Simulation of Ground-Water Flow in the Intermediate and Floridan Aquifer Systems in Peninsular Florida

By Nicasio Sepúlveda

U.S. GEOLOGICAL SURVEY
Water-Resources Investigations Report 02-4009

Prepared in cooperation with the

South Florida Water Management District
St. Johns River Water Management District

science for a changing world

Tallahassee, Florida
2002

U.S. DEPARTMENT OF THE INTERIOR
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U.S. GEOLOGICAL SURVEY
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CONVERSION FACTORS AND VERTICAL DATUM

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
	Area	
acre	0.4047	hectare
square mile (mi^2)	2.590	square kilometer
	Flow Rate	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
million gallons per day (Mgal/d)	0.04381	cubic meter per second
inch per year (in/yr)	25.4	millimeter per year
	Hydraulic Conductivity	
foot per day (ft/d)	0.3048	meter per day
	***Transmissivity**	
foot squared per day (ft^2/d)	0.09290	meter squared per day
	Leakance	
foot per day per foot [(ft/d)/ft]	1.0	meter per day per meter

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

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:
°C=(°F-32)/1.8

Sea level: In this report, "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)--a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929.

Horizontal coordinate information (latitude-longitude) is referenced to the North American Datum of 1927 (NAD27).

Acronyms and additional abbreviations used in report:

DEM	digital elevation model
FPZ	Fernandina permeable zone
FDEP	Florida Department of Environmental Protection
FAS	Floridan aquifer system
IAS	intermediate aquifer system
ICU	intermediate confining unit
LFA	Lower Floridan aquifer
MCU	middle confining unit
MSCU	middle semiconfining unit
mg/L	milligrams per liter
MODFLOW	U.S. Geological Survey Modular Three-Dimensional Ground-Water Flow Model
NOAA	National Oceanic and Atmospheric Administration
ROMP	Regional Observation and Monitoring Well Program
RMS	root mean square
SJRWMD	St. Johns River Water Management District
SFWMD	South Florida Water Management District
SWFWMD	Southwest Florida Water Management District
SR	surface runoff
SAS	surficial aquifer system
SRWMD	Suwannee River Water Management District
UFA	Upper Floridan aquifer
USGS	U.S. Geological Survey
UTM	Universal Transverse Mercator

Simulation of Ground-Water Flow in the Intermediate and Floridan Aquifer Systems in Peninsular Florida

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Abstract

A numerical model of the intermediate and Floridan aquifer systems in peninsular Florida was used to (1) test and refine the conceptual understanding of the regional ground-water flow system; (2) develop a data base to support subregional ground-water flow modeling; and (3) evaluate effects of projected 2020 ground-water withdrawals on ground-water levels. The four-layer model was based on the computer code MODFLOW-96, developed by the U.S. Geological Survey. The top layer consists of specified-head cells simulating the surficial aquifer system as a source-sink layer. The second layer simulates the intermediate aquifer system in southwest Florida and the intermediate confining unit where it is present. The third and fourth layers simulate the Upper and Lower Floridan aquifers, respectively. Steady-state ground-water flow conditions were approximated for time-averaged hydrologic conditions from August 1993 through July 1994 (1993-94). This period was selected based on data from Upper Floridan aquifer wells equipped with continuous water-level recorders. The grid used for the ground-water flow model was uniform and composed of square 5,000-foot cells, with 210 columns and 300 rows.

The active model area, which encompasses about 40,800 square miles in peninsular Florida, includes areas of various physiographic regions classified according to natural features. Hydrogeologic conditions vary among physiographic regions, requiring different approaches to estimating hydraulic properties for different areas. The altitudes of water levels for the surficial aquifer system and heads in the Upper Floridan aquifer, for time-averaged 1993-94 conditions, were computed by using a multiple linear regression of measured water levels in each of the physiographic regions.

Ground-water flow simulation was limited vertically to depths containing water with chloride concentrations less than 5,000 milligrams per liter. Water-level altitudes in the Floridan aquifer system beneath which chloride concentrations exceed 5,000 milligrams per liter were estimated from previously developed maps and analytical results of ground-water samples. Flow across the interface represented by this chloride concentration was assumed to be negligible.

The ground-water flow model was calibrated using time-averaged data for 1993-94 at 1,624 control points, flow measurements or estimates at 156 springs in the study area, and baseflow estimates of rivers in the unconfined areas of the Upper Floridan aquifer obtained by using a generalized hydrograph separation of recorded discharge data. Transmissivity of the intermediate aquifer system, Upper Floridan aquifer, and Lower Floridan aquifer; leakance of the upper and lower confining units of the intermediate aquifer system, the intermediate confining unit, the middle confining unit, and the middle semiconfining unit; spring and riverbed conductances; and net recharge rates to unconfined areas of the Upper Floridan aquifer were adjusted until a reasonable fit was obtained.

Root-mean-square residuals between computed and simulated heads in the intermediate aquifer system, Upper Floridan aquifer, and Lower Floridan aquifer were 3.47, 3.41, and 2.89 feet, respectively. The overall root-mean-square residual was 3.40 feet. Simulated spring flow was 96 percent of the total measured (or estimated) spring flow in the study area.

Simulations were made to project water-level declines from 1993-94 to 2020 conditions. The calibrated flow model was used to simulate the potentiometric surfaces of the intermediate aquifer system, Upper Floridan aquifer, and Lower Floridan aquifer for 2020 using water-use projections provided by the Water Supply Assessment plans of the State Water Management Districts. Water-use projections for 2020 were based on estimated population growth and 1995 withdrawals. Heads in the Upper Floridan aquifer under projected 2020 water-use stresses were simulated for two scenarios: (1) assigning interpolated 1993-94 heads along the lateral boundaries of the Upper Floridan aquifer; and (2) assigning 1993-94 simulated flux rates across the same boundaries.

Projected 2020 ground-water withdrawals for municipal, industrial, commercial, agricultural, and self-supplied domestic uses was approximately 3,400 million gallons per day, an increase of about 36 percent from 1993-94. The largest projected drawdown in the potentiometric surface of the Upper Floridan aquifer, for both scenarios, was simulated in Orange County, with a drawdown of 10 feet in the central part of the County. Projected drawdowns of 6 feet were simulated in parts of Duval and Polk Counties.

INTRODUCTION

The intermediate and Floridan aquifer systems are the principal sources of water supply in much of peninsular Florida. As the population of the State continues to grow, the demand for water continues to increase. In some areas of Florida, decreasing water levels and increasing mineralization of ground water have become problems for local and state water-management officials. Ground-water flow models are important tools for assessing the effects of present and future ground-water development. For this reason, a number of ground-water flow models have been developed for areas within peninsular Florida; however, these areally extensive models are of a relatively coarse resolution. In addition, because Florida comprises several Water Management Districts, most ground-water modeling efforts have been focused within the boundaries of individual Districts, thus reducing the potential to simulate inter-District ground-water flow under current and projected stresses. This is particularly true along the common boundaries of the St. Johns River Water Management District (SJRWMD), Southwest Florida Water Management District (SWFWMD), South Florida Water Management District (SFWMD), and the Suwannee River Water Management District (SRWMD). Present and projected development of the ground-water resources in these Districts require reliable estimates of inter-District ground-water flow. As a result, the U.S. Geological Survey (USGS) began a 5-year project in 1996 in cooperation with SJRWMD and SFWMD to develop a fine-resolution, areally extensive ground-water flow model of the intermediate and Floridan aquifer systems extending from Camden and Charlton Counties, Georgia, to just south of Martin County in south Florida (fig. 1).

The objective of developing such a model is to refine the conceptual understanding of regional ground-water flow in the intermediate aquifer system and the Floridan aquifer system. The data base of hydraulic properties resulting from the model could be used as input to an interpolation algorithm that extracts specific hydraulic properties and data to obtain appropriate general-head boundaries, specified fluxes, or initial estimates of hydraulic properties needed to develop fine-resolution ground-water flow studies on smaller scales. Leake and Claar (1999) developed computer programs to generate input files for a local model of finer resolution from the input files of a regional model of coarser resolution.

Hydrologic conditions reflected by the time average from August 1993 to July 1994 (1993-94) potentiometric-surface maps, ground-water withdrawals, and water-level and spring flow measurements constitute the steady-state approximation referenced in this report. The rationale for selecting the 1993-94 period is explained later in the report.

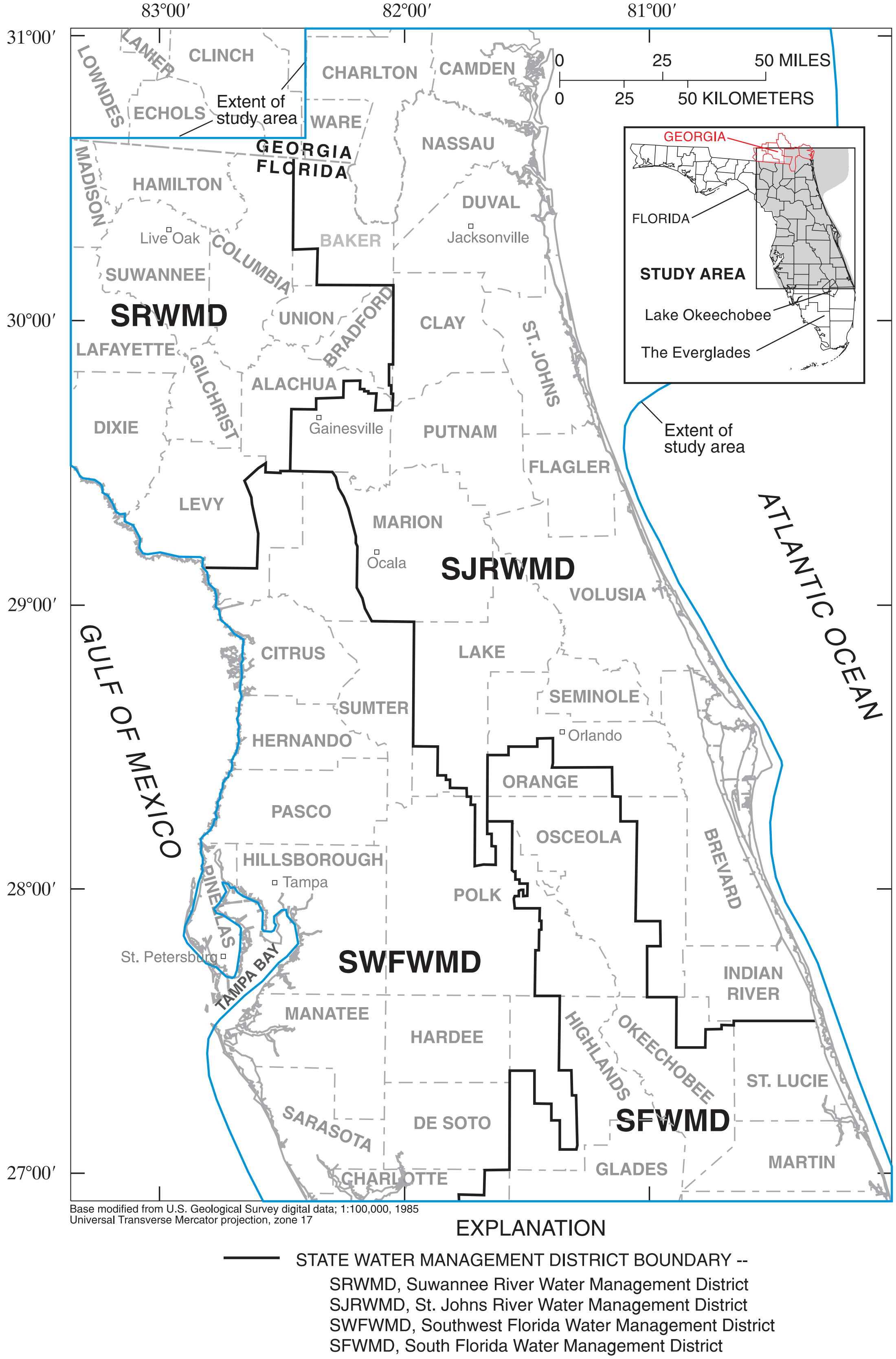


Figure 1. Location of study area and Water Management District boundaries.

Purpose and Scope

This report presents the results of a numerical model used to simulate the regional ground-water flow system in peninsular Florida. The model was used to (1) refine the conceptual understanding of the intermediate aquifer system and the Floridan aquifer system; (2) develop a data base to support subregional ground-water flow modeling; and (3) evaluate relative effects of 2020 ground-water withdrawals on ground-water levels for which the model was constructed. Hydrogeologic data are presented, including a conceptual model of the flow system and applications of a finite-difference flow model based on this conceptualization. The flow model simulations are designed to characterize the complex four layer aquifer system that underlies the study area. Discussions in this report include modeling procedures, imposition of boundary conditions, calibration strategies, rationale for a steady-state assumption, sensitivity analyses, volumetric flow estimates among hydrogeologic units, and specific areas where substantial water-level declines could occur based on 2020 projected ground-water withdrawals.

Geographical information system data bases or coverages (Environmental Systems Research Institute, Inc., 1997) were developed to manage spatially distributed information of hypsography and hydrography that covered the study area. Digital coverages were projected into the same coordinate system to achieve consistency of coordinate systems among coverages. The coordinate system of all coverages was the Universal Transverse Mercator (UTM) projection, zone 17 of the Florida coordinate system, west zone (Snyder, 1983). The 1927 North American Datum was used for all coverages generated in this study; the unit length was feet (ft).

Multiple linear regressions were used to generate the altitude of the water table of the surficial aquifer system, and the time-averaged heads in the intermediate aquifer system and the Floridan aquifer system, which comprises the Upper Floridan aquifer and the Lower Floridan aquifer. The regressions applied to the surficial aquifer system allowed for the estimation of the altitude of the water table at any point in the study area. The regressions applied to the intermediate aquifer system and the Upper Floridan aquifer allowed for the generation of the potentiometric surfaces of these two aquifers.

Previous Studies

Numerous investigations of ground-water flow in the intermediate aquifer system and the Floridan aquifer system in peninsular Florida have been conducted. Fourteen flow models, developed from these investigations, provided initial estimates of the areal distribution of hydraulic properties for the regional model discussed in this report (table 1). The extent of those flow models encompasses a large part of the study area (appendix A). Conceptualizations of the ground-water flow system differed among the various models.

The surficial aquifer system was simulated as a constant-head source-sink bed in 12 of the 14 ground-water flow models listed in table 1. Models developed by Hancock and Basso (1993) and Yobbi (1996) simulated the surficial aquifer system as an active layer, and calibrated to water levels measured at wells tapping the surficial aquifer, stream stages, and lake elevations.

Flow in parts of the intermediate aquifer system was simulated in southwest Florida (appendix A1) by Ryder (1985), Barcelo and Basso (1993), Metz (1995), and Yobbi (1996), and in parts of north-central Florida by Groszos and others (1992). The simulated transmissivity value for the intermediate aquifer system in north-central Florida was characteristic of a low-permeability confining unit (Motz, 1995). In this study, the intermediate aquifer system in north-central Florida is simulated as part of the intermediate confining unit.

Ground-water flow in the Upper Floridan aquifer was simulated by models developed in all of the studies listed in table 1 (appendix A2). The Upper Floridan aquifer is the most developed aquifer in the study area (Ryder, 1985; Tibbals, 1990). Simulation of ground-water flow in the Lower Floridan aquifer (appendix A3) was limited because of a substantially smaller number of observation wells tapping the Lower Floridan aquifer.

Acknowledgments

The author would like to thank the SFWMD, SJRWMD, and SWFWMD for providing the water-use, water-quality, and ground-water flow model data bases used in this study. The author also wants to thank Ronald Ceryak of SRWMD for providing information on hydraulic properties of aquifers in the SRWMD area.

Table 1. Description of ground-water flow models considered in the study area

[Abbreviations used in layering description: SAS, surficial aquifer system; IAS, intermediate aquifer system; UFA, Upper Floridan aquifer; LFA, Lower Floridan aquifer; SH, specified head; UT, uniform transmissivity; FPZ, Fernandina Permeable Zone]

Model number	Authors (year)	General location	Number of rows	Number of columns	Grid type	Layering description
1	Grubb and Rutledge (1979)	Parts of Polk, Lake, Sumter, Hernando, and Pasco Counties	36	40	Uniform cell size of 5,400 by 6,075 feet	SAS, layer 1, SH UFA, layer 2
2	Ryder (1985)	West-central Florida	49	32	Uniform cell size of 4 miles by 4 miles	SAS, layer 3, SH IAS, layer 2 UFA, layer 1
3	Fretwell (1988)	Pasco County	38	54	Uniform cell size of 1 square mile	SAS, layer 1, SH UFA, layer 2
4	Yobbi (1989)	Citrus and Hernando Counties	22	18	Uniform cell size of 2 miles by 2 miles	UFA, one-layer model
5	Tibbals (1990)	East-central Florida	50	24	Uniform cell size of 4 miles by 4 miles	SAS, layer 3, SH UFA, layer 2 LFA, layer 1
6	Lukasiewicz (1992)	Martin and St. Lucie Counties	54	53	Uniform cell size of 1 square mile	SAS, layer 1, SH UFA, layer 2 LFA, layer 3 LFA, layer 4, SH
7	Barcelo and Basso (1993)	Southwest Florida	56	60	Uniform cell size of 2 miles by 2 miles	SAS, layer 1, SH IAS, layer 2 UFA, layer 3
8	Blanford and Birdie (1993)	Hernando County	33	43	Uniform cell size of 1 square mile	UFA, one-layer model
9	Hancock and Basso (1993)	Parts of Hernando, Pasco, Hillsborough, and Pinellas Counties	62	69	Variable cell size, ranging from 2,640 by 2,640 feet to 1 square mile	SAS, layer 1 UFA, layer 2 UFA, layer 3
10	Metz (1995)	Hardee and DeSoto Counties	47	46	Uniform cell size of 5,390 by 6,050 feet	SAS, layer 1, SH IAS, layer 2 UFA, layer 3
11	Motz (1995)	North-central Florida	53	54	Variable cell size, ranging from 5,000 by 5,000 feet to 15,000 by 20,000 feet	SAS, layer 1, SH IAS, layer 2, UT UFA, layer 3 LFA, layer 4 FPZ, layer 5
12	Murray and Halford (1996)	Orange, Seminole, and parts of Volusia, Lake, and Osceola Counties	40	55	Uniform cell size of 5,322 by 6,050 feet	SAS, layer 1, SH UFA, layer 2 LFA, layer 3
13	Yobbi (1996)	Parts of Polk, Osceola, Hardee, De Soto, Highlands, and Glades Counties	86	41	Uniform cell size of 1 square mile	SAS, layer 1 IAS, layer 2 UFA, layer 3
14	Durden (1997)	Northeast Florida	68	35	Variable cell size, ranging from 5,222 by 6,057 feet to 18,280 by 23,499 feet	SAS, layer 1, SH UFA, layer 2 LFA, layer 3 FPZ, layer 4

DESCRIPTION OF STUDY AREA

The study area (fig. 1) extends about 284 miles (mi) from Charlton and Camden Counties, Georgia, in the north to near the Palm Beach - Martin County line in south Florida. The west-to-east extent of the study area spans about 200 mi from the Gulf of Mexico to the Atlantic Ocean. The study area encompassed about 40,800 square miles (mi^2). Some offshore areas in northeast and southwest Florida are considered to be part of the study area because hydraulic data suggest these areas may affect ground-water flow in the Upper Floridan aquifer.

The land-surface altitude in the study area ranges from sea level to about 285 ft in an area in south-central Polk County. About 75 percent of the land surface in the study area has an altitude less than 100 ft, and about 40 percent has an altitude less than 50 ft.

Groups of Physiographic Regions

The study area is subdivided into 52 distinct physiographic regions (White, 1970). Although the main physiographic regions of the study area generally correspond to distinct hydrogeologic regions, the delineation of physiographic features in an area of low relief, such as Florida, can be difficult. The delineations of physiographic regions by White (1970), therefore, were based on a combination of natural features, rather than on single elevation contours. The 52 physiographic regions delineated by White (1970) were grouped into 10 generalized regions based on geomorphology and the correlation of water levels between physiographic regions (fig. 2). Not all regions are contiguous.

Climate

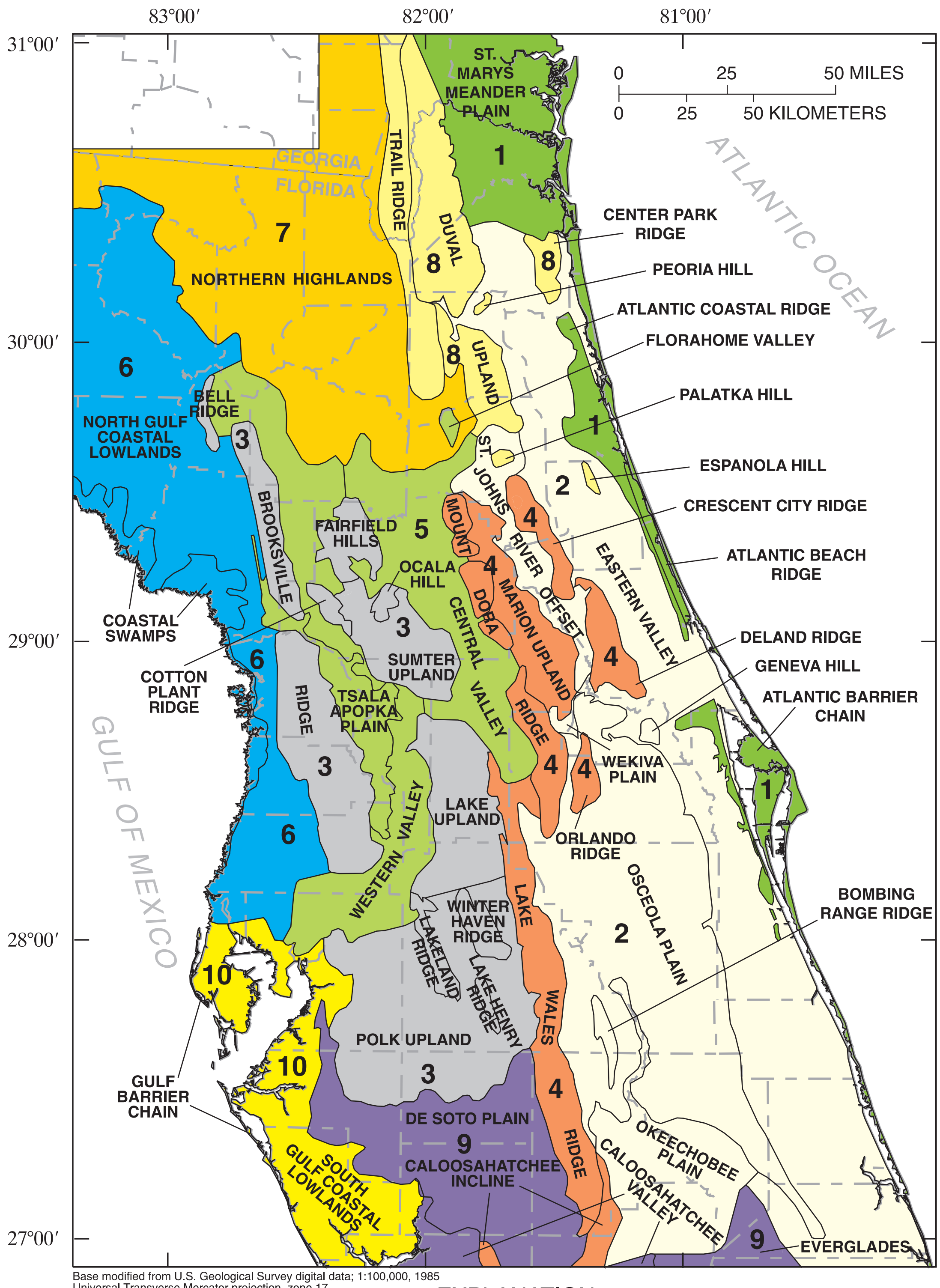
The climate of the study area is classified as subtropical and is characterized by warm, normally wet summers and mild, dry winters. Maximum temperatures usually exceed 90 °F during the summer, but may fall below freezing for several days in the winter in the northern and central parts of the study area (fig. 1). The 30-year average (1961-90) annual rainfall for the study area, computed from rainfall data collected from National Oceanic and Atmospheric Administration (NOAA) stations, is 51.20 inches per year (in/yr). Measured rainfall at 53 NOAA stations in the study area averaged 53.23 inches (in.) from August 1993 to July 1994 (fig. 3), which was 4 percent higher than the 30-year average. Absolute differences between rainfall measured in 1993-94 and the long-term average (1961-90) at individual stations were less than 10 in. at all but five stations.

HYDROGEOLOGIC FRAMEWORK

Comprehensive descriptions of the hydrogeology in all or in parts of the study area were presented by Ryder (1985), Miller (1986), Meyer (1989), Sprinkle (1989), Tibbals (1990), and Arthur and others (2001). This report presents a brief description of the hydrogeologic framework of the Floridan Aquifer system (FAS) and underlying and overlying units, including areal variations in thickness and occurrence throughout Florida.

The surficial aquifer system (SAS), which is the uppermost water-bearing hydrogeologic unit, includes sediments of Holocene, Pleistocene, and Pliocene ages (fig. 4). The SAS mostly consists of variable amounts of sand, sandy clay, shell beds, silt, and clay. Limestone units within the SAS are primarily in southwest Florida. In coastal areas, the SAS consists of cemented shell and shelly marl. The SAS extends throughout most of the study area, except where the Upper Floridan aquifer (UFA) is unconfined, and is used for water supply only in coastal areas where the UFA contains brackish water. The SAS is used primarily for individual household water supply in areas where the intermediate aquifer system (IAS) and the FAS are deep or contain poor quality water. In some places the clays in the SAS are thick and continuous enough to divide the SAS into two or three separate layers, but generally the aquifer system is undivided. In most parts of central, east, and northeast Florida, the SAS either provides recharge or receives discharge from the UFA.

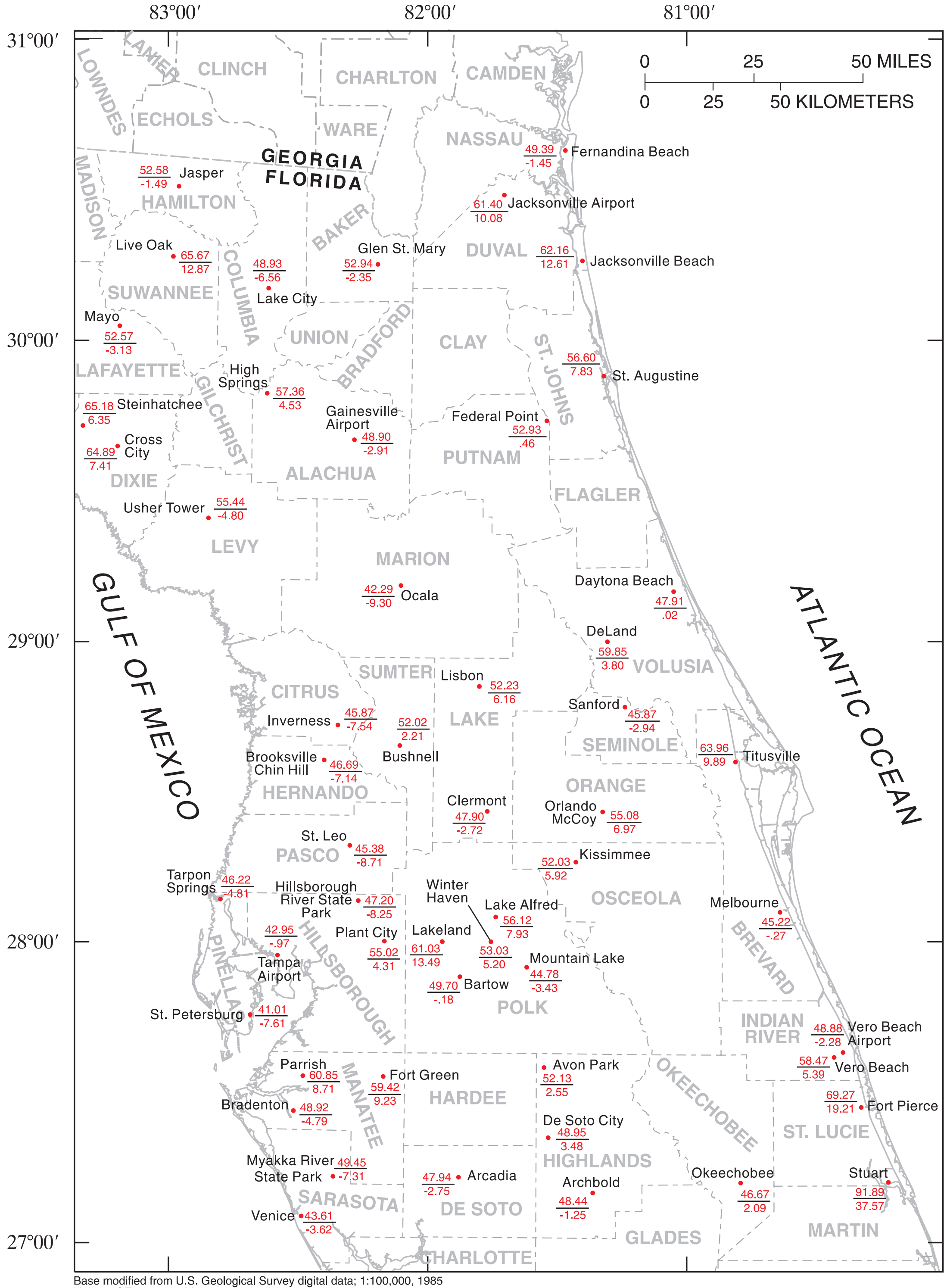
Carbonate rocks of Miocene age within the intermediate confining unit (ICU) in southwest Florida are permeable enough to form a productive aquifer, the IAS. The IAS underlies the SAS and extends throughout most of southwest Florida. The unit consists mainly of clastic sediments interbedded with carbonate rocks that generally coincide with the Hawthorn Group (fig. 4). Although the IAS is less permeable than the underlying UFA, the carbonate rock units within the IAS are sufficiently permeable and productive to constitute a water-supply source. Confining beds that overlie the UFA and underlie the SAS limit the vertical extent of the IAS in west-central Florida. The thickness of the IAS varies from about 25 ft in parts of Hillsborough and Polk Counties to about 400 ft in Charlotte County (Ryder, 1985). The thickness generally increases north to south (Ryder, 1985).



EXPLANATION

10 GROUP NUMBER -- Color indicates areal extent of each group of physiographic regions

Figure 2. Groups of physiographic regions (modified from White, 1970, plate 1).



EXPLANATION

Archbold
48.44
-1.25

RAINFALL STATION -- Top number is rainfall from August 1993 through July 1994, in inches. Bottom number is top number minus annual average rainfall at station based on 1961 to 1990 data, in inches. Name refers to National Oceanic and Atmospheric Administration station

Figure 3. Measured rainfall at National Oceanic and Atmospheric Administration stations from August 1993 through July 1994.

SYSTEM	SERIES	STRATIGRAPHIC UNIT	GENERAL LITHOLOGY	HYDROGEOLOGIC UNIT
QUATERNARY	HOLOCENE	SURFICIAL DEPOSITS	Undifferentiated fluvial sands and residuum with interbedded clay, shell, and limestone.	SURFICIAL AQUIFER SYSTEM
QUATERNARY	PLEISTOCENE	SURFICIAL DEPOSITS	Undifferentiated terrace and shallow marine deposits.	SURFICIAL AQUIFER SYSTEM
TERTIARY	PLIOCENE	UNDIFFERENTIATED DEPOSITS (southwest Florida)	Clayey and pebbly sand; clay, marl, shell, phosphatic.	SURFICIAL AQUIFER SYSTEM
TERTIARY	MIOCENE	HAWTHORN GROUP (generally absent in north-central Florida)	Highly variable sequence of mostly clay, silt, and sand - all phosphatic, phosphatic limestone, or dolomite, in lower part. In southwest Florida, white to light-gray, sandy, hard to soft, locally clayey, fossiliferous limestone containing phosphate and chert in some places.	INTERMEDIATE AQUIFER SYSTEM OR INTERMEDIATE CONFINING UNIT
TERTIARY	OLIGOCENE	SUWANNEE LIMESTONE (absent in northeast Florida)	Cream to tan, crystalline, highly vuggy limestone containing prominent gastropod and pelecypod cast and molds.	UPPER FLORIDAN AQUIFER
TERTIARY	EOCENE	OCALA LIMESTONE	(UPPER) White, generally soft, somewhat friable, porous coquina composed of large foraminifera bryozoan fragments and whole to broken echinoid remains, all loosely bound by a matrix of micritic limestone. (LOWER) Cream to white, generally fine-grained, soft to semi-indurated micritic limestone containing abundant miliolid remains and scattered large foraminifers.	UPPER FLORIDAN AQUIFER
TERTIARY	EOCENE	AVON PARK FORMATION	Mainly cream-colored, highly microfossiliferous chalky limestone that locally contains some gypsum and chert that is commonly partially dolomitized.	UPPER FLORIDAN AQUIFER MIDDLE CONFINING/ MIDDLE SEMICONFINING UNIT
TERTIARY	EOCENE	OLDSMAR FORMATION	Consists mostly of off-white to light-gray micritic to finely pelletal limestone thickly to thinly interbedded with gray to tan to light-brown, fine to medium crystalline, and commonly vuggy, dolomite.	LOWER FLORIDAN AQUIFER
TERTIARY	PALEOCENE	CEDAR KEYS FORMATION	(UPPER) Gray to cream, coarsely crystalline dolomite that is moderately to highly porous. (LOWER) Tan to gray, finely crystalline to microcrystalline dolomite interbedded with white to clear anhydrite.	LOWER FLORIDAN AQUIFER SUB-FLORIDAN CONFINING UNIT

Figure 4. Stratigraphic units, general lithology, and hydrogeologic units.

In areas away from southwest Florida, beds of clay and carbonate rocks of Pliocene and Miocene ages form the ICU. The hydrogeologic units, ICU and IAS, within the Hawthorn Group (fig. 4) are differentiated based on the permeability of the rock. In contrast to the IAS, the ICU is considerably less permeable. The ICU and the IAS coalesce at the boundaries of the IAS. The map showing the estimated thickness of the ICU generated by Miller (1986) was highly regionalized and based on sparse data. The more localized maps of Planert and Aucott (1985), Lukasiewicz (1992), and Spechler (1995) were used to modify Miller's (1986) map of the ICU thickness in southwest, east-central, south, and northeast Florida, respectively. The resulting map shows that thickness varies from 0 ft in the northwest part of the study area (fig. 5) to about 750 ft in the southeast. The UFA is considered to be unconfined in areas where the ICU is absent or very thin, including areas along the Withlacoochee River in west-central Florida and along parts of the Hillsborough River. The thickness of the ICU within the areal extent of the IAS represents the cumulative thickness of the IAS and overlying and underlying confining beds of the IAS (fig. 5). The seaward extent of the IAS coincides with those areas where the transmissivity was simulated to be higher than 100 feet squared per day (ft^2/d) by Barcelo and Basso (1993).

A thick sequence of limestone and dolomitic limestone of Oligocene and Eocene ages and having variable permeability forms the FAS. The FAS is the principal source of ground water in the study area. The aquifer system ranges in thickness from about 1,300 ft in the northwest part of the study area to about 3,500 ft in southwest Florida (Miller, 1986). The FAS is divided into two aquifers of relatively high permeability, referred to as the UFA and the Lower Floridan aquifer (LFA). These aquifers are separated by a less permeable unit called the middle confining unit (MCU) in west-central Florida and in the northwest part of the study area, and the middle semiconfining unit (MSCU) in east-central Florida. The altitude of the top of the UFA, defined as the first occurrence of vertically persistent, permeable, consolidated carbonate rocks, ranges from 100 ft above to 850 ft below sea level (fig. 6). The top of the UFA coincides either with the top of the Suwannee Limestone or the top of the Ocala Limestone, depending on location (fig. 4). The map in figure 6 showing the altitude of the top of the UFA, as identified by Miller (1986), was refined using the results of more localized studies by Knochenmus and Hughes (1976), Buono and Rutledge (1979), Shaw and Trost (1984), Planert and Aucott (1985), Navoy and Bradner (1987), Schiner and others (1988), Phelps (1990), Lukasiewicz (1992), Spechler (1993, plate 1), and Bradner (1994).

Lithologic data that establish the base of the UFA are less numerous than data defining the top of the UFA. A generalized contour map of the base of the UFA (fig. 7) was revised from Miller (1986) using additional information from Tibbals (1990) and files of the SJRWMD (Brian McGurk, SJRWMD, written commun., 1997). The base of the UFA ranges in depth from about 250 ft below sea level in parts of Marion and Sumter Counties to 2,100 ft below sea level in Charlton County, Ga., and in Charlotte County, Fla. (fig. 7). The base of the UFA is marked by the top of either the MCU, denoted analogously to Miller's (1986) notation by units II, III, and IV in west-central Florida and the northwest part of the study area, or the top of the MSCU, denoted by unit I in east-central Florida.

Rather than a single low-permeability unit separating the UFA and the LFA, several units of regional extent separate the UFA from the LFA (figs. 7 and 8). Common boundaries of the MCU and MSCU delineate the approximate updip limit of the Lower Floridan aquifer (fig. 8). Any of these regionally extensive low-permeability units may contain thin layers of moderate to high permeability. These confining units are not continuous and do not necessarily consist of the same rock type everywhere.

In east-central Florida, the UFA and LFA are separated by the MSCU, a sequence of somewhat permeable, soft, chalky limestone that locally contains some gypsum and chert and commonly is partially dolomitized (fig. 4). Although the MSCU, zone I in figure 7, is considered to be the leakiest of all confining units in the study area (Miller, 1986), the hydraulic connection between the MSCU and the LFA varies from place to place. This semiconfining unit is thin or absent in the northwest part of the study area (fig. 8), but is as much as 600 to 800 ft thick in the south-central part of the study area (Tibbals, 1990).

In west-central Florida and in the northwest part of the study area, the UFA and LFA are separated by the MCU, which is composed of gypsiferous dolomite and dolomitic limestone of considerably lower permeability than that of the MSCU in east-central Florida (Miller, 1986). The MCU, zones II through IV in figure 7, limits the movement of ground water between the UFA and LFA. At some locations, the confining unit is a very fine-grained limestone; in other places the MCU is a dolomite with pore spaces filled with anhydrite. The presence of intergranular evaporites in the MCU suggests that the exchange of vertical fluxes between the UFA and LFA could be higher in east-central Florida than in west-central Florida. The UFA and LFA merge vertically into one aquifer where no MCU or MSCU is present (fig. 8).

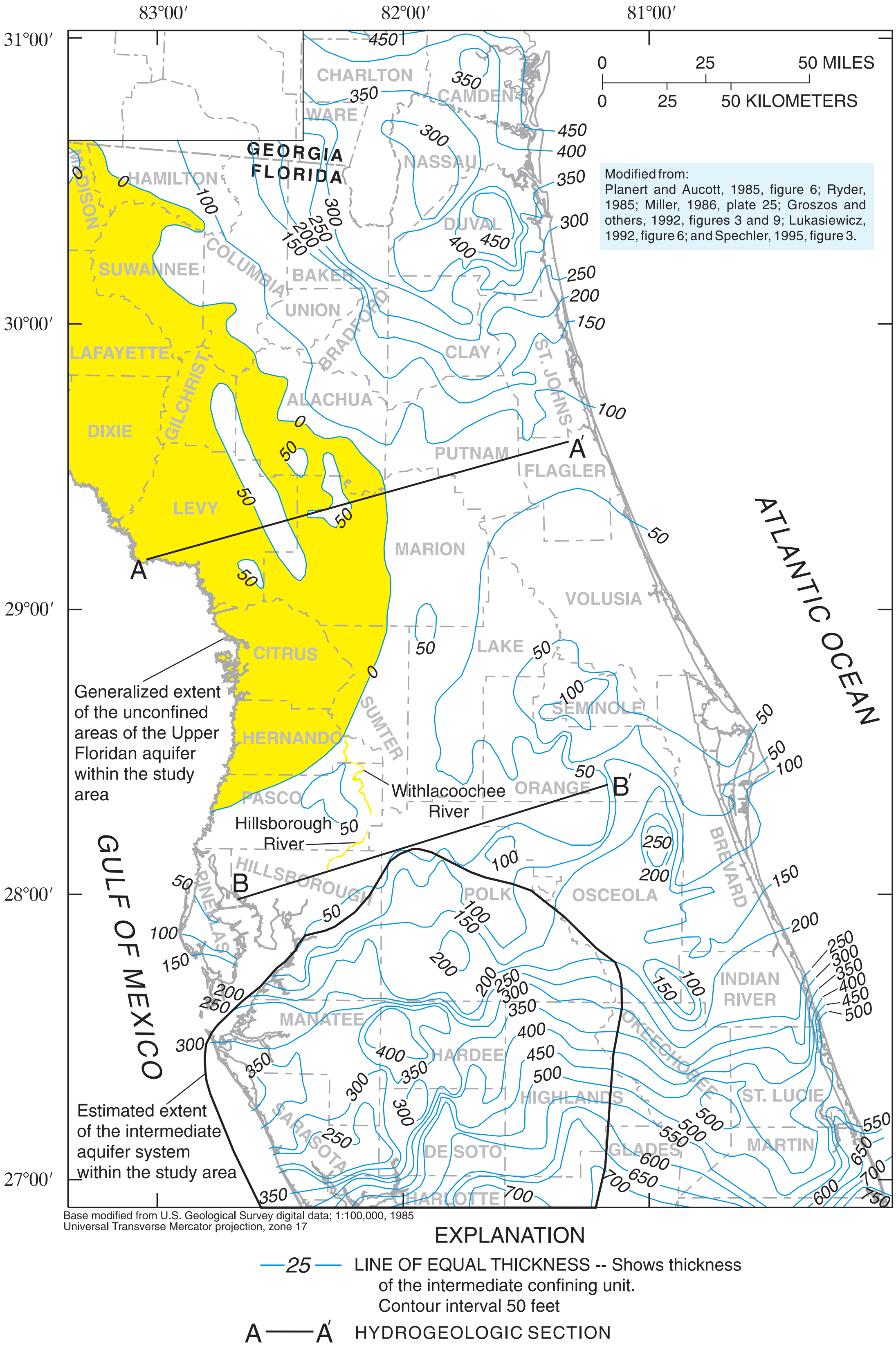
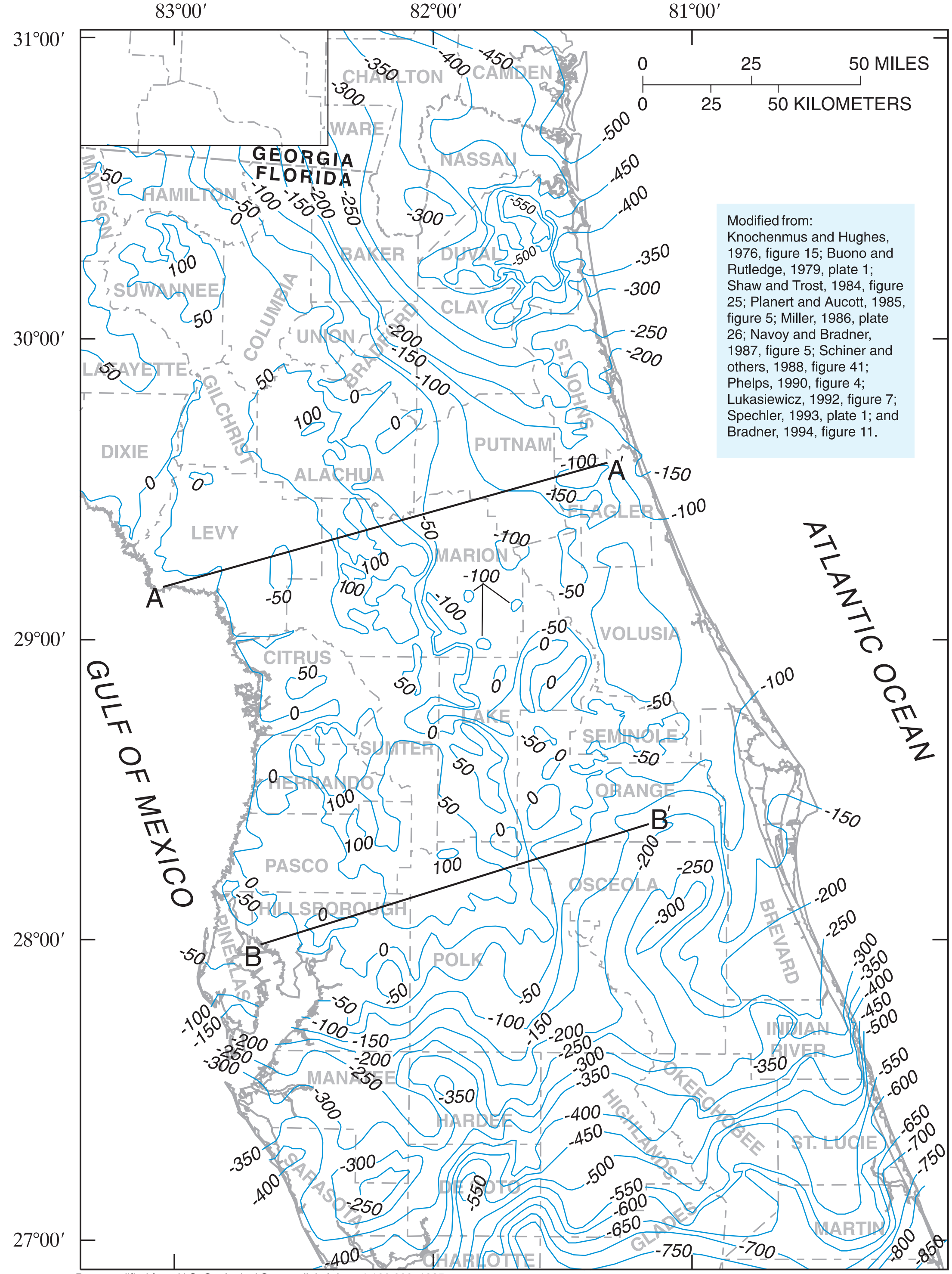


Figure 5. Generalized extent of the unconfined areas of the Upper Floridan aquifer, the intermediate aquifer system, and thickness of the intermediate confining unit.



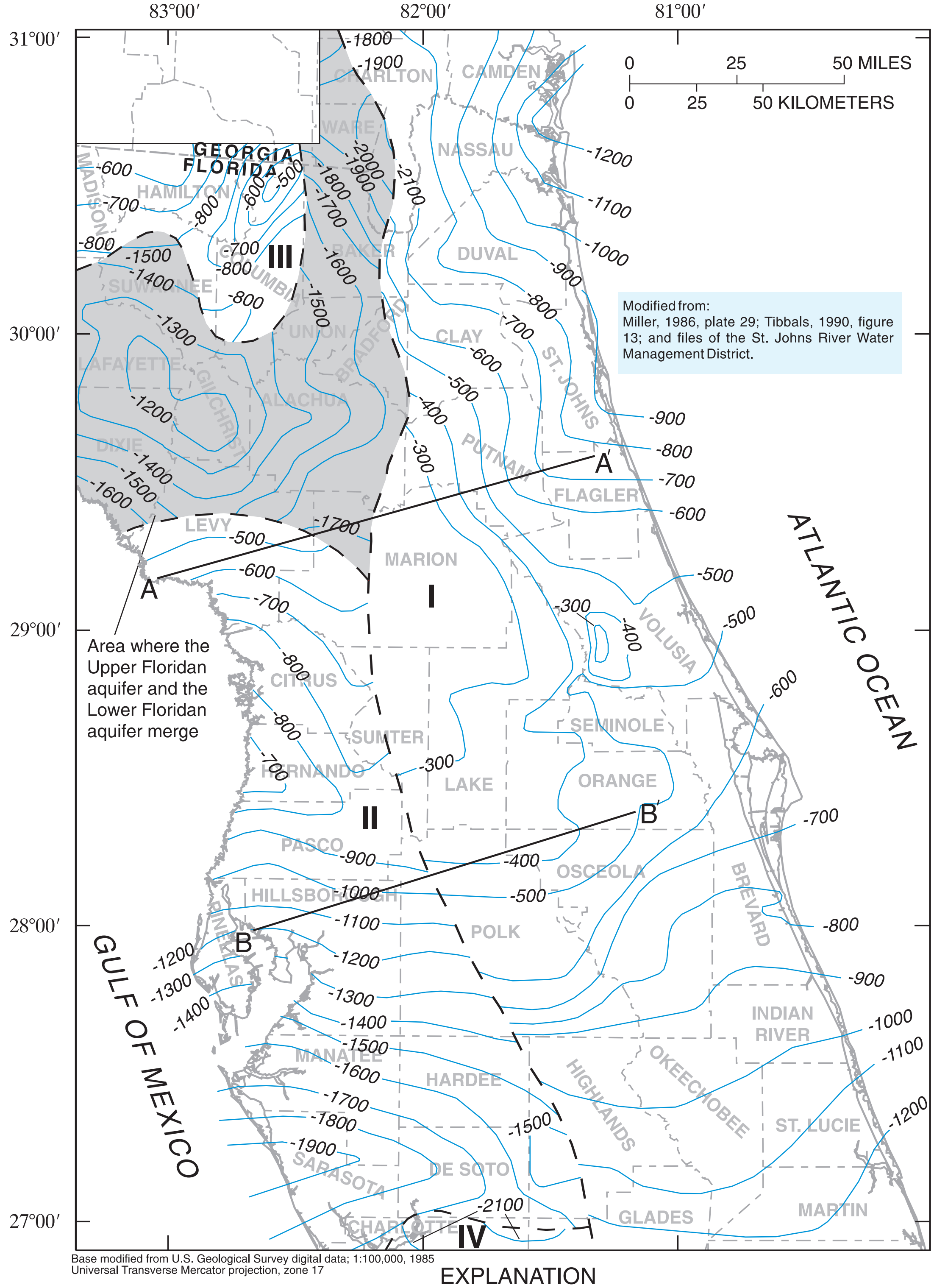
Base modified from U.S. Geological Survey digital data; 1:100,000, 1985
Universal Transverse Mercator projection, zone 17

EXPLANATION

—-300— STRUCTURE CONTOUR -- Shows altitude of the top of the Upper Floridan aquifer. Contour interval 50 feet. Datum is sea level

A——A′ HYDROGEOLOGIC SECTION

Figure 6. Altitude of the top of the Upper Floridan aquifer.



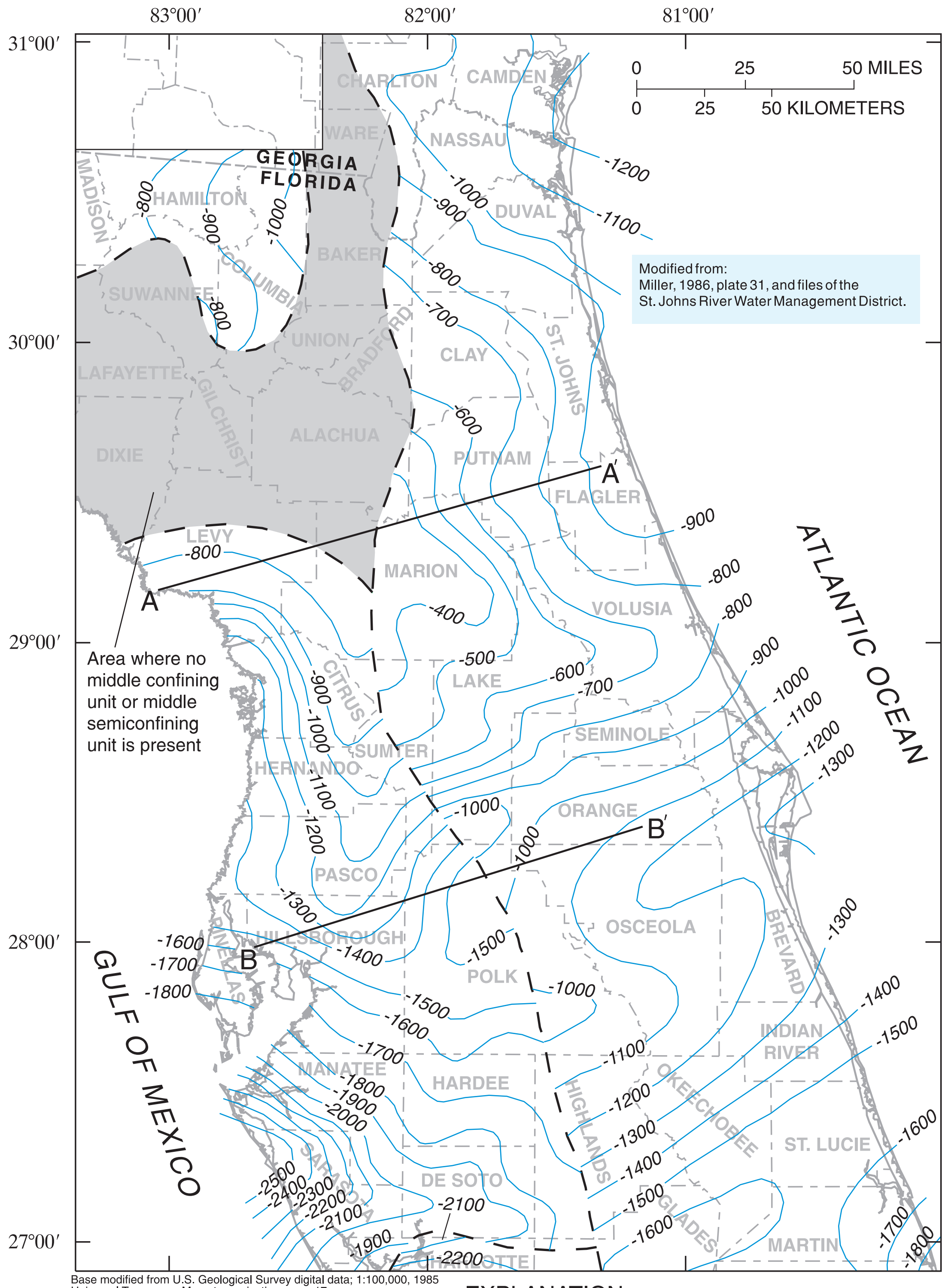
EXPLANATION

-300 STRUCTURE CONTOUR -- Shows altitude of the base of the Upper Floridan aquifer. Contour interval 100 feet. Datum is sea level

APPROXIMATE AREAL BOUNDARY BETWEEN CONFINING UNITS UNDERLYING THE UPPER FLORIDAN AQUIFER -- **I** is middle semiconfining unit; **II**, **III**, and **IV** are middle confining units

A——A′ HYDROGEOLOGIC SECTION

Figure 7. Altitude of the base of the Upper Floridan aquifer.



EXPLANATION

-500 STRUCTURE CONTOUR -- Shows altitude of the top of the Lower Floridan aquifer. Contour interval 100 feet. Datum is sea level

APPROXIMATE UPDIP LIMIT OF THE LOWER FLORIDAN AQUIFER

A——A′ HYDROGEOLOGIC SECTION

Figure 8. Extent and areal configuration of the top of the Lower Floridan aquifer.

A discontinuity in the surface of the MCU can be seen along section A-A' in figure 9. Although it is not certain whether the MCU in southwest Florida and the MSCU in east-central Florida merge, the information shown in section B-B' does not preclude this possibility (fig. 9). Given the contrast in permeability between the MCU and the MSCU, ground-water exchange between the UFA and LFA could be quite variable in areas near this discontinuity (fig. 9). For example, exchange of ground water between the UFA and LFA probably is higher in east-central Florida than in southwest Florida because the permeability of the MSCU is higher than the permeability of the MCU.

The altitude of the top of the LFA ranges from -400 ft in Marion County to -2,500 ft along the Gulf Coast near Sarasota County (Miller, 1986; fig. 8). Discontinuities in the configuration of the top of the LFA are due to discontinuities in the configurations of the MCU and the MSCU in the study area. In northeast Florida, the LFA is subdivided into two zones, the upper zone of the LFA and the Fernandina permeable zone (FPZ). In southeast-central Florida, a localized productive zone called the Boulder zone occurs within the LFA.

A base of generally low-permeability dolomite and evaporite beds of Paleocene age form the sub-Floridan confining unit, or the base of the FAS. This base is defined as the first occurrence of vertically persistent beds of anhydrite or, in their absence, the top of the transition from generally permeable carbonate rocks to much less permeable gypsiferous and anhydritic carbonate beds (Miller, 1986). These beds of very low permeability serve as the hydraulic base of the FAS and, in the study area, range in altitude from about -1,200 ft in the northwest part of the study area to about -4,100 feet in south Florida (Miller, 1986; fig. 10).

GROUND-WATER FLOW SYSTEM

Average hydrologic conditions from August 1993 to July 1994 were used as the basis for discussion of the general ground-water flow characteristics in the study area. Hydrologic conditions may change from one time frame to another depending on rainfall amounts, ground-water withdrawal patterns, and substantial changes in surface-water discharge or recharge patterns. The rationale for selecting this period is presented later in the report. Unless otherwise specified, the term "average hydrologic conditions" in this report refers to 1993-94 average conditions.

The assessment of ground-water flow was achieved by estimating the altitude of the water table of the SAS, and the potentiometric surfaces of the IAS and the UFA. The SAS generally is recharged by rainfall, irrigation, and, in areas where the water table is below the potentiometric surface of the underlying UFA, by diffuse upward leakage from the UFA. The assessment of vertical flow between the UFA and the LFA and flow within the LFA itself could be conducted only at a few sites because of the paucity of water-level measurements available for the LFA.

Ground-water flow in areas where chloride concentration exceeds 5,000 milligrams per liter (mg/L) was not considered to be part of the flow system in this study, based on the fact that advective flow in such areas is considered to be lower than in areas where chloride concentrations are lower than 5,000 mg/L. Ground-water density increases associated with higher chloride concentrations generally decrease the potential of water movement. Thus, transmissivity is lower than would be the case if the entire FAS contained freshwater.

Recharge to or discharge from the UFA occurs mostly through infiltration to or from the ICU, where this unit is present. The leakage rate to the UFA in confined areas is a function of the hydraulic gradient between the SAS and UFA and the vertical conductance of the ICU. Recharge to the UFA in the northwest part of the study area, where the ICU is absent, occurs in the form of net aquifer recharge from rainfall infiltration (Ryder, 1985; Fretwell, 1988; Yobbi, 1989; Blandford and Birdie, 1993; and Motz, 1995).

The spatial variability of transmissivities, as well as vertical leakance, in the FAS is quite high. Transmissivities of the UFA, derived from the models listed in table 1, range from 2,000 ft^2/d in St. Lucie County (Lukasiewicz, 1992) to 13,000,000 ft^2/d in Citrus County (Yobbi, 1989). Simulated transmissivities in the LFA range from 33,000 ft^2/d in parts of east-central Florida (Tibbals, 1990) to 780,000 ft^2/d in parts of northeast Florida (Durden, 1997). Vertical leakance of the upper confining unit of the IAS, based on models in table 1, range from 1.0 x 10-6 (ft/d)/ft in parts of Hardee and De Soto Counties (Metz, 1995) to 1.3 x 10-1 (ft/d)/ft in the Gulf of Mexico (Barcelo and Basso, 1993). Similarly, simulated vertical leakance values of the ICU and the MSCU range over five orders of magnitude (Durden, 1997; Motz, 1995; Lukasiewicz, 1992).

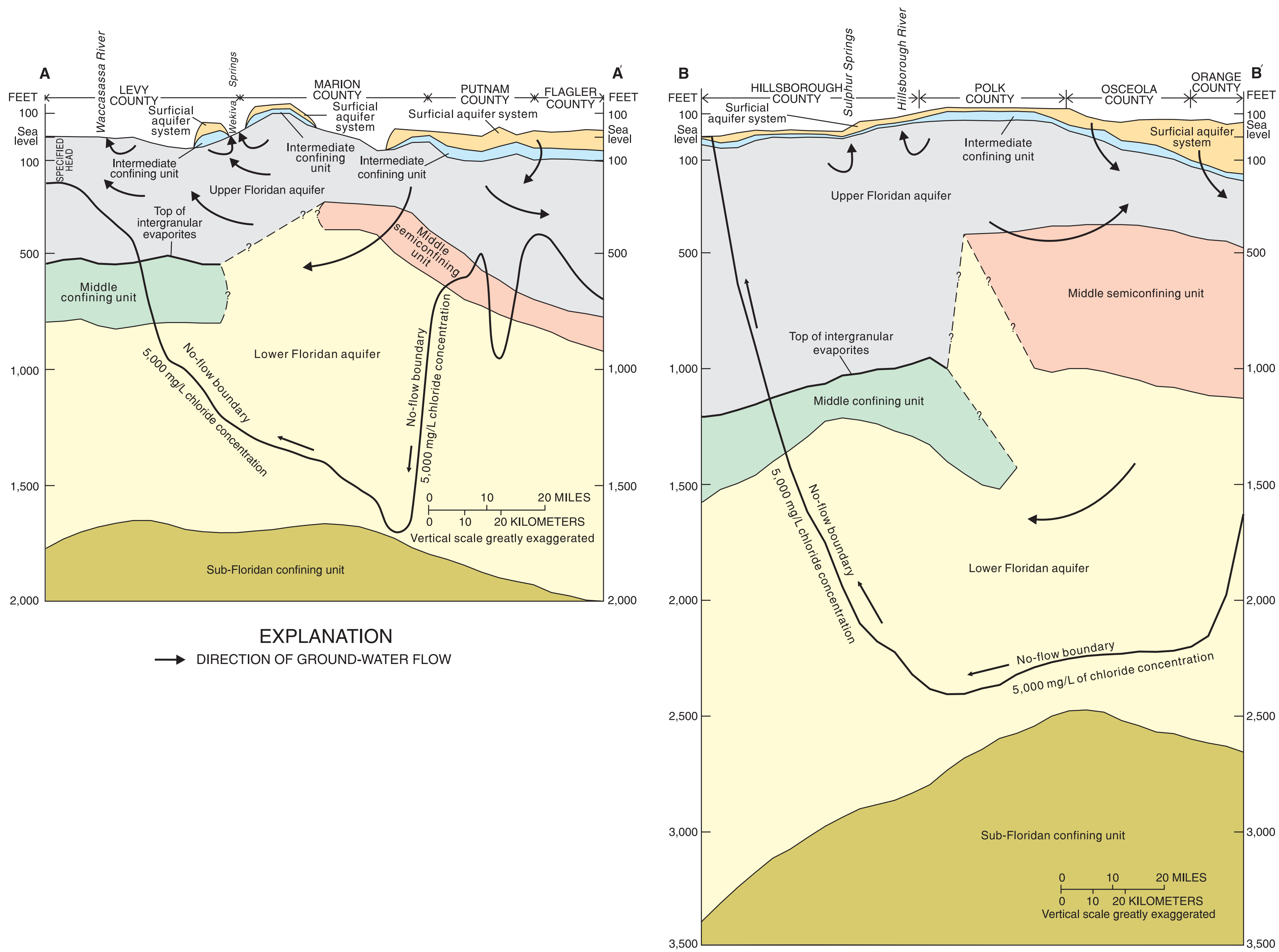


Figure 9. Generalized hydrogeologic sections A-A′ and B-B′ showing conceptualized ground-water flow (modified from Miller, 1986; refer to figure 5 for locations of sections).

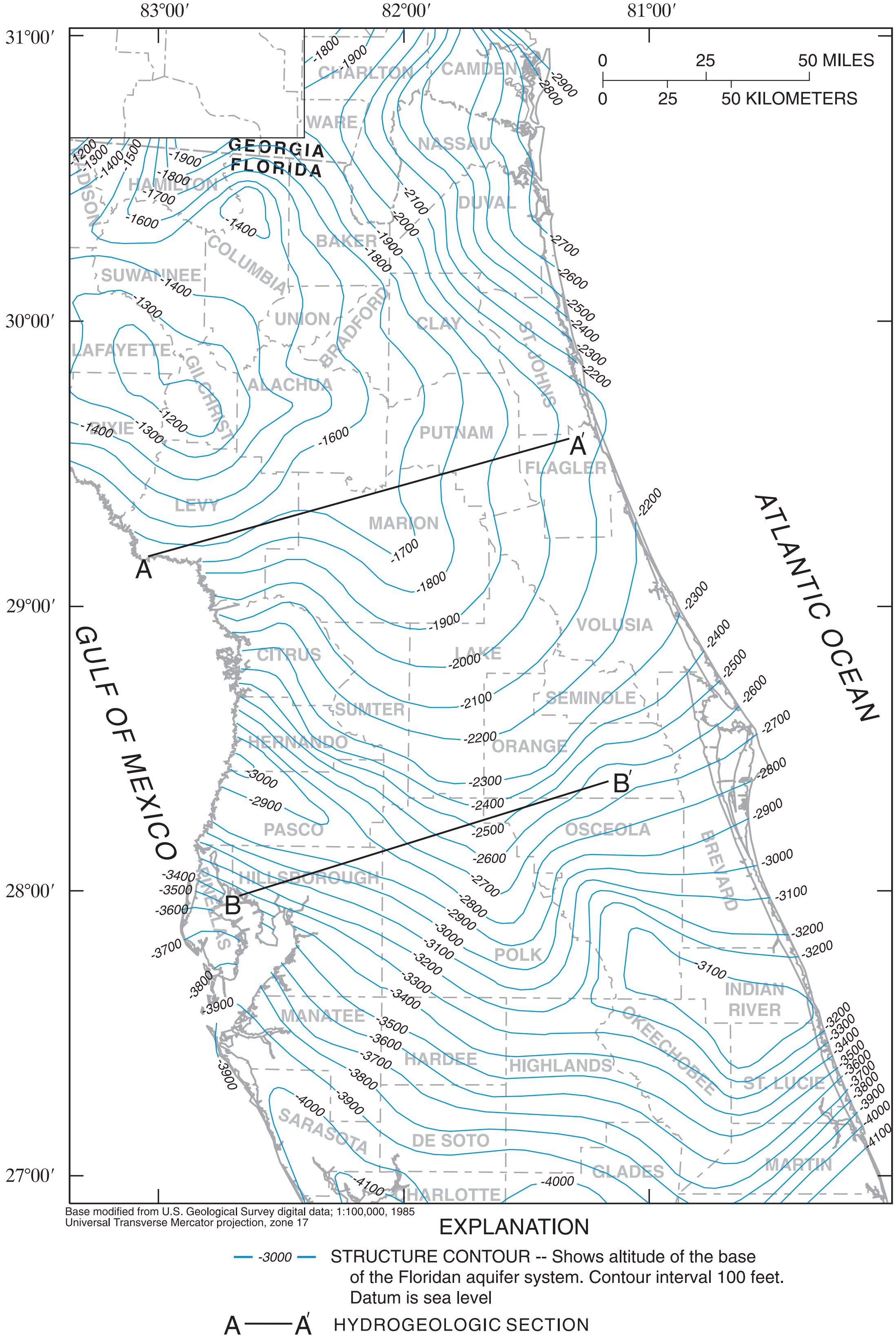


Figure 10. Altitude of the base of the Floridan aquifer system (modified from Miller, 1986).

Altitude of the Water Table of the Surficial Aquifer System

In this study, the altitude of the water table was estimated to specify the water levels in the SAS. Water levels in the SAS are not actively simulated in this model. Instead, the SAS was simulated as a source-sink layer with specified heads as one of the hydraulic properties determining the leakage rates to and from the underlying layer, namely the ICU or the IAS.

A commonly used algorithm for generating the altitude of the water table in an unconfined aquifer is to perform a linear regression between the measured water levels and the land-surface altitude. This algorithm, however, generally fails to provide reliable estimates in upland areas of low recharge or high hydraulic conductivity. In such areas, land-surface altitudes and water levels generally are not correlated.

The algorithm presented herein introduces the concept of the "minimum water table" to refer to the surface interpolated strictly from the measured altitude at drains in the SAS such as streams and lakes. This minimum water table becomes one of the variables used in the regression of the water table. To account for areas where the water table emulates land-surface altitude, a second variable is added to the regression: the vertical distance between land-surface altitude and the minimum water table. A limitation of this algorithm is its inability to estimate the water table in areas where ground-water mounds are formed by perched layers in the SAS.

The altitude of the water table was approximated by using a series of multiple linear regressions (one for each group of physiographic regions) among the measured levels in SAS wells, the interpolated minimum water table, and the difference between land-surface altitude and the minimum water table. Water-level measurements at SAS wells were compiled from data bases of the SJRWMD, SFWMD, SWFWMD, SRWMD, and USGS. The minimum water-table surface was interpolated from measured or estimated stages at lakes and streams (fig. 11). A digital land-surface elevation model was generated from digitized hypsography obtained from the SJRWMD, SFWMD, SWFWMD, and USGS.

Average lake elevations for 1993-94 were computed for 544 gaged lakes in the study area (fig. 11). Average river stages for the same period were computed for 233 stream gaging stations (fig. 11). Gaged rivers were divided in segments according to the location of the stream gaging stations. In cases where upstream or downstream end nodes of the river segments coincided with a lake, the lake elevation was used as the river stage at the node. The river stage was computed at all discrete nodes located along the meander of each river segment through linear interpolation of measured river stages. The computed lake elevations and river stages were assumed to be representative of the water-table elevation at the same sites. All lake elevations, river stages, and water levels were referenced to the National Geodetic Vertical Datum of 1929.

The digital representation of hypsography for the study area was generated from 5-ft contour interval hypsography digitized by SJRWMD, SFWMD, SWFWMD, and SRWMD from 7.5-minute USGS topographic quadrangle maps. A digital elevation model (DEM) of square cells 100-ft wide was generated by using the digitized hypsography, lake elevations from gaged lakes, and river stages computed along the meanderings of gaged rivers. The DEM was generated by using quintic splines. Using the DEM, the land-surface altitude could be interpolated at any point in the study area. The maximum absolute difference between the estimated land-surface altitude from the DEM and the land-surface altitude at surveyed points was 5.75 ft.

Elevations for ungaged lakes and stages along ungaged rivers were interpolated by using the DEM. Although some of the ungaged lakes may not be representative of the regional water table (some of the lakes may be perched), determining which lakes to exclude was beyond the scope of this study.

The minimum water table was generated from the interpolation of lake elevations, river stages, and the ocean shoreline (which was assigned a water-table altitude of zero feet). The relations among minimum water table, water table, and land-surface altitude are shown in figure 12. The minimum water table was bounded above by land-surface altitude and below by the bottom of the SAS, defined to be the sum of the thickness of the ICU (fig. 5) and the altitude of the top of the UFA (fig. 6).

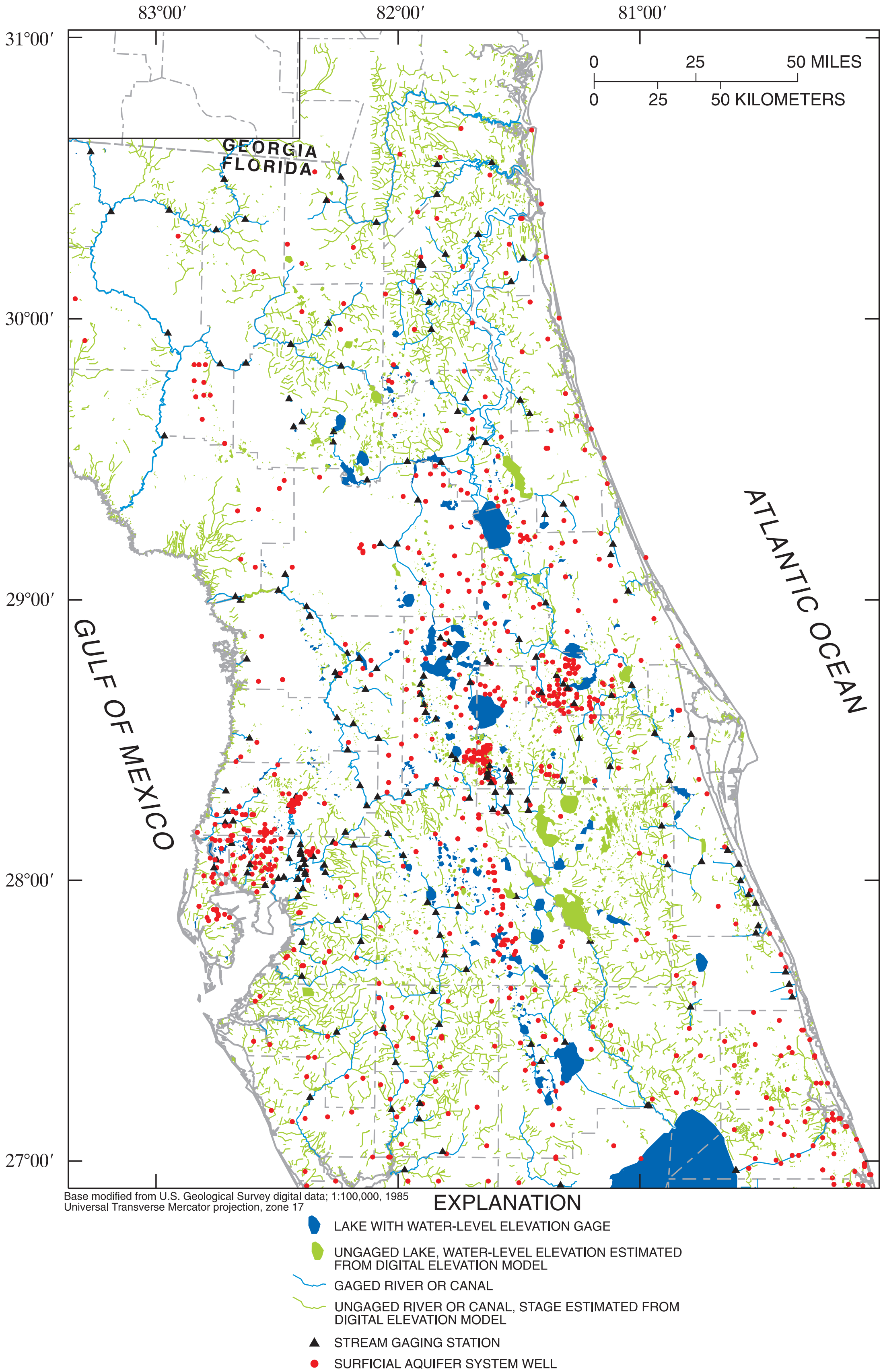


Figure 11. Lakes, streams, locations of stream gaging stations, and surficial-aquifer wells used to estimate the altitude of the water table of the surficial aquifer system.

Elevations of the minimum water table at 1,050 wells tapping the SAS were interpolated from the generated minimum water-table surface. Water-table measurements at the SAS wells were grouped by the physiographic region (fig. 2) in which each well was located. Land-surface altitudes at the SAS wells were interpolated from the DEM. Multiple linear regressions for each group of physiographic regions were computed based on the equation:

$$WT_i = \beta_1 MINWT_i + \beta_2 (LSA_i - MINWT_i), \quad (1)$$

where

WT_i is the water-table measurement at SAS well i, in feet,

$MINWT_i$ is the minimum water table interpolated at SAS well i, in feet,

LSA_i is the land-surface altitude interpolated at SAS well i, in feet, and

β_1 and β_2 are the dimensionless regression coefficients of the multiple linear regression.

Multiple linear regressions computed for each group of physiographic regions indicated a strong correlation between the response variable WT_i and the regressor variables $MINWT_i$ and $LSA_i - MINWT_i$ in equation 1 (table 2). The root-mean-square (RMS) residual between measured and linearly regressed water-table altitudes was computed for all groups of physiographic regions, resulting in a weighted average residual of 3.53 ft, with the difference between the regressed and measured water-table altitudes ranging from -17.20 to 18.49 ft (table 2). The linearly regressed and measured water-table altitudes were strongly correlated (fig. 13). Although the overall improvement to the RMS residuals resulting from computing a multiple linear regression for each group, instead of one regression for all groups, of physiographic regions does not seem considerable, the results show that for some physiographic groups, the regression coefficient for variable $LSA_i - MINWT_i$ is not negligible. For groups 3, 4, 5, and 7, the same regression coefficient is small (table 2). Groups 3, 4, and 7 are classified as uplands and ridges, whereas group 5 is classified as a valley (fig. 2). A leaky ICU or a high SAS hydraulic conductivity could result in a lack of correlation between the water table and the land-surface altitude. The water table increasingly emulates land-surface altitude as regression coefficient β_2 in equation 1 increases. As the value of β_2 decreases, the water table becomes increasingly correlated with the minimum water table.

In areas where the minimum water table, the land-surface altitude, and the water table coincide, the water table was redefined as the minimum water table in order to correct small errors introduced by values of β_1

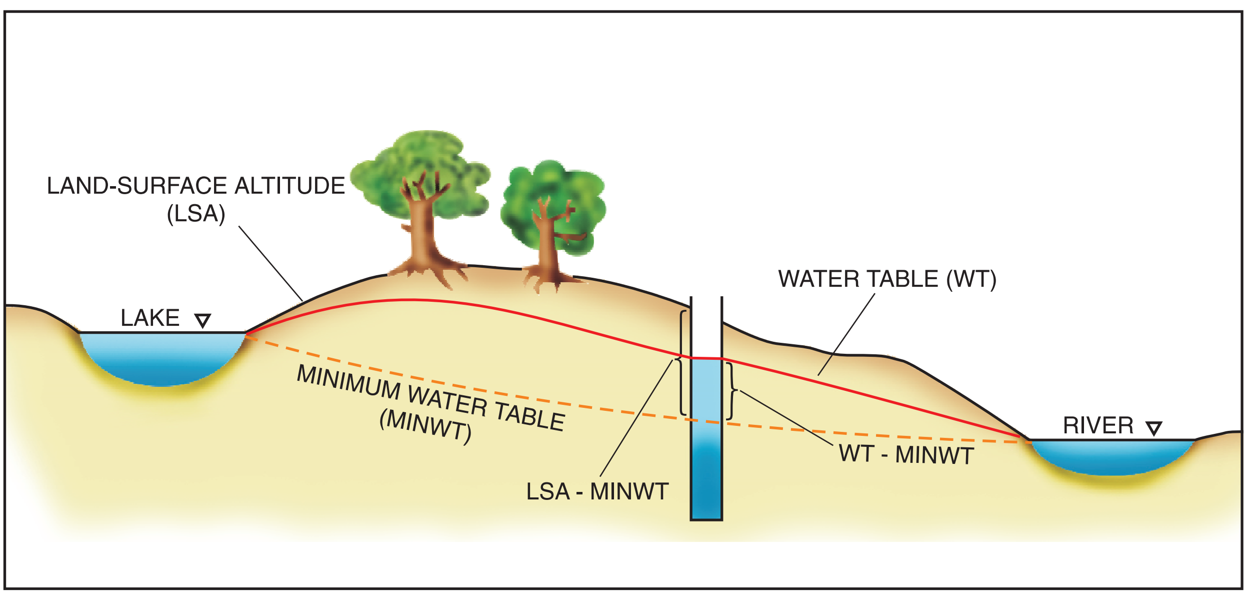


Figure 12. Relations among water table, minimum water table, and land-surface altitude.

Table 2. Multiple linear regression coefficients for the minimum water table and the difference between land-surface altitude and minimum water table

[Group number refers to figure 2. Refer to equation 1 for the definition of regression coefficients; na, not applicable]

	Number of surficial aquifer system wells	Regression coefficient of minimum water table (β_1)	Regression coefficient of difference between digital elevation and minimum water table (β_2)	Root-mean-square residual (feet)	Range of values of difference between regressed and measured water table (feet)	Correlation coefficient
Group number			**Multiple linear regressions**			
1	23	1.00	0.48	3.36	[-6.04, 6.60]	0.97
2	226	1.04	.39	3.29	[-7.68, 18.49]	.99
3	94	1.06	.10	4.10	[-12.09, 7.35]	.99
4	364	1.09	.04	4.07	[-17.20, 12.76]	.99
5	74	1.09	.14	3.88	[-9.68, 11.54]	.99
6	140	1.06	.28	2.53	[-7.45, 7.61]	.99
7	14	1.05	.06	4.32	[-8.32, 5.74]	.99
8	16	1.02	.49	3.72	[-6.59, 7.51]	.99
9	37	.96	.85	1.79	[-3.28, 4.29]	.99
10	62	1.02	.42	1.83	[-6.28, 4.04]	.99
Weighted mean	1,050	na	na	3.53	[-17.20, 18.49]	na
Regression coefficient			**Regressions without grouping**			
$\beta_1 = 0$	1,050	0.00	2.27	50.79	[-79.17, 330.31]	0.39
$\beta_1 = 1$	1,050	1.00	.26	5.68	[-19.26, 41.37]	.42
$\beta_1 = \beta_2$	1,050	.83	.83	13.88	[-28.81, 25.23]	.88
$\beta_2 = 0$	1,050	1.11	.00	4.76	[-24.25, 21.10]	.99
$\beta_1 \neq \beta_2 \neq 0$	1,050	1.08	.10	4.27	[-21.88, 19.32]	.99

in table 2 that deviate from unity. Setting the value of β_1 in equation 1 to unity would lower substantially the correlation coefficient of the resulting linear regression. Similarly, a nonunity value of β_2 is needed to maintain a reliable correlation coefficient.

If only one multiple linear regression were computed to approximate the water table, instead of one for each group of physiographic regions, then the wrong conclusion could be drawn that WT_i was weakly correlated with LSA_i - $MINWT_i$ over the study area, reducing equation 1 to a linear regression. The correlation between variables WT_i and LSA_i - $MINWT_i$ tends to increase as the correlation between variables WT_i and $MINWT_i$ decreases; the correlation between variables WT_i and LSA_i - $MINWT_i$ is variable across the study area (fig. 14). The inclusion of only $MINWT_i$ or LSA_i - $MINWT_i$ in equation 1 significantly reduces the correlation coefficient of the water-table regression.

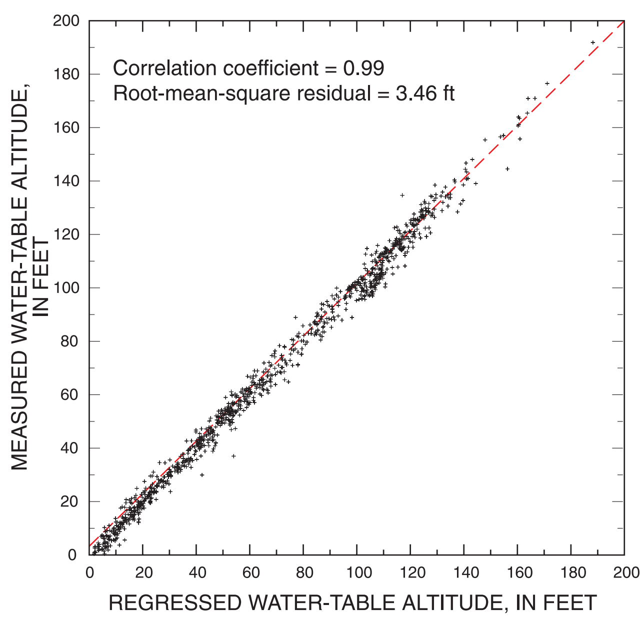


Figure 13. Regressed and measured water-table altitudes for all groups of physiographic regions.

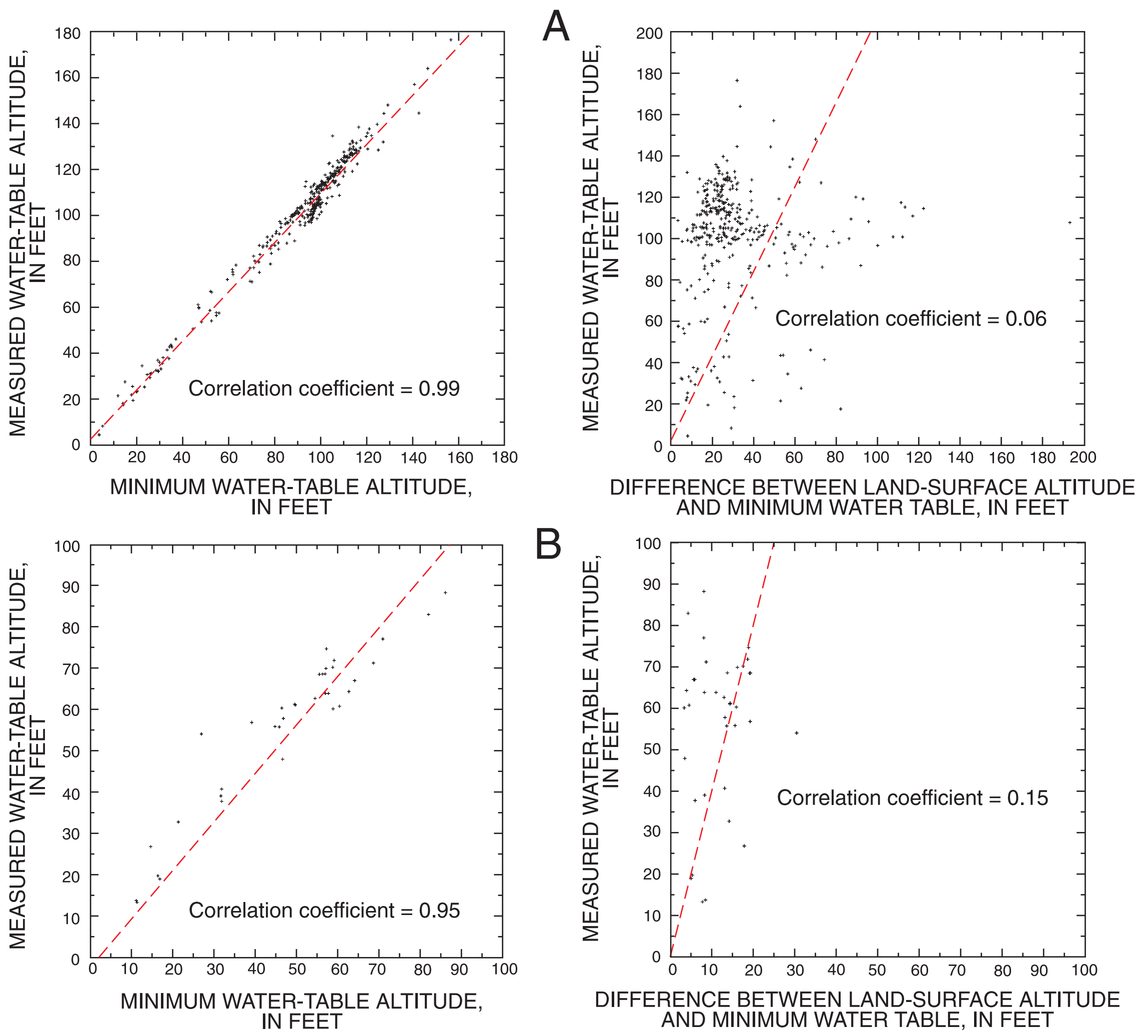


Figure 14. Correlation between water table, minimum water table, and difference between land-surface altitude and minimum water table for (A) group 4 and (B) group 9 of physiographic regions (refer to figure 2 for physiographic regions).

The application of equation 1, and the regression coefficients in table 2, resulted in an estimated water-table altitude that ranged from 0 to 240 ft (fig. 15). The estimated water table for average 1993-94 conditions was greater than 150 ft in areas of Alachua, Baker, Bradford, Clay, Columbia, Polk, and Suwannee Counties (fig. 15). Water-table altitudes generally decrease coastward. Water-table altitudes beyond the shoreline were assumed to be the equivalent freshwater head of the water column obtained from the digitized bathymetry. Areas where the UFA is considered unconfined (fig. 5) were excluded from the water-table map (fig. 15) because, in general, the SAS is absent in this area or its areal extent is minimal.

Potentiometric Surface of the Intermediate Aquifer System

A data base of well hydrographs from continuous water-level recorders was generated for the purpose of assessing hydrologic conditions in the study area. Data from the SJRWMD, SRWMD, and USGS were used to generate hydrographs for sites throughout the study area (fig. 16; appendix B).

Daily measurements from 11 wells tapping the IAS in southwest Florida (fig. 16; appendix B) equipped with continuous water-level recorders were used to obtain monthly average water levels for September 1993 and May 1994 and average water levels for the period from August 1993 to July 1994.

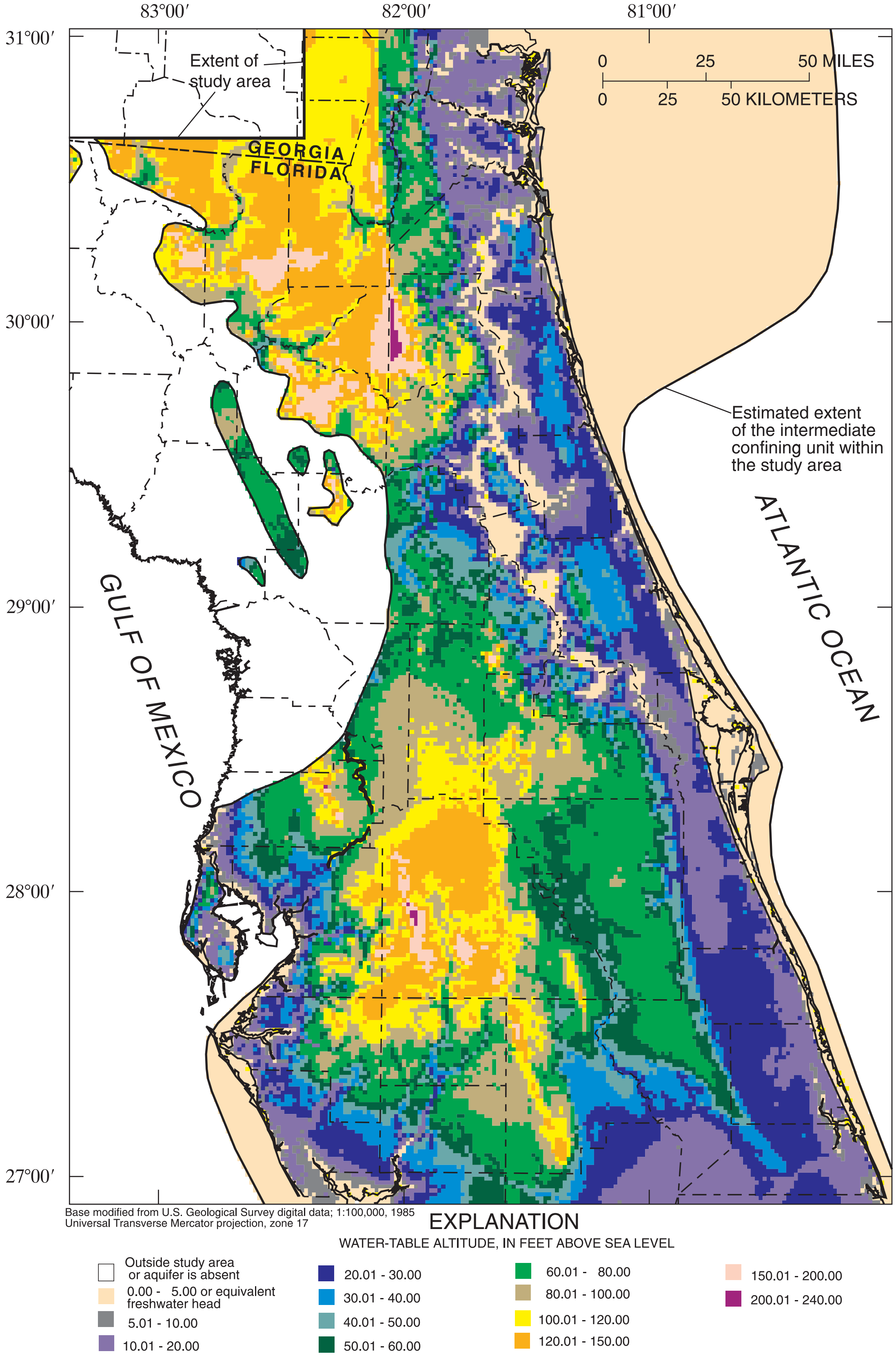


Figure 15. Estimated altitude of the water table of the surficial aquifer system, average conditions for August 1993 through July 1994.

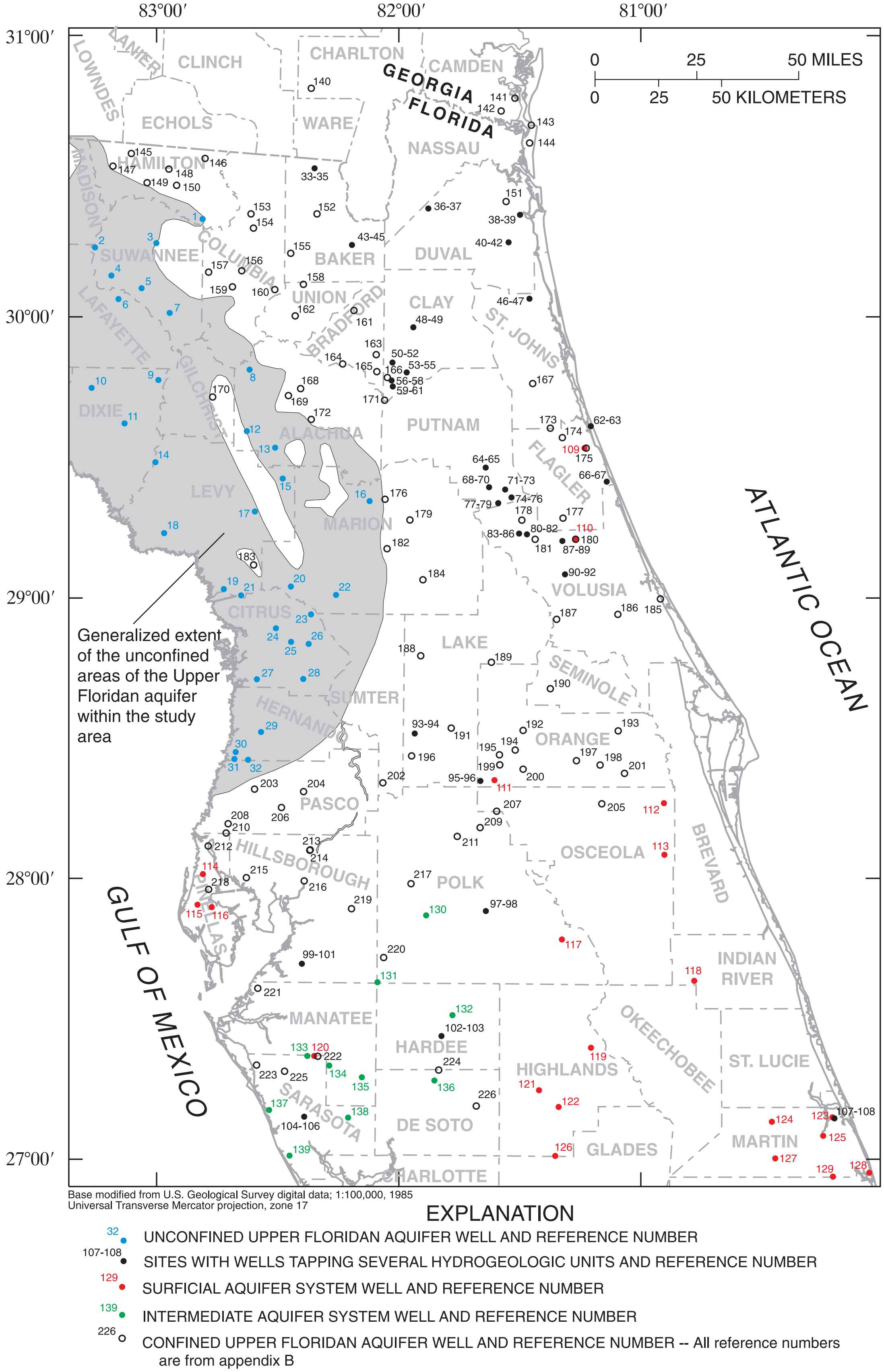


Figure 16. Location of wells equipped with continuous water-level recorders.

The average heads from August 1993 to July 1994 at these 11 wells were linearly regressed with the September 1993 and May 1994 monthly averages according to the multiple linear regression:

$$\overline{h_i} = \beta_I + \beta_S \overline{h_{Si}} + \beta_M \overline{h_{Mi}} , \qquad (2)$$

where

$\overline{h_i}$ is the computed average water-level measurement at well i, in feet,

$\overline{h_{Si}}$ is the computed monthly average for September 1993 at well i, in feet,

$\overline{h_{Mi}}$ is the computed monthly average for May 1994 at well i, in feet,

β_I is the intercept of the multiple linear regression, in feet, and

β_S and β_M are the dimensionless regression coefficients of the multiple linear regression.

Regression coefficients β_S and β_M represent the influence of the September 1993 ($\overline{h_{Si}}$) and May 1994 ($\overline{h_{Mi}}$) averages on the resulting annual averages $\overline{h_i}$.

Regression coefficients β_I, β_S, and β_M, computed by using data from the IAS wells equipped with continuous water-level recorders, were 0.54, 0.63, and 0.37, respectively. The correlation coefficient of this multiple linear regression was 0.99, implying a strong correlation between the annual averages and the monthly averages of September 1993 and May 1994 at the water-level recorder sites. Lack of sufficient water-level data in the IAS precluded the computation of separate multiple linear regressions for the groups of physiographic regions within the IAS, namely groups 2, 3, 4, 5, 9, and 10 (fig. 2).

A total of 107 water levels was measured in IAS observation wells during both the months of September 1993 (Mularoni, 1994a) and May 1994 (Metz and Brendle, 1994b). Water levels at these sites were compiled to estimate the potentiometric surface of the IAS. The assumption was made that the single measurement made at each of the IAS wells in September 1993 and May 1994 was representative of the monthly average at the site. Estimated annual average heads at these 107 observation wells were computed from equation 2 using the September 1993 and May 1994 water levels and the regression coefficients β_I, β_S, and β_M. The 107 estimated annual averages and the 11 annual average heads computed from continuous water-level data constituted the 118 control points used to generate the potentiometric-surface map of the IAS (fig. 17).

The estimated average 1993-94 potentiometric surface of the IAS shows altitudes of 120 ft in south-central Polk County and in the area where Polk, Hillsborough, Hardee, and Manatee Counties meet (fig. 17). The thickness of the IAS decreases towards the northern, eastern, and western boundaries of the model. The IAS continues beyond the southern boundary of the model area. Ground water flows laterally from areas of potentiometric surface highs toward boundaries where the aquifer pinches out. In particular, upward leakage in discharge areas in parts of Sarasota, De Soto, Highlands, and Glades Counties causes ground water to move towards the eastern and western boundaries of the aquifer.

Potentiometric Surface of the Upper Floridan Aquifer

Daily measurements at UFA wells equipped with continuous water-level recorders were used to obtain monthly averages for September 1993 and May 1994 and averages for 1993-94. Regression coefficients β_I, β_S, and β_M for the UFA were obtained from the continuous water-level data by making a multiple linear regression (equation 2) for each group of physiographic regions (table 3). The regression coefficients β_I, β_S, and β_M calculated for the UFA showed that the estimated annual averages were influenced more by the September 1993 averages than by the May 1994 averages for physiographic regions 3, 4, 5, 6, 9, and 10 (table 3). The correlation coefficients for all regressions indicated a strong correlation between the annual averages and the September 1993 and May 1994 averages (table 3).

Water-level measurements made during the months of September 1993 and May 1994 in the SJRWMD, SWFWMD, and parts of SFWMD to generate potentiometric-surface maps for the UFA (Metz and Brendle, 1994a; Mularoni, 1994b; Schiffer and others, 1994; and Spechler and others, 1993) were assumed to represent monthly averages. Water-level measurements made in the SRWMD and the computed annual average heads at UFA wells equipped with continuous water-level recorders were used to increase the density of water-level measurements. Estimated annual average heads at UFA observation wells were computed from equation 2 using the compiled September 1993 and May 1994 water-level data and the regression coefficients for the respective physiographic regions.

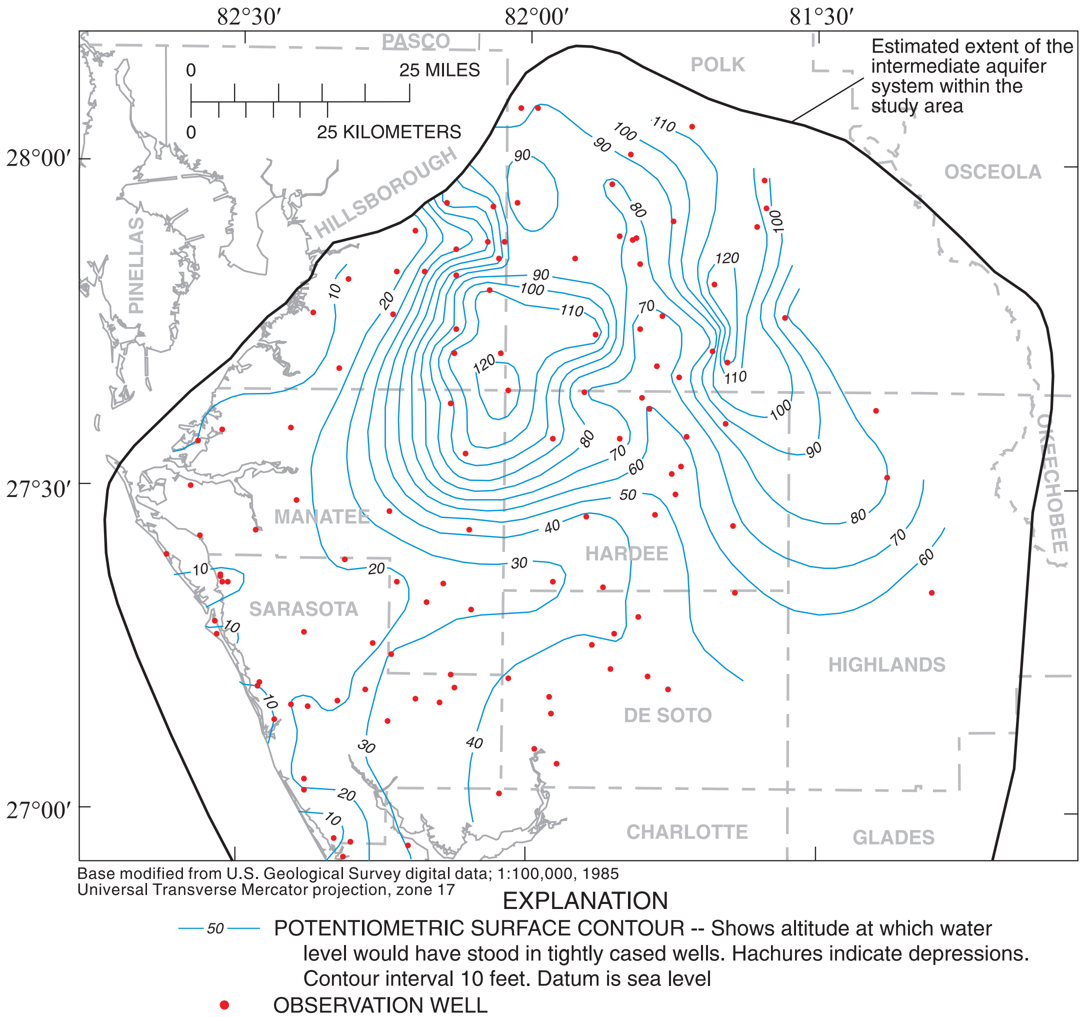


Figure 17. Estimated potentiometric surface of the intermediate aquifer system, average conditions for August 1993 through July 1994.

Table 3. Multiple linear regression coefficients for September 1993 and May 1994 water-level averages in the Upper Floridan aquifer for each group of physiographic regions

[Group number refers to figure 2. Refer to equation 2 for the definition of regression coefficient; na, not applicable]

Group number	Number of Upper Floridan aquifer wells	Intercept (feet) (β_I)	Regression coefficient of September 1993 (β_S)	Regression coefficient of May 1994 (β_M)	Root-mean-square residual (feet)	Range of values of difference between regressed and measured heads (feet)	Correlation coefficient
1	9	0.77	0.08	0.90	0.60	[-0.80, 0.87]	0.99
2	16	.62	.39	.62	.22	[-0.33, 0.34]	.99
3	16	.02	.68	.32	.36	[-0.73, 0.84]	.99
4	15	.79	.58	.42	.39	[-0.71, 0.60]	.99
5	16	-.22	.55	.46	.21	[-0.48, 0.35]	.99
6	23	.25	.64	.35	.46	[-1.34, 0.78]	.99
7	32	-.57	.13	.87	.59	[-1.22, 1.17]	.99
8	4	.39	.25	.75	.35	[0.21, 0.54]	.99
9	4	-3.42	.77	.29	.25	[-0.19, 0.42]	.99
10	8	-.12	.62	.36	.27	[-0.29, 0.53]	.99
Weighted mean	143	na	na	na	.40	[-1.34, 1.17]	na
No grouping	143	.22	.54	.46	.85	[-3.18, 4.62]	.99

Several UFA water-level measurements in SRWMD were obtained by correlating measured water levels of May 1990 (Meadows, 1991) and of May-June 1995 (Mahon and others, 1997) with average water levels for 1993-94 obtained from continuous water-level recorders in the area (fig. 16). A multiple linear regression among average water levels for 1993-94, water levels of May-June 1995, and water levels of May 1990 was used to calculate regression coefficients for May-June 1995 and May 1990. The computed multiple linear regression coefficients were used to estimate annual average water levels for 1993-94 at sites without continuous recorders for which only May-June 1995 and May 1990 measurements were available. The 39 additional annual average water levels estimated through this regression were used to improve the definition of the 1993-94 potentiometric surface of the UFA. At sites where measured May 1990, September 1993, May 1994, and May-June 1995 water levels were available, annual average water levels for 1993-94 were computed using both approximations, the May 1990 and May-June 1995 regression coefficients, and the September 1993 and May 1994 regression coefficients listed in table 3. A comparison of both approximations showed that the maximum absolute difference between the estimated and the computed annual average heads was 0.3 ft.

An area of high potentiometric-surface altitude for the UFA was documented in Gilchrist County (fig. 18), with a steep gradient towards the Santa Fe River, the Suwannee River, and eastern Alachua County (Col and others, 1997). This potentiometric high is associated with both low aquifer transmissivity and high recharge rates (Col and others, 1997). Water-level data collected at an additional 28 sites by the Florida Geological Survey were used to enhance the resolution of the UFA potentiometric surface across the County. A total of 1,483 average 1993-94 water levels were used to generate a potentiometric-surface map for the UFA (fig. 18). Of these points, 23 were outside the study area but were used to assess, in part, the heads of the UFA near the lateral boundaries of the study area.

Ground-water divides, which can be delineated from the potentiometric surface, define the regional direction of ground-water flow. Ground water generally flows away from the ground-water divides. A clear example of a ground-water divide based on the potentiometric-surface map of the UFA can be seen in southwest Lake County extending across central Polk and Highlands Counties (fig. 18). This ground-water divide perpendicularly crosses the closed UFA potentiometric- surface contours, ranging from 80 to 125 ft. Analogously, in areas of potentiometric highs characterized by closed contours of higher altitude than the surrounding area, ground water flows perpendicular to the ground-water divide.

Highly transmissive areas in the UFA are characterized by widely spaced potentiometric-surface contours, particularly in Suwannee, south-central Columbia, northwest Alachua, south-central Marion, west-central Citrus, and west-central Lake Counties (fig.18). This characterization of the potentiometric surface of the UFA also can be observed in parts of Osceola and southwest Polk Counties.

Poorly transmissive areas are characterized by closely spaced contours, particularly in central Gilchrist, southeast Levy, east-central Clay, central Putnam, and northeast Marion Counties. Large horizontal hydraulic gradients are identified by areas of closely spaced contours in figure 18. Areas of large horizontal hydraulic gradients are typically characterized by a zone of low transmissivity that causes abrupt changes in water levels.

Water-Level Measurements in the Lower Floridan Aquifer

Annual average heads were computed at 24 sites tapping the LFA where monthly water-level measurements were available. Monthly values were regressed, using equation 2, to compute annual average 1993-94 heads. The correlation coefficient of this multiple linear regression was 0.99. The resulting regression coefficients were 0.60 for September 1993 and 0.40 for May 1994. These regression coefficients were used to estimate 1993-94 average heads at 22 LFA wells for which only September 1993 and May 1994 measurements were available. The 46 resulting annual average heads were not sufficient to generate a potentiometric-surface map for the LFA.

Chloride Concentrations in Ground Water

A data base containing site location, water-sample depth, and chloride concentration of ground-water samples from UFA wells was created with water-quality data from the SJRWMD, SFWMD, SWFWMD, SRWMD, and the USGS. The chloride data were used to estimate the altitudes in the FAS where chloride concentrations are approximately 5,000 mg/L. SJRWMD generated a map of altitudes where chloride concentrations of 5,000 mg/L are present in the FAS in east-central Florida (Brian McGurk, SJRWMD, written commun., 1999). Lines of equal chloride concentrations depicted in the SJRWMD map were extended across the study area (fig. 19) with the aid of the water-quality data base and a generalized contour map showing the altitude of water having 10,000 mg/L chloride concentration generated by Sprinkle (1989).

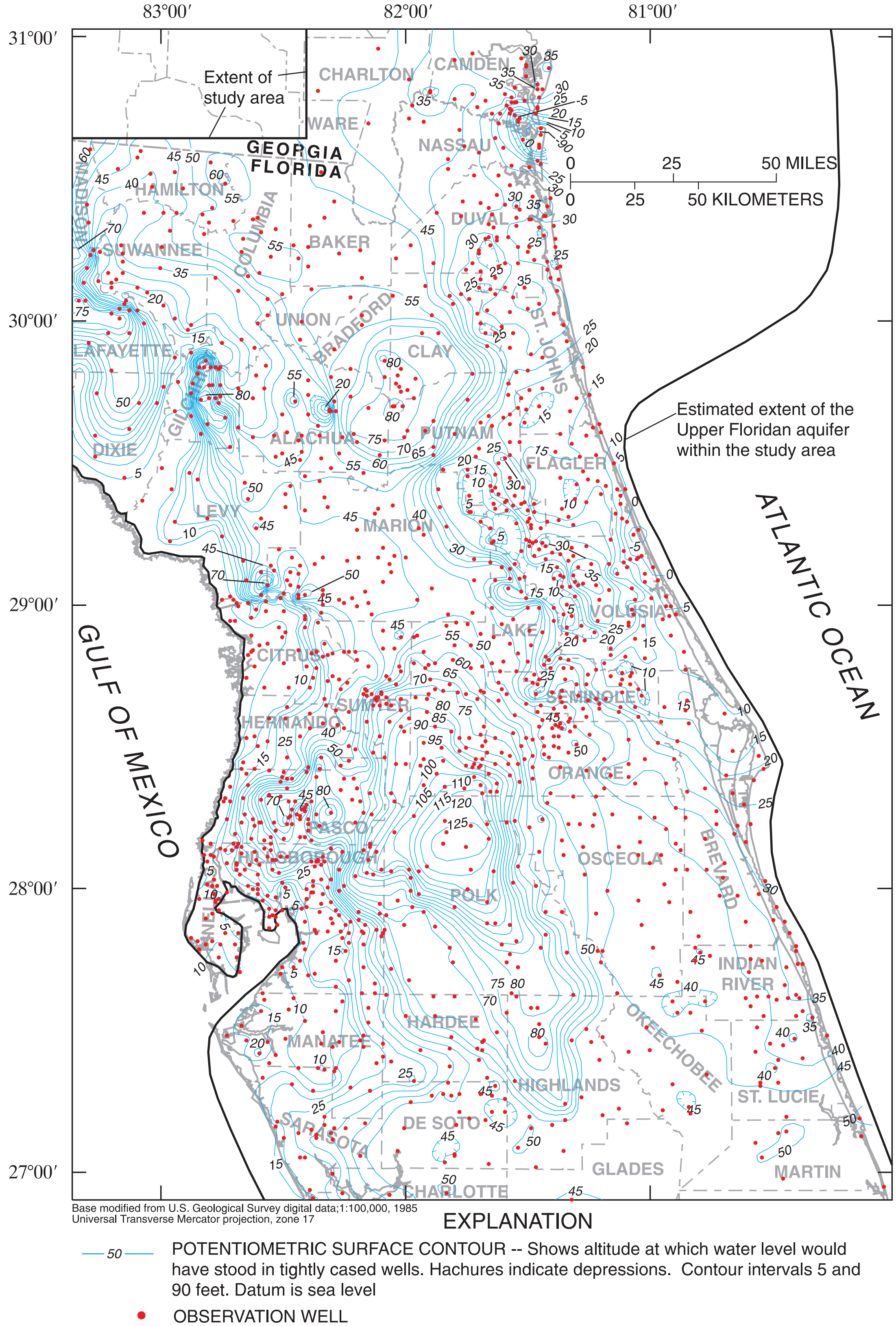
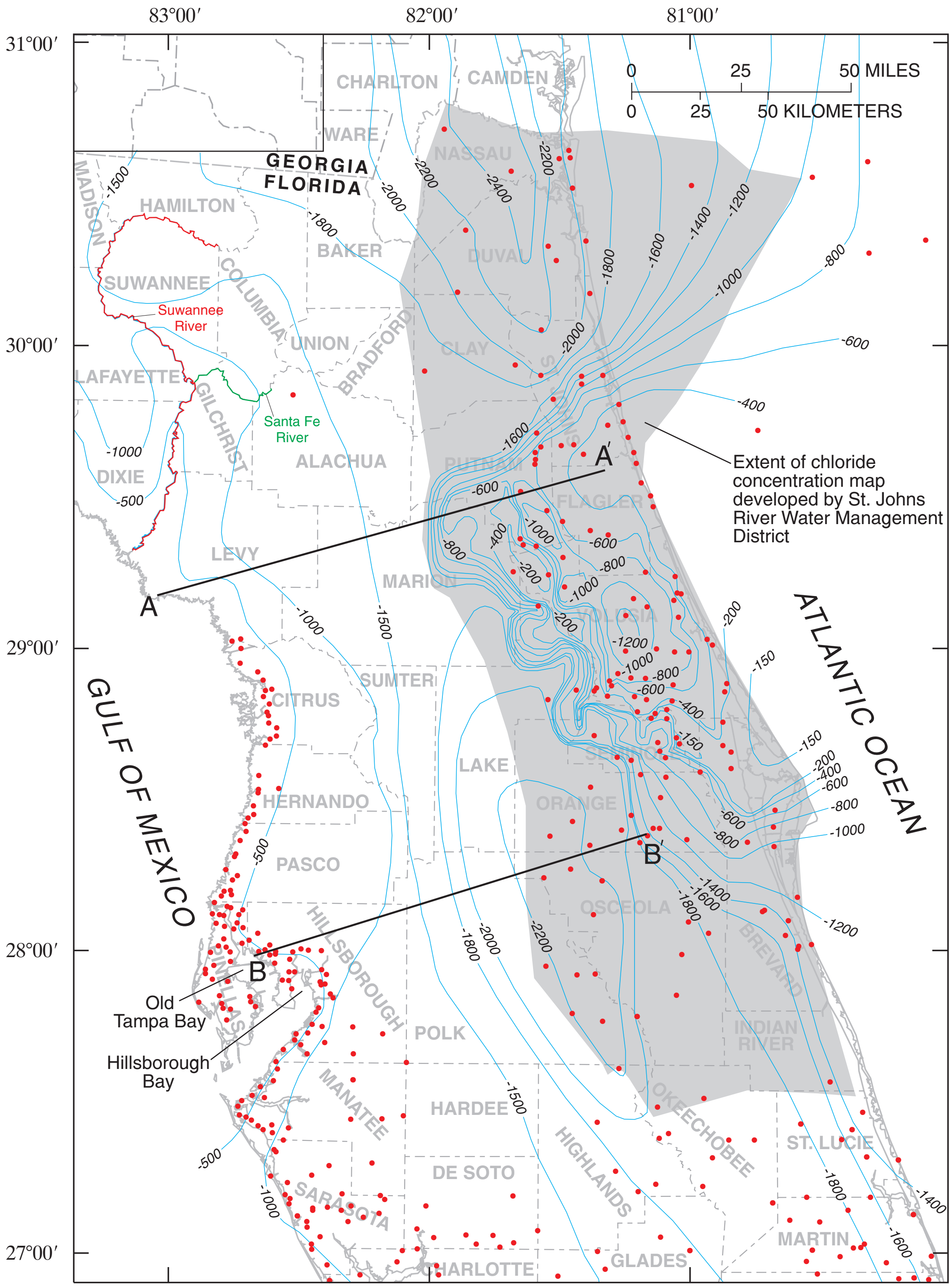


Figure 18. Estimated potentiometric surface of the Upper Floridan aquifer, average conditions for August 1993 through July 1994.



Base modified from U.S. Geological Survey digital data; 1:100,000, 1985
Universal Transverse Mercator projection, zone 17

EXPLANATION

-200 ALTITUDE CONTOUR -- Shows estimated altitude of ground water with 5,000 milligrams per liter chloride concentration. Contour interval is variable. Datum is sea level

A——A′ HYDROGEOLOGIC SECTION

● OBSERVATION WELL

Figure 19. Estimated altitude of water containing a chloride concentration of 5,000 milligrams per liter in the Floridan aquifer system (modified from Brian McGurk, St. Johns River Water Management District, written commun., 1999; and Sprinkle, 1989).

The map generated by Sprinkle (1989, p. I50) was used to approximate the occurrence of 5,000-mg/L chloride concentrations in the northwest part of the study area. The data indicated saltwater encroachment along the meanderings of the Suwannee and Santa Fe Rivers. Chloride concentrations in ground water were assumed to decrease away from these rivers.

In west-central Florida, generalizations based on chloride trends from east-central Florida were required because of the paucity of available data. Chloride data in east-central Florida and data published by Hickey (1990) provided estimates of the gradients in Polk County where chloride concentrations change from east to west. Water-level contours of -1,500; -1,800; and -2,000 ft are closely spaced in the vicinity of Lake, Polk, and Highlands Counties, reflecting the assumption that chloride concentrations in ground water increase from east-central to west-central Florida (fig. 19).

The purpose of approximating the altitude at which 5,000 mg/L of chloride is present in ground water was to estimate the base of the ground-water flow model; that is, the location beyond which horizontal and vertical ground-water flow is attenuated due to the density increase caused by the increased chloride concentration. Generally, water levels in the UFA near the coastlines of the study area are above sea level and decrease seaward, which minimizes the movement of seawater inland (Todd, 1980). Lines of equal chloride concentration at offshore sites in the Atlantic Ocean were estimates based on a few offshore points documented by Scholle (1979), Johnston and others (1982), and Johnston (1983). Chloride data from a well in Hillsborough Bay (Sinclair, 1979) indicated there is no ground water in the bay with chloride concentrations less than 5,000 mg/L. The same situation was assumed to occur in Old Tampa Bay (fig. 19) based on chloride trends obtained from Dames and Moore (1988).

Sulfate concentrations near the base of the UFA in southwest Florida tend to increase from east-central to west-central Florida (Hickey, 1990). Increases in sulfate concentrations in ground water also increase the density of ground water. There were insufficient sulfate data to assess specific areas where sulfate concentrations would cause increases in ground-water density equivalent to a chloride concentration of 5,000 mg/L; however, the occurrence of high sulfate concentrations in southwest Florida would have the equivalent effect of displacing the base of ground-water flow farther east (fig. 19).

Recharge to and Discharge from the Upper Floridan Aquifer

The areal distribution of recharge and discharge areas to the UFA were delineated by comparing the altitude of the water table of the SAS and the potentiometric surface of the UFA (fig. 20). Recharge to the UFA (and the IAS) occurs mainly by downward leakage from the SAS through the ICU (where present) when the altitude of the water table is higher than the potentiometric surface of underlying aquifers. The estimated recharge areas, based on figures 15, 17, and 18, are areas where either the water table has a higher altitude than the potentiometric surface or the UFA is unconfined.

Recharge and discharge areas for the UFA were delineated where there were no measured water levels in the IAS by comparing the altitude of the water table of the SAS and the interpolated heads of the UFA. In areas where measured water levels were available for the IAS, the altitudes of the potentiometric surfaces of the IAS and the UFA were compared to identify areas of recharge to and discharge from the UFA.

In areas where the potentiometric surface of the UFA (and the IAS) is above the altitude of the water table of the SAS, there is a potential for water to discharge from the UFA as upward leakage to the SAS through the ICU (fig. 20). This is the case in some coastal areas. Discharge from the UFA also occurs as ground-water withdrawals, spring flows, and flow from the unconfined areas of the UFA to swamps and rivers.

Recharge to the UFA also occurs at discrete points, both naturally occurring and anthropogenic. Recharge occurs at natural sinkholes such as Alachua and Haile Sinks (fig. 21). These sinks were assigned a combined recharge rate to the UFA of 10 million gallons per day (Mgal/d), based on estimates by Phelps (1987). No recharge rates for other natural sinks in the study area are available. Artificial recharge to the freshwater part of the UFA occurs from drainage wells, injection wells in Alachua County, and rapid-infiltration basins.

Water Use

Within the study area, ground-water withdrawals from the IAS, UFA, and LFA for public-water supply, commercial or industrial (including thermoelectric-power generation and recreational uses), and agricultural purposes were compiled or estimated for 1993-94 (depending on the water-use type). Most of the ground-water withdrawals were compiled from consumptive user permit data bases and water-use data files from SJRWMD, SFWMD, SWFWMD, and SRWMD. The estimation of other types of discharge from wells, such as self-supplied domestic water-use data and discharge rates from free-flowing wells, is presented in this section.

Total estimated ground-water withdrawals from the IAS, UFA, and LFA for public-water supply, commercial and industrial, agricultural, and self-supplied domestic uses for 1993-94 were 2,488 Mgal/d (table 4).

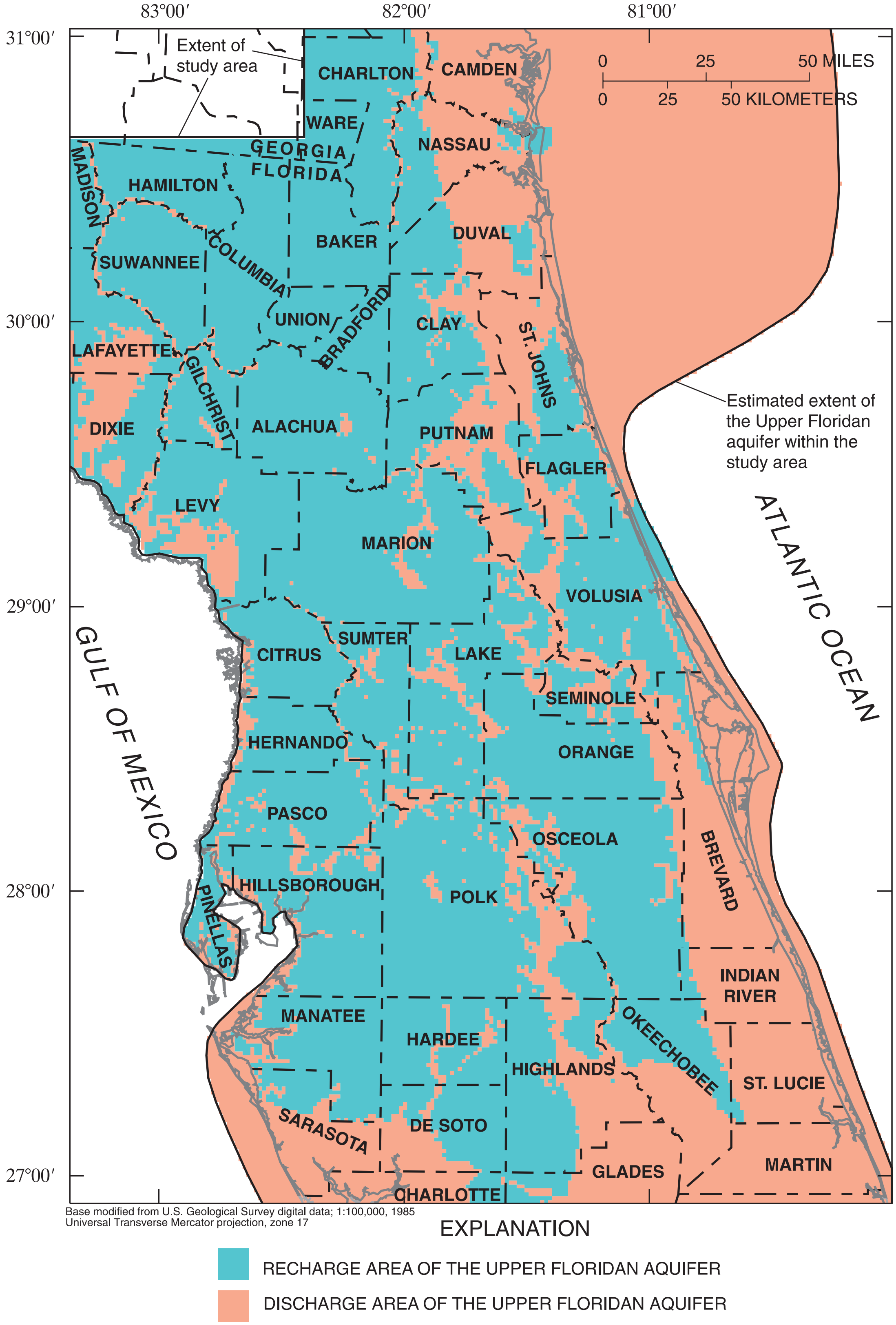


Figure 20. Distribution of recharge and discharge areas of the Upper Floridan aquifer, average conditions for August 1993 through July 1994.

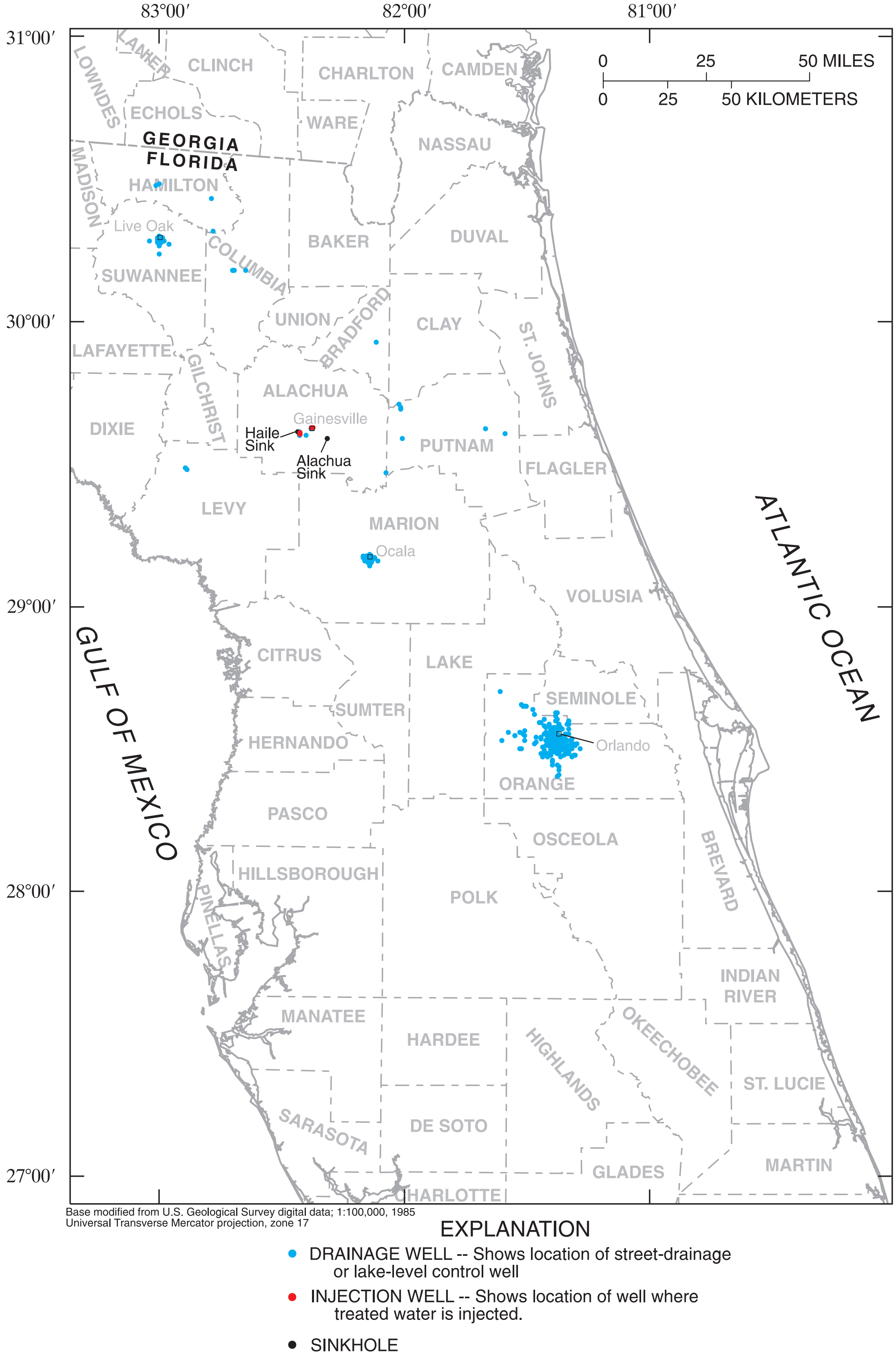


Figure 21. Locations of Upper Floridan aquifer drainage and injection wells.

Table 4. Estimated ground-water withdrawals and uses, by county and by Water Management District, from the intermediate aquifer system, Upper Floridan aquifer, and Lower Floridan aquifer, August 1993 through July 1994

[Source: St. Johns River Water Management District (SJRWMD); South Florida Water Management District (SFWMD); Southwest Florida Water Management District (SWFWMD); Suwannee River Water Management District (SRWMD); and U.S. Geological Survey. All rates are in million gallons per day; -- indicates no wells are tapping the aquifer or aquifer is absent]

County	Intermediate aquifer system				Upper Floridan aquifer				Lower Floridan aquifer		
	Public-water supply	Industrial and commercial[a]	Agricultural	Domestic	Public-water supply	Industrial and commercial[a]	Agricultural	Domestic	Public-water supply	Industrial and commercial[a]	Agricultural
Alachua	--	--	--	--	24.62	5.99	34.96	6.93	--	--	--
Baker	--	--	--	--	.80	.23	.14	1.24	0.31	--	0.05
Bradford	--	--	--	--	4.08	3.49	2.25	2.08	--	--	--
Brevard	--	--	--	--	2.61	1.02	13.75	0.52	--	--	--
Charlotte	0.11	0.07	14.29	1.17	.43	.07	4.91	--	--	--	--
Citrus	--	--	--	--	10.17	6.26	1.57	6.73	--	--	--
Clay	--	--	--	--	2.66	3.87	.77	2.90	7.43	1.77	--
Columbia	--	--	--	--	4.22	3.17	13.42	4.36	--	--	--
DeSoto	.95	.24	6.12	0.52	.64	.16	53.87	.01	--	--	--
Dixie	--	--	--	--	1.69	.79	4.29	1.10	--	--	--
Duval	--	--	--	--	27.70	14.36	1.35	.08	73.42	12.34	.12
Flagler	--	--	--	--	1.46	.08	6.25	.95	--	--	--
Gilchrist	--	--	--	--	2.32	.38	24.62	1.10	--	--	--
Glades	--	--	1.27	.01	.44	--	6.36	--	--	--	.18
Hamilton	--	--	--	--	16.94	14.80	16.54	.78	--	--	--
Hardee	.04	.08	5.83	.42	1.39	.09	54.83	.01	--	--	--
Hernando	--	--	--	--	17.06	22.60	3.71	2.66	--	--	--
Highlands	.33	.25	17.41	.21	6.91	2.01	96.22	.01	--	--	18.54
Hillsborough	.01	.02	.95	.55	65.41	25.56	72.34	9.48	--	--	--
Indian River	--	--	--	--	5.21	.23	31.35	.09	--	--	--
Lafayette	--	--	--	--	.59	.57	22.08	.71	--	--	--
Lake	--	--	--	--	26.01	27.80	29.43	9.55	1.73	.32	.32
Levy	--	--	--	--	3.20	3.85	25.62	3.31	--	--	--
Madison	--	--	--	--	.28	.26	7.79	.17	--	--	--
Manatee	.16	.27	2.24	2.42	11.09	1.16	77.39	.02	--	--	--
Marion	--	--	--	--	18.54	6.44	8.46	21.76	--	--	.04
Martin	--	--	--	--	1.20	.42	9.65	--	--	--	--
Nassau	--	--	--	--	4.46	34.00	.42	.13	--	1.91	--
Okeechobee	--	--	--	--	--	.39	24.42	.03	--	--	.34
Orange	--	--	--	--	111.81	7.73	18.43	12.60	60.41	.40	.11
Osceola	--	--	--	--	18.27	2.62	46.12	6.28	.97	--	.02
Palm Beach	--	--	--	--	.42	--	--	--	--	--	--
Pasco	--	--	--	--	95.89	16.00	20.07	8.07	--	--	--
Pinellas	--	--	--	--	40.69	1.87	.68	4.46	--	--	--
Polk	.30	1.60	3.88	.80	59.39	90.61	127.12	5.69	.88	--	.47
Putnam	--	--	--	--	3.38	7.22	6.58	9.42	--	.98	--
St. Johns	--	--	--	--	6.63	.01	21.01	2.12	.02	--	--
St. Lucie	--	--	--	--	1.10	.25	11.42	.43	--	--	--
Sarasota	2.94	.83	.94	4.96	15.79	3.16	4.38	.03	--	--	--
Seminole	--	--	--	--	50.03	.39	7.90	7.90	6.91	--	--
Sumter	--	--	--	--	2.51	1.20	8.96	3.11	--	--	--
Suwannee	--	--	--	--	5.05	3.33	63.69	2.94	--	--	--
Union	--	--	--	--	1.11	.09	1.73	.72	--	--	--
Volusia	--	--	--	--	47.37	.71	16.53	7.39	--	.12	.01
Camden, Ga.	--	--	--	--	2.43	34.36	.01	--	--	--	--
Charlton, Ga.	--	--	--	--	.70	--	--	--	--	--	--
Total	**4.84**	**3.36**	**52.93**	**11.06**	**724.70**	**349.60**	**1,003.39**	**147.87**	**152.08**	**17.84**	**20.20**
Water Management District											
SJRWMD	--	--	--	--	289.61	98.91	156.44	69.93	135.09	17.48	0.63
SFWMD	0.01	0.10	11.38	0.25	58.43	10.57	184.50	11.27	16.99	.36	19.57
SWFWMD	4.83	3.26	41.55	10.81	332.24	171.26	452.50	45.92	--	--	--
SRWMD	--	--	--	--	44.42	68.86	209.95	20.75	--	--	--

	Intermediate aquifer system	Upper Floridan aquifer	Lower Floridan aquifer	Total by aquifer	Public-water supply	Industrial and commercial	Agricultural	Domestic	Total by use
Total	**72.19**	**2,225.56**	**190.12**	**2,487.87**	**881.62**	**370.80**	**1,076.52**	**158.93**	**2,487.87**

[a]Includes mining, thermoelectric power generation, recreational, and landscape irrigation uses.

Pumping rates were 72 Mgal/d from the IAS; 2,226 Mgal/d from the UFA; and 190 Mgal/d from the LFA. Corresponding withdrawals were 882 Mgal/d for public-water supply; 371 Mgal/d for commercial and industrial; 1,076 Mgal/d for agricultural uses; and 159 Mgal/d for self-supplied domestic uses. Estimated ground-water withdrawals from self-supplied domestic wells for 1993-94 were obtained from USGS data (Richard L. Marella, written commun., 1998).

Ground-water withdrawals for public-water supply and commercial or industrial purposes were compiled from the monthly operating reports of SJRWMD, SFWMD, SWFWMD, and SRWMD, which are based on meter readings. Ground-water withdrawals were distributed according to aquifer source by using the well locations, penetration depths of individual wells in each well field, well status, and well capacity from the consumptive user permit data base. Pumping rates for Camden, Charlton, and Ware Counties, Ga., for public-water supply and industrial purposes were obtained from the USGS.

Several assumptions were made to apportion total water withdrawals among individual wells in the same well field and between aquifers for wells with open intervals tapping more than one aquifer. At well fields where only the cumulative withdrawal was specified, each active well was assigned a ground-water withdrawal equal to the total withdrawn multiplied by the ratio of the well capacity to the sum of well capacities for all active wells in the well field. Assigned water withdrawals from each aquifer from wells with open intervals tapping more than one aquifer were set equal to the total withdrawal rate multiplied by the ratio of the transmissivity of the interval open to a particular aquifer to the transmissivity of the entire open interval of the well.

Ground-water withdrawal data for SRWMD were provided by SRWMD (Ronald Ceryak, written commun., 1997). Measured and estimated pumping rates from wells in SWFWMD were provided by the SWFWMD (Tabitha Ostow, written commun., 1999). Pumping rates from wells used for agricultural purposes in SJRWMD and SFWMD were estimated from the required application rates for each crop type, which depend on rainfall, watering needs, and estimated evapotranspiration rates. These application rates were computed by the Water Management Districts. The application rate for each cultivated acre, adjusted by the irrigation method, was multiplied by the number of cultivated acres to obtain the estimated pumping rate for a specific crop. Many wells pumped water for more than one crop type. Total ground-water withdrawals for well fields were the sum of pumping rates for all crop types. When ground water was not the only source for irrigation, adjustments to pumping rates were made by using the estimated ground-water use percentage listed in the water-use permit data base.

Estimates of discharge rates from free-flowing UFA wells in SJRWMD were obtained from SJRWMD (Brian McGurk, written commun., 1997). Discharge rates for 1993-94 were estimated to be 6.81 Mgal/d, of which more than 50 percent occurred in Brevard County (table 5). No information is available about free-flowing wells, if any, outside SJRWMD.

Table 5. Estimated discharge rates from free-flowing wells, by county, in the Upper Floridan aquifer in the St. Johns River Water Management District, August 1993 through July 1994

[Source: Brian McGurk, St. Johns River Water Management District. Rates are in million gallons per day]

County	Discharge
Brevard	3.44
Indian River	2.00
Putnam	.03
St. Johns	.36
Seminole	.87
Volusia	.11
Total	**6.81**

Artificial Recharge from Drainage and Injection Wells

Artificial recharge to the UFA occurs through about 364 active drainage wells and 41 injection wells (fig. 21). Of these wells, 242 are concentrated in the Orlando metropolitan area and were verified to be active (CH2M Hill, 1997). These drainage wells, cased to the top of the UFA and then drilled open-hole into the UFA, generally are used as a means to dispose of street runoff from storm drains and to control lake levels. Total recharge to the UFA through drainage wells in the study area was estimated to be 68 Mgal/d (table 6) based on total rainfall for 1993-94. The recharge rate at drainage wells is strongly correlated to the amount of total rainfall for any period.

Recharge to the UFA through drainage wells in the Orlando metropolitan area for 1993-94 was approximated from recorded rainfall data at nearby NOAA stations (fig. 3) and from adjustments to previously estimated long-term recharge rates at these wells by CH2M Hill (1997) and Bradner (1996). Estimates of recharge rates from drainage wells were based on a water-budget analysis of the basins containing street-runoff and lake-level control wells.

Table 6. Estimated recharge rates for drainage wells to the Upper Floridan aquifer, by county, August 1993 through July 1994

[Source: CH2M Hill, 1997; Bradner, 1996; Phelps, 1987. Rates, in million gallons per day, are rounded to integers]

County	Recharge
Alachua	11
Marion	4
Orange	45
Putnam	1
Seminole	2
Suwannee	5
Total	**68**

For street-runoff wells, the first step was to calculate a runoff coefficient for the drainage area. The runoff coefficient can be defined as the fraction of the total rainfall that becomes runoff over a given time period. CH2M Hill (1997) calculated an average runoff coefficient of 0.578 for a group of street-runoff drainage wells in Orange County. An average runoff coefficient, weighted by the contributing drainage areas of each well, was computed for the same group of street-runoff drainage wells used by CH2M Hill (1997). The resulting area-weighted average runoff coefficient used in this study was 0.478. An area-weighted average runoff coefficient lower than the 0.578 value computed by CH2M Hill (1997) is attributed to predominantly lower runoff coefficients for street-runoff drainage wells with larger contributing drainage areas.

The total area drained by street-runoff wells in metropolitan Orlando was estimated to be 6,083 acres (CH2M Hill, 1997). The 30-year average recharge rate to the UFA at street-runoff drainage wells, computed from the product of runoff coefficient, total rainfall at the Orlando McCoy station (fig. 3), and drainage area, was estimated to be 10.40 Mgal/d. The estimated recharge rate to the UFA from street-runoff drainage wells for 1993-94 was 11.91 Mgal/d, equal to 10.40 Mgal/d multiplied by the ratio of rainfall for this period (fig. 3) to the 30-year rainfall average.

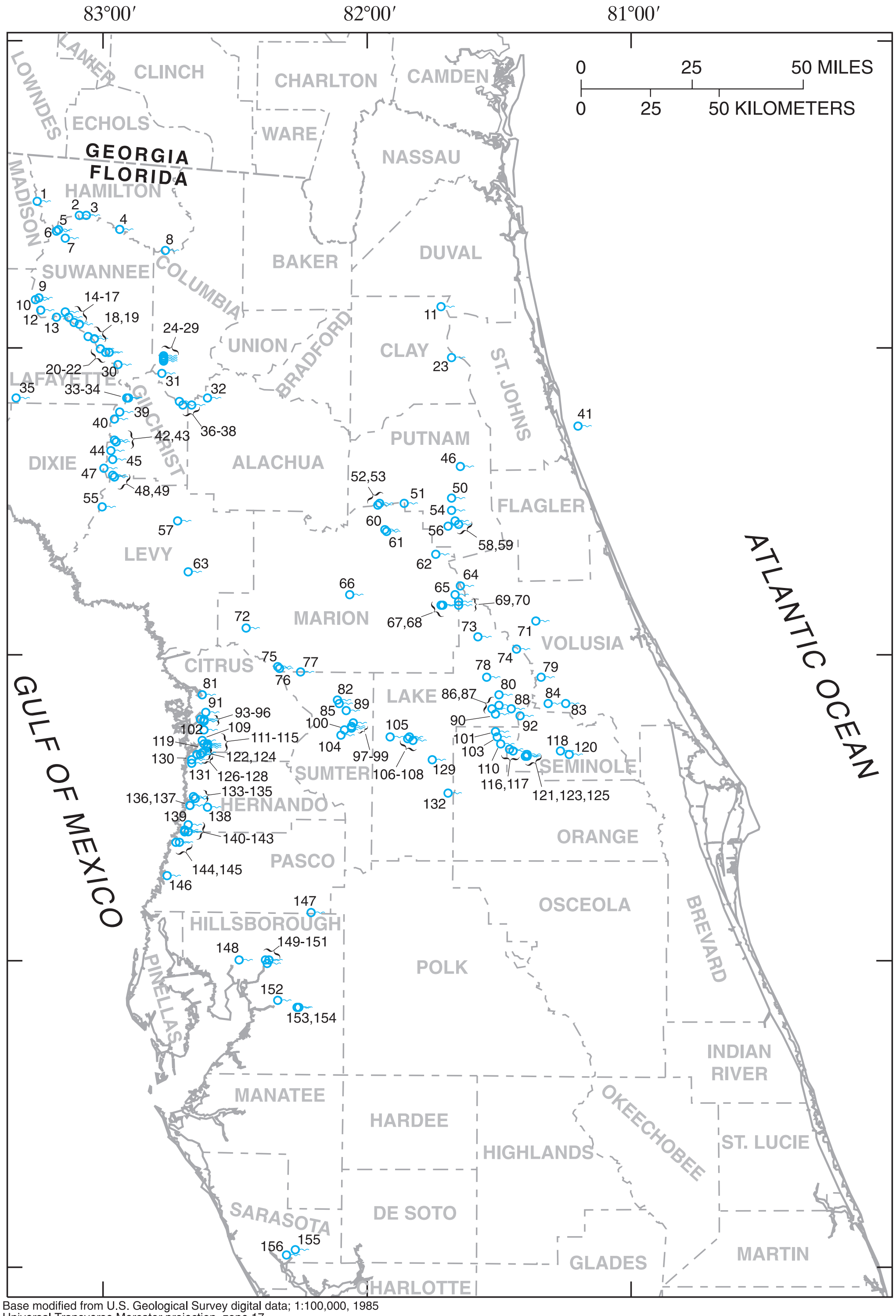
A water-budget analysis of the basins contributing drainage to 10 lake-level control wells (Bradner, 1996) showed a basin-area weighted recharge rate to the UFA of 10.84 in/yr. This recharge rate is lower than the non-weighted numerical average of 18.08 in/yr computed by CH2M Hill (1997) for the same basins. The total area drained by these lake-level control wells in metropolitan Orlando was estimated to be 33,031 acres (CH2M Hill, 1997). The 30-year average recharge rate to the UFA at lake-level control wells, computed from the product of drainage area and basin-area weighted recharge rate, was estimated to be 26.64 Mgal/d. The estimated recharge rate to the UFA for 1993-94 at lake-level control wells was 30.50 Mgal/d, equal to 26.64 Mgal/d multiplied by the ratio of rainfall for this period to the 30-year rainfall average.

Recharge to the UFA through drainage wells outside the Orlando area but in Orange and Seminole Counties for 1993-94 was estimated to be 4.21 Mgal/d. Recharge to the UFA from drainage wells outside Orange and Seminole Counties (fig. 21), assuming all were street-runoff wells, was estimated to be 11.57 Mgal/d.

Additional recharge to the UFA occurs through injection wells monitored by the Florida Department of Environmental Protection (FDEP). Recharge rates from injection wells (fig. 21) were obtained from FDEP. A total of 10.62 Mgal/d recharged the UFA by injection wells in Alachua County during the 1993-94 period. The injection wells in Alachua County were the only FDEP wells recharging the freshwater part of the UFA.

Spring Flow

More than 150 springs discharge water from the UFA in the study area. A major factor in spring flow is the net aquifer recharge from rainfall; however, spring response is delayed by aquifer-matrix storage. Higher spring flows are common in late fall after the rainy season, whereas lower flows occur in late spring when rainfall is low. Spring flows from the UFA tend to create depressions in the potentiometric surface, the areal extent of which depends on the magnitude of the spring flow and aquifer and confining-unit properties in the vicinity of the spring. A summary of spring-flow data for springs discharging from the UFA and the locations of these springs was compiled (fig. 22, appendix C) from Rosenau and others (1977), Yobbi (1989, 1992), USGS (1994, 1995, 1996, 1997, 1999), and Leel Knowles (USGS, written commun., 1999). The springs in the study area with the highest flows, based on measured values or estimated flow measurements for 1993-94, are Silver Springs (number 66 in fig. 22), Rainbow Springs (number 72), Crystal River Spring Group (number 81), Alapaha Rise (number 2), and Ichetucknee Springs (combined flow of numbers 24 through 29 in fig. 22). Total spring flow from the UFA was approximately 6,380 cubic feet per second (ft^3/s) or 4,130 Mgal/d (appendix C).



EXPLANATION

156 SPRING AND REFERENCE NUMBER -- Number refers to spring number in appendix C

Figure 22. Locations of Upper Floridan aquifer springs.

Of the 156 springs in the study area, only 28 were measured during 1993-94 (U.S. Geological Survey, 1994, 1995; appendix C). Average flows from the remaining 128 springs were estimated by using the following approximations. Spring flow measurements by the USGS (1996, 1997, 1999) and Rosenau and others (1977) at 87 springs either prior to or after 1993-94 were used to estimate 1993-94 flows by multiplying the measured flow by the ratio of the 1993-94 rainfall to the rainfall that occurred during the year in which the measurement was made. Although the ratio between spring flow and rainfall is not constant from one year to the next, measured flows varied somewhat linearly with rainfall in those years when more than one flow measurement was available. Flows at nine unmeasured third and fourth magnitude springs were assigned flow values based on field reconnaissance (Leel Knowles, USGS, written commun., 1999). Flow at Crescent Beach submarine spring (spring 41, appendix C) also has never been measured; the estimated flow of 30 ft^3/s is highly generalized (Rick Spechler, USGS, oral commun., 2000).

Average flows for 1993-94 at 31 springs in Citrus, Hernando, and Pasco Counties were estimated from the average May 1988 to April 1989 flows computed by Yobbi (1992). The average of the flow measurements at Weeki Wachee Springs (spring 138 in fig. 22) was 185 ft^3/s from May 1988 to April 1989 (Yobbi, 1992), and 129 ft^3/s from August 1993 to July 1994 (U.S. Geological Survey, 1994, 1995), or about 70 percent of the average flow from May 1988 to April 1989. Because of the lack of additional spring-flow measurements from May 1988 to April 1989 and from August 1993 to July 1994, average flows from August 1993 to July 1994 for springs in Citrus, Hernando, and Pasco Counties were estimated to be 70 percent of the flows determined by Yobbi (1992) from May 1988 to April 1989. Similarly, the average flow in 1993-94 for additional springs listed by Yobbi (1989) was assumed to be 70 percent of the average flow for the period of record (appendix C).

Recharge to the Unconfined Upper Floridan Aquifer

A generalized water budget for unconfined areas of the UFA within the study area was used to estimate upper and lower bounds for the net aquifer recharge rate in these areas. Total rainfall, direct runoff estimates derived from separation of discharge hydrographs, and evapotranspiration estimates based on physiographic regions were used to approximate the net aquifer recharge in unconfined areas of the UFA. The estimated net aquifer recharge rate to unconfined areas of the UFA for the 1993-94 period was computed from the equation:

$$NR = TR - ET - SR \,, \qquad (3)$$

where

NR is net recharge to unconfined areas of the UFA, in inches per year,

TR is total rainfall, in inches per year,

ET is evapotranspiration, in inches per year, and

SR is surface runoff, in inches per year.

Equation 3 assumes that changes in storage were negligible, an assumption that is supported by data from continuous ground-water level recorders. Rainfall for the 1993-94 period was computed from data collected at NOAA stations (fig. 3). The unconfined areas of the UFA were divided into Thiessen (1911) polygons, which were based on the location of rain gages.

Net recharge to unconfined areas of the UFA is the subcomponent of the water budget that drives ground-water flow through the UFA when applied water exceeds evapotranspirative losses and overcomes capillary effects in the unsaturated zone. These recharge rates vary areally based on topography and physiography. Recharge rates to the aquifer are expected to be lower near coastal lowlands and swamps than in the Northern Highlands (fig. 2) or in other areas of high land-surface altitude. In low-lying areas, the potentiometric surface of the UFA is close to land surface and evapotranspiration (ET) rates probably are high. Recharge rates also are expected to be low near rivers, where surface runoff is more likely to discharge to rivers rather than recharge ground water. Aquifer recharge rates should decrease from the Northern Highlands (fig. 2) towards rivers in the unconfined areas of the UFA having the largest flows, namely, the Suwannee, Santa Fe, Steinhatchee, Waccasassa, and Withlacoochee Rivers, and parts of the Hillsborough River (fig. 23).

Several discharge areas along the Suwannee River in the unconfined areas of the UFA can be identified from the UFA potentiometric surface (fig. 18). The UFA discharges to the Suwannee River in areas where the stage at the Suwannee River is lower than the surrounding potentiometric surface. The Suwannee River recharges the UFA in areas where the river stage is higher that the surrounding potentiometric surface of the UFA. Surface water from the coastal plains and swamps discharges to the Gulf of Mexico.

Evapotranspiration varies areally; a range of ET values was obtained from documented minimum and maximum measured rates. The minimum ET rate was assumed to be 27 in/yr, measured at a herbaceous, successional vegetation in a deforested area of the Lake Wales Ridge during the 1993-94 period (Sumner, 1996). The maximum ET rate was assumed to be 46 in/yr, the mean evapotranspiration measured at seven vegetated sites (rather than open water) in the Everglades (fig. 1) from January 1996 to December 1997 (German, 2000).

Estimates of surface runoff (SR) were computed by applying a generalized hydrograph separation approximation to calculate base flow and surface runoff from the daily discharge data obtained from 10 USGS stream gaging stations (table 7, fig. 23). Estimates of SR, normalized per unit area of each respective drainage basin, ranged from 0.5 to 8 in/yr (table 7). The hydrograph separation approximation used in this study considered most hydrograph peaks to be part of SR (fig. 24). As a first approximation, the hydrograph separation code HYSEP (Sloto and Crouse, 1996) was used with a substantially larger drainage area

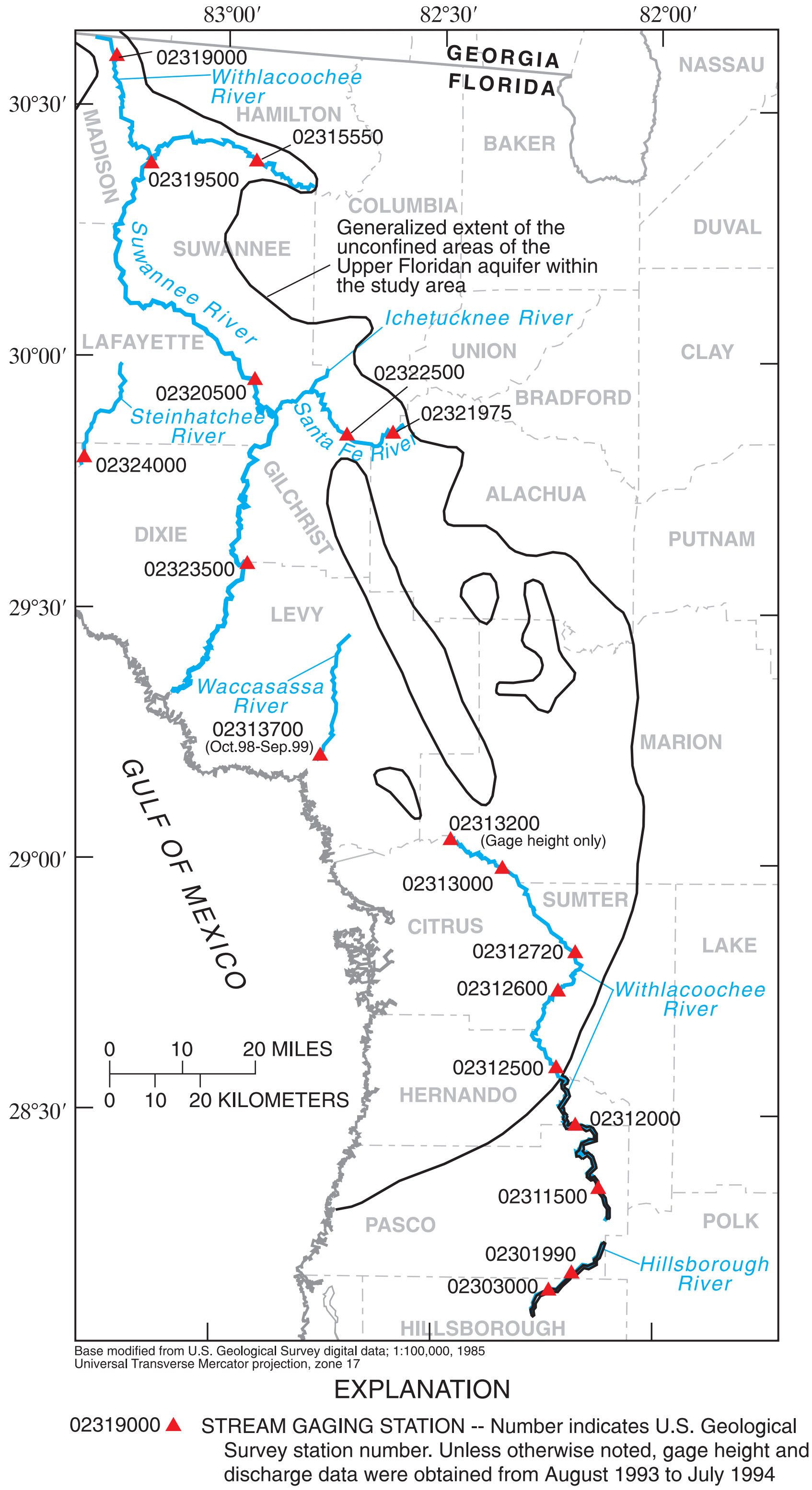


Figure 23. Rivers in the unconfined areas of the Upper Floridan aquifer and locations of stream gaging stations.

Table 7. Surface-runoff rates calculated from hydrograph separation approximations applied to August 1993 through July 1994 daily discharge data obtained from stream gaging stations in the unconfined areas of the Upper Floridan aquifer

[Station number refers to figure 23; USGS, U.S. Geological Survey. Average surface-runoff flow rates are rounded to one significant figure; mi^2, square miles; ft^3/s, cubic feet per second; in/yr, inches per year]

USGS station number	Station name	Drainage area (mi^2)	Average daily discharge (ft^3/s)	Estimated average base flow (ft^3/s)	Estimated average surface-runoff flow (ft^3/s)	Average surface-runoff flow per unit area (in/yr)
02303000	Hillsborough River near Zephyrhills	220	123	67	56	3.0
02312000	Withlacoochee River at Trilby	570	47	25	22	.5
02313000	Withlacoochee River near Holder	1,825	319	252	67	.5
02313700	Waccasassa River near Gulf Hammock	480	193	89	104	3.0
02319000	Withlacoochee River near Pinetta	2,120	1,714	621	1,093	7.0
02319500	Suwannee River at Ellaville	6,970	5,961	1,933	4,028	8.0
02320500	Suwannee River at Branford	7,880	6,678	3,269	3,409	6.0
02322500	Santa Fe River near Fort White	1,017	1,067	925	142	2.0
02323500	Suwannee River near Wilcox	9,640	9,410	5,056	4,354	6.0
02324000	Steinhatchee River near Cross City	350	205	36	169	7.0

than the actual area in order to increase the number of days after which SR ceases. The resulting surface runoff from HYSEP at each gaging station was adjusted so that large areas of the hydrograph peaks were considered to be part of SR. The frequency of storm events during the wet season, the large capacity of riverbank storage in the Suwannee, Withlacoochee, Waccasassa, Steinhatchee, Santa Fe, and Hillsborough Rivers, the large hydraulic connection between the UFA and these rivers, and the potential for slow overland drainage from swamps are some of the reasons why surface runoff would be underestimated if HYSEP was directly applied to these hydrographs. Surface runoff to the Suwannee River was estimated to be 7 in/yr, the rounded mean of the three stations on this river (table 7). The lowest surface-runoff rate, 0.5 in/yr, occurred at the Withlacoochee River in west-central Florida.

Because of the uncertainty of ET and SR and rather than computing a specific net recharge rate to unconfined areas of the UFA, ranges of values for the net recharge rate were estimated. These ranges were used to bracket final net recharge rates obtained during model calibration. The minimum net recharge rate was estimated from equation 3 by using the maximum ET rate; the maximum net recharge rate was estimated by using the minimum ET rate. The application of equation 3 to unconfined areas of the UFA resulted in net recharge rates that ranged from 0 to 18 in/yr in some areas, and from 13 to 32 in/yr in other areas (fig. 25). Estimated net recharge rates generally increased from the coastline inland.

Discharge to Swamps

Land-use maps indicate that about 12 percent of the unconfined areas of the UFA are swamps. These swamps include coastal or bay swamps, cypress and mangrove swamps, and river and lake swamps. Swamp areas located within the areal extent of the unconfined areas of the UFA were delineated to encompass all contiguous areas of swamp adjacent to the coast (fig. 26). Inland swamp areas also were delineated. Hydrologically, swamps generally are areas where the potentiometric surface of the UFA is at or near land surface. Swamps generally are considered to be discharge areas of the UFA because water drains out of the UFA into the swamps.

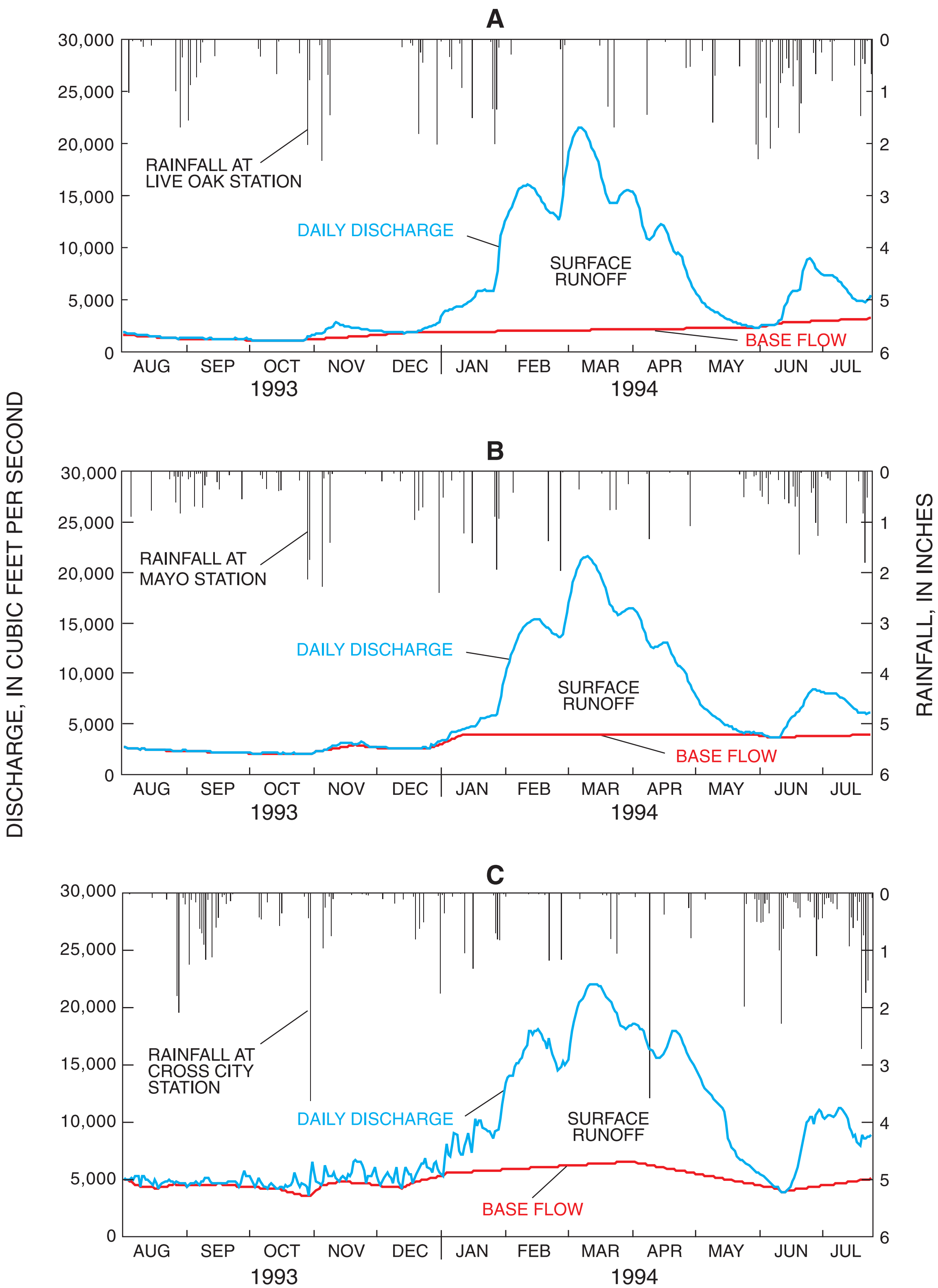


Figure 24. Approximation of base flow and surface runoff from daily recorded discharges at Suwannee River gaging stations (A) 02319500, (B) 02320500, and (C) 02323500 (refer to figure 3 for rainfall station locations and to figure 23 for gaging station locations).

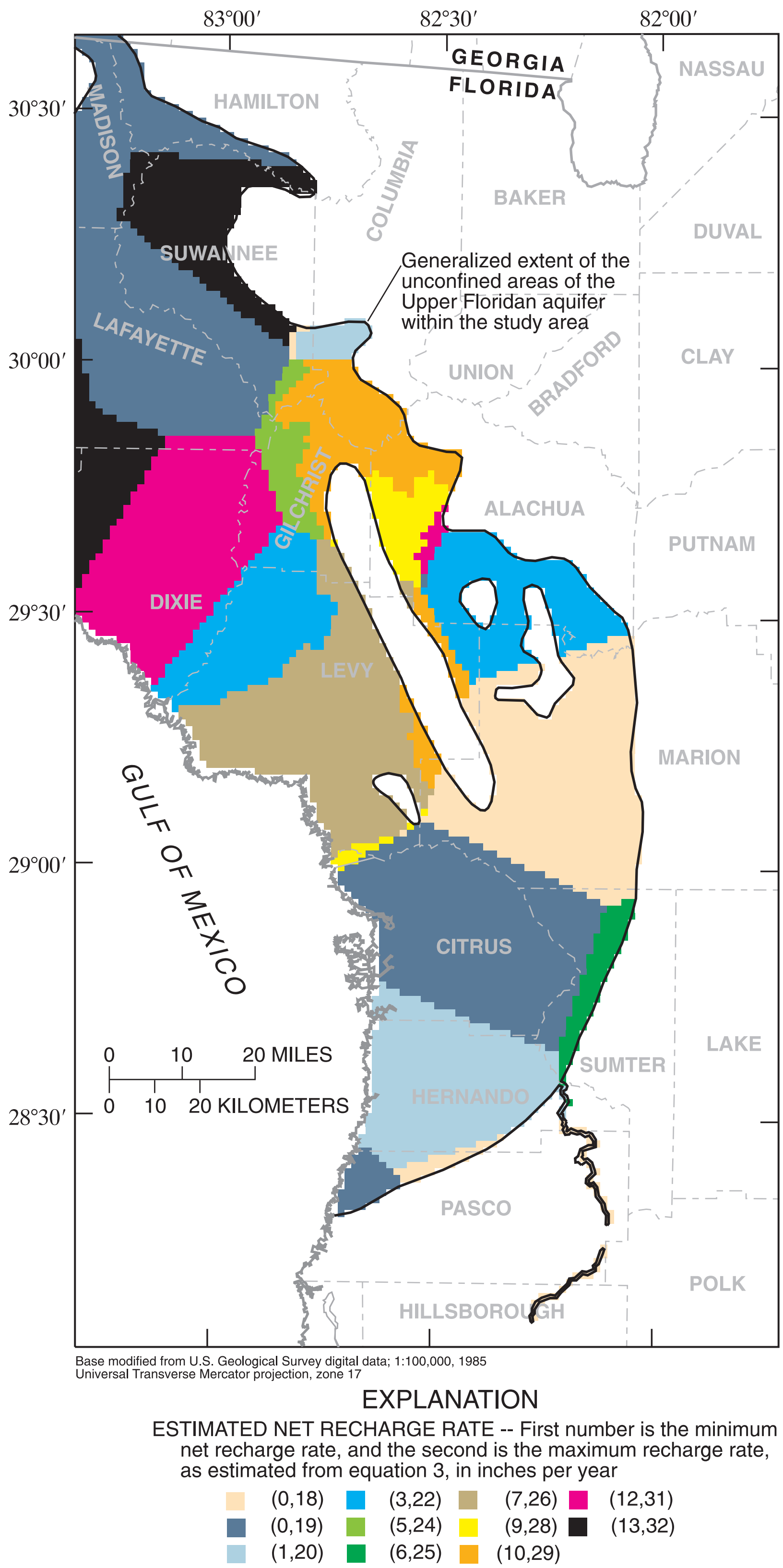


Figure 25. Estimated minimum and maximum net recharge rates in the unconfined areas of the Upper Floridan aquifer.

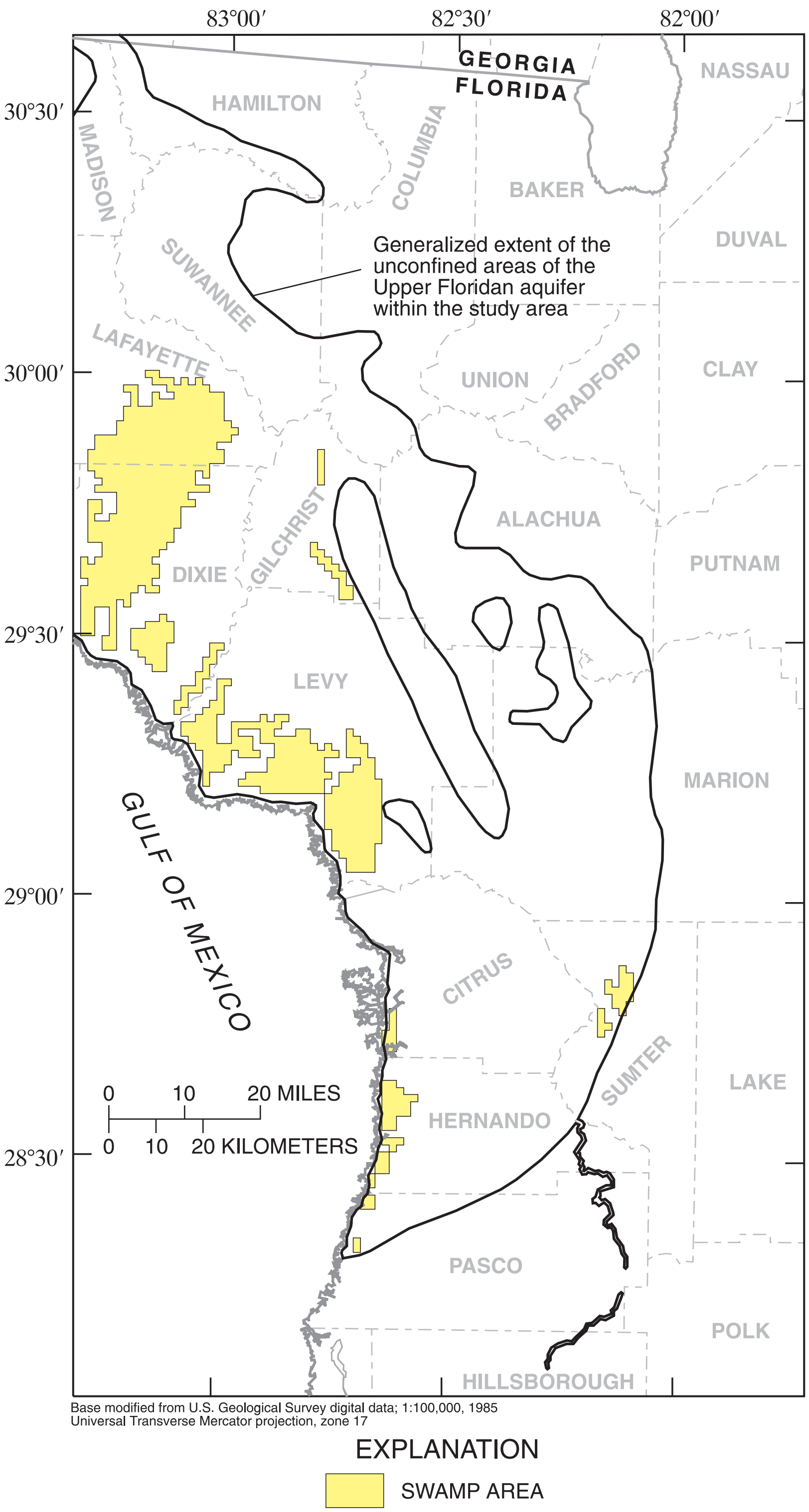


Figure 26. Areal extent of swamps in the unconfined areas of the Upper Floridan aquifer.

SIMULATION OF GROUND-WATER FLOW

A steady-state ground-water flow model of the ground-water flow in the IAS and FAS was constructed and calibrated to time-averaged data for the period August 1993 through July 1994. The rationale for calibrating the model for this time period is explained in this section. Estimates of hydraulic properties obtained from local and regional ground-water flow models (table 1) were integrated with the hydrogeologic data discussed in previous sections. The model was developed using the USGS finite-difference ground-water flow code MODFLOW-96 (Harbaugh and McDonald, 1996). The calibrated model was used to analyze the response of the FAS to projected ground-water withdrawals in 2020.

A uniformly spaced grid of square 5,000-ft cells was used as the framework to discretize the ground-water flow system horizontally. The UTM coordinates of the grid corners given in table 8 facilitate reproduction of the grid. Grid spacing (fig. 27) resulted from the need to use a finer grid resolution than in previous models (table 1). The grid consisted of 300 rows and 210 columns and was oriented along a north-south axis for simplicity because the majority of stresses or boundary conditions were not aligned along any particular axis.

Steady-State Approximation

The program MODFLOW-96 (Harbaugh and McDonald, 1996), used to simulate flow in the FAS, solves the

Table 8. Geographical information system coordinates of the corners of the ground-water flow model grid

[X and Y coordinates refer to Universal Transverse Mercator projection (Snyder, 1983), zone 17]

Grid corner	X coordinate (feet)	Y coordinate (feet)
Upper left	900000	11270000
Upper right	1950000	11270000
Lower right	1950000	9770000
Lower left	900000	9770000

three-dimensional ground-water flow equation using finite-difference approximation and a block-centered grid. The equation solved by MODFLOW-96 can be written, after time averaging, as:

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial \bar{h}}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial \bar{h}}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial \bar{h}}{\partial z}\right)-\overline{W} = S_s\frac{(h_{t_2}-h_{t_1})}{t_2-t_1}, \qquad (4)$$

where

K_{xx}, K_{yy}, K_{zz} are the hydraulic conductivities along the columns, rows, and layers, respectively, in feet per day,

$\bar{h}$ is the average head for the time interval $[t_1, t_2]$, in feet,

$\overline{W}$ is the average flux per unit volume for the time interval $[t_1, t_2]$ and denotes the sink or source of water, in (feet/days)/feet,

S_s is the specific storage of the aquifer, in feet^{-1},

x, y, z are the spatial coordinates, in feet,

t is time, in days, and

t_1, t_2 are times at the beginning and end of the time interval, in days.

The term $\overline{W}$ represents: drainage to springs or swamps; aquifer-river interactions; withdrawals from pumping; recharge from injection or drainage wells; and net recharge rates from rainfall infiltration in the unconfined areas of the UFA.

A steady-state approximation to equation 4 implies that the magnitude of the right-hand side, which also can be written as $S_s\,\Delta h/\Delta t$, is small. The expression $S\,\Delta h/\Delta t$ was evaluated instead of $S_s\,\Delta h/\Delta t$ in order to approximate the product of specific storage and aquifer thickness with a single value. The expression $S\,\Delta h/\Delta t$, used to assess the error introduced in the model by a steady-state approximation, was estimated by using the measured UFA heads at the beginning and at the end of any 1-year interval, and the estimated storage coefficient S for the UFA. Head data from UFA wells from October 1987 to September 1997 were used to evaluate the magnitude of $S\,\Delta h/\Delta t$. Estimates of this value are much smaller in areas where the UFA is confined than in areas where the UFA is unconfined because the storage coefficient of the confined UFA can be two orders of magnitude smaller than the storage coefficient of unconfined areas of the UFA.

The 1-year interval having the smallest RMS water-level difference from the first to the last day of the interval, for 32 wells tapping the unconfined areas of the UFA, was August 1, 1993, through July 31, 1994. The RMS value for this period was 0.71 ft, with a mean of 0.22 ft. This RMS water-level difference amounts to a value of 0.86 in/yr for $S\,\Delta h/\Delta t$, assuming a storage coefficient of 0.10. The RMS water-level difference for the same 1-year period in the IAS and in confined areas of the UFA were 2.46 and 2.15 ft, respectively, both of which resulted in values of approximately 0.03 in/yr for $S\,\Delta h/\Delta t$ assuming a storage coefficient of 0.001 for confined aquifers.

Although head fluctuations during this period (August 1, 1993, through July 31, 1994) were substantial in some wells in unconfined areas of the UFA wells (fig. 28), net head differences ranged from -1.07 to 1.66 ft (table 9). The locations of wells tapping the unconfined areas of the UFA (fig. 16) and the head differences listed in table 9 indicate that positive and negative head differences were uniformly distributed in these areas. It was assumed, based on the relatively small 0.86 in/yr RMS water-level difference in the unconfined areas of the UFA, that for the period from August 1, 1993, through July 31, 1994, the FAS was at steady-state conditions.

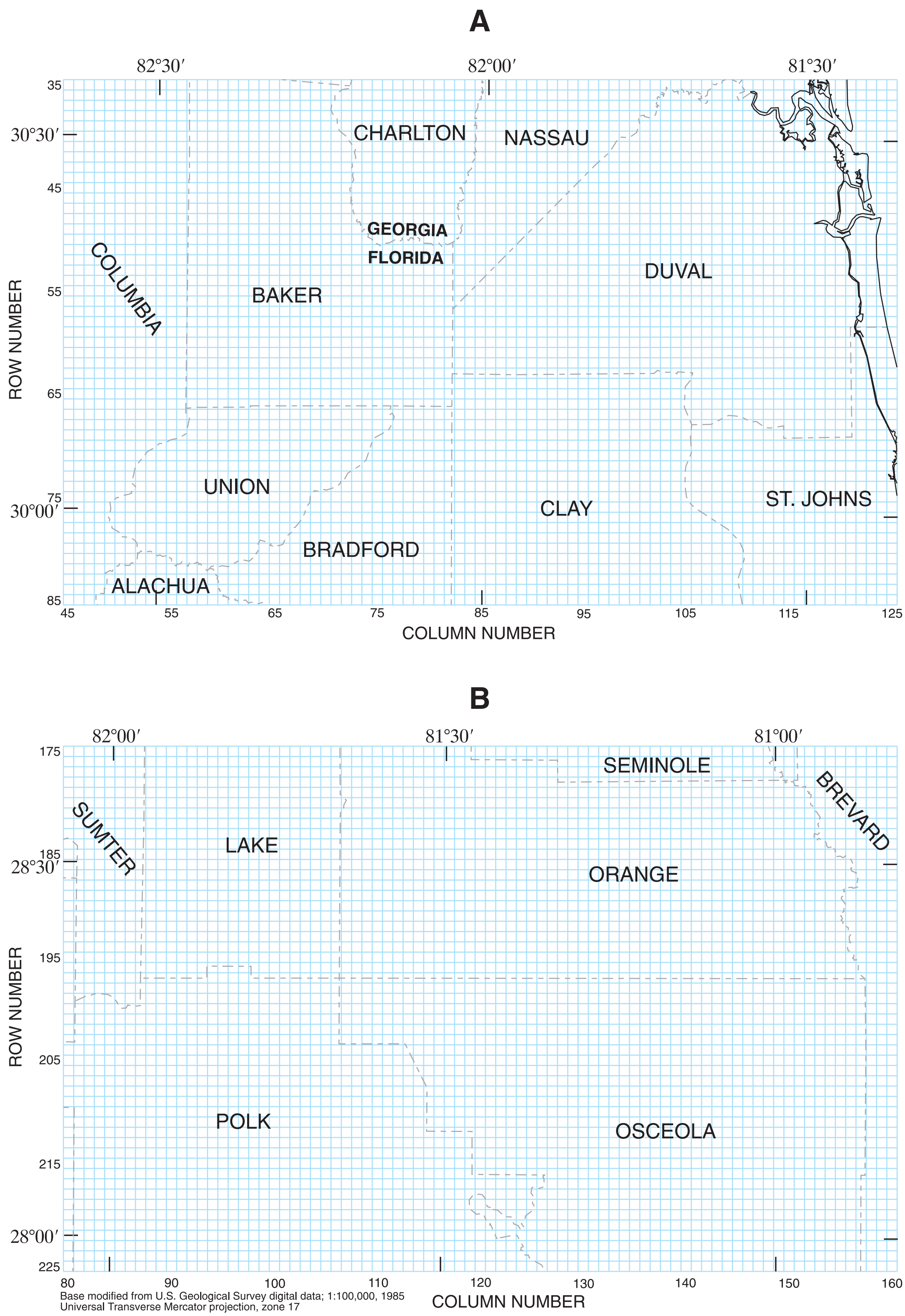


Figure 27. Parts of the uniform grid used to develop the ground-water flow model, shown in the vicinity of (A) Duval and (B) Orange Counties.

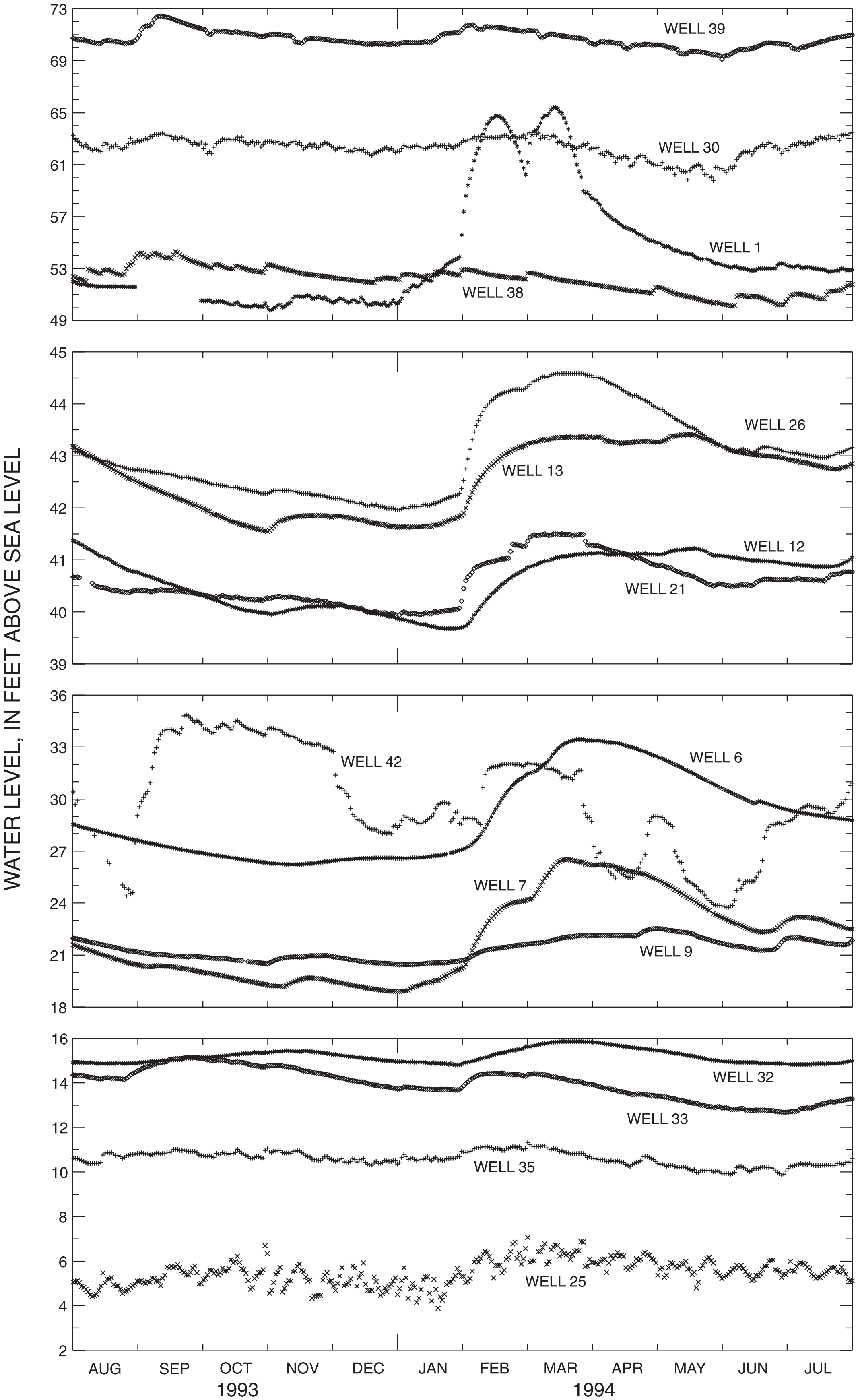


Figure 28. Hydrographs showing water-level fluctuations in wells tapping unconfined areas of the Upper Floridan aquifer (gaps indicate data not available; refer to figure 16 for well locations).

Table 9. Differences in water levels measured at wells tapping the unconfined areas of the Upper Floridan aquifer and equipped with continuous water-level recorders

[Map location number refers to figure 16; --, data not available]

Map location number	Water level (feet above sea level)		Difference (feet)
	August 1, 1993	July 31, 1994	
1	52.00	52.90	0.90
2	24.16	--	--
3	44.60	45.61	1.01
4	25.96	27.18	1.22
5	23.60	25.03	1.43
6	28.54	28.78	.24
7	21.59	22.49	.90
8	33.61	33.57	-.04
9	21.97	21.84	-.13
10	38.71	39.22	.51
11	33.86	35.52	1.66
12	41.37	41.05	-.32
13	43.18	42.85	-.33
14	2.16	3.56	1.40
15	45.14	45.14	.00
16	45.65	46.27	.62
17	43.32	42.89	-.43
18	10.17	9.60	-.57
19	--	4.43	--
20	39.28	38.69	-.59
21	5.05	5.11	.06
22	43.18	43.16	-.02
23	31.87	32.13	.26
24	4.10	4.31	.21
25	6.15	6.71	.56
26	26.63	26.30	-.33
27	5.81	6.20	.39
28	14.90	14.98	.08
29	14.35	13.28	-1.07
30	12.97	12.78	-.19
31	10.62	10.60	-.02
32	14.87	14.04	-.83

Conceptual Model

The regional ground-water flow system was simulated as a quasi three-dimensional ground-water flow model with four layers. A challenging aspect of model development was the synthesis of the layering schemes from the local or regional models into a single regional model (figs. 29-36). The SAS, IAS (or ICU in areas where the IAS is absent), the UFA, and the LFA were designated layers 1 through 4, respectively. The SAS (layer 1) was simulated as a source-sink layer. Confining layers were simulated by using vertical leakance arrays, similar to the approach used in models 1-3, 5-7, and 9-14 (table 1). Model-simulated ground-water flow occurs horizontally within the aquifers and vertically through the confining units.

The IAS (layer 2) in southwest and south-central Florida was simulated as a single active aquifer bounded above and below by arrays of leakance values. Outside the areas where the IAS is a productive aquifer, a 1-ft thick layer was used to simulate the transition of the IAS into areas where this aquifer becomes the ICU. A transmissivity value of 0.01 ft^2/d was used to simulate negligible horizontal flow through the ICU. The combination of this low transmissivity and a vertical leakance between the SAS and the ICU equal to the vertical leakance between the ICU and the UFA allowed the ICU to be simulated as a single confining unit. The transmissivity value of 0.01 ft^2/d does not necessarily represent the hydraulic conductivity of the ICU in the 1-ft thick layer.

Because this model is restricted to simulating the movement of freshwater within the aquifers, areas where the IAS, the UFA, and the LFA (layers 2-4) contain water with chloride concentrations exceeding 5,000 mg/L are considered inactive, thus minimizing potential errors introduced by simulating aquifer areas containing water of variable density. In general, the thickness of the UFA (layer 3) is the difference between the top (fig. 6) and the bottom of the UFA (fig. 7). In areas where chloride concentrations in the UFA are greater than 5,000 mg/L (fig. 19), however, the thickness is assumed to be the difference between the top of the UFA (fig. 6) and the base of freshwater. The effective freshwater thickness of the LFA (layer 4) is the difference between the top of the LFA (fig. 8) and either the altitude at which water with chloride concentrations exceeding 5,000 mg/L occur (fig. 19) or the base of the LFA (fig. 10), whichever is higher. Some offshore areas in the UFA, estimated to have chloride concentrations less than 5,000 mg/L, were considered active areas.

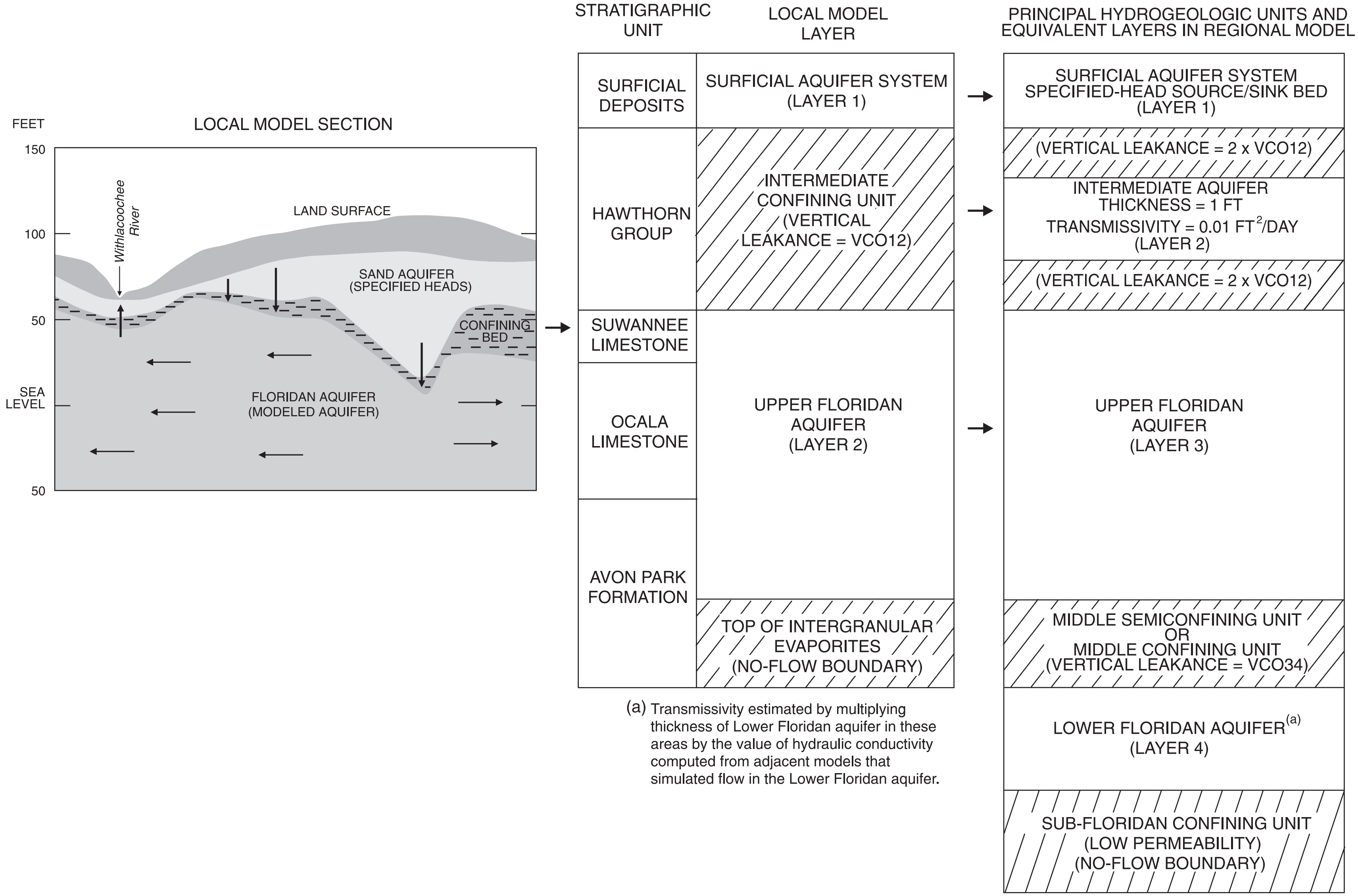


Figure 29. Layering scheme and representation of geologic units in local models 1 and 3, and corresponding layering scheme in the regional model (refer to table 1 for model numbers).

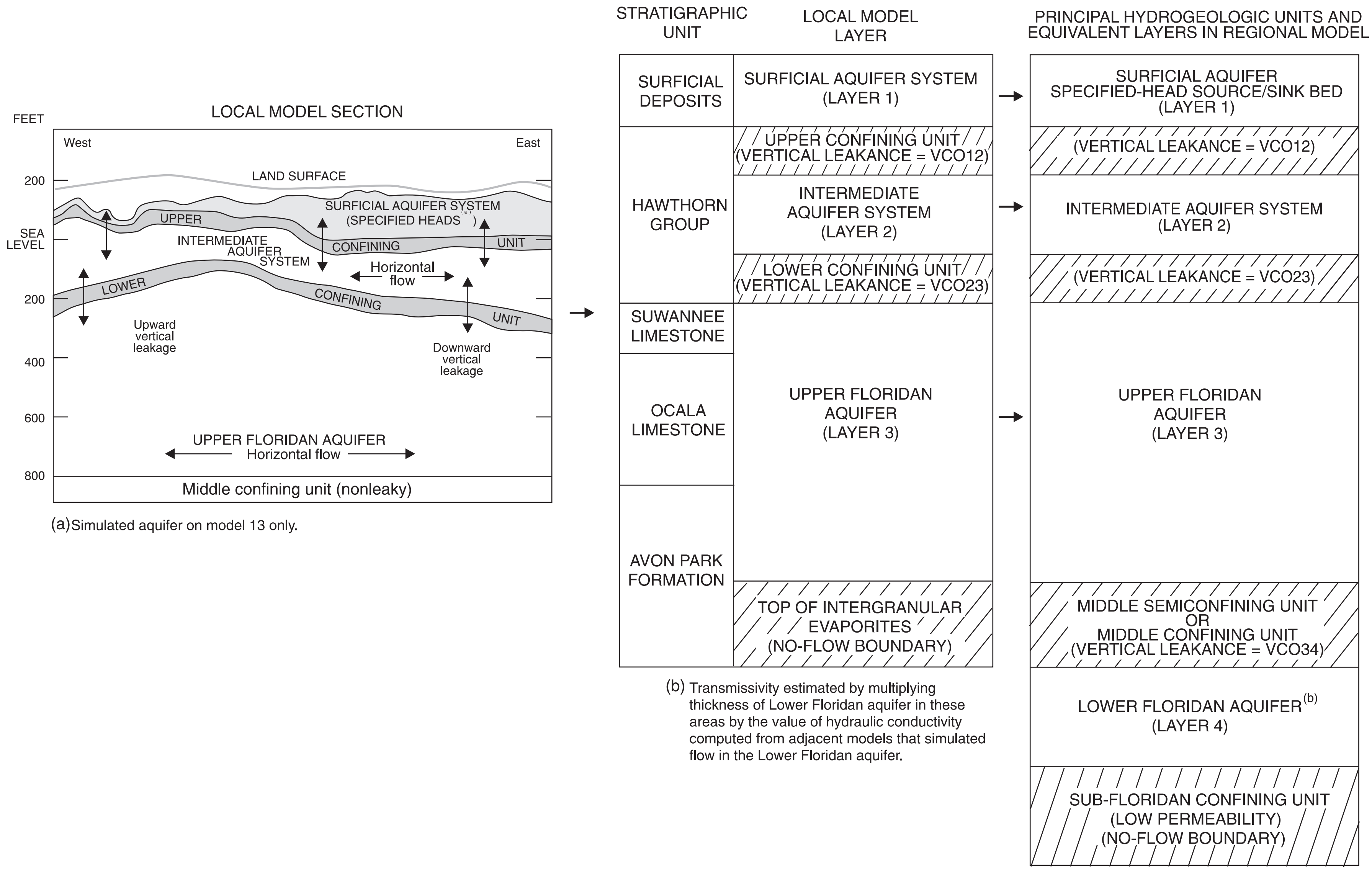


Figure 30. Layering scheme and representation of geologic units in local models 2, 7, 10, and 13, and corresponding layering scheme in the regional model (refer to table 1 for model numbers).

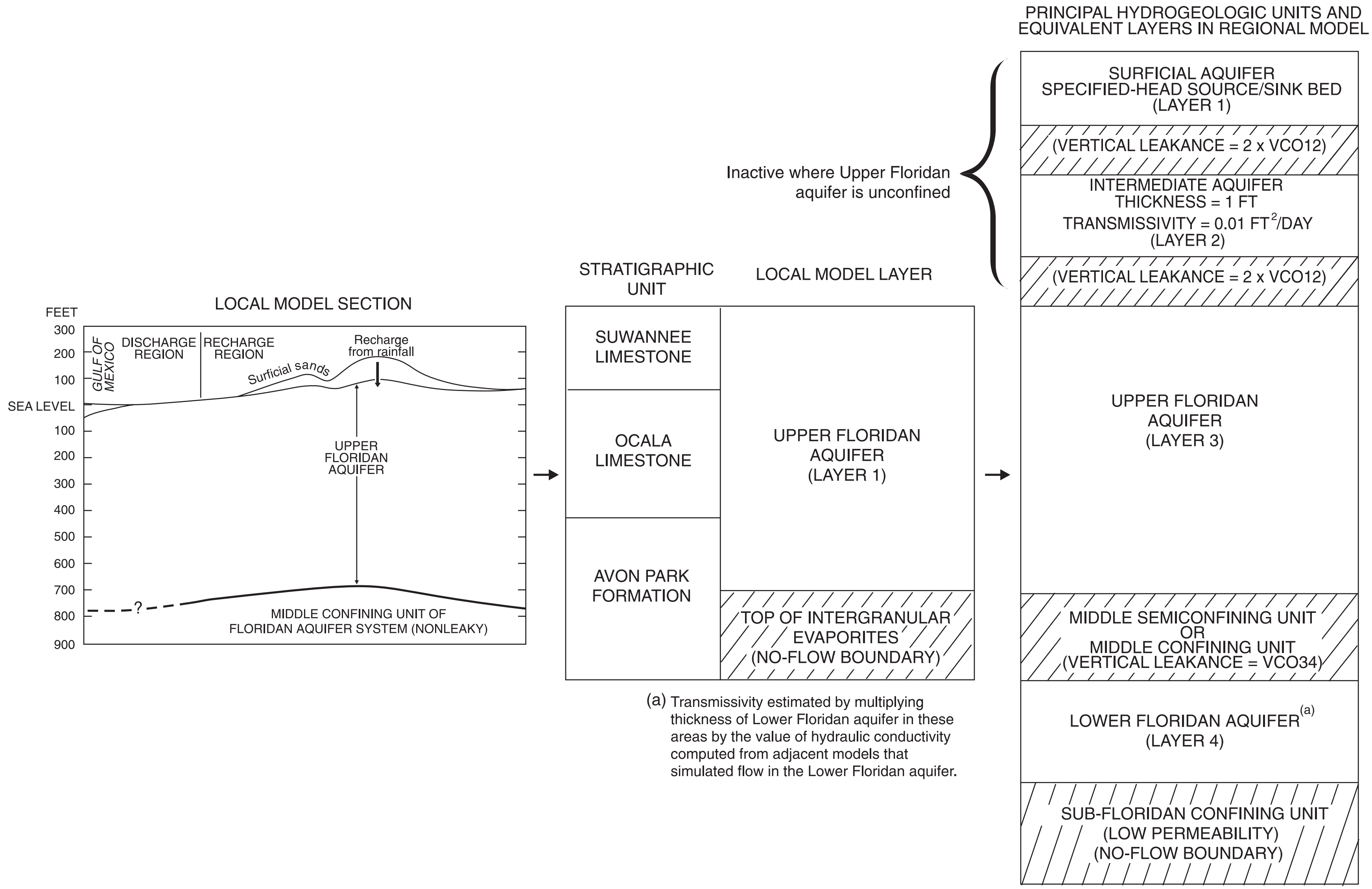


Figure 31. Layering scheme and representation of geologic units in local models 4 and 8, and corresponding layering scheme in the regional model (refer to table 1 for model numbers).

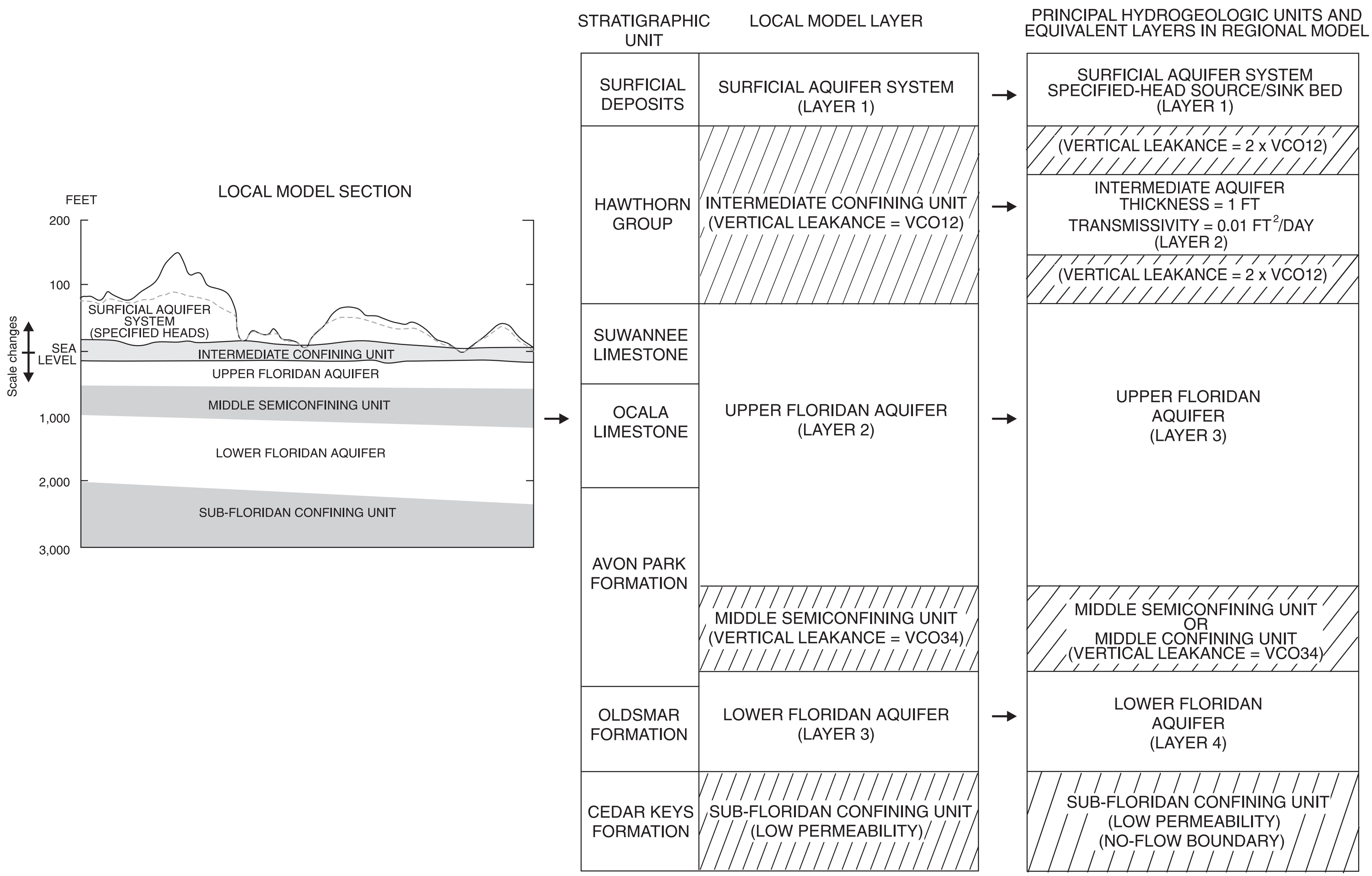


Figure 32. Layering scheme and representation of geologic units in local models 5 and 12, and corresponding layering scheme in the regional model (refer to table 1 for model numbers).

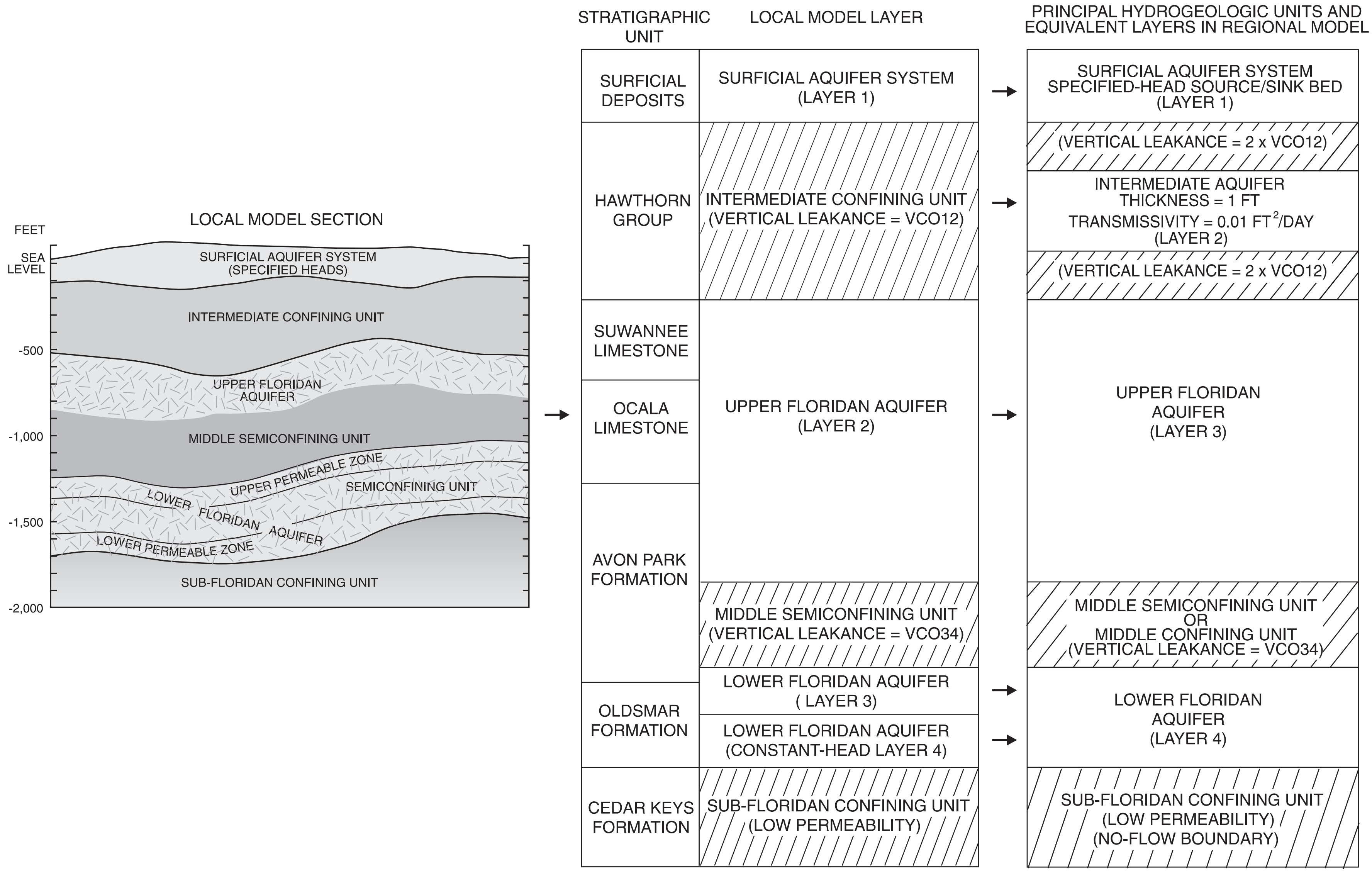


Figure 33. Layering scheme and representation of geologic units in local model 6, and corresponding layering scheme in the regional model (refer to table 1 for model number).

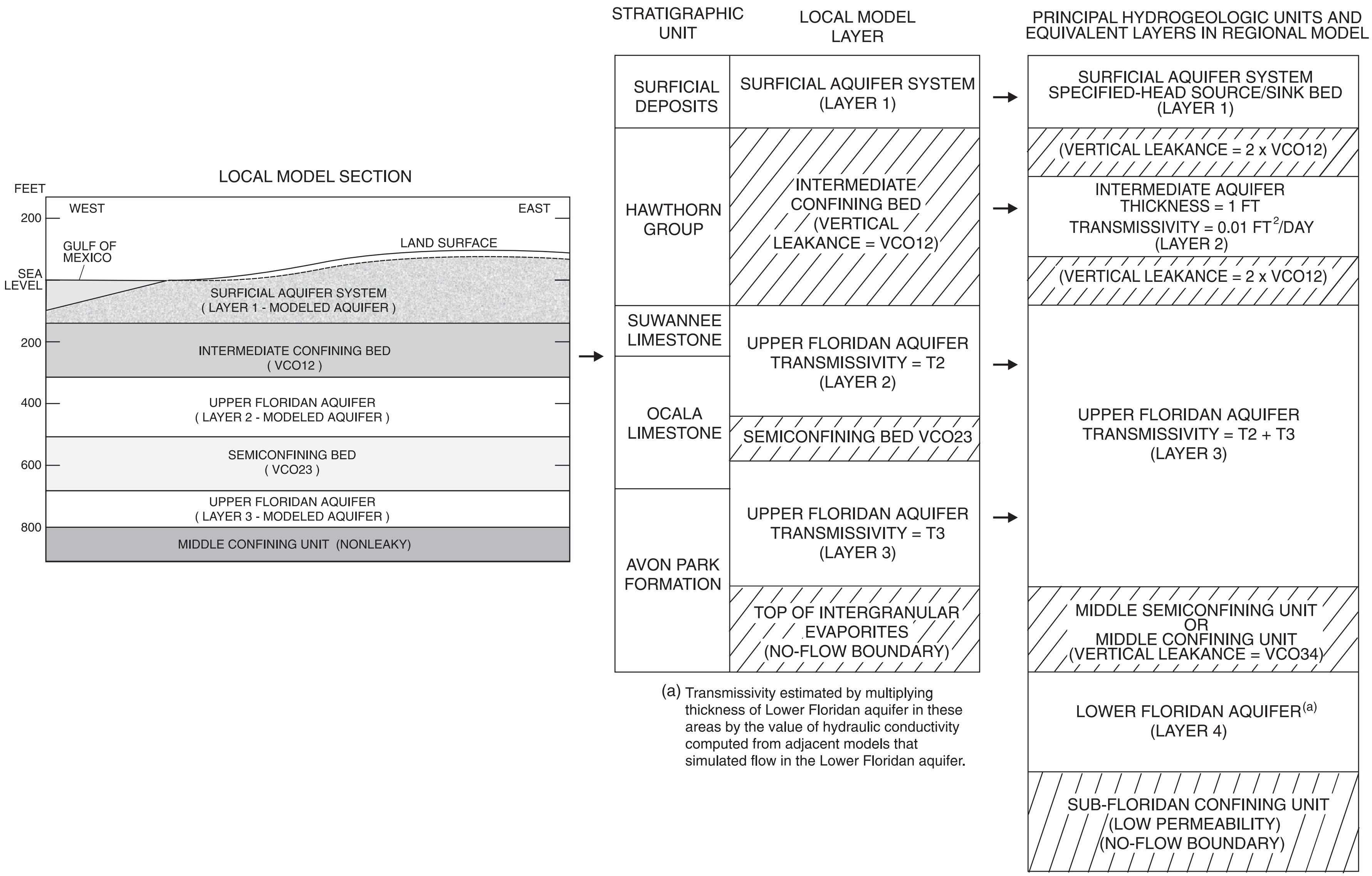


Figure 34. Layering scheme and representation of geologic units in local model 9, and corresponding layering scheme in the regional model (refer to table 1 for model number).

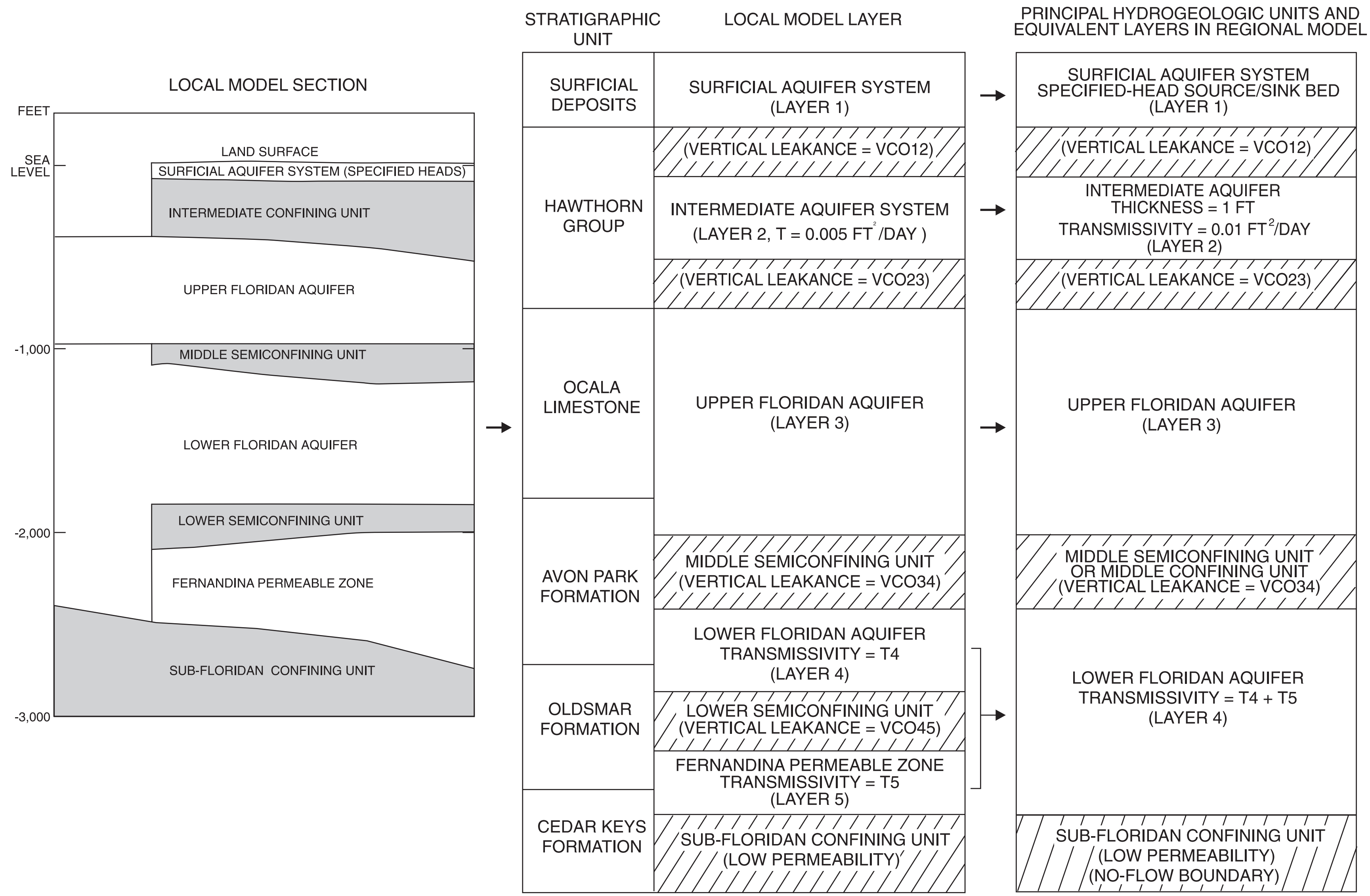


Figure 35. Layering scheme and representation of geologic units in local model 11, and corresponding layering scheme in the regional model (refer to table 1 for model number).

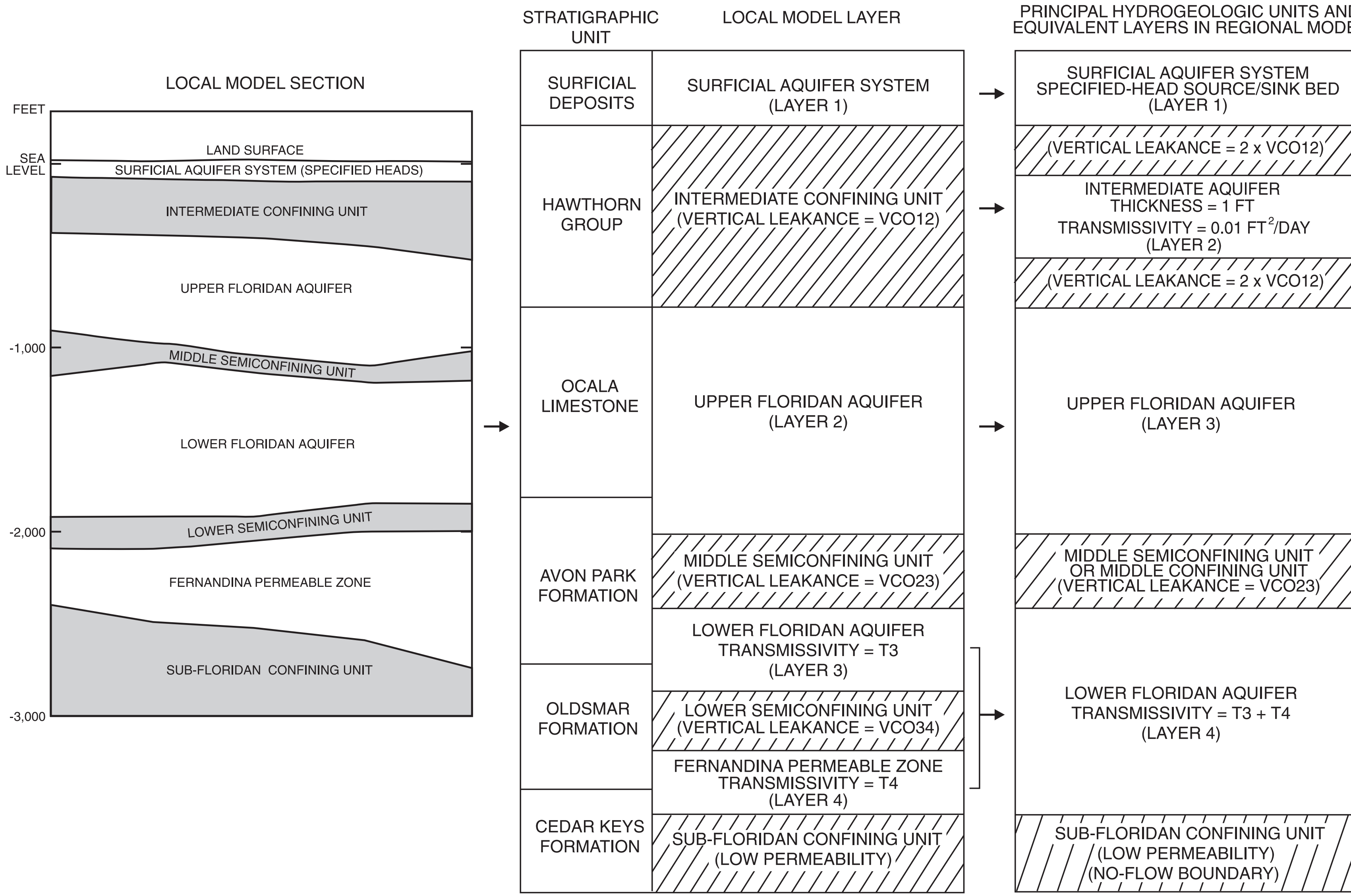


Figure 36. Layering scheme and representation of geologic units in local model 14, and corresponding layering scheme in the regional model (refer to table 1 for model number).

In offshore areas, water is discharged from the UFA to the SAS, which was simulated with a water table equal to the equivalent freshwater head of the sea water column. The saltwater part of the FAS was not included in the model because the interface is relatively sharp and movement of the interface is assumed to have little or no effect on simulated heads (fig. 9). The assumption was made that a sharp freshwater-saltwater interface occurs laterally and that flow across this interface is negligible. This sharp interface determined which model areas were considered inactive.

Recharge to or discharge from the IAS is assumed to occur through the upper or lower confining units of the IAS. Physiographic regions identified as ridges are simulated with higher leakance values than plains and valley because confining units along ridges are thinner and more permeable. As a result, leakage rates along Lake Wales Ridge, DeLand Ridge, Orlando Ridge, and Crescent City Ridge are higher than those of the Osceola Plain or De Soto Plain (fig. 2). Flow entering or leaving the IAS across the southern or western boundaries of the model is simulated by the difference in hydraulic heads between the IAS and UFA and the vertical leakance of the confining units. Flow entering or leaving the IAS through the northern or eastern boundaries is determined by the water exchanges between the IAS and ICU along these boundaries.

The MCU was represented by vertical leakance values that limit water exchange between the UFA (layer 3) and the LFA (layer 4) in west-central and southwest Florida, and in the northwest part of the study area to a greater degree than in areas where the MSCU is present (fig. 9). However, the rate of water exchange between the UFA and LFA in areas where the MCU is present should not be zero, as suggested by Hickey (1990). The MSCU in east-central, southeast, and northeast Florida was represented by an array of vertical leakance values that allows water exchange between the UFA and the LFA. In areas where no MSCU or MCU is present, the vertical exchange of water between the UFA and the LFA was simulated at a rate that depends on the vertical hydraulic conductivity of the two aquifers, which was assumed to be proportional to the horizontal hydraulic conductivity of the aquifers.

The River, Drain, and Recharge packages (Harbaugh and McDonald, 1996) were used in this ground-water flow model. The River package was used to simulate the discharge of water to and from rivers in unconfined areas of the UFA (fig. 23). The discharge of ground water to swamps in unconfined areas of the UFA (fig. 26) and the flow from UFA springs located outside river cells were simulated by using the Drain package. Flow from springs was simulated as discharge to drain cells using the measured or estimated spring pool altitude as the drain elevation. Flow from UFA springs located in river cells was simulated as the base flow of the river at the respective river cells. The net recharge rates to unconfined areas of the UFA were assigned using the Recharge package.

The solution of the ground-water flow equation (eq. 4) allows areal variations in transmissivity to simulate regional heterogeneities. No estimates of anisotropy were available, however, so a lateral anisotropy ratio of 1:1 was assumed.

Boundary Conditions

Model boundaries were assigned to approximate the true ground-water flow system as accurately as possible. The SAS (layer 1) was simulated as a layer of constant heads. This allows the UFA to discharge to the SAS or to receive leakage from the SAS at rates dictated by the relative difference in head between the water table and the UFA and the vertical leakance of the ICU in areas where this unit exists. The altitude of the water table was used to define these constant heads. A no-flow boundary condition was applied along all lateral boundaries of layer 2 (the IAS or ICU). Flow entering or leaving cells in layer 2 is assumed to occur as either horizontal flow to neighboring cells or vertical flow to either the SAS (layer 1) or the UFA (layer 3).

Lateral boundary conditions for the UFA (layer 3) and the LFA (layer 4) were either no-flow or specified-head. For the UFA (layer 3), a combination of no-flow and specified-head boundaries were used. Along the Gulf of Mexico in Citrus, Hernando, and Pasco Counties, most of the lateral flow in the UFA is assumed to be discharged by numerous springs. Based on this observation, no-flow conditions were applied to the boundary of layer 3 in those areas (fig. 37). For the LFA (layer 4) no-flow conditions were applied along all lateral boundaries. The eastern and western boundaries of the LFA coincided with the location at which the chloride concentration in the LFA exceeds 5,000 mg/L. Specified heads in the UFA along the northeastern boundary of the model, from about 70 mi offshore from Camden County, Ga., to about 20 mi offshore from St. Johns County (fig. 37), were set equal to the equivalent freshwater head. The application of this boundary condition limits water exchange between the simulated SAS and the UFA along these boundary cells. Specified heads, interpolated or extrapolated from the 1993-94 potentiometric surface of the UFA, were assigned to the remaining lateral boundaries of the UFA.

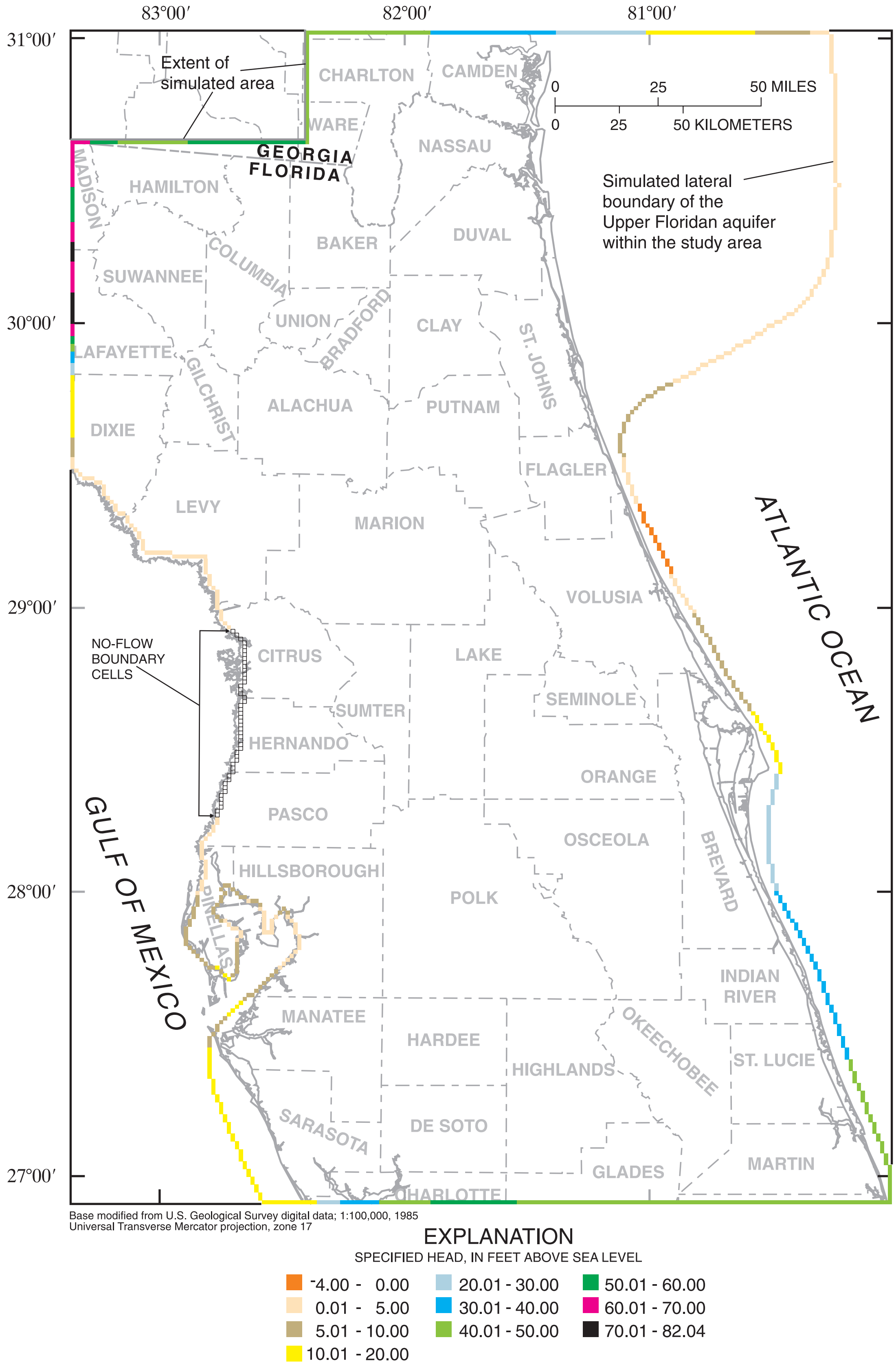


Figure 37. Specified heads along the lateral boundary cells of the Upper Floridan aquifer.

Recharge and Discharge

Total discharge from the UFA as spring flow for average 1993-94 conditions was estimated to be approximately 4,130 Mgal/d (appendix C). Additional discharge, in the form of ground-water withdrawals from the IAS, UFA, and LFA for the 1993-94 time period, was estimated to be approximately 2,490 Mgal/d (tables 4 and 5). These withdrawals were applied to the corresponding model cells of their respective aquifers, and the resulting areal distributions are shown in figures 38 through 40. Ground-water withdrawals from the IAS exceeded 0.5 Mgal/d in grid cells in Charlotte, De Soto, Highlands, and Sarasota Counties (fig. 38). Ground-water withdrawals from the UFA exceeded 5 Mgal/d in grid cells in Alachua, Hamilton, Hernando, Hillsborough, Lake, Manatee, Marion, Nassau, Orange, Pasco, Pinellas, and Polk Counties, and in Camden County, Ga (fig. 39). The largest ground-water withdrawals (greater than 5 Mgal/d) from the LFA were in Orange and Duval Counties (fig. 40).

Artificial recharge to the UFA occurs through drainage and injection wells and rapid-infiltration basins. Drainage and injection wells (fig. 21) were simulated as recharge wells at the respective cell locations of the various wells. Recharge rates from drainage and injection wells to the UFA (layer 3) were highest in Orange County (fig. 39). Rapid-infiltration basins were simulated by increased leakance values of the ICU rather than directly applied recharge or injection wells to the UFA.

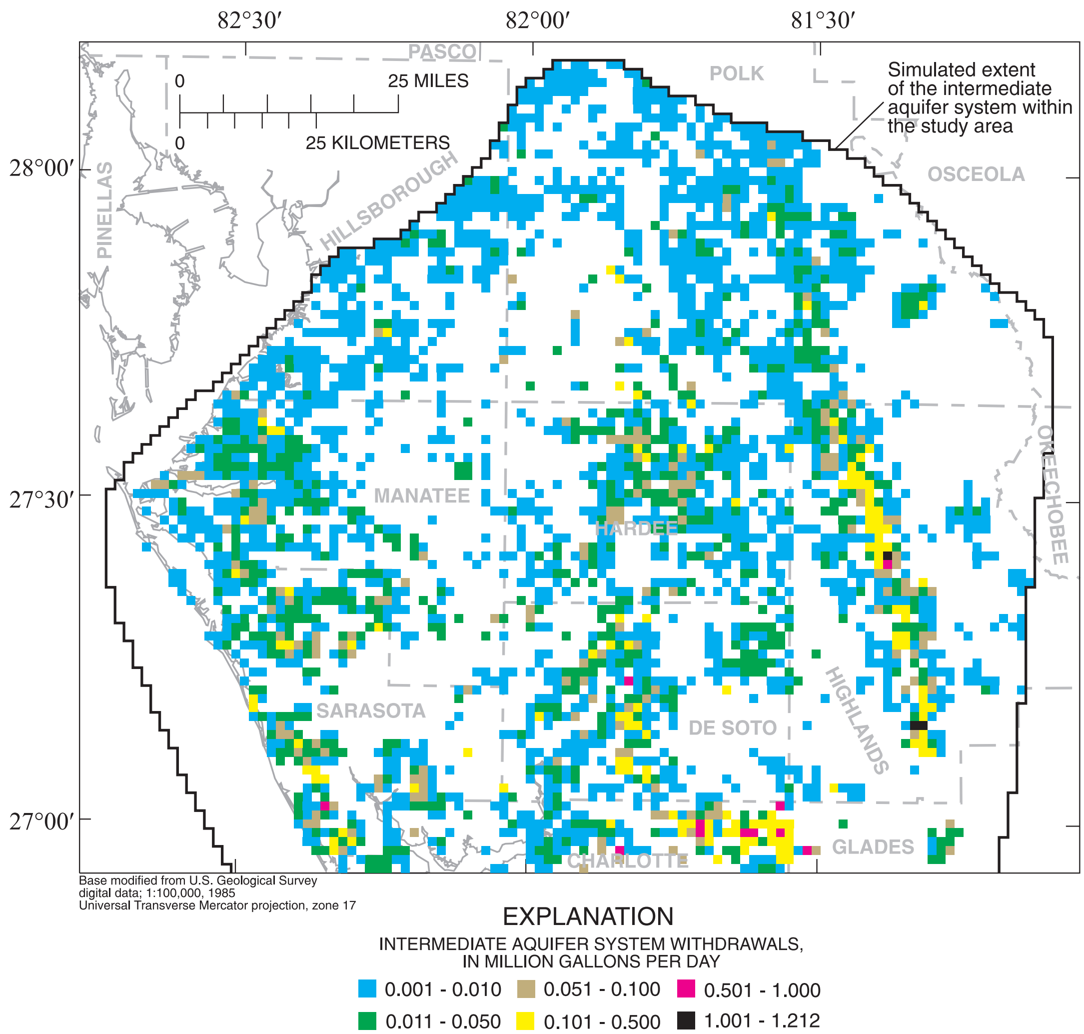


Figure 38. Average ground-water withdrawal rates from the intermediate aquifer system, August 1993 through July 1994.

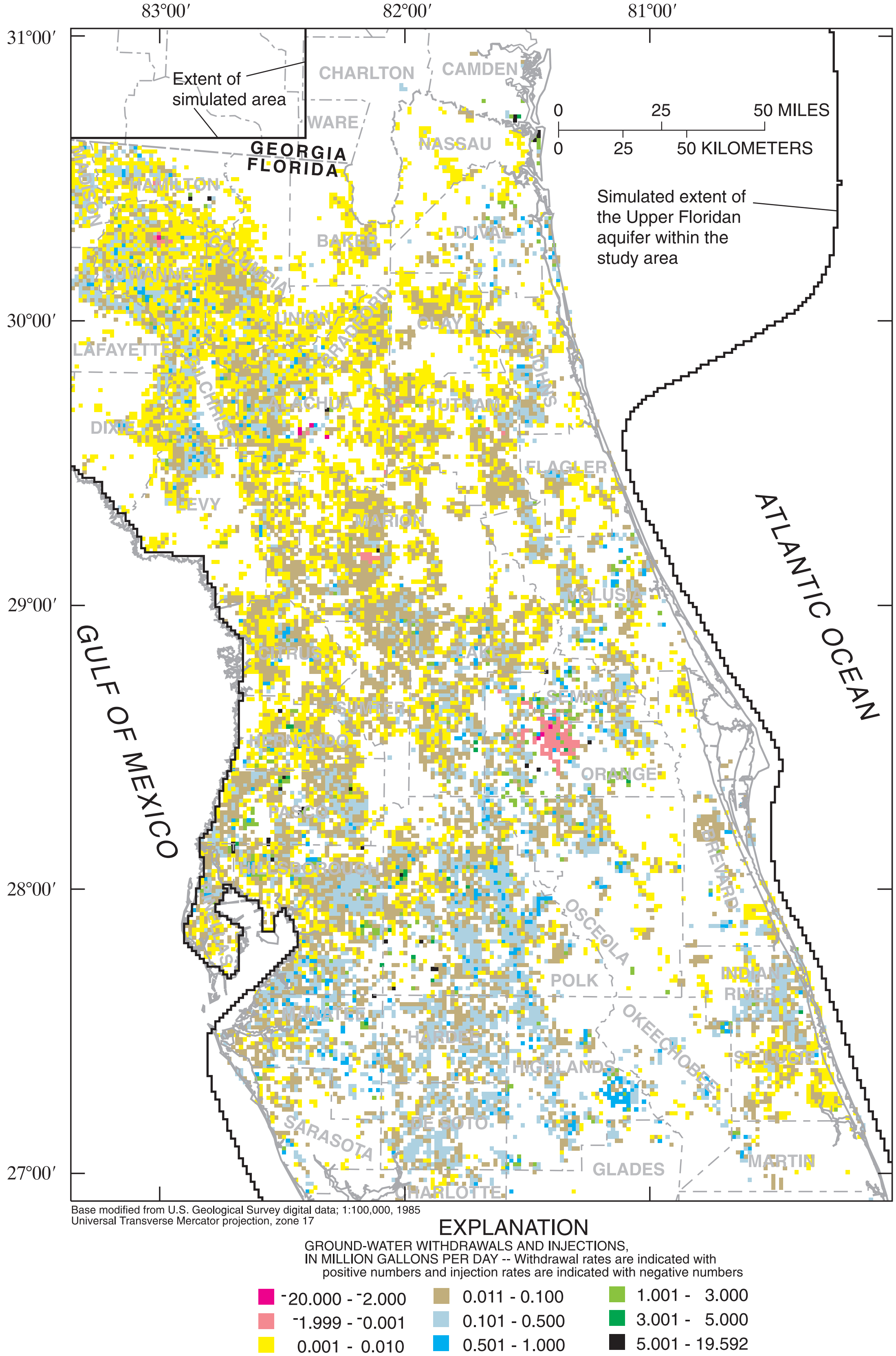


Figure 39. Average ground-water withdrawal rates from and injection rates to the Upper Floridan aquifer, August 1993 through July 1994.

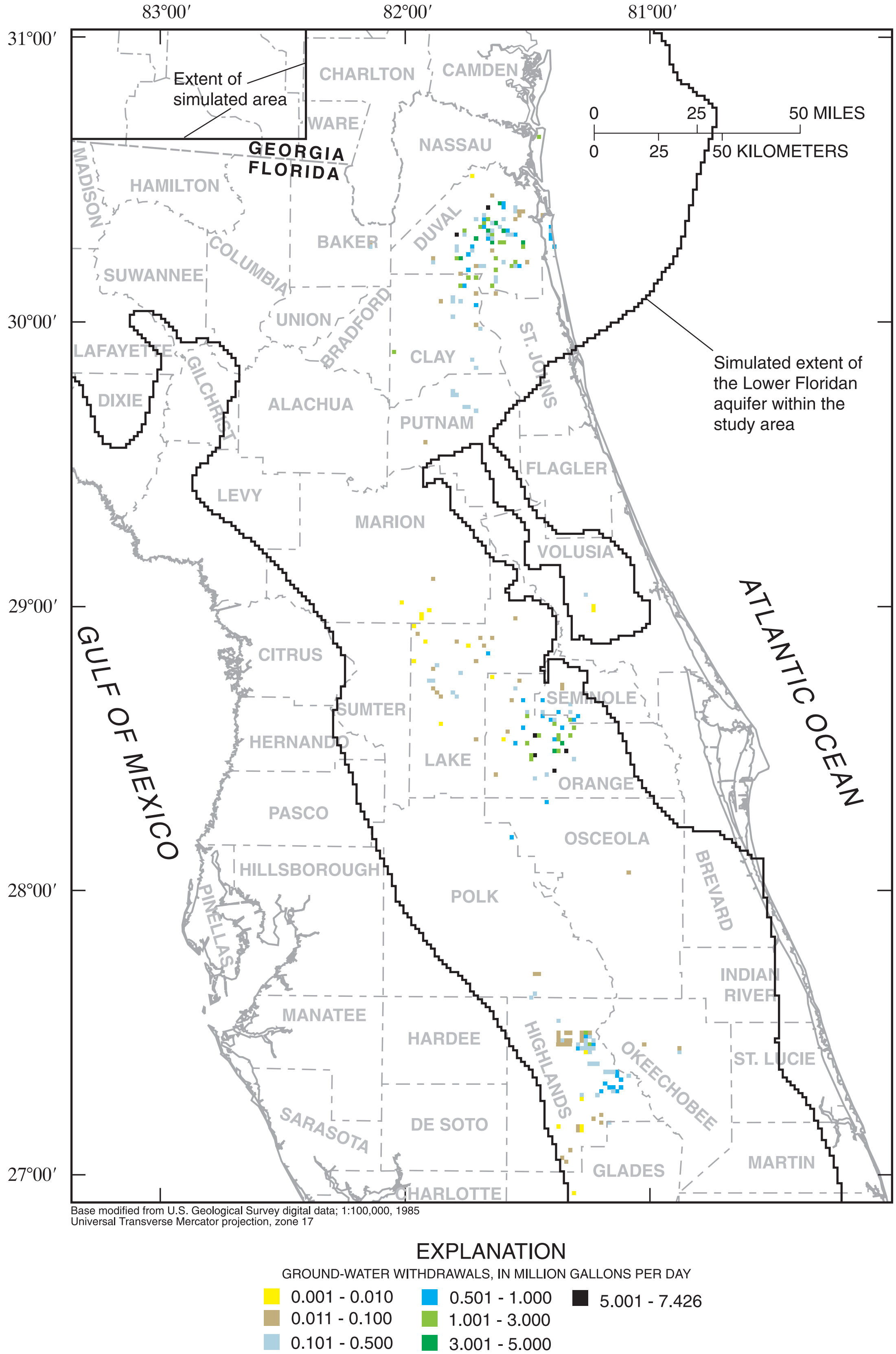


Figure 40. Average ground-water withdrawal rates from the Lower Floridan aquifer, August 1993 through July 1994.

Initial Distribution of Hydraulic Properties from Local Models

The initial estimate of transmissivity and leakance values for the model area was obtained from the previously calibrated local models (table 1). The model grid developed in this study (fig. 27), referred to as the "regional model grid," was used as a framework for storing and analyzing transmissivity and leakance values obtained from the local models. The data set of all transmissivity and leakance values from local models was used to generate the initial distribution of these properties and to identify areas of discrepancy where model areas overlap.

The initial distribution of transmissivity and leakance values for the regional model was obtained from local models by overlaying the set of center points and model grid cells of both the regional model and the local models. The center points of the regional model grid cells were intersected with the local model grid cells; transmissivity and leakance assigned by the local models at the center points of the regional model grid were stored in corresponding regional grid cells. In addition, center points of the local model grid cells were intersected with the regional model grid cells; transmissivity and leakance values assigned by the local models at the center points of the local model grid cells also were stored in the corresponding regional grid cells.

Transmissivity of the UFA and leakance values of the ICU from local models 1 and 3 (appendix A2, fig. 29) were stored in the regional model grid. Leakance values for the ICU in the regional model in the areas of local models 1 and 3 were computed by multiplying by 2 the leakance from those models. A factor of 2 was used because the true vertical thickness of the ICU was divided into two units of equal thickness (an upper unit between the SAS and the ICU and a lower unit between the ICU and the UFA). The equivalent leakance of each unit is twice the total leakance of the ICU based on the definition of vertical leakance. The resulting value was applied as the leakance between the SAS and ICU and between the ICU and UFA. This process was repeated in all models that simulate vertical leakance of the ICU. Consequently, the vertical leakance of the ICU in areas outside the IAS, to be used in areas where there is no IAS, should be equal to one-half the simulated vertical leakance in the regional model.

Transmissivity of the IAS and UFA and leakance of the upper and lower confining units of the IAS from local models 2, 7, 10, and 13 (appendixes A1 and A2; fig. 30) were stored in the regional model grid. Transmissivity of the LFA in these areas, as well as in all areas where flow in the LFA was actively simulated in the regional model but not in the local models, was calculated by multiplying the estimated thickness of the LFA (figs. 8 and 10) by the value of hydraulic conductivity computed from adjacent models.

Transmissivity values for the UFA in west-central Florida, as well as directly applied net recharge rates to the UFA, were the hydraulic parameters from local models 4 and 8 (appendix A2, fig. 31) stored in the regional model grid. Directly applied net recharge rates to the UFA were bracketed by the ranges shown in figure 25.

Transmissivity values for the UFA and LFA and leakance of the ICU and MSCU in east-central Florida were the hydraulic properties from local models 5 and 12 (fig. 32) that were stored in the regional model grid. The main difference between the layering schemes of models 5 and 12, compared to model 6, was that model 6 simulated the LFA with two layers, the lower of which was a constant-head layer (fig. 33).

Transmissivity values for the UFA and leakance of the ICU were the hydraulic properties from local model 9 that were stored in the regional model grid (fig. 34). The transmissivity values of the UFA in the area encompassed by model 9 were the sum of the model-derived transmissivities for layers 2 and 3 (fig. 34). A study of the simulated hydraulic gradients between layers 2 and 3 of the UFA in model 9 found these gradients to be minimal (Hancock and Basso, 1993; Sepúlveda, 2001); accordingly, layers 2 and 3 were treated in the regional model as a single layer and the assigned leakance between layers 2 and 3 was not used for this study.

The hydraulic properties from local models 11 and 14 stored in the regional model grid were transmissivity of the UFA and LFA, and leakance from the ICU and the MSCU (figs. 35 and 36). The areal extent of the IAS in north-central Florida was simulated in the regional model as part of the ICU because the simulated transmissivity in local model 11 for the IAS (Motz, 1995) was characteristic of a confining unit. The simulation of the IAS in model 11 coincides with areas where the ICU is present (appendix A1). The transmissivity of the FPZ simulated in models 11 and 14 was added to the transmissivity of the LFA only in areas where this zone contains water with chloride concentrations less than 5,000 mg/L; otherwise, the FPZ was excluded from the simulation area (figs. 35 and 36). The main difference between the layering schemes of models 11 and 14 was that model 11 simulated the IAS in parts of north-central Florida as a separate layer, whereas model 14 simulated only the ICU (with vertical leakance) because the IAS is absent in northeast Florida.

A regional model grid cell, in an area of overlapping local models, for which the transmissivity of the IAS, UFA, or LFA in a local model was either less than one-half or greater than twice the resulting geometric mean of transmissivities from local models, was designated as a cell with a transmissivity discrepancy. The geometric mean was assumed to give a better estimate of the true mean in heterogeneous media than the arithmetic or harmonic mean (Bouwer, 1978, p. 133). Areas of transmissivity discrepancy in the IAS were found mainly in parts of Charlotte, De Soto, Polk, Manatee, Hardee, and Sarasota Counties (fig. 41). Areas of transmissivity discrepancy in the UFA were mostly in parts of Marion, Hernando, Lake, Orange, Hillsborough, Hardee, Highlands, Okeechobee, Indian River, and St. Lucie Counties (fig. 42). Areas of transmissivity discrepancy in the LFA were mostly in parts of Alachua, Clay, St. Johns, Putnam, Marion, and Orange Counties (fig. 43).

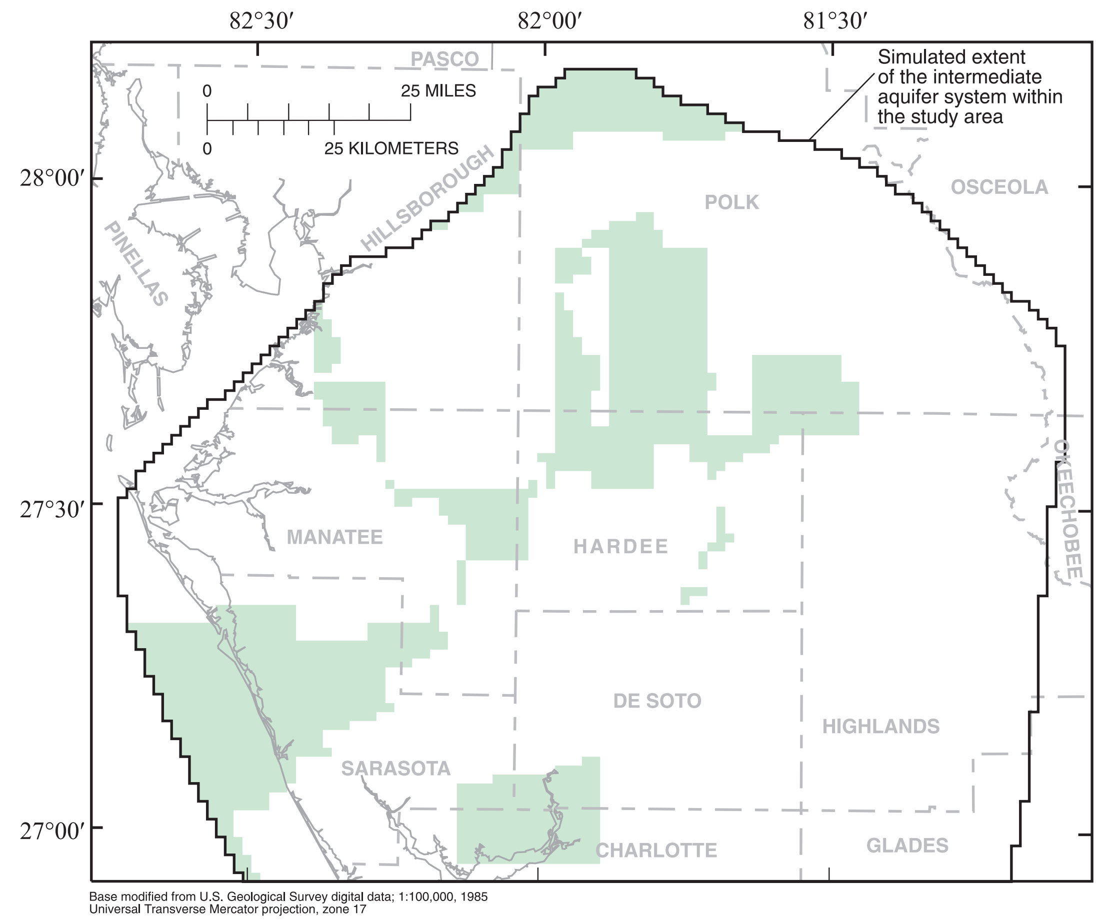


Figure 41. Cells where transmissivity of the intermediate aquifer system in some local models is either less than one-half or greater than twice the geometric mean of all transmissivities for the same cell.

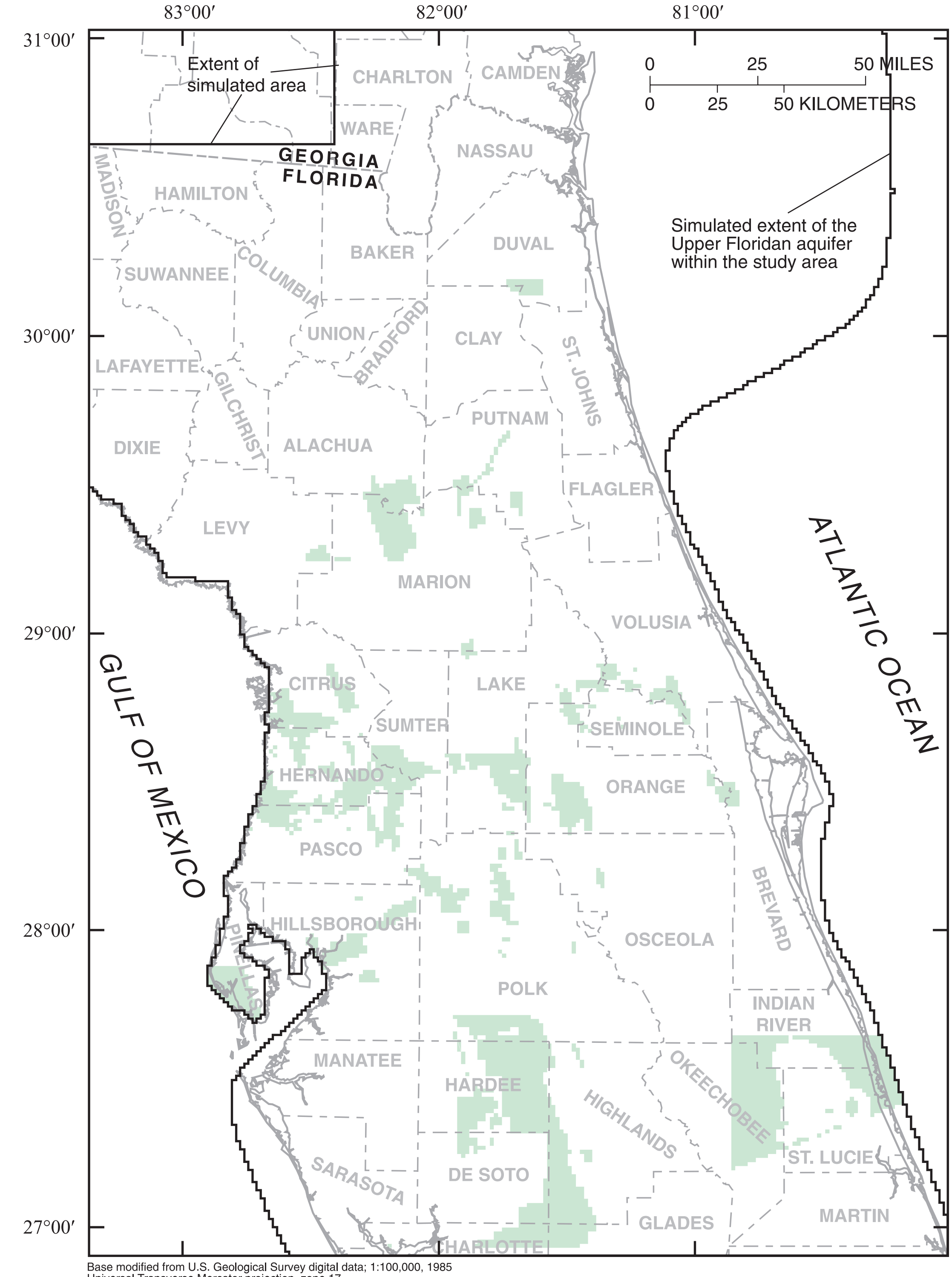
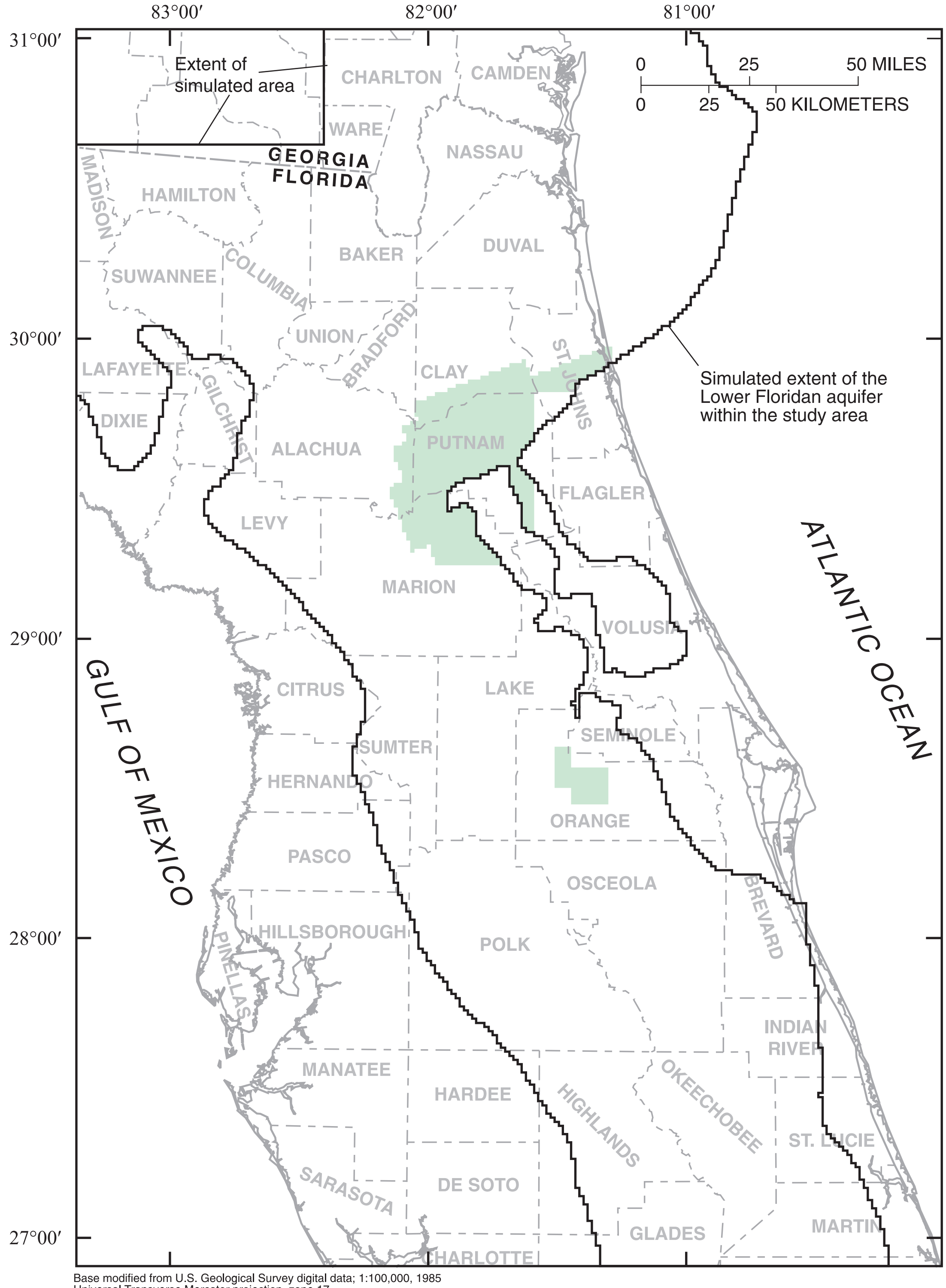


Figure 42. Cells where transmissivity of the Upper Floridan aquifer in some local models is either less than one-half or greater than twice the geometric mean of all transmissivities for the same cell.



Base modified from U.S. Geological Survey digital data; 1:100,000, 1985
Universal Transverse Mercator projection, zone 17

Figure 43. Cells where transmissivity of the Lower Floridan aquifer in some local models is either less than one-half or greater than twice the geometric mean of all transmissivities for the same cell.

A regional model grid cell, in an area of overlapping local models, for which the leakance of the upper or lower confining units of the IAS, the ICU, or the MSCU in a local model was not within one order of magnitude of the resulting geometric mean of leakances from local models, was designated as a cell with a leakance discrepancy. Areas of leakance discrepancy in the upper confining unit of the IAS were mostly in parts of Manatee, Hardee, and Highlands Counties (fig. 44). Areas of discrepancy in the ICU were mainly in parts of Clay, Putnam, Marion, Lake, Polk, Hardee, and Highlands Counties (fig. 45). Areas of discrepancy in the MSCU were mostly in parts of Clay, St. Johns, Orange, Indian River, Okeechobee, and St. Lucie Counties (fig. 46).

In cases where more than one transmissivity or leakance value occurred in any of the regional grid cells (in areas of overlap of the local models), the set of parameters from the local model that resulted in smaller differences between simulated and measured water levels was used to generate the initial distribution of transmissivity and leakance values. The following preferential order of local models was used to assign transmissivity and leakance in model overlap areas: 14, 11, 12, 13, 10, 7, 4, 9, 3, 1, 6, 5, 2, and 8. Initial estimates for transmissivity and leakance in areas outside the boundaries of these local models but inside the regional model area were estimated by extrapolation of data and were further refined during calibration.

Initial estimates of transmissivity for the IAS were obtained from local models 1, 7, 10, and 13, whereas initial estimates of the leakance of the upper confining unit of the IAS were obtained from models 1, 5, 7, 10, and 13. These initial estimates were refined during calibration. The differences between the lateral extent of models 2 and 7 along the Gulf of Mexico and the simulated extent of the IAS shown in appendix A1 can be attributed to excluding from simulation those areas in the IAS with a simulated transmissivity in model 7 of less than 1 ft^2/d (Barcelo and Basso, 1993).

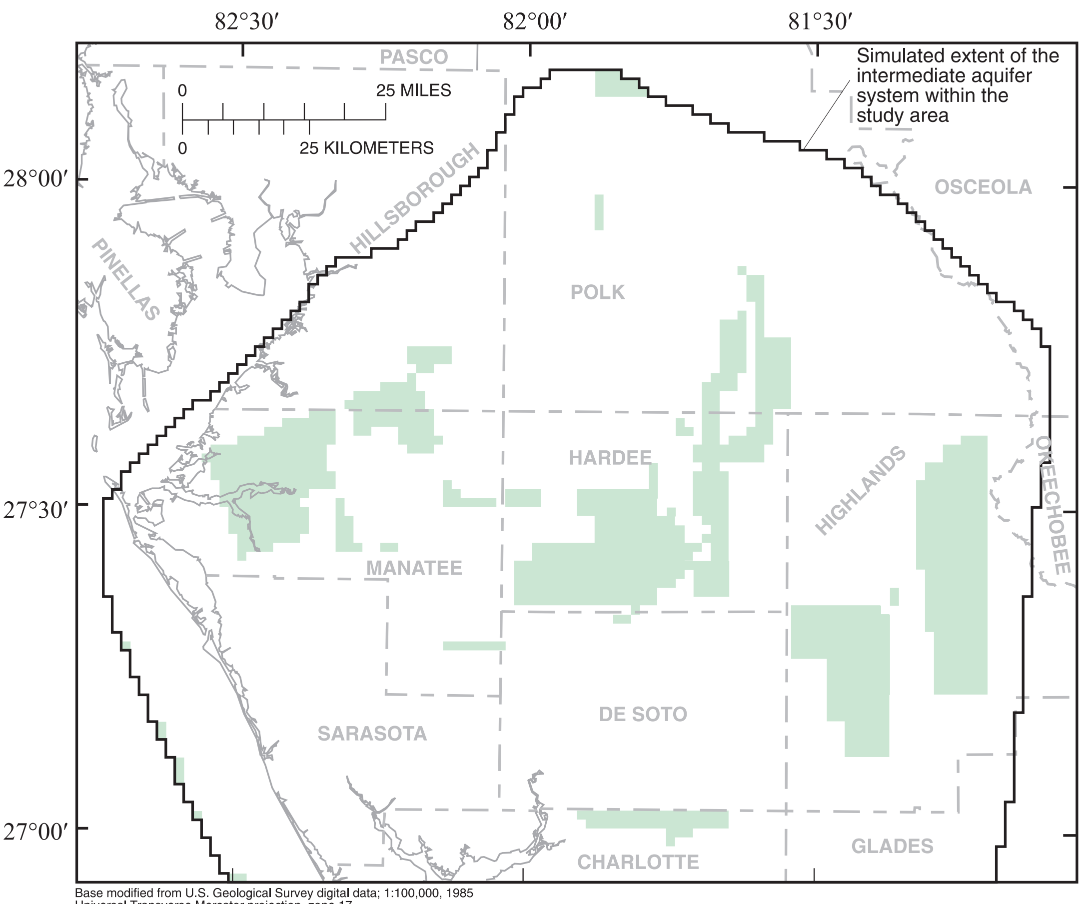
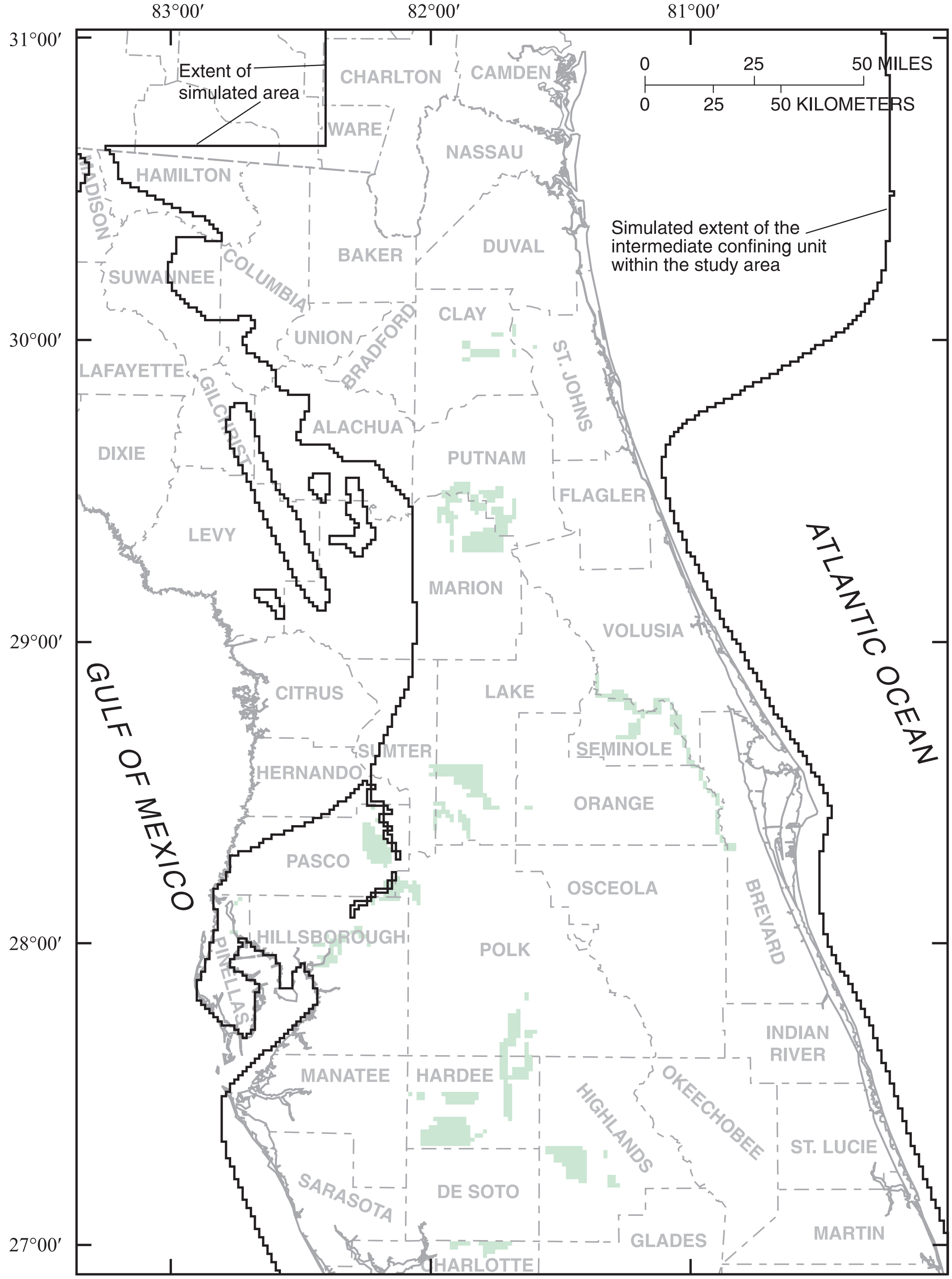


Figure 44. Cells where leakance of the upper confining unit of the intermediate aquifer system in some local models is not within one order of magnitude of the geometric mean of all leakances for the same cell.



Base modified from U.S. Geological Survey digital data; 1:100,000, 1985
Universal Transverse Mercator projection, zone 17

Figure 45. Cells where leakance of the intermediate confining unit in some local models is not within one order of magnitude of the geometric mean of all leakances for the same cell.

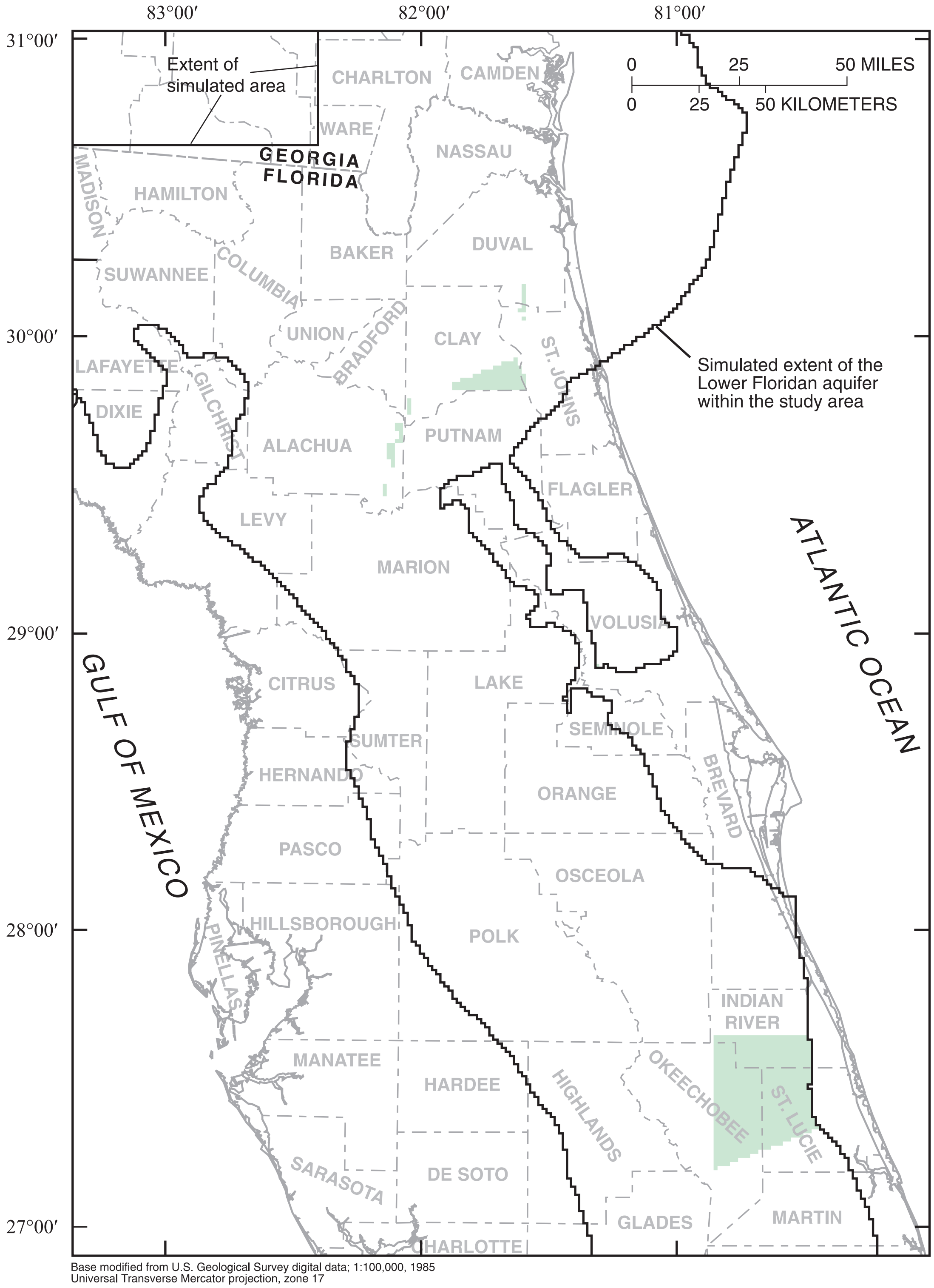


Figure 46. Cells where leakance of the middle semiconfining unit in some local models is not within one order of magnitude of the geometric mean of all leakances for the same cell.

The distribution of transmissivity for the UFA was initially selected from models 1 through 14 (appendix A2) and was refined during calibration. All local models, except for the one-layer local models 4 and 8, were used to generate the initial estimates of the leakance of the ICU and the lower confining unit of the IAS. A large area in the SRWMD was not simulated by the ground-water flow models shown in appendix A2. The western lateral boundary of the IAS and that of the UFA were assumed to coincide along the Gulf of Mexico, an assumption made because the lack of chloride data precluded mapping the altitude at which 5,000-mg/L concentrations of chloride are present in the Gulf of Mexico. The IAS and UFA share a common western boundary, which is the reason for the differences between the lateral extent of the UFA along the Gulf of Mexico in models 2 and 7 and that simulated in the regional model (appendix A2). Differences between the lateral extent of the simulated area in the regional model and the lateral extent of models 4, 5, and 6 in the Gulf of Mexico and the Atlantic Ocean are due to differences between the grid resolution of these models and that of the regional model grid.

Local models 5, 6, 11, 12, and 14 (appendix A3) were used to generate the initial distribution of transmissivity of the LFA and the leakance of the MSCU. Large differences between the lateral extent of models 5, 6, and 14 along the Atlantic Ocean and the simulated extent of the LFA (fig. 40) in the regional model are due to the exclusion from simulation of aquifer areas containing water with chloride concentrations greater than 5,000 mg/L.

Calibration of Ground-Water Flow Model

Computed average heads in the IAS, UFA, and LFA for the August 1, 1993, to July 31, 1994, steady-state period were the control points used to calibrate the ground-water flow model. The number of control points for the IAS, UFA, and LFA respectively were: 118; 1,460; and 46. The measured or estimated spring flows (appendix C) and base-flow estimates of rivers in the unconfined areas of the UFA also were used for comparison to calibrate the model. No parameter estimation technique was used to achieve model calibration.

Calibration of the regional ground-water flow model was accomplished by adjusting input hydraulic parameters within reasonable ranges from the initial distribution of values until the model closely approximated observed field conditions based on aquifer heads, spring flows, and river flows. The “goodness” or improvement of the calibration generally is based on the differences between simulated and measured or estimated heads, spring flows, and stream discharges. Simulated heads and flows from a calibrated, deterministic ground-water model commonly depart from measured heads and flows, even after a diligent calibration effort. The difference between model results and what actually occurs in the aquifers, referred to as model error, is the cumulative result of simplification of the conceptual model, grid scale, measurement errors, and the difficulty in obtaining sufficient measurements to account for all of the spatial variation in hydraulic properties throughout the model area. Calibration was considered to be achieved when the RMS residual for water levels was comparable to the error associated with the time average of measurements used to calibrate the model, namely the RMS residual associated with the approximation of the altitude of the water table of the SAS (3.53 ft, table 2). The calibration criterion used for spring flows was to be as close as possible to the measured or estimated flow of major springs, as long as none of the hydraulic values used deviated substantially from the initial distribution of values.

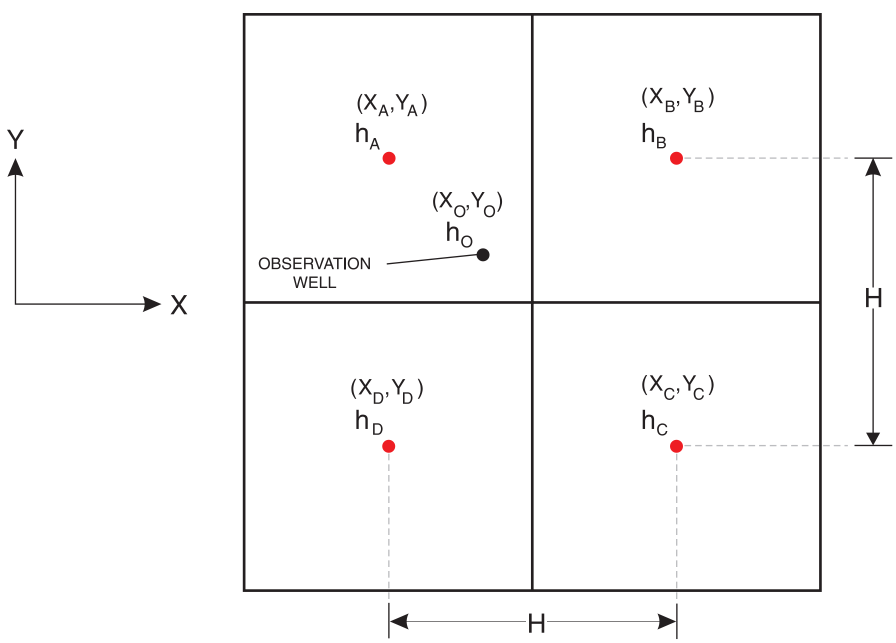
Hydraulic parameters that were adjusted during calibration of the ground-water flow model included: the net recharge rate to unconfined areas of the UFA; the transmissivity of the IAS, UFA, and LFA; the riverbed conductance (where the UFA is unconfined); the leakance of the upper and lower confining units of the IAS, ICU, MCU, and MSCU; and the conductance of swamps and springs in the UFA.

The calibration process was iterative and consisted of (1) assigning initial hydraulic parameters from local models; (2) comparing simulated and average heads and simulated and estimated spring flows for the steady-state period of 1993-94; and (3) adjusting hydraulic parameters aimed at minimizing the differences between simulated and average heads and between simulated and estimated spring flows for 1993-94. The guiding principle of calibration was that the model parameter with the highest sensitivity for a given area or aquifer was adjusted first; other less sensitive parameters were adjusted only if reasonable residuals were not achieved. In cases where two parameters were about equally sensitive, each was adjusted separately.

The initial distribution of hydraulic parameters from the local model was used to define contiguous zones of equal values. The areal extents of the transmissivity zones for the IAS, UFA, and LFA were independent from each other. The areal extents of the leakance zones for the upper and lower confining units of the IAS, ICU, MCU, and MSCU were also independent from each other. The areal extents of these zones were modified during calibration.

Because measured water levels rarely coincide with the center of a cell, simulated water levels at observation wells were interpolated laterally from simulated heads at the centers of the four cells surrounding the observation well (fig. 47) to allow for a continuous distribution of water levels. The neighboring cells used in the bilinear interpolation were those for which the coordinates of the center of the cells completely encompassed the coordinates of the observation well (fig. 47). Vertical interpolation was not necessary because of the discontinuity and associated refraction of potential fields across zones of differing transmissivities.

Simulated and measured water levels in the IAS, UFA, and LFA agree reasonably well throughout most of the study area (fig. 48). About 85 percent of simulated water levels are within 5 ft of measured values, with RMS values of 3.47, 3.41, and 2.89 ft for the IAS, UFA, and LFA, respectively (table 10). The RMS residual for all layers in the model was 3.40 ft. The histogram of residuals for the UFA appears to be normally distributed (fig. 48), indicating the error in the model also is normally distributed.



EXPLANATION

h_A ● SIMULATED HEAD

h_O ● OBSERVED HEAD -- Simulated head at observation well is obtained from $h_O = a\,h_A + b\,h_B + c\,h_C + d\,h_D$, where weights are $a=(1-|X_O-X_A|/H)(1-|Y_A-Y_O|/H)$, $b=(1-|X_B-X_O|/H)(1-|Y_B-Y_O|/H)$, $c=(1-|X_C-X_O|/H)(1-|Y_O-Y_C|/H)$, $d=(1-|X_O-X_D|/H)(1-|Y_O-Y_D|/H)$, and satisfy the condition $a + b + c + d = 1$

Figure 47. Bilinear interpolation used to determine simulated water levels at observation wells from simulated water levels at the center of cells.

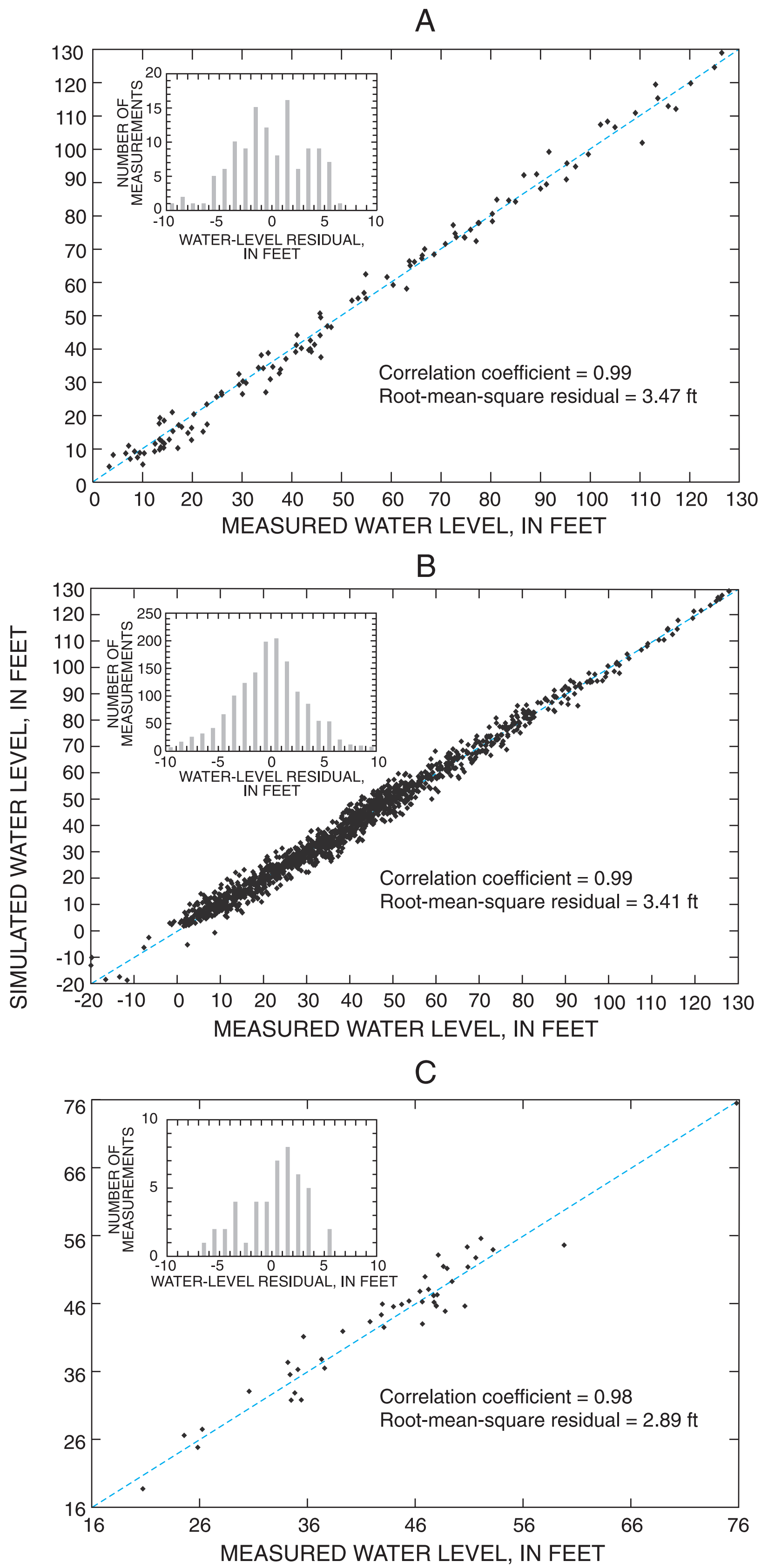


Figure 48. Comparison of simulated to measured water levels in the (A) intermediate aquifer system, (B) Upper Floridan aquifer, and (C) Lower Floridan aquifer for the calibrated model.

Table 10. Water-level residual statistics for the calibrated model

Aquifer	Number of water-level measurements	Minimum residual (feet)	Maximum residual (feet)	Mean residual (feet)	Root-mean-square residual (feet)
Intermediate aquifer system	118	-9.62	6.89	-0.18	3.47
Upper Floridan aquifer	1,460	-9.90	9.90	-.19	3.41
Lower Floridan aquifer	46	-6.90	5.21	.17	2.89
Entire model	1,624	-9.90	9.90	-.18	3.40

Transmissivity of the Intermediate Aquifer System

The process of modifying the initial transmissivity distribution of the IAS during calibration included: (1) testing all IAS transmissivity values from local models in the discrepancy areas shown in figure 41; (2) finding values that decreased the absolute value of residuals at control points within the discrepancy areas; (3) using recent transmissivity estimates for Sarasota County (Knochenmus and Bowman, 1998); (4) assigning low transmissivity values along the western, eastern, and northern boundaries of the IAS to simulate decreasing aquifer thickness; (5) making limited transmissivity changes in and near areas of potentiometric-surface highs (fig. 17) to reduce residuals at nearby control points; and (6) making transmissivity changes to areas in the IAS where residuals were unreasonably large and sensitive to changes in transmissivity.

Transmissivity in the IAS from the calibrated model ranged from 100 ft^2/d along the northern, eastern, and western boundaries of the IAS to 30,000 ft^2/d in parts of Sarasota County (fig. 49). All transmissivity values for this model were rounded to two significant figures to simplify the calibration process because more significant figures for transmissivity values generally did not result in meaningful changes in simulated water levels. Changes made to the initial distribution of transmissivity of the IAS (fig. 49) generally were small because heads in the IAS were more sensitive to changes in the leakance of the confining units of the IAS.

Transmissivity of the Upper Floridan Aquifer

Substantial changes to the initial distribution of transmissivity of the UFA were required to decrease the absolute value of differences between simulated and computed average heads for the calibration period. Procedures in addition to those discussed in the previous section for the IAS were required to modify the transmissivity of the UFA during model calibration. The simulation of flow from several springs not included in any of the local models resulted in a higher transmissivity in the vicinity of these springs than the initial values. Steep hydraulic gradients in the potentiometric surface of the UFA in some areas needed to be simulated with “barriers” of low transmissivity zones not included in the initial distribution of transmissivity. The effects of replacing specified- or general-head boundaries used in local models with internally simulated heads in the regional model generally required changes to the initial transmissivity distribution. The effects of including ground-water withdrawals in areas of the regional model that were not included in local models also required changes to the initial transmissivity distribution for the UFA.

Transmissivity of the UFA from the calibrated model ranged from 3,000 ft^2/d in areas where either limestone comprising the aquifer has low permeability or where the UFA is thin to 12,000,000 ft^2/d in areas of cavernous limestone near springs. Transmissivity values were low in recharge areas in north-central Lafayette County, central Gilchrist County, east-central Bradford County, parts of Levy and Marion Counties, north Lake County, and north-central Volusia County (fig. 50). Areas in the vicinity of springs were given higher transmissivity values than the surrounding areas, which allowed more water to reach the springs. The highest transmissivity values were in the vicinity of Alapaha Rise, Silver Springs, Rainbow Springs, and Crystal River Spring Group (figs. 22 and 50). These springs all had estimated or measured flows in excess of 400 ft^3/s (appendix C).

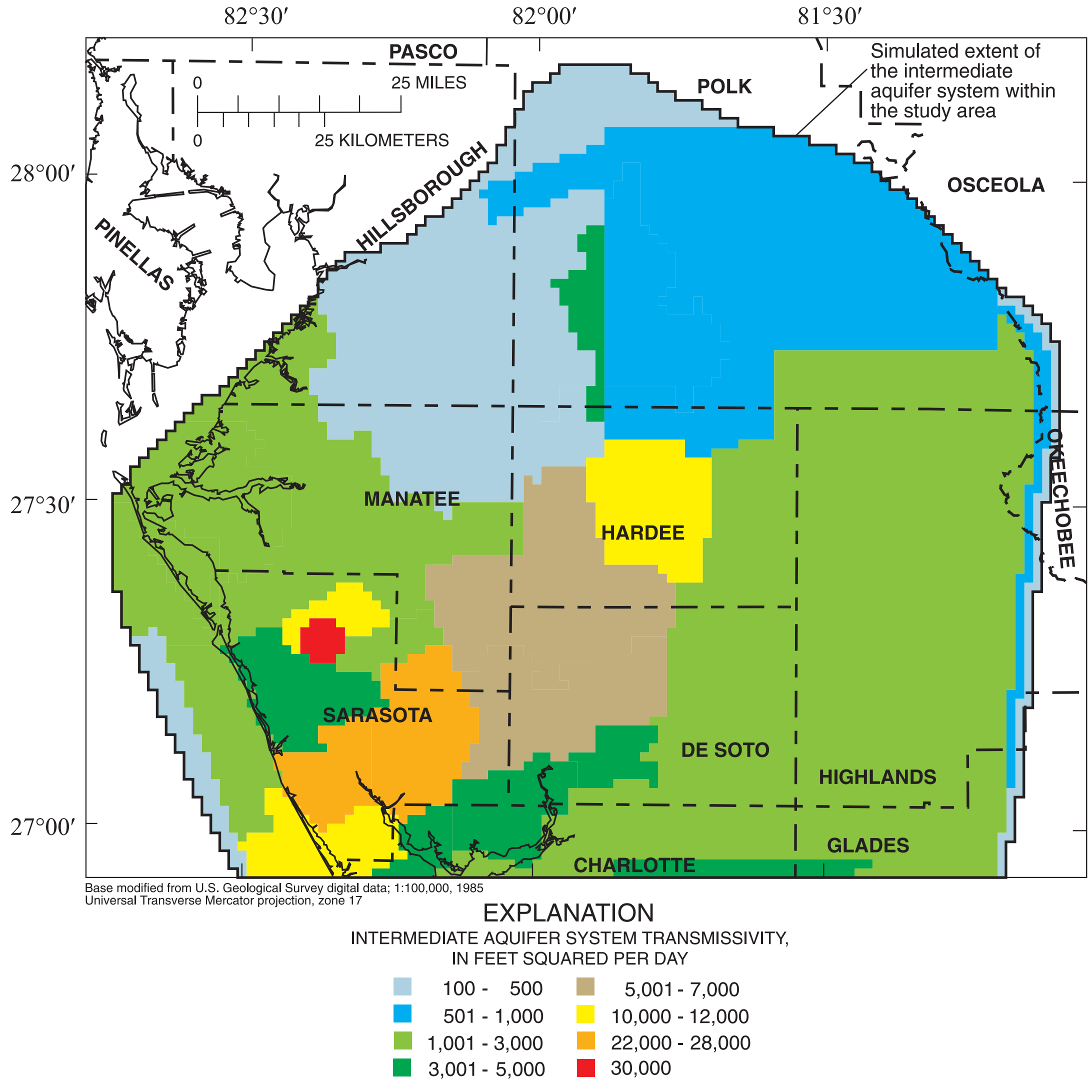


Figure 49. Transmissivity of the intermediate aquifer system from the calibrated model.

Transmissivity of the Lower Floridan Aquifer

The distribution of transmissivity of the LFA from the calibrated model (fig. 51) was generated, in part, by identifying the values that decreased the absolute value of residuals at control points within the discrepancy areas (fig. 43). Simulated transmissivity values in Orange, Seminole, and Lake Counties (Brian McGurk, SJRWMD, 2000, written commun.) were evaluated and incorporated in the LFA transmissivity distribution in areas where these values decreased the residuals at control points. Transmissivity values in west-central Florida and in the northwest areas of the model depended on the thickness of the LFA and the equivalent hydraulic conductivity assigned in adjacent models in east-central Florida (figs. 29-31).

Changes to the initial distribution of transmissivity values for the LFA were made in zones where residuals at control points were unreasonably large; these changes were of regional scale because of the paucity of water levels available from the LFA. Transmissivity values for the LFA in areally extensive parts of northeast Florida agreed with those used by Durden (1997).

Transmissivity values for the LFA and derived from the calibrated model ranged from 5,000 ft^2/d along parts of the lateral boundaries of the LFA to 760,000 ft^2/d in northeast Florida. High transmissivity values also were simulated in parts of Orange County and south Florida (fig. 51). Transmissivities are low (5,000 ft^2/d) along the lateral boundary of the LFA, reflecting a limited movement of freshwater through a thin part of the aquifer because of proximity to the freshwater-saltwater interface.

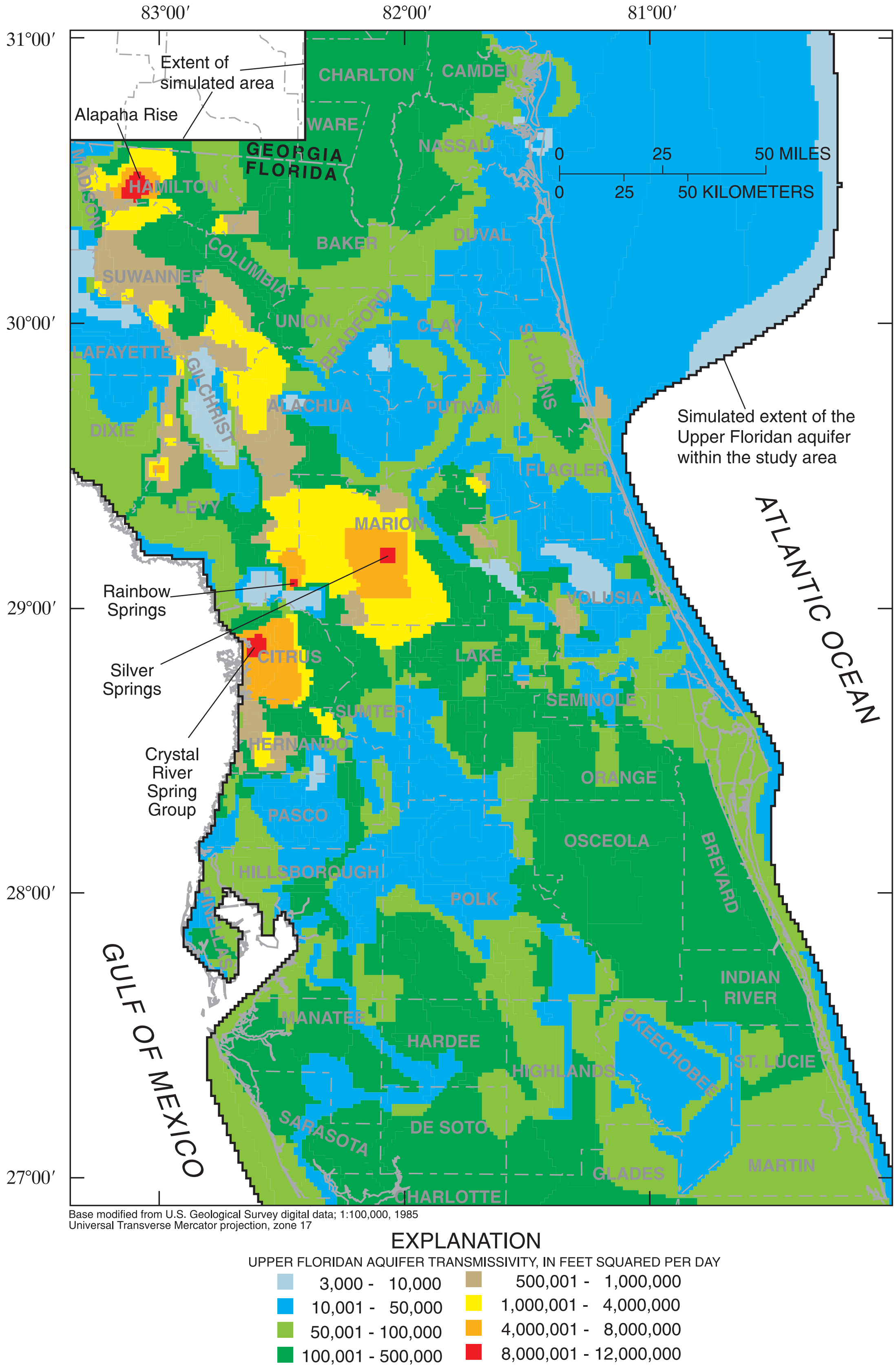


Figure 50. Transmissivity of the Upper Floridan aquifer from the calibrated model.

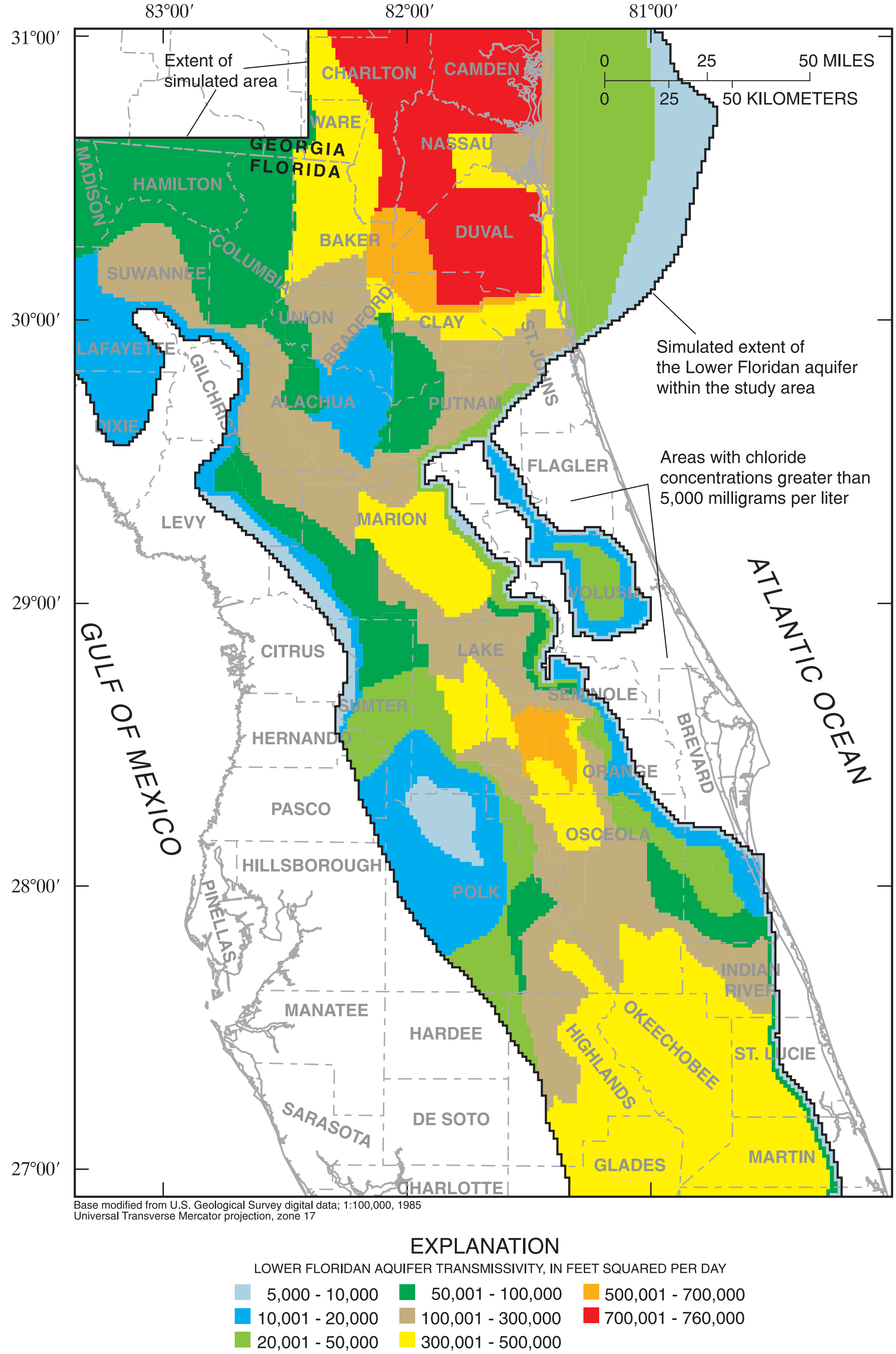


Figure 51. Transmissivity of the Lower Floridan aquifer from the calibrated model.

Leakance of the Upper Confining Unit of the Intermediate Aquifer System

Prescribing the distribution of the water table of the SAS (as discussed previously) rather than using the water-table altitudes from local models required modifying the initial distribution of leakances. Simulated heads in the IAS were sensitive to simulated leakance values of the upper confining unit. Leakance values were adjusted so that the simulated leakage rates were within the range of values of simulated leakage rates in models 7, 10, and 13.

As shown in figure 52, simulated leakance of the upper confining unit of the IAS ranged from 1.0×10^{-6} (ft/d)/ft to 1.4×10^{-3} (ft/d)/ft. These leakance values resulted in simulated leakage rates to the IAS that ranged from upward leakage of about 60 in/yr in parts of Hardee County to downward leakage of about 34 in/yr in parts of Highlands County (fig. 53). Most of Hardee County, however, is a recharge area of the IAS. The highest leakance values are in the Lake Wales Ridge physiographic area (fig. 2), where aquifer recharge is highest and confining beds are relatively thin and permeable (fig. 53). Simulated leakance values within the De Soto Plain physiographic area (fig. 2) that were approximately the same magnitude as those of the Lake Wales Ridge area, resulted in downward vertical leakage rates lower than in the Lake Wales Ridge area (fig. 53). This indicates that the vertical hydraulic gradients between the SAS and the IAS in the Lake Wales Ridge area are higher than those in the De Soto Plain. Large areas of the IAS have simulated vertical leakage rates (upward or downward) less than or

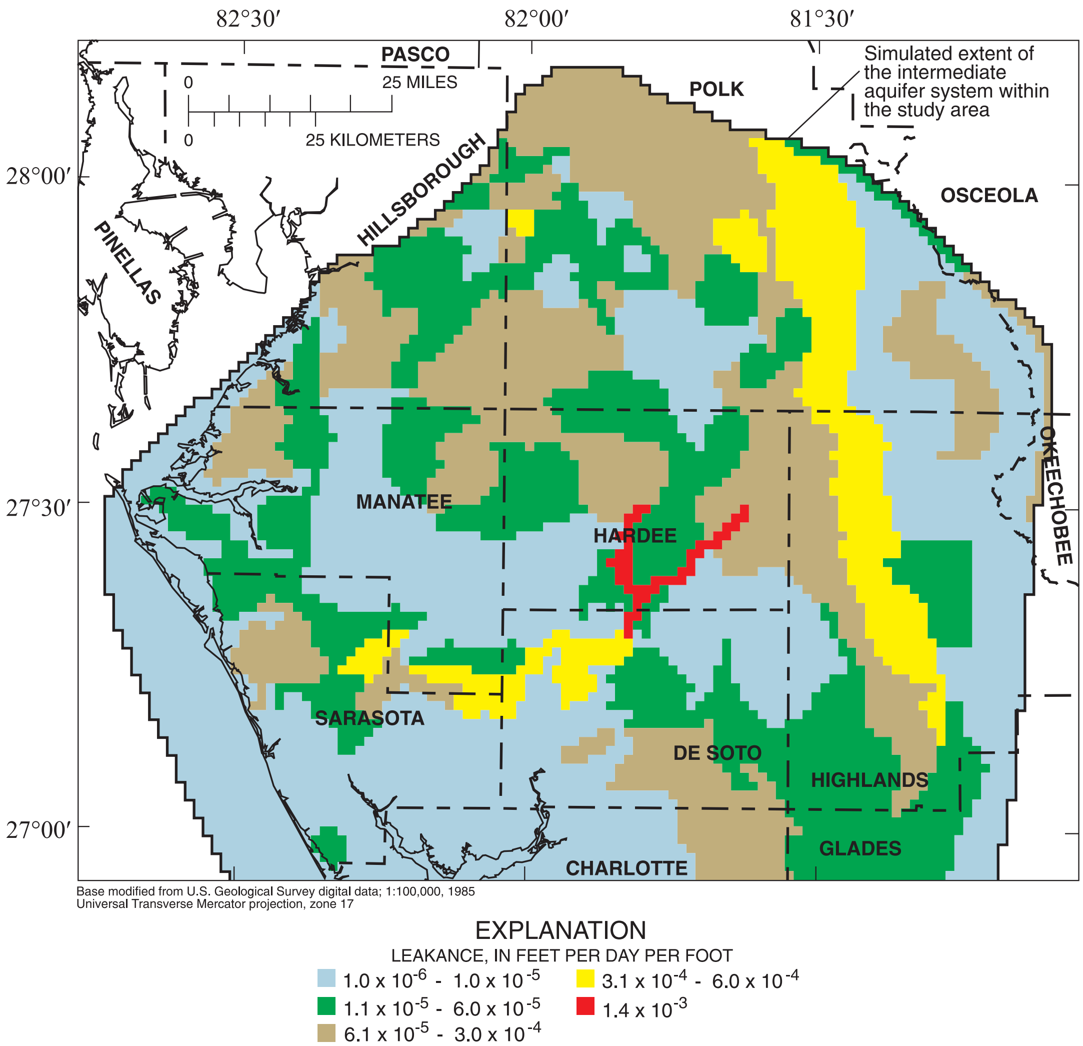


Figure 52. Leakance of the upper confining unit of the intermediate aquifer system from the calibrated model.

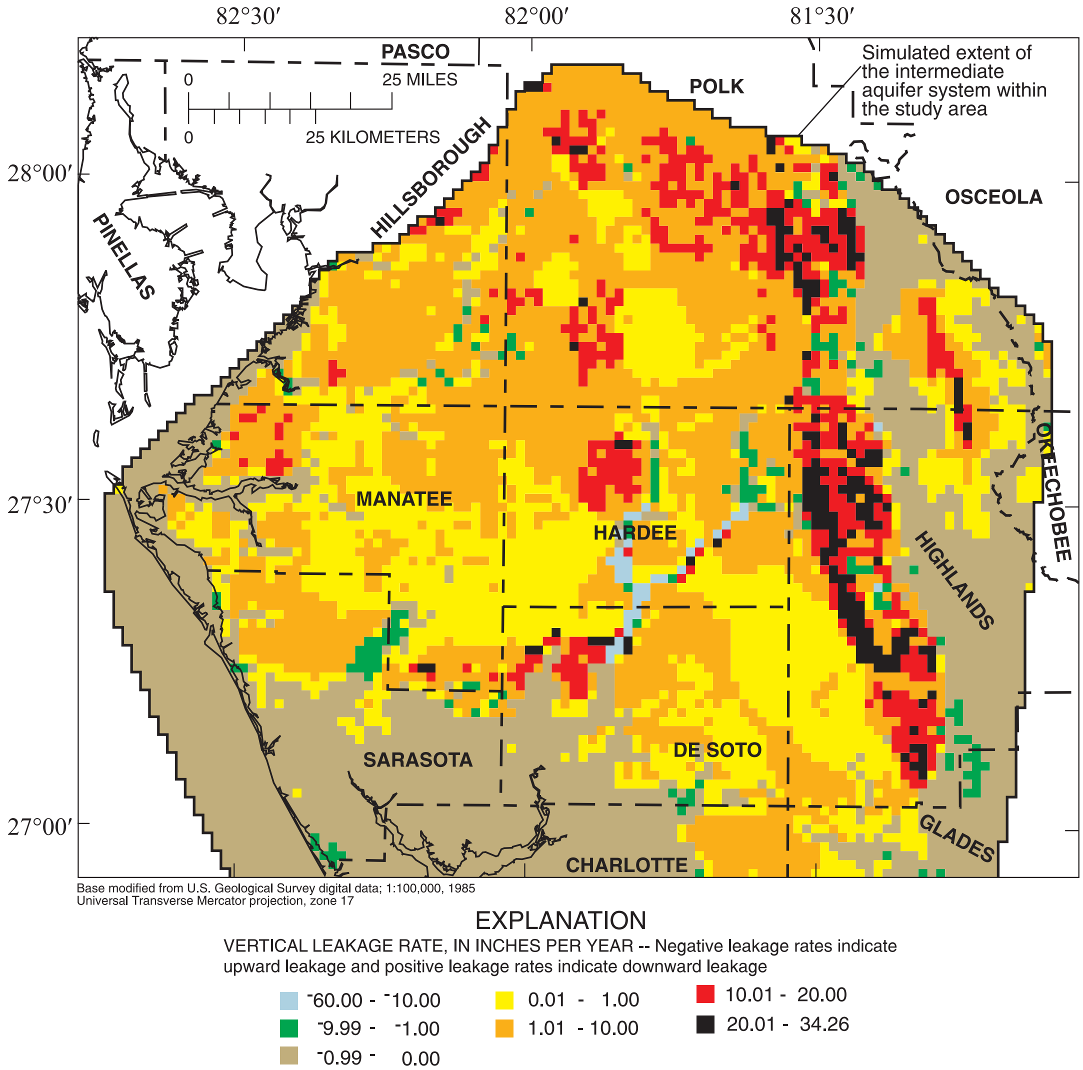


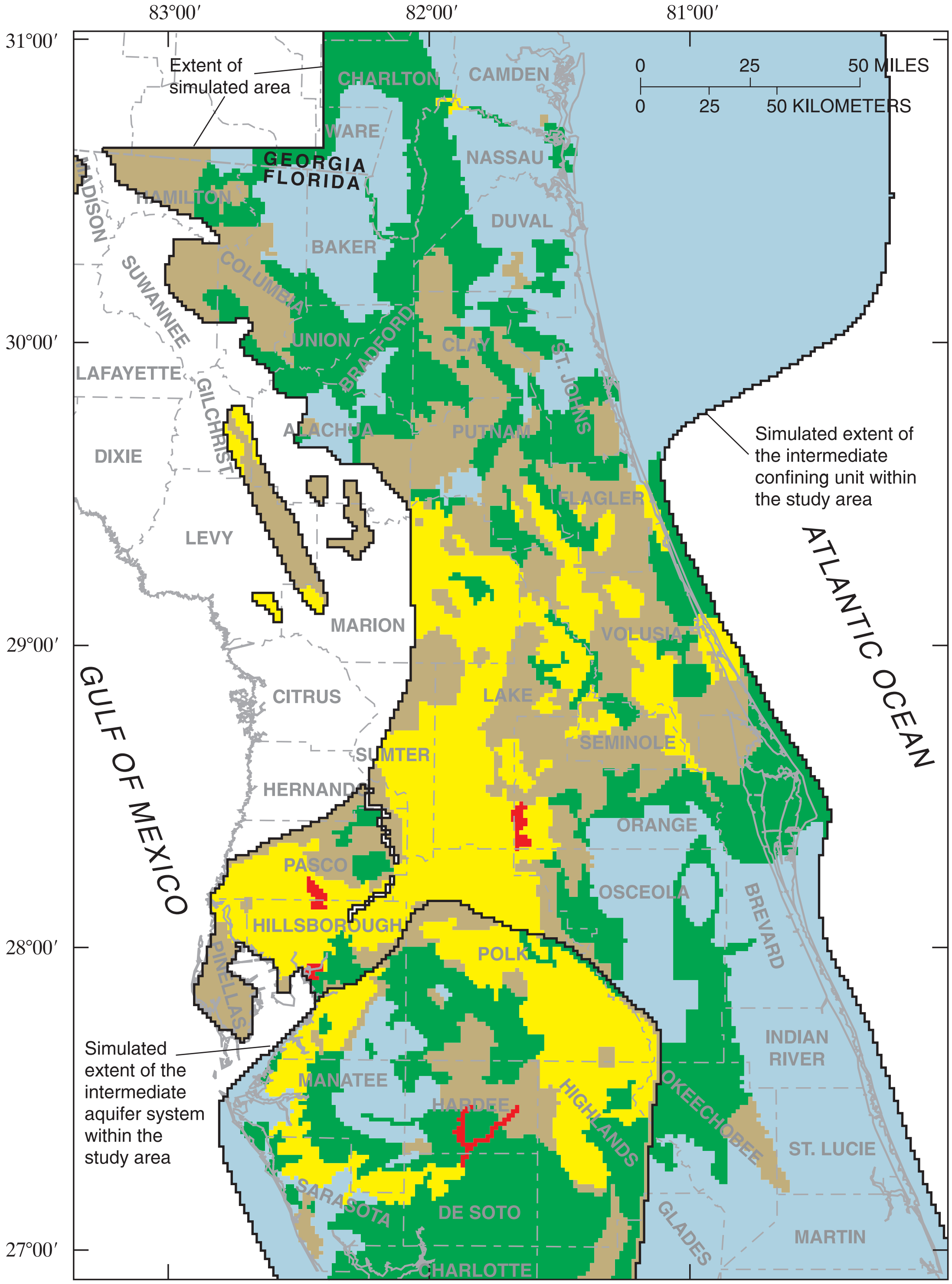
Figure 53. Simulated vertical leakage rates to and from the intermediate aquifer system through the upper confining unit, average August 1993 through July 1994 conditions.

equal to 1.0 in/yr (fig. 53), resulting from a relatively low leakance value for the upper confining unit of the intermediate aquifer system.

Leakance of the Intermediate Confining Unit

The initial leakance distribution of the ICU was modified in some areas to reduce the simulated downward leakage rates to a fraction of the 1993-94 rainfall, except in areas of artificial recharge such as rapid-infiltration basins. In such areas, leakance values were adjusted so that the simulated leakage rates were within the range of simulated leakage rates for models shown in appendix A1. The range of simulated leakage rates was used to determine the sensitivity of simulated heads to the vertical leakance values. If changes in leakage rates did not substantially reduce the magnitude of the residuals, then transmissivity was adjusted.

Simulated leakance values of the ICU ranged from 1.0 x 10^{-6} (ft/d)/ft to 7.0 x 10^{-3} (ft/d)/ft (fig. 54). This range of values included simulated leakance values of the lower confining unit of the IAS as an extension of the ICU throughout the simulated extent of the IAS. The largest leakance values were simulated in parts of Orange, Pasco, Hillsborough, and Hardee Counties. The initial leakance values were increased in recharge areas of the UFA to increase simulated water levels as needed to match water levels at control points. In discharge areas of the UFA, leakance values of the



Base modified from U.S. Geological Survey digital data; 1:100,000, 1985
Universal Transverse Mercator projection, zone 17

EXPLANATION

LEAKANCE, IN FEET PER DAY PER FOOT

- 1.0×10^{-6} - 1.0×10^{-5}
- 1.1×10^{-5} - 6.0×10^{-5}
- 6.1×10^{-4} - 3.0×10^{-4}
- 3.1×10^{-4} - 1.0×10^{-3}
- 1.1×10^{-3} - 7.0×10^{-3}

Figure 54. Leakance of the intermediate confining unit and the lower confining unit of the intermediate aquifer system from the calibrated model.

ICU were decreased from initial values to increase simulated heads as needed. Changes in simulated heads in the UFA caused by adjustments to transmissivity values were assessed in separate runs of the model. The main reasons for the spatial variability in leakance values of the ICU are the spatial variability in ICU thickness, and in vertical hydraulic gradients between the SAS and the UFA and between the IAS and the UFA (where the IAS is present).

Upward leakage was as high as 80 in/yr in parts of coastal Hillsborough County near Hillsborough Bay, whereas downward leakage was as high as 108 in/yr in southwest Orange County (fig. 55). The largest downward leakage rates to the UFA were simulated in areas where artificial recharge occurs through rapid-infiltration basins (O'Reilly, 1998). Most of the leakage rates to and from the UFA were less than 10 in/yr. High downward leakage rates to the UFA also were simulated in parts of physiographic region 4 (fig. 2), particularly along the Lake Wales Ridge region (fig. 55). Simulated leakage rates to the UFA in SFWMD were consistent with previous estimates by Fairbank and Hohner (1995, plate VI).

Leakance of the Middle Confining and Middle Semiconfining Units

The presence or absence of evaporites is the main reason for a marked difference in leakance for the MCU as compared to the MSCU (Miller, 1986). The simulated leakance of the MCU ranged from 6.2×10^{-6} to 1.4×10^{-4} (ft/d)/ft (fig. 56). The largest simulated leakance of the MSCU was 2.0×10^{-3} (ft/d)/ft. As indicated by Hickey (1990), the leakance of the MCU could be as high as 5.0×10^{-4} (ft/d)/ft, assuming a uniform thickness of 200 ft for the MCU and a vertical hydraulic conductivity of 0.1 ft/d. Areas where neither the MCU or the MSCU are present were simulated with larger leakance values than those simulated for the MCU (fig. 56). Leakance values in those areas were derived from the simulated transmissivity of the UFA, the estimated freshwater thickness of the UFA, and an estimated ratio of 100:1 between horizontal and vertical hydraulic conductivity.

Large leakance values also were simulated in areas of strong hydraulic connection between the UFA and LFA, indicated by the relatively small hydraulic gradients between these two aquifers. These areas include parts of Brevard, Duval, Indian River, Marion, Nassau, and Orange Counties, and Charlton County, Ga. The simulated large leakance values in areas of Baker, Nassau, Duval, and Clay Counties, and Charlton and Ware Counties, Ga., combined with large transmissivities in the LFA for the same areas (fig. 51), could explain the source of water withdrawn from the LFA in discharge areas of Duval County.

The simulated vertical leakage rate in areas where the MCU is present was mostly less than 1.0 in/yr (fig. 57), a consequence of the low simulated leakance for the MCU. In contrast, high simulated leakage to the LFA occurred in parts of Alachua, Clay, Highlands, Lake, Orange, Polk, and Putnam Counties (fig. 57). Some parts of Highlands County, adjacent to the MCU-MSCU transition zone, had simulated downward leakage rates to the LFA that ranged from 5 to 8 in/yr.

Recharge and Discharge Areas of the Upper Floridan Aquifer

Rivers represent a feature where both recharge to and discharge from the UFA can occur. Flow between the aquifer and rivers in unconfined areas of the UFA was simulated using the River package of the MODFLOW-96 River Package (Harbaugh and McDonald, 1996). Simulated flow between the aquifer and the river is determined by riverbed conductance and the difference between river stage and the simulated water level in the river cell. The river stage and altitude of the riverbed bottom were assigned by using linear interpolation of measured stages at gaging stations (fig. 58).

Conductance values assigned to riverbed cells depended on the interaction between the UFA and the rivers. The potentiometric surface of the UFA suggests that river-aquifer interactions along the meanderings of the Steinhatchee River, Waccasassa River, and parts of the Withlacoochee and Hillsborough Rivers in west-central Florida is not as strong as the interactions along the Suwannee, Santa Fe, and Ichetucknee Rivers, and the Withlacoochee River in Madison County (figs. 18 and 58).

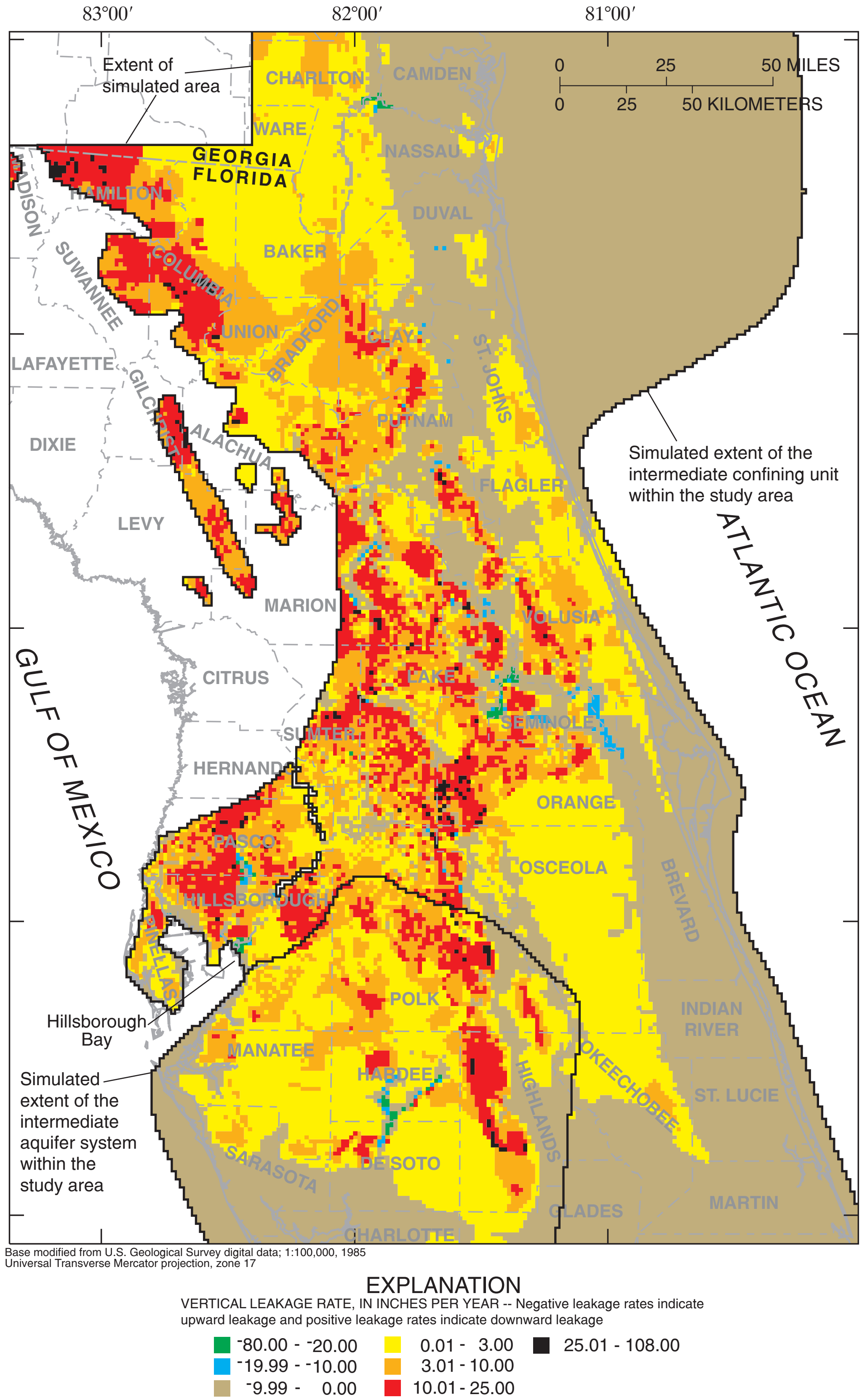


Figure 55. Simulated vertical leakage rates to and from the Upper Floridan aquifer, average August 1993 through July 1994 conditions.

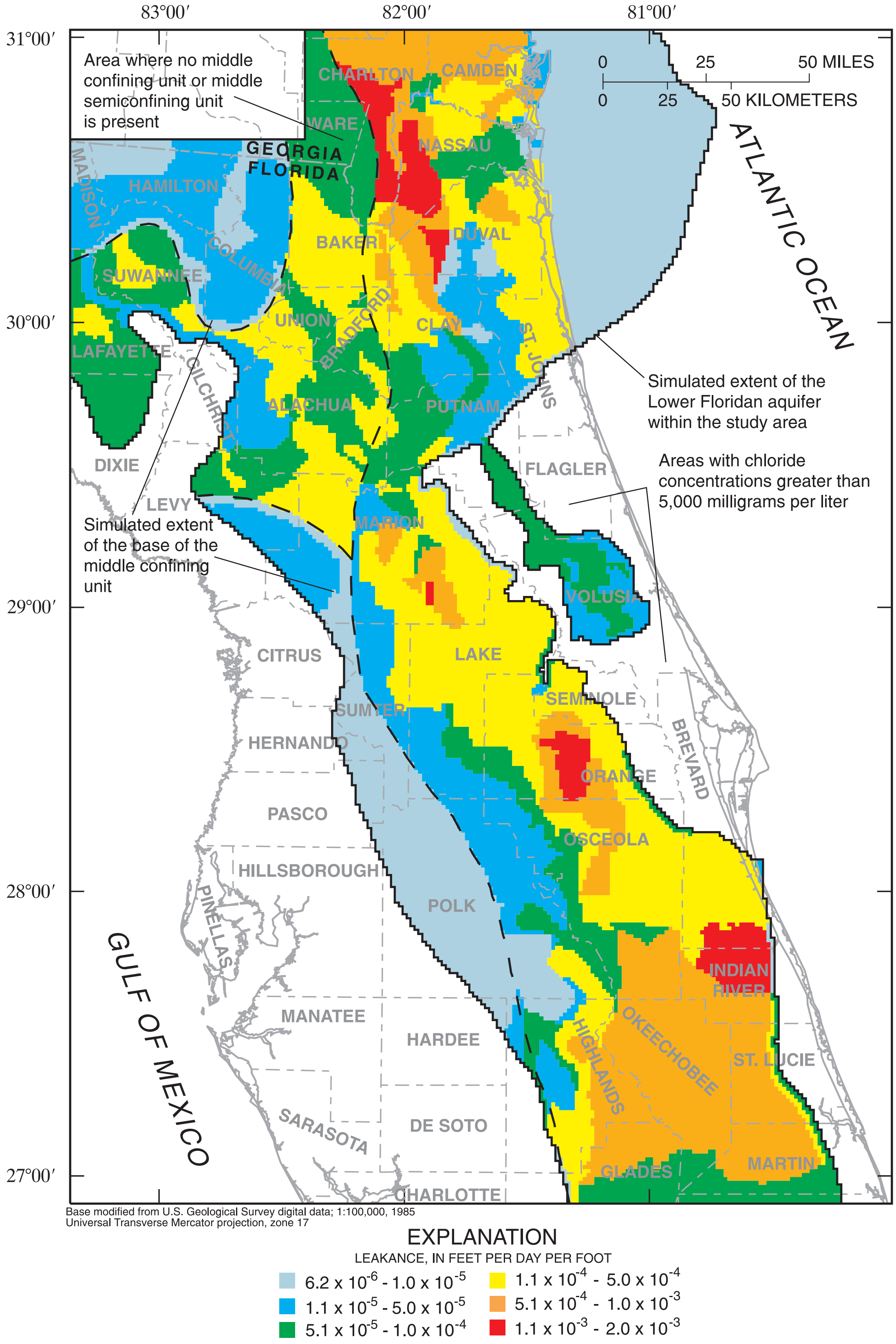


Figure 56. Leakance of the middle confining and middle semiconfining units from the calibrated model.

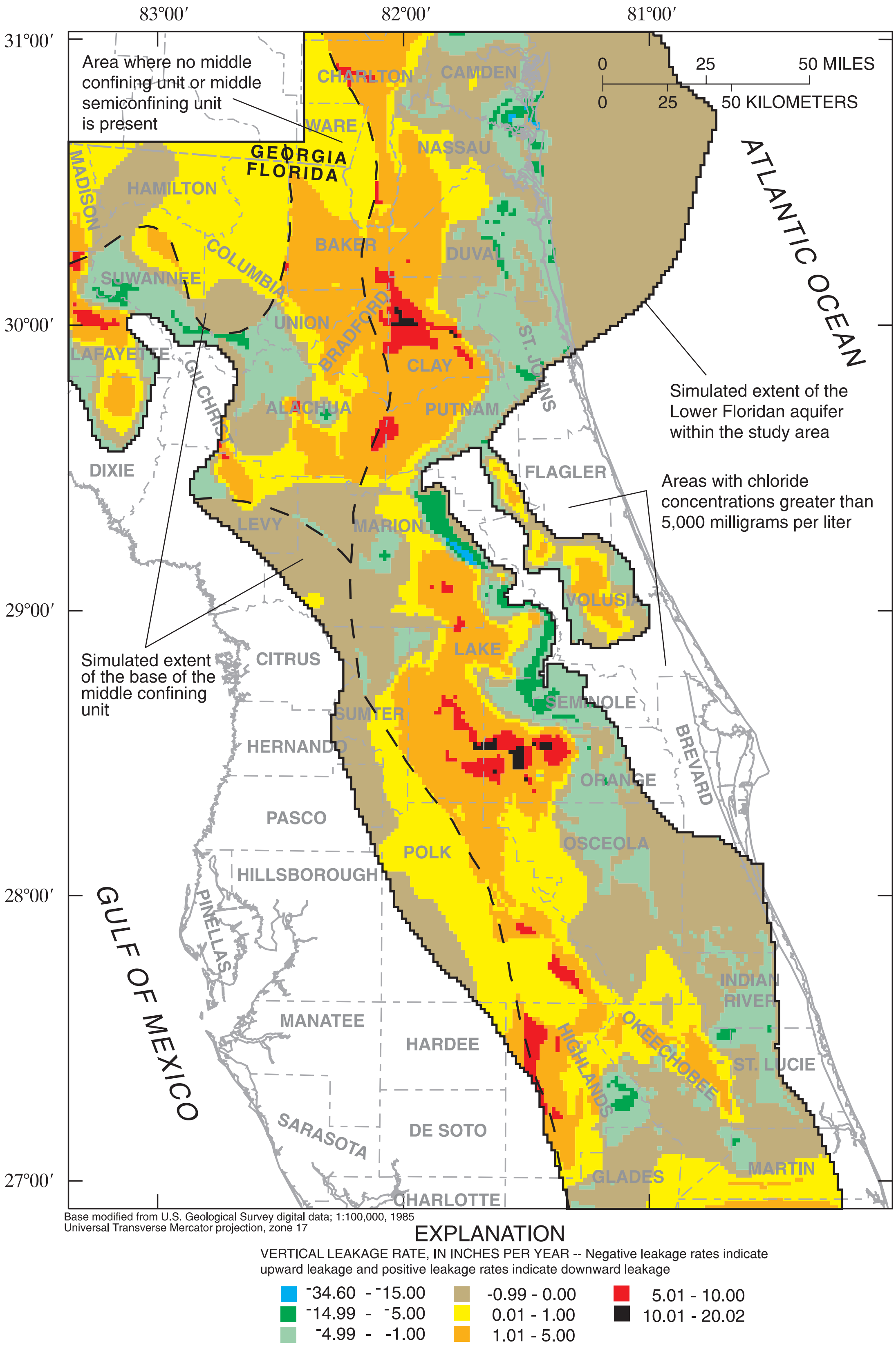


Figure 57. Simulated vertical leakage rates to and from the Lower Floridan aquifer through the middle confining and middle semiconfining units, average August 1993 through July 1994 conditions.

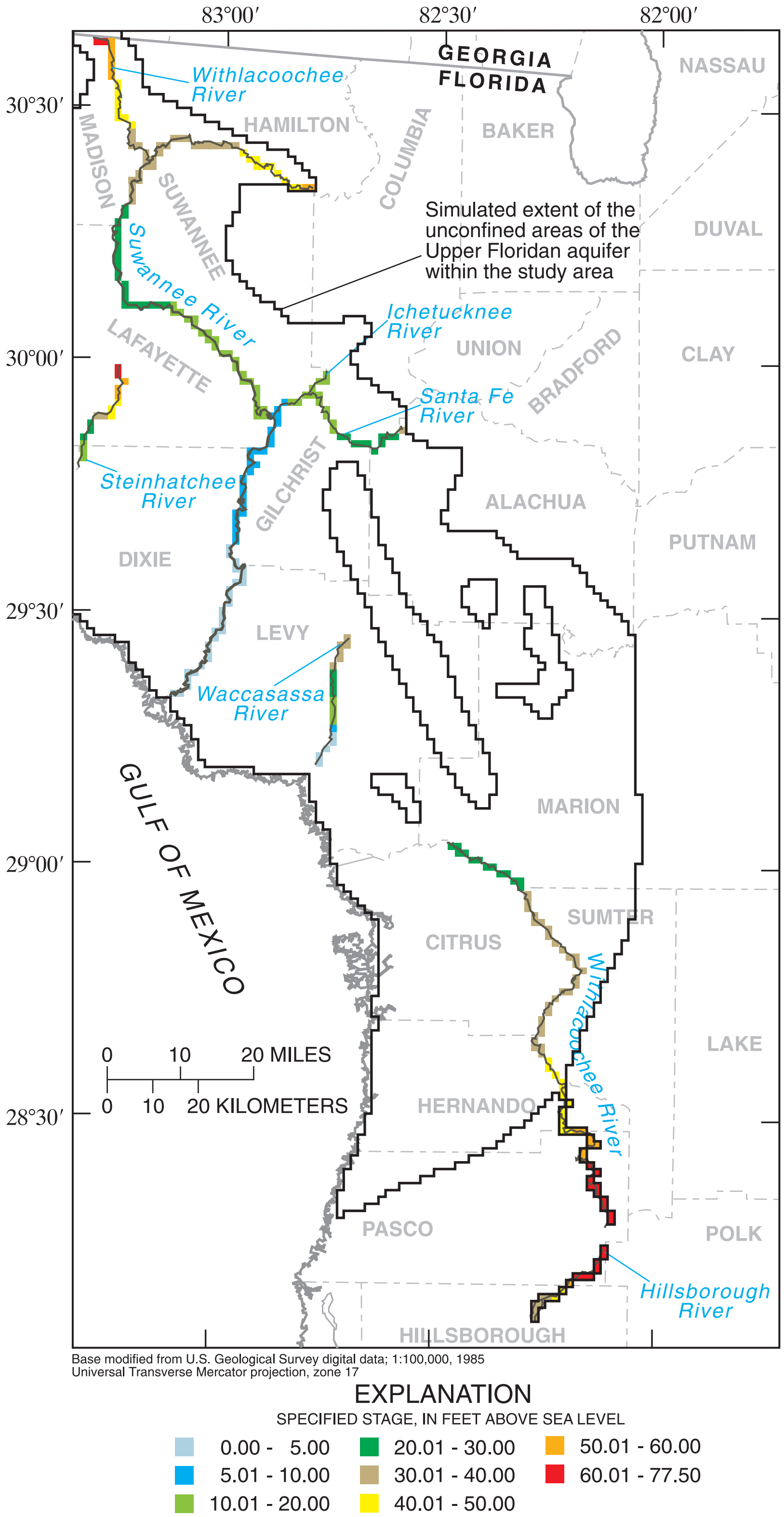


Figure 58. Specified stages along the simulated river cells in the unconfined areas of the Upper Floridan aquifer, average August 1993 through July 1994 conditions.

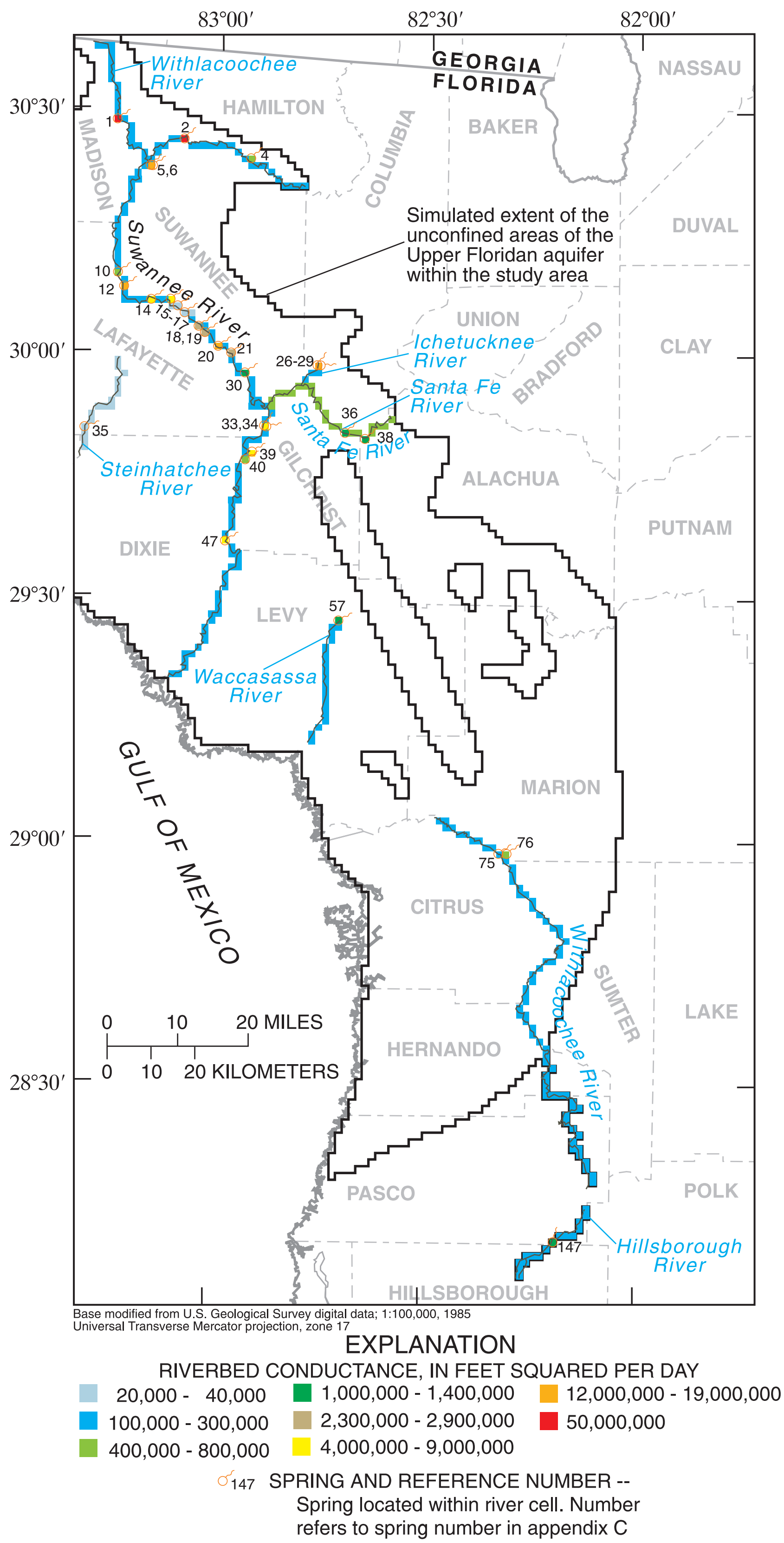


Figure 59. Simulated riverbed conductance of river cells in the unconfined areas of the Upper Floridan aquifer.

A strong hydraulic connection between the karstic aquifer and a river cell was reflected by a large riverbed conductance. For example, water levels in the UFA near some sections of the Suwannee River are nearly the same as the river stage, supporting the large riverbed conductance values. The simulated riverbed conductance of a cell that did not contain a UFA spring generally was lower than that of a cell that contained a spring (fig. 59). The riverbed conductance of a cell with a spring was adjusted based on the estimated or measured spring flow and the head difference between the river stage and the simulated head at the river cell.

A comparison of estimated and simulated base flows of rivers in the unconfined areas of the UFA (table 11) shows that the simulated base flow generally is lower than the estimated base flow. Reasons for this include the fact that riverbank storage is not accounted for in the simulated base flow. Also, the drainage area for four of the seven rivers is larger than the drainage area of the unconfined simulated sections of the rivers. Finally, the simulated base flow does not reflect the hydraulic routing of discharge from UFA springs and swamps to river cells.

Simulated recharge to and discharge from the UFA occurs across lateral boundaries of the model at specified-head cells (fig. 37). Simulated hydraulic gradients in the vicinity of the boundaries and simulated transmissivity values at the specified head cells determine the flux and direction across these boundaries. Simulated flows leaving or entering the model area along the eastern and most of the northern, southern and western boundaries were less than 1 ft^3/s per cell (fig. 60). Water enters the model area at rates equal to

Table 11. Estimated and simulated base flow of rivers in the unconfined areas of the Upper Floridan aquifer, average August 1993 through July 1994 conditions

[Station number refers to figure 23. Simulated base flow is flow captured by river cells in unconfined areas of the Upper Floridan aquifer, which generally have a smaller drainage area than the river basins. SRWMD, Suwannee River Water Management District; SWFWMD, Southwest Florida Water Management District; mi^2, square miles; ft^3/s, cubic feet per second; --, does not apply or not available]

USGS station number	Station name	Drainage area (mi^2)	Average daily discharge (ft^3/s)	Estimated average base flow (ft^3/s)	Simulated base flow (ft^3/s)
02303000	Hillsborough River near Zephyrhills	220	123	67	35
02312000	Withlacoochee River at Trilby	570	47	25	30
02313000	Withlacoochee River near Holder	1,825	319	252	121
02313700	Waccasassa River near Gulf Hammock	480	[a]193	[a]89	79
02319000	Withlacoochee River near Pinetta	2,120	1,714	621	6
02319500	Suwannee River at Ellaville	6,970	5,961	[b]1,933	[b]683
02320500	Suwannee River at Branford	7,880	6,678	[b]3,269	[b]1,430
02322500	Santa Fe River near Fort White	1,017	1,067	925	275
02323500	Suwannee River near Wilcox	9,640	9,410	[c]5,056	[c]2,502
02324000	Steinhatchee River near Cross City	350	205	36	17
--	Unconfined sections of Hillsborough River	--	--	--	68
--	Unconfined sections of Withlacoochee River - SWFWMD	--	--	--	92
--	Unconfined sections of Withlacoochee River - SRWMD	--	--	--	90
--	Ichetucknee River	--	--	--	305
--	Unconfined sections of Santa Fe River	--	--	--	[d] 872
--	Unconfined sections of Suwannee River	--	--	--	[c]2,585

[a]Based on October 1998 through September 1999 discharge data.
[b]Includes base flow of Withlacoochee River - SRWMD.
[c]Includes base flow of Santa Fe River and Withlacoochee River - SRWMD.
[d]Includes base flow of Ichetucknee River.

or greater than 2 ft^3/s per cell across a few cells on the northern and western boundaries, and some cells on the southern boundaries in Charlotte County. Flow rates of similar magnitude leave the model area across cells on the northern boundary and in coastal Pinellas County (fig. 60). Flow leaving the model area totaled 462 ft^3/s, with 113 ft^3/s across the northern boundary, 40 ft^3/s across the eastern boundary, 53 ft^3/s across the southern boundary, and 256 across the western boundary. Flow entering the model area totaled 317 ft^3/s, with the highest flow rate (151 ft^3/s) across the southern boundary and the lowest flow rate (18 ft^3/s) across the eastern boundary. Flow entering the model area across the northern boundary totaled 52 ft^3/s, whereas 96 ft^3/s entered across the western boundary. entering the model area along the Gulf of Mexico (western boundary) totaled 5 ft^3/s. Flows entering the model area across cells in the Gulf of Mexico and Atlantic Ocean probably are induced by pumping from the UFA near these boundaries (fig. 39).

Mapped recharge and discharge areas were compared with areas in which vertical recharge to and discharge from the UFA were simulated (fig. 20). Discrepancies between the areal distributions of mapped and model-simulated recharge and discharge areas of the UFA (figs. 20 and 61) are isolated throughout the model area and occur mainly at cells where the hydraulic gradient between the SAS and the UFA (or the SAS and the IAS) is relatively small. In the unconfined areas of the UFA, discrepancies between mapped and simulated recharge and discharge areas occurred at some river and swamp cells. Some swamp cells in Sumter County, mapped as discharge areas, were identified as recharge areas because the simulated net recharge rate at each cell exceeded the simulated flux drained out of the cell.

Simulated net recharge rates to unconfined areas of the UFA were adjusted from a range of values established by the maximum and minimum recharge rates presented previously (fig. 25), average water levels, and spring flow. Net recharge rates are high near areas where the water table is deep, as is the case in the Northern Highlands region (fig. 2), and generally decrease coastward where evapotranspiration is high.

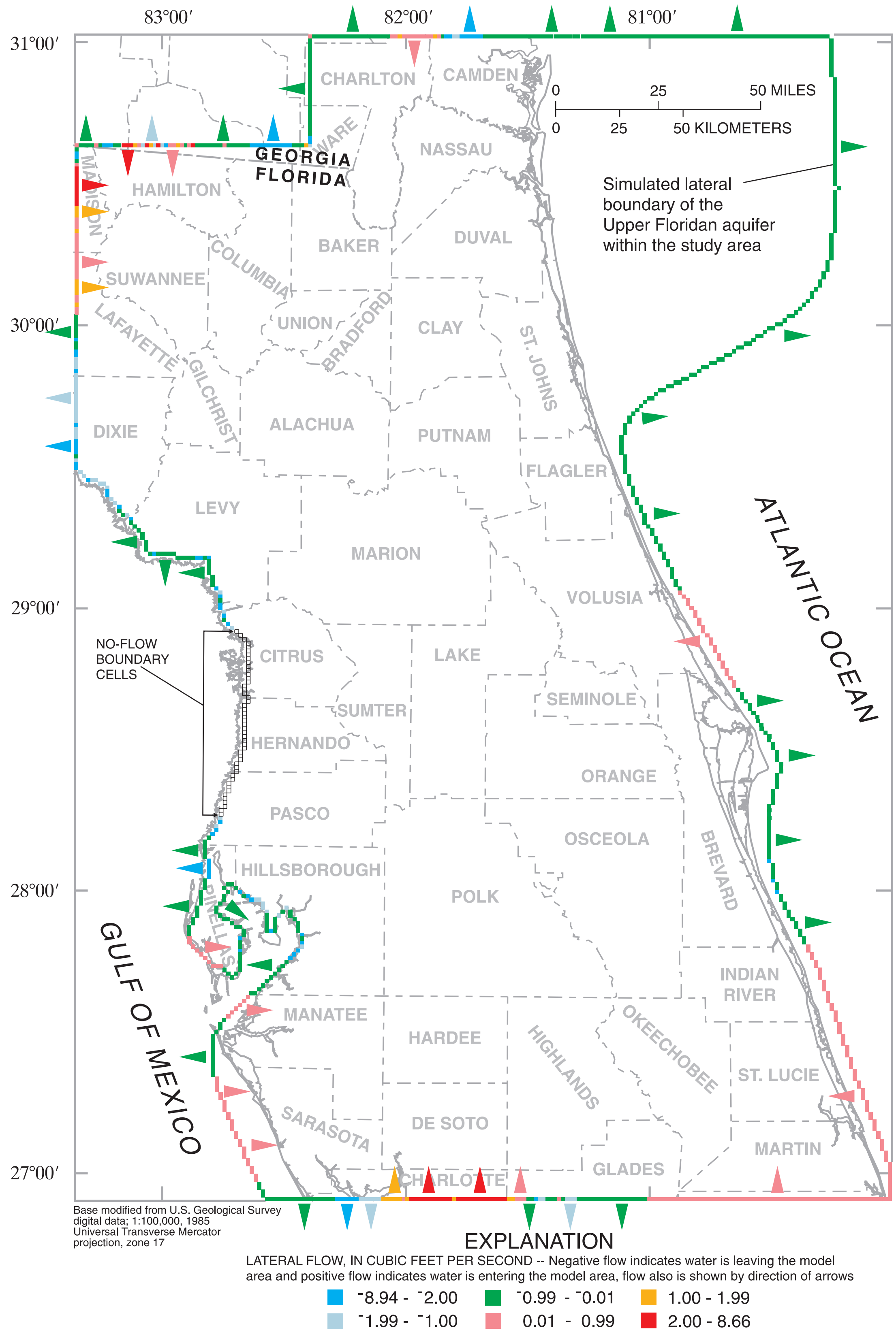


Figure 60. Simulated lateral flow to and from the Upper Floridan aquifer across model boundaries, average August 1993 through July 1994 conditions.

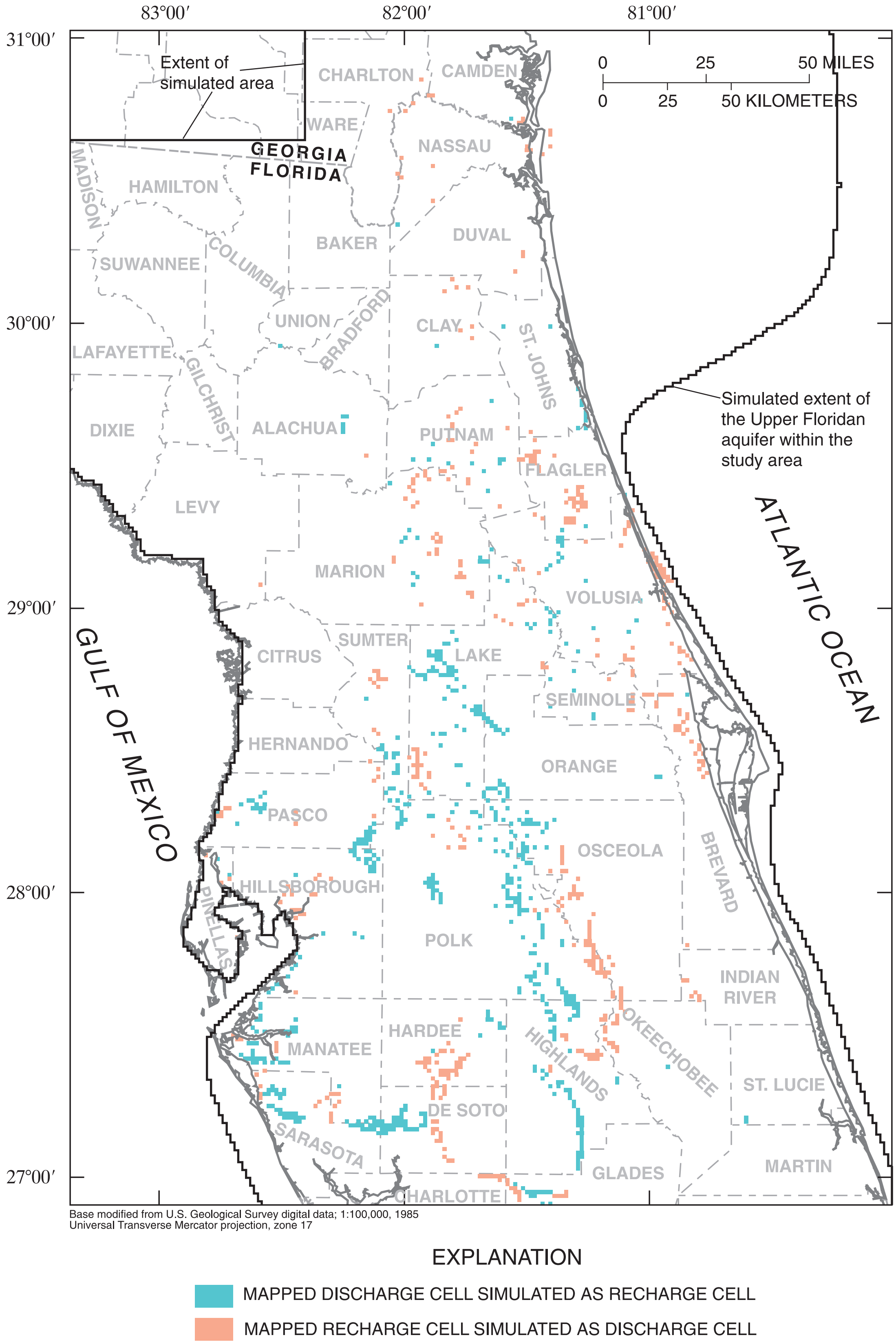


Figure 61. Location of differences between simulated and estimated recharge and discharge cells in the Upper Floridan aquifer, average August 1993 through July 1994 conditions.

Net recharge rates to the aquifer, which ranged from 0 to 24 in/yr (fig. 62), were rounded off to integers. Cells with specified heads along lateral boundaries of the UFA were not assigned recharge rates (fig. 62). The highest recharge rate, 24 in/yr, was simulated in parts of Suwannee and Columbia Counties. The average of all net recharge rates was about 13.6 in/yr for 6,364 cells in the unconfined areas of the UFA (approximately 5,700 mi^2). Total recharge to unconfined areas of the UFA was about 5,720 ft^3/s.

Spring Flow

Flow from springs (fig. 22) located outside river cells was simulated by drain cells; flow from springs in river cells was simulated as the flow from the aquifer to the river (fig. 59). Spring-pool elevation (table 12) was used as the drain-cell elevation. The simulated spring-pool elevation of springs in river cells was the computed river stage of the cell. Conductance at either drain or river cells was adjusted to reduce the difference between estimated or measured and simulated spring flow.

Of the 156 springs in the study area, 130 had flows simulated with a residual (difference between measured or estimated and simulated flow) of less than 5 ft^3/s; 11 spring flows were simulated with a residual between 5 and 10 ft^3/s; 10 spring flows were simulated with a residual between 10 and 20 ft^3/s; and 5 had residuals greater than 20 ft^3/s. The largest residuals occurred at springs simulated as river cells. Simulated flows at Blue Springs and Alapaha Rise (springs 1 and 2, respectively, fig. 22) were underestimated by about 28 and 54 ft^3/s, respectively (table 12). Simulated spring flow was 96 percent of the total estimated 6,380 ft^3/s spring flow for 1993-94.

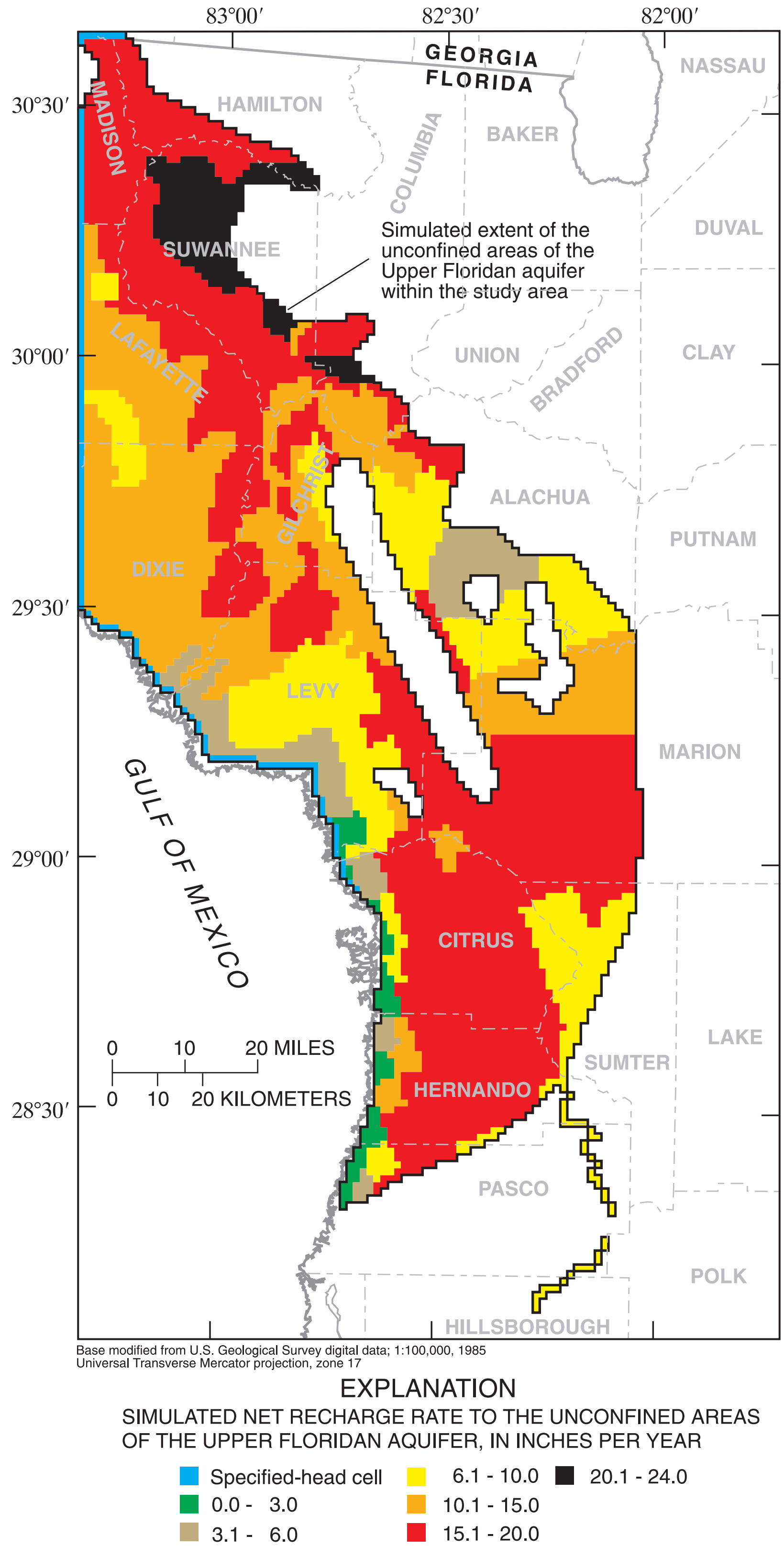


Figure 62. Simulated recharge rates to the unconfined areas of the Upper Floridan aquifer, average August 1993 through July 1994 conditions.

Table 12. Comparison of measured or estimated and residual flows from Upper Floridan aquifer springs, average August 1993 through July 1994 conditions

[Spring number refers to figure 22. Row and column refer to model grid. Flows from springs in the same row and column were combined. River cells: WNW, Withlacoochee River in northwest Florida; WWC, Withlacoochee River in west-central Florida; SUR, Suwannee River; ICH, Ichetucknee River; STR, Steinhatchee River; SFR, Santa Fe River; WAC, Waccasassa River; and HIR, Hillsborough River. Springs simulated as river cells are indicated by the name of the nearest river; drain, indicates spring was simulated as drain cell. Residual flow is simulated flow minus measured or estimated flow; ft^3/s, cubic feet per second]

Spring number	Spring name	Row	Column	River cell	Measured or estimated flow (ft^3/s)	Residual flow (ft^3/s)	Pool elevation or river stage (feet)
1	Blue Spring near Madison	41	7	WNW	118.0	-28.2	42.0
2	Alapaha Rise near Fort Union	44	17	SUR	427.0	-54.1	36.2
3	Holton Spring near Fort Union	44	19	drain	12.5	.0	38.3
4	Suwannee Springs near Live Oak	47	27	SUR	9.8	5.2	41.5
5, 6	Suwanacoochee Spring and Ellaville Spring at Ellaville	48	12	SUR	112.0	-.8	33.0
7	Falmouth Spring at Falmouth	49	14	drain	134.0	7.8	32.5
8	White Sulphur Springs at White Springs	52	37	drain	42.3	11.1	50.0
9	Charles Springs near Dell	63	8	drain	4.7	-.1	24.5
10	Allen Mill Pond Spring near Dell	64	7	SUR	12.2	-1.1	23.8
11	Wadesboro Spring near Orange Park	65	103	drain	1.0	.1	24.0
12	Blue Spring near Dell	66	8	SUR	70.0	-16.0	23.6
13	Peacock Springs	67	14	drain	81.1	.4	19.0
14	Telford Spring at Luraville	68	12	SUR	35.8	-3.8	21.6
15	Running Springs (East and West) near Luraville	68	15	SUR	88.0	-.4	19.9
16	Convict Spring near Mayo	69	16	SUR	1.1	.2	19.6
17	Royal Spring near Alton	70	17	SUR	1.9	-.3	19.0
18	Owens Spring	72	19	SUR	43.3	-1.2	17.4
19	Mearson Spring near Mayo	73	20	SUR	51.0	-1.2	17.0
20	Troy Spring near Branford	75	22	SUR	132.0	-18.3	16.0
21	Little River Springs near Branford	76	24	SUR	67.0	-7.8	14.9
22	Ruth Spring near Branford	76	23	drain	7.5	.1	16.5
23	Green Cove Springs at Green Cove Springs	77	106	drain	3.0	.1	21.0
24, 25	Ichetucknee Head Spring near Fort White and Cedar Head Spring	77	37	drain	49.0	6.9	22.0
26-29	Blue Hole, Roaring, Singing, Boiling, Mill Pond, Grassy Hole, and Coffee Springs (parts of Ichetucknee Springs)	78	37	ICH	258.0	.5	19.0
30	Branford Springs at Branford	79	26	SUR	35.8	-5.3	13.2
31	Jamison Spring	81	37	drain	3.0	.0	16.5
32	Hornsby Spring near High Springs	87	48	drain	49.8	1.3	30.5
33, 34	Turtle Spring near Hatchbend and Fletcher Spring	87	29	SUR	61.9	-10.1	9.3
35	Steinhatchee Spring near Clara	87	2	STR	.7	.5	21.1
36	Ginnie Spring near High Springs	88	41	SFR	57.1	-.9	23.3
37	Blue Springs near High Springs (including Lilly Springs)	89	42	drain	41.2	.3	24.5
38	Poe Springs near High Springs	89	44	SFR	53.6	-.3	26.3
39	Rock Bluff Springs near Bell	91	27	SUR	33.2	-7.2	9.0
40	Guaranto Spring near Rock Bluff Landing	92	26	SUR	12.0	-1.6	7.9
41	Crescent Beach Submarine Spring	94	135	drain	30.0	12.6	0.5

Table 12. Comparison of measured or estimated and residual flows from Upper Floridan aquifer springs, average August 1993 through July 1994 conditions--Continued

[Spring number refers to figure 22. Row and column refer to model grid. Flows from springs in the same row and column were combined. River cells: WNW, Withlacoochee River in northwest Florida; WWC, Withlacoochee River in west-central Florida; SUR, Suwannee River; ICH, Ichetucknee River; STR, Steinhatchee River; SFR, Santa Fe River; WAC, Waccasassa River; and HIR, Hillsborough River. Springs simulated as river cells are indicated by the name of the nearest river; drain, indicates spring was simulated as drain cell. Residual flow is simulated flow minus measured or estimated flow; ft^3/s, cubic feet per second]

Spring number	Spring name	Row	Column	River cell	Measured or estimated flow (ft^3/s)	Residual flow (ft^3/s)	Pool elevation or river stage (feet)
42, 43	Lumbercamp Springs and Sun Springs near Wannee	97	26	drain	46.3	-1.7	4.0
44	Hart Springs near Wilcox	100	25	drain	90.8	-2.0	4.2
45	Otter Springs near Wilcox	102	25	drain	16.0	-.3	2.0
46	Whitewater Springs	103	107	drain	1.2	.2	23.5
47	Copper Springs near Oldtown (including Little Copper Spring)	104	23	SUR	25.4	-6.8	4.7
48	Bell Springs	105	25	drain	5.1	-.1	2.0
49	Fannin Springs near Wilcox (including Little Fannin Spring)	106	26	drain	97.7	-.3	.5
50	Satsuma Spring	111	106	drain	1.1	.0	18.0
51	Blue Springs near Orange Springs	112	94	drain	.5	.0	31.0
52	Orange Spring at Orange Springs	112	89	drain	2.0	-.5	54.5
53	Camp Seminole Spring at Orange Springs	113	88	drain	.8	-.4	54.5
54	Welaka Spring near Welaka	114	106	drain	1.0	-1.0	11.0
55	Manatee Spring near Chiefland	113	23	drain	187.0	-9.3	2.8
56	Mud Spring near Welaka	116	106	drain	2.3	.2	8.3
57	Blue Spring near Bronson	116	40	WAC	8.0	-.5	38.4
58	Beecher Springs near Fruitland	117	107	drain	6.3	.0	2.0
59	Croaker Hole Spring near Welaka	118	105	drain	90.3	1.5	6.8
60	Tobacco Patch Landing Spring Group near Fort McCoy	118	90	drain	1.0	.0	30.8
61	Wells Landing Springs near Fort McCoy	119	90	drain	5.0	-.1	30.8
62	Salt Springs near Eureka	124	102	drain	79.0	.3	1.8
63	Wekiva Springs near Gulf Hammock	129	43	drain	45.4	-.2	24.5
64	Silver Glen Springs near Astor	132	108	drain	100.0	-21.2	1.9
65	Sweetwater Springs along Juniper Creek	134	106	drain	12.5	2.5	7.0
66	Silver Springs near Ocala	134	81	drain	640.0	-19.7	40.0
67, 68	Morman Branch Seepage into Juniper Creek and Juniper Creek Tributary near Astor	136	107	drain	3.0	3.3	14.0
69, 70	Juniper Springs and Fern Hammock Springs near Ocala	136	103	drain	18.8	-10.9	23.5
71	Ponce de Leon Springs near De Land	140	125	drain	24.3	-.6	4.0
72	Rainbow Springs near Dunnellon	142	57	drain	637.0	-16.6	30.8
73	Alexander Springs near Astor	144	112	drain	113.0	-10.6	10.5
74	Mosquito Springs Run, Alexander Springs Wilderness	147	121	drain	2.0	-.6	16.0
75	Wilson Head Spring near Holder	151	64	WWC	1.9	.5	29.4
76	Blue Spring near Holder	151	65	WWC	10.6	.1	29.7
77	Gum Springs near Holder	152	70	drain	67.6	3.5	35.5
78	Camp La No Che Springs near Paisley	153	114	drain	1.0	-.3	41.3
79	Blue Spring near Orange City	153	127	drain	135.0	-8.9	2.5

Table 12. Comparison of measured or estimated and residual flows from Upper Floridan aquifer springs, average August 1993 through July 1994 conditions--Continued

[Spring number refers to figure 22. Row and column refer to model grid. Flows from springs in the same row and column were combined. River cells: WNW, Withlacoochee River in northwest Florida; WWC, Withlacoochee River in west-central Florida; SUR, Suwannee River; ICH, Ichetucknee River; STR, Steinhatchee River; SFR, Santa Fe River; WAC, Waccasassa River; and HIR, Hillsborough River. Springs simulated as river cells are indicated by the name of the nearest river; drain, indicates spring was simulated as drain cell. Residual flow is simulated flow minus measured or estimated flow; ft^3/s, cubic feet per second]

Spring number	Spring name	Row	Column	River cell	Measured or estimated flow (ft^3/s)	Residual flow (ft^3/s)	Pool elevation or river stage (feet)
80	Blackwater Springs near Cassia	158	117	drain	1.4	-1.4	38.5
81	Crystal River Spring Group	157	46	drain	613.2	50.6	1.5
82	Little Jones Creek Head Spring near Wildwood	159	79	drain	8.0	.1	42.0
83	Green Springs	160	133	drain	.3	.0	17.0
84	Gemini Springs near DeBary (all 3)	160	129	drain	10.5	-.8	2.8
85	Little Jones Creek Spring No. 2 near Wildwood	160	79	drain	5.0	.0	42.0
86	Messant Spring near Sorrento	160	117	drain	12.0	-.6	30.0
87	Seminole Springs near Sorrento	161	115	drain	37.0	-22.5	40.0
88	Palm Springs Seminole State Forest	161	120	drain	.5	.2	28.5
89	Little Jones Creek Spring No. 3 near Wildwood	161	80	drain	3.0	.0	43.0
90	Droty Springs near Sorrento	162	116	drain	.6	-.6	39.0
91	Halls River Head Spring	162	47	drain	4.8	-.2	1.5
92	Island Spring near Sanford	162	122	drain	6.4	.0	16.0
93	Halls River Springs	163	46	drain	102.2	.5	1.5
94-96	Homosassa Springs, Southeast Fork of Homosassa Springs, and Trotter Spring at Homosassa Springs	164	47	drain	120.7	.8	1.5
97	Fenney Springs near Coleman, Head Spring of Shady Brook Creek	164	82	drain	15.0	-3.0	48.0
98, 99	Shady Brook Creek Springs No. 2 and 3	165	82	drain	5.8	.0	44.5
100	Shady Brook Creek Spring No. 4	166	80	drain	2.9	.1	46.0
101	Sulphur Camp Springs	166	116	drain	.6	-.1	34.0
102	Hidden River Springs near Homosassa (including Hidden River Head Spring)	166	47	drain	6.7	-.1	2.0
103	Rock Springs near Apopka	167	116	drain	53.0	-1.5	26.5
104	Shady Brook Creek Spring No. 5	167	79	drain	2.9	.2	47.0
105	Bugg Spring at Okahumpka	167	91	drain	8.6	-.1	63.0
106, 108	Blue Springs near Yalaha and Holiday Springs at Yalaha	168	96	drain	6.6	-1.9	65.0
107	Mooring Cove Springs near Yalaha	168	95	drain	.4	-.4	68.5
109	Potter Spring near Chassahowitzka (including Ruth Spring)	168	46	drain	14.4	-.2	1.5
110	Witherington Spring near Apopka	169	117	drain	1.0	.0	32.0
111	Salt Creek Head Spring	169	47	drain	.4	.0	1.5
112	Lettuce Creek Spring	169	48	drain	3.7	-.1	2.5
113, 115	Crab Creek Spring and Chassahowitzka Springs near Chassahowitzka	170	48	drain	99.6	-.3	1.5
114, 119	Unnamed Tributary above Chassahowitzka Springs and Baird Creek Head Spring near Chassahowitzka	170	47	drain	23.7	.0	1.5
116	Wekiwa Springs in State Park near Apopka	171	119	drain	56.5	-.9	13.5
117	Miami Springs near Longwood	171	120	drain	4.0	-.1	15.0

Table 12. Comparison of measured or estimated and residual flows from Upper Floridan aquifer springs, average August 1993 through July 1994 conditions--Continued

[Spring number refers to figure 22. Row and column refer to model grid. Flows from springs in the same row and column were combined. River cells: WNW, Withlacoochee River in northwest Florida; WWC, Withlacoochee River in west-central Florida; SUR, Suwannee River; ICH, Ichetucknee River; STR, Steinhatchee River; SFR, Santa Fe River; WAC, Waccasassa River; and HIR, Hillsborough River. Springs simulated as river cells are indicated by the name of the nearest river; drain, indicates spring was simulated as drain cell. Residual flow is simulated flow minus measured or estimated flow; ft^3/s, cubic feet per second]

Spring number	Spring name	Row	Column	River cell	Measured or estimated flow (ft^3/s)	Residual flow (ft^3/s)	Pool elevation or river stage (feet)
118	Lake Jesup Spring near Wagner	171	131	drain	.6	.6	32.0
120	Clifton Springs near Oviedo	172	133	drain	1.5	.9	30.0
121	Starbuck Spring near Longwood	172	124	drain	12.3	-.2	23.0
122	Beteejay Lower Spring near Chassahowitzka (including Beteejay Head Spring)	171	46	drain	7.3	.0	1.8
123, 125	Palm Springs and Sanlando Springs near Longwood	172	123	drain	22.6	.0	23.0
124	Rita Maria Spring near Chassahowitzka	171	47	drain	3.3	.0	2.0
126, 127	Unnamed Spring No. 10, 11, 12, Ryle Creek Lower Spring, and Ryle Creek Head Spring near Bayport	172	45	drain	27.3	1.0	1.5
128	Blue Run Head Spring near Chassahowitzka	172	46	drain	4.6	.0	1.2
129	Double Run Road Seepage near Astatula	173	101	drain	2.0	.1	67.0
130	Unnamed Spring No. 8	173	44	drain	4.9	.2	1.5
131	Blind Creek Springs (including unnamed spring No. 7 and Blind Creek Head Spring)	174	44	drain	42.7	-15.1	1.3
132	Apopka (Gourdneck) Spring near Oakland	181	105	drain	31.4	-1.2	69.0
133	Unnamed Spring No. 6	182	44	drain	2.8	.0	1.5
134, 135	Salt Spring and Mud Spring near Bayport	182	45	drain	39.3	-1.5	1.5
136, 137	Jenkins Creek Spring No. 5 and Unnamed Spring No. 4	184	44	drain	21.6	-.1	1.5
138	Weeki Wachee Springs near Brooksville	184	48	drain	129.0	1.9	9.8
139	Unnamed Spring No. 2	188	43	drain	.7	.0	8.0
140, 142, 143	Boat Spring, Unnamed Spring No. 1, and Magnolia Springs at Aripeka	190	42	drain	7.2	.0	1.5
141	Bobhill Springs	190	43	drain	1.8	.0	8.0
144	Unnamed Spring No. 3 near Aripeka	193	41	drain	17.8	-1.4	1.5
145	Horseshoe Spring near Hudson	193	40	drain	9.7	-3.5	.5
146	Salt Springs near Port Richey	200	38	drain	8.2	2.3	1.0
147	Crystal Springs near Zephyrhills	209	72	HIR	37.0	-5.1	52.0
148	Sulphur Springs at Sulphur Springs	220	55	drain	25.0	-.5	5.0
149	Lettuce Lake Spring	221	61	drain	8.3	-.4	14.5
150, 151	Six-Mile Creek Spring and Eureka Springs near Tampa	221	62	drain	2.6	-.1	14.5
152	Buckhorn Spring near Riverview	230	64	drain	15.0	-3.1	10.0
153, 154	Lithia Springs Minor and Lithia Springs Major near Lithia	232	69	drain	39.1	-5.0	9.5
155	Little Salt Spring near Murdock	289	68	drain	.9	.0	25.0
156	Warm Mineral Springs near Woodmere	290	67	drain	6.7	-.1	6.0
	Totals				6,383.8	-224.7	

Potentiometric Surfaces

The simulated potentiometric surface of the IAS for the average August 1993 through July 1994 conditions generally reflects the main features of the estimated potentiometric surface of the IAS (figs. 17 and 63). The potentiometric-surface highs in southwest and south-central Polk County were reasonably simulated, as were the decreasing heads west and south of the potentiometric highs. A potentiometric-surface high was simulated in northwest Highlands County; there were an insufficient number of measured water levels to determine whether this high in the estimated potentiometric surface exists. The RMS residual between simulated and computed heads in the IAS was 3.47 ft, with differences ranging from -9.62 ft in Charlotte County to 6.89 ft in Sarasota County. About 85 percent of the water-level measurements in the IAS were simulated within 5 ft. The largest residuals in the IAS were located in the parts of Charlotte, Sarasota, and De Soto Counties (figs. 17 and 63).

The simulated potentiometric surface of the UFA for 1993-94 replicated the main features of the estimated potentiometric surface (figs. 18 and 64). Both simulated and estimated potentiometric surfaces of the UFA show the potentiometric highs in Lafayette, Gilchrist, northwest Putnam, southeast Levy, central Volusia, east-central and west-central Pasco, and north-central Polk Counties.

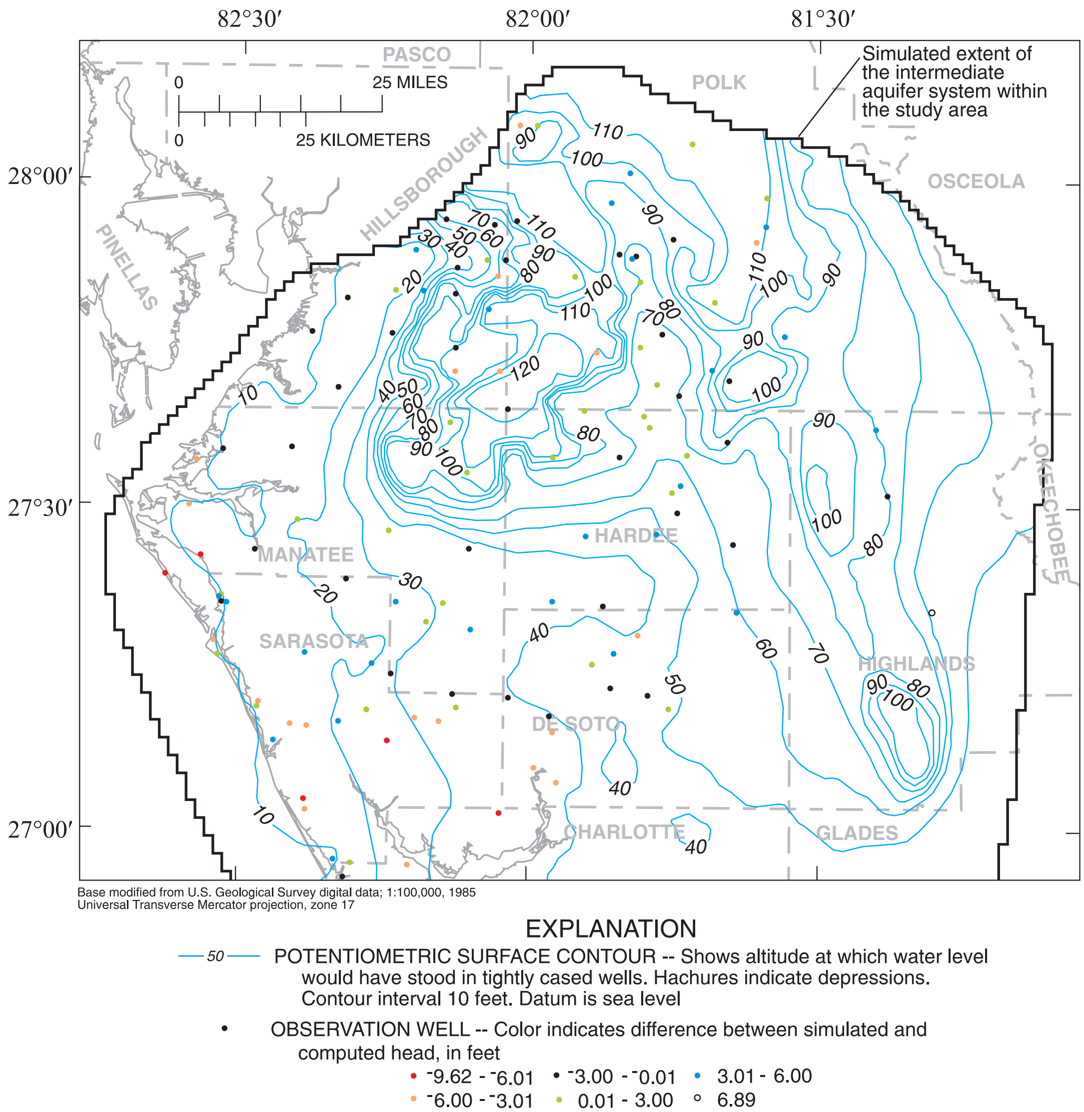
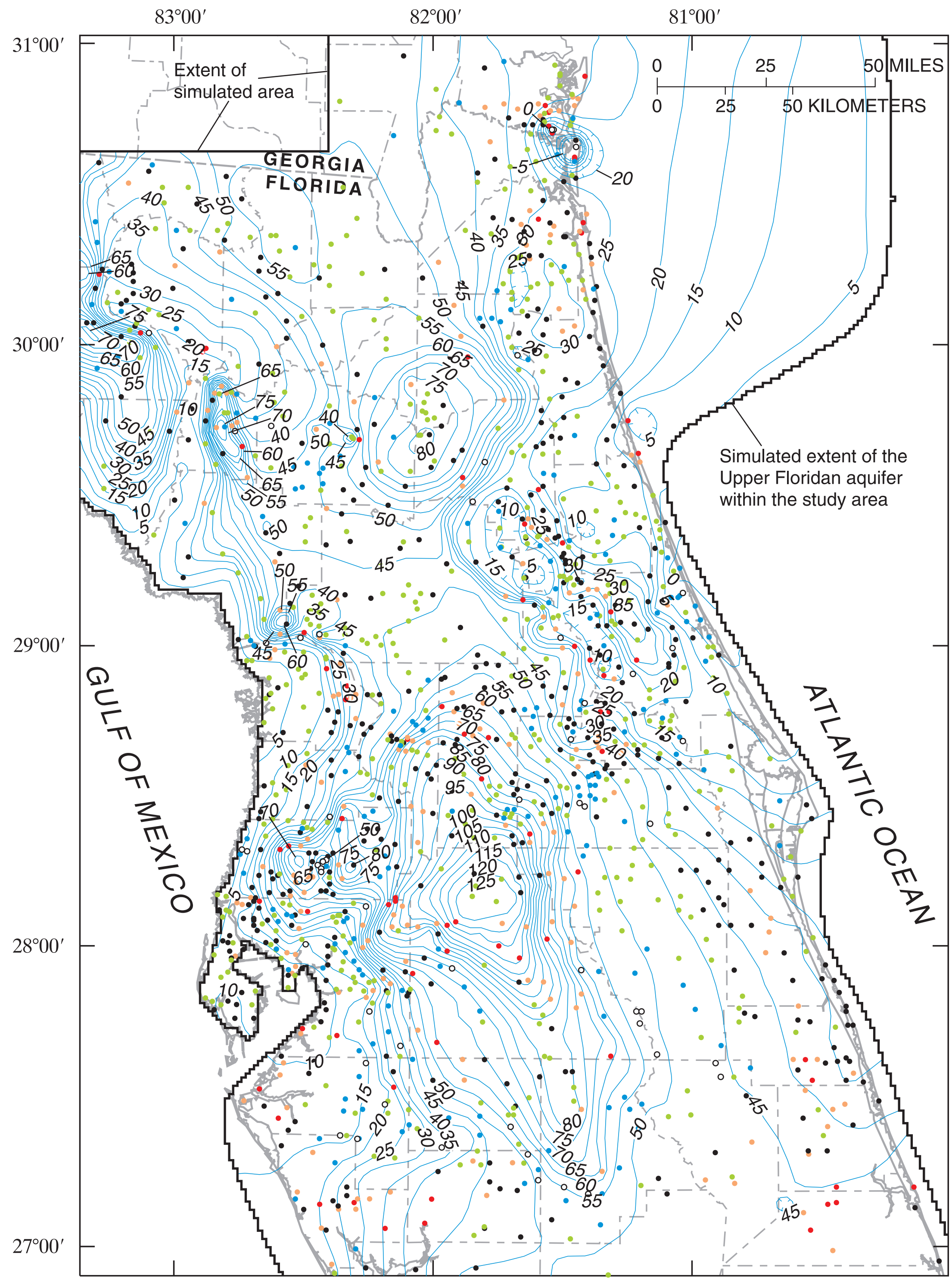


Figure 63. Simulated potentiometric surface of the intermediate aquifer system, average August 1993 through July 1994 conditions.



Base modified from U.S. Geological Survey digital data; 1:100,000, 1985
Universal Transverse Mercator projection, zone 17

EXPLANATION

—50— POTENTIOMETRIC SURFACE CONTOUR -- Shows altitude at which water level would have stood in tightly cased wells. Hachures indicate depressions. Contour interval 5 feet. Datum is sea level

• OBSERVATION WELL -- Color indicates difference between simulated and computed head, in feet

- ⁻9.90 - ⁻6.01
- ⁻6.00 - ⁻3.01
- ⁻3.00 - ⁻0.01
- 0.01 - 3.00
- 3.01 - 6.00
- 6.01 - 9.90

Figure 64. Simulated potentiometric surface of the Upper Floridan aquifer, average August 1993 through July 1994 conditions.

The simulated surface shows the depressions present in numerous areas across the Florida peninsula. Ground-water flow in the UFA was simulated reasonably well by the model, including the locations of the main recharge and discharge areas of the UFA. The RMS residual between simulated and computed heads in the UFA was 3.41 ft, with differences ranging from -9.90 ft in Manatee County to 9.90 ft in Camden County, Ga. About 85 percent of water-level measurements in the UFA were simulated within 5 ft.

The RMS residual between simulated and computed heads in the LFA for 1993-94 was 2.89 ft, with differences ranging from -6.90 ft in Okeechobee County to 5.21 ft in Orange County. About 91 percent of the water-level measurements in the LFA were simulated within 5 ft (fig. 65). Differences in heads between the UFA and the LFA (figs. 64 and 65) in areas where the MSCU is present are smaller than in areas where the aquifers are separated by the MCU, implying that the hydraulic gradients between the two aquifers are determined mainly by the permeability of the intervening confining unit. Small differences in heads exist between the two aquifers in areas where no MCU or MSCU is present.

Ground-Water Flow Budget

Volumetric flow rates simulated in the IAS, UFA, and LFA were computed to quantify contributions of each component of the ground-water flow system (fig. 66). Separate net flow rates were computed for the unconfined and confined areas of the UFA. Spring flow represented the largest discharge flux in the model area (4,559 ft^3/s simulated from drain cells and 1,600 ft^3/s from river cells). The second largest discharge was from water withdrawals from all aquifers (3,860 ft^3/s). Total recharge to the UFA, from both net recharge to the unconfined areas and from leakage through the IAS-ICU layer, was 11,855 ft^3/s.

Sensitivity Analyses

Sensitivity analyses were conducted to assess the response of simulated heads to specified changes in selected model parameters. Those parameters considered for sensitivity analysis included the transmissivities of the IAS, UFA, and LFA; the leakances of the upper confining unit of the IAS, the ICU, and the MSCU; the net recharge rate to unconfined areas of the UFA; and the specified heads along segments of lateral boundaries of the UFA. Parameters were varied from the values used to achieve calibration in order to assess the response of simulated heads to changes in model parameters. The RMS errors of the differences between simulated and computed heads were used as the criterion to assess the effects of changes made to parameter values used in the calibrated model.

The effect each parameter had on simulation results was assessed by varying independently from 0.2 to 2.0 times the values of transmissivity and net recharge rates, from 0.5 to 1.5 times the specified heads along lateral boundaries of the UFA, and from 0.01 to 10.0 times the leakance values (fig. 67). These ranges of values may not include all the uncertainties associated with some of the parameters; the ranges were aimed at providing a perspective on parameter sensitivity.

The sensitivity analyses indicated that simulated heads were sensitive to changes in specific ranges of values for leakance and transmissivity. Simulated heads were more sensitive to changes in leakance values of the upper confining unit of the IAS, the ICU, and the MSCU between 1.0×10^{-5} and 1.0×10^{-3} (ft/d)/ft than to changes in leakance values either less than 1.0×10^{-5} or greater than 1.0×10^{-3} (ft/d)/ft (fig. 67). Simulated heads were sensitive to all transmissivity value ranges tested for the UFA. Simulated heads were more sensitive to changes in transmissivity values of the LFA greater than 100,000 ft^2/d than to changes in transmissivities less than or equal to 100,000 ft^2/d. Changes in net recharge rates to unconfined areas of the UFA of 10 in/yr or greater caused larger RMS residuals than changes to rates less than 10 in/yr. Changes in RMS residuals were not sensitive to changes in transmissivity values of the IAS or to changes in specified heads in the UFA (fig. 67).

Effects of Projected 2020 Ground-Water Withdrawals

The calibrated model was used to evaluate the potential effects of projected 2020 ground-water withdrawals on water levels in the IAS, UFA, and LFA and on spring flow from the UFA. Boundary conditions simulating the greatest and smallest possible drawdowns that could occur were used to bracket the effects of projected 2020 withdrawals.

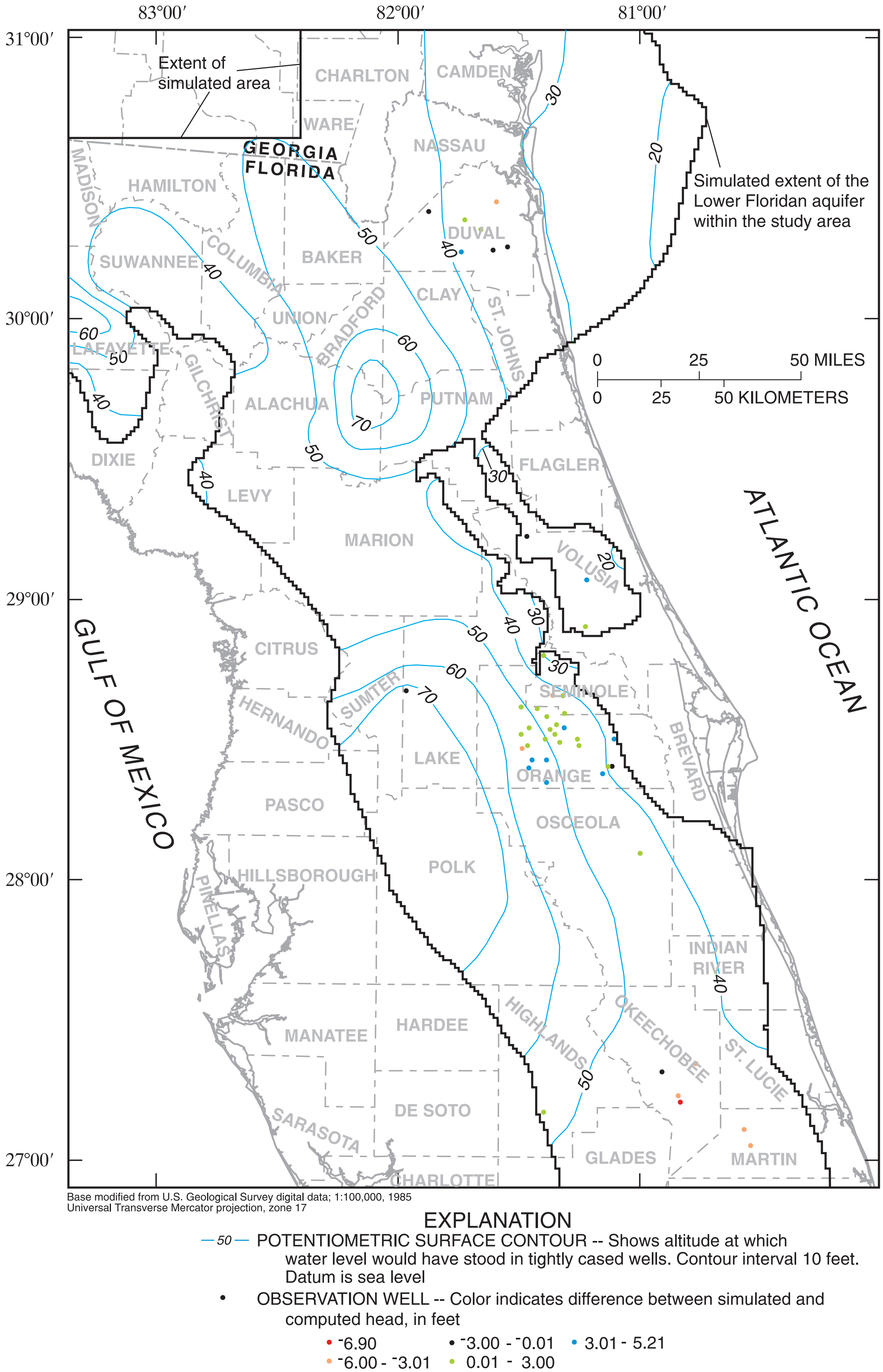
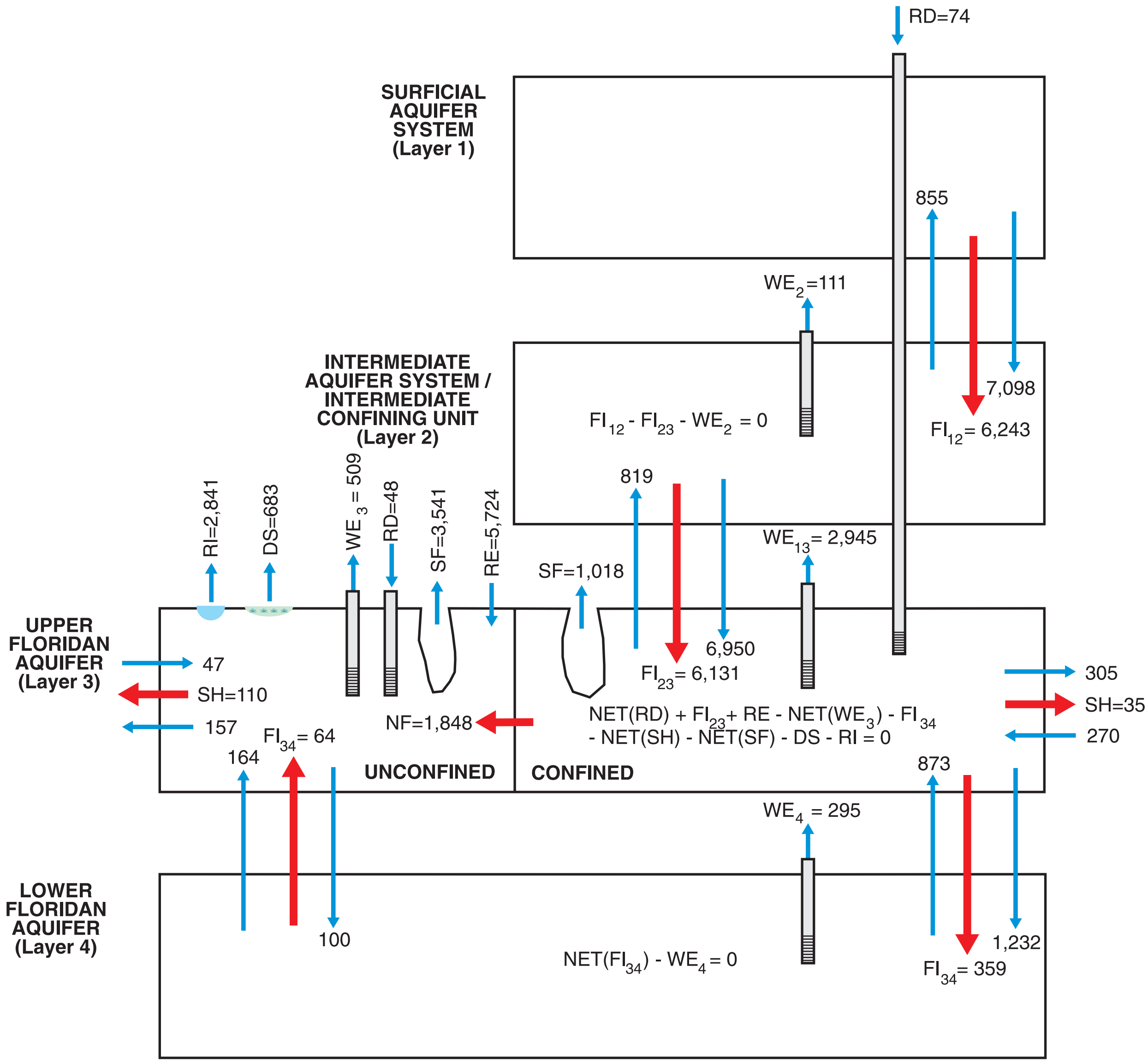


Figure 65. Simulated potentiometric surface of the Lower Floridan aquifer, average August 1993 through July 1994 conditions.



EXPLANATION

FLOW ACROSS BOUNDARY
NET FLOW ACROSS BOUNDARY
NF NET FLOW ACROSS UNCONFINED/CONFINED BOUNDARY
WE_N WELL WITHDRAWALS FROM LAYER N
FI_{NM} NET FLOW ACROSS INTERFACE OF LAYERS N AND M
SF SPRING FLOW FROM LAYER 3
DS DISCHARGE TO SWAMPS
SH FLOW ACROSS SPECIFIED-HEAD BOUNDARY IN LAYER 3
RI NET FLOW FROM AQUIFER TO RIVER
RD RECHARGE FROM DRAINAGE AND INJECTION WELLS IN LAYER 3
RE NET RECHARGE FROM RAINFALL INFILTRATION
NET NET FLOW FROM UNCONFINED/CONFINED AREAS IN LAYER 3
691 FLOW RATE, IN CUBIC FEET PER SECOND

Figure 66. Simulated volumetric flow budget for the intermediate aquifer system, Upper Floridan aquifer, and Lower Floridan aquifer, average August 1993 through July 1994 conditions.

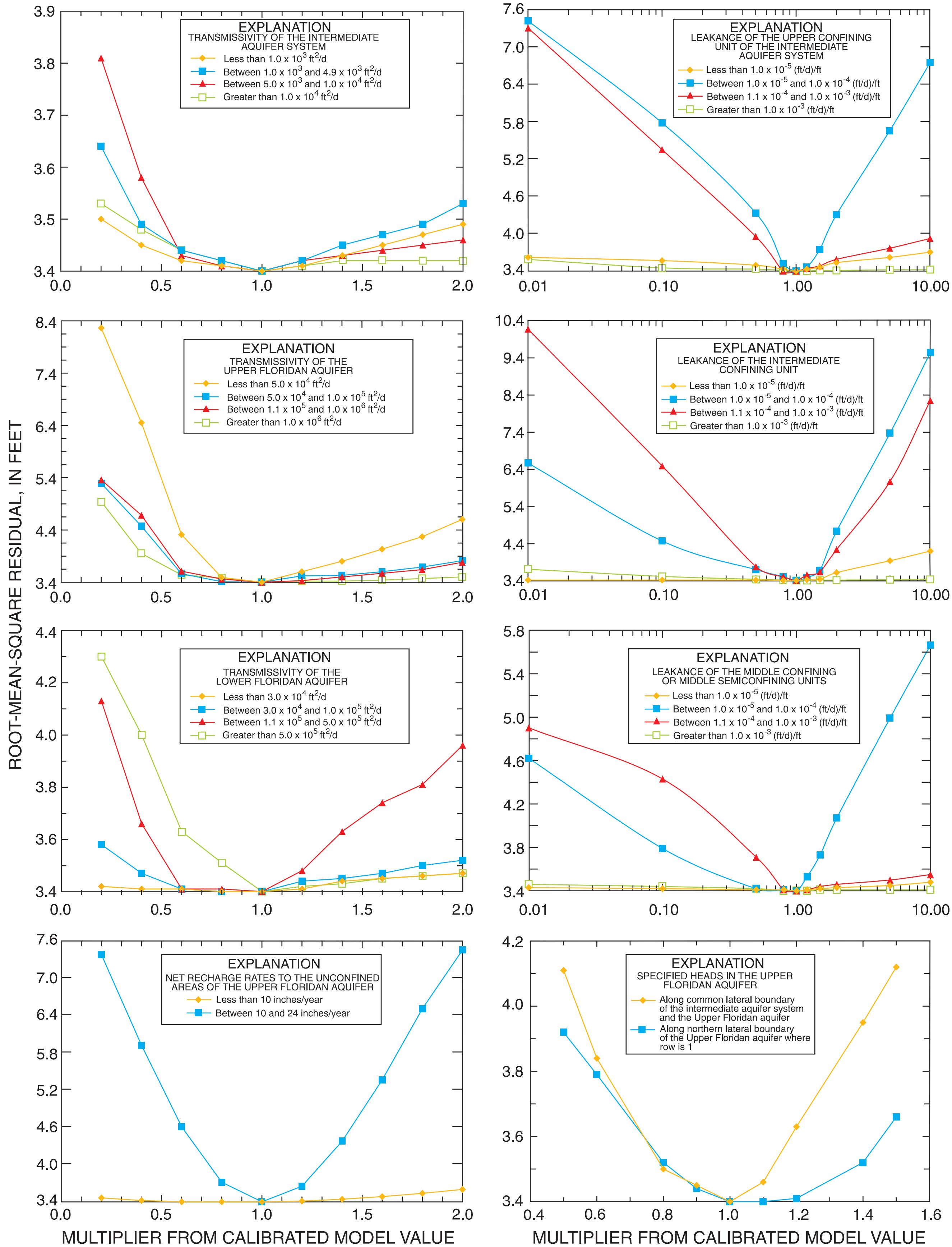


Figure 67. Model sensitivity to changes in selected model parameters.

Projected 2020 Ground-Water Withdrawals and Artificial Recharge

Projected ground-water withdrawals from the IAS, UFA, and LFA for 2020 were estimated from the Water-Supply Assessment plans of the SJRWMD, SFWMD, SWFWMD, SRWMD (St. Johns River Water Management District, 1998; South Florida Water Management District, 1998; Southwest Florida Water Management District, 1998; Suwannee River Water Management District, 1998), water-use data for 1995, and USGS data. Measured and estimated pumping rates from wells in SWFWMD for 1995 were provided by SWFWMD (Tabitha Ostow, written commun., 2000). Water-use data from wells in SRWMD for 1995 were provided by SRWMD (Ronald Ceryak, written commun., 1999). Projected 2020 water-use data for municipal well fields in SJRWMD and SFWMD were estimated by the water-supply utilities, whereas other uses in SJRWMD and SFWMD were estimated from compiled 1995 water-use data from files of the SJRWMD, SFWMD, and USGS; and the Water-Supply Assessment plans. Projected 2020 withdrawal estimates were based on projected population increases from 1995 to 2020 and projected changes in water use trends.

Projected 2020 ground-water withdrawals for public-water supply, industrial and commercial, agricultural, and self-supplied domestic uses totaled 96 Mgal/d from the IAS; 2,989 Mgal/d from the UFA; and 308 Mgal/d from the LFA (table 13). These totals represent increases from 1993-94 water withdrawals of 33, 34, and 62 percent from the IAS, UFA, and LFA, respectively (tables 4 and 13). Orange County had the largest projected increase in withdrawals, from 211 Mgal/d in 1993-94 to 391 Mgal/d in 2020 (tables 4 and 13). The smallest increase, from 3.65 to 4.82 Mgal/d, was projected for Union County. Projected self-supplied domestic water use for 2020 was calculated based on 1995 estimates by Marella (1999) and by using multipliers for each county based on projected population increases. Projected ground-water withdrawals from self-supplied domestic wells in the IAS and UFA were approximately 17 and 196 Mgal/d, respectively (table 13).

Projected increases in withdrawal rates from the respective aquifers vary from one part of the study area to another. Ground-water withdrawals from the IAS are expected to increase from 72 Mgal/d in 1993-94 to 96 Mgal/d in 2020. The most substantial increases are projected in central Glades, northeast Charlotte, and west-central Sarasota Counties (figs. 38 and 68). Smaller increases are anticipated for north-central Sarasota and west-central Polk Counties. Ground-water withdrawals from the UFA are anticipated to increase from 2,226 Mgal/d in 1993-94 to 2,989 Mgal/d in 2020. In particular, total projected withdrawals in Orange, Seminole, and Volusia Counties are estimated to increase from 289 Mgal/d in 1993-94 to 485 Mgal/d in 2020 (tables 4 and 13). Projected increases in withdrawals from the UFA in St. Lucie and Duval Counties were 13 and 27 Mgal/d, respectively, from 1993-94 to 2020 rates. No significant increases in ground-water withdrawals are anticipated in southwest, south-central, northwest, or north-central Florida (figs. 39 and 69). Ground-water withdrawals from the LFA are anticipated to increase from 190 Mgal/d in 1993-94 to 308 Mgal/d in 2020 (tables 4 and 13). Projected withdrawals from the LFA in Orange and Duval Counties are expected to increase in 2020 by 69 and 21 Mgal/d, respectively, from 1993-94 rates (tables 4 and 13); increases in central Orange County and central Duval County are particularly apparent (figs. 40 and 70). Smaller increases are projected for Lake and Highlands Counties.

Recharge to the UFA from drainage wells for 2020 was estimated, assuming rainfall was equal to the 1961-90 average at NOAA stations near drainage wells (figs. 3 and 21), by using the weighted-average runoff coefficient of 0.478, and the procedure presented previously to calculate 1993-94 rates. Recharge from drainage wells was estimated to be about 62 Mgal/d (table 14). Recharge to the UFA through injection wells for 2020 in Alachua County was assumed to be 10.62 Mgal/d, the same as for the calibration period. The amount of recharge to the UFA from drainage wells is largely dependent on rainfall, but recharge from injection wells could increase with population. No relation, however, has been established that could be used to estimate recharge to the UFA from injection wells due to population increases.

Table 13. Projected 2020 ground-water withdrawals and uses, by county and by Water Management District, from the intermediate aquifer system, Upper Floridan aquifer, and Lower Floridan aquifer

[Source: St. Johns River Water Management District (SJRWMD); South Florida Water Management District (SFWMD); Southwest Florida Water Management District (SWFWMD); Suwannee River Water Management District (SRWMD); and US Geological Survey. All rates are in million gallons per day; -- indicates no wells are tapping the aquifer or aquifer is absent]

County	Intermediate aquifer system				Upper Floridan aquifer				Lower Floridan aquifer		
	Public-water supply	Industrial and commercial[a]	Agricultural	Domestic	Public-water supply	Industrial and commercial[a]	Agricultural	Domestic	Public-water supply	Industrial and commercial[a]	Agricultural
Alachua	--	--	--	--	39.97	7.46	24.52	9.16	--	--	--
Baker	--	--	--	--	1.22	.31	.24	1.55	0.55	--	0.12
Bradford	--	--	--	--	5.33	3.57	2.64	2.54	--	--	--
Brevard	--	--	--	--	8.09	1.02	10.51	.16	--	--	--
Charlotte	0.03	0.16	17.85	1.76	.56	--	5.47	--	--	--	--
Citrus	--	--	--	--	18.97	7.05	1.39	12.03	--	--	--
Clay	--	--	--	--	4.39	3.68	1.90	3.46	15.40	0.51	--
Columbia	--	--	--	--	7.03	4.43	14.42	6.96	--	--	--
DeSoto	2.03	.59	6.96	.79	1.01	.22	60.43	.03	--	--	--
Dixie	--	--	--	--	2.87	1.46	8.45	1.87	--	--	--
Duval	--	--	--	--	45.80	21.70	2.80	.04	89.76	16.92	.33
Flagler	--	--	--	--	5.00	.11	4.69	.11	--	--	--
Gilchrist	--	--	--	--	4.33	.63	43.20	2.05	--	--	--
Glades	--	--	9.48	.02	.80	--	13.66	--	--	--	.19
Hamilton	--	--	--	--	18.24	14.93	19.52	1.39	--	--	--
Hardee	.17	.12	6.86	.71	2.88	2.28	48.59	.02	--	--	--
Hernando	--	--	--	--	31.74	20.30	2.81	4.71	--	--	--
Highlands	.56	.30	15.14	.36	14.16	3.12	120.42	.02	--	.14	25.49
Hillsborough	.02	.01	.69	.76	79.38	18.32	76.05	13.00	--	--	--
Indian River	--	--	--	--	20.96	.07	34.94	.06	--	--	--
Lafayette	--	--	--	--	2.61	.42	16.96	1.27	--	--	--
Lake	--	--	--	--	90.11	25.55	40.65	2.25	3.54	.56	.53
Levy	--	--	--	--	5.65	6.03	62.99	5.62	--	--	--
Madison	--	--	--	--	.38	.37	11.17	.23	--	--	--
Manatee	.31	.39	1.76	3.61	18.52	1.96	93.30	.04	--	--	--
Marion	--	--	--	--	41.73	5.10	10.60	30.92	.01	--	.04
Martin	--	--	--	--	5.06	.58	10.58	--	--	--	--
Nassau	--	--	--	--	11.50	29.24	2.62	.09	--	1.29	--
Okeechobee	--	--	--	--	1.19	.71	32.68	.05	--	--	.49
Orange	--	--	--	--	207.34	15.85	17.93	19.85	128.81	1.31	.15
Osceola	--	--	--	--	30.44	1.95	54.81	11.32	9.04	--	.02
Palm Beach	--	--	--	--	1.38	--	--	--	--	--	--
Pasco	--	--	--	--	115.58	11.86	18.26	11.07	--	--	--
Pinellas	--	--	--	--	43.28	2.04	.58	6.11	--	--	--
Polk	.71	.82	4.11	1.25	103.69	76.27	127.23	8.51	.72	--	.61
Putnam	--	--	--	--	4.24	8.80	11.57	10.27	--	1.09	--
St. Johns	--	--	--	--	17.49	.02	29.20	1.39	--	--	--
St. Lucie	--	--	--	--	12.58	.39	13.26	.43	--	--	--
Sarasota	8.76	.96	.41	7.40	30.08	4.80	4.76	.06	--	--	--
Seminole	--	--	--	--	86.99	.36	6.71	6.56	10.44	--	--
Sumter	--	--	--	--	4.18	2.92	11.66	5.58	--	--	--
Suwannee	--	--	--	--	8.09	4.55	81.55	4.99	--	--	--
Union	--	--	--	--	1.57	.14	2.11	1.00			
Volusia	--	--	--	--	94.79	1.27	18.14	8.94	--	.18	.01
Camden, Ga.	--	--	--	--	3.52	49.82	.20	--	--	--	--
Charlton, Ga.	--	--	--	--	1.01	--	--	--	--	--	--
Total	**12.59**	**3.35**	**63.26**	**16.66**	**1,255.73**	**361.67**	**1,176.17**	**195.71**	**258.27**	**22.00**	**27.98**
Water Management District											
SJRWMD	--	--	--	--	615.96	103.59	193.62	75.43	196.13	20.58	1.16
SFWMD	--	.02	20.90	.40	102.36	16.07	234.40	18.81	62.14	1.42	26.82
SWFWMD	12.59	3.33	42.36	16.26	474.83	151.39	471.92	69.43	--	--	--
SRWMD	--	--	--	--	62.58	90.62	276.23	32.04	--	--	--
	Intermediate aquifer system	Upper Floridan aquifer	Lower Floridan aquifer	Total by aquifer	Public-water supply	Industrial and commercial	Agricultural	Domestic	Total by use		
Total	**95.86**	**2,989.28**	**308.25**	**3,393.39**	**1,526.59**	**387.02**	**1,267.41**	**212.37**	**3,393.39**		

[a]Includes mining, thermoelectric power generation, recreational, and landscape irrigation uses.

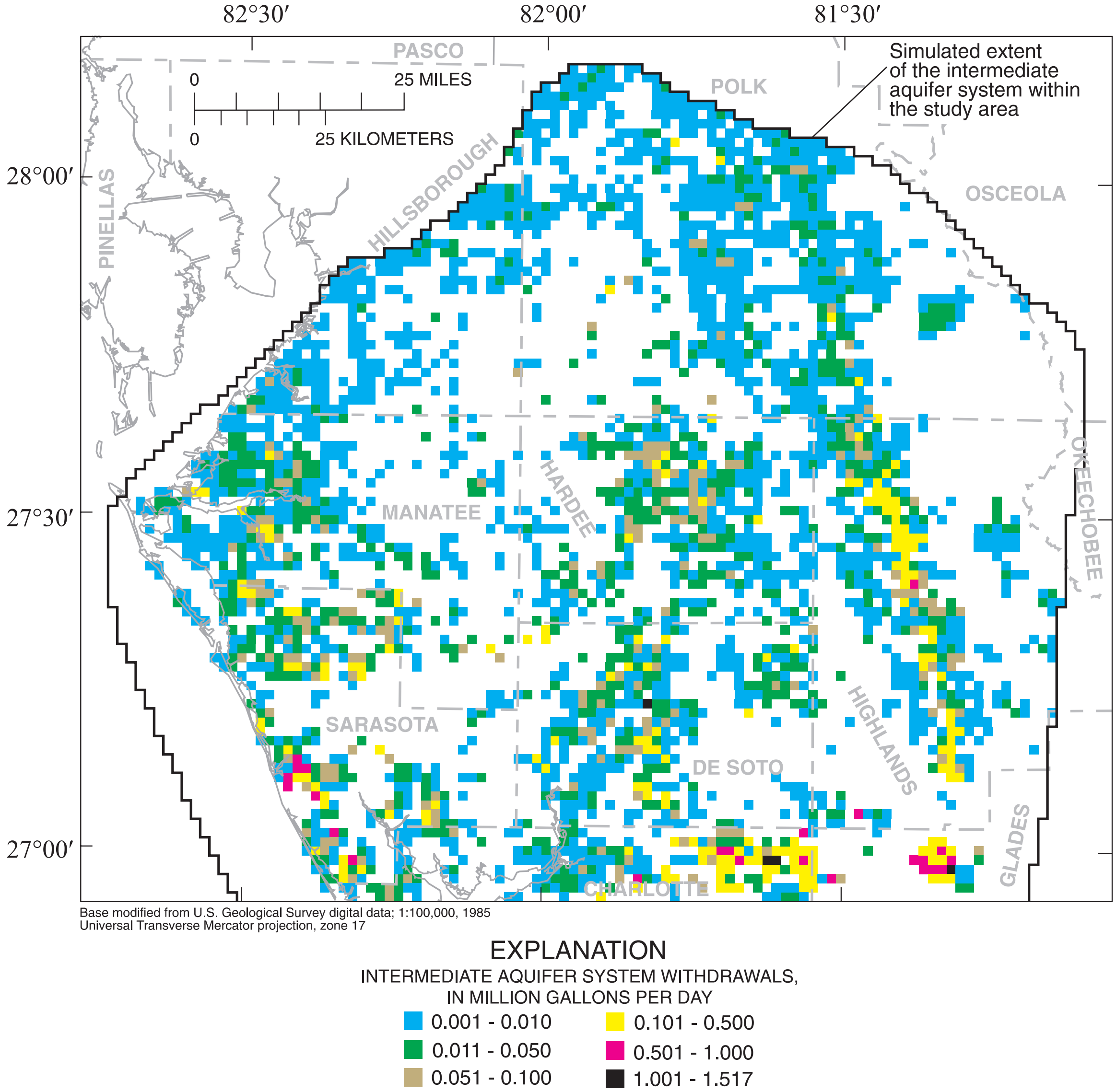


Figure 68. Projected 2020 ground-water withdrawal rates from the intermediate aquifer system.

Simulated 2020 Scenarios and Boundary Conditions

Specified heads interpolated from the estimated potentiometric-surface map (fig. 18) were applied along the lateral boundaries of the UFA for the 1993-94 steady-state calibration. Increased withdrawals in 2020 could potentially affect heads along the lateral boundaries of the model. Fluxes across the lateral boundaries may increase due to projected increases in withdrawals.

Consequently, conditions in 2020 were bracketed by simulating two scenarios, one with specified 1993-94 lateral boundary heads and another with specified 1993-94 lateral boundary fluxes. The 1993-94 specified-head boundaries allowed as much water as was needed to enter the model area to maintain heads at the boundaries for projected 2020 conditions, which may not be realistic and could have underestimated drawdowns. Specified-head boundaries can be regarded as the best-case drawdown scenario for 2020 simulations. On the other hand, the 1993-94 specified-flux boundaries limited the flow of water across the boundary to the rates for 1993-94 conditions. Increased withdrawals result in lower water levels because no additional flow is allowed to enter the model area across the lateral boundaries to supply water needed to support additional withdrawals. Specified-flux boundaries can be regarded as the worst-case drawdownscenario for 2020 simulations.

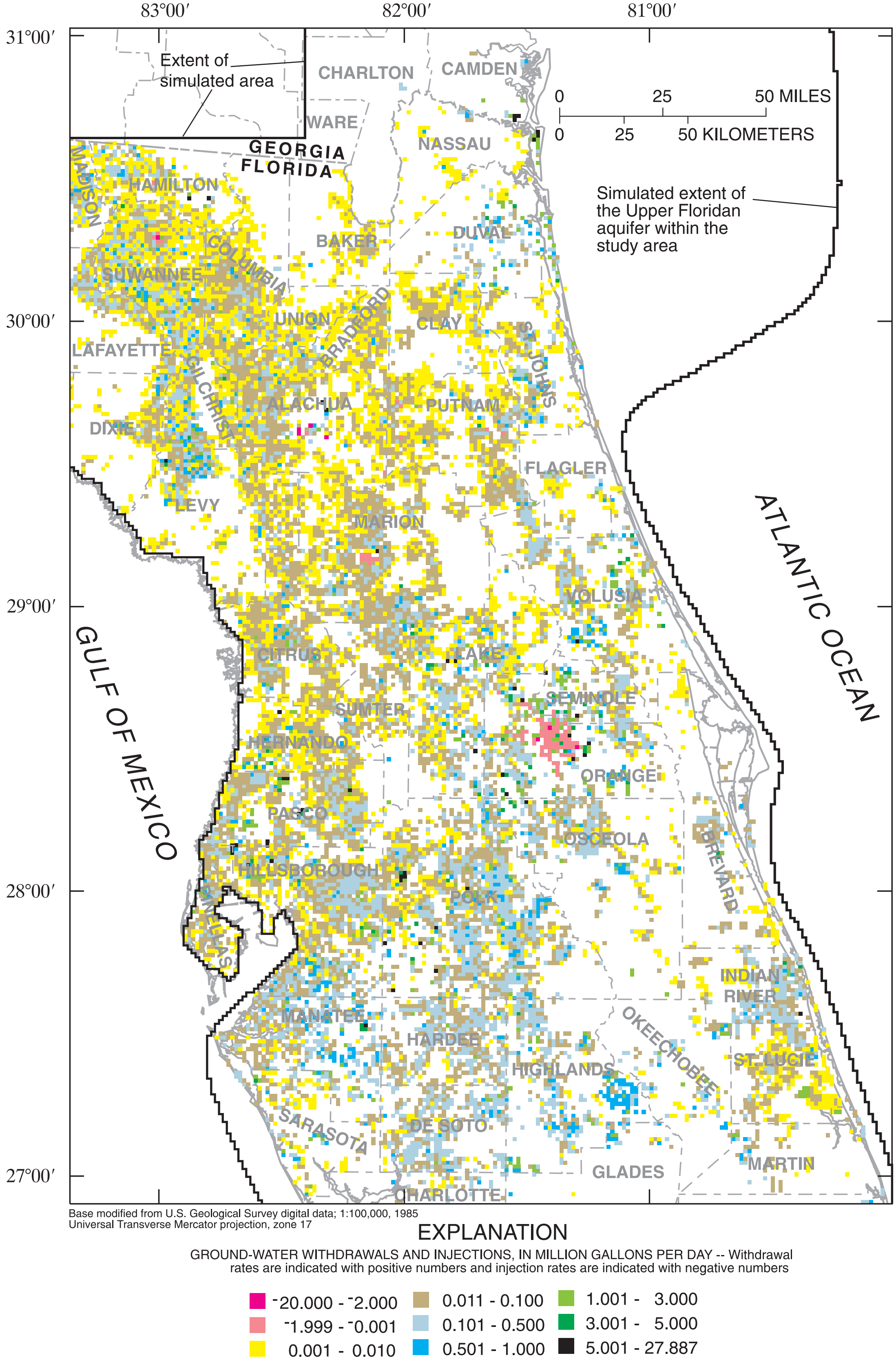


Figure 69. Projected 2020 ground-water withdrawal rates from and injection rates to the Upper Floridan aquifer.

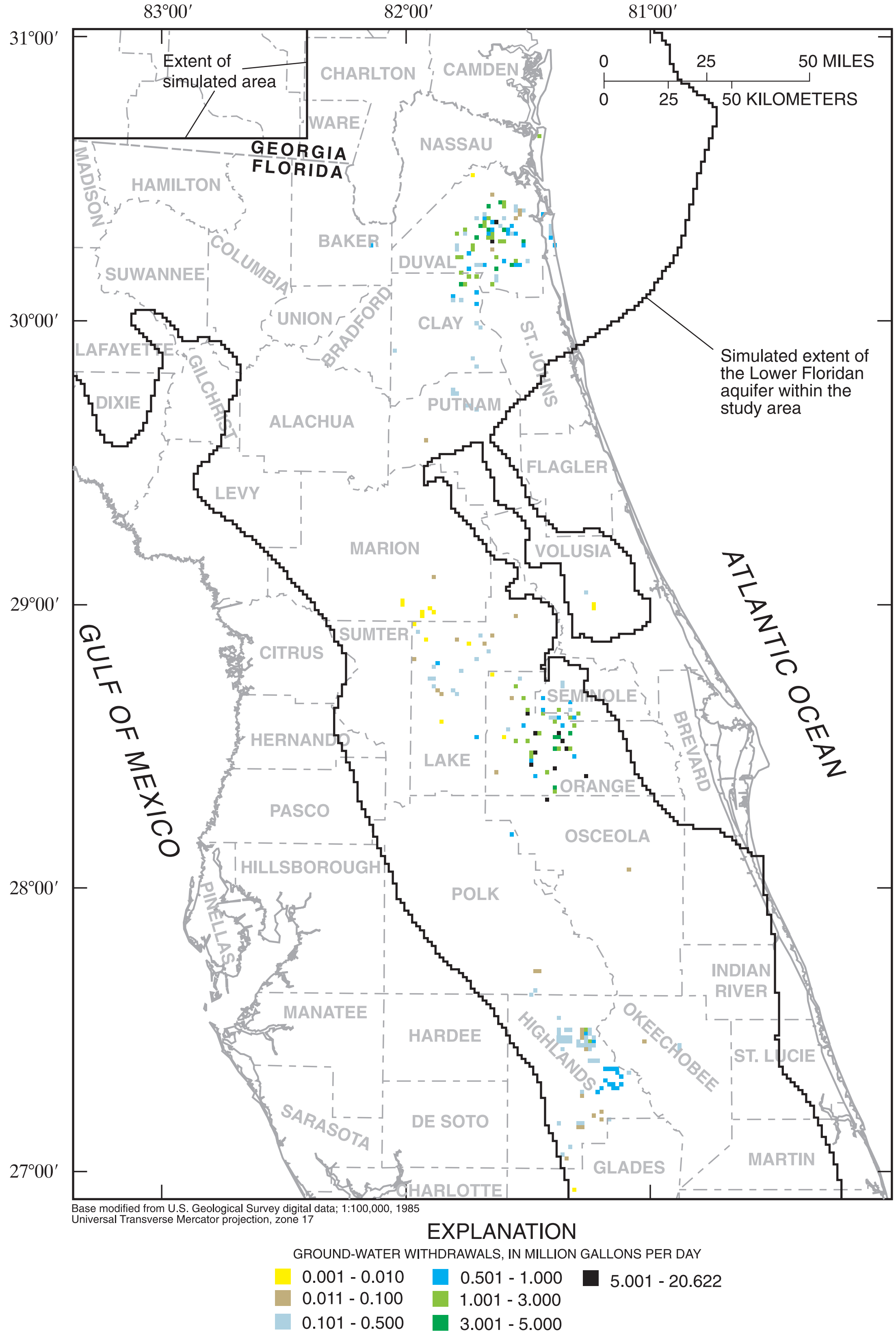


Figure 70. Projected 2020 ground-water withdrawal rates from the Lower Floridan aquifer.

Table 14. Projected 2020 recharge rates for drainage wells to the Upper Floridan aquifer by county

[Source: CH2M Hill, 1997; Bradner, 1996; Phelps, 1987. Rates, in million gallons per day, are rounded to integers]

County	Recharge
Alachua	11
Marion	5
Orange	39
Putnam	1
Seminole	1
Suwannee	5
Total	**62**

The 1993-94 water-table altitude was used for the 2020 simulations by again modeling the SAS as a constant-head layer. This assumption allowed for induced increases in vertical leakage to the UFA resulting from projected pumping increases. Simulated net recharge rates to unconfined areas of the UFA in 2020 were assumed to be equal to the 1993-94 calibrated rates, which is consistent with applying the altitude of the SAS from 1993-94 for the 2020 simulations.

As with the 1993-94 simulation, no-flow boundary conditions were imposed along the lateral boundaries of the IAS or ICU and LFA layers for 2020 simulations. Similarly, no-flow boundaries in the UFA established along coastal Citrus, Hernando, and Pasco Counties during model calibration also were applied for the 2020 simulations.

Projected 2020 Drawdowns

Simulated 2020 drawdowns (compared to 1993-94 heads) were computed at each model grid cell for each aquifer layer. Very few cells had increases in water levels from 1993-94 conditions, and therefore, were not shown in the drawdown maps. The greatest water level increase was 2 ft.

A projected drawdown of 20 ft in the IAS potentiometric surface for 2020 was simulated in central Glades County (fig. 71), regardless of which lateral boundary condition was used for the UFA. In that area, withdrawals are projected to increase substantially from 1993-94 to 2020. Drawdowns of 12 and 14 ft were simulated in west-central Sarasota County and west-central Polk County, respectively. Very little difference was observed between the simulated IAS heads for the two lateral boundary conditions used for the UFA (specified-head and specified-flux).

The two scenarios for simulating boundary conditions in the UFA (specified-head and specified-flux) had relatively the same effect on simulated water levels in some areas of the model. For example, a drawdown of 10 ft was simulated in central Orange County using either method; however, the extent of the 10-ft drawdown area was greater for the specified-flux condition. The same was true for the 6-ft drawdown in Seminole, Osceola, and Duval Counties. In western Polk County, the maximum drawdown for the specified-flux scenario was 6 ft, whereas the maximum for the specified-head scenario was 4 ft. Drawdowns of 4 ft were projected in an areally extensive part of northeast Florida, and in northeast Volusia, west-central Polk, and central Manatee Counties. No substantial projected drawdowns were simulated in the northwest and west-central parts of the model area (fig. 72), due to relatively small projected increases in ground-water withdrawals from the UFA.

Simulated drawdowns in the southeastern part of the model area (St. Lucie and Okeechobee Counties) were much more sensitive to the lateral boundary conditions in the UFA. A projected drawdown of 12 ft was simulated in the UFA in parts of St. Lucie County with the specified-flux boundary, compared to simulated drawdowns of only 2 ft with the specified-head boundary (fig. 72). A low transmissivity combined with a relatively large increase in ground-water withdrawals, as is the case in St. Lucie County, results in larger drawdowns, whereas high transmissivity combined with a small increase in ground-water withdrawals results in smaller drawdowns, as is the case in Marion County.

The largest projected drawdown in the potentiometric surface of the LFA for 2020 was simulated in Orange County (fig. 73) using either of the two lateral boundary conditions for the UFA. A drawdown of 10 ft extends through the central part of Orange County for the specified-flux boundary condition, whereas a maximum drawdown of 8 ft was simulated using the specified-head boundary. Drawdowns up to 8 ft also extend into parts of Osceola and Seminole Counties for both lateral boundary conditions. For both boundary conditions, a drawdown of 4 ft extends through a large area in Duval County, with a maximum of 6 ft simulated for specified-flux conditions. Simulated drawdowns in the potentiometric surfaces of the UFA and LFA in Orange and Duval Counties were consistent with projected increases in ground-water withdrawals from these aquifers. No substantial projected

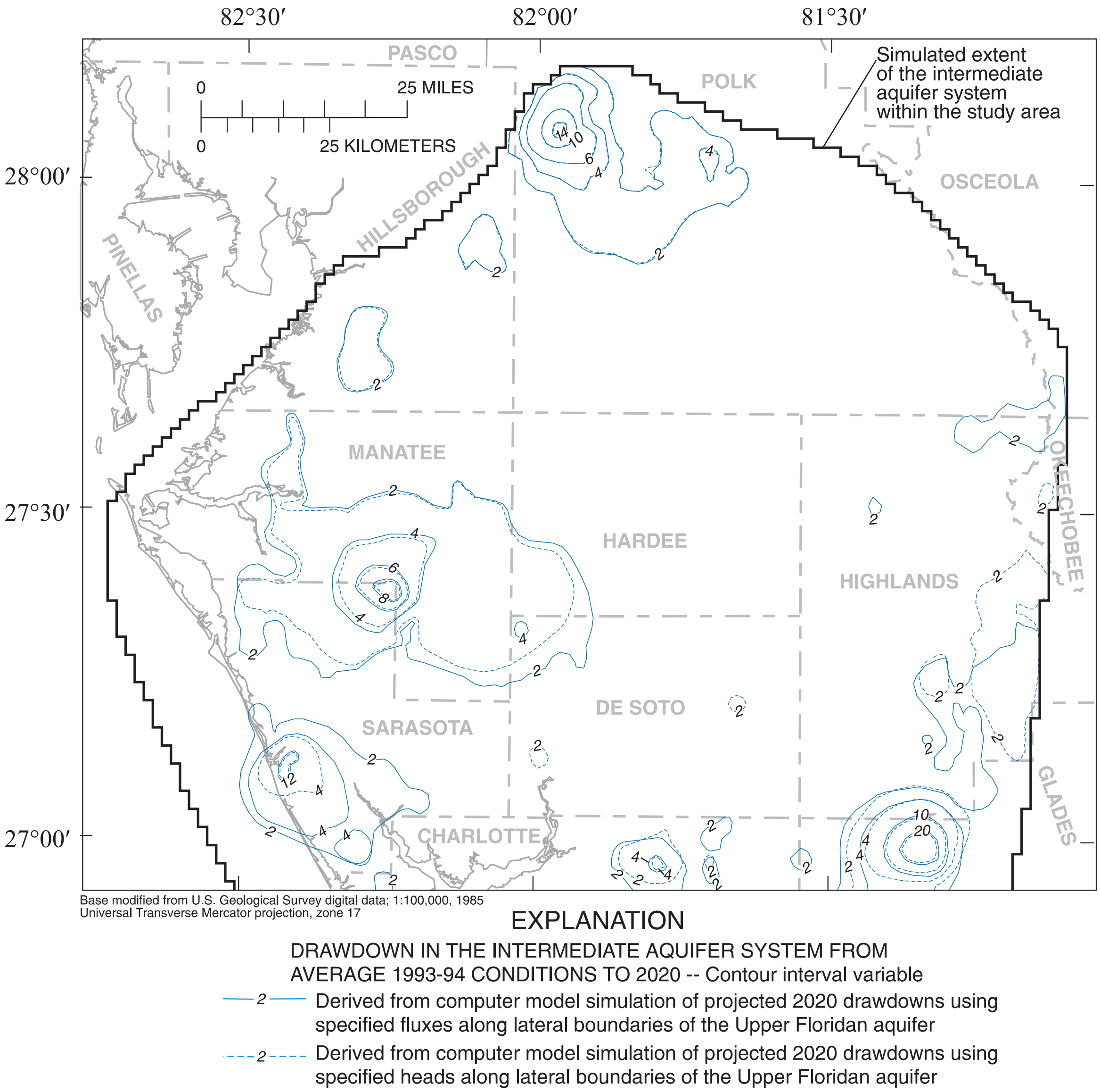
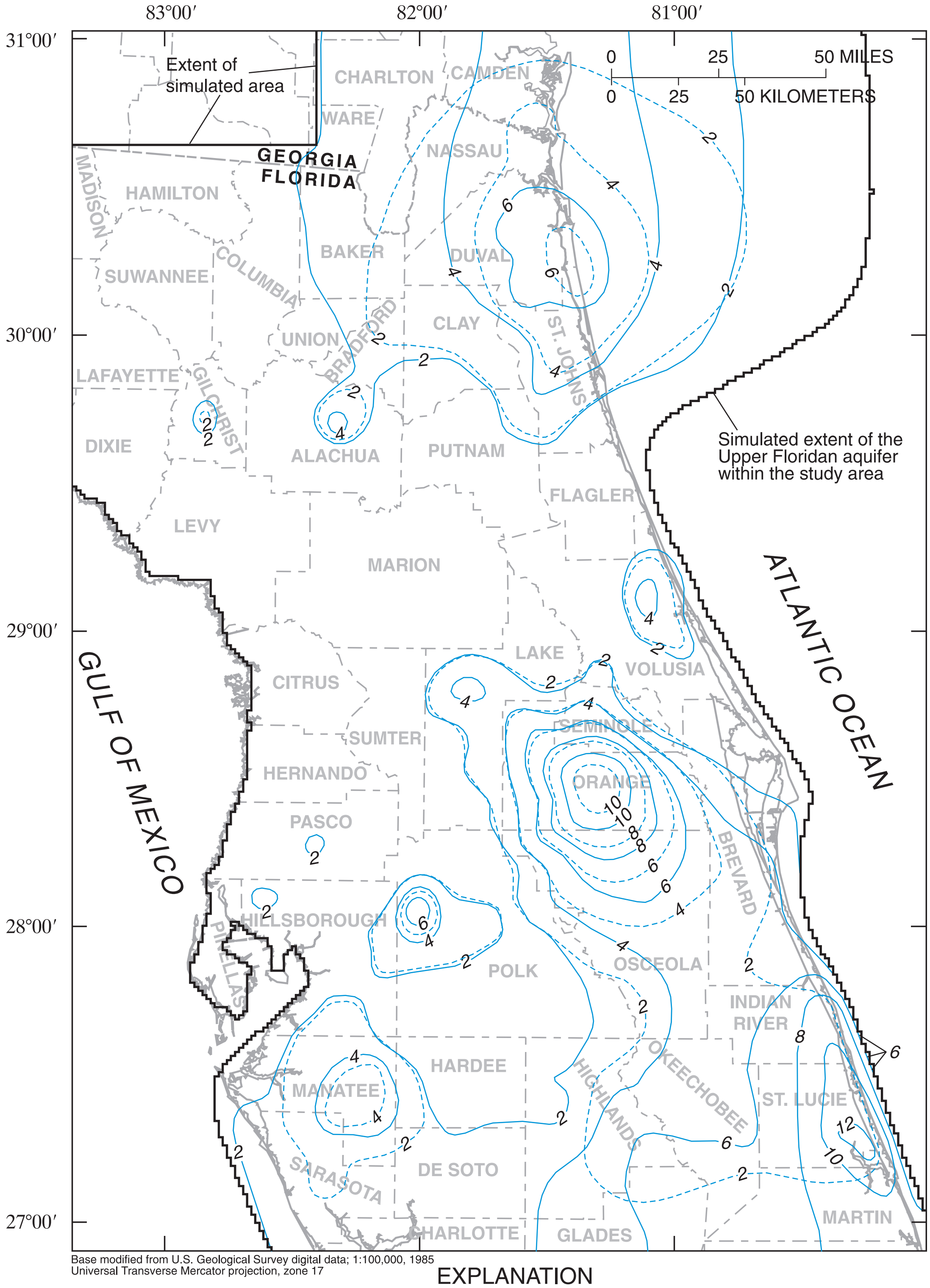


Figure 71. Simulated intermediate aquifer system drawdowns from average August 1993 through July 1994 conditions to projected 2020 conditions.

drawdowns were simulated in the northwest and west-central parts of the model area (fig. 73) owing to the absence of ground-water withdrawals from the LFA.

Upward flow from the LFA to the UFA is less in the southeastern part of the model for the specified-head lateral boundary condition in the UFA, as compared to the specified-flux boundary condition. Simulation with the specified-flux lateral boundary results in drawdowns of 6 ft extending through a large area in the southeastern part of the model area. The simulation of the specified-head lateral boundary condition results in drawdowns of only 2 ft for the same area (fig. 73). A no-flow condition along the lateral boundary of the LFA, combined with the fact that no water is withdrawn from the LFA in the southeast part of the model area (fig. 70), indicates that the projected drawdown in the LFA was due solely to increased upward flow from the LFA to the UFA.



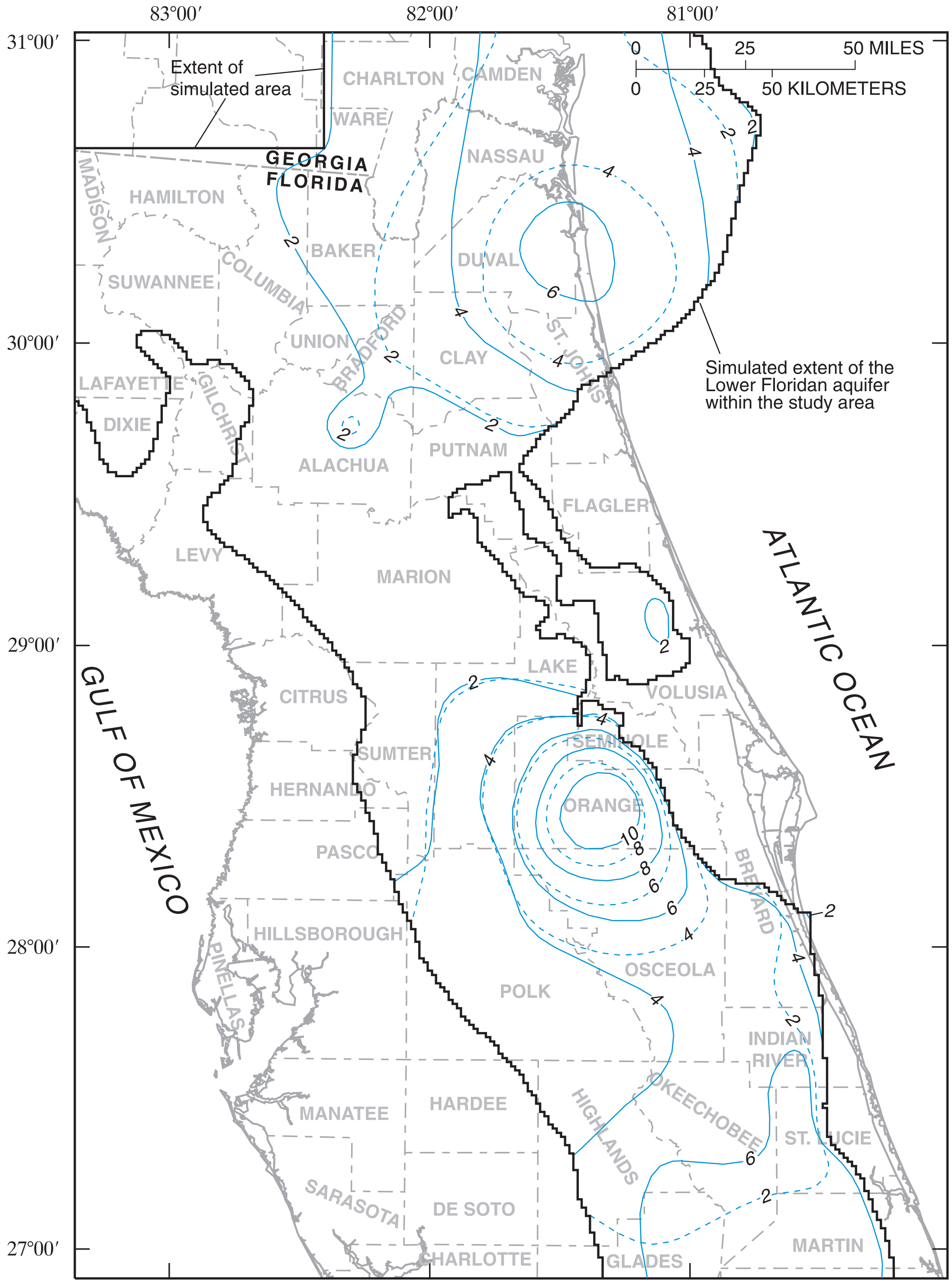
EXPLANATION

DRAWDOWN IN THE UPPER FLORIDAN AQUIFER FROM AVERAGE 1993-94 CONDITIONS TO 2020 -- Contour interval 2 feet

—2— Derived from computer model simulation of projected 2020 drawdowns using specified fluxes along lateral boundaries of the Upper Floridan aquifer

--2-- Derived from computer model simulation of projected 2020 drawdowns using specified heads along lateral boundaries of the Upper Floridan aquifer

Figure 72. Simulated Upper Floridan aquifer drawdowns from average August 1993 through July 1994 conditions to projected 2020 conditions.



EXPLANATION

DRAWDOWN IN THE LOWER FLORIDAN AQUIFER FROM AVERAGE 1993-94 CONDITIONS TO 2020 -- Contour interval 2 feet

—2— Derived from computer model simulation of projected 2020 drawdowns using specified fluxes along lateral boundaries of the Upper Floridan aquifer

- -2- - Derived from computer model simulation of projected 2020 drawdowns using specified heads along lateral boundaries of the Upper Floridan aquifer

Figure 73. Simulated Lower Floridan aquifer drawdowns from average August 1993 through July 1994 conditions to projected 2020 conditions.

Projected 2020 River and Spring Flow

The Hillsborough, Waccasassa, Steinhatchee, and Withlacoochee Rivers had minor changes in simulated base flow from 1993-94 to 2020 (table 15). The reduction in base flow for 2020 in the Suwannee and Santa Fe Rivers of about 4 percent compared to 1993-94 conditions can be attributed solely to projected increases in ground-water withdrawals because no other hydraulic properties changed from the calibrated model for 1993-94 conditions. There were no significant differences between 2020 base flows of rivers in unconfined areas of the UFA simulated with specified-flux lateral boundaries in the UFA (table 15) and the base flows simulated with specified-head lateral boundaries.

Simulated 2020 spring flows at 145 of the 156 UFA springs were within 10 ft^3/s of the 1993-94 flows. Simulated flows at Manatee Spring and Silver Springs decreased by more than 20 ft^3/s relative to simulated 1993-94 flows (fig. 22; table 16). This is a decrease of 16 percent for Manatee Spring and 8 percent for Silver Springs. Simulated flows at Blue Spring near Orange City, Rock Springs, Apopka Spring, and Weeki Wachee Springs decreased between 15 and 17 ft^3/s relative to simulated 1993-94 flows because of projected increases in ground-water withdrawals in 2020. Total simulated spring flow for the specified-flux boundary condition was about 20 ft^3/s less than that simulated with the specified-head boundary condition. Total simulated spring flow for 2020 for the worst-case drawdown scenario was about 5,800 ft^3/s, which was 94 percent of the simulated spring flow for 1993-94 (table 16). In the confined areas of the UFA, simulated spring flow for 2020 decreased 14 percent from the 1993-94 simulated flow, whereas spring flow decreased 5 percent in the unconfined areas.

Table 15. Projected 2020 base flow of rivers in the unconfined areas of the Upper Floridan aquifer for specified-flux boundary conditions

[Station number refers to figure 23. Simulated base flow is flow captured by river cells in unconfined areas of the Upper Floridan aquifer, which generally have a smaller drainage area than the river basins; difference in base flow is simulated 2020 base flow minus simulated 1993-94 base flow. SRWMD, Suwannee River Water Management District; SWFWMD, Southwest Florida Water Management District; mi^2, square miles; ft^3/s, cubic feet per second; --, does not apply or not available]

USGS station number	Station name	Drainage area (mi^2)	Simulated 2020 base flow (ft^3/s)	Simulated 1993-94 base flow (ft^3/s)	Difference in base flow (ft^3/s)
02303000	Hillsborough River near Zephyrhills	220	35	35	0
02312000	Withlacoochee River at Trilby	570	32	30	2
02313000	Withlacoochee River near Holder	1,825	115	121	-6
02313700	Waccasassa River near Gulf Hammock	480	77	79	-2
02319000	Withlacoochee River near Pinetta	2,120	5	6	-1
02319500	Suwannee River at Ellaville	6,970	[a]660	[a]683	-23
02320500	Suwannee River at Branford	7,880	[a]1,386	[a]1,430	-44
02322500	Santa Fe River near Fort White	1,017	266	275	-9
02323500	Suwannee River near Wilcox	9,640	[b]2,420	[b]2,502	-82
02324000	Steinhatchee River near Cross City	350	17	17	0
--	Unconfined sections of Hillsborough River	--	69	68	1
--	Unconfined sections of Withlacoochee River - SWFWMD	--	86	92	-6
--	Unconfined sections of Withlacoochee River - SRWMD	--	83	90	-7
--	Ichetucknee River	--	298	305	-7
--	Unconfined sections of Santa Fe River	--	[c]851	[c]872	-21
--	Unconfined sections of Suwannee River	--	[b]2,494	[b]2,585	-91

[a]Includes base flow of Withlacoochee River - SRWMD.
[b]Includes base flow of Santa Fe River and Withlacoochee River - SRWMD.
[c]Includes base flow of Ichetucknee River.

Table 16. Comparison of simulated 2020 and simulated August 1993 through July 1994 flow of Upper Floridan aquifer springs for specified-flux boundary conditions

[Spring number refers to figure 22. Row and column refer to model grid. Flows from springs in the same row and column are combined. River cells: WNW, Withlacoochee River in northwest Florida; WWC, Withlacoochee River in west-central Florida; SUR, Suwannee River; ICH, Ichetucknee River; STR, Steinhatchee River; SFR, Santa Fe River; WAC, Waccasassa River; and HIR, Hillsborough River. Springs simulated as river cells are indicated by the name of the nearest river; drain, indicates spring was simulated as drain cell; flow difference is simulated 2020 flow minus simulated 1993-94 flow; ft^3/s, cubic feet per second]

Spring number	Spring name	Row	Column	River cell	Simulated 2020 flow (ft^3/s)	Simulated 1993-94 flow (ft^3/s)	Flow difference (ft^3/s)
1	Blue Spring near Madison	41	7	WNW	85.2	89.8	-4.6
2	Alapaha Rise near Fort Union	44	17	SUR	366.1	372.9	-6.8
3	Holton Spring near Fort Union	44	19	drain	11.9	12.5	-.6
4	Suwannee Springs near Live Oak	47	27	SUR	14.0	14.9	-.9
5, 6	Suwanacoochee Spring and Ellaville Spring at Ellaville	48	12	SUR	108.1	111.2	-3.1
7	Falmouth Spring at Falmouth	49	14	drain	138.2	141.8	-3.6
8	White Sulphur Springs at White Springs	52	37	drain	45.1	53.5	-8.4
9	Charles Springs near Dell	63	8	drain	4.5	4.6	-.1
10	Allen Mill Pond Spring near Dell	64	7	SUR	10.9	11.1	-.2
11	Wadesboro Spring near Orange Park	65	103	drain	.0	1.1	-1.1
12	Blue Spring near Dell	66	8	SUR	53.4	54.0	-.6
13	Peacock Springs	67	14	drain	79.8	81.5	-1.7
14	Telford Spring at Luraville	68	12	SUR	31.3	32.0	-.7
15	Running Springs (East and West) near Luraville	68	15	SUR	84.4	87.6	-3.2
16	Convict Spring near Mayo	69	16	SUR	1.3	1.3	.0
17	Royal Spring near Alton	70	17	SUR	1.5	1.6	-.1
18	Owens Spring	72	19	SUR	40.6	42.1	-1.5
19	Mearson Spring near Mayo	73	20	SUR	48.0	49.8	-1.8
20	Troy Spring near Branford	75	22	SUR	110.5	113.7	-3.2
21	Little River Springs near Branford	76	24	SUR	57.5	59.2	-1.7
22	Ruth Spring near Branford	76	23	drain	7.2	7.6	-.4
23	Green Cove Springs at Green Cove Springs	77	106	drain	1.6	3.1	-1.5
24, 25	Ichetucknee Head Spring near Fort White and Cedar Head Spring	77	37	drain	50.6	55.9	-5.3
26-29	Blue Hole, Roaring, Singing, Boiling, Mill Pond, Grassy Hole, and Coffee Springs (parts of Ichetucknee Springs)	78	37	ICH	252.4	258.5	-6.1
30	Branford Springs at Branford	79	26	SUR	29.7	30.4	-.7
31	Jamison Spring	81	37	drain	3.0	3.0	.0
32	Hornsby Spring near High Springs	87	48	drain	48.1	51.1	-3.0
33, 34	Turtle Spring near Hatchbend and Fletcher Spring	87	29	SUR	50.3	51.8	-1.5
35	Steinhatchee Spring near Clara	87	2	STR	1.2	1.2	.0
36	Ginnie Spring near High Springs	88	41	SFR	54.5	56.2	-1.7
37	Blue Springs near High Springs (including Lilly Springs)	89	42	drain	40.4	41.5	-1.1
38	Poe Springs near High Springs	89	44	SFR	51.7	53.3	-1.6
39	Rock Bluff Springs near Bell	91	27	SUR	23.7	26.0	-2.3
40	Guaranto Spring near Rock Bluff Landing	92	26	SUR	9.7	10.4	-.7
41	Crescent Beach Submarine Spring	94	135	drain	37.3	42.6	-5.3
42, 43	Lumbercamp Springs and Sun Springs near Wannee	97	26	drain	42.6	44.6	-2.0
44	Hart Springs near Wilcox	100	25	drain	80.3	88.8	-8.5
45	Otter Springs near Wilcox	102	25	drain	15.0	15.7	-.7
46	Whitewater Springs	103	107	drain	.5	1.4	-.9
47	Copper Springs near Oldtown (including Little Copper Spring)	104	23	SUR	15.6	18.6	-3.0
48	Bell Springs	105	25	drain	4.5	5.0	-.5
49	Fannin Springs near Wilcox (including Little Fannin Spring)	106	26	drain	87.1	97.4	-10.3
50	Satsuma Spring	111	106	drain	1.0	1.1	-.1
51	Blue Springs near Orange Springs	112	94	drain	.5	0.5	.0
52	Orange Spring at Orange Springs	112	89	drain	.9	1.5	-.6
53	Camp Seminole Spring at Orange Springs	113	88	drain	.1	.4	-.3
54	Welaka Spring near Welaka	114	106	drain	.0	.0	.0
55	Manatee Spring near Chiefland	113	23	drain	149.6	177.7	-28.1

Table 16. Comparison of simulated 2020 and simulated August 1993 through July 1994 flow of Upper Floridan aquifer springs for specified-flux boundary conditions--Continued

[Spring number refers to figure 22. Row and column refer to model grid. Flows from springs in the same row and column are combined. River cells: WNW, Withlacoochee River in northwest Florida; WWC, Withlacoochee River in west-central Florida; SUR, Suwannee River; ICH, Ichetucknee River; STR, Steinhatchee River; SFR, Santa Fe River; WAC, Waccasassa River; and HIR, Hillsborough River. Springs simulated as river cells are indicated by the name of the nearest river; drain, indicates spring was simulated as drain cell; flow difference is simulated 2020 flow minus simulated 1993-94 flow; ft^3/s, cubic feet per second]

Spring number	Spring name	Row	Column	River cell	Simulated 2020 flow (ft^3/s)	Simulated 1993-94 flow (ft^3/s)	Flow difference (ft^3/s)
56	Mud Spring near Welaka	116	106	drain	2.3	2.5	-.2
57	Blue Spring near Bronson	116	40	WAC	6.2	7.5	-1.3
58	Beecher Springs near Fruitland	117	107	drain	6.3	6.3	.0
59	Croaker Hole Spring near Welaka	118	105	drain	90.4	91.8	-1.4
60	Tobacco Patch Landing Spring Group near Fort McCoy	118	90	drain	1.0	1.0	.0
61	Wells Landing Springs near Fort McCoy	119	90	drain	4.6	4.9	-.3
62	Salt Springs near Eureka	124	102	drain	78.8	79.3	-.5
63	Wekiva Springs near Gulf Hammock	129	43	drain	44.4	45.2	-.8
64	Silver Glen Springs near Astor	132	108	drain	78.4	78.8	-.4
65	Sweetwater Springs along Juniper Creek	134	106	drain	14.9	15.0	-.1
66	Silver Springs near Ocala	134	81	drain	570.7	620.3	-49.6
67, 68	Morman Branch Seepage into Juniper Creek and Juniper Creek Tributary near Astor	136	107	drain	6.2	6.3	-.1
69, 70	Juniper Springs and Fern Hammock Springs near Ocala	136	103	drain	7.8	8.0	-.2
71	Ponce de Leon Springs near De Land	140	125	drain	23.2	23.7	-.5
72	Rainbow Springs near Dunnellon	142	57	drain	606.6	620.4	-13.8
73	Alexander Springs near Astor	144	112	drain	101.1	102.3	-1.2
74	Mosquito Springs Run, Alexander Springs Wilderness	147	121	drain	.9	1.4	-.5
75	Wilson Head Spring near Holder	151	64	WWC	2.2	2.4	-.2
76	Blue Spring near Holder	151	65	WWC	10.4	10.7	-.3
77	Gum Springs near Holder	152	70	drain	67.6	71.1	-3.5
78	Camp La No Che Springs near Paisley	153	114	drain	.0	.7	-.7
79	Blue Spring near Orange City	153	127	drain	110.5	126.1	-15.6
80	Blackwater Springs near Cassia	158	117	drain	.0	.0	.0
81	Crystal River Spring Group	157	46	drain	650.5	663.8	-13.3
82	Little Jones Creek Head Spring near Wildwood	159	79	drain	7.2	8.1	-.9
83	Green Springs	160	133	drain	.0	.3	-.3
84	Gemini Springs near DeBary (all 3)	160	129	drain	7.8	9.8	-2.0
85	Little Jones Creek Spring No. 2 near Wildwood	160	79	drain	4.6	5.0	-.4
86	Messant Spring near Sorrento	160	117	drain	10.4	11.4	-1.0
87	Seminole Springs near Sorrento	161	115	drain	6.1	14.5	-8.4
88	Palm Springs Seminole State Forest	161	120	drain	.0	.7	-.7
89	Little Jones Creek Spring No. 3 near Wildwood	161	80	drain	2.8	3.0	-.2
90	Droty Springs near Sorrento	162	116	drain	.0	.0	.0
91	Halls River Head Spring	162	47	drain	4.6	4.7	-.1
92	Island Spring near Sanford	162	122	drain	4.9	6.4	-1.5
93	Halls River Springs	163	46	drain	101.0	102.7	-1.7
94-96	Homosassa Springs, Southeast Fork of Homosassa Springs, and Trotter Spring at Homosassa Springs	164	47	drain	119.6	121.5	-1.9
97	Fenney Springs near Coleman, Head Spring of Shady Brook Creek	164	82	drain	10.7	12.0	-1.3
98, 99	Shady Brook Creek Springs No. 2 and 3	165	82	drain	5.7	5.8	-.1
100	Shady Brook Creek Spring No. 4	166	80	drain	2.8	3.0	-.2
101	Sulphur Camp Springs	166	116	drain	.0	.5	-.5
102	Hidden River Springs near Homosassa (including Hidden River Head Spring)	166	47	drain	6.5	6.6	-.1
103	Rock Springs near Apopka	167	116	drain	35.7	51.5	-15.8
104	Shady Brook Creek Spring No. 5	167	79	drain	2.9	3.1	-.2
105	Bugg Spring at Okahumpka	167	91	drain	6.2	8.5	-2.3
106, 108	Blue Springs near Yalaha and Holiday Springs at Yalaha	168	96	drain	.0	4.7	-4.7

Table 16. Comparison of simulated 2020 and simulated August 1993 through July 1994 flow of Upper Floridan aquifer springs for specified-flux boundary conditions--Continued

[Spring number refers to figure 22. Row and column refer to model grid. Flows from springs in the same row and column are combined. River cells: WNW, Withlacoochee River in northwest Florida; WWC, Withlacoochee River in west-central Florida; SUR, Suwannee River; ICH, Ichetucknee River; STR, Steinhatchee River; SFR, Santa Fe River; WAC, Waccasassa River; and HIR, Hillsborough River. Springs simulated as river cells are indicated by the name of the nearest river; drain, indicates spring was simulated as drain cell; flow difference is simulated 2020 flow minus simulated 1993-94 flow; ft^3/s, cubic feet per second]

Spring number	Spring name	Row	Column	River cell	Simulated 2020 flow (ft^3/s)	Simulated 1993-94 flow (ft^3/s)	Flow difference (ft^3/s)
107	Mooring Cove Springs near Yalaha	168	95	drain	.0	.0	.0
109	Potter Spring near Chassahowitzka (including Ruth Spring)	168	46	drain	14.0	14.3	-.3
110	Witherington Spring near Apopka	169	117	drain	.1	1.0	-.9
111	Salt Creek Head Spring	169	47	drain	.4	.4	.0
112	Lettuce Creek Spring	169	48	drain	3.5	3.6	-.1
113, 115	Crab Creek Spring and Chassahowitzka Springs near Chassahowitzka	170	48	drain	97.9	99.3	-1.4
114, 119	Unnamed Tributary above Chassahowitzka Springs and Baird Creek Head Spring near Chassahowitzka	170	47	drain	23.4	23.7	-.3
116	Wekiwa Springs in State Park near Apopka	171	119	drain	43.0	55.6	-12.6
117	Miami Springs near Longwood	171	120	drain	2.9	3.9	-1.0
118	Lake Jesup Spring near Wagner	171	131	drain	.0	1.2	-1.2
120	Clifton Springs near Oviedo	172	133	drain	.0	2.4	-2.4
121	Starbuck Spring near Longwood	172	124	drain	5.9	12.1	-6.2
122	Beteejay Lower Spring near Chassahowitzka (including Beteejay Head Spring)	171	46	drain	7.2	7.3	-.1
123, 125	Palm Springs and Sanlando Springs near Longwood	172	123	drain	11.5	22.6	-11.1
124	Rita Maria Spring near Chassahowitzka	171	47	drain	3.2	3.3	-.1
126, 127	Unnamed Spring No. 10, 11, 12, Ryle Creek Lower Spring, and Ryle Creek Head Spring near Bayport	172	45	drain	27.9	28.3	-.4
128	Blue Run Head Spring near Chassahowitzka	172	46	drain	4.6	4.6	.0
129	Double Run Road Seepage near Astatula	173	101	drain	.0	2.0	-2.0
130	Unnamed Spring No. 8	173	44	drain	5.1	5.1	.0
131	Blind Creek Springs (including unnamed spring No. 7 and Blind Creek Head Spring)	174	44	drain	27.3	27.6	-.3
132	Apopka (Gourdneck) Spring near Oakland	181	105	drain	13.9	30.2	-16.3
133	Unnamed Spring No. 6	182	44	drain	2.8	2.8	.0
134, 135	Salt Spring and Mud Spring near Bayport	182	45	drain	37.2	37.8	-.6
136, 137	Jenkins Creek Spring No. 5 and Unnamed Spring No. 4	184	44	drain	21.0	21.6	-.6
138	Weeki Wachee Springs near Brooksville	184	48	drain	115.6	130.9	-15.3
139	Unnamed Spring No. 2	188	43	drain	.6	.7	-.1
140, 142, 143	Boat Spring, Unnamed Spring No. 1, and Magnolia Springs at Aripeka	190	42	drain	7.0	7.2	-.2
141	Bobhill Springs	190	43	drain	1.6	1.8	-.2
144	Unnamed Spring No. 3 near Aripeka	193	41	drain	16.0	16.4	-.4
145	Horseshoe Spring near Hudson	193	40	drain	6.1	6.2	-.1
146	Salt Springs near Port Richey	200	38	drain	9.8	10.5	-.7
147	Crystal Springs near Zephyrhills	209	72	HIR	31.9	31.9	.0
148	Sulphur Springs at Sulphur Springs	220	55	drain	23.9	24.5	-.6
149	Lettuce Lake Spring	221	61	drain	7.5	7.8	-.3
150, 151	Six-Mile Creek Spring and Eureka Springs near Tampa	221	62	drain	2.4	2.5	-.1
152	Buckhorn Spring near Riverview	230	64	drain	10.1	11.9	-1.8
153, 154	Lithia Springs Minor and Lithia Springs Major near Lithia	232	69	drain	30.0	34.1	-4.1
155	Little Salt Spring near Murdock	289	68	drain	.1	.9	-.8
156	Warm Mineral Springs near Woodmere	290	67	drain	5.3	6.6	-1.3
				Total	5,796.6	6,159.4	-362.8

Projected 2020 Ground-Water Flow Budget

A comparison of the projected flow budget for 2020 to 1993-94 conditions showed a reduction in spring flow for 2020 in both confined and unconfined areas of the UFA, mainly due to projected increases in ground-water withdrawals in the UFA. An increase in projected ground-water withdrawals in the confined areas of the UFA of 946 ft^3/s induced an increase in net downward leakage from the IAS or ICU layer to the UFA layer of 937 ft^3/s, almost equal to the increase in water withdrawals (figs. 66 and 74). Total recharge to the UFA, in the form of both net recharge or net downward leakage through the IAS or ICU layer, was 12,792 ft^3/s, an increase of about 8 percent from 1993-94 conditions. Changes in net flow across the unconfined-confined boundary of the UFA (fig. 5) were not significant because net simulated flow to unconfined areas from confined areas decreased only 3 percent in 2020 from 1993-94 conditions (figs. 66 and 74).

MODEL LIMITATIONS

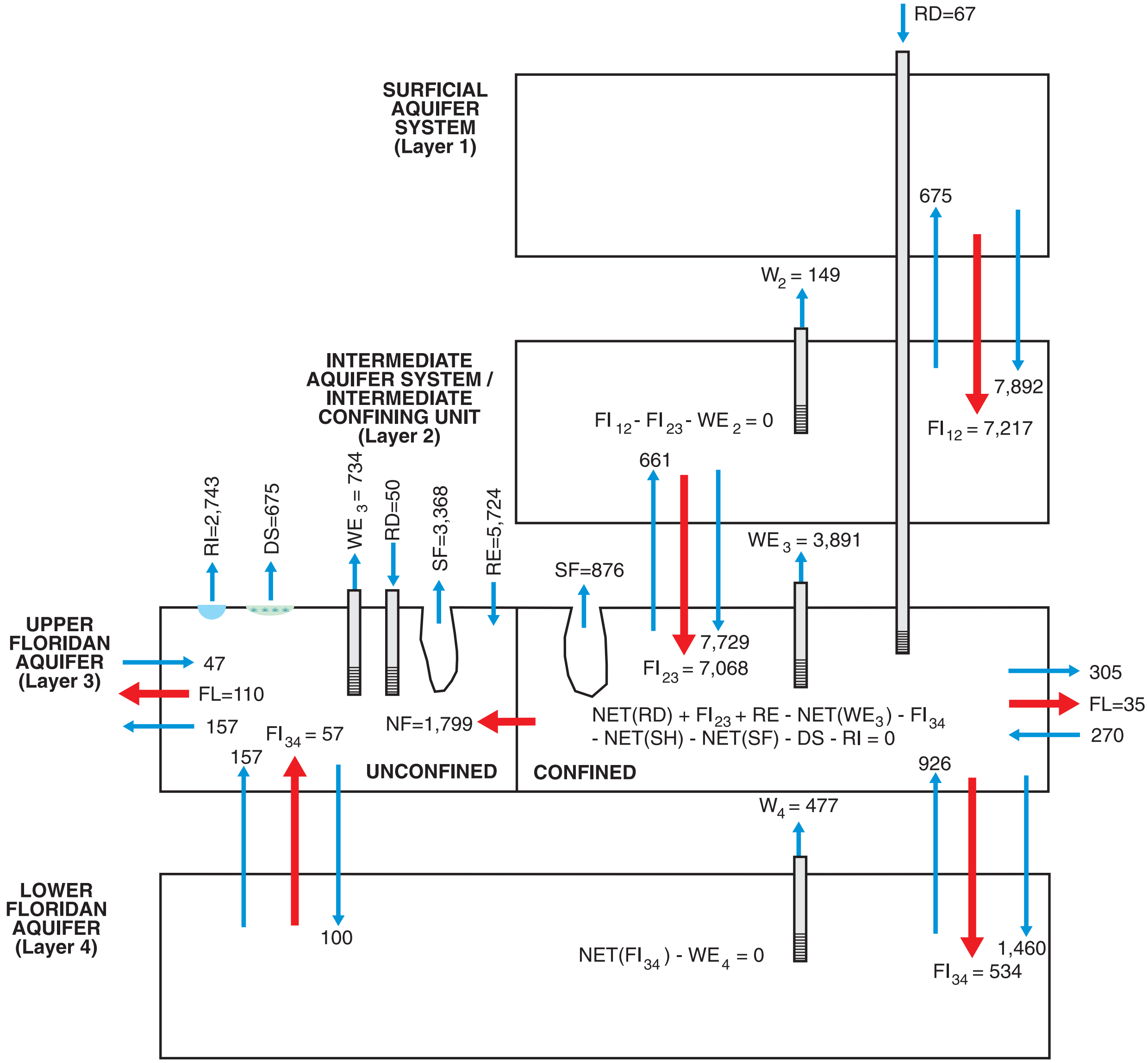
Some of the limiting factors of the ground-water flow model presented in this report are: simplifications in the conceptual model, inherent model assumptions, lack of water-level and flow measurements in areas where spatial variability of hydraulic and hydrologic properties is poorly known, and inaccuracies in land-surface altitude measurements. Model simulations are based on the assignment of hydraulic properties to grid cells, the use of specified heads in the UFA along lateral boundaries of the model, the grid resolution, the estimated average water table and Floridan aquifer heads, the estimated ground-water withdrawals, and the assumption of steady-state conditions in the Floridan aquifer for 1993-94. An error in any of these can limit the accuracy of model simulations.

Ground-water flow simulations generally are based on conceptual models that are simplified representations of complex heterogeneous ground-water flow systems. Assumptions such as isotropy, vertical homogeneity within each layer, and the absence of preferential flow zones are examples of simplified representations that can be sources of error in a ground-water flow model. The lack of sufficient measurements to account for the spatial variation of hydraulic properties throughout the model area necessitated these simplifications. Simplifying the model does not invalidate model results, although model results should be interpreted at scales larger than the representative grid cell. The ground-water flow equation solved by the model (equation 4) is the continuity equation for flow derived from the principal of conservation of mass and the assumptions that water is incompressible and of constant viscosity, incorporated with Darcy's law (Bouwer, 1978, p. 202). This equation is valid for ground-water flow conditions where the velocity of ground water is low and flow is laminar. In karstic terrains, it is possible for flow through caverns and solution channels to be turbulent. Thus, the equation is not valid for the entire Floridan aquifer system. Simplifications made in this study were the assumptions that laminar flow was everywhere and that effective transmissivity was uniform throughout each grid cell of the model such that mass is conserved, along with known hydraulic gradients.

Inaccuracies inherent in the algorithm used to estimate the water table distribution or the estimated potentiometric surface of the UFA, such as lack of data and residual errors, could lead to errors in the delineation of recharge or discharge areas. In turn, these inaccuracies can lead to inaccuracies in leakance and leakage rates among the SAS, IAS or ICU, and UFA.

The assumption of constant water levels in areas where the SAS is present may introduce error into the model. Temporal changes in the water table of the SAS would bring temporal changes in leakage rates between the SAS and the IAS or ICU. In particular, in the vicinity of some cells, induced leakage due to large ground-water withdrawals from the UFA could cause these cells to go dry. Simulating active cells in the SAS, however, was beyond the scope of this study. The water table of the SAS was generated for a year when total rainfall was nearly equal to the overall 30-year average rainfall computed from NOAA rainfall stations. The estimated water table for the SAS in this study should be modified for local or regional ground-water flow studies for which simulation periods correspond to hydrologic conditions that deviate from average rainfall conditions.

The assumption of uniform heads throughout the vertical thickness of each grid cell is another possible source of error in the simulated heads. Vertical hydraulic gradients between the SAS and the UFA suggest that simulated heads in the ICU could represent, at best, a value within the range of heads observed throughout the thickness of the ICU. The simulated heads in the ICU should be interpreted as an interpolation from the hydraulic gradients between the SAS and the UFA.



EXPLANATION

(blue arrow)	FLOW ACROSS BOUNDARY
(red arrow)	NET FLOW ACROSS BOUNDARY
NF	NET FLOW ACROSS UNCONFINED/CONFINED BOUNDARY
WE_N	WELL WITHDRAWALS FROM LAYER N
FI_{NM}	NET FLOW ACROSS INTERFACE OF LAYERS N AND M
SF	SPRING FLOW FROM LAYER 3
DS	DISCHARGE TO SWAMPS
FL	SPECIFIED FLOW ACROSS LATERAL BOUNDARY IN LAYER 3
RI	NET FLOW FROM AQUIFER TO RIVER
RD	RECHARGE FROM DRAINAGE AND INJECTION WELLS IN LAYER 3
RE	NET RECHARGE FROM RAINFALL INFILTRATION
NET	NET FLOW FROM UNCONFINED/CONFINED AREAS IN LAYER 3
818	FLOW RATE, IN CUBIC FEET PER SECOND

Figure 74. Simulated volumetric flow budget for the intermediate aquifer system, Upper Floridan aquifer, and Lower Floridan aquifer for projected 2020 conditions for the specified-flux boundary conditions (worst-case drawdown scenario).

Simulation of the observed hydraulic gradients in the ICU would require additional layering of this hydrogeologic unit, which is beyond the scope of this study.

The simulated transmissivities in the IAS, UFA, and LFA and the leakances of the upper confining unit of the IAS, ICU, and MSCU in this study may vary from values in previously published local ground-water flow models. Many of the modifications to transmissivity values from previous ground-water flow models were based on additional data available from aquifer tests and on the need to reduce differences between simulated and measured heads. Areas in the IAS, UFA, or LFA where ground-water withdrawals were minimal for 1993-94 may require changes to simulated values of transmissivity and leakance as future aquifer stresses from increased ground-water withdrawals reflect aquifer responses in areas previously not stressed.

Lack of data for the MSCU and LFA precludes a reliable estimation of their respective leakance and transmissivity values; only 46 LFA control points were available during this study. The no-flow boundaries specified along the perimeter of active cells in the LFA was based on the assumption of minimal ground-water flow across the estimated surface beneath which the FAS contains water with chloride concentrations greater than 5,000 mg/L. The estimated surface shown in figure 19 can be updated as more water-quality data become available. In addition, flow in the LFA might be understood better as the potentiometric surface of the LFA becomes better defined by more head measurements as additional wells are drilled. The assumption of a stationary freshwater-saltwater interface also could introduce error in the model if ground-water withdrawals or lack of recharge induce movement of this interface.

In spite of the limitations, the model can indicate the general movement of ground water in the study area. By providing estimates to hydraulic parameters, this model can be used to generate initial estimates of the hydraulic properties needed for more localized studies. In addition, the model also can provide a good assessment of drawdowns in response to projected ground-water withdrawals.

SUMMARY AND CONCLUSIONS

A four-layer, finite-difference steady-state ground-water flow model of the intermediate aquifer system (IAS) and the Floridan aquifer system (FAS) in peninsular Florida was developed and calibrated. Hydraulic properties were extracted from this model for smaller-scale ground-water flow models within the study area. The active model area is about 40,800 square miles (mi^2) and extends approximately 284 miles (mi) from Charlton and Camden Counties, Georgia, to just south of the Palm Beach - Martin County line in Florida. The west-to-east extent of the study area spans about 200 miles from the Gulf of Mexico to the Atlantic Ocean.

The hydrogeologic framework of the study area includes sediments that form the surficial aquifer system (SAS); the less permeable clay and carbonate rocks that form the intermediate confining unit (ICU), the accumulation of more permeable carbonate rocks than those of the ICU that form the IAS in southwest Florida; and a thick sequence of carbonate rocks of variable permeability that form the FAS. A base of generally low permeability dolomite and evaporite beds form the sub-Floridan confining unit. In east-central Florida, the Upper Floridan aquifer (UFA) and Lower Floridan aquifer (LFA) are separated by the middle semiconfining unit (MSCU), a less permeable, commonly partially dolomitized limestone that locally contains some gypsum and chert. The MSCU is thin or absent in the northwest part of the study area, but is as much as 600 to 800 ft thick in the south-central part of the study area. In west-central Florida, the UFA and LFA are separated by the middle confining unit (MCU), a gypsiferous dolomite and dolomitic limestone of considerably lower permeability than the MSCU in east-central Florida.

The IAS and FAS were approximately at steady-state conditions for the period August 1, 1993, through July 31, 1994. Errors introduced by this steady-state approximation were estimated to be minimal. A uniformly spaced grid of 5,000-foot square cells (210 columns and 300 rows) was used to discretize the hydraulic properties of the SAS, IAS or ICU, UFA, and LFA, and to implement the ground-water flow model. The flow model was calibrated using average heads for the IAS, UFA, and LFA for 1993-94, measured or estimated spring flows, and measured river flows in the unconfined areas of the UFA.

The time-averaged altitude of the water table of the SAS and time-averaged heads of the IAS, UFA, and LFA were generated from computed average heads for the August 1993 through July 1994 period. Multiple linear regressions among the water-level measurements at SAS wells, an interpolated minimum water-table surface, and the difference between land-surface altitude and the interpolated minimum water table were used to approximate the altitude of the water table in the study area where the SAS is present.

The altitude of the water table and the potentiometric surfaces of the IAS and UFA were used to identify the areal extent of recharge and discharge areas within the UFA. Recharge to the UFA occurs mainly from downward leakage from the SAS through the ICU when the water table is higher than the potentiometric level of the UFA. Artificial recharge to the UFA occurs from drainage wells, injection wells, and rapid-infiltration basins.With the exception of swamps, springs, and some river segments in the unconfined areas of the UFA, most of the unconfined areas of the UFA is recharged by rainfall. Discharge from the UFA occurs mainly by upward leakage to the SAS through the ICU when the potentiometric surface is higher than the water table. Discharge from the UFA also occurs as ground-water withdrawals, spring flows, and flow from the unconfined areas of the UFA to swamps and rivers.

Boundary conditions varied among the various aquifer layers. The SAS was simulated as a layer of constant heads. No-flow conditions were imposed along the lateral boundaries of the ICU layer. Lateral boundaries of the UFA generally were specified heads. Areas of the UFA and LFA containing water with chloride concentrations greater than 5,000 milligrams per liter (mg/L) were considered inactive and delineated by no-flow boundaries. All lateral boundaries of the LFA in the model were assumed to be no flow.

Ground-water withdrawals for 1993-94 within the study area from the IAS, UFA, and LFA totaled 2,488 million gallons per day (Mgal/d). Additional discharge from the UFA occurred from spring flow which, for 1993-94, was estimated to be about 4,126 Mgal/d. Total recharge to the UFA from 364 drainage wells in the study area was estimated to be 68 Mgal/d, based on rainfall data for 1993-94. Artificial recharge to the UFA from injection wells in Alachua County was estimated to be 10.62 Mgal/d.

The ground-water flow model was calibrated by independently varying the following parameters: net recharge rate to unconfined areas of the UFA; transmissivity of the IAS, UFA, and LFA; riverbed conductance of rivers in the unconfined areas of the UFA; leakance of the upper confining unit of the IAS, the ICU, the MCU, and the MSCU; and the conductance of swamps and springs in the UFA that were simulated as drain cells. Simulated and measured heads at control points of the IAS, UFA, and LFA showed a close agreement across most of the study area, with residuals of less than 5 feet (ft) in about 85 percent of the control points. The root-mean-square residuals for the IAS, UFA, and LFA were 3.47, 3.41, and 2.89 ft, respectively. Simulated spring flow was within 5 cubic feet per second (ft^3/s) of the estimated flow in about 83 percent of the springs. The largest spring-flow residuals occurred in springs simulated as river cells. Simulated flow was about 96 percent of an approximate total estimated spring flow of 6,380 ft^3/s for 1993-94.

The effects of projected increases in ground-water withdrawals for 2020 relative to 1993-94 rates were analyzed by using, in two separate simulations, specified-head and specified-flux boundary conditions for lateral boundaries of the UFA. Projected 2020 ground-water withdrawals from the IAS, UFA, and LFA were estimated to be 3,394 Mgal/d, which represents an increase of about 36 percent from 1993-94. A projected drawdown of 20 ft in the IAS potentiometric surface for 2020 was simulated in central Glades County, resulting from projected increases in ground-water withdrawals. A projected drawdown of 10 ft in the UFA potentiometric surface for 2020 was simulated in central Orange County using either of the two lateral boundary conditions for the UFA, with a projected 8 ft drawdown extending to parts of Osceola and Seminole Counties. A projected drawdown of 6 ft in the UFA for 2020 was simulated for Duval County for both lateral boundary conditions. A projected drawdown of 10 ft in the LFA potentiometric surface for 2020 was simulated in Orange County. Simulated drawdowns in the potentiometric surfaces of the UFA and LFA in Orange and Duval Counties were consistent with projected increases in ground-water withdrawals from these aquifers. No substantial projected drawdowns in the UFA or LFA were simulated in the northwest and west-central parts of the model area.

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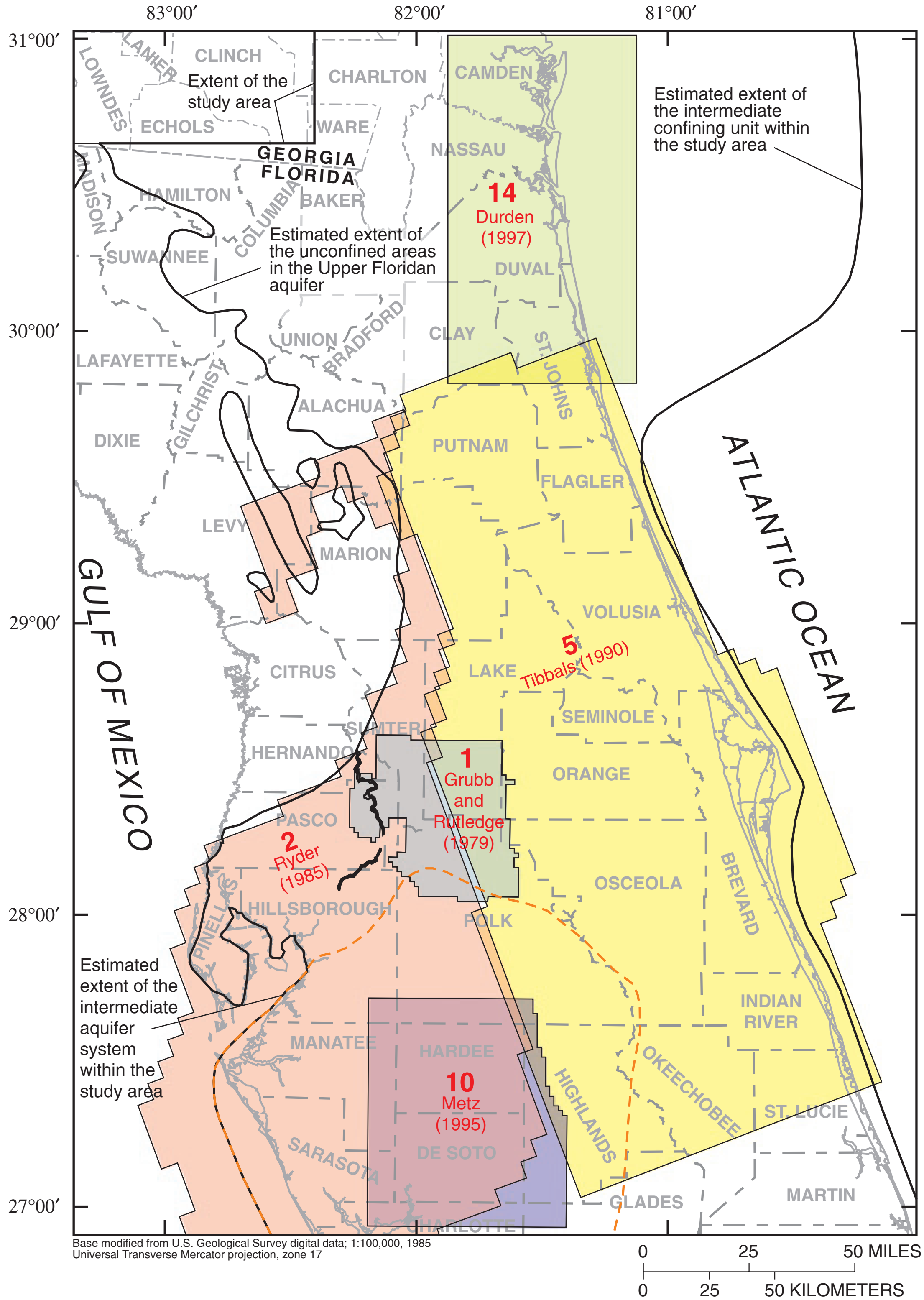
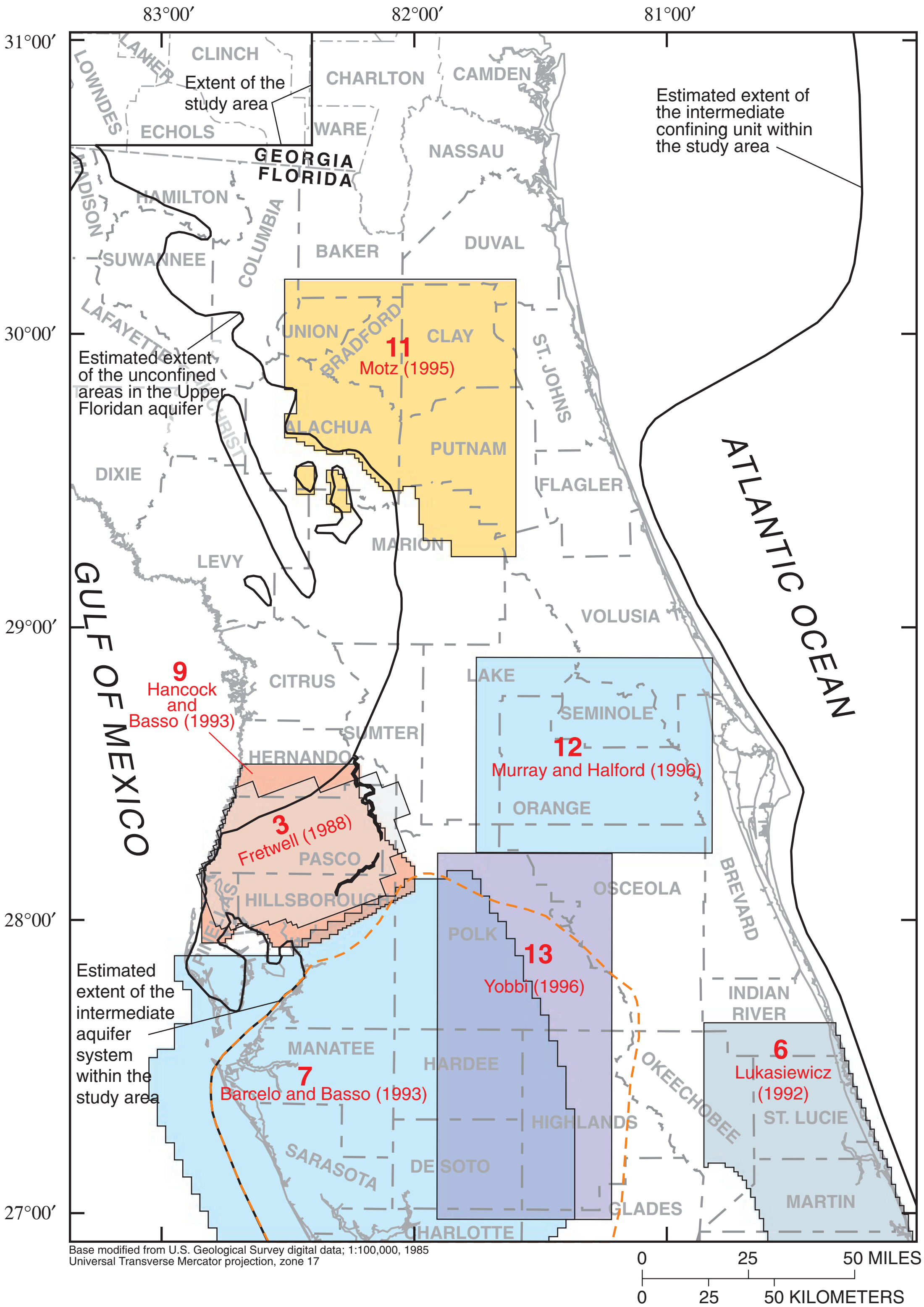
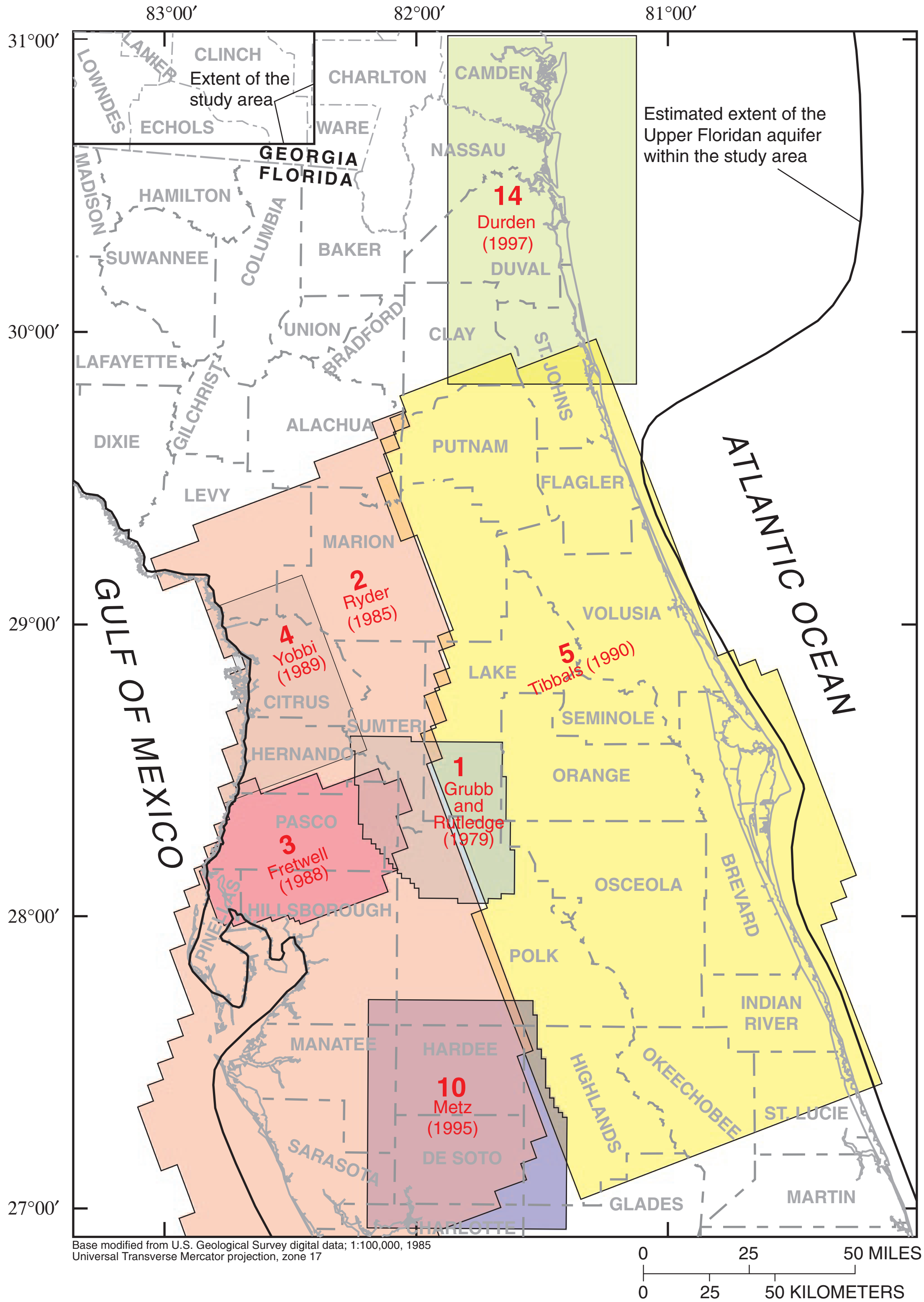
APPENDIXES



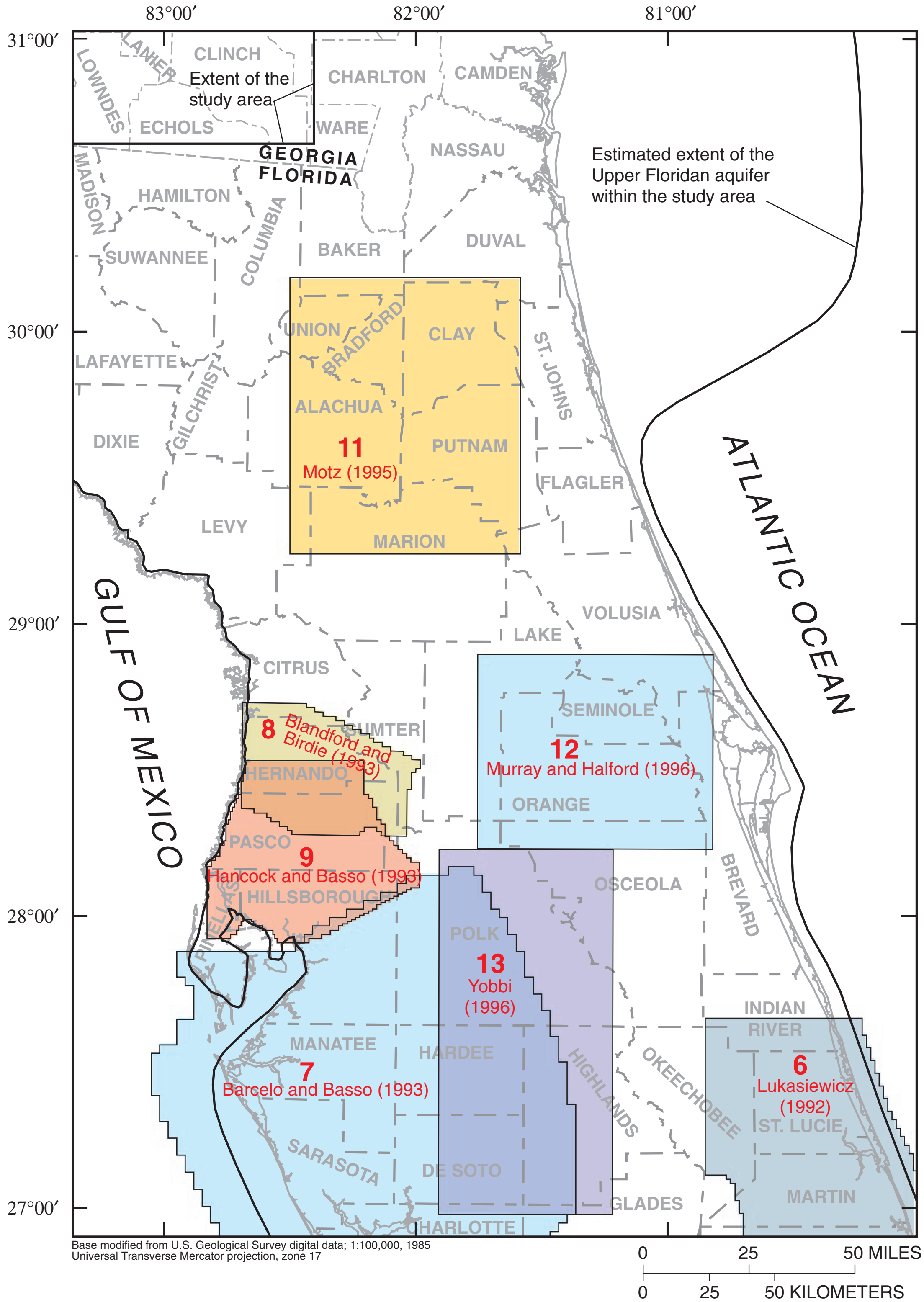
Appendix A1. Location and extent of simulated areas in the intermediate aquifer system or intermediate confining unit compiled from local ground-water flow models (refer to table 1 for general description of models).



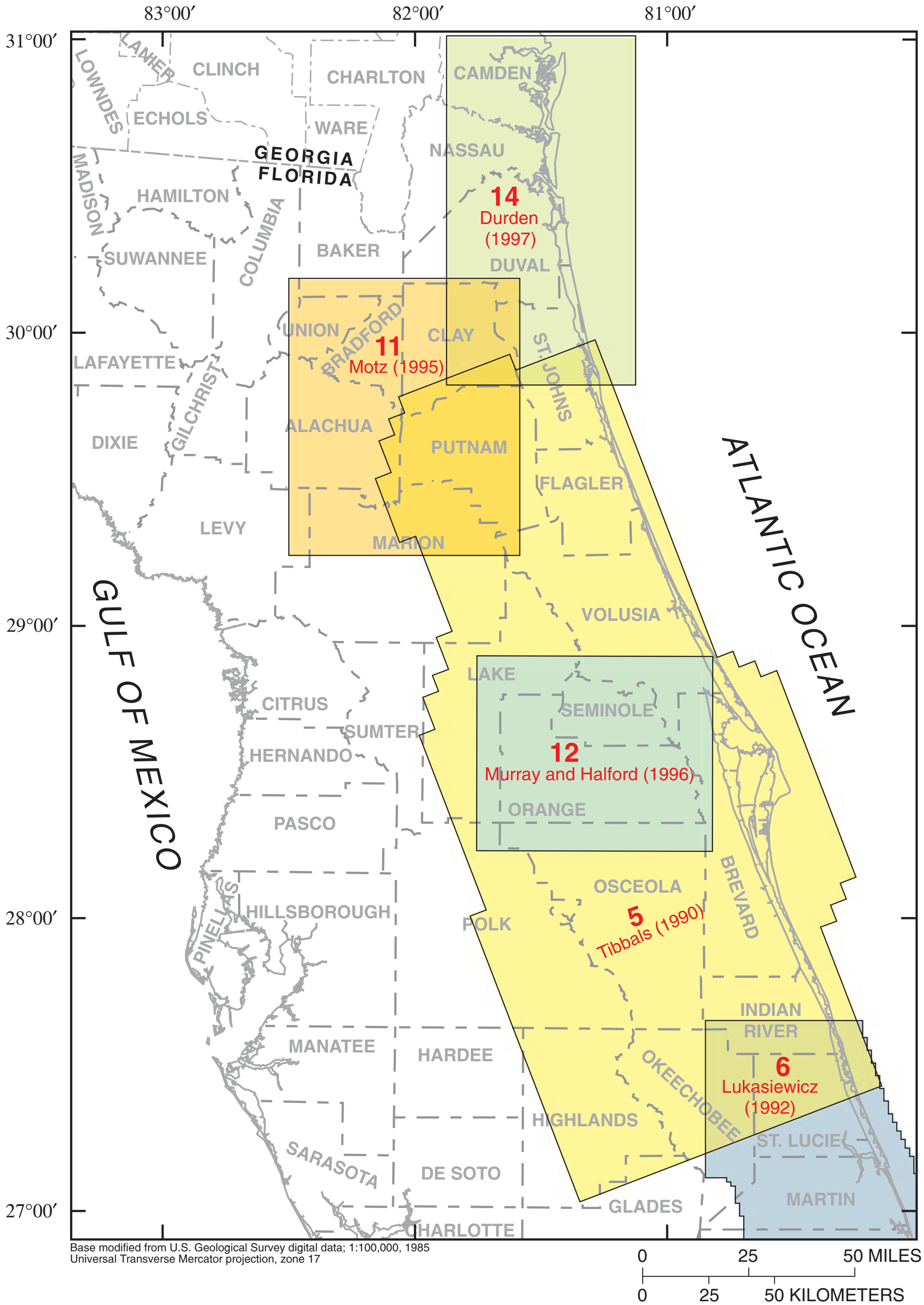
Appendix A1. Location and extent of simulated areas in the intermediate aquifer system or intermediate confining unit compiled from local ground-water flow models (refer to table 1 for general description of models)--Continued.



Appendix A2. Location and extent of simulated areas in the Upper Floridan aquifer compiled from local ground-water flow models (refer to table 1 for general description of models).



Appendix A2. Location and extent of simulated areas in the Upper Floridan aquifer compiled from local ground-water flow models (refer to table 1 for general description of models)--Continued.



Appendix A3. Location and extent of simulated areas in the Lower Floridan aquifer compiled from local ground-water flow models (refer to table 1 for general description of models).

Appendix B. Description of wells equipped with continuous water-level recorders

[Well number refers to figure 16. Site numbers with 13 digits indicate data source was St. Johns River Water Management District; site numbers ending with 85 indicate data source was Suwannee River Water Management District (SRWMD); data source of all other site numbers was U.S. Geological Survey (USGS). Hydrogeologic units: CUFA, confined Upper Floridan aquifer; UUFA, unconfined Upper Floridan aquifer; SAS, surficial aquifer system; ICU, intermediate confining unit; IAS, intermediate aquifer system; LFA, Lower Floridan aquifer. --, data not available; ROMP, Regional Observation and Monitoring Well Program]

Well number	Site number	Well name	Latitude	Longitude	Well depth (feet)	Hydrogeo-logic unit
1	302127082475885	Morgan	302127	824758	260	UUFA
2	301458083141985	Advent Christian Village	301458	831419	60	UUFA
3	301610082591585	Brickles	301610	825915	180	UUFA
4	300904083100985	Moore	300904	831009	144	UUFA
5	300629083024185	Suwannee Farms	300629	830241	247	UUFA
6	300403083081785	Koon	300403	830817	--	UUFA
7	300117082554285	Daniel	300117	825542	--	UUFA
8	294928082355385	08S17E03 High Springs City	294928	823553	300	UUFA
9	294654082581085	Georgia Pacific	294654	825810	35	UUFA
10	294458083142885	DOF Hines Lookout Tower	294458	831428	92	UUFA
11	293731083061885	City of Cross City	293731	830618	145	UUFA
12	293619082362385	USGS Alachua County	293619	823623	252	UUFA
13	293252082292385	Straughn	293252	822923	60	UUFA
14	292921082583285	DNR Manatee Springs State Park	292921	825832	99	UUFA
15	292615082272601	ROMP 134 near Williston	292615	822726	1,185	UUFA
16	2921380820616	M-0012 Johnston C.C.	292138	820616	63	UUFA
17	291910082341185	USGS Levy County	291910	823411	86	UUFA
18	291414082560985	DOF Rosewood Tower	291414	825609	254	UUFA
19	290230082412501	ROMP 125 at Crackertown	290230	824125	280	UUFA
20	290312082250801	USGS CE 14 near Dunnellon	290312	822508	190	UUFA
21	290112082371101	USGS CE 5 near Inglis	290112	823711	125	UUFA
22	290133082140901	ROMP 119 near Ocala	290133	821409	502	UUFA
23	285720082201301	ROMP 116 near Tsala Apopka Lake	285720	822013	55	UUFA
24	285414082284201	North Lecanto near Lecanto	285414	822842	335	UUFA
25	285124082245601	ROMP 113 near Inverness	285124	822456	150	UUFA
26	285102082204001	DOT Highway 41 near Inverness	285102	822040	450	UUFA
27	284317082330601	Chassahowitzka 1 near Chassahowitzka	284317	823306	176	UUFA
28	284330082215401	ROMP 109 near Floral City	284330	822154	260	UUFA
29	283201082315601	Weeki Wachee	283201	823156	259	UUFA
30	282742082375901	ROMP TR18-1 near Aripeka	282742	823759	580	UUFA
31	282613082381701	ROMP TR18-3 near Aripeka	282613	823817	622	UUFA
32	282605082345801	ROMP 97 near Aripeka	282605	823458	355	UUFA
33	3032350822035	BA0059 Eddy Fire Tower 1151	303235	822035	20	SAS
34	3032350822035	BA0058 Eddy Fire Tower 1153	303235	822035	40	ICU
35	3032350822035	BA0057 Eddy Fire Tower 1152	303235	822035	360	CUFA
36	302416081522601	D-0348 J-0413	302416	815226	708	CUFA
37	302416081522602	D-0349 J-0414	302416	815226	2,230	LFA
38	302301081295001	DS-522 Ft. Caroline Park	302301	812950	34	SAS
39	302301081295002	DS-523 Ft. Caroline Park	302301	812950	204	ICU
40	301710081323601	DS-520	301710	813236	60	SAS
41	301710081323602	DS-521	301710	813236	120	ICU
42	301710081323603	D-3824	301710	813236	740	CUFA
43	3016180821109	BA0056 Macclenny 1160	301618	821109	40	SAS
44	3016180821109	BA0055 Macclenny 1161	301618	821109	60	ICU
45	3016180821109	BA0054 Macclenny 1162	301618	821109	368	CUFA
46	3005070812727	SJ0030 Durbin Firetower	300507	812727	120	SAS

Appendix B. Description of wells equipped with continuous water-level recorders--Continued

[Well number refers to figure 16. Site numbers with 13 digits indicate data source was St. Johns River Water Management District; site numbers ending with 85 indicate data source was Suwannee River Water Management District (SRWMD); data source of all other site numbers was U.S. Geological Survey (USGS). Hydrogeologic units: CUFA, confined Upper Floridan aquifer; UUFA, unconfined Upper Floridan aquifer; SAS, surficial aquifer system; ICU, intermediate confining unit; IAS, intermediate aquifer system; LFA, Lower Floridan aquifer. --, data not available; ROMP, Regional Observation and Monitoring Well Program]

Well number	Site number	Well name	Latitude	Longitude	Well depth (feet)	Hydrogeo-logic unit
47	3005070812727	SJ0029 Durbin Firetower	300507	812727	603	CUFA
48	2958510815553	C-0127 Penney Farms Tower	295851	815553	136	SAS
49	2958510815553	C-0128 Penney Farms Tower	295851	815553	405	CUFA
50	2951160820058	C-0456 Lake Lowery	295116	820058	20	SAS
51	2951160820058	C-0440 Lake Lowery	295116	820058	124	ICU
52	2951160820058	C-0439 Lake Lowery	295116	820058	198	CUFA
53	2949110815726	C-0455 Gold Head 3	294911	815726	42	SAS
54	2949110815726	C-0454 Gold Head 2	294911	815726	110	ICU
55	2949110815726	C-0453 Gold Head 1	294911	815726	375	CUFA
56	2947280820109	C-0444 Chester Moody	294728	820109	87	SAS
57	2947280820109	C-0443 Chester Moody	294728	820109	131	ICU
58	2947280820109	C-0442 Chester Moody	294728	820109	240	CUFA
59	2946110820049	C-0438 Lake Geneva 3	294611	820049	20	SAS
60	2946110820049	C-0437 Lake Geneva 2	294611	820049	85	ICU
61	2946110820049	C-0436 Lake Geneva 1	294611	820049	146	CUFA
62	2937540811219	F-0191 Washington Oaks State Park	293754	811219	36	SAS
63	2937540811219	F-0200 Washington Oaks State Park	293754	811219	148	CUFA
64	2928590813757	P-0409 Fruitland	292859	813757	55	SAS
65	2928590813757	P-0408 Fruitland	292859	813757	148	CUFA
66	2926030810825	F-0177 Bulow Ruins	292603	810825	43	SAS
67	2926030810825	F-0176 Bulow Ruins	292603	810825	120	CUFA
68	2924470813706	P-0778 Marvin Jones Road	292447	813706	50	SAS
69	2924470813706	P-0777 Marvin Jones Road	292447	813706	110	ICU
70	2924470813706	P-0776 Marvin Jones Road	292447	813706	160	CUFA
71	2924180813309	P-0742 Niles Road	292418	813309	27	SAS
72	2924180813309	P-0143 Niles Road	292418	813309	66	ICU
73	2924180813309	P-0705 Niles Road	292418	813309	400	CUFA
74	2922390813137	P-0724 Silver Pond	292239	813137	25	SAS
75	2922390813137	P-0146 Silver Pond	292239	813137	55	ICU
76	2922390813137	P-0696 Silver Pond	292239	813137	400	CUFA
77	2921240813452	P-0734 Middle Road	292124	813452	20	SAS
78	2921240813452	P-0736 Middle Road	292124	813452	100	ICU
79	2921240813452	P-0735 Middle Road	292124	813452	360	CUFA
80	2914580812942	V-0525 West Pierson	291458	812942	14	SAS
81	2914580812942	V-0524 West Pierson	291458	812942	39	ICU
82	2914580812942	V-0068 West Pierson	291458	812942	125	CUFA
83	2914480812749	V-0528 Pierson Airport	291448	812749	23	SAS
84	2914480812749	V-0557 Pierson Airport	291448	812749	98	ICU
85	2914480812749	V-0531 Pierson Airport	291448	812749	210	CUFA
86	2914480812749	V-0530 Pierson Airport	291448	812749	1,060	LFA
87	2913230811912	V-0770 State Road 40 and State Road 11	291323	811912	35	SAS
88	2913230811912	V-0501 State Road 40 and State Road 11	291323	811912	70	ICU
89	2913230811912	V-0769 State Road 40 and State Road 11	291323	811912	440	CUFA
90	2906140811833	V-0744 Lee Airport	290614	811833	36	SAS
91	2906140811833	V-0743 Lee Airport	290614	811833	72	ICU
92	2906140811833	V-0742 Lee Airport	290614	811833	460	CUFA

Appendix B. Description of wells equipped with continuous water-level recorders--Continued

[Well number refers to figure 16. Site numbers with 13 digits indicate data source was St. Johns River Water Management District; site numbers ending with 85 indicate data source was Suwannee River Water Management District (SRWMD); data source of all other site numbers was U.S. Geological Survey (USGS). Hydrogeologic units: CUFA, confined Upper Floridan aquifer; UUFA, unconfined Upper Floridan aquifer; SAS, surficial aquifer system; ICU, intermediate confining unit; IAS, intermediate aquifer system; LFA, Lower Floridan aquifer. --, data not available; ROMP, Regional Observation and Monitoring Well Program]

Well number	Site number	Well name	Latitude	Longitude	Well depth (feet)	Hydrogeo-logic unit
93	283204081544902	Mascotte near Mascotte	283204	815449	30	SAS
94	283204081544901	Mascotte near Mascotte	283204	815449	160	CUFA
95	282202081384602	Lake Oliver near Vineland	282202	813846	30	SAS
96	282202081384601	Lake Oliver near Vineland	282202	813846	318	CUFA
97	275411081372002	ROMP 57 near Lake Wales	275411	813720	140	SAS
98	275411081372001	ROMP 57 near Lake Wales	275411	813720	634	CUFA
99	274240082212702	ROMP 50 near Wimauma	274240	822127	37	SAS
100	274240082212701	ROMP 50 near Wimauma	274240	822127	562	CUFA
101	274240082212703	ROMP 50 Avon Park near Wimauma	274240	822127	1,430	LFA
102	272728081474703	ROMP 30 near Zolfo Springs	272728	814747	15	SAS
103	272728081474701	ROMP 30 Avon Park near Zolfo Springs	272728	814747	1,266	CUFA
104	270959082203003	ROMP 19 near Sarasota	270959	822030	67	SAS
105	270959082203002	ROMP 19 near Sarasota	270959	822030	205	IAS
106	270959082203001	ROMP 19 near Sarasota	270959	822030	425	CUFA
107	270952080135202	M-1183	270952	801352	21	SAS
108	270952080135201	M-1141	270952	801352	109	ICU
109	2933130811352	F-0164 Levitt Development	293313	811352	90	SAS
110	2913530811604	V-0088 Union Camp	291353	811604	20	SAS
111	282210081352601	Disney at tree farm near Vineland	282210	813526	18	SAS
112	281722080543001	USGS OS171 near Deer Park	281722	805430	19	SAS
113	280619080542601	USGS OS179 at Deer Park	280619	805426	18	SAS
114	280132082452803	ROMP TR14-2 near Dunedin	280132	824528	22	SAS
115	275458082464004	ROMP TR13-1A near Largo	275458	824640	20	SAS
116	275430082431403	ROMP TR13-2 near Largo	275430	824314	16	SAS
117	274812081190301	P49 near Frostproof	274812	811903	17	SAS
118	273923080471801	IR 25 USGS near Yeehaw Junction	273923	804718	19	SAS
119	272504081120101	H11A near Lake Placid	272504	811201	16	SAS
120	272258082181701	KME water table 09 near Verna	272258	821817	42	SAS
121	271559081242501	Lake Groves Road near Lake Placid	271559	812425	23	SAS
122	271226081194301	Bairs Den near Lake Placid	271226	811943	35	SAS
123	271007080142101	M-1179	271007	801421	20	SAS
124	270913080284901	M-1255	270913	802849	28	SAS
125	270609080163401	M-1261	270609	801634	20	SAS
126	270157081203101	USGS H15A near Palmdale	270157	812031	23	SAS
127	270124080280202	M-1048	270124	802802	80	SAS
128	265812080053901	PB-565	265812	800539	22	SAS
129	265725080141801	M-1234	265725	801418	18	SAS
130	275314081514202	ROMP 59 Hawthorn near Bartow	275314	815142	142	IAS
131	273851082031502	ROMP 40 Hawthorn near Duette	273851	820315	180	IAS
132	273156081451401	Rowell	273156	814514	267	IAS
133	272258082195301	KME 04	272258	821953	440	IAS
134	272058082143701	Verna T O-2 near Verna	272058	821437	530	IAS
135	271832082064801	Edgeville 3 at Edgeville	271832	820648	600	IAS
136	271757081493003	ROMP 26 Hawthorn near Gardner	271757	814930	180	IAS
137	271118082285301	Osprey 9	271118	22853	255	IAS
138	270952082095901	Carlton 13 near Arca	270952	820959	287	IAS

Appendix B. Description of wells equipped with continuous water-level recorders--Continued

[Well number refers to figure 16. Site numbers with 13 digits indicate data source was St. Johns River Water Management District; site numbers ending with 85 indicate data source was Suwannee River Water Management District (SRWMD); data source of all other site numbers was U.S. Geological Survey (USGS). Hydrogeologic units: CUFA, confined Upper Floridan aquifer; UUFA, unconfined Upper Floridan aquifer; SAS, surficial aquifer system; ICU, intermediate confining unit; IAS, intermediate aquifer system; LFA, Lower Floridan aquifer. --, data not available; ROMP, Regional Observation and Monitoring Well Program]

Well number	Site number	Well name	Latitude	Longitude	Well depth (feet)	Hydrogeo-logic unit
139	270137082235301	Manasota 14	270137	822353	305	IAS
140	304942082213801	USGS OK-9	304943	822138	700	CUFA
141	304756081311101	U.S. Navy in Kings Bay	304756	813111	990	CUFA
142	304512081343601	Huntley-Jiffy (Davis)	304510	813438	--	CUFA
143	304213081270801	N-19 Ft. Clinch, Fernandina Beach	304210	812708	710	CUFA
144	3038230812733	N-0190 Fernandina Beach ITT 8	303823	812733	1,020	CUFA
145	303510083054985	Prescott	303510	830549	188	CUFA
146	303425082473685	Cypress Creek	303425	824736	200	CUFA
147	303224083101785	Santa Deas	303224	831017	195	CUFA
148	303158082562985	Stafford Scaff at Jasper	303158	825629	279	CUFA
149	302859083015085	Carter	302859	830150	167	CUFA
150	302833082542985	Deas	302833	825429	105	CUFA
151	302550081331501	D-3840 St. John's River Power Park	302550	813315	750	CUFA
152	302251082194985	USGS ONF 6A	302251	821949	338	CUFA
153	302243082360285	ONF University of Florida 1	302241	823604	227	CUFA
154	301933082350585	USGS ONF 2V	301939	823526	262	CUFA
155	301423082261185	USGS Ocean Pond	301423	822611	134	CUFA
156	301031082381085	DOT	301031	823810	836	CUFA
157	301006082461785	St. Regis Paper Company	301006	824617	250	CUFA
158	300747082225885	USGS Lake Butler	300747	822258	35	CUFA
159	300706082402285	Vernon Norton	300706	824022	140	CUFA
160	300635082295985	Lulu Community Center	300635	822959	214	CUFA
161	300220082103085	USGS Railford	300220	821030	294	CUFA
162	300101082245285	USGS Lake Butler	300101	822452	254	CUFA
163	295257082045785	USGS Starke	295257	820457	324	CUFA
164	295055082130885	USGS Graham	295055	821308	206	CUFA
165	294920082044585	SRWMD Santa Fe Swamp	294920	820445	208	CUFA
166	294807082020903	Keystone Heights	294807	820209	250	CUFA
167	2947010812633	SJ0317 SKYES	294701	812633	290	CUFA
168	294530082232085	City of Gainsville	294530	822320	284	CUFA
169	294402082262185	DNR San Felasco Hammock	294402	822621	168	CUFA
170	294330082445085	USGS Trenton	294330	824450	103	CUFA
171	294313082024685	USGS Melrose	294313	820246	259	CUFA
172	293857082203985	University of Florida	293857	822039	406	CUFA
173	2937290812212	SJ0115 Countyline	293729	812212	609	CUFA
174	2935290811917	F-0165 ITT-LW-20	293529	811917	140	CUFA
175	2933130811324	F-0158 ITT Palm Coast	293313	811324	284	CUFA
176	2922040820228	M-0052 Fort McCoy	292204	820228	160	CUFA
177	2918180811904	F-0251 Relay Tower	291818	811904	147	CUFA
178	2917480812903	V-0510 Mew	291748	812903	130	CUFA
179	2917400815620	M-0025 C354 Gores Landing	291740	815620	280	CUFA
180	2913440811557	V-0090 Union Camp	291344	811557	151	CUFA
181	2913430812546	V-0089 Jones near Pierson	291343	812546	414	CUFA
182	2911300820150	M-0026 CE47 near Silver Springs	291130	820150	192	CUFA
183	290743082341501	Tidewater 1 near Dunnellon	290743	823415	784	CUFA
184	290455081530401	USGS Moss Bluff Park	290455	815304	225	CUFA

Appendix B. Description of wells equipped with continuous water-level recorders--Continued

[Well number refers to figure 16. Site numbers with 13 digits indicate data source was St. Johns River Water Management District; site numbers ending with 85 indicate data source was Suwannee River Water Management District (SRWMD); data source of all other site numbers was U.S. Geological Survey (USGS). Hydrogeologic units: CUFA, confined Upper Floridan aquifer; UUFA, unconfined Upper Floridan aquifer; SAS, surficial aquifer system; ICU, intermediate confining unit; IAS, intermediate aquifer system; LFA, Lower Floridan aquifer. --, data not available; ROMP, Regional Observation and Monitoring Well Program]

Well number	Site number	Well name	Latitude	Longitude	Well depth (feet)	Hydrogeo-logic unit
185	2901030805519	V-0508 Smith Street and US 1	290103	805519	210	CUFA
186	285745081054001	USGS at Alamana	285745	810540	21	CUFA
187	2856380812031	V-0083 Blue Springs	285638	812031	432	CUFA
188	284842081533001	College Street at Leesburg	284842	815330	245	CUFA
189	284725081361901	Wolf Sink near Sorrento	284725	813619	205	CUFA
190	284147081220201	USGS SEM 125 at Longwood	284147	812202	146	CUFA
191	283314081455501	City of Clermont	283314	814555	525	CUFA
192	283253081283401	USGS OR47 at Orlo Vista	283252	812835	350	CUFA
193	283249081053201	Bithlo 1 at Bithlo	283249	810532	492	CUFA
194	282835081305201	Palm Lake Drive near Windermere	282839	813026	235	CUFA
195	282738081341401	Lake Sawyer near Windermere	282738	813414	178	CUFA
196	282717081553101	ROMP 101 near Bay Lake	282717	815531	404	CUFA
197	282623081153801	Cocoa-P near Taft	282623	811538	439	CUFA
198	282531081095701	USGS Cocoa D near Narcoossee	282531	810957	300	CUFA
199	282528081340901	Bay Lake near Windermere	282528	813409	223	CUFA
200	282434081283102	Sea World Drive near Vineland	282434	812831	239	CUFA
201	282341081040101	USGS Cocoa A near Bithlo	282341	810401	516	CUFA
202	282127082022501	Cumpressco Ranch near Tarrytown	282127	820225	143	CUFA
203	281949082332001	State Highway 52 near Fivay Junction	281949	823320	73	CUFA
204	281926082212901	Junction of 52 and 581 near Darby	281926	822129	113	CUFA
205	281714081093001	Lake Joel near Ashton	281714	810930	750	CUFA
206	281558082264601	Pasco 13 near Drexel	281558	822646	49	CUFA
207	281532081345001	Loughman near Loughman	281532	813450	250	CUFA
208	281222082393401	Seven Springs near Odessa	281222	823934	301	CUFA
209	281202081391701	PO-1 Thornhill near Davenport	281202	813847	151	CUFA
210	281022082400201	Eldr Wild 3	281022	824002	350	CUFA
211	281008081441801	Lake Alfred near Lake Alfred	281008	814418	425	CUFA
212	280734082442101	ROMP TR15-3 near Tarpon Springs	280734	824421	150	CUFA
213	280655082193001	Morris Bridge 3a near Branchton	280659	821943	600	CUFA
214	280652082195101	Morris Bridge WF 3C near Thonotosassa	280652	821951	1,037	CUFA
215	280053082350202	Sheldon Road near Citrus Park	280053	823502	330	CUFA
216	280022082210501	SWFWMD west of Vandenburg Apt.	280022	822105	37	CUFA
217	275959081552501	Sanlon Ranch near Eaton Park	275959	815525	1,220	CUFA
218	275815082440401	Pinellas 665	275815	824404	299	CUFA
219	275429082093901	ROMP 61 near Pleasant Grove	275429	820939	1,000	CUFA
220	274409082015001	Bethlehem Road near Bradley Junction	274409	820150	1,000	CUFA
221	273718082315501	FP&L at Piney Point	273718	823155	950	CUFA
222	272255082172202	KME near Verna	272255	821722	1,200	CUFA
223	272053082320202	City of Sarasota injection well 2 at Sarasota	272053	823202	1,500	CUFA
224	272012081482501	Marshall near Gardner	272012	814825	478	CUFA
225	271938082251801	Sarasota 9	271938	822518	730	CUFA
226	271232081392201	ROMP 15 Avon Park near Arcadia	271232	813922	1,360	CUFA

Appendix C. Description and flow measurements of Upper Floridan aquifer springs

[Spring number refers to figure 22. If more than one date of measurement is listed, measured flow is an average of measurements; ft^3/s, cubic feet per second; dates are shown in month-year format]

Spring number	Spring name	Latitude	Longitude	County	Measured or estimated flow (ft^3/s)	Date(s) of measurement(s)
1	Blue Spring near Madison	302849	831440	Madison	[a]118.0	07-95, 11-95
2	Alapaha Rise near Fort Union	302614	830513	Hamilton	[a]427.0	08-95, 11-95
3	Holton Spring near Fort Union	302615	830327	Hamilton	[a]12.5	07-95, 11-95
4	Suwannee Springs near Live Oak	302339	825604	Suwannee	[a]9.8	07-95
5	Suwanacoochee Spring at Ellaville	302309	831018	Madison	[b]43.0	11-73
6	Ellaville Spring at Ellaville	302303	831021	Suwannee	[b]69.0	11-73
7	Falmouth Spring at Falmouth	302140	830807	Suwannee	[b]134.0	11-73
8	White Sulphur Springs at White Springs	301947	824540	Hamilton	[a]42.3	06-98
9	Charles Springs near Dell	301002	831350	Suwannee	[a]4.7	07-95, 11-95
10	Allen Mill Pond Spring near Dell	300945	831433	Lafayette	[a]12.2	07-95, 11-95
11	Wadesboro Spring near Orange Park	300925	814320	Clay	[b]1.0	03-72
12	Blue Spring near Dell	300733	831334	Lafayette	[a]70.0	07-95, 11-95
13	Peacock Springs	300718	830757	Suwannee	[a]81.1	06-98
14	Telford Spring at Luraville	300624	830957	Suwannee	[a]35.8	07-95, 11-95
15	Running Springs (East and West) near Luraville	300615	830659	Suwannee	[a]88.0	07-95, 11-95
16	Convict Spring near Mayo	300518	830546	Lafayette	[a]1.1	07-95, 11-95
17	Royal Spring near Alton	300501	830430	Suwannee	[a]1.9	07-95
18	Owens Spring	300244	830229	Lafayette	[b]43.3	09-73
19	Mearson Spring near Mayo	300228	830132	Lafayette	[a]51.0	07-95, 11-95
20	Troy Spring near Branford	300021	825951	Lafayette	[a]132.0	07-95, 11-95
21	Little River Springs near Branford	295947	825759	Suwannee	[a]67.0	07-95, 11-95
22	Ruth Spring near Branford	295944	825838	Lafayette	[a]7.5	07-95, 11-95
23	Green Cove Springs at Green Cove Springs	295936	814040	Clay	[b]3.0	03-72
24	Ichetucknee Head Spring near Fort White	295902	824543	Suwannee	[c]41.0	07-95, 11-95
25	Cedar Head (or Alligator Hole) Spring	295900	824532	Columbia	[c]8.0	07-95, 11-95
26	Blue Hole (or Jug) Spring	295847	824531	Columbia	[c]77.0	07-95, 11-95
27	Roaring Springs (including Singing Spring)	295835	824531	Columbia	[c]48.0	07-95, 11-95
28	Boiling Spring	295825	824537	Suwannee	[c]116.0	07-95, 11-95
29	Mill Pond Spring (including Grassy Hole Springs and Coffee Spring)	295804	824537	Columbia	[c]17.0	07-95, 11-95
30	Branford Springs at Branford	295717	825544	Suwannee	[a]35.8	05-98, 06-98
31	Jamison Spring	295532	824556	Columbia	[b]3.0	04-77
32	Hornsby Spring near High Springs	295059	823536	Alachua	[a]49.8	07-95, 12-95
33	Turtle Spring near Hatchbend	295055	825324	Lafayette	[a]27.9	07-95, 11-95
34	Fletcher Spring	295048	825334	Lafayette	[b]34.0	11-72
35	Steinhatchee Spring near Clara	295028	831829	Lafayette	[b]0.7	10-72
36	Ginnie Spring near High Springs	295010	824201	Gilchrist	[a]57.1	07-95, 12-95
37	Blue Springs near High Springs (including Lilly Springs)	294947	824059	Gilchrist	[a]41.2	07-95, 12-95
38	Poe Springs near High Springs	294933	823858	Alachua	[a]53.6	07-95, 12-95
39	Rock Bluff Springs near Bell	294756	825508	Gilchrist	[a]33.2	08-95, 12-95
40	Guaranto Spring near Rock Bluff Landing	294646	825624	Dixie	[b]12.0	11-72
41	Crescent Beach Submarine Spring	294606	811230	offshore	[d]30.0	
42	Lumbercamp Springs	294227	825608	Gilchrist	[b]6.2	11-72
43	Sun Springs near Wannee	294216	825601	Gilchrist	[a]40.1	08-95, 12-95
44	Hart Springs near Wilcox	294030	825705	Gilchrist	[a]90.8	08-95, 12-95
45	Otter Springs near Wilcox	293840	825636	Gilchrist	[b]16.0	11-72
46	Whitewater Springs	293806	813853	Putnam	[b]1.2	04-72
47	Copper Springs near Oldtown (including Little Copper Spring)	293650	825826	Dixie	[b]25.4	11-75
48	Bell Springs	293550	825630	Gilchrist	[b]5.1	10-72
49	Fannin Springs near Wilcox (including Little Fannin Spring)	293515	825608	Levy	[a]97.7	07-95, 12-95
50	Satsuma Spring	293159	814036	Putnam	[b]1.1	03-72
51	Blue Springs near Orange Springs	293051	815125	Marion	[a].5	05-99
52	Orange Spring at Orange Springs	293038	815638	Marion	[a]2.0	05-99
53	Camp Seminole Spring at Orange Springs	293021	815706	Marion	[a].8	05-99
54	Welaka Spring near Welaka	292935	814025	Putnam	[e]1.0	
55	Manatee Spring near Chiefland	292922	825837	Levy	[a]187.0	07-95, 12-95
56	Mud Spring near Welaka	292735	813945	Putnam	[b]2.3	06-72
57	Blue Spring near Bronson	292702	824157	Levy	[b]8.0	06-74
58	Beecher Springs near Fruitland	292654	813849	Putnam	6.3	09-93

Appendix C. Description and flow measurements of Upper Floridan aquifer springs--Continued

[Spring number refers to figure 22. If more than one date of measurement is listed, measured flow is an average of measurements; ft^3/s, cubic feet per second; dates are shown in month-year format]

Spring number	Spring name	Latitude	Longitude	County	Measured or estimated flow (ft^3/s)	Date(s) of measurement(s)
59	Croaker Hole Spring near Welaka	292618	814121	Putnam	90.3	09-93
60	Tobacco Patch Landing Spring Group near Fort McCoy	292542	815526	Marion	[a]1.0	05-99
61	Wells Landing Springs near Fort McCoy	292521	815512	Marion	[a]5.0	05-99
62	Salt Springs near Eureka	292100	814358	Marion	79.0	09-93, 05-94
63	Wekiva Springs near Gulf Hammock	291649	823923	Levy	[b]45.4	06-67
64	Silver Glen Springs near Astor	291443	813837	Marion	100.0	09-93, 05-94
65	Sweetwater Springs along Juniper Creek	291307	813936	Marion	12.5	09-93, 05-94
66	Silver Springs near Ocala	291257	820311	Marion	640.0	09-93, 05-94
67	Morman Branch Seepage into Juniper Creek near Astor	291129	813858	Marion	[a]1.0	06-97
68	Juniper Creek Tributary near Astor	291104	813845	Lake	[a]2.0	06-97
69	Juniper Springs near Ocala	291101	814246	Marion	8.1	09-93, 05-94
70	Fern Hammock Springs near Ocala	291100	814229	Marion	10.7	09-93, 05-94
71	Ponce de Leon Springs near De Land	290802	812147	Volusia	24.3	09-93, 05-94
72	Rainbow Springs near Dunnellon	290608	822616	Marion	637.0	09-93, 05-94
73	Alexander Springs near Astor	290450	813430	Lake	113.0	09-93, 05-94
74	Mosquito Springs Run, Alexander Springs Wildnerness	290220	812604	Lake	[a]2.0	06-97
75	Wilson Head Spring near Holder	285840	821908	Marion	[b]1.9	06-72
76	Blue Spring near Holder	285809	821852	Citrus	[b]10.6	05-72
77	Gum Springs near Holder	285731	821354	Sumter	[b]67.6	06-72
78	Camp La No Che Springs near Paisley	285702	813224	Lake	[a]1.0	06-97
79	Blue Spring near Orange City	285650	812023	Volusia	135.0	09-93, 05-94
80	Blackwater Springs near Cassia	285318	812952	Lake	[e]1.4	
81	Crystal River Spring Group	285300	823600	Citrus	[f]613.0	
82	Little Jones Creek Head Spring near Wildwood	285208	820541	Sumter	[e]8.0	
83	Green Springs	285145	811455	Volusia	[b].3	04-72
84	Gemini Springs near DeBary (all 3)	285144	811839	Volusia	10.5	09-93, 05-94
85	Little Jones Creek Spring No. 2 near Wildwood	285134	820518	Sumter	[e]5.0	
86	Messant Spring near Sorrento	285121	812956	Lake	12.0	09-93, 05-94
87	Seminole Springs near Sorrento	285044	813122	Lake	37.0	09-93, 05-94
88	Palm Springs Seminole State Forest	285038	812701	Lake	[a].5	06-97
89	Little Jones Creek Spring No. 3 near Wildwood	285011	820349	Sumter	[e]3.0	
90	Droty Springs near Sorrento	284940	813038	Lake	[a].6	06-97
91	Halls River Head Spring	284935	823450	Citrus	[g]4.8	
92	Island Spring near Sanford	284922	812503	Seminole	[a]6.4	04-97, 08-97
93	Halls River Springs	284804	823610	Citrus	[f]102.2	
94	Homosassa Springs at Homosassa Springs	284758	823520	Citrus	[g]72.4	
95	Southeast Fork of Homosassa Springs at Homosassa Spring	284751	823523	Citrus	[f]43.1	
96	Trotter Spring at Homosassa Springs	284747	823510	Citrus	[g]5.2	
97	Fenney Springs near Coleman, Head Spring of Shady Brook Creek	284742	820219	Sumter	[b]15.0	03-72
98	Shady Brook Creek Spring No. 2	284708	820246	Sumter	[e]2.9	
99	Shady Brook Creek Spring No. 3	284646	820238	Sumter	[e]2.9	
100	Shady Brook Creek Spring No. 4	284612	820420	Sumter	[e]2.9	
101	Sulphur Camp Springs	284612	813034	Orange	[a].6	06-97
102	Hidden River Springs near Homosassa (including Hidden River Head Spring)	284559	823520	Citrus	[g]6.7	
103	Rock Springs near Apopka	284521	813004	Orange	53.0	09-93, 05-94
104	Shady Brook Creek Spring No. 5	284515	820501	Sumter	[e]2.9	
105	Bugg Spring at Okahumpka	284507	815406	Lake	8.6	09-93, 05-94
106	Blue Springs near Yalaha	284455	814941	Lake	[a]3.0	09-97
107	Mooring Cove Springs near Yalaha	284452	814954	Lake	[a].4	06-97
108	Holiday Springs at Yalaha	284424	814905	Lake	[a]3.6	09-96
109	Potter Spring near Chassahowitzka (including Ruth Spring)	284354	823548	Citrus	[g]14.4	
110	Witherington Spring near Apopka	284353	812922	Orange	1.0	05-93
111	Salt Creek Head Spring	284323	823506	Citrus	[g].4	
112	Lettuce Creek Spring	284308	823437	Citrus	[g]3.7	
113	Crab Creek Spring	284300	823434	Citrus	[g]34.8	
114	Unnamed Tributary above Chassahowitzka Springs (including Bubba Spring)	284254	823438	Citrus	[g]20.5	

Appendix C. Description and flow measurements of Upper Floridan aquifer springs--Continued

[Spring number refers to figure 22. If more than one date of measurement is listed, measured flow is an average of measurements; ft^3/s, cubic feet per second; dates are shown in month-year format]

Spring number	Spring name	Latitude	Longitude	County	Measured or estimated flow (ft^3/s)	Date(s) of measurement(s)
115	Chassahowitzka Springs near Chassahowitzka	284254	823435	Citrus	[g]64.8	
116	Wekiwa Springs in State Park near Apopka	284243	812736	Orange	56.5	09-93, 05-94
117	Miami Springs near Longwood	284236	812634	Seminole	4.0	09-93, 05-94
118	Lake Jessup Spring near Wagner	284236	811605	Seminole	[b].6	05-72
119	Baird Creek Head Spring near Chassahowitzka	284230	823440	Citrus	[g]3.2	
120	Clifton Springs near Oviedo	284156	811414	Seminole	[b]1.5	06-72
121	Starbuck Spring near Longwood	284148	812328	Seminole	12.3	09-93, 05-94
122	Beteejay Lower Spring near Chassahowitzka (including Beteejay Head Spring)	284131	823535	Citrus	[g]7.3	
123	Palm Springs near Longwood	284127	812334	Seminole	4.1	09-93, 05-94
124	Rita Maria Spring near Chassahowitzka	284126	823528	Hernando	[g]3.3	
125	Sanlando Springs near Longwood	284119	812345	Seminole	18.5	09-93, 05-94
126	Unnamed Spring No. 10 (including No. 11 and No.12)	284114	823652	Hernando	[f]19.0	
127	Ryle Creek Lower Spring near Bayport (including Ryle Creek Head Spring)	284113	823650	Hernando	[g]8.3	
128	Blue Run Head Spring near Chassahowitzka	284113	823606	Hernando	[g]4.6	
129	Double Run Road Seepage near Astatula	284039	814425	Lake	[a]2.0	06-96
130	Unnamed Spring No. 8	284017	823808	Hernando	[f]4.9	
131	Blind Creek Springs (including unnamed spring No. 7 and Blind Creek Head Spring)	283932	823806	Hernando	[f]42.7	
132	Apopka (Gourdneck) Spring near Oakland	283400	814051	Lake	[a]31.4	12-92
133	Unnamed Spring No. 6	283254	823737	Hernando	[f]2.8	
134	Salt Spring near Bayport	283246	823709	Hernando	[g]22.3	
135	Mud Spring near Bayport	283240	823701	Hernando	[g]17.0	
136	Jenkins Creek Spring No. 5	283120	823804	Hernando	[g]15.3	
137	Unnamed Spring No. 4	283118	823806	Hernando	[f]6.3	
138	Weeki Wachee Springs near Brooksville	283100	823425	Hernando	129.0	09-93, 05-94
139	Unnamed Spring No. 2	282720	823830	Hernando	[f].7	
140	Boat Spring at Aripeka	282621	823929	Hernando	[g].4	
141	Bobhill Springs	282607	823834	Hernando	[g]1.8	
142	Unnamed Spring No. 1	282600	823926	Hernando	[f]6.3	
143	Magnolia Springs at Aripeka	282558	823926	Pasco	[g].5	
144	Unnamed Spring No. 3 near Aripeka	282352	824027	Pasco	[b]17.8	08-60
145	Horseshoe Spring near Hudson	282350	824121	Pasco	[b]9.7	12-72
146	Salt Springs near Port Richey	281733	824306	Pasco	[b]8.2	12-72
147	Crystal Springs near Zephyrhills	281030	821120	Pasco	37.0	09-93, 05-94
148	Sulphur Springs at Sulphur Springs	280115	822705	Hillsborough	25.0	10-93, 05-94
149	Lettuce Lake Spring	280104	822102	Hillsborough	[b]8.3	05-73
150	Six-Mile Creek Spring	280104	822018	Hillsborough	[b]1.3	05-71, 10-71
151	Eureka Springs near Tampa	280022	822039	Hillsborough	[b]1.3	05-73
152	Buckhorn Spring near Riverview	275322	821810	Hillsborough	[b]15.0	06-72
153	Lithia Springs Minor near Lithia	275201	821349	Hillsborough	8.0	09-93, 05-94
154	Lithia Springs Major near Lithia	275158	821352	Hillsborough	31.1	09-93, 05-94
155	Little Salt Spring near Murdock	270430	821400	Sarasota	[b].9	05-72
156	Warm Mineral Springs near Woodmere	270333	821540	Sarasota	[b]6.7	05-74
				Total	**6,383.8**	

[a]Estimated as the product of measured flow and the ratio of August 1993 through July 1994 rainfall that occurred during the year in which actual flow measurement(s) were made.

[b]Estimated as the product of measured flow from Rosenau and others (1977) and ratio of August 1993 through July 1994 rainfall that occurred during the year in which actual flow measurement(s) were made.

[c]Total flow of Ichetucknee Springs is the combined flow, in downstream order, from Ichetucknee Head Spring, Cedar Head Spring, Blue Hole Spring, Roaring Springs, Boiling Spring, and Mill Pond Spring. Estimated flow of 307 ft^3/s from Ichetucknee Springs for 1993-94 was obtained as the product of combined flow of 287 ft^3/s for 1995 and the ratio of August 1993 through July 1994 rainfall to 1995 rainfall.

[d]Highly generalized estimate.

[e]Estimated flow from Leel Knowles (USGS, written commun., 2000).

[f]Estimated to be 70 percent of average of flow measurements from Yobbi (1989).

[g]Estimated to be 70 percent of average of flow measurements from Yobbi (1992).