steady-state simulations because estimated withdrawal rates for agricultural and industrial wells already existed (Nick Sepulveda, U.S. Geological Survey, Orlando, Florida, written commun., 2002), measured withdrawal rates for public-supply wells are available for year 2000, and because year-2000 withdrawal rates are considered representative of withdrawal conditions for 1997–2001. The steady-state flow assumption is reasonable for the study area for 1997–2001 because the Floridan aquifer system has high transmissivity values, a large volume of water circulates through the system, and pumping rates were relatively stable during the time period of study. Other significant changes made to the Yobbi (2000) ground-water model for this study include:

- The surficial aquifer system and Floridan aquifer system were both modeled as convertible from confined to unconfined aquifers to prevent surficial aquifer system nodes from going dry during steady-state simulations. The model modification did not affect the resulting heads, recharge rates, or other parameters.

- The number of drain cells in layer 2 was reduced to represent only those cells with identified springs.

- All drain cells in layer 1 were removed because it was assumed that the springs emanate from the Floridan aquifer system (layer 2).

- The number of river cells was reduced to better represent model areas actually containing river channels.

- The potentiometric surface of the surficial aquifer system in the north-central portion of the model dropped below the bottom of layer 1. The dry cells in layer 1 were therefore deactivated by this study (fig. 5.6) to correct the problem. Dry cells probably occurred because the surficial aquifer is very thin or not present in the area where the Floridan aquifer system outcrops (fig. 5.1).

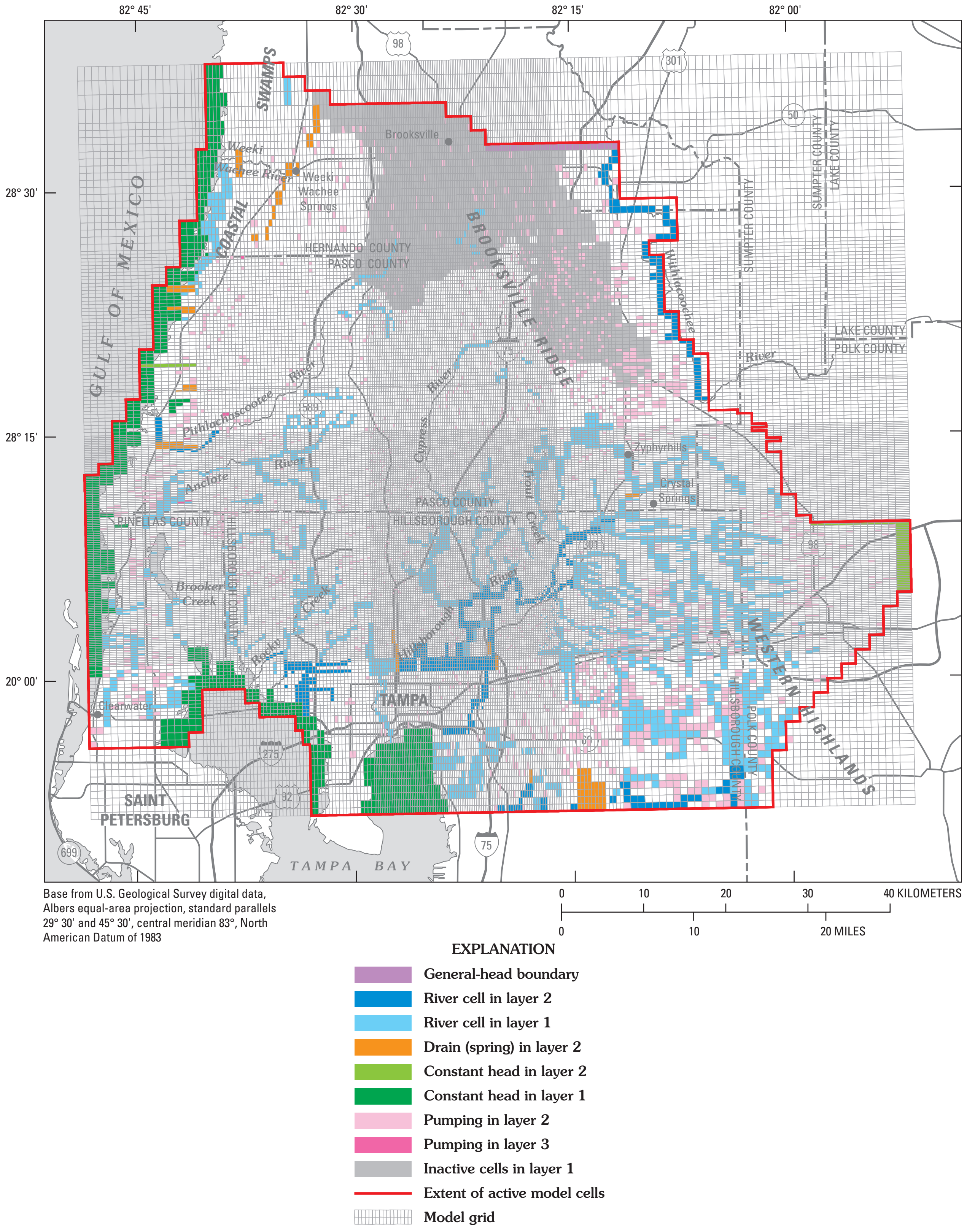
Initial conditions for starting heads, hydraulic conductivity, base of the surficial aquifer system, transmissivity, leakance, hydraulic parameter zones, watershed boundaries, and boundary conditions were derived from the original Central-Northern Tampa Bay model and Yobbi's optimized hydraulic parameters (SDI Environmental Services, Inc., 1997; Yobbi, 2000) with those exceptions previously mentioned. Land-surface elevation, thickness of the active freshwater flow system, base of the Floridan aquifer system, and recharge estimates were derived from Sepulveda (2002).

Modeled Area and Spatial Discretization

The Central-Northern Tampa Bay ground-water flow model covers 5,426 km^2 in Hillsborough, Pasco, Hernando, Pinellas, and Polk Counties of Florida (fig. 5.2). The Central-Northern Tampa Bay model had 121 columns, 131 rows, and 2 layers, and cell sizes ranged from about 300 to 1,600 m on a side. The Central-Northern Tampa Bay model simulated flow in the surficial aquifer system as layer 1 and flow in the Floridan aquifer system as layer 2. The updated Northern Tampa Bay regional ground-water flow model has 227 columns, 234 rows, and 4 model layers; cell sizes range from approximately 200 to 1,600 m on a side. Additional rows and columns were added in the middle of the modeled area to improve the simulation in areas where multiple large pumping wells or other stresses are in close proximity to one another (fig. 5.6). In addition, the Floridan aquifer system in the Northern Tampa Bay regional model was divided into three layers (layers 2, 3, and 4) to resolve weak-sink problems in the particle-tracking analysis (see discussion of weak-sink problems in Section 1 of this Professional Paper). The layer spacing in the Floridan aquifer system was computed by dividing the total thickness of the active freshwater zone of the Floridan aquifer system into thirds.

Boundary Conditions

Model layer 1 lateral boundaries are represented by no-flow cells except where the layer 1 boundary coincides with the coastline of the Gulf of Mexico and Tampa Bay, where the boundary is represented with constant heads (fig. 5.6). The surficial aquifer in the central northern portion of the modeled area is very thin if present and created problems with the steady-state potentiometric surface of layer 1 dropping below the bottom of layer 1, so the layer 1 cells in this area are inactive. In layers 2, 3, and 4, the southeastern and most of the northern boundary are no-flow boundaries representing ground-water flow lines in the Floridan aquifer system. The



Base from U.S. Geological Survey digital data, Albers equal-area projection, standard parallels 29° 30' and 45° 30', central meridian 83°, North American Datum of 1983

Figure 5.6. Ground-water flow model grid and boundary conditions, Northern Tampa Bay regional study area, Florida.

extreme part of the northeastern boundary is represented by a general-head boundary in layer 2 (fig. 5.6). The southeastern edge of the study area is represented as a specified-head boundary in layers 2, 3, and 4. The coastline is represented as a no-flow boundary in layers 2, 3, and 4.

Model Stresses

Hydrologic stresses on the Northern Tampa Bay regional ground-water flow system include recharge from precipitation and surface water and discharge to wells, rivers, and springs.

Recharge

Recharge is defined as the amount of water that infiltrates and percolates through the unsaturated zone to reach the aquifer, in this case the surficial aquifer system (layer 1). In the Northern Tampa Bay regional model, the complexities of rainfall, runoff, infiltration, percolation, and evapotranspiration were highly simplified. The MODFLOW Recharge package was used to assign initial values of recharge to the modeled area using watershed by watershed recharge estimates from Aucott (1988). Final recharge values were derived from model calibration as discussed in the “Model Calibration” section.

Pumping

Total pumping withdrawal from the Floridan aquifer system in the modeled area for all public water supply, agricultural, and industrial wells was 1.8 Mm^3/d in 2000. Approximately 1.34 Mm^3/d were withdrawn for public-supply wells; the remaining 0.23 Mm^3/d was the estimated withdrawal for agricultural and industrial purposes. Withdrawal rates for agricultural and industrial wells for 2000 were compiled and estimated by Nicasio Sepulveda of the U.S. Geological Survey in Orlando, Florida, from permit data from the Southwest Florida Water Management District—measured withdrawal rates were not available. Withdrawal rates for public-supply wells for 2000 were computed from average monthly withdrawal rates obtained from the Southwest Florida Water Management District. Domestic-well withdrawals of approximately 45,000 m^3/d are insignificant compared to public-supply withdrawals and were assumed offset by septic-tank-effluent recharge. Withdrawals are spaced throughout the modeled area based on actual well locations, and the largest public-supply withdrawals are concentrated in the southeastern part of the modeled area (fig. 5.6). The MODFLOW Well package was used to simulate ground-water pumping.

Rivers

The MODFLOW River package was used to simulate river/aquifer interaction in the modeled area. Major rivers included in the Northern Tampa Bay regional model were the Hillsborough, Withlacoochee, Anclote, and Pithlachascotee Rivers, and their tributaries. Other surface-water features simulated as rivers include Brooker, Rocky, Trout, and Cypress Creeks. River stage, conductance, bottom elevations, and layer of interaction were obtained from the optimized ground-water flow model (Yobbi, 2000). Most river cells were located in layer 1 (83 percent), but stretches of the Hillsborough and Withlacoochee Rivers and a few small rivers along the Gulf of Mexico (Weeki Wachee) were simulated in layer 2 (17 percent). Discharge to streams from the ground-water system was calculated for calibration purposes, but riverbed conductances were not altered for this study to improve model fit. Lakes and wetlands were assumed to be part of the surficial aquifer system and were not explicitly simulated.

Drains

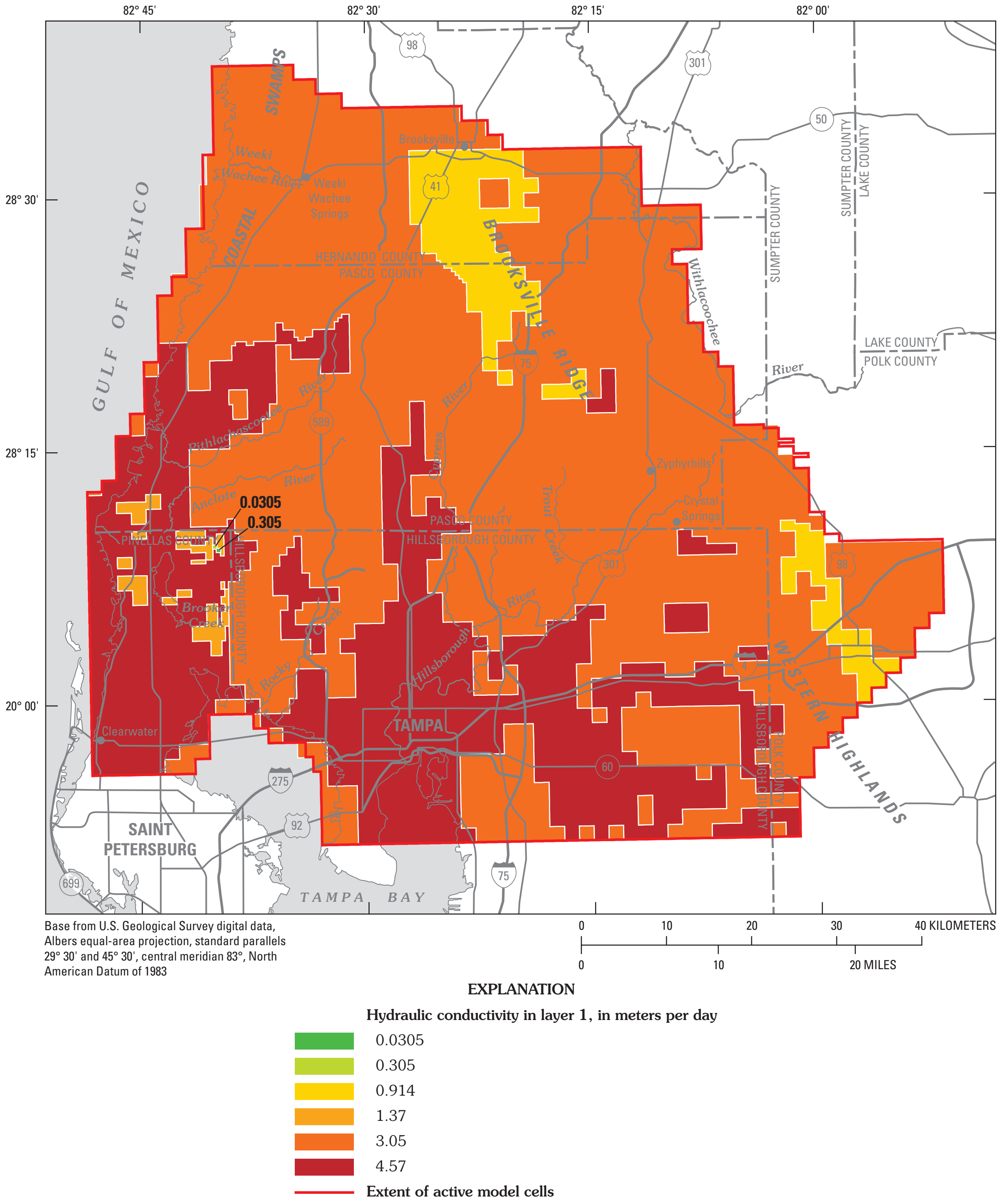
Sixty-nine springs were simulated in layer 2 to represent discharge from the Floridan aquifer system using the MODFLOW Drain package. Spring stage, drain conductance, and bottom elevations were taken from the optimized model (Yobbi, 2000). Springs in the study emanate from the Floridan aquifer system (not the surficial aquifer system), so drains in the Northern Tampa Bay regional model were simulated only in layer 2. In the optimized model (Yobbi, 2000), drain cells in layer 1 were used to simulate wetlands. The layer 1 drains of Yobbi (2000) were eliminated from the current regional model because they were negatively affecting the models ability to determine flowpaths.

Aquifer Properties

Hydraulic conductivities (K) used for model layer 1 were defined using five different zones and values ranging from 0.3 to 5 m/d (fig. 5.7) (Yobbi, 2000). A hydraulic conductivity of 3.0 m/d or less was used in most of the upland areas of the model (3,500 km^2). Hydraulic conductivity was greatest (4.5 m/d) along the coast and river/wetland areas (1,600 km^2).

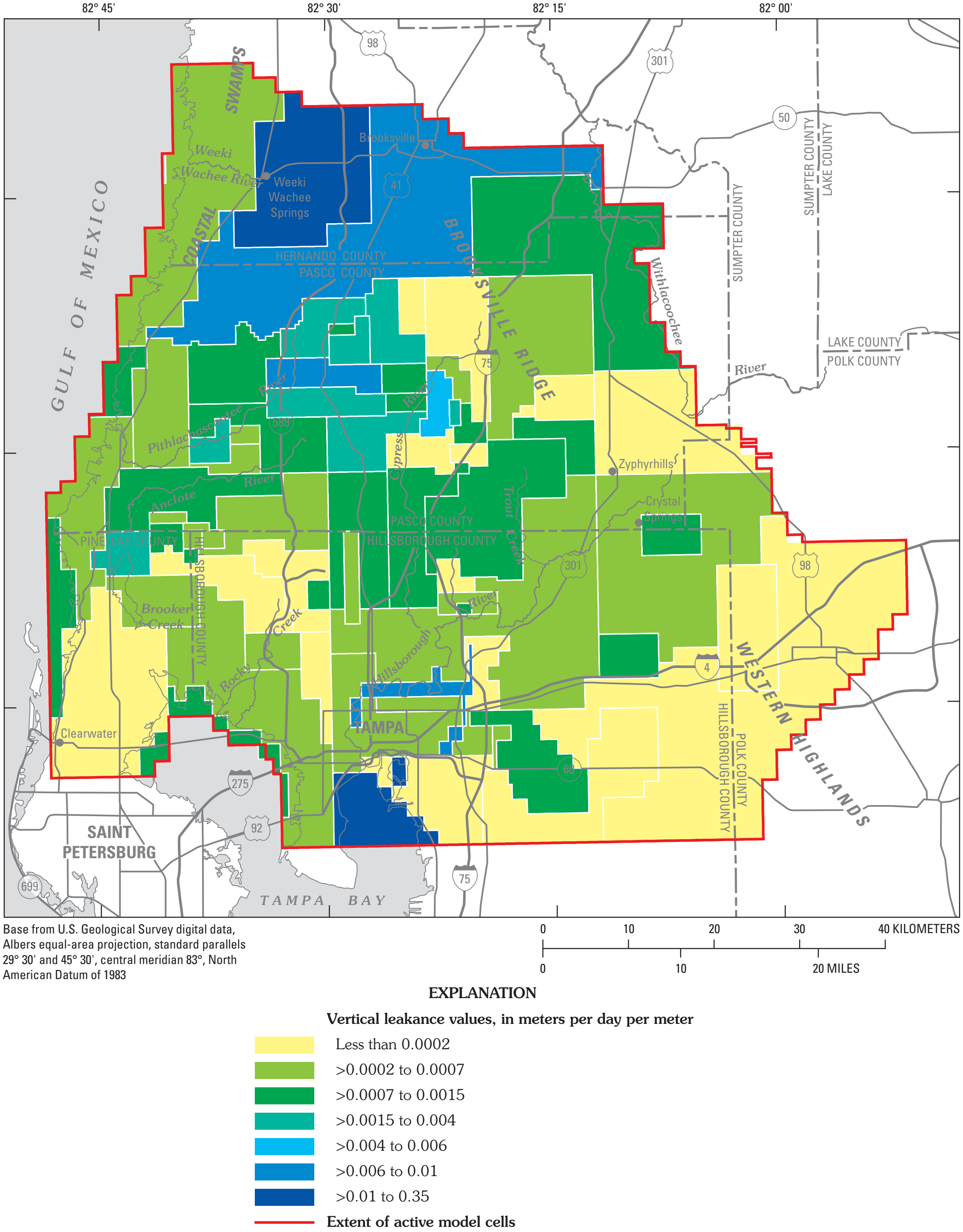
Vertical leakance values used to simulate leakage between the surficial aquifer system and the Floridan aquifer system (through the intermediate confining unit) ranged from 1×10^{-6} to 3.5×10^{-1} m/d/m (fig. 5.8) and were based on aquifer-test data reported in Knochenmus and Robinson (1996) and other references (SDI Environmental Services, Inc., 1997). Smaller values were assigned in areas where the intermediate confining unit is thick and(or) not breached and the Floridan aquifer system is confined. Vertical leakance values of 0.35 m/d/m were assigned in areas where the Floridan aquifer system is considered unconfined. Using leakance values greater than 0.35 m/d/m resulted in equal model-computed head values for layers 1 and 2 in the optimized model (Yobbi, 2000).

Transmissivity of the Floridan aquifer system was defined by 23 zones with transmissivity values ranging from 60 to 500,000 m^2/d for each (fig. 5.9) (Yobbi, 2000). Transmissivity values for the Floridan aquifer system were derived from aqui-



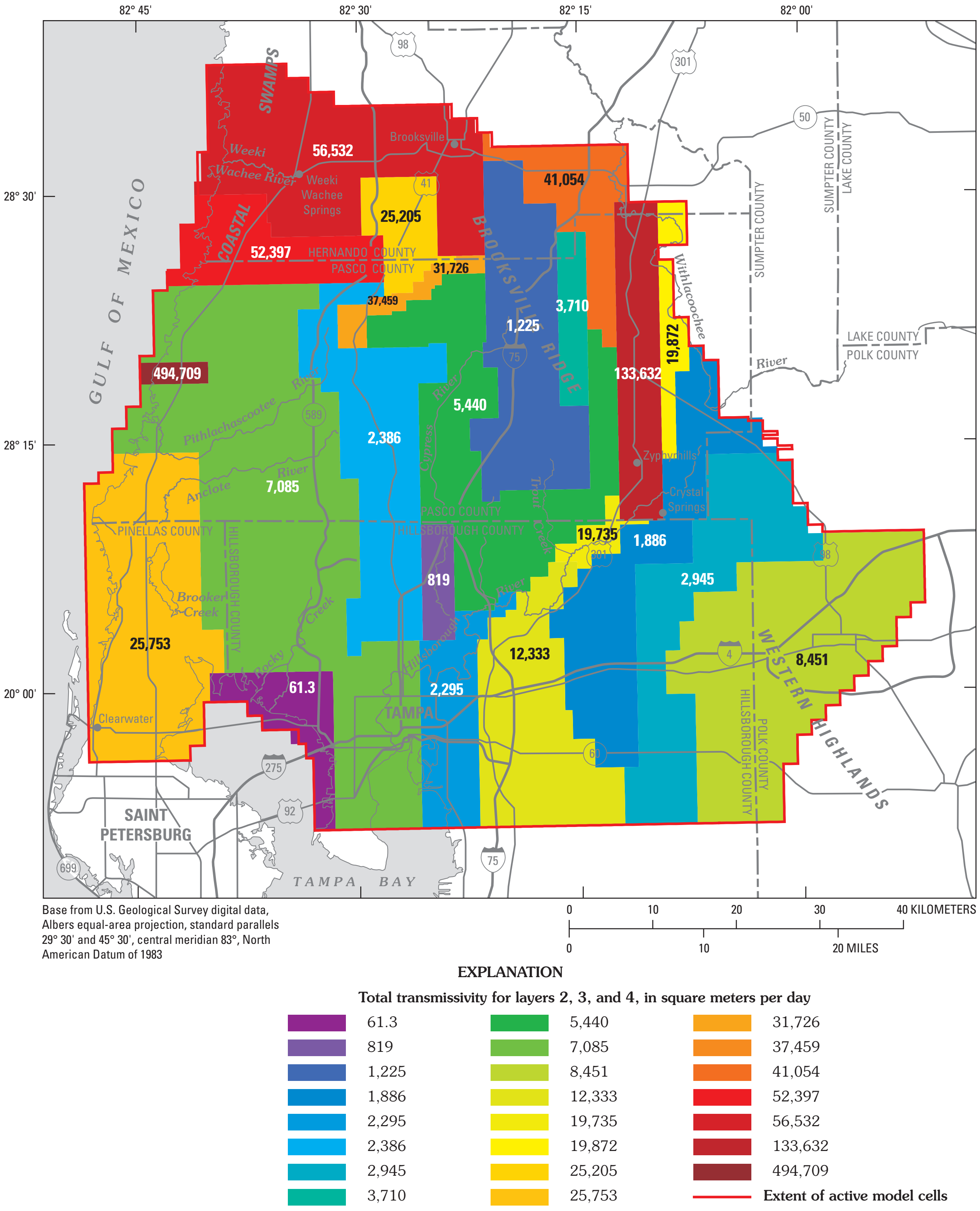
Base from U.S. Geological Survey digital data, Albers equal-area projection, standard parallels 29° 30' and 45° 30', central meridian 83°, North American Datum of 1983

Figure 5.7. Distribution of hydraulic conductivity for model layer 1, Northern Tampa Bay regional study area, Florida.



Base from U.S. Geological Survey digital data, Albers equal-area projection, standard parallels 29° 30' and 45° 30', central meridian 83°, North American Datum of 1983

Figure 5.8. Distribution of vertical leakance values assigned between model layers 1 and 2, Northern Tampa Bay regional study area, Florida.



Base from U.S. Geological Survey digital data, Albers equal-area projection, standard parallels 29° 30' and 45° 30', central meridian 83°, North American Datum of 1983

Figure 5.9. Distribution of transmissivity values assigned to the Floridan aquifer (model layers 2, 3, and 4), Northern Tampa Bay regional study area, Florida.

fer tests and published values (SDI Environmental Services, Inc., 1997), and the transmissivity distribution for the Northern Tampa Bay regional model (layers 2, 3, and 4) was the same as that based on parameter-estimation results of Yobbi (2000). Because the total thickness of the Floridan aquifer system was divided into equal thirds when layers 3 and 4 were added to the model, the total transmissivity shown in figure 5.9 was also divided into thirds and an identical transmissivity distribution was assigned to each of layers 2, 3, and 4. Transmissivity values were smallest in areas where the Floridan aquifer system is confined or semiconfined, and transmissivity values were largest in the northern sections of the modeled area, coastal areas, and in the Withlacoochee River Basin (Yobbi, 2000).

Model Calibration and Sensitivity

The Northern Tampa Bay regional model was recalibrated to year-2000 conditions using a trial-and-error approach by adjusting recharge and comparing model-computed (simulated) hydraulic head and ground-water discharge to measured hydraulic head and streamflow and spring-flow data. The optimized hydraulic conductivity, transmissivity, and vertical leakance distributions of Yobbi (2000) were not modified during model calibration.

Initial recharge values were adjusted during model calibration until the difference between model-computed and measured hydraulic heads and ground-water discharge were minimized. Calibrated recharge values in the modeled area ranged between 0 and 63.5 cm/yr (fig. 5.10), and the average recharge rate for the study area (23.1 cm/yr) was kept less than the Yobbi (2000) value of 33 cm/yr. Recharge is greatest in areas where the Floridan aquifer system is unconfined or semiconfined. Zero recharge was specified in discharge areas such as the Hillsborough River and the coastal areas (fig. 5.10).

Model-computed hydraulic head was compared to median head values for the year 2000 from 187 monitoring wells in the Floridan aquifer system and 210 wells in the surficial aquifer system. Model-computed discharge was compared to the increase in base flow to the Hillsborough River between gages on the Hillsbourough River near Zephyrhills, Florida, (station 02301990) and the Hillsborough River above Crystal Springs, near Zephyrhills, Florida, (station 02303000) (Coffin and Fletcher, 2001). The calibration goal was to reduce the difference between simulated and measured head (residual), especially in the Floridan aquifer system.

The overall goodness of fit of the model to the observation data was evaluated using summary measures and graphical analyses. The root-mean-squared error (RMSE), the range, the standard deviation, and the standard-mean error of the residuals (SME), were used to evaluate the model calibration. The RMSE is a measure of the variance of the residuals and was calculated as:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N} (h_{meas} - h_{sim})i^2}{N}}$$

where h_{meas} is the measured hydraulic head, h_{sim} is the model-computed (simulated) hydraulic head, $(h_{meas} - h_{sim})$ is the head residual, and N is the number of wells used in the computation. If the ratio of the RMSE 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).

The SME was calculated as:

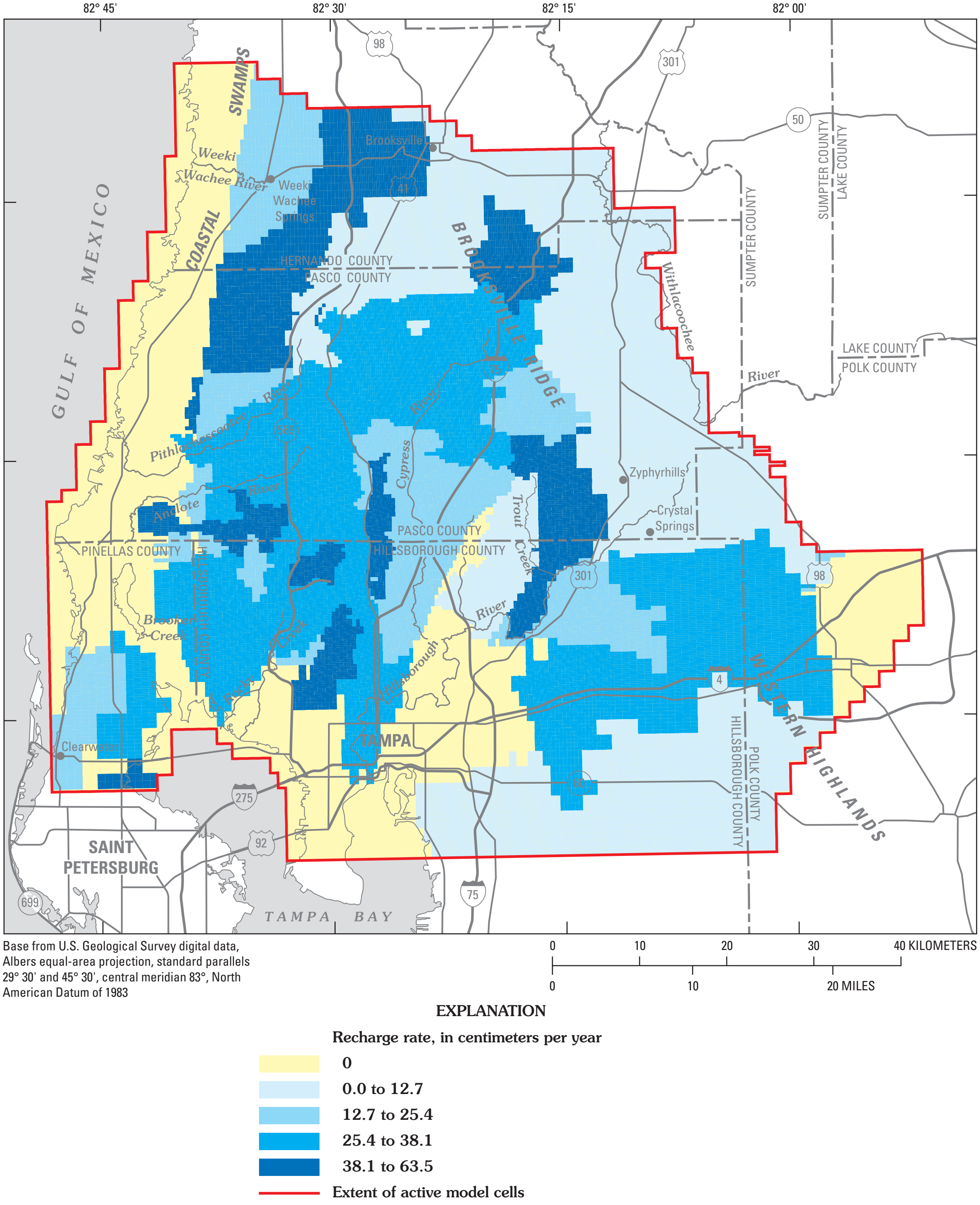
$$SME = \frac{\sigma(h_{meas} - h_{sim})}{\sqrt{N}}$$

where $\sigma(h_{meas} - h_{sim})$ is the standard deviation of the residuals.

Model-Computed Hydraulic Heads

The spatial distribution of model-computed hydraulic heads for model layers 1 and 2 (figs. 5.11*A* and 5.11*B*) present a reasonable representation of potentiometric surfaces for the surficial and Floridan aquifer systems, respectively. Model-computed hydraulic head maps for both layers indicate highest heads in the northern and eastern parts of the modeled area and the lowest heads in the western and southwestern parts of the modeled area along the Gulf of Mexico. The maps of model-computed hydraulic head indicate ground-water flow is from the northern and eastern parts of the modeled area toward the coastal lowlands consistent with land-surface topography and previous maps of hydraulic head (Yobbi, 2000).

A simple method of assessing overall model fit is to plot the model-computed hydraulic head values against the measured observations. For a perfect fit, all points should fall on the 1:1 diagonal line, and a reasonable model fit is indicated in figures 5.12*A* and 5.12*B*. The spatial distribution of the head residuals is shown in figure 5.13 and can be used to understand the geographic distribution of head residuals. Head residual in the surficial aquifer system range from -8.9 to 19.1 m with a mean of 0.6 m (median of 0.3 m) (figs. 5.13 and 5.14*A*). Head residuals in the surficial aquifer system are greatest in the southern parts of the modeled area in locations where there are few water-level measurements and where head values are highest (figs. 5.11*A* and 5.13). Head residuals in the Floridan aquifer system range from –6.6 to 7.9 m and average 0.2 m (median also of 0.2 m) (figs. 5.13 and 5.14*B*). Floridan aquifer system head residuals are smallest in the northern coastal lowlands and center of the model area and largest in northern Pinellas County and southeastern parts of the modeled area (fig. 5.13). The average residual for the entire model is 0.28 m. The RMSE for the entire model is 2.63 m, which is



Base from U.S. Geological Survey digital data, Albers equal-area projection, standard parallels 29° 30' and 45° 30', central meridian 83°, North American Datum of 1983

Figure 5.10. Ground-water flow model calibrated recharge rates, Northern Tampa Bay regional study area, Florida.

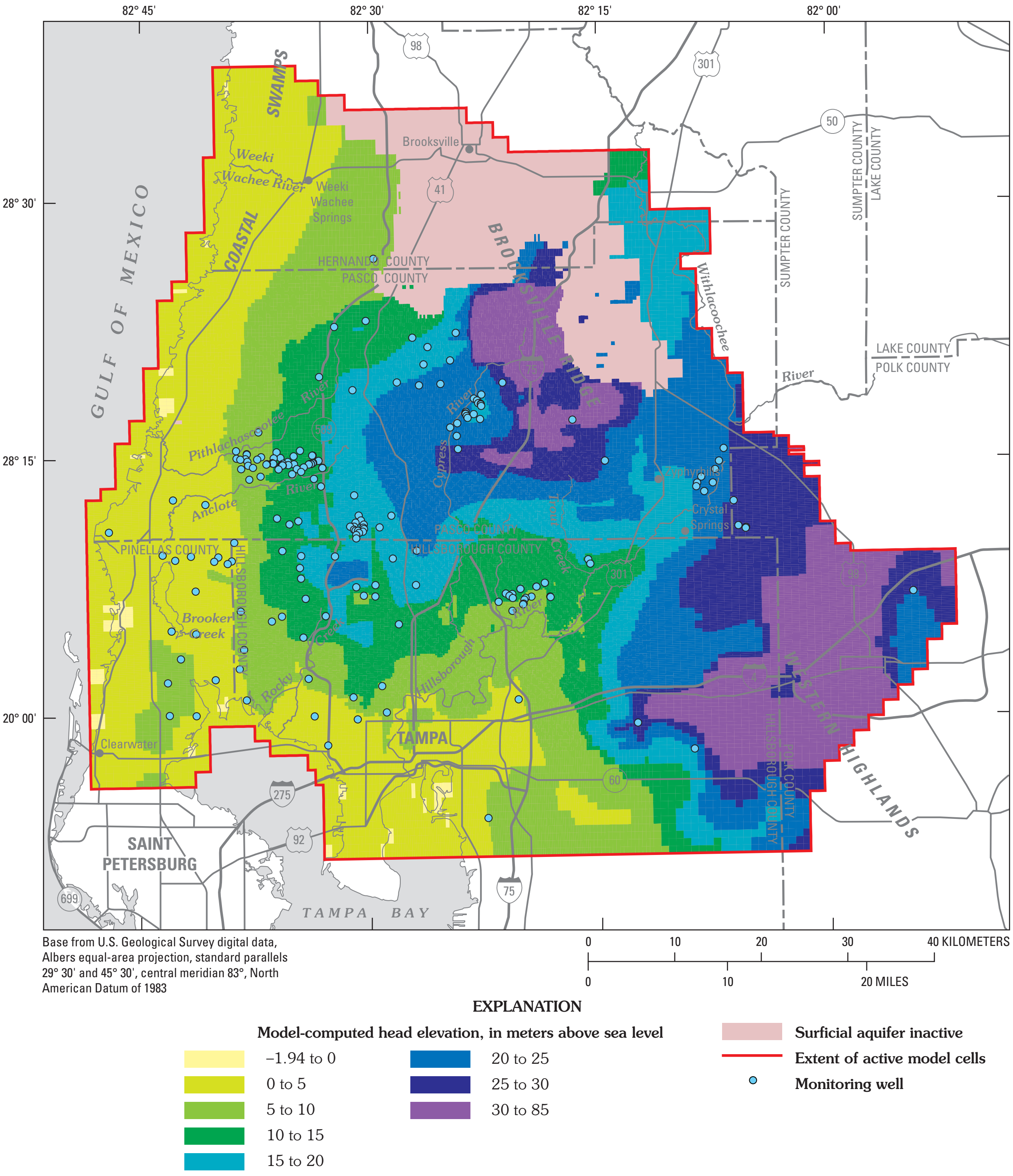
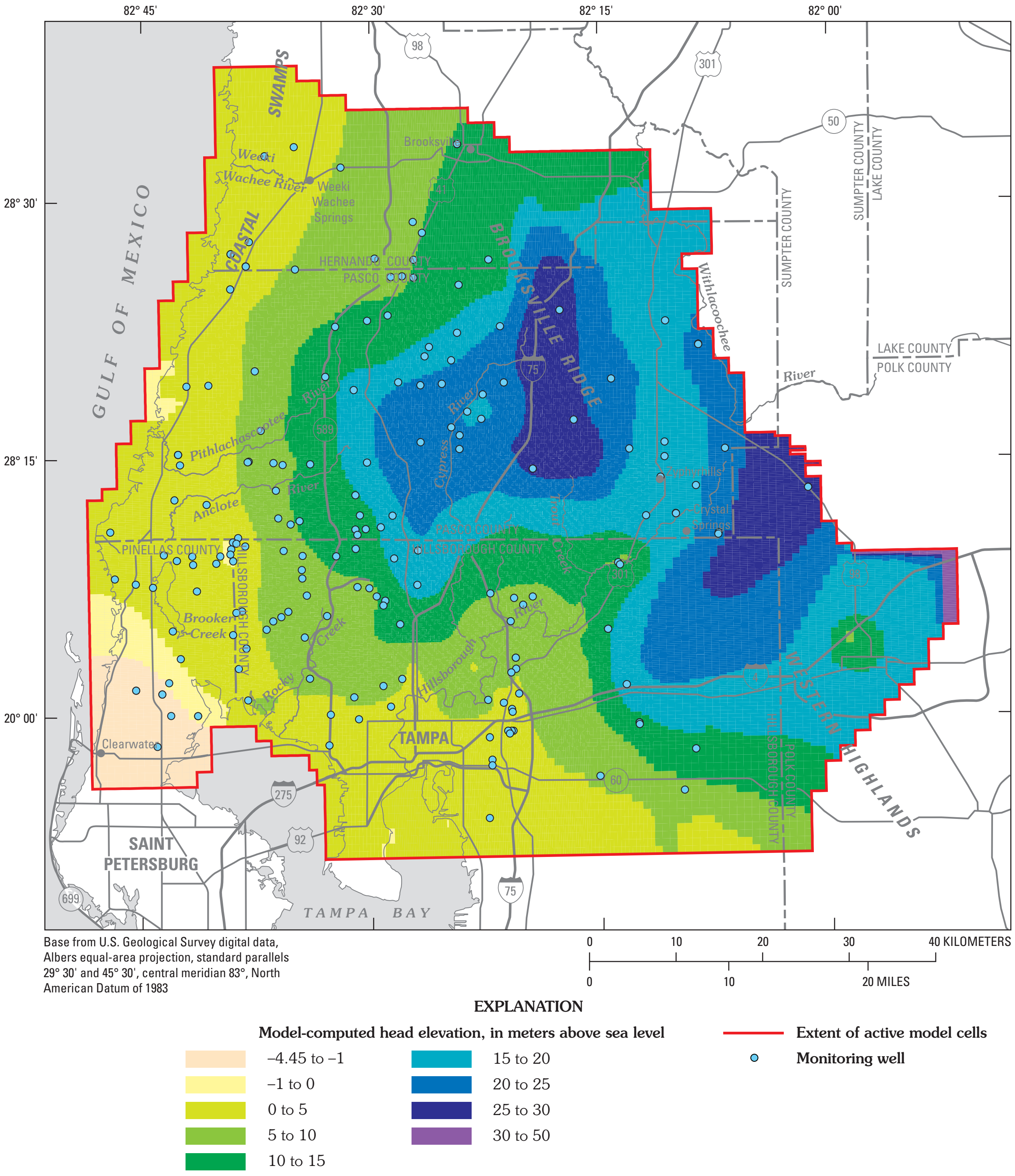


Figure 5.11*A*. Distribution of model-computed hydraulic heads for the surficial aquifer system (model layer 1), Northern Tampa Bay regional study area, Florida.



Base from U.S. Geological Survey digital data, Albers equal-area projection, standard parallels 29° 30' and 45° 30', central meridian 83°, North American Datum of 1983

Figure 5.11*B*. Distribution of model-computed hydraulic heads for the uppermost Floridan aquifer system (model layer 2), Northern Tampa Bay regional study area, Florida.

approximately 6 percent of the range of head observations for the model (41.3 m) and also indicates a reasonable model fit. The standard deviation of the residuals is 2.62 m, and the SME is 0.13 m. Ultimately, more water-level measurements and more accurate recharge estimates could improve the model fit for the surficial aquifer system. Of all residuals in both the surficial and Floridan aquifer systems, ninety percent are between –1.6 and 1.6 m (figs. 5.14*A* and 5.14*B*).

Model-Computed Discharge and Recharge

Model-computed base-flow and spring discharge were compared to measured discharge as another model-calibration criterion. The segment of the Hillsborough River used to calibrate the model is located between gaging stations 02301990 and 02303000. This segment was chosen because there are no major flow-altering structures between the two gages. The estimated base-flow increase (based on measured values) in the reach is 121,000 m^3/d; the model-computed discharge to the river in the reach was 112,000 m^3/d. The difference of 9,000 m^3/d is considered a good match between simulated and measured discharge along this stream segment. The difference between simulated discharge and measured discharge to springs was calculated for several important springs including the Weeki Wachee Spring as a further check on model calibration. For Weeki Wachee Spring, the measured average discharge is approximately 450,000 m^3/d (Coffin and Fletcher, 2001); however, the model-computed steady-state discharge is 122,000 m^3/d. Model-computed discharge from the aquifer to this and other springs is lower than measured values indicating the model does a poor job of simulating discharge to springs. This regional-scale simulation likely does not include sufficient localized karst features to adequately simulate local springs.

Recharge is the most sensitive parameter in this model according to Yobbi (2000). Simulated hydraulic heads in the surficial aquifer system and Floridan aquifer system can be readily manipulated by adding or subtracting recharge from an area. A complete description of hydraulic-parameter sensitivities is provided by Yobbi (2000).

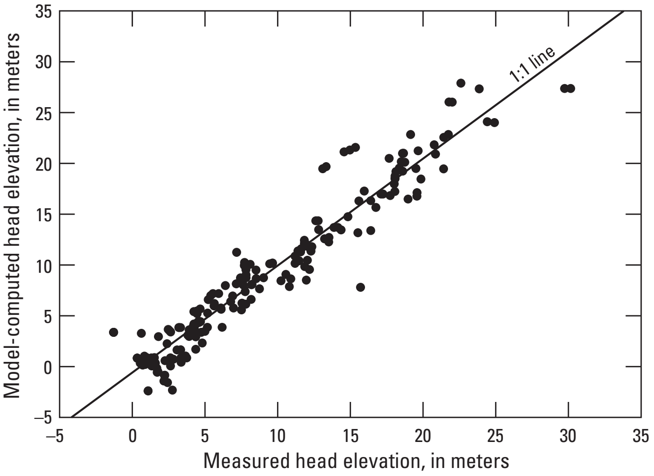


Figure 5.12*A*. Relation between model-computed and measured hydraulic head for model layer 1, Northern Tampa Bay regional study area, Florida.

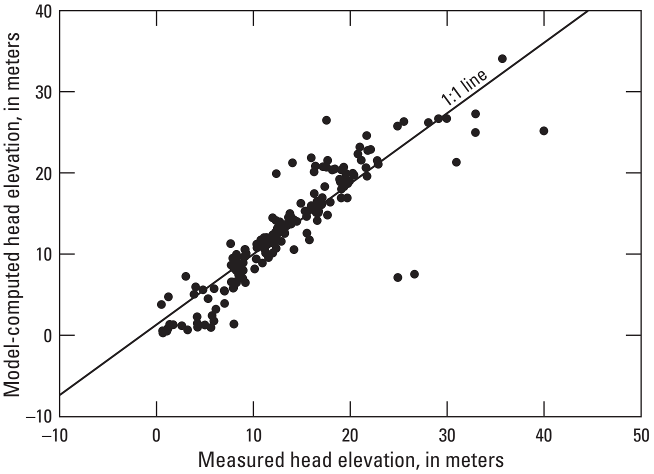
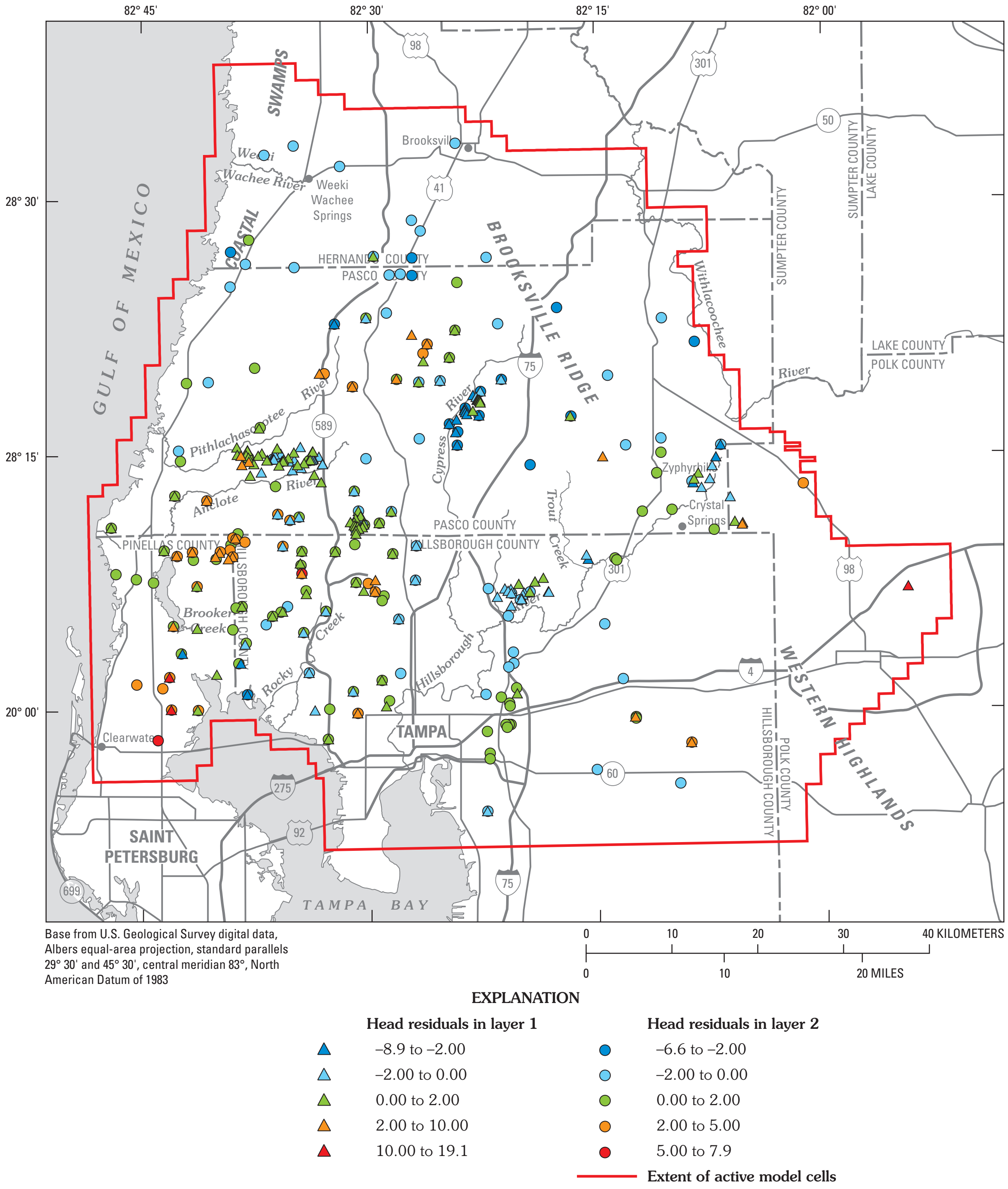


Figure 5.12*B*. Relation between model-computed and measured hydraulic head for model layer 2, Northern Tampa Bay Regional study area, Florida.

Model-Computed Water Budget

The Northern Tampa Bay regional model simulated water budget for the year 2000 is shown in table 5.3. Recharge from precipitation composed most of the inflow of water to the modeled area at 3.44 Mm^3/d (55.4 percent of model inflow). Inflow to the modeled area through constant head cells along the southeastern border composed the second highest amount of inflow to the modeled area (2.17 Mm^3/d or 35.0 percent of model inflow). River inflow to the aquifer was somewhat balanced by river outflow (0.59 Mm^3/d inflow compared to 0.83 Mm^3/d outflow, respectively) (table 5.3; fig. 5.15). Inflow to the aquifer from the rivers occurred mainly in the upper reaches of the Hillsborough and Withlacoochee Rivers and their tributaries and along lower sections of the Hillsborough River. Outflow from the aquifer to rivers was simulated in smaller rivers near the Gulf of Mexico and the mid section of the Hillsborough River among others. Other simulated discharge included outflow at constant-head boundaries along the Gulf of Mexico and Tampa Bay and at the northern general-head boundary to the Withlacoochee River (2.36 Mm^3/d or 38.0 percent of model outflow), wells (1.81 Mm^3/d or 29.1 percent of model outflow—84 percent of which was to public-supply wells), and springs (0.90 Mm^3/d or 14.6 percent of model outflow). There was zero percent error between model-calculated inflows and outflows for this steady-state simulation.



Base from U.S. Geological Survey digital data, Albers equal-area projection, standard parallels 29° 30' and 45° 30', central meridian 83°, North American Datum of 1983

Figure 5.13. Distribution of head residuals for model layers 1 and 2, Northern Tampa Bay regional study area, Florida.

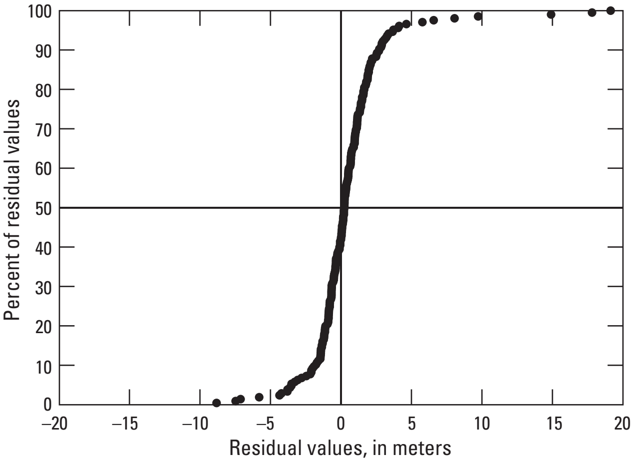


Figure 5.14*A*. Probability distribution of head residuals for model layer 1, Northern Tampa Bay regional study area, Florida.

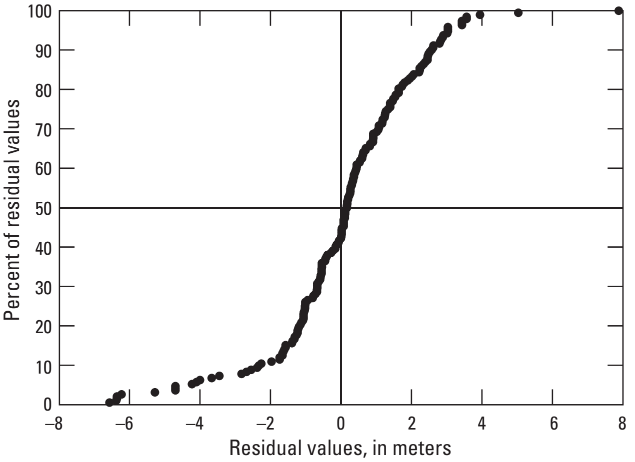


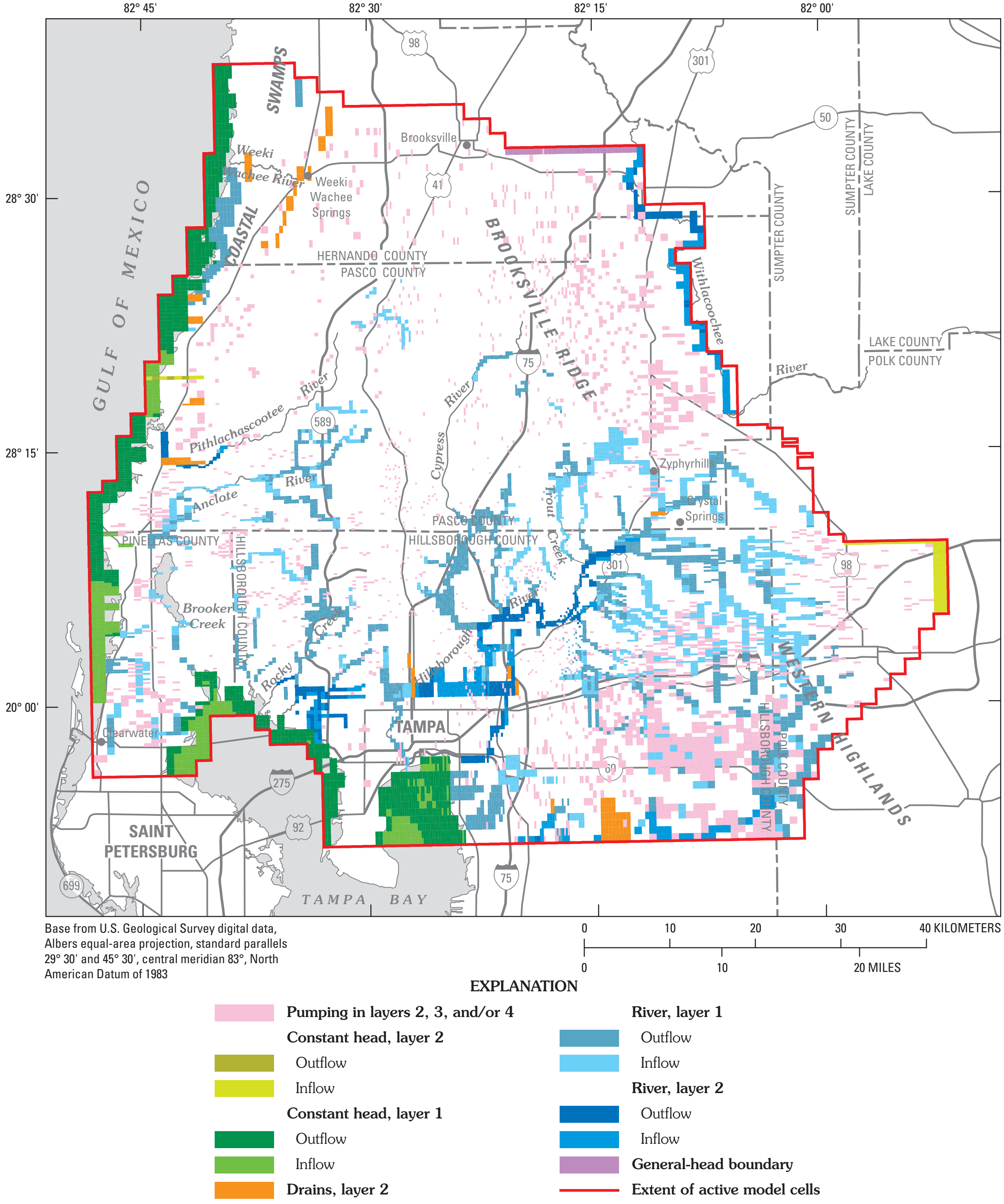
Figure 5.14*B*. Probability distribution of head residuals for model layer 2, Northern Tampa Bay regional study area, Florida.

Table 5.3. Model-computed water budget for year 2000, Northern Tampa Bay regional study area, Florida.

[m^3/d, cubic meters per day]

Water-budget component	Flow (m^3/d)	Percentage of inflow or outflow*
Model inflow		
Precipitation recharge	3,440,000	55.4
Lateral ground-water inflow from constant-head wells	2,173,000	35.0
Rivers	591,000	9.5
TOTAL INFLOW	6,207,000	**100**
Model outflow		
To the Gulf of Mexico, Tampa Bay and the central-northern portion of modeled area	2,360,000	38.0
Wells	1,810,000	29.1
Rivers	830,000	13.4
Springs	904,000	14.6
TOTAL OUTFLOW	6,207,000	**100**

*Total may not equal 100 percent because of rounding.



Base from U.S. Geological Survey digital data, Albers equal-area projection, standard parallels 29° 30' and 45° 30', central meridian 83°, North American Datum of 1983

Figure 5.15. Model-computed ground-water inflows and outflows, Northern Tampa Bay regional study area, Florida.

Simulation of Areas Contributing Recharge to Wells

The calibrated steady-state ground-water flow model was used to estimate areas contributing recharge and zones of contribution for approximately 104 public-supply wells from the four quartiles of pumping rates using the MODPATH (Pollock, 1994) particle-tracking post processor and methods outlined in Section 1 of this Professional Paper. The model-computed areas contributing recharge represent advective ground-water 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.

Along with output from the ground-water flow model, the MODPATH simulation requires effective porosity values to calculate ground-water flow velocities. For the Northern Tampa Bay regional model, porosity values were assumed uniform within each layer based on typical regional values. A porosity of 0.25 was used for the surficial aquifer system (model layer 1), and a porosity of 0.15 was used for the Floridan aquifer system (model layers 2, 3, and 4). Because of the karst nature of ground-water flow in the study area, the porosity values used for this regional simulation would not be applicable to local karst conditions.

Results of the MODPATH simulations used to delineate areas contributing recharge for selected wells are shown on figure 5.16. In general, areas contributing recharge extend upgradient (fig. 5.4) toward the northeast boundary of the modeled area. Summary statistics were computed for the particle-tracking results for wells from all quartiles of pumping rates. Areas contributing recharge ranged from near 0 to 1.25 km^2, and the average area contributing recharge was approximately 0.26 km^2. Minimum computed traveltimes for all wells ranged from 0.7 to 233 years and averaged 19 years. Maximum computed traveltimes ranged from 32 to 1,875 years and averaged 600 years. On the basis of average traveltimes of particles reaching the wells, about 3 percent of the flow to a public-supply well was less than 10 years old, about 36 percent of the flow to a public-supply well was less than 50 years old, and about 80 percent of the flow to a public-supply well was less than 200 years old. Simulated traveltimes are probably much longer than actual traveltimes in the aquifer because the regional ground-water flow model does not accurately represent flow through local karst dissolution features.

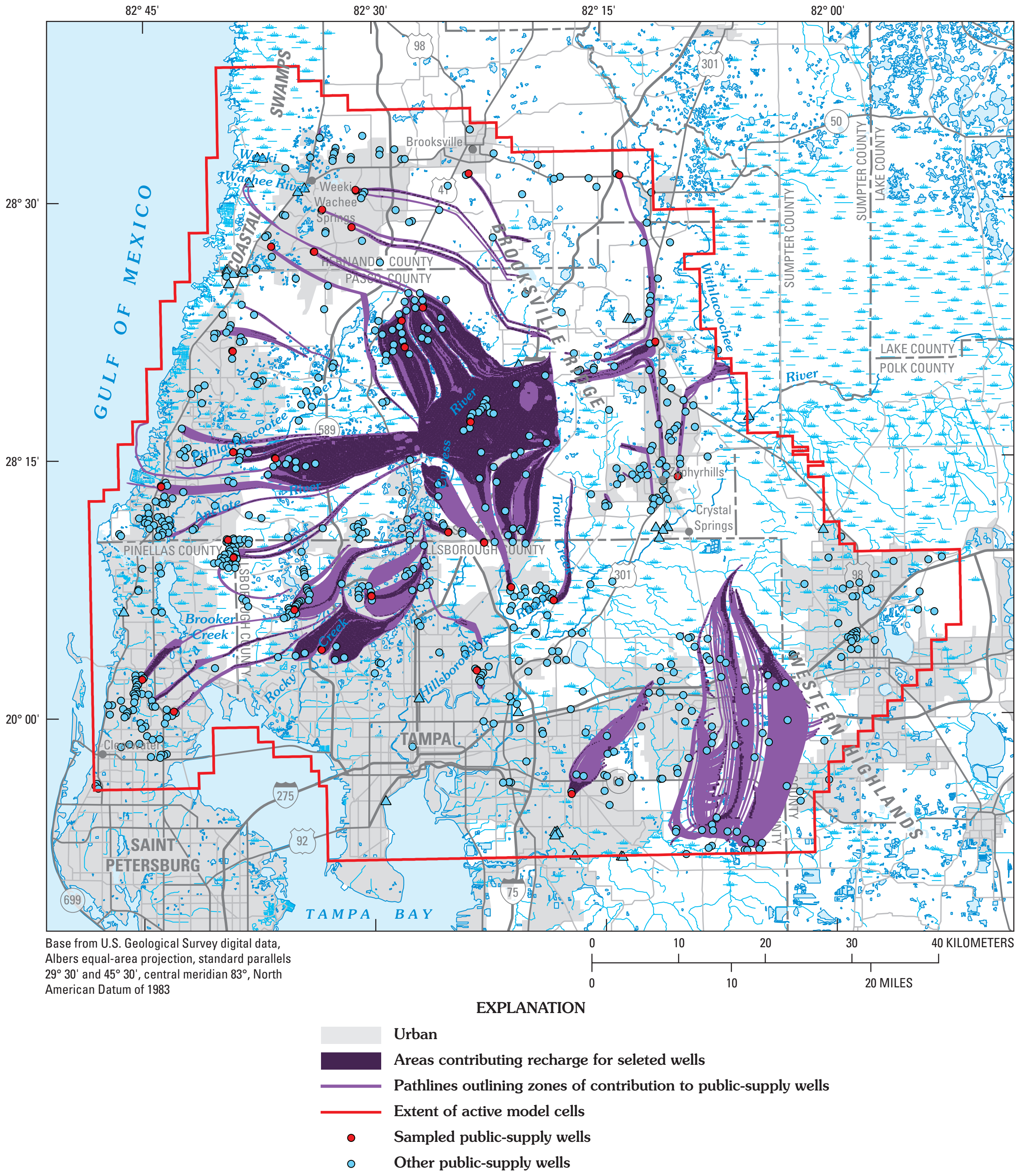
Limitations and Appropriate Use of the Model

The ground-water flow model for the Northern Tampa Bay regional study area was designed to delineate areas contributing recharge to public-supply wells, to help guide data collection, and to support future local modeling efforts. Sources of error in the model may include the steady-state flow assumption and errors in the conceptual model of the system, hydraulic properties, and boundary conditions.

The steady-state flow assumption is reasonable for the study area for 1997–2001 because the Floridan aquifer system has high transmissivity values, a large volume of water circulate through the system, and pumping rates were relatively stable during the time period of study. However, errors related to the steady-state assumption can be substantial, and further calibration for transient conditions may be needed to accurately represent temporal changes in the system.

For karst terrains, where a substantial percentage 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. Secondary porosity created by karst dissolution features contributes to uncertainty in values of hydraulic conductivity, which can vary by up to five orders of magnitude (Langevin, 2003; Bush and Johnston, 1988), and porosity, which also can vary substantially. Knochenmus and Robinson (1996) used very low effective porosities in order to achieve realistic traveltimes in the Floridan aquifer system and 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. Changes to input porosity values will change computed traveltimes from recharge to discharge areas in direct proportion to changes of effective porosity because there is an inverse linear relation between ground-water flow velocity and effective porosity and a direct linear relation between traveltime and effective porosity. For example, a one-percent decrease in porosity will result in a one-percent increase in velocity and a one-percent decrease in particle traveltime. A detailed sensitivity analysis of porosity distributions was beyond the scope of this regional study.

The ground-water flow model for the Northern Tampa Bay regional study area represents a first approximation of ground-water conditions and the areas contributing recharge to public-supply wells in the modeled area. The model is suitable for evaluating regional water budgets and ground-water flow paths in the study area for the time period of interest but may not be suitable for long-term predictive simulations. To improve contributing area delineation, the model could incorporate karst features, possibly using a probabilistic (Monte Carlo) simulation approach over a much smaller area. Additional hydraulic head observations in the surficial aquifer system in the southern part of the modeled area would improve the calibration of the existing model as would additional measurements of recharge and discharge if possible. This regional model does provide a useful tool to evaluate aquifer vulnerability at a regional scale, to facilitate comparisons of ground-water traveltime between regional aquifer systems, and to guide future detailed investigations in the study area.



Base from U.S. Geological Survey digital data, Albers equal-area projection, standard parallels 29° 30' and 45° 30', central meridian 83°, North American Datum of 1983

EXPLANATION

- ▨ Urban
- ■ Areas contributing recharge for seleted wells
- — Pathlines outlining zones of contribution to public-supply wells
- — Extent of active model cells
- ● Sampled public-supply wells
- ○ Other public-supply wells

Figure 5.16. Model-computed areas contributing recharge for selected public-supply wells, Northern Tampa Bay regional study area, Florida.

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