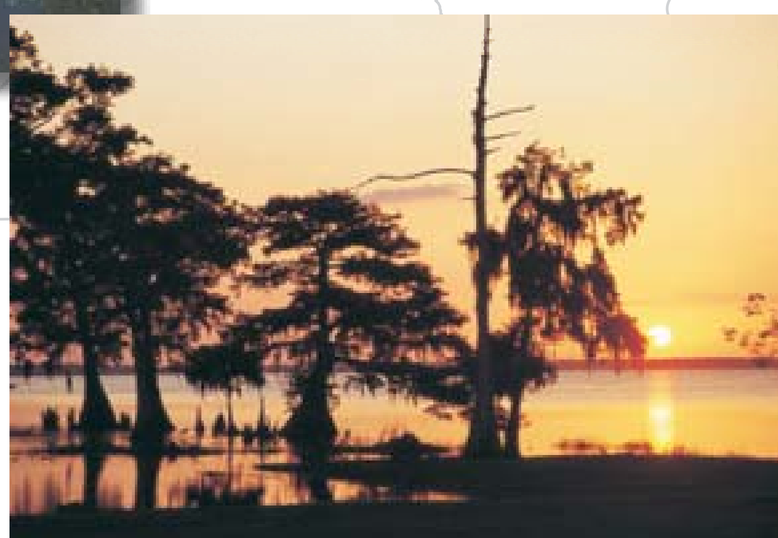
Hydrogeology, Water Quality, and Simulated Effects of Ground-Water Withdrawals from the Floridan Aquifer System, Seminole County and Vicinity, Florida



U.S. GEOLOGICAL SURVEY
Water Resources
Investigations Report 01-4182

Prepared in cooperation with the
Seminole County
St. Johns River Water Management District

USGS
science for a changing world

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Bottom:

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By Rick M. Spechler and Keith J. Halford

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Tallahassee, Florida
2001

U.S. DEPARTMENT OF THE INTERIOR
GALE A. NORTON, Secretary

U.S. GEOLOGICAL SURVEY
CHARLES G. GROAT, Director

For additional information write to:

District Chief
U.S. Geological Survey
Suite 3015
227 N. Bronough Street
Tallahassee, FL 32301

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CONTENTS

FIGURES

TABLES

CONVERSION FACTORS, VERTICAL DATUM, ABBREVIATIONS AND ACRONYMS

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
	Area	
square foot (ft^2)	0.0929	square meter
square mile (mi^2)	2.590	square kilometer
	Flow	
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
gallon per minute (gal/min)	0.06309	liter per second
inch per year (in/yr)	25.4	millimeter per year
	Hydraulic Conductivity	
foot per day (ft/d)	0.3048	meter per day
	Leakance	
foot per day per foot [(ft/d)/ft]	1.000	meter per day per meter
	****Transmissivity***	
foot squared per day (ft^2/d)	0.0929	meter squared per day

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.

Altitude: In this report, altitude refers to distance above or below sea level.

***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.

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

Acronyms and additional abbreviations used in report:

µg/L	micrograms per liter
µS/cm	microsiemens per centimeter at 25 °C
mg/L	milligrams per liter
MODFLOW	U.S. Geological Survey Modular Three-Dimensional Ground-Water Flow Model
OUC	Orlando Utilities Commission
RIB	Rapid Infiltration Basin
RMS	Root mean square
SJRWMD	St. Johns River Water Management District
SS	Sum of squares
USGS	U.S. Geological Survey

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By Rick M. Spechler and Keith J. Halford

Abstract

The hydrogeology and ground-water quality of Seminole County in east-central Florida was evaluated. A ground-water flow model was developed to simulate the effects of both present day (September 1996 through August 1997) and projected 2020 ground-water withdrawals on the water levels in the surficial aquifer system and the potentiometric surface of the Upper and Lower Floridan aquifers in Seminole County and vicinity.

The Floridan aquifer system is the major source of ground water in the study area. In 1965, ground-water withdrawals from the Floridan aquifer system in Seminole County were about 11 million gallons per day. In 1995, withdrawals totaled about 69 million gallons per day. Of the total ground water used in 1995, 74 percent was for public supply, 12 percent for domestic self-supplied, 10 percent for agriculture self-supplied, and 4 percent for recreational irrigation.

The principal water-bearing units in Seminole County are the surficial aquifer system and the Floridan aquifer system. The two aquifer systems are separated by the intermediate confining unit, which contains beds of lower permeability sediments that confine the water in the Floridan aquifer system. The Floridan aquifer system has two major water-bearing zones (the Upper Floridan aquifer and the Lower Floridan aquifer), which are separated by a less-permeable semiconfining unit.

Upper Floridan aquifer water levels and spring flows have been affected by ground-water development. Long-term hydrographs of four wells tapping the Upper Floridan aquifer show a general downward trend from the early 1950ís until 1990. The declines in water levels are caused predominantly by increased pumpage and below average annual rainfall. From 1991 to 1998, water levels rose slightly, a trend that can be explained by an increase in average annual rainfall. Long-term declines in the potentiometric surface varied throughout the area, ranging from about 3 to 12 feet. Decreases in spring discharge also have been observed in a few springs with long-term record.

Chloride concentrations in water from the Upper Floridan aquifer in Seminole County range areally from 6.2 to 5,300 milligrams per liter. Chloride concentrations are lowest in the recharge areas of the Floridan aquifer system in the western part of Seminole County and near Geneva. The most highly mineralized water occurs adjacent to the Wekiva River in northwestern Seminole County, around the eastern part of Lake Jesup, and along the St. Johns River in eastern Seminole County. Analysis of limited long-term water-quality data indicates that the chloride concentrations in water for most wells in the Floridan aquifer system in Seminole County have not changed significantly in the 20-year period from 1976 to 1996, and probably not since the mid 1950ís. Analysis of water samples collected from some Upper Floridan aquifer springs, however, indicates that the water has become more mineralized during recent years. Increases in specific conductance and concentrations of major cations and anions

were observed at several of the springs within the study area where long-term water-quality data were available. Associated with these increases in the mineralization of spring water has been an increase in total nitrate-plus-nitrite as nitrogen concentration.

A three-dimensional model was developed to simulate ground-water flow in the surficial and Floridan aquifer systems. The steady-state ground-water flow model was calibrated to water-level data that was averaged over a 1-year period from September 1996 through August 1997. The calibrated flow model generally produced simulated water levels in reasonably close agreement with measured water levels. As a result, the calibrated model was used to simulate the effects of expected increases in ground-water withdrawals on the water levels in the surficial aquifer system and on the potentiometric surface of the Upper and Lower Floridan aquifers in Seminole County.

The calibrated flow model was used to simulate the possible effects of increased ground-water withdrawals from the Floridan aquifer system in the year 2020. Ground-water withdrawals in the study area have been projected to increase from 412 million gallons per day (637 cubic feet per second) in 1996-97 to 591 million gallons per day (915 cubic feet per second) in 2020. Based on projected 2020 ground-water withdrawals, the simulated maximum drawdowns were about 16 feet in the surficial aquifer system and about 19 feet in the Upper and Lower Floridan aquifers.

INTRODUCTION

Rapid growth in Seminole County, Fla., and adjacent areas is creating an ever-increasing demand for freshwater. In 1965, the population of Seminole County was about 73,000 and total ground-water withdrawals were estimated to be about 11 million gallons per day. By 1995, the population and ground-water withdrawals were estimated to be about 324,000 and 69 million gallons per day, respectively. The population is projected to reach about 509,000 by the year 2020. As population increases, additional water supplies will be needed.

Ground water, the principal source of water supply in Seminole County, is obtained from two aquifers: the surficial aquifer system and the Floridan aquifer system. The surficial aquifer system has limited use because of low yields to wells and the potential for contamination. Water withdrawn from the surficial aquifer system is used primarily for lawn irrigation. The Floridan aquifer system is the principal source of water supply in the study area. Wells open to the Floridan aquifer system yield large quantities of good quality water; however, dissolved solid and chloride concentrations exceed secondary limits for potable water supply in parts of eastern and northwestern Seminole County. There also is concern that in some areas heavy withdrawals from the Floridan aquifer system might cause saltwater intrusion, which could result in ground water quality degradation. Increased withdrawals from the Floridan aquifer system also could lower lake levels and the potentiometric surface of the Upper Floridan aquifer and decrease the flow from Upper Floridan aquifer springs.

As the demand for water in Seminole County increases, additional information about the aquifers is needed to manage and to develop the water supply effectively. The U.S. Geological Survey (USGS), in cooperation with Seminole County and the St. Johns River Water Management District (SJRWMD), conducted a study from 1994 to 1999 to describe the hydrogeology and ground-water quality and evaluate the effects of increased pumpage on the ground-water resources of Seminole County.

Purpose and Scope

This report presents a description of the hydrogeology of the surficial and Floridan aquifer systems in Seminole County, characterizes present-day water-quality conditions in the Upper Floridan aquifer, and quantifies the effects of future ground-water withdrawals. Ground-water level and quality, surface-water stage and discharge, and water-use data are presented. A numerical model of the ground-water flow system was constructed and used to evaluate the effects of anticipated increases in pumping on water levels in the surficial and Floridan aquifer systems and on spring flow from the Upper Floridan aquifer. Although the primary area of interest was Seminole County, population growth and urbanization in adjacent central Florida counties affect Seminole County, so the study area was expanded to consider the larger, more regional system (fig. 1).

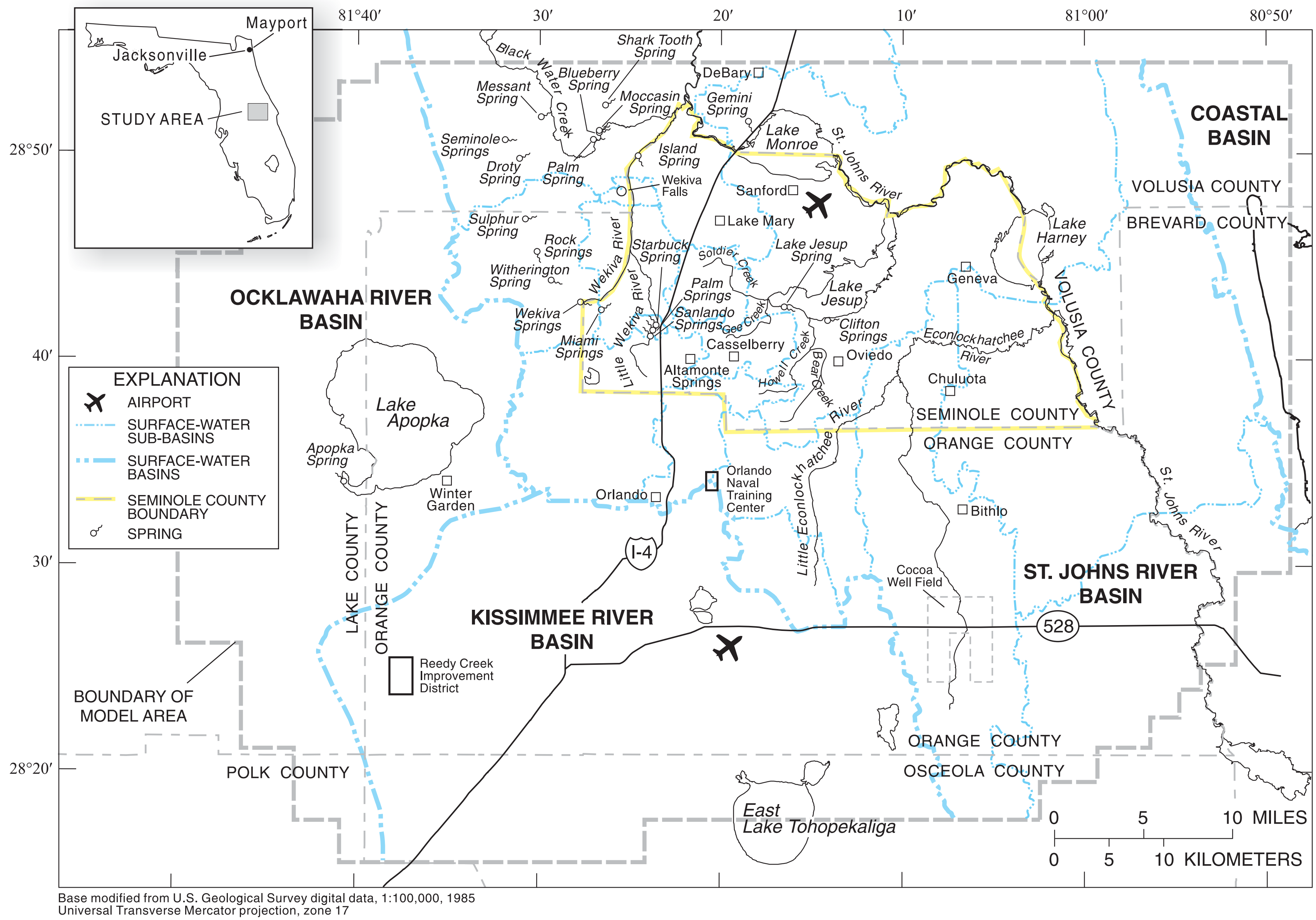


Figure 1. Location of study area, model area, and surface-water drainage basins.

Previous Investigations

Numerous reports on the ground-water resources, hydrology, and geology of the study area are available. The ground-water resources of Seminole County were first described by Stringfield (1934). A study of the water resources of the Florida Peninsula (Stringfield, 1936) included information about Seminole County. Stubbs (1937) also reported on the ground-water hydrology of Seminole County, with emphasis on the water supply for the city of Sanford. Data reports by Heath and Barraclough (1954), Barraclough (1961), and an interpretive report by Barraclough (1962) provided a reconnaissance of the ground-water resources of Seminole County. Tibbals (1977) studied the availability and quality of ground water in the county and delineated recharge and discharge areas. Phelps and Rohrer (1987) described the hydrogeology and geochemistry of the Geneva freshwater lens in eastern Seminole County, and Boniol and others (1993) examined the recharge features of the lens. Toth and others (1989) evaluated the water quality in the Wekiva River Basin of Seminole, Orange, and Lake Counties.

Reports describing the hydrogeology in all or parts of Orange County include Unklesbay (1944), Lichtler and others (1968), Lichtler (1972), Knochenmus (1975), Tibbals and Frazee (1976), Kimrey (1978), Shaw and Trost (1984), German (1989), and Bradner (1991); in Brevard County by Brown and others (1962); in Lake County by Knochenmus (1971), Knochenmus and Hughes (1976), Grubb (1978), and Grubb and Rutledge (1979); in Osceola County by Frazee (1980), Shaw and Trost (1984), and Schiner (1993); and in Volusia County by Wyrick (1960), Knochenmus and Beard (1971), Rutledge (1982, 1985), McGurk and others (1989), Kimrey (1990), and Phelps (1990).

Ground-water flow modeling studies have been performed for all or parts of the study area by Bush (1978), Grubb and Rutledge (1979), Planert and Aucott (1985), Skipp (1988), Tibbals (1981, 1990), GeoTrans, Inc. (1991), HydroGeoLogic (1992, 1994), and Murray and Halford (1996).

Reports describing the regional geology, hydrology, and geochemistry of the Floridan aquifer system in the study area include those by Miller (1986), Bush and Johnston (1988), Johnston and Bush (1988), and Sprinkle (1989).

Acknowledgments

The authors gratefully acknowledge the assistance of Brian McGurk, Paula Presley, Nolan Col, Bruce Florence, Robert Brooks, Alan Story, and Mark Ward, St. Johns River Water Management District; Gina Paulmeno, Charles Womack, and Ruth Lala, Seminole County Utilities; Rick Diaz, Lake Mary Utilities; and Allen Nettles, Seminole County Public Schools. Appreciation also is expressed to the many residents in the area who permitted access to their properties and allowed the sampling of water and measuring of water levels in their wells.

Well-Numbering System

The USGS assigns a unique site identification number to each inventoried well and surface-water site. A 15-digit number based on latitude and longitude is used to identify wells in the USGS data storage and retrieval systems. The first six digits denote the degrees, minutes, and seconds of latitude; the next seven digits denote degrees, minutes, and seconds of longitude; and the last two digits denote a sequential number for a site within a one-second grid. For example, well 283740081031401 is the first well inventoried at latitude 28^{o}37'40" N, longitude 081^{o}03'14" W. Once assigned, a site identification number does not change, even though the latitude and longitude of the location may be revised later. Surface-water sites that are part of the long-term data collection network are assigned an eight-digit downstream order number, such as 02234600 for Wekiva Springs, which designates the major river basin (02) and the order in which the tributary joins the main stream. Surface-water sites that are not part of the long-term network usually are given a 15-digit number.

The SJRWMD uses an identification system similar to the USGS for identifying wells, using latitude and longitude as a primary identifier. They also use a sequential local number assigned to each well as it is added to their network files. An abbreviation for the county where the well is located precedes the well number and, thus, distinguishes it from a well having the same number in another county. The prefixes S, OR, BR, L, OS, PO, and V indicate a well drilled in Seminole, Orange, Brevard, Lake, Osceola, Polk, and Volusia Counties, respectively.

Description of the Study Area

The study area encompasses 2,500 square miles (mi^2) in east-central Florida and includes all of Seminole and Orange Counties and parts of Brevard, Lake, Osceola, Polk, and Volusia Counties. The primary area of interest, however, is Seminole County, which covers about 345 mi^2 of which 298 mi^2 is land and about 47 mi^2 is water (Purdum and others, 1988, p. 118). The location of Seminole County and the boundaries of the study area for the ground-water flow model are shown in figure 1.

Rapid population increases over the past 30 years have occurred in Seminole County and in adjacent Orange County, the most populated county in east-central Florida. This trend is expected to continue through the year 2020. From 1965 to 1995, the population of Seminole County increased from about 73,000 to 324,000 (fig. 2). During the same period, the population of Orange County increased from about 300,000 to 759,000. Total population in Seminole and Orange Counties is projected to reach about 509,000 and 1,236,000, respectively, by 2020 (Smith and Nogle, 1999).

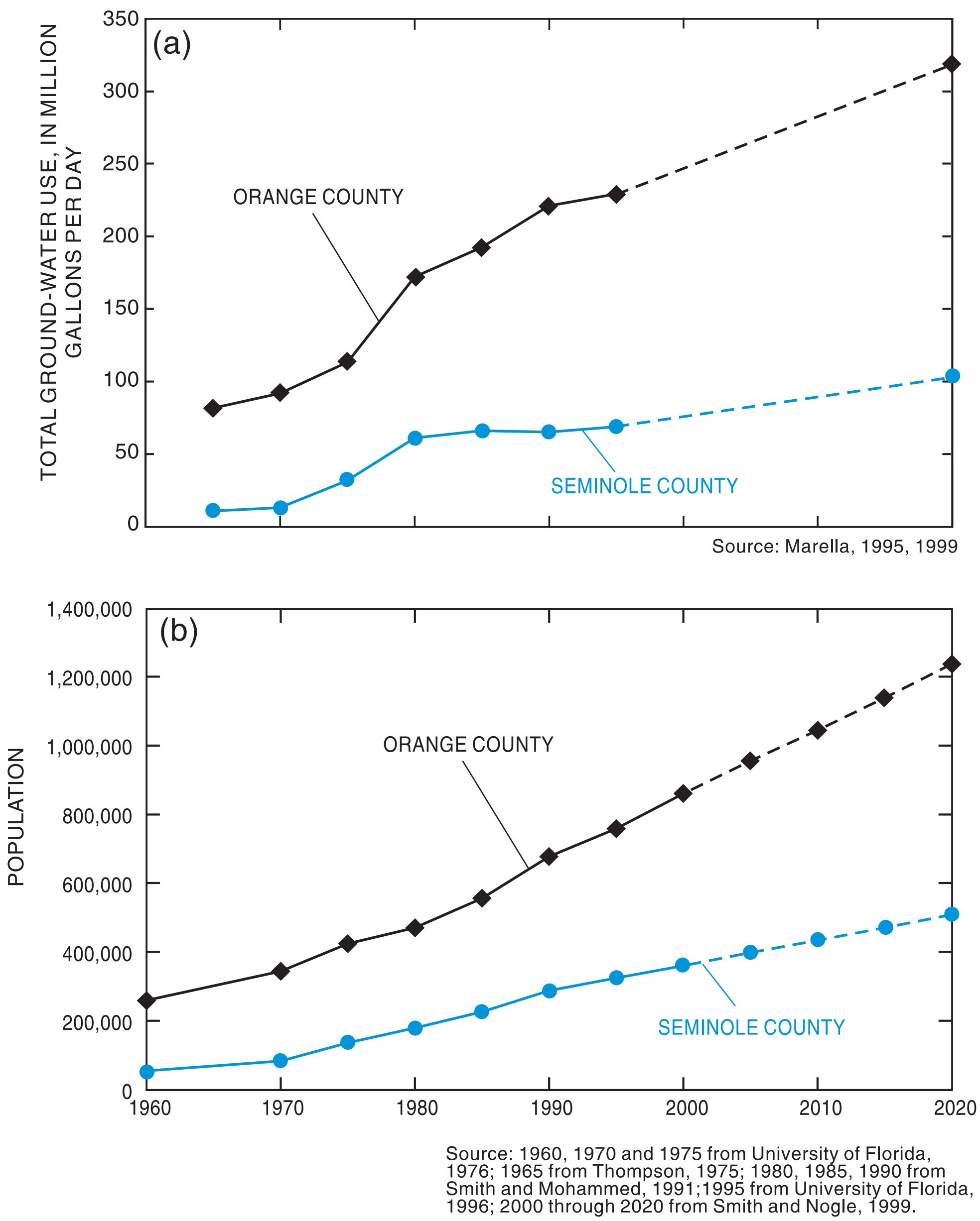


Figure 2. Historical and projected (a) total ground-water use and (b) population for Seminole and Orange Counties, Florida.

The topography of Seminole County can be divided into two types: level lowlands and hilly uplands (ridges) (Barraclough, 1962, p. 7). The level lowlands include the areas adjacent to the St. Johns, Wekiva, and Econlockhatchee Rivers and Lake Jesup. Land-surface altitude ranges from about 2-3 feet (ft) above sea level near the St. Johns River to about 30 ft above sea level where the lowlands merge into the hilly uplands. The hilly uplands include the remainder of the county. Surface features of this area include many hills and lakes. Land surface altitude ranges from about 30 ft above sea level to more than 125 ft above sea level in the vicinity of Altamonte Springs.

Sinkholes in all stages of development are common throughout the area and range from small depressions and recently collapsed depressions a few feet in diameter to large lakes. Sinkholes are formed by the collapse of surface deposits into caverns created by the dissolution of underlying limestone by infiltrating and circulating ground water. Many of the natural lakes, ponds, and topographic depressions in the western part of the study area were formed this way. Larger lakes often are formed by the coalescence of several sinkholes. The sinkholes permit local hydraulic connection between the surficial aquifer system and the Upper Floridan aquifer, and are important avenues of natural recharge to the Floridan aquifer system.

The study area is divided into four major surface-water drainage basins and numerous minor surface-water drainage basins. The major drainage basins are the: St. Johns River basin, Ocklawaha River basin, Kissimmee River basin, and Coastal basin (fig. 1). The St. Johns River is the most prominent surface-water feature in the study area and defines the eastern and northern boundaries of Seminole County and the eastern boundary of Orange County. The St. Johns River flows north and discharges in the Atlantic Ocean at Mayport, Florida. Occasionally, combined drought, wind, and tidal effects can influence river stages and flow at Lake Monroe, about 161 miles upstream. More than one-half of the study area is drained by the St. Johns River, including all of Seminole County, most of the northern and eastern parts of Orange County, and parts of Brevard, Lake, Osceola, and Volusia Counties. Major tributaries within the St. Johns River basin include the Wekiva and Econlockhatchee Rivers.

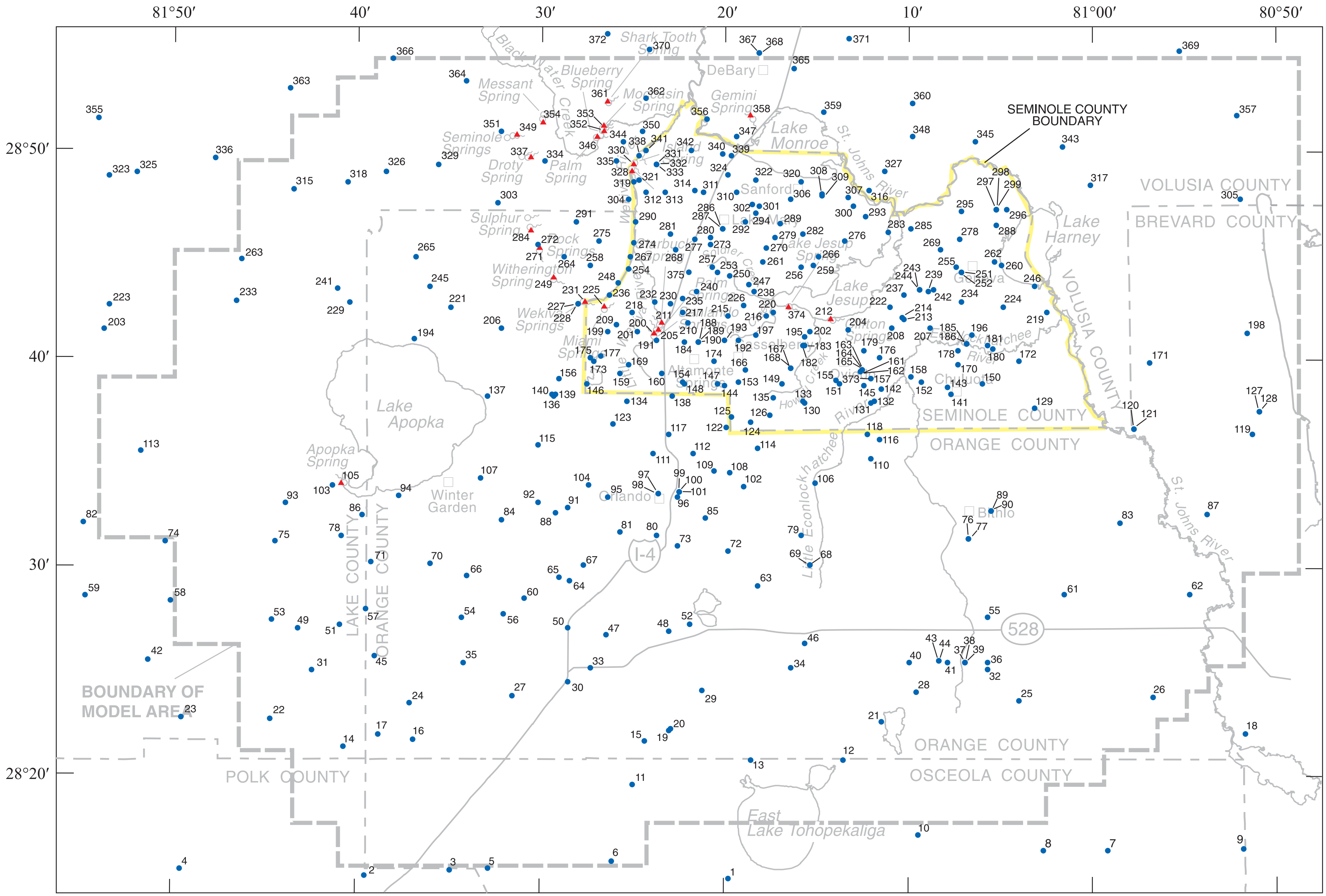
In the western part of the St. Johns River basin (the hilly uplands of western Seminole and northwestern Orange County), much of the drainage is into closed depressions where the water either seeps into the ground or evaporates. Many of these depressions probably are drained through permeable material into the underlying Floridan aquifer system. The bottom of some sinkhole lakes, however, may contain relatively impermeable sediments, and the rate of seepage may be less than in areas adjacent to the lakes.

The Ocklawaha River basin drains parts of northwestern Orange and eastern Lake Counties. This basin contains few surface streams and drainage is mostly into closed depressions or lakes. The Kissimmee River basin drains much of the southwestern parts of Orange and northwestern Osceola Counties. Drainage within this basin also is poorly developed. The Coastal basin drains a small area of northeastern Brevard and southeastern Volusia Counties. Water from the coastal area drains into lagoons that connect to the Atlantic Ocean.

The climate of Seminole and surrounding counties is classified as humid subtropical and is characterized by warm, relatively wet summers and mild, relatively dry winters. Temperatures commonly exceed 90 ^{o}F from June to September, and may fall below freezing for a few days in the winter months. Mean annual rainfall for the study area (1970-97) is about 51 inches (averaged from rainfall data collected at Sanford and the Orlando International Airport) and from September 1996 through August 1997, about 52 inches per year (in/yr). Rainfall is unevenly distributed during the year with about 55 percent of the annual rainfall total derived from thunderstorms that occur frequently during the months of June through September. Thunderstorms usually are localized and distribute rainfall unevenly across the area. During the summer months and early fall, tropical storms and hurricanes also can bring heavy precipitation into the area. During the winter, rainfall is associated with frontal system activity, which is usually of a longer duration and areally more uniform than convectional precipitation.

Data Collection

A review of existing wells and water-level and water-quality data in the study area was conducted to determine where additional data were needed. Data collection generally included monthly or continuous water-level measurements from 43 surficial aquifer system and 232 Floridan aquifer system wells, monthly stage measurements from 100 lakes, monthly discharge measurements from 21 springs, and continuous discharge measurements from 16 streamflow sites. Water samples collected from 126 wells and 13 springs in Seminole and adjacent counties were analyzed for common inorganic constituents. Sampled wells included public supply, domestic, irrigation, dedicated monitoring, and free-flowing wells. The location of wells, springs, lakes and streams used for data collection are shown in figures 3 and 4.



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

EXPLANATION

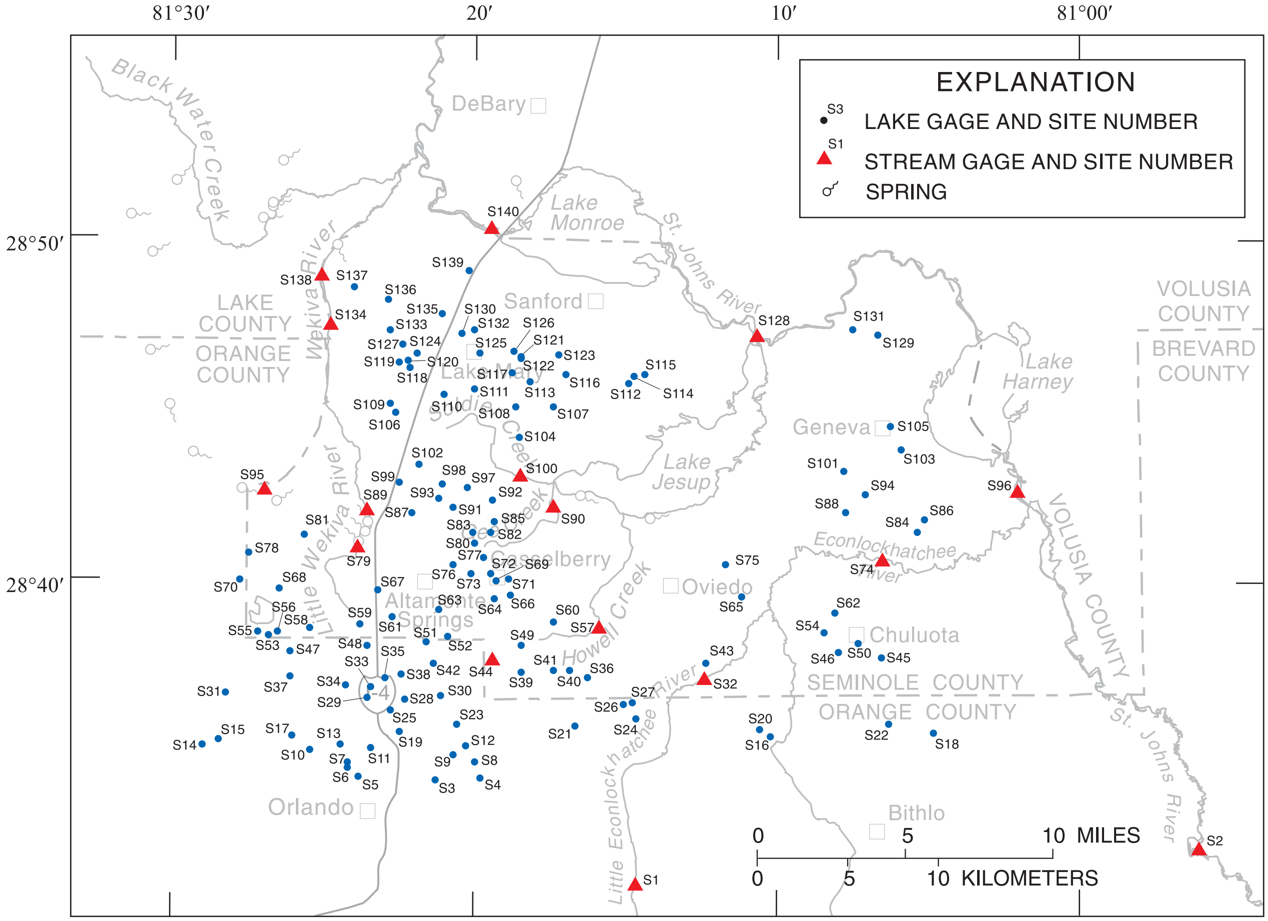
1 WELL AND SITE NUMBER

200 SPRING AND SITE NUMBER

0 5 10 MILES

0 5 10 KILOMETERS

Figure 3. Location of well and spring data-collection sites (site information in appendix 1).



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

Figure 4. Location of lake and stream data-collection sites (site information in appendix 2).

The location of surficial aquifer system supplementary well data-collection sites (water-level data used in this study but collected prior to 1996) is shown in figure 5. Well construction data, spring information, and general information on the lake and stream data-collection sites are presented in appendixes 1, 2, and 3.

Hydrogeologic maps and sections were generated by using data from borehole-geophysical, geologistsí, and drillersí logs. Slug tests were performed on 21 surficial aquifer system monitoring wells to quantify a range of hydraulic conductivity for the surficial aquifer system. The altitude of the measuring points of monitoring wells were determined by instrument leveling so that accurate potentiometric-surface maps and hydrographs could be constructed.

Twenty-four surficial aquifer system monitoring wells also were constructed in areas where ground-water data were not available. The boreholes were constructed using a hollow-stem auger. Initially, nominal 2 1/4-inch inner diameter hollow-stem augers were used to drill a test hole. Split-spoon samples were collected every 5 ft and were used to determine the depth to water and to provide additional data on surficial aquifer system lithology. Following split-spoon sampling, the test holes were enlarged by using a 6 1/4-inch hollow-stem auger. Four-inch diameter monitoring wells were constructed by installing 10 ft of slot 0.01 schedule 40 PVC screen and an appropriate length of PVC riser casing. Wells screens were set below the estimated minimum water table. The screens were packed with a clean, well sorted sand. Above the screens, the filter packs were topped with bentonite seal. The remaining annulus from the bentonite seal to land surface was grouted with Type I Portland cement. The monitoring wells were completed with flush-mounted steel protective casings. Monitoring wells were developed by pumping. Monitoring well data are provided in appendix 1.

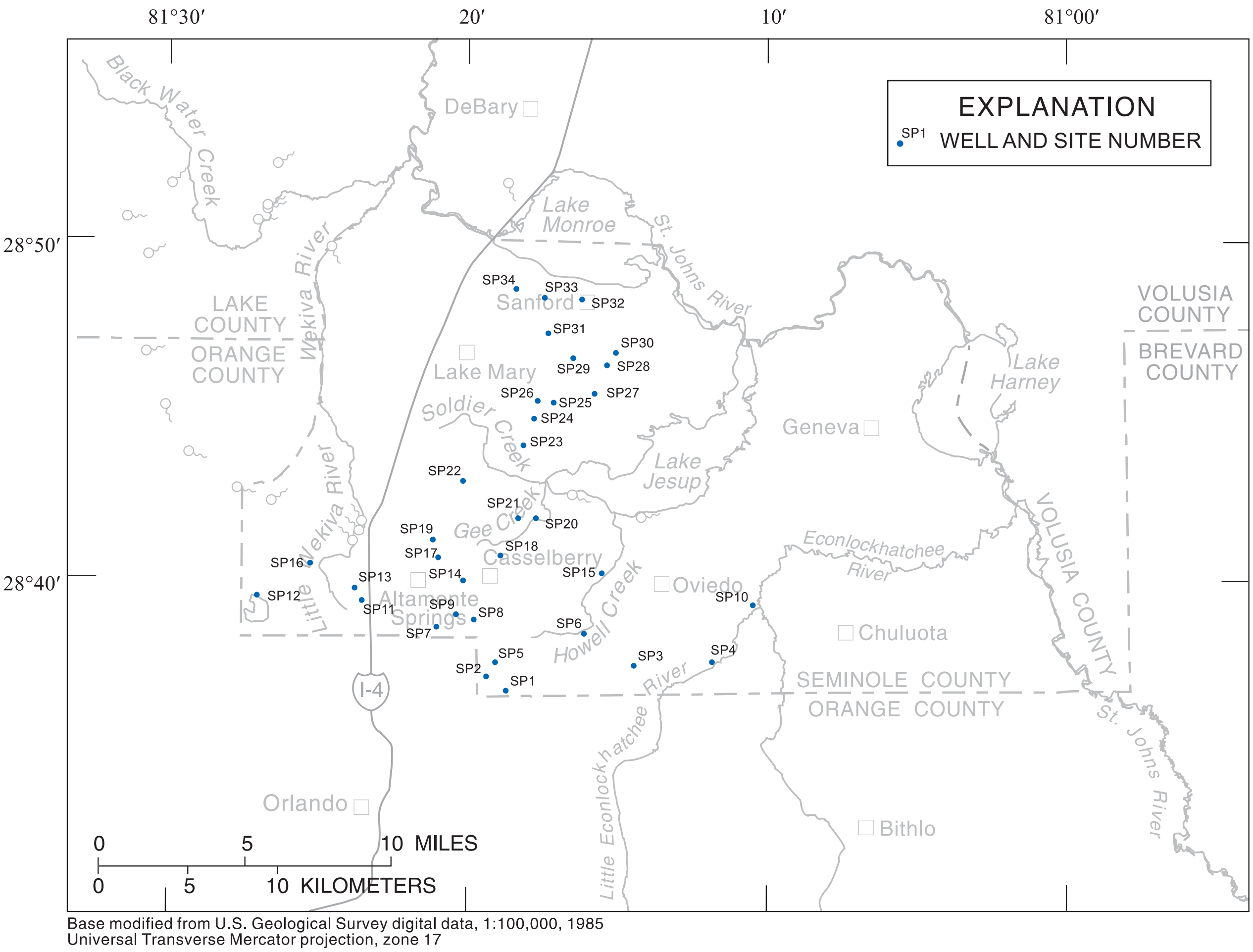


Figure 5. Location of supplementary well data-collection sites (site information in appendix 3).

Water Use

The Floridan aquifer system is the principal source of water supply in the study area. The aquifer supplies nearly all the ground water used for public supply, domestic self-supplied, agricultural irrigation, commercial-industrial self-supplied, and recreational irrigation. In Seminole and Orange Counties, less than one percent of the total amount of the ground-water withdrawn is from the surficial aquifer system (Marella, 1999, p. 11). Withdrawals vary from season to season and from year to year, primarily as a function of the amount and distribution of rainfall. As population continues to increase, withdrawals for public supply also will continue to increase.

Detailed water-use data are collected by the USGS and SJRWMD every 5 years. In 1965, ground-water withdrawals from the Floridan aquifer system in Seminole County were about 11 million gallons per day (Mgal/d) (fig. 2). In 1995, withdrawals totaled about 69 Mgal/d (107 cubic feet per second (ft^3/s)). Of the total water used in 1995, 74 percent was for public supply, 12 percent for domestic self-supplied, 10 percent for agricultural self-supplied, and 4 percent for recreational irrigation (fig. 6). Ground-water withdrawals from the Floridan aquifer in adjacent Orange County, one of the most populated counties in the state, increased from 82 Mgal/d (127 ft^3/s) in 1965 to about 229 Mgal/d (354 ft^3/s) in 1995 (fig. 2). About 72 percent of the ground-water withdrawn was used for public supply, 10 percent for agriculture self-supplied, 8 percent for commercial self-supplied, 6 percent for domestic self-supplied, and 4 percent for recreational irrigation (fig. 6).

To estimate water use from September 1996 through August 1997 (the period for which the ground-water flow model was calibrated), calendar year 1995 water-use data were used as an estimate for agricultural self-supplied, commercial-industrial, recreational irrigation, and power generation. This approach was used because insufficient data were available for the model calibration period to determine site specific discharge rates for these withdrawal categories. Public supply, which accounted for the largest percentage of the ground water withdrawn, were updated using 1996-97 data. These data were obtained by B. Florence (SJRWMD, written commun., 1998), R. L. Marella (USGS, written commun., 1998), Florida Department of Environmental Protection, and from the public utilities.

Average ground-water withdrawals from September 1996 through August 1997 within the study area were approximately 386 Mgal/d (597 ft^3/s). Free-flowing wells, which generally are not included in water-use statistics, accounted for another 15 Mgal/d (23 ft^3/s). Public supply accounted for 275 Mgal/d (425 ft^3/s), about 71 percent of the water withdrawn from the Floridan aquifer system. Agricultural self-supplied accounted for about 21 percent or 80 Mgal/d (123 ft^3/s), and commercial-industrial for about 8 percent or 31 Mgal/d (48 ft^3/s). Of the total water withdrawn from the Floridan aquifer system, about 73 percent or 280 Mgal/d (433 ft^3/s) was from the Upper Floridan aquifer and about 27 percent or 106 Mgal/d (164 ft^3/s) was from the Lower Floridan aquifer. The areal distributions of ground-water withdrawals from the Upper and Lower Floridan aquifers are shown in figures 7 and 8, respectively. Little water is withdrawn from the surficial aquifer system in the study area, so water use from this aquifer system was considered zero for this study.

The accuracy of the water-use data varies by category. For example, public-supply and larger industrial water-use estimates usually are more accurate because the usage generally is metered, whereas agricultural water use estimates often are less accurate because this type of water use generally is not metered.

Water use for public supply is usually reported by well field, not by individual wells, therefore, pumpage estimates for each well also had to be determined. Where data were not available, assumptions were made to apportion total pumpage between individual wells and between the Upper and Lower Floridan aquifers. At well fields containing multiple wells, the average daily well-field discharge rate was divided by the number of active wells to obtain an average pumping rate per well. Discharge from wells that penetrate both the Upper and Lower aquifers was divided equally between the two aquifers.

GEOLOGIC FRAMEWORK

The study area is underlain by a thick sequence of sedimentary rocks that overlie a basement complex of igneous and metamorphic strata. The primary water-bearing sediments are composed of limestone, dolomite, shell, and sand that range in age from late Paleocene to Holocene. Descriptions of major stratigraphic units and corresponding hydrogeologic units are given in figure 9. Stratigraphic units, in ascending order, are: the Cedar Keys Formation of late Paleocene age, the Oldsmar Formation of early Eocene age, the Avon Park Formation of middle Eocene age, the Ocala Limestone of late Eocene age, the Hawthorn Formation of Miocene age, and the undifferentiated deposits of Pliocene to Holocene age.

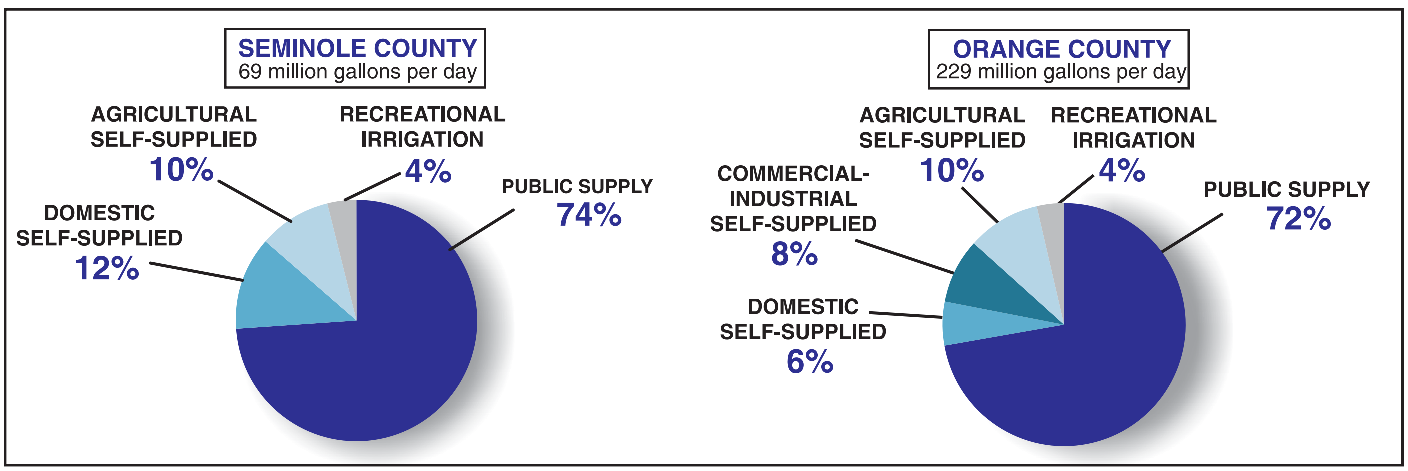


Figure 6. Total ground-water use in Seminole and Orange Counties, Florida, by category for 1995 (data from Marella, 1999).

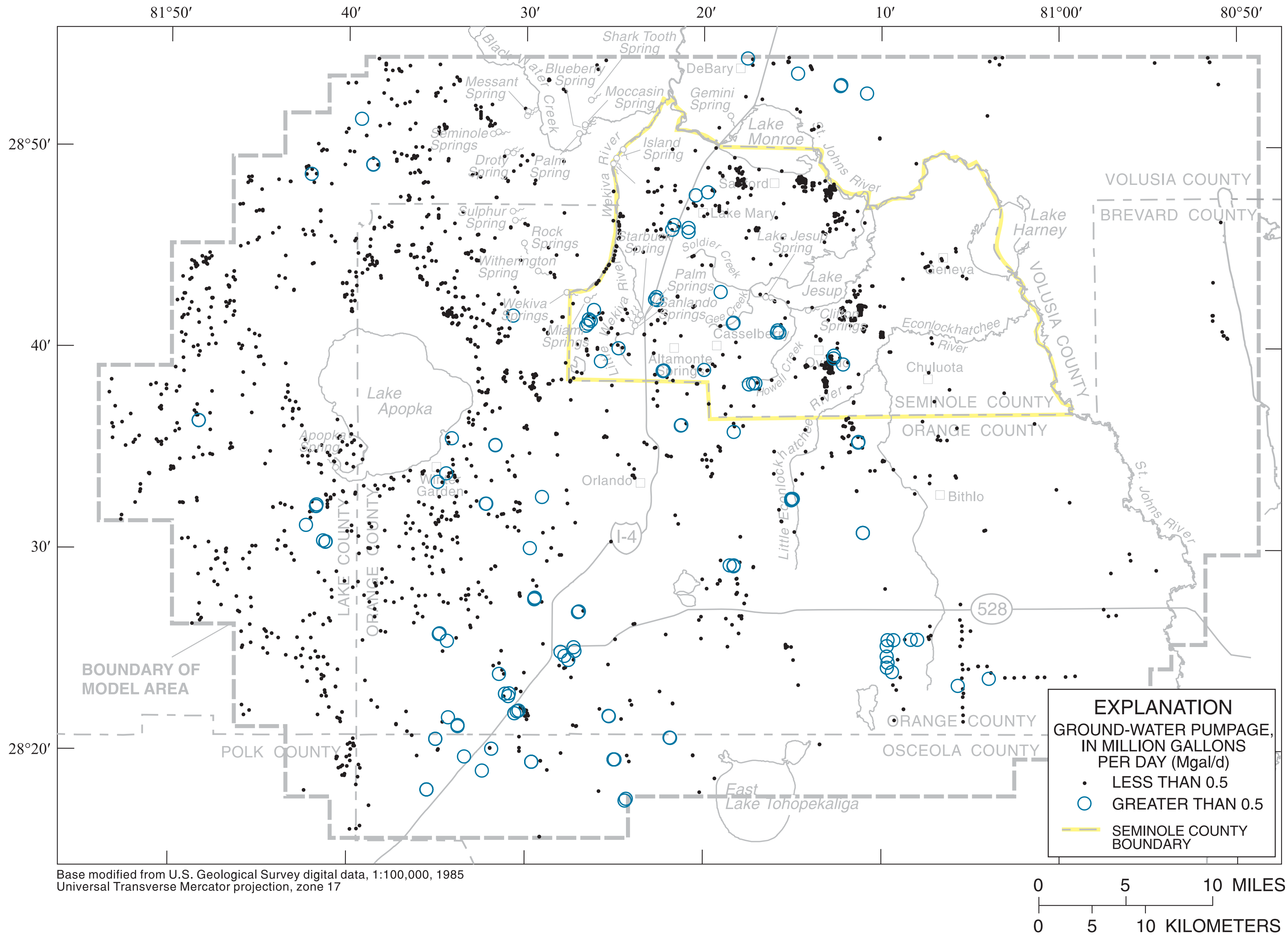


Figure 7. Distribution of average Upper Floridan aquifer pumpage, September 1996 through August 1997.

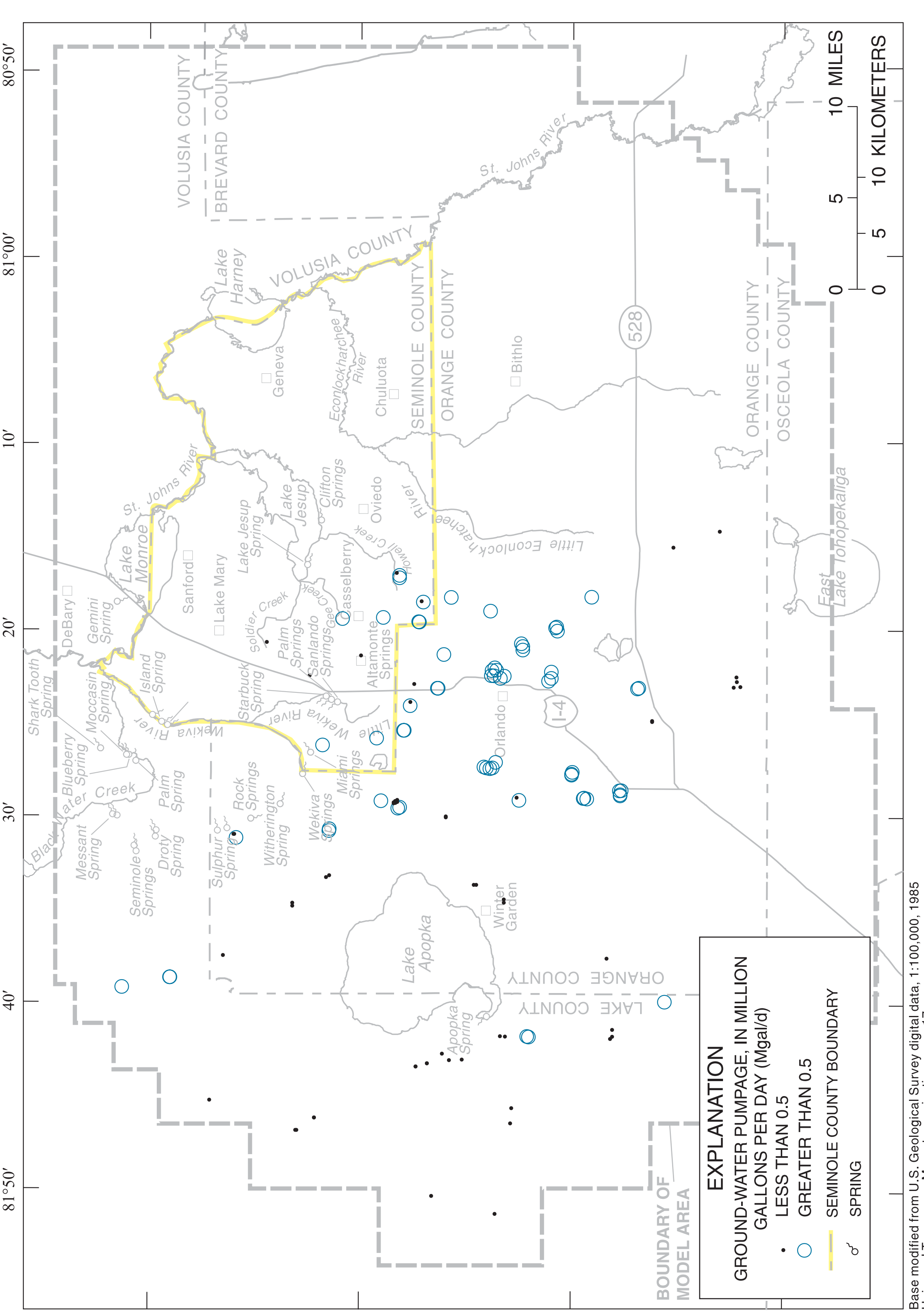


Figure 8. Distribution of average Lower Floridan aquifer pumpage, September 1996 through August 1997.

SERIES		STRATIGRAPHIC UNIT	APPROXIMATE THICKNESS (feet)	LITHOLOGY	AQUIFER
HOLOCENE		UNDIFFERENTIATED DEPOSITS	0-150	Alluvium, freshwater marl, peats and muds in stream and lake bottoms. Also, some dunes and other windblown sand.	SURFICIAL AQUIFER SYSTEM
PLEISTOCENE				Mostly quartz sand. Locally may contain deposits of shell and thin beds of clay.	
PLIOCENE			0-100	Interbedded deposits of sand, shell fragments, and sandy clay; base may contain phosphatic clay.	
MIOCENE		HAWTHORN GROUP	0-200	Interbedded quartz, sand, silt and clay, often phosphatic; phosphatic limestone often found at base of formation.	
EOCENE	UPPER	OCALA LIMESTONE	0-200	Cream to tan, soft to hard, granular, porous, foraminiferal limestone.	FLORIDAN AQUIFER SYSTEM
	MIDDLE	AVON PARK FORMATION	600-1,600	Light brown to brown, soft to hard, porous to dense, granular to chalky, fossiliferous limestone and brown, crystalline dolomite.	
	LOWER	OLDSMAR FORMATION	300-1,350	Alternating beds of light brown to white, chalky, porous, fossiliferous limestone and porous crystalline dolomite.	
PALEOCENE		CEDAR KEYS FORMATION	500-2,200	Dolomite, with considerable anhydrite and gypsum, some limestone.	

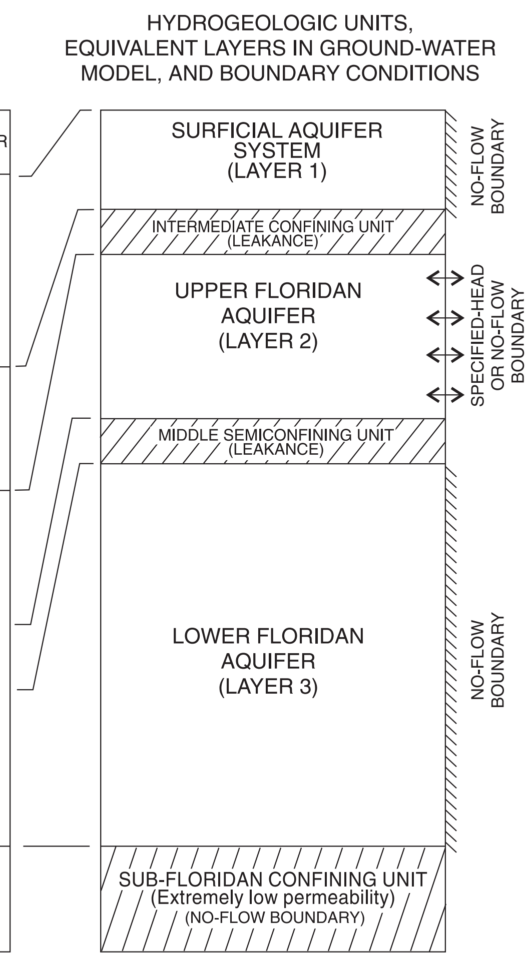


Figure 9. Geologic units, hydrogeologic units, and equivalent layers and boundary conditions used in the ground-water flow model (modified from Murray and Halford, 1996).

Subsurface structures, such as collapse features (paleosinkholes) and related fractures, joints, and faults, can have an effect on the ground-water flow system. Previous investigators have inferred the presence of faults in the study area. Wyrick (1960, p. 11) and Barraclough (1962, p. 18) postulated a general east-west trending fault along the northern edge of Seminole County. An east-west trending fault just south of Lake Monroe in Seminole County was inferred by Tibbals (1977, sheet 1). Brown and others (1962, fig. 9) postulated a north-south trending fault that generally ran along the St. Johns River in western Brevard County. Displacement in these fault systems is probably small, but if present, could have some effect on the ground-water flow system. The faults are not discernible from well records compiled for this report, and the faults inferred by previous investigators are not shown on the hydrogeologic or other geologic maps.

Numerous circular depressions also are present on the surface of the Ocala Limestone (top of the Upper Floridan aquifer). Some of the depressions could be erosional features formed before the Hawthorn Group was deposited; however, most were formed by sinkhole collapse caused by the gradual dissolution of the underlying carbonate material. Marine seismic and land-based seismic reflection have revealed buried collapse features and other karst features at numerous locations in east-central and northeastern Florida. Marine seismic-reflection investigations along the St. Johns River in northeastern Florida by Snyder and others (1989) and Spechler (1994, 1996) revealed a number of buried collapse features that originated in the rocks of the Floridan aquifer system. Marine seismic-reflection profiles collected off the coast of eastern and northeastern Florida also show the presence of these buried collapse features (Meisburger and Field, 1976; Popenoe and others, 1984). Using land-based seismic reflection, these features were also discovered at several locations in Duval and St. Johns Counties (Odum and others, 1997). Seismic reflection studies (J. Kindinger, USGS, written commun., 1999) showed the presence of buried collapse features and other karst features underlying many lakes in east-central Florida, including Lake Monroe and the southern part of Lake Harney. Numerous subsidence features also were observed from seismic profiles in Lake Jesup, some of which extended deep within the subsurface.

HYDROGEOLOGY

The principal water-bearing units in the study area are the surficial aquifer and the Floridan aquifer systems (fig. 9). The two aquifer systems are separated by the intermediate confining unit, which contains sediments of lower permeability that confine the water in the Floridan aquifer system. The Floridan aquifer system has two major water-bearing zones (the Upper Floridan aquifer and the Lower Floridan aquifer), which are separated by a less-permeable semiconfining unit. Underlying the Floridan aquifer system are low permeability limestone and dolomite that contain considerable gypsum and anhydrites, and that define the bottom of the freshwater flow system in the study area. The thickness of the freshwater zone varies considerably and is generally thinnest in the eastern part of the study area and thickens toward the west. Saline water underlies the freshwater in all of the study area. Generalized hydrogeologic sections based on geophysical, geologistsí, and drillersí logs are shown in figure 10.

Surficial Aquifer System

The surficial aquifer system is the uppermost water-bearing unit in the study area. The system is unconfined and consists mainly of lenses of fine-to-medium quartz sand and varying amounts of shell and clay. The deposits generally are discontinuous and their lithology and texture can vary considerably over short distances both vertically and laterally. In some areas, discontinuous and relatively impermeable beds of reddish-brown hardpan are present within a few feet of the surface (Barraclough, 1962, p. 17). These layers of hardpan are composed of slightly to well-indurated, iron-oxide cemented sand and clay.

The upper boundary of the surficial aquifer system is defined by the water table. In the swampy lowlands and flatlands, the water table generally is at or near land surface throughout most of the year. In areas of higher land-surface elevations, the water table generally is a subdued reflection of land-surface topography but can be tens of feet below land surface. In addition to the influence of topography, the slope of the water table varies depending on the hydrologic conditions, such as antecedent rainfall and evapotranspiration rates. During wet periods, when rainfall exceeds evapotranspiration, the slope steepens as the storage of water in the surficial aquifer system increases. During dry periods, the slope flattens as water drains from storage or is lost to evapotranspiration.

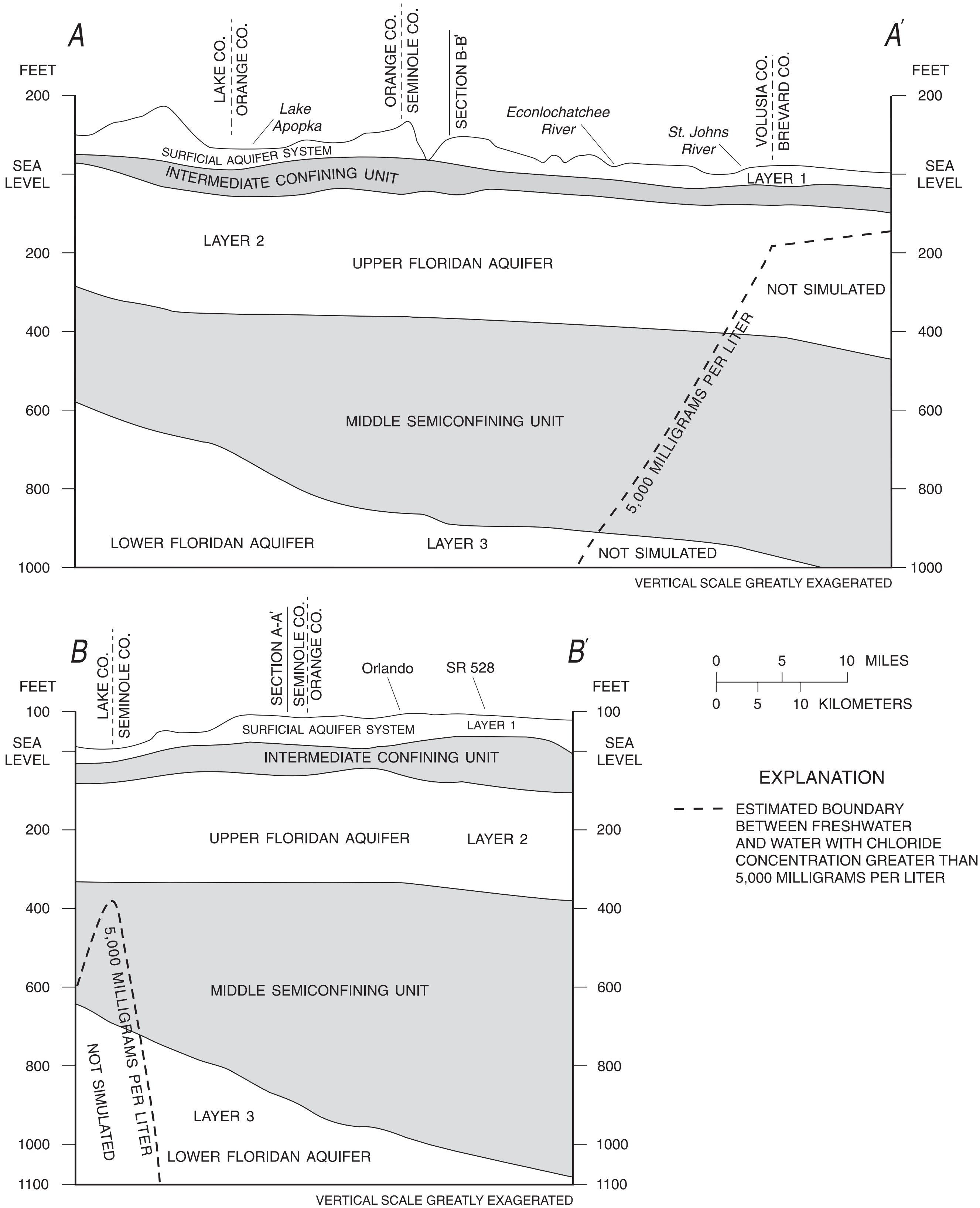


Figure 10. Generalized hydrogeologic sections A-A' and B-B' (section lines shown in figure 11). Based on interpolation of data shown in figures 11, 14, and 16 and Miller (1986).

The base of the surficial aquifer system is defined by the first persistent beds of Miocene or Pliocene age containing a significant increase in clay or silt. The altitude of the base of the surficial aquifer system ranges from about 75 ft below to more than 75 ft above sea level across the study area (fig. 11). Thickness of the surficial aquifer system is highly variable. In the low-lying areas around Lake Jesup, and along the Econlockhatchee, Little Wekiva, Wekiva and St. Johns Rivers in Seminole County, the surficial aquifer system is about 10-20 ft thick. In western Seminole County along the sand ridges, thickness can exceed 60 ft. Along the St. Johns River basin in eastern Orange County, thickness is generally less than 10 ft and increases to more than 150 ft along the high ridge areas of western Orange and eastern Lake Counties (Murray and Halford, 1996, p. 8).

The water-bearing properties of the surficial aquifer system vary considerably from place to place and are dependent largely upon aquifer thickness, grain-size distribution, sorting, packing, and cementation of the sediments within the aquifer. Horizontal hydraulic conductivity values were determined from slug tests performed on 21 surficial aquifer system monitoring wells in Seminole County (table 1). Values ranged from 0.5 to 40 feet per day (ft/d). Hydraulic conductivity values determined from slug tests performed on 10 surficial aquifer system wells in Lake County ranged from 0.2 to 35 ft/d (L. Knowles, USGS, written commun., 1998). A slug test performed at the Reedy Creek Improvement District rapid-infiltration basin (RIB) site in southwest Orange County yielded horizontal hydraulic conductivity values from 25 to 160 ft/d (CH2M Hill, 1989). An additional test conducted just north of the Reedy Creek site yielded values of 35 to 67 ft/d (CH2M Hill, 1993). Camp, Dresser and McKee, Inc. (1984) reported hydraulic conductivity values of 20 to 80 ft/d based on laboratory analyses of numerous cores collected at several RIB sites in southwestern Orange and southeastern Lake Counties. Halford (1998a) reported an average hydraulic conductivity of about 30 ft/d at the Orlando Naval Training Center in central Orange County.

The altitude of the water table in the surficial aquifer system varies seasonally and responds to changes in rates of recharge and discharge. Water levels are generally highest in September or October, which is at or near the end of the rainy season, and gradually decrease during the dry season to their lowest levels in April or May (figs. 12 and 13). Rainfall events cause sharp rises in water level in the surficial aquifer system, whereas lack of rainfall causes a gradual decline. Hydrographs of wells in Seminole and northern Orange Counties completed in the surficial aquifer system indicate that seasonal fluctuations of 2 to 5 ft are common, and recharge from summer rainfall generally is adequate to replenish the aquifer.

Recharge to the surficial aquifer system is chiefly by the infiltration of rainfall. Most of the rain that falls in the study area drains into streams or is lost to evapotranspiration. Some rainfall, however, percolates down through the surficial deposits and enters the surficial aquifer system. Recharge to the surficial aquifer system also includes septic-tank effluent, irrigation, land application of reclaimed water, lateral ground-water inflow from adjacent areas, and upward leakage in areas where the head in the underlying Upper Floridan aquifer is higher than in the surficial aquifer system. Water is discharged from the surficial aquifer system by evapotranspiration, by downward leakage to the Floridan aquifer system in areas where the potentiometric surface of the Upper Floridan aquifer is below the water table, by seepage into lakes and streams, and by withdrawal from wells.

The surficial aquifer system provides small amounts of water for lawn irrigation and domestic use. The water is used for domestic supply primarily in rural areas where wells tapping the Upper Floridan aquifer yield water that is too highly mineralized. Well yields depend on the thickness and permeability of the aquifer sediments and generally are less than 20 gallons per minute (gal/min).

Table 1. Horizontal hydraulic conductivity values for surficial aquifer system test wells in Seminole County, Florida (locations shown in fig. 3)

Site number	USGS site identification number	Horizontal hydraulic conductivity, feet per day
126	283719081173601	14
133	283800081154601	6
149	283852081165501	2
152	283858081092001	2
154	283858081221801	40
162	283932081123601	3
166	283933081185701	4
173	283957081270601	6
176	284007081113501	2
184	284049081221501	5
195	284105081154301	5
215	284206081195401	5
217	284216081221801	6
218	284216081250701	10
220	284217081172501	5
235	284255081222201	3
252	284412081071103	18
253	284414081202501	3
289	284630081170101	0.5
302	284728081183101	4
314	284808081213901	18

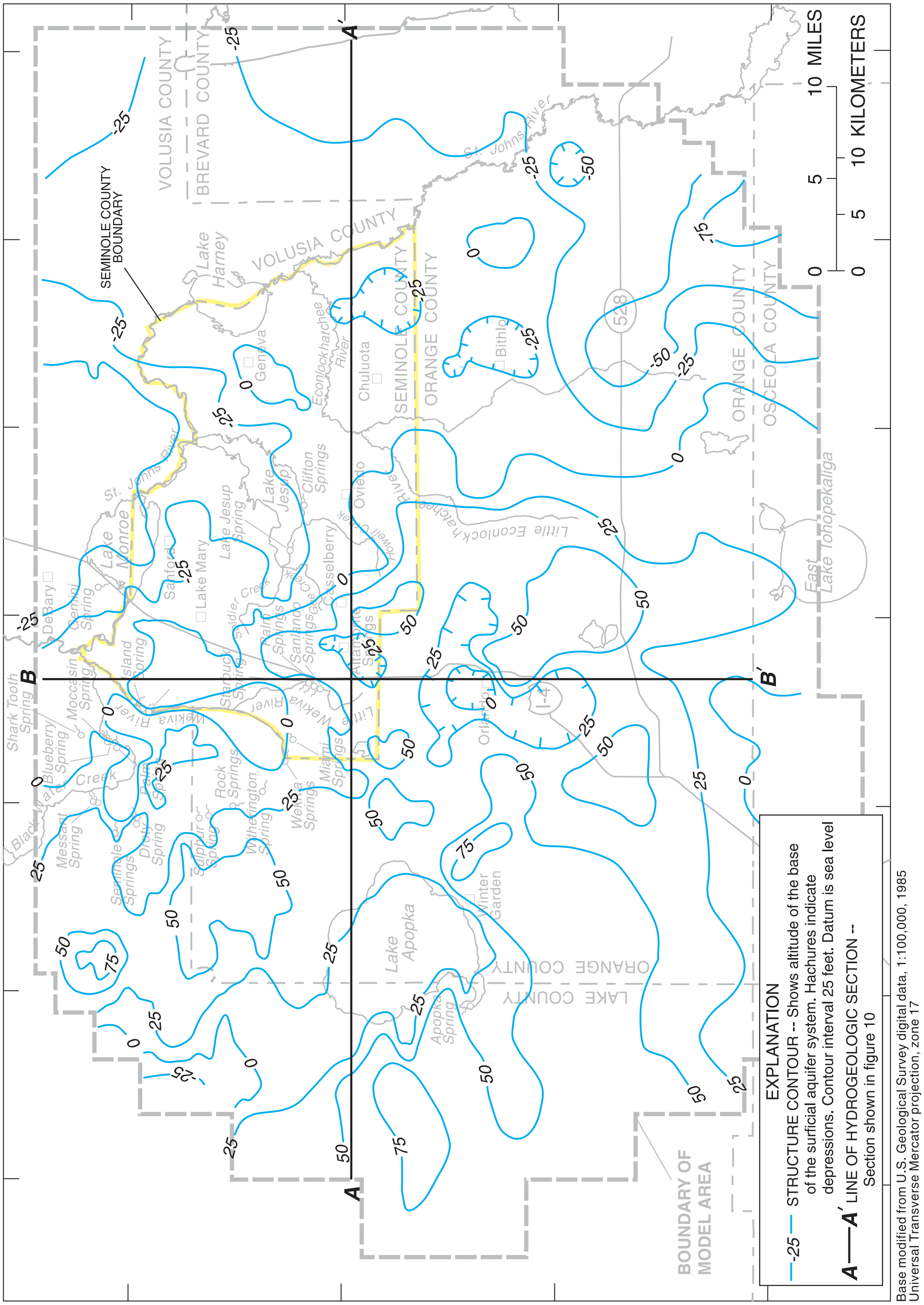


Figure 11. Altitude of the base of the surficial aquifer system.

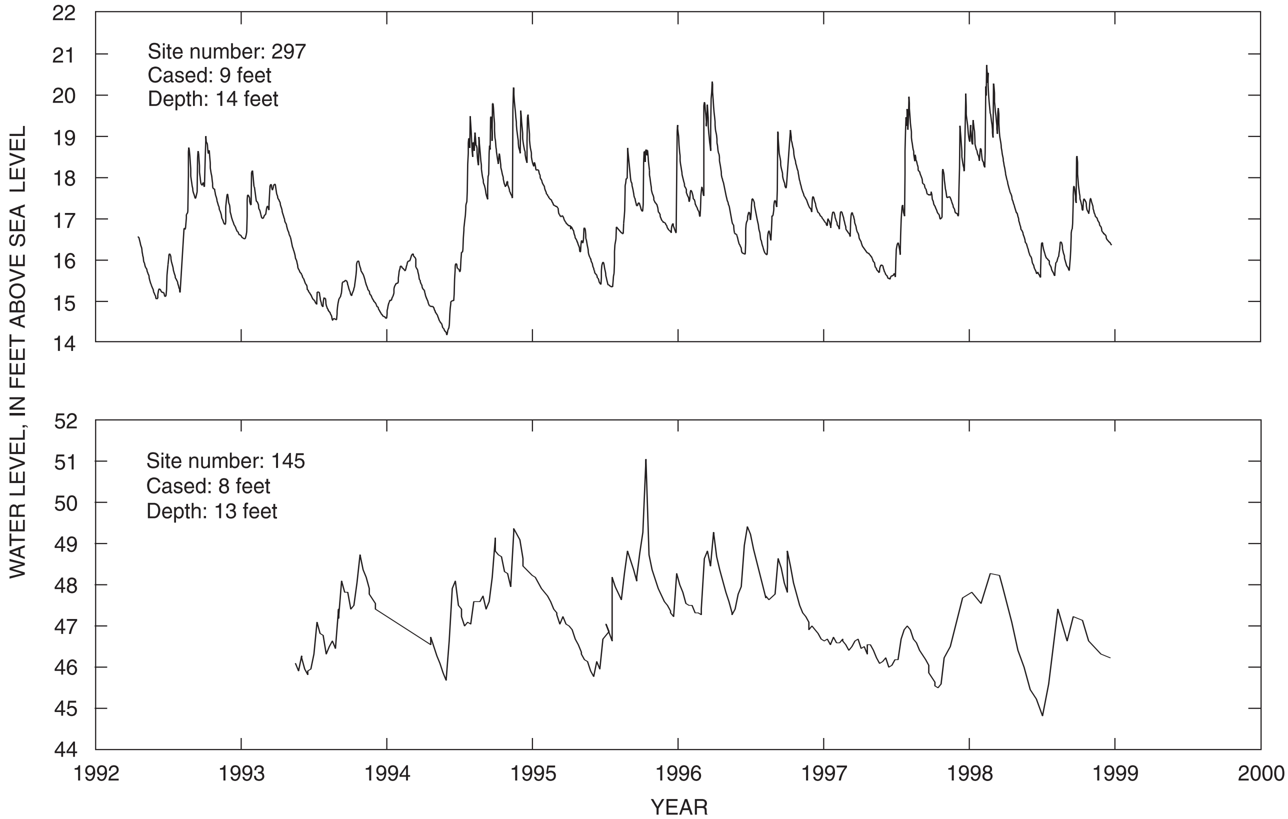


Figure 12. Water levels at sites 297 and 145 in the surficial aquifer system, 1992-1999 (site locations shown in figure 3).

Intermediate Confining Unit

The intermediate confining unit underlies the surficial aquifer system and consists primarily of the Hawthorn Group of late-to-middle Miocene age and, locally, low permeability beds of early Pliocene age. Throughout most of the study area, the intermediate confining unit serves as a confining layer (except where breached by sinkholes) that restricts the vertical movement of water between the surficial aquifer system and the Upper Floridan aquifer. The unit consists of interbedded, locally highly phosphatic clay, silt, sand, limestone, and dolomite. The basal part of the intermediate confining unit often contains permeable zones of limestone and dolomite. These carbonates, although in direct contact with the limestones of the Upper Floridan aquifer are, however, still considered to be part of the intermediate confining unit because their hydraulic conductivities are at least an order of magnitude less than that of the underlying Floridan aquifer system limestone (Miller, 1986, p. B43).

Thickness of the intermediate confining unit is highly variable throughout the study area due to past erosional processes and sinkhole formation. Data from geophysical, geologistsí, drillersí logs, and from previous investigations were used to construct a generalized map of the of the intermediate confining unit thickness (fig. 14). Thickness of the unit generally ranges from less than 25 ft in parts of Seminole and southern Volusia Counties to more than 200 ft in southeastern Orange County. In Seminole County, the intermediate confining unit thickness ranges from less than 25 ft around Lake Mary and north of Lake Jesup to greater than 100 ft in the extreme southwestern part of the county. The unit is locally relatively thin or absent across western Seminole, western Orange, and eastern Lake Counties. In these areas, sinkholes are common. These sinkholes, which often are filled with permeable surficial sands, provide direct avenues for water from the surficial aquifer system to recharge the underlying Floridan aquifer system.

The leakance of the intermediate confining unit is highly variable across the study area and depends on the vertical hydraulic conductivity and thickness of the individual strata of the unit. Leakance of the intermediate confining unit reported from aquifer tests range

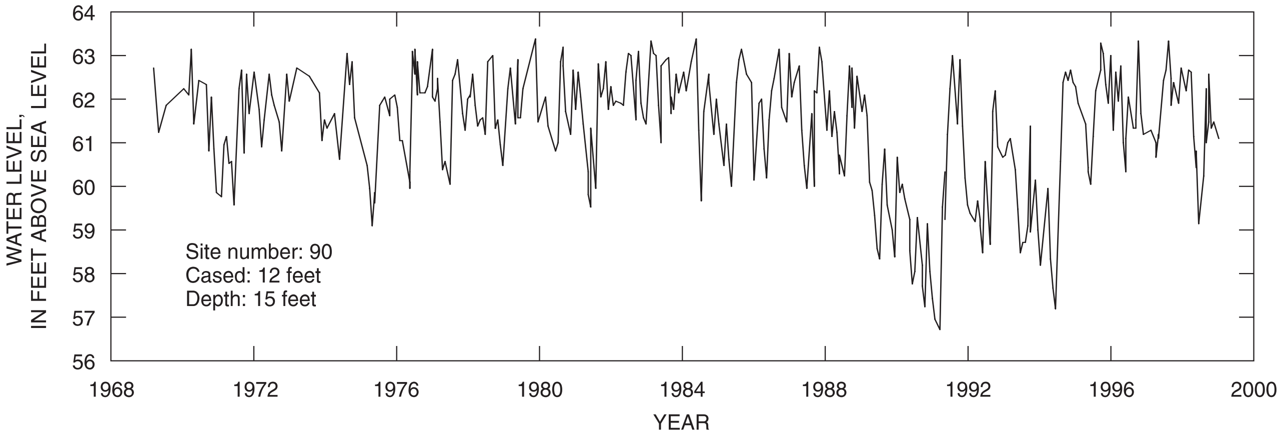


Figure 13. Water levels at site 90 in the surficial aquifer system, 1968-1999 (site location shown in figure 3).

from $1x10^{-4}$ 1/d in eastern Orange County to about $2x10^{-2}$ 1/d in northeastern Polk County, and from $3x10^{-4}$ 1/d to $1x10^{-2}$ 1/d in Seminole County (Murray and Halford, 1996, p. 11). Leakance values calibrated in a regional flow model ranged from $1x10^{-5}$ 1/d to $4x10^{-3}$ 1/d (Murray and Halford, 1996, p. 55).

Floridan Aquifer System

The Floridan aquifer system, the principal source of ground water in east-central Florida, underlies all of Florida, and parts of Alabama, Georgia, and South Carolina. Miller (1986, p. B45) defined the Floridan aquifer system as a vertically continuous sequence of carbonate rocks of generally high permeability that are hydraulically connected in varying degrees and whose permeability is, in general, an order of magnitude to several orders of magnitude greater than those rocks that bound the system. The aquifer ranges from about 2,000 to 2,600 ft in thickness in the study area (Miller, 1986, plate 27) and includes the following stratigraphic units in descending order: the Ocala Limestone, the Avon Park Formation, the Oldsmar Formation, and the upper part of the Cedar Keys Formation (fig. 9). The top of the Floridan aquifer system is defined by the Ocala Limestone of upper Eocene age. The base of the system is generally defined by the first occurrence of relatively impermeable, persistent beds of gypsum or anhydrite found in the upper part of the Paleocene-age Cedar Keys Formation.

The Floridan aquifer system is divided into two aquifers of relatively high permeability, referred to as the Upper Floridan and the Lower Floridan aquifers. These aquifers are separated by a less permeable unit, the middle semiconfining unit, that restricts the vertical movement of water.

The Upper Floridan aquifer consists of the Ocala Limestone and the dolomitic limestones of the upper one-third of the Avon Park Formation. The Ocala Limestone is fossiliferous, and permeable intervals are characterized by vuggy and cavernous porosity. The permeability of the upper Avon Park Formation is due primarily to fractures. Permeability of both units has been enhanced by the movement of water along bedding planes, joints, and fractures.

Permeability within the Upper Floridan aquifer is not uniform with depth. Numerous reports describing well drilling and testing in the study area have documented the presence of a zone of hard, fractured dolomite in the upper part of the Avon Park Formation containing abundant secondary porosity. Several reports (Ardaman and Associates, Inc. 1993; Boyle Engineering Corporation, 1995; CH2M-Hill, 1996; Jamaal and Associates, Inc, 1990; and Yovaish Engineering Sciences, Inc., 1994) describe this zone as a major source of water within the Upper Floridan aquifer. Flow logs from three wells (fig. 15) show that two distinct zones of different permeabilities exist in the Upper Floridan aquifer and are, herein, referred to as zone A and zone B. Zone A, which consists of about the top two-thirds of the aquifer, generally corresponds with the Ocala Limestone. Zone B, which consists of about the bottom one-third of the Upper Floridan aquifer, has a hydraulic conductivity that can be much greater than that found in zone A.

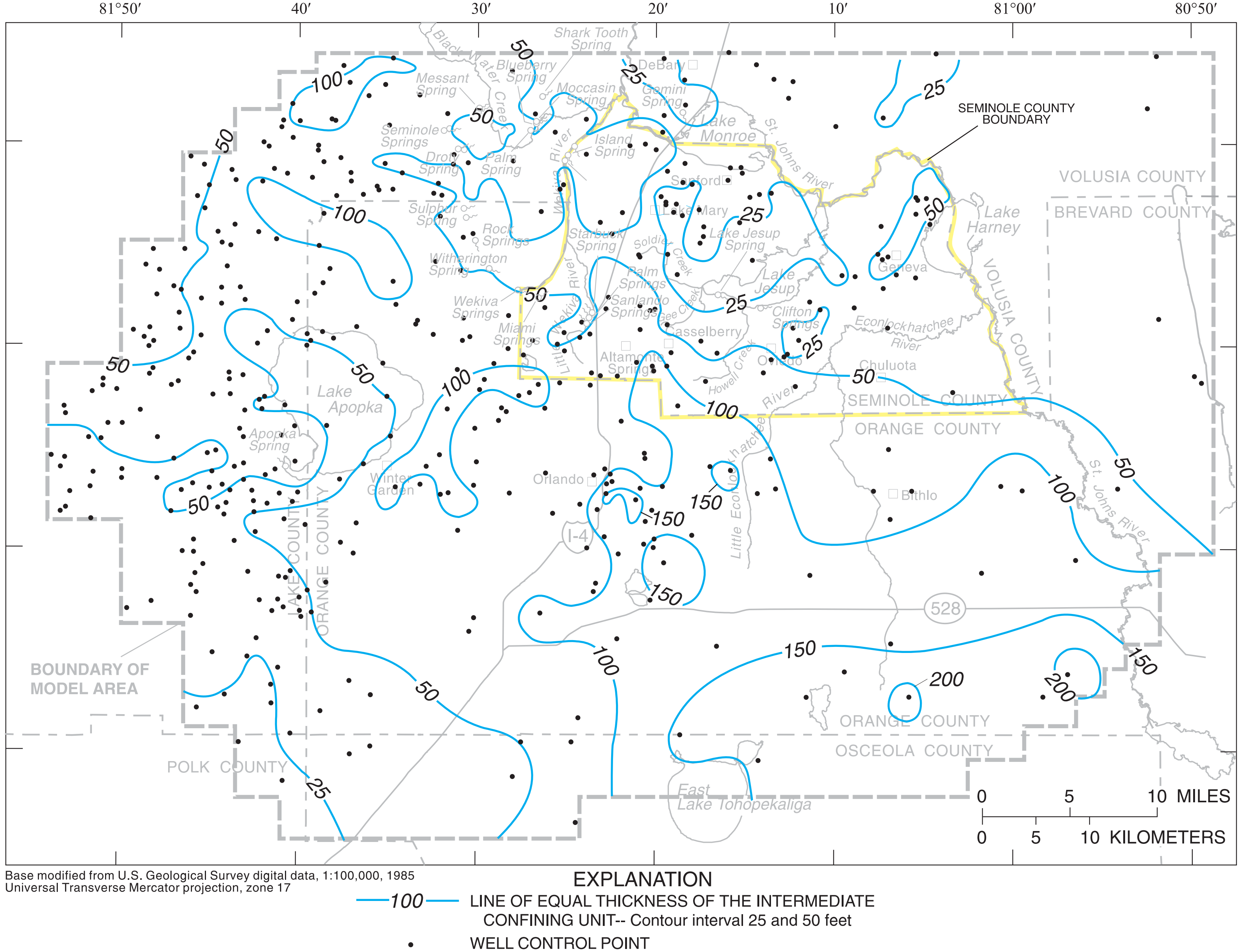


Figure 14. Generalized thickness of the intermediate confining unit.

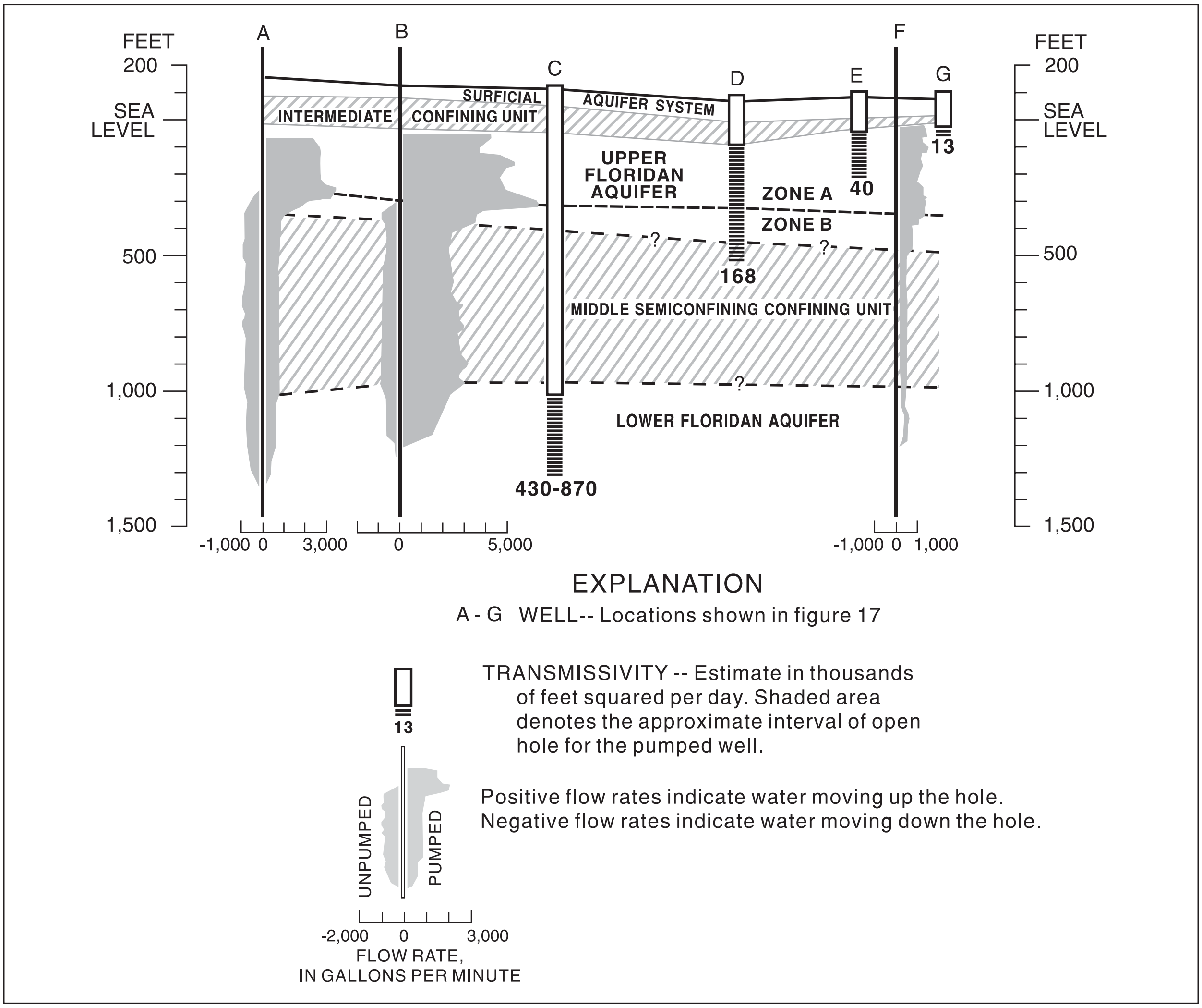
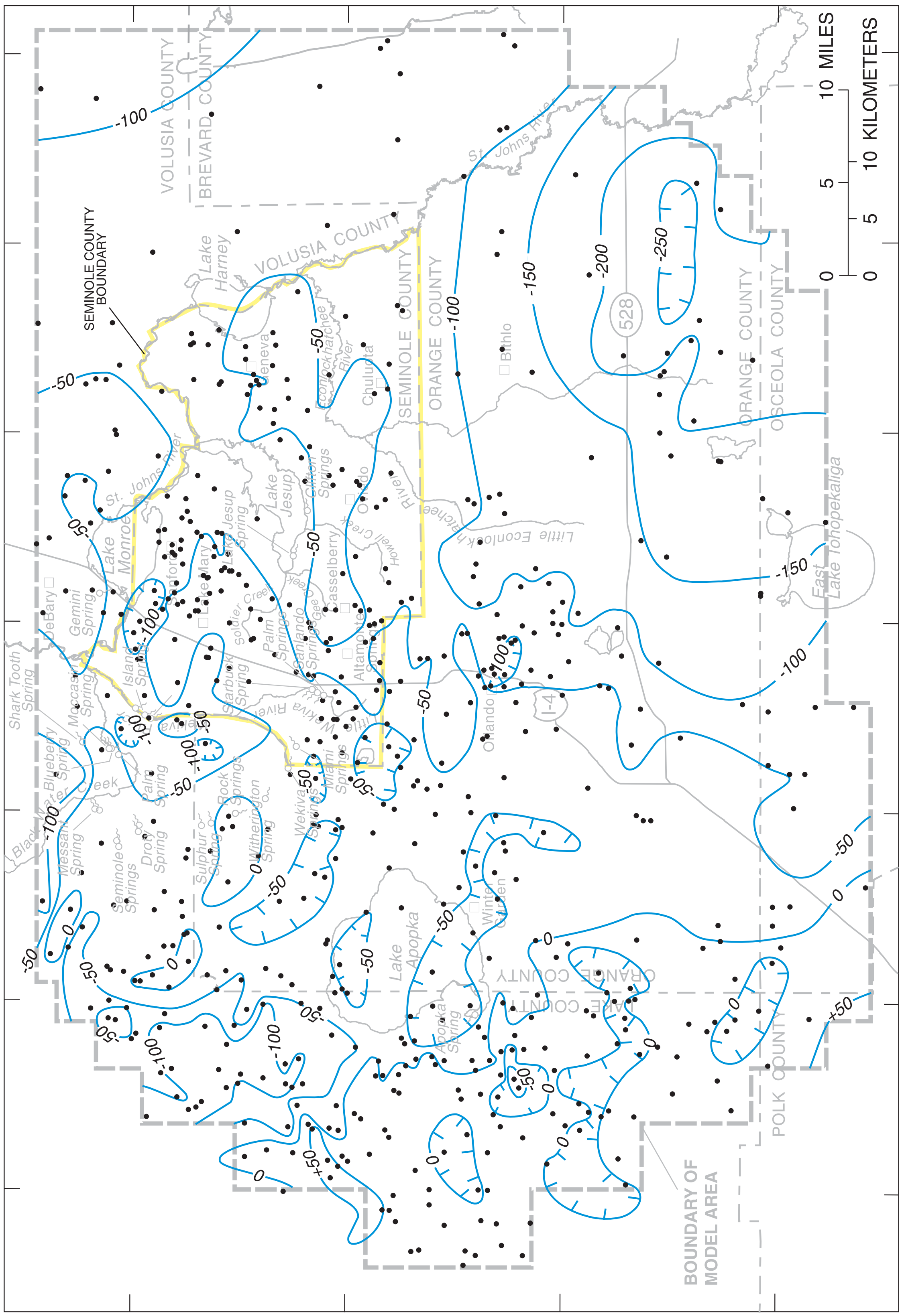


Figure 15. Generalized schematic diagram showing flow zones in the Floridan aquifer system.

Although a strong contrast in hydraulic conductivity between zones A and B of the Upper Floridan aquifer is clearly shown by the flow logs, making accurate estimates of hydraulic conductivity values can be somewhat subjective. The flow logs can be difficult to interpret because volumetric flow rates are estimated from measured spinner revolution and borehole diameter. Spinner revolutions can be affected by variations in tool speed, as well as by whether or not the tool is centered in the borehole. The diameter of the borehole also can vary widely. Zone B, however, generally has hydraulic conductivities that range from about 3 to more than 10 times greater than the hydraulic conductivities in zone A (B. McGurk, SJRWMD, oral commun., 2000).

A generalized contour map of the altitude of the top of the Upper Floridan aquifer is shown in figure 16. The altitude of the top of the Upper Floridan aquifer ranges from about 50 ft above sea level in the western part of the study area to more than 250 ft below sea level in southeastern Orange County. In Seminole County, the altitude of the top of the Upper Floridan aquifer ranges from more than 100 ft below sea level in the northwestern part of the county near Lake Monroe to less than 50 ft below sea level in much of the eastern, western, and southern parts of the county. The Ocala Limestone is absent in some areas as a result of past erosional processes (Tibbals, 1990, p. E11). The top of the Upper Floridan aquifer in these areas is defined by the dolomitic limestones of the Avon Park Formation. The surface of the Upper Floridan aquifer is irregular and paleokarstic. Sinkhole-type depressions on the surface are common, however, many of these features are small and are not shown in figure 16. The Upper Floridan aquifer averages about 300 ft in thickness throughout most of the study area (Miller, 1986, plate 28).



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

EXPLANATION

-200 STRUCTURE CONTOUR--Shows altitude of the top of the Floridan aquifer system. Datum is sea level. Hachures indicate depression. Contour interval 50 feet

• WELL CONTROL POINT

Figure 16. Altitude of the top of the Upper Floridan aquifer.

The middle semiconfining unit separates the Upper and Lower Floridan aquifers, and is composed of beds of relatively less permeable limestone and dolomitic limestone. The middle semiconfining unit (middle confining unit I of Miller, 1986, p. B56) generally occurs in the middle one-third of the Avon Park Formation and ranges in thickness from about 300 ft in eastern Lake County to about 700 ft in northern Osceola County (Miller, 1986, p. B57). In Seminole County, the unit ranges in thickness from about 400 to 550 ft. In the extreme southwestern part of the study area there is a separate and distinct second confining unit (middle confining unit II of Miller, 1986, p. B56) that underlies the middle semiconfining unit. The unit is composed primarily of gypsiferous dolomite and dolomitic limestone, which forms a non-leaky confining unit that separates freshwater from more mineralized water in the underlying rocks.

The middle semiconfining unit, like aquifers, can store and transmit water, but at much lower rates. Water from zones of higher hydraulic head can leak through the semiconfining unit to water-bearing zones of lower head. The rate of flow or leakage depends on the thickness, vertical hydraulic conductivity, and the hydraulic gradient across the middle semiconfining unit. Although locally the middle semiconfining unit may yield moderate amounts of water, it seldom is used as a source of water supply.

The Lower Floridan aquifer, which lies beneath the middle semiconfining unit, includes about the lower one-third of the Avon Park Formation and all of the Oldsmar Formation. The aquifer is highly productive and is composed of alternating beds of limestone and fractured dolomite. Permeability within this zone is primarily related to secondary porosity developed along bedding planes, joints, and fractures. The top of the Lower Floridan aquifer dips from the northwest to southeast across the study area, with altitudes ranging from about 600 ft to more than 1,200 ft below sea level (Miller, 1986, plate 31). Thickness of the aquifer ranges about 1,300 to 1,600 ft across the study area (Miller, 1986, plate 32). In Seminole County, the unit ranges in thickness from about 1,300 to 1,500 ft.

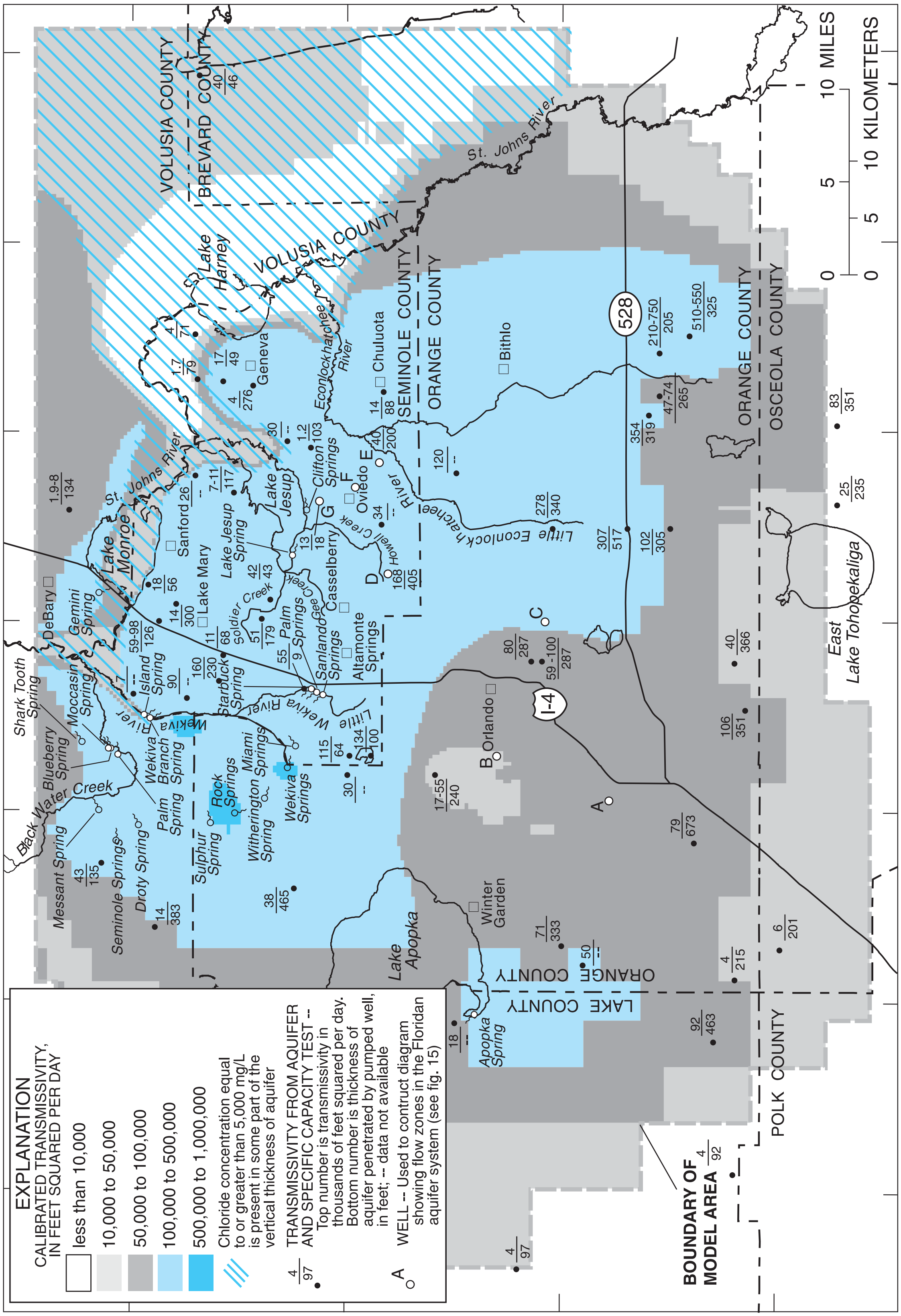
The sub-Floridan confining unit underlies the Lower Floridan aquifer. This unit is composed of low-permeability rocks and serves as the hydraulic base of the Floridan aquifer system. The sub-Floridan confining unit consists of dolomite and limestone deposits that contain abundant evaporite minerals. The uppermost stratigraphic occurrence of persistent evaporite deposits in the upper part of the Cedar Keys Formation generally is recognized as the top of the sub-Floridan confining unit (Miller, 1986, p. B74).

More recent data collected from wells in Orange County, however, indicates that the top of the sub-Floridan confining unit may be considerably higher than as mapped by Miller (1986, plate 33). At one well, located in southern Orange County (site 34), a gypsiferous dolomite was first found at about 2,240 ft below land surface (McGurk and Sego, 1999, p. 6). Flowmeter and video logs of the test hole indicated little flow of water entering or leaving the borehole below 2,000 ft (McGurk and Sego, 1999, p. 14). Another well, located at the Southern Regional well field in southern Orange County (site 19), was drilled to a depth of 2,467 ft. Gypsiferous dolomite was found at about 2,250 ft below land surface (Boyle Engineering Corp., 1995); however, decreasing permeability was reported in the dolomites and limestones below 2,050 ft.

Overview of Hydraulic Characteristics

Transmissivity estimates of the Upper and Lower Floridan aquifers vary widely across the study area. Variations from one aquifer test to another can be attributed to differences in well-penetration intervals and depths and to the heterogeneity of the aquifer system. Bush and Johnston (1988) observed that the carbonate rocks of the Floridan aquifer system are nearly always characterized by an uneven distribution of permeability. Variations in the hydraulic characteristics of the rock strata within the Floridan aquifer system are complex and closely related to the geologic framework of the system. The porosity and permeability of the strata result from a combination of (1) the original texture of the rock; (2) processes that have acted on the rock, such as dolomization and recrystalization; (3) joints, fractures, and other structural deformities; and (4) mineral dissolution and precipitation (Schiner, 1993). Movement of water through the Floridan aquifer system is mostly through the porous limestone, and is enhanced by networks of small fractures or solution openings that occur along joints or bedding planes. In some places, flow may be through large cavernous features of paleokarst, resulting in a dual-porosity flow system.

Transmissivity estimates for the Upper Floridan aquifer, as determined from aquifer and specific capacity tests, ranged from about 1,200 feet squared per day (ft^2/d) in Seminole County to greater than 500,000 ft^2/d in Orange County (fig. 17). Aquifer test analysis is based on the assumptions that the Upper Floridan aquifer is homogeneous and the wells fully penetrate the aquifer.



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

Figure 17. Model-calibrated transmissivity of the Upper Floridan aquifer and results of selected aquifer tests (compiled from Lichtler and others (1968); Tibbals (1977); Post, Buckley, Schuh, and Jerigan, Inc. (1989); Szell (1993); Yovaish Engineering Sciences, Inc. (1996); and from the files of SJRWMD).

As discussed previously, flow logs from wells in the study area indicate that the bottom one-third of the Upper Floridan aquifer generally is much more permeable than the top two-thirds (fig. 15). As a result, transmissivity estimates for the Upper Floridan aquifer cannot be treated equally because results from a partially penetrating well can be much different than results from a test that penetrates the entire thickness of the aquifer.

Few data are available describing the hydraulic properties of the middle semiconfining unit in the study area. Reported leakance values ranged from 1.2×10^{-5} 1/d to 1×10^{-3} 1/d (Szell, 1993; Murray and Halford, 1996; and Barnes, Ferland and Associates, Inc., 1997). The vertical hydraulic conductivity of the middle semiconfining unit ranges from 0.004 to 0.6 ft/d, based on thickness values that range from 300 to 600 ft. The horizontal hydraulic conductivity calculated for the middle semiconfining unit in the Cocoa well field (fig. 1) in eastern Orange County is about 20 ft/d (Phelps and Schiffer, 1996).

Only a few values of transmissivity have been calculated for the Lower Floridan aquifer (fig. 18). A transmissivity of about 200,000 ft^2/d was reported in western Orange County (Yovaish Engineering Sciences Inc., 1996). Lichtler and others (1968, p. 136) reported a transmissivity of 575,000 ft^2/d from an aquifer test near Orlando. Another test conducted near Orlando yielded a value of 668,000 ft^2/d (Szell, 1993, p. 193). Transmissivity estimates exceeding 500,000 ft^2/d were reported from several aquifer tests conducted south of Orlando. Murray and Halford (1996, p. 56) determined that model-derived transmissivity values in the Lower Floridan aquifer for the study area ranged from about 5,000 to more than 600,000 ft^2/d.

The storage coefficient of most confined aquifers ranges from about 1.0×10^{-5} to 1.0×10^{-3} (Lohman, 1972). In the study area, storage coefficient values calculated from aquifer tests conducted in both the Upper and Lower Floridan aquifers range from 1×10^{-4} to 1×10^{-3} (Murray and Halford, 1996, p. 17).

Effects of Geohydrologic Interpretation on Estimates of Hydraulic Characteristics

The hydraulic properties of an aquifer usually are estimated by conducting an aquifer test, which consists of applying a known stress to an aquifer and measuring changes in water level, drawdown or recovery. The hydraulic properties of the aquifer are then estimated by fitting an analytical or numerical model to the measured water levels. The assumptions and boundary conditions of the model should be consistent with the hydrogeology of the site and the configuration of observation wells. The geohydrologic interpretation of a test site can greatly affect model selection, which in turn affects hydraulic property estimates.

The transmissivity of the Upper and Lower Floridan aquifers has been estimated at many locations within the study area (figs. 17 and 18) by fitting observed drawdown data to the Hantush-Jacob (1955) solution, which also is known as the leaky aquifer solution. The Hantush-Jacob solution assumes that the stressed aquifer is homogeneous and isotropic, and is bounded vertically by an impermeable unit above or below the aquifer and a leaky confining unit opposite of the impermeable confining unit. While the analysis of a Lower Floridan aquifer test is reasonably consistent with a Hantush-Jacob solution, the analysis of an Upper Floridan aquifer test is not.

Previous investigators (Frazee, 1980; Knochenmus and Hughes, 1976; Lichtler, 1972; Lichtler and others, 1968; Szell, 1993; and Tibbals, 1977) have analyzed Upper Floridan aquifer tests with the Hantush-Jacob solution by conceptualizing either the entire Floridan aquifer system or the Upper Floridan aquifer as a homogeneous, isotropic unit. Either the sub-Floridan confining unit or middle semiconfining unit has been assumed to be an impermeable boundary. In both conceptualizations, leakage originates in the surficial aquifer system and the rate of leakage is controlled by the vertical leakance of the intermediate confining unit.

The conceptual and analytical models used in the past to interpret many of the Upper Floridan aquifer tests are not completely consistent with the geohydrologic structure within the study area. The Upper Floridan aquifer is not a single homogeneous unit, and the middle semiconfining unit is more similar to an aquifer than an impervious unit. These inconsistencies make comparisons between aquifer-test estimates of transmissivity for the Upper Floridan and estimates from model calibration difficult. The magnitude of these difficulties can be illustrated by simulating the response of the surficial and Floridan aquifer systems to a typical partially penetrating aquifer test in the Upper Floridan aquifer.

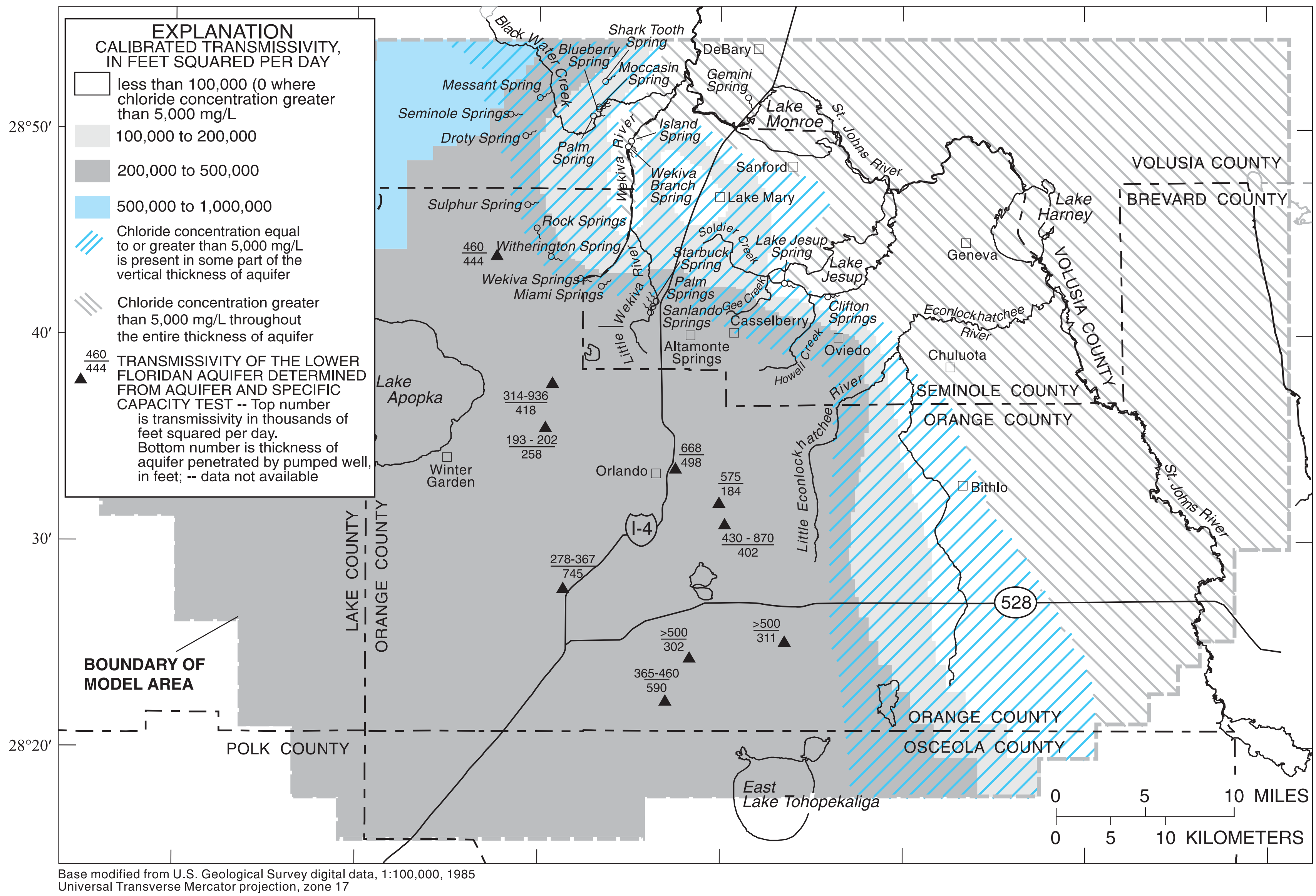


Figure 18. Model-calibrated transmissivity of the Lower Floridan aquifer and results of selected aquifer tests (compiled from Lichtler and others (1968); Tibbals (1977); Post, Buckley, Schuh, and Jerigan, Inc. (1989); Szell (1993); Yovaish Engineering Sciences, Inc. (1996); and from the files of SJRWMD).

Table 2. Model-input hydraulic properties of the surficial and Floridan aquifer systems assumed for a hypothetical aquifer test

[Specific yield was 0.1; a wellbore diameter of 12 inches was simulated]

Hydrogeologic unit	Approximate thickness, feet	Lateral hydraulic conductivity, feet per day	Vertical hydraulic conductivity, feet per day	Specific storage, 10^6 per foot	Transmissivity, feet squared per day	Storage coefficient
Surficial aquifer system	50	5	0.05	3	250	0.0002
Intermediate confining unit	50	0.6	.006	5	30	.0003
Zone A of Upper Floridan aquifer	210	200	2	1.5	42,000	.0003
Zone B of Upper Floridan aquifer	110	2,000	20	1.5	220,000	.0002
Middle semiconfining unit	580	50	.5	1.5	29,000	.0009
Lower Floridan aquifer	300	2,000	20	1.5	600,000	.0005

Drawdowns from pumping a 12-inch well at 600 gallons per minute were simulated for 2 days to generate ìmeasuredî drawdowns from a system with known hydraulic properties. A radially symmetric model of the surficial and Floridan aquifer systems was constructed in which lateral hydraulic conductivity values were proportional to the results from flow logs (fig. 15). The wellbore was simulated as a zone of high hydraulic conductivity having a specific yield of 1.0. The hydraulic properties that were used to simulate the surficial and Floridan aquifer systems are summarized in table 2. The production well was open to the top 140 ft of the Upper Floridan aquifer, and drawdowns were observed 42 ft from the production well and 30 ft below the top of the Upper Floridan aquifer. The aquifer-test model was discretized radially into 99 columns that ranged in width from 0.05 ft near the well to about 70,000 ft at a distance more than 400,000 ft from the well. Vertically, the aquifer-test model was discretized uniformly into 130 rows, each 10 ft thick.

Transmissivity, vertical leakance, and storage coefficient values were estimated by matching a Hantush-Jacob solution to the ìmeasuredî drawdown at the observation well (fig. 19). Drawdowns from the first 10 minutes of the test were not analyzed because wellbore storage affected the ìmeasuredî drawdown during this period.

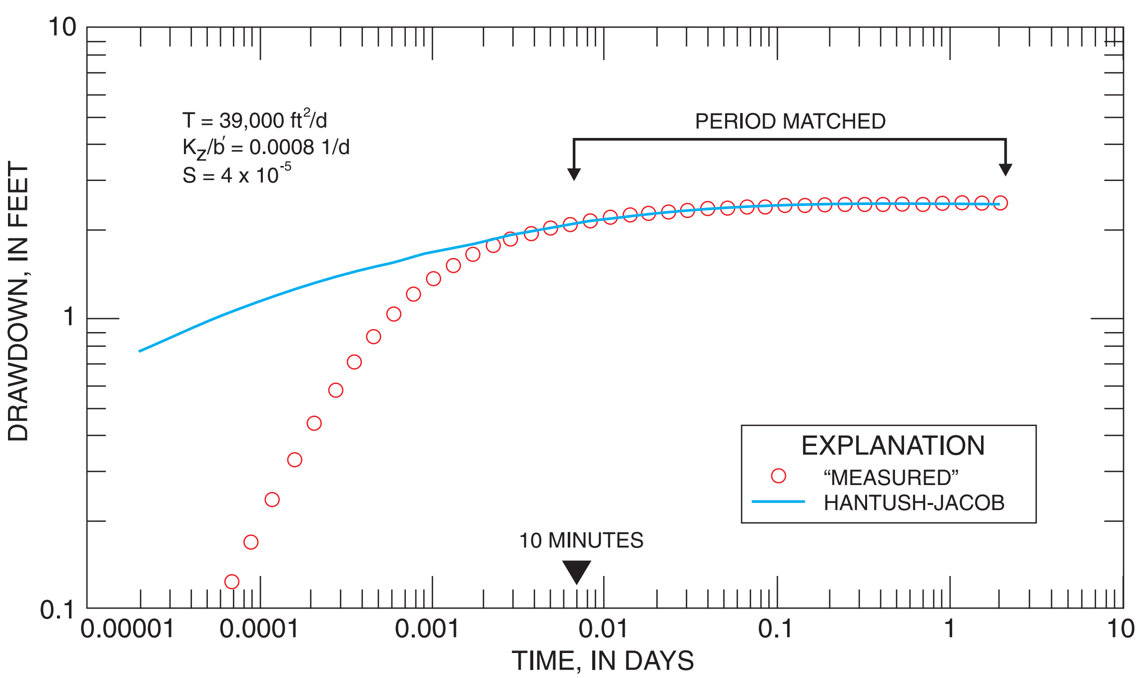


Figure 19. Estimates of transmissivity (T), vertical leakance (Kz/b'), and storage coefficient (S) from match of Hantush-Jacob solution to ìmeasuredî drawdown after wellbore storage effects have dissipated.

The analytically derived transmissivity estimate of 39,000 ft^2/d is a good estimate of the model-simulated transmissivity of zone A of the Upper Floridan aquifer (42,000 ft^2/d), but not of the entire Upper Floridan aquifer (262,000 ft^2/d). This discrepancy between transmissivity estimates is a natural consequence of the irregular distribution of water-producing zones that form the Upper Floridan aquifer. The analytically derived vertical leakance (0.0008 1/d) and storage (4×10^{-5}) estimates could not be related easily to any individual geohydrologic unit or combination of units.

Estimates of hydraulic properties, especially vertical leakance and storage coefficient, from an aquifer test cannot be improved unless an analytical model is used that more closely approximates the hydrogeology of the site and the flow patterns induced in the aquifer systems. Flow patterns in the radial aquifer-test model of the surficial and Floridan aquifer systems could not be approximated by a Hantush-Jacob solution during much of the simulated test. Fifty-eight percent of the pumpage originated below zone A of the Upper Floridan aquifer and 76 percent passed through zone B of the Upper Floridan aquifer after 3 hours of pumping (fig. 20). Near the end of the 2-day test, 68 percent of the pumpage originated below zone A of the Upper Floridan aquifer and 83 percent passed through zone B of the Upper Floridan aquifer. After 2 days, 48 percent of the water that originated in and above zone A of the Upper Floridan aquifer passed through zone B of the Upper Floridan aquifer.

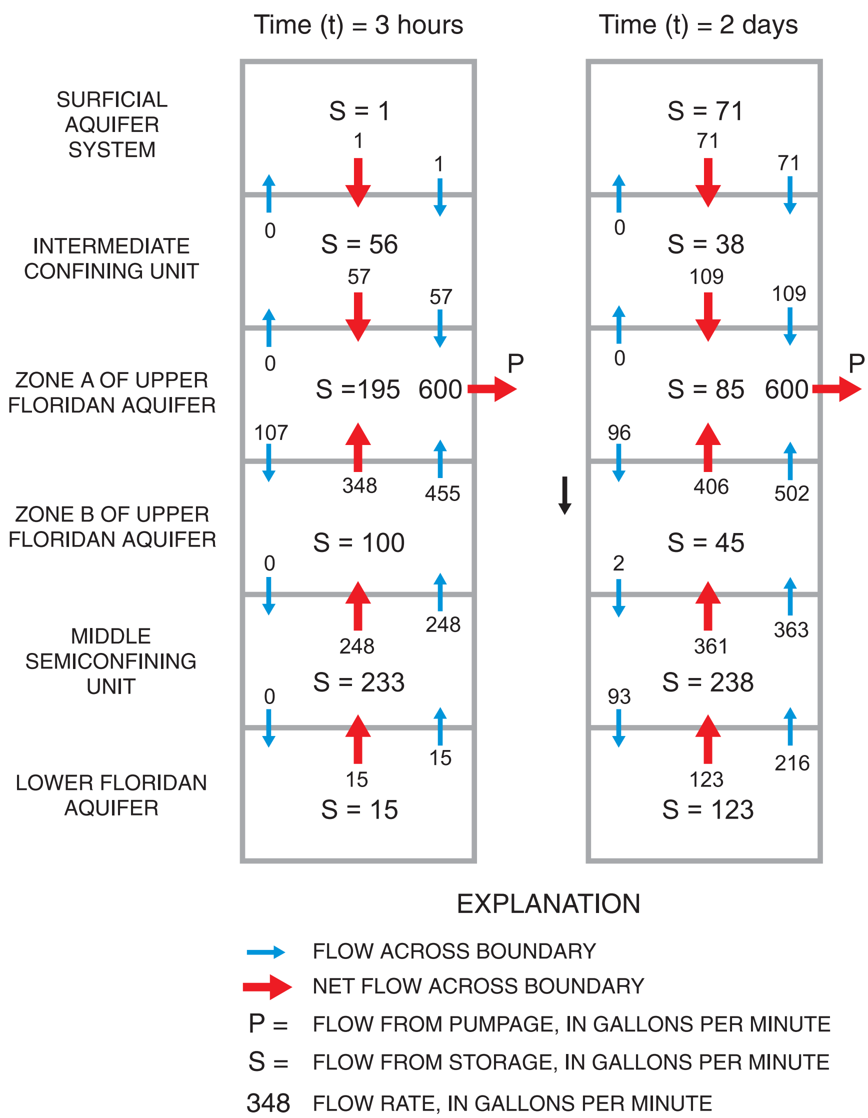


Figure 20. Simulated volumetric flow budget of the surficial and Floridan aquifer systems for 3 hours and for 2 days after pumping commenced from the top of the Upper Floridan aquifer at 600 gallons per minute.

Ground-Water Flow System

The Upper Floridan aquifer is recharged by downward leakage from the surficial aquifer system, through breaches in the intermediate confining unit caused by sinkholes or where the confining unit is thin or missing, by lateral inflow across the study area boundaries, and through drainage wells. Water is discharged from the Upper Floridan aquifer by pumping, springs, free-flowing wells, diffuse upward leakage of water to the surficial aquifer system where the potentiometric surface of the Upper Floridan aquifer is above the water table, and lateral outflow.

Estimated rates of recharge from the surficial aquifer system to the Upper Floridan aquifer range from nearly 0 in/yr to greater than 10 in/yr in Seminole County and across the study area (Murray and Halford, 1996, p. 14). Highest rates of recharge occur in the western parts of Seminole and Orange Counties, southeastern Lake County, and in the area around Geneva. These areas are characterized by karstic sand ridges with relatively deep water tables or an intermediate confining unit that is relatively thin. These areas also include numerous closed basins where the intermediate confining unit has been breached by sinkholes and the infiltration rate of ground water is high.

Significant amounts of recharge also occur through numerous drainage wells in the greater Orlando area and parts of southwestern Seminole County. Drainage wells primarily are used for control of lake levels and for the disposal of storm water by emplacing surface water directly into the Upper Floridan aquifer. From about 1910 to as late as 1960 drainage wells also were used to drain wetlands, dispose of surplus effluent from industrial sites, and to receive effluent from septic tanks. By the late 1970ís, more than 400 drainage wells had been drilled. By this time, however, the State of Florida stopped granting permits for the construction or replacement of any drainage wells.

The quantity of water that recharges the Floridan aquifer system by drainage wells can only be estimated. Two methods were used to estimate recharge, based on whether the drainage wells were used to provide street and urban drainage or lake-level control. Recharge values were estimated from September 1996 through August 1997. Street and urban recharge estimates were based on methods used by CH2M HILL (1997), with some minor modifications. For 124 street and urban wells that could be verified as active, recharge for the 1-year period was estimated to be 14.44 Mgal/d (22.3 cubic feet per second (ft^3/s)). Lake recharge estimates were based on methods used by Bradner (1996). For 118 lake-level control wells that could be verified as active, recharge for the 1-year period was estimated to be 31.16 Mgal/d (48.2 ft^3/s). The total amount of surface runoff estimated to be recharging the Floridan aquifer system by drainage wells, therefore, was 45.6 Mgal/d (70.6 ft^3/s).

Several municipalities in Seminole County dispose of reclaimed water from municipal treatment facilities by processes that recharge the ground water. Treated effluent from wastewater treatment plants is applied to RIBs or distributed for irrigation to lawns, golf courses, landscapes, and agricultural areas. From September 1996 through August 1997, about 15 Mgal/d (23 ft^3/s) of treated wastewater was applied to RIB sites or as irrigation in Seminole County. Reclaimed water application rates at various RIB sites in Seminole County accounted for about 4 of the 15 Mgal/d; the remainder was applied as irrigation to lawns, golf courses, landscapes, and agricultural areas. Much of the reclaimed water at RIB sites eventually recharges the Upper Floridan aquifer (OíReilly, 1998). The effects of the RIB sites on the Upper Floridan aquifer primarily is a function of the reclaimed water application rate and the hydraulic properties of the surficial aquifer system and the intermediate confining unit.

Natural discharge from the Upper Floridan aquifer occurs primarily by spring flow. From September 1996 through August 1997, 21 springs in the study area (fig. 1) collectively discharged about 278 ft^3/s of water from the aquifer (table 3). These springs, which augment surface-water flow, include eight second-magnitude springs (average discharge of 10 to 100 ft^3/s), five third-magnitude springs (average discharge of 1 to 10 ft^3/s), and eight fourth-magnitude springs (average discharge of less than 1 ft^3/s) (table 3). Wekiva Springs, the largest spring in the study area, discharged an average of about 69 ft^3/s based on 12 measurements during the study period. The spring feeds the upper reaches of the Wekiva River.

Undocumented spring flow or upward diffuse flow also could be a source of discharge from the Upper Floridan aquifer. Tibbals (1990, p. 28) indicated that the vicinity of the St. Johns River, especially around Lake Jesup and Lake Harney, was a likely area of ground-water discharge.

Abandoned flowing wells also discharge water from the Upper Floridan aquifer. As of 1995, about 250 abandoned flowing wells were in the study area (from the files of the SJRWMD). About 200 of these wells were in Seminole County, primarily south of Lake Monroe and near Lake Jesup. Total discharge from

Table 3. Average measured and simulated discharge from Upper Floridan aquifer springs, September 1996 through August 1997, and simulated discharge, 2020

Spring	USGS site identification number	Stage, feet above mean sea level	Spring conductance, feet squared per day	Measured discharge, cubic feet per second	Simulated discharge, cubic feet per second		Percent reduction in simulated discharge	Simulated discharge at the end of transient 180-day drought period, cubic feet per second	Percent reduction at end of drought period
					1996-97	2020			
Apopka Spring	283400081405100	66.68	2,600,000	31.00	31	17.7	43	0	100
Blueberry Spring	285102081263900	8	240	0.07	0.1	0.1	0	0.1	0
Clifton Springs	284156081141401	9	7,400	1.45	1.5	1	33	.4	60
Droty Spring	284940081303800	18	2,700	.65	.7	.6	14	.5	17
Gemini Spring	285144081183900	2.14	59,000	10.16	10.2	7.6	25	6.7	12
Island Spring	284922081250300	7	26,000	6.45	6.5	5.7	12	4.7	18
Lake Jesup Spring	284236081160500	2	2,500	[a].72	.7	.6	14	.4	33
Messant Spring	02235255	25	124,000	[b]14.83	14.8	13.2	11	11.3	14
Miami Springs	02234650	14.63	27,000	5.70	5.7	4.5	21	2.6	42
Moccasin Spring	285105081263800	12	1,200	.29	.3	.3	0	.2	33
Palm Springs (Seminole County)	02234996	22.82	52,000	4.96	5	2.9	42	0	100
Palm Spring (Lake County)	285038081270100	12	2,100	.53	.5	.5	0	.4	20
Rock Springs	02234610	25.85	566,00	58.83	58.8	44.6	24	23.9	46
Sanlando Springs	02234991	26.82	496,000	21.08	21.1	6.7	68	0	100
Seminole Springs	02235250	30	555,000	[b]35.17	35.2	29.8	15	22.6	24
Shark Tooth Spring	285224081262400	12	500	.13	.1	.1	0	.1	0
Starbuck Spring	02234997	22.41	165,000	14.91	14.9	8.7	42	0	100
Sulphur Spring	284612081303400	25	2,600	.40	.4	.3	25	.2	33
Wekiva Branch Spring	284903081250800	7	2,200	.60	.6	.5	17	.4	20
Wekiva Springs	02234600	13.17	347,000	68.67	68.7	56.4	18	37.9	33
Witherington Spring	02234620	28	16,000	[a]1.73	1.7	1.1	35	.2	82
Study area					**278.5**	**202.9**	**27**	**112.6**	**45**
Seminole County					**48.9**	**24.4**	**50**	**3.4**	**86**

[a]Discharge estimated from previous measurements.
[b]Discharge estimated from historical measurements.

abandoned flowing wells is estimated to be 15 Mgal/d (23 ft^3/s) in the study area, of which, about 12 Mgal/d (19 ft^3/s) was in Seminole County, based on data from the files of the SJRWMD.

The potentiometric surface of the Upper Floridan aquifer in east-central Florida is mapped semiannually by the USGS and SJRWMD during periods when water levels are generally at their highest (September) and lowest (May). These maps are based on water levels measured in several hundred wells tapping the Upper Floridan aquifer.

The regional configuration of the potentiometric surface of the Upper Floridan aquifer for May 1997 for Seminole County and adjacent counties is shown in figure 21. Ground water moves from areas of high potential to areas of low potential, along flow lines perpendicular to the lines of equal head. The May 1997 potentiometric surface represents conditions near the end of the dry season when withdrawals from the aquifer are near maximum and water levels generally are at their lowest. Ground water in the Upper Floridan aquifer moves from southwest to northeast across the study area. The potentiometric surface ranges from about 120 ft above sea level in extreme northeastern Polk County to about 8 ft above sea level in southern Volusia County, northeast of Lake Harney. During September 1996, which represents conditions when water levels were near seasonal highs, the potentiometric surface ranges from 125 ft above sea level to about 10 ft above sea level (German, 1997). The most prominent features on the May 1997 potentiometric-surface map are the depressions in eastern and western Seminole County and in southern Orange County. In western Seminole County, most of the depressions are related to spring discharge. The depressions in the potentiometric surface near Lake Harney in eastern Seminole County are likely the result of undocumented spring discharge or upward diffuse leakage. Depressions in the potentiometric surface in southern Orange County indicate ground-water withdrawal sites.

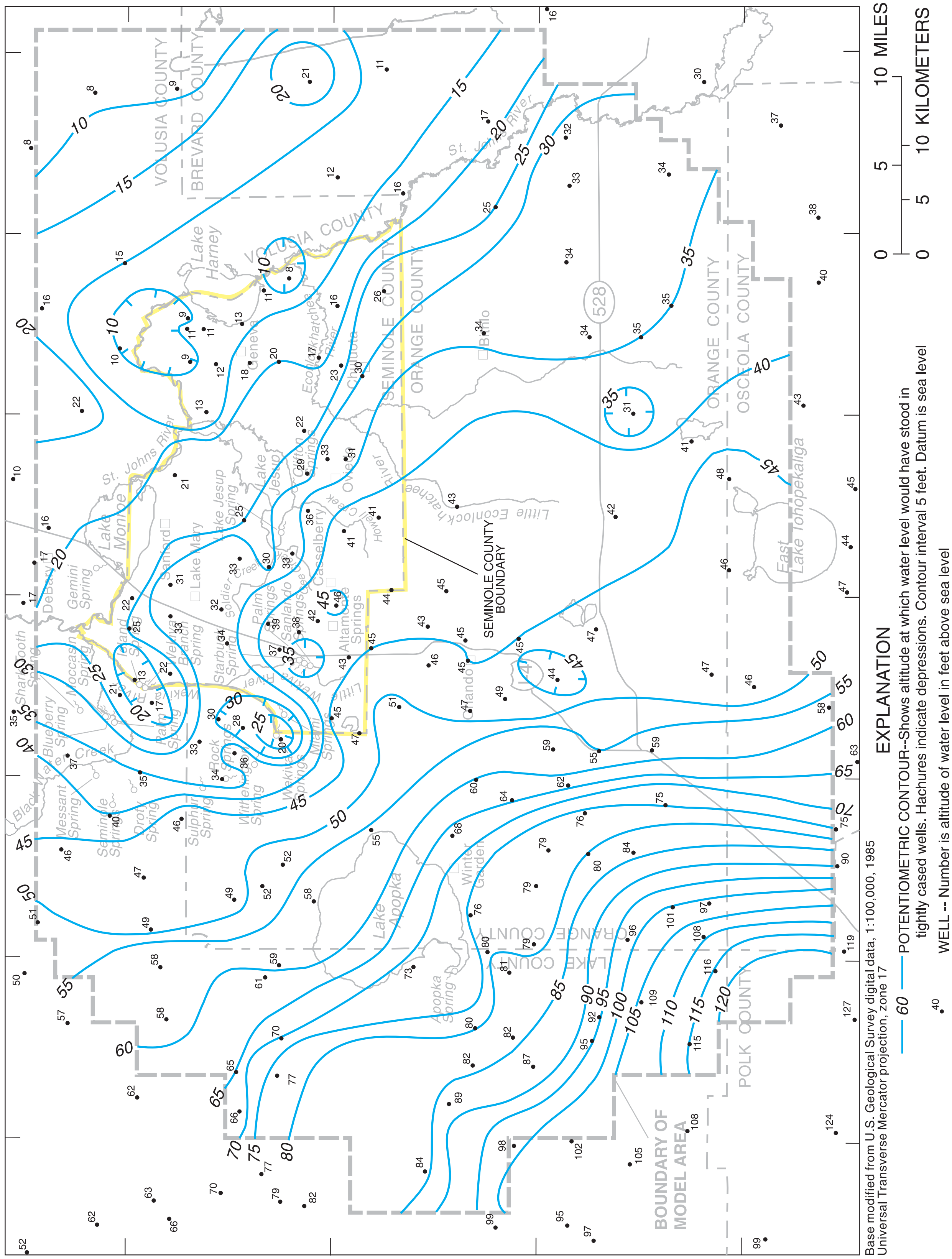


Figure 21. Potentiometric surface of the Upper Floridan aquifer, May 1997 (from Sepulveda, 1997).

Detailed potentiometric-surface maps of the Lower Floridan aquifer were not constructed because few wells within the study area penetrate this aquifer. However, data available from about 35 wells located primarily in central and western Orange County (A. OíReilly, U. S. Geological Survey, written commun., 1998) indicate that the potentiometric surface of the Lower Floridan aquifer is similar to the Upper Florida aquifer. Potentiometric surfaces of the Upper and Lower Floridan aquifers in May 1997 indicate that in recharge areas, the Upper Floridan aquifer heads are about 0 to 6 ft higher than the heads in the Lower Floridan aquifer. In discharge areas, where only a few wells are available for observation, the Lower Floridan aquifer heads are about 0 to 6 ft higher than the heads in the Upper Floridan aquifer.

The potentiometric surface of the Upper Floridan aquifer is constantly fluctuating, mainly in response to seasonal variations in rainfall and ground-water withdrawals. Seasonal and year-to-year fluctuations of water levels in four wells open to the Upper Floridan aquifer in Seminole and northern Orange County are shown in figure 22. Seasonal fluctuations typically range from 2 to 5 ft. The range of fluctuation of the potentiometric surface of the Floridan aquifer also varies to some extent with topography. In general, the fluctuations are largest in the ridge areas, which are the principal areas of recharge for the Floridan aquifer in Seminole County, and smallest in discharge areas.

Population growth in east-central Florida since the 1950ís has resulted in increased water withdrawals from the Floridan aquifer system, which subsequently have caused some declines in the potentiometric surface of the Upper Floridan aquifer. Declines in the potentiometric surface for long periods of time, resulting from increased water use and decreased rainfall, are important because declines indicate change in the long-term balance between recharge and discharge. Over time, these changes could shift the natural position of the saltwater-freshwater interface, causing more mineralized water to intrude into the freshwater aquifers.

Long-term hydrographs of four Upper Floridan aquifer observation wells (fig. 22) indicate a general downward trend of water levels from the early 1950ís to about 1990. Some of the decline in water levels can be attributed to an increase in pumpage, but part of the decline may be due to long-term below-average rainfall (fig. 23). From 1940 to 1960, rainfall was abundant and for many of those years rainfall was above average, producing a cumulative surplus of rainfall of about 18 inches at Sanford. The next 30 years, however, were drier. From 1961 to 1990 rainfall was below average for many of the years, and by 1990 there was a cumulative deficit in rainfall of about 58 inches. During this time, the four hydrographs showed declines in water levels ranging from 7 to 27 ft. From 1991 to 1998, water levels began to rise, a trend that can be explained by a period of above average rainfall. The lowest water levels generally occurred during the summers of 1981 and 1990 because of drought conditions that affected much of Florida.

Decreases in discharge also have been observed in some springs with long-term record (fig. 24). At Palm Springs, discharge decreased from about 12 ft^3/s in 1960 to about 5 ft^3/s in 1997. A decrease in ground-water discharge also appears to have occurred at Wekiva Springs since 1959. At other springs, including Sanlando and Starbuck Springs, however, decreases in spring discharge are not discernible.

UPPER FLORIDAN AQUIFER WATER QUALITY

The chemical and physical characteristics of ground water in the Floridan aquifer system are affected by many factors, such as, the initial chemical composition of water entering the aquifer, the composition and solubility of rocks with which it comes in contact, and the length of time the water remains in contact with these rocks. Additionally, the quality of the ground water can be affected by the mixing of freshwater with relict or connate seawater.

The chemical characteristics of water also can determine its suitability for various uses. The Florida Department of Environmental Protection has established primary regulations and secondary standards for drinking-water distributed by public water-supply systems (Florida Department of State, 1989). Secondary drinking-water standards, pertaining to the aesthetic qualities of water, set maximum recommended limits for dissolved solids at 500 milligrams per liter (mg/L) and chloride and sulfate concentrations at 250 mg/L.

During this investigation, water samples from 86 wells tapping and 13 springs discharging from the Upper Floridan aquifer were analyzed by the USGS for major chemical constituents from 1995 to 1997 (apps. 4 and 5). In addition, water-quality data collected by SJRWMD (38 wells) and the City of Sanford (1 well) during 1991-1995 were used and are included in Appendix 4. Water-quality data collected in 1986 by SJRWMD for one additional well also were used. Although most of the samples collected were in Seminole County, a few samples also were collected in adjacent Brevard, Lake, Orange, and Volusia Counties. The locations of wells and springs sampled are shown in figure 3.

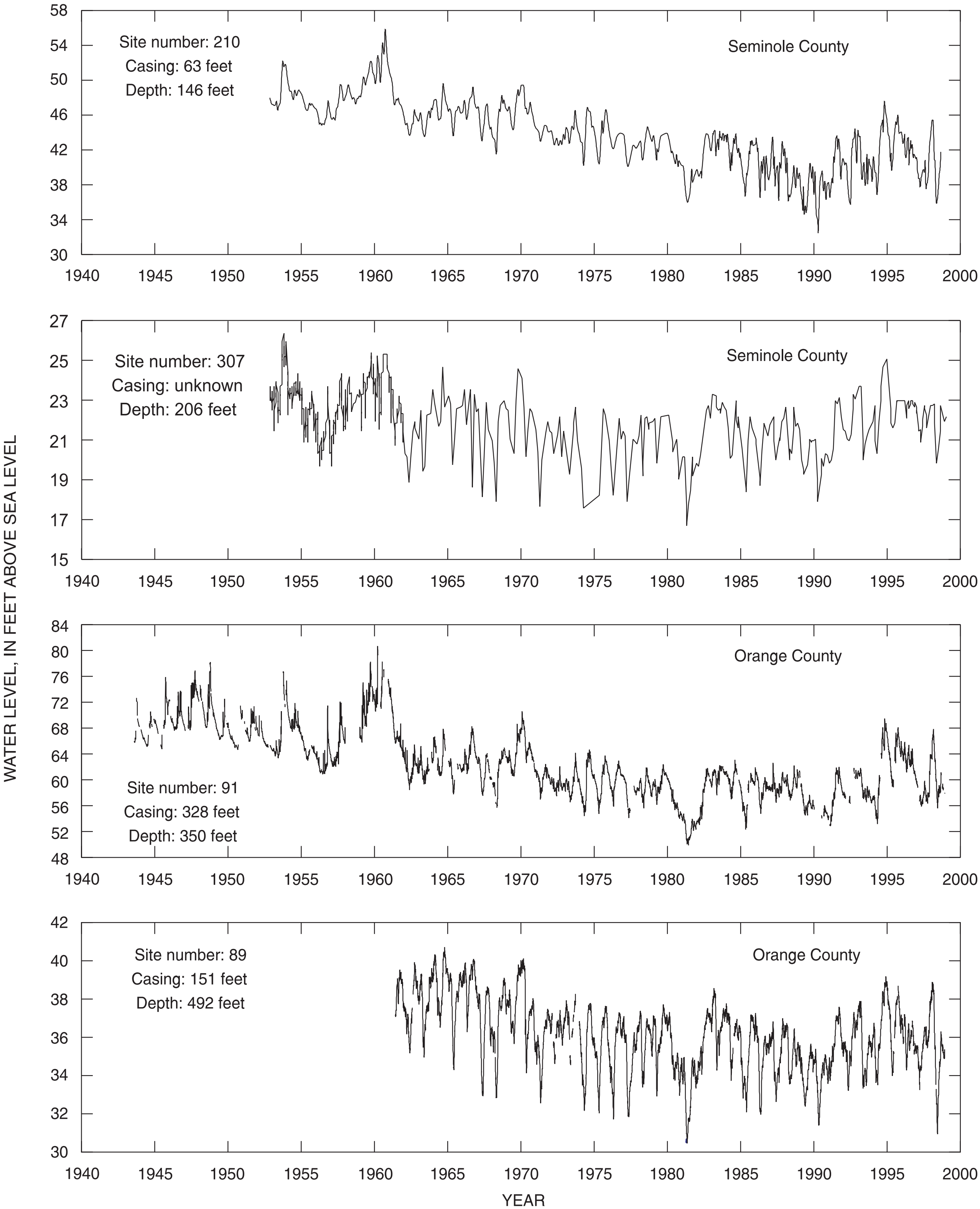


Figure 22. Water levels in selected wells open to the Upper Floridan aquifer (well locations shown in figure 3).

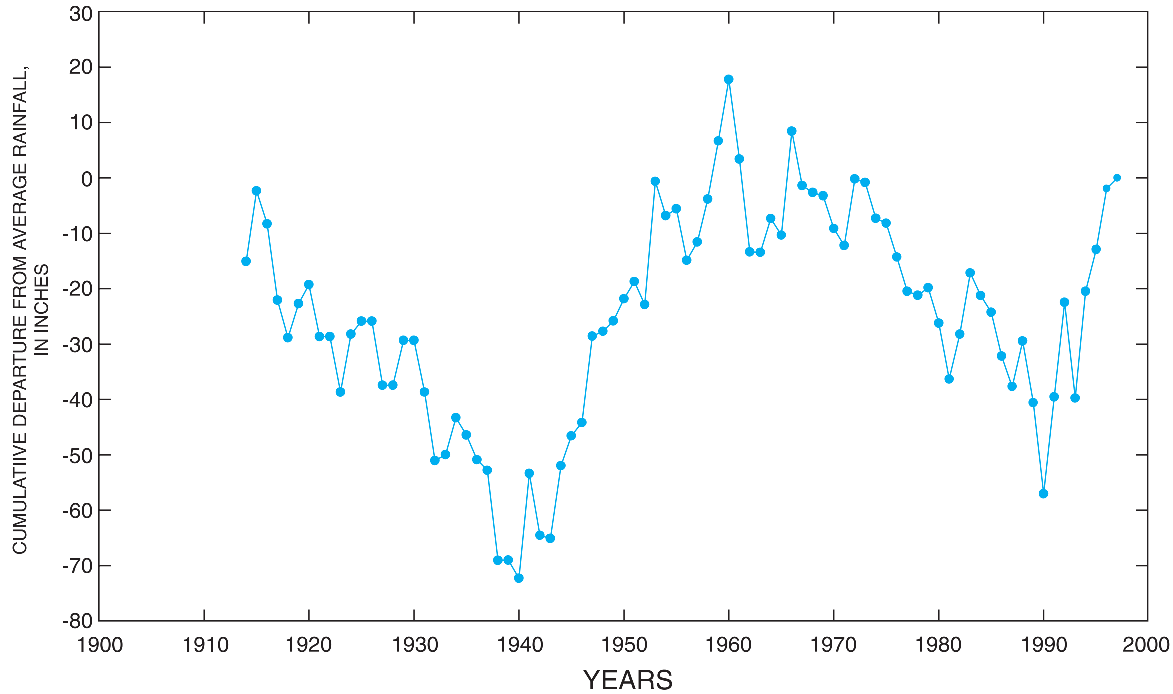


Figure 23. Cumulative departure from average rainfall at Sanford, Florida, 1914-1997.

The wells sampled range in depth from 38 to 595 ft and tap only the Upper Floridan aquifer. Wells were cased to the top of the Ocala Limestone (top of the Floridan aquifer system) and completed as open holes. Because most water samples were collected at the wellhead, the samples represent a composite from the open-hole section of the borehole.

Purging methods varied depending upon the type of well. Some of the wells sampled were monitoring wells, but many were used for private or public water supply. For monitoring wells, samples were collected after at least three casing volumes of water were purged and when temperature and specific conductance became stable. Depending on the depth to water, either a centrifugal or submersible pump was used to sample monitoring wells. Public supply wells have high-yielding pumps that were used routinely. For those wells, sampling commenced after field-measured parameters stabilized.

Water samples for springs were collected near the spring vent. At sites where a spring pool was present, the sample was collected in a weighted bottle lowered into the spring vent.

Water samples were processed at the time of collection using standard USGS procedures (Wood, 1976). Samples collected to determine dissolved-constituent concentrations were filtered through a 0.45-micron membrane filter. All water samples collected by the USGS were analyzed at a USGS laboratory using analytical procedures described in Fishman and Friedman (1989).

Major Constituents

The principal chemical constituents of ground water in Seminole County that affect potability are chloride and sulfate. Maps of specific conductance, chloride, and sulfate in water from the Upper Floridan aquifer were constructed to delineate areas of poorer water-quality (figs. 25-27).

The extent of mineralization of water in the Upper Floridan aquifer is indicated by the specific conductance. In Seminole County, specific conductance ranges from 210 to 14,700 microsiemens per centimeter (μS/cm) (fig. 25, apps. 4 and 5). Water having the lowest specific conductance generally occurs in the southwestern part of Seminole County, near Lake Mary, and around Geneva. In these areas, land surface altitude generally exceeds 30 ft, and recharge to the aquifer from rainfall occurs at a relatively high rate through a more permeable or breached intermediate confining unit. Highest specific conductance values occur in discharge areas near the St. Johns and Wekiva Rivers. Most of the mineralized water in the Upper Floridan aquifer in eastern Seminole County and near the St. Johns and Wekiva Rivers probably is a mixture of freshwater and relict seawater that entered the aquifer system during a higher stand of sea level in the geologic past. Movement of this mineralized water is relatively slow, particularly beneath the St. Johns River from Lake Harney northward.

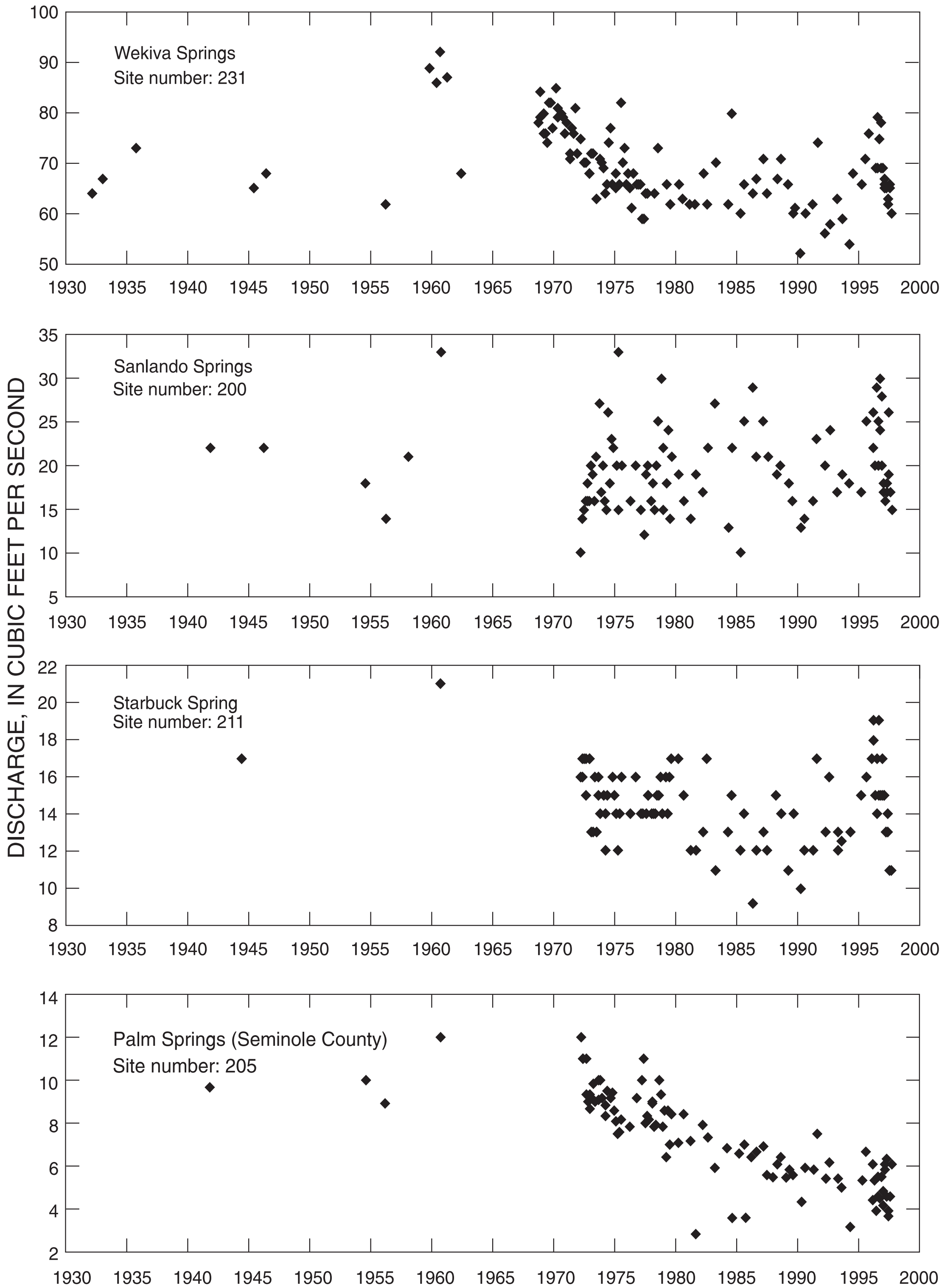
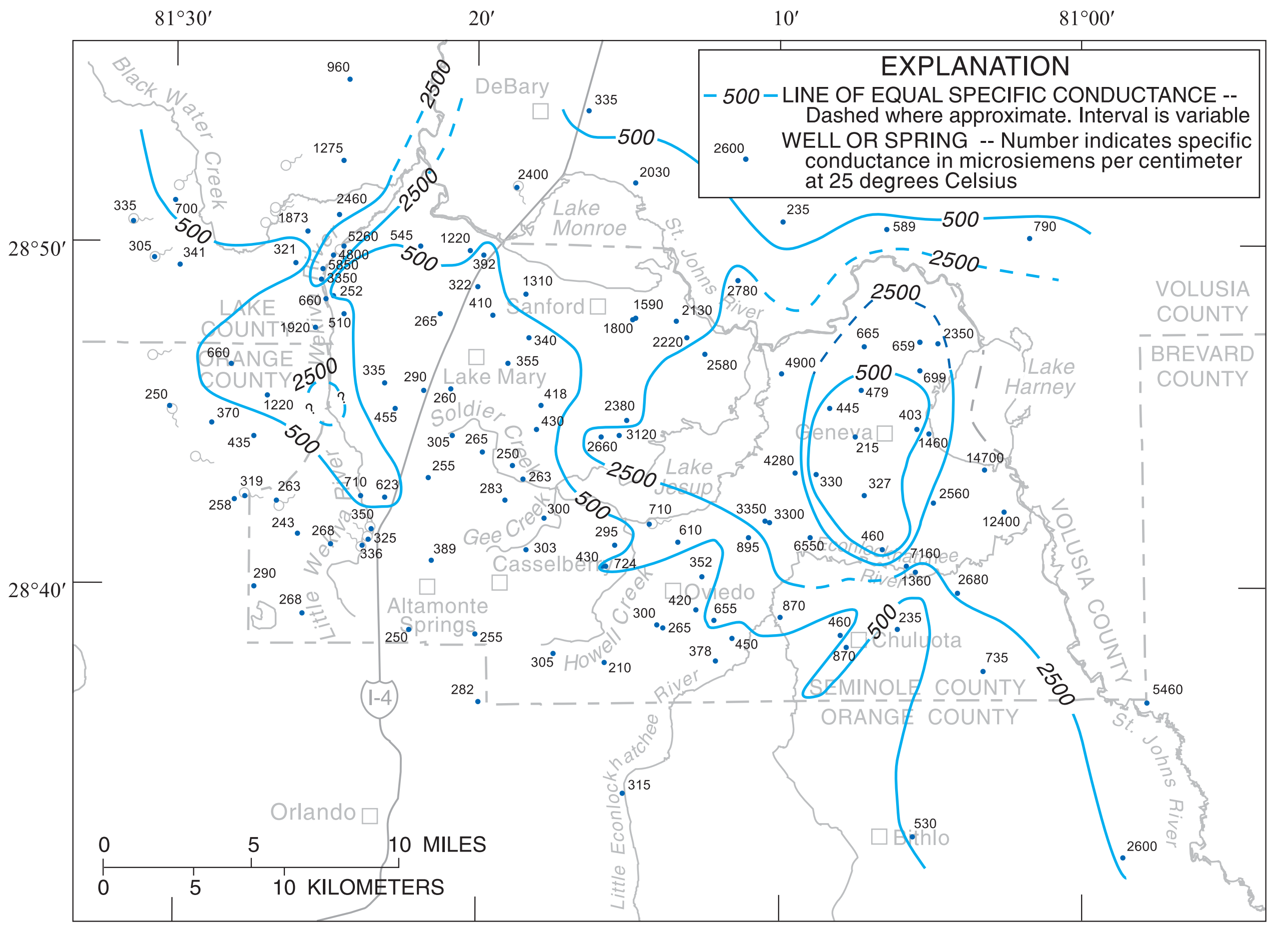


Figure 24. Discharge of selected Upper Floridan aquifer springs (spring locations shown in figure 3).



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

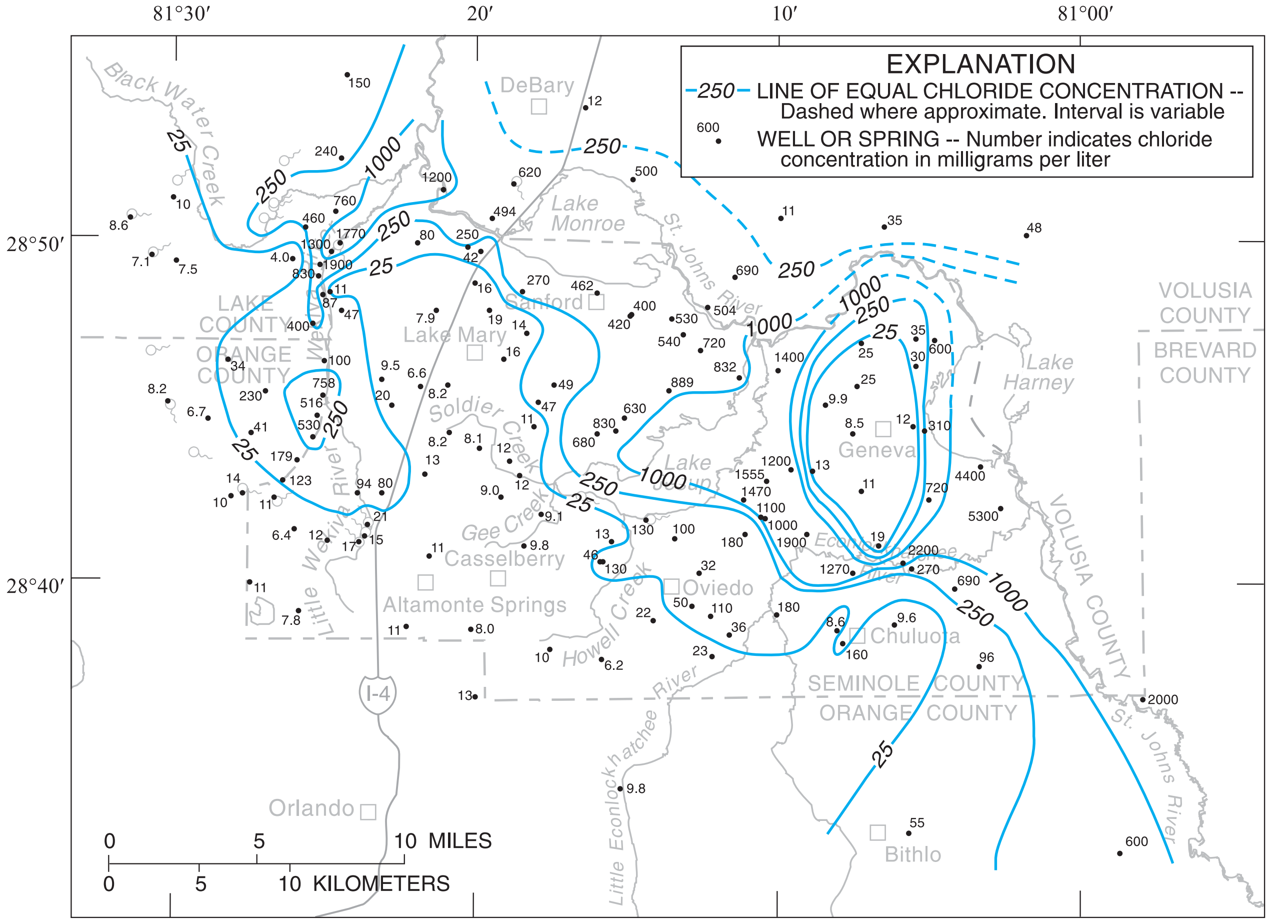
Figure 25. Generalized distribution of specific conductance of water from the Upper Floridan aquifer.

The relatively small amount of water discharged from the Upper Floridan aquifer to the St. Johns and Wekiva Rivers by diffuse upward leakage and undocumented spring flow is replenished by the upward movement of more saline water from deeper in the aquifer (Murray and Halford, 1996, p. 28).

Although specific conductance values cannot be used to determine precisely the dissolved solids concentrations in natural waters, they can provide a practical estimate. For the range of specific conductance values found in Seminole County, multiplication of the specific conductance by 0.6 to 0.7 gives a reasonable approximation of the dissolved solids concentration. Thus, specific conductance values in figure 25 indicate that water in much of the eastern part of the county exceeds the 500 mg/L recommended standard for dissolved solids (Florida Department of State, 1989). Water in the remainder of the county probably is below the standard for dissolved solids concentrations.

Chloride in ground water can be derived from several sources, including the dissolution of chloride minerals, contamination from septic tank effluent, agricultural activities, industrial waste, small amounts contributed by rainfall, and by the mixing of connate or relict seawater with fresh ground water. Chloride is the major anion of seawater and is an important indicator of saltwater intrusion.

In Seminole County, chloride concentrations of water in the Upper Floridan aquifer range from 6.2 to 5,300 mg/L (fig. 26, apps. 4 and 5). The lowest concentrations, generally less than 25 mg/L, occur in areas of high recharge in southwestern Seminole County, near Lake Mary, and around Geneva. Chloride concentrations ranging from 25 to 250 mg/L are found primarily in a northwesterly trending area that extends from Chuluota to Lake Monroe and in a narrow strip along the Wekiva River. Chloride concentrations ranging



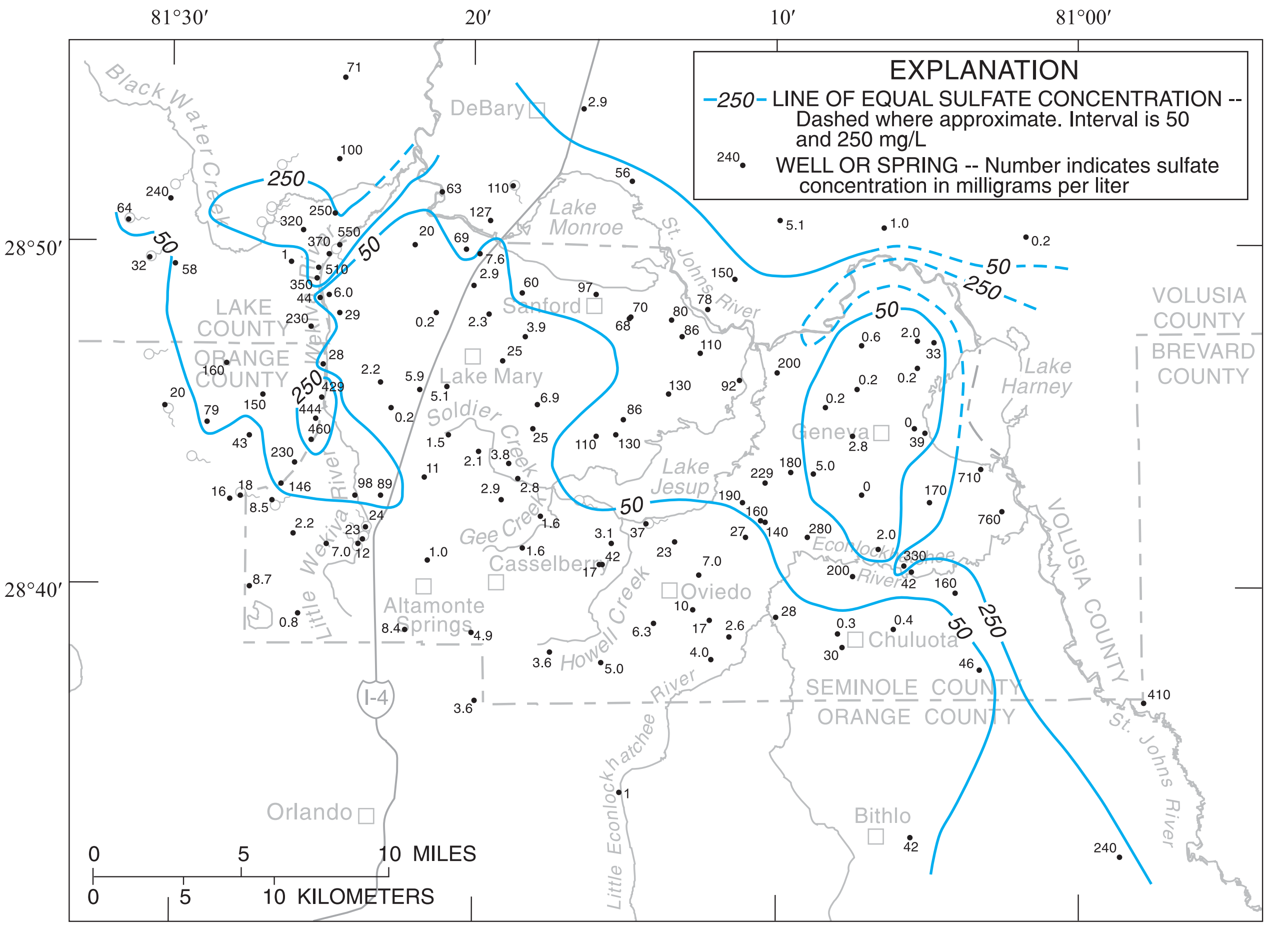
Base modified from U.S. Geological Survey digital data, 1:100,000, 1985
Universal Transverse Mercator projection, zone 17

Figure 26. Generalized distribution of chloride concentrations of water from the Upper Floridan aquifer.

from 250 to 1,000 mg/L are found primarily in a small area of the Wekiva River, the area around Lake Monroe extending south to the north side of Lake Jesup, and in the area around Geneva. Chloride concentrations exceed 1,000 mg/L in the discharge areas adjacent to the Wekiva and St. Johns Rivers in northwestern Seminole County, around the eastern part of Lake Jesup, and along the Econlockhatchee and St. Johns Rivers in eastern Seminole County. The highest chloride concentration (5,300 mg/L) occurs south of Lake Harney. Ground water having a chloride concentration exceeding 1,000 mg/L is unsuitable for drinking, for many industrial uses, and for the irrigation of most crops.

The most abrupt changes in chloride concentrations of water in the Upper Floridan aquifer occur around the ìGeneva Freshwater Lens.î This isolated lens of freshwater contains water with a chloride concentration less than 25 mg/L and is surrounded by brackish water. Chloride concentrations around most of the edge of the lens increase from about 25 mg/L to about 1,000 mg/L in less than 1 mile. At the eastern edge of the lens, chloride concentrations increase from 25 mg/L to more than 4,000 mg/L in less than 3 miles. Abrupt changes in chloride concentrations also occur in parts of the Upper Floridan aquifer in northwestern Seminole County. In this area, chloride concentrations also increase from 25 mg/L to more than 1,000 mg/L over a distance of about 1 mile.

In Seminole County, sulfate concentrations of water in the Upper Floridan aquifer range from 0 to 760 mg/L (fig. 27, apps. 4 and 5). Sulfate concentrations of less than 50 mg/L are found across much of the study area, with concentrations of less than 10 mg/L found primarily in southwestern Seminole County, near Lake Mary, and around Geneva.



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

Figure 27. Generalized distribution of sulfate concentrations of water from the Upper Floridan aquifer.

Sulfate concentrations of 50 to 250 mg/L are found primarily in a northwesterly trending band extending from Chuluota, across Lake Jesup to Lake Monroe, and in an area west of the Wekiva River. Sulfate concentrations generally exceed the 250 mg/L recommended standard for drinking water along the St. Johns River in eastern Seminole County and near parts of the Wekiva River. The highest sulfate concentration of 760 mg/L is found south of Lake Harney.

Probable sources of sulfate in the Upper Floridan aquifer include the mixing of relict seawater with freshwater, and to a lesser extent, from the dissolution of sulfate-bearing minerals, such as gypsum or anhydrite. In the eastern part of the county, high sulfate concentrations typically are present in water that also has high chloride concentrations. This indicates that the source of sulfate probably is due, in part, to the mixing of ancient seawater with freshwater.

Thirteen springs discharging from the Upper Floridan (fig. 3) also were sampled for major cations and anions. The quality of water discharging from Upper Floridan aquifer springs, like those from the numerous wells sampled, varied considerably (app. 5). Water sampled at Droty, Miami, Palm, Rock, Sanlando, Starbuck, and Wekiva Springs contained low concentrations of chloride (less than 25 mg/L) and sulfate (less than 35 mg/L). Water sampled from Seminole and Messant Springs contained somewhat higher sulfate concentrations (64 and 240 mg/L, respectively), but low concentrations of chloride (less than 10 mg/L). At Clifton, Gemini, Island, and Wekiva Branch Springs, water sampled was more mineralized, containing chloride concentrations ranging from 130 to 1,900 mg/L, and sulfate concentrations ranging from 37 to 510 mg/L.

Water-quality analyses of ground water from wells and springs in the study area indicate differences in the ionic composition of water in the Upper Floridan aquifer. One method of graphically displaying the ionic compositions of various water types is by using a trilinear diagram (fig. 28). Three end-member water types are characterized in the Upper Floridan aquifer: a calcium bicarbonate type, a calcium magnesium sulfate or calcium sulfate type, and a sodium chloride type.

Calcium bicarbonate type water results from the dissolution of limestone. This water type typically predominates in the recharge areas located primarily in the western part of Seminole County and is indicative of waters that have relatively short, shallow flow paths. The dominant ion is bicarbonate and the water commonly is low in chloride, sulfate, and dissolved-solids concentrations, indicated by the clustering of data just above the left apex of the diamond-shaped area in figure 28.

Calcium-magnesium-sulfate water type is less common in the Upper Floridan aquifer in Seminole County. As water moves downgradient, the dissolved-solids concentration of the water increases. This increase in mineralization also corresponds to increases in magnesium and sulfate concentrations, primarily due to the dissolution of dolomite and gypsum, respectively. Calcium-magnesium-sulfate type water probably has traveled along longer and deeper flow paths than the calcium-magnesium-bicarbonate type water. The final product is a water type higher in calcium, magnesium, and sulfate, as represented by the clustering of data toward the apex of the diamond.

Sodium chloride water type represents the mixing of freshwater with entrapped relict seawater or from the upwelling of deeper more saline water. This water type is predominant in many of the wells in eastern Seminole County and in the vicinity of the Wekiva River. Analyses of sodium chloride water are plotted above the right apex of the diamond (fig. 28).

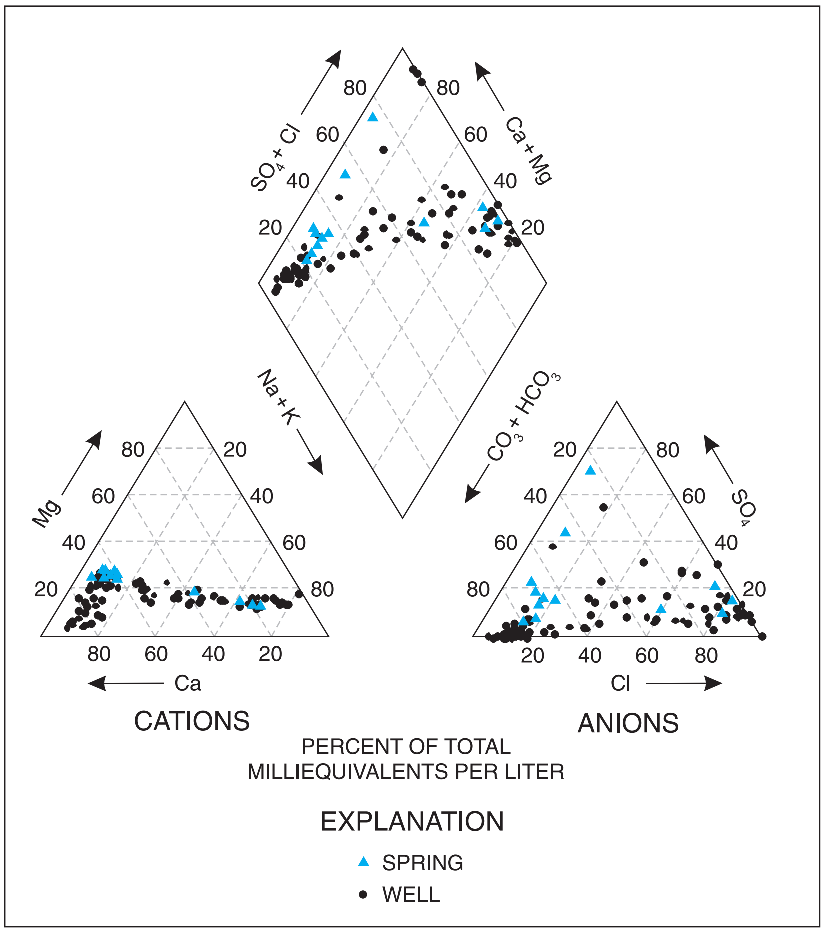


Figure 28. Chemical composition of water from selected wells and springs from the Upper Floridan aquifer.

Vertical Distribution of Chloride Concentrations

Little historical data are available on the quality of water underlying the Upper Floridan aquifer in Seminole County. Since the early 1990ís, however, several monitoring wells have been drilled into the Lower Floridan aquifer in Seminole and adjacent counties to acquire information about variations in water quality within the Floridan aquifer system. Chloride concentrations in water samples collected during the drilling of four monitoring wells in Seminole County are shown in figure 29. Water samples at all sites were collected through the drill stem as the wells were drilled. In general, chloride concentrations increased with depth. Water in the Lower Floridan aquifer was more mineralized than in the Upper Floridan aquifer, especially in areas located near the transition zones.

Well data show that throughout much of western Seminole County, ground water having chloride concentrations less than 25 mg/L extends to considerable depths in the Floridan aquifer system. In much of the extreme southwestern part of Seminole County, chloride concentrations change little with depth until about 1,800 ft below land surface. Ardaman and Associates, Inc. (1993) reported that chloride concentrations at the Charlotte Street monitoring well near Altamonte Springs (fig. 29) did not change during the drilling operations. The well, 1,506 ft deep, yielded water having chloride concentrations of less than 12 mg/L.

Chloride concentrations in water from the Oviedo monitoring well ranged from 16 mg/L to about 80 mg/L to a depth of 1,095 ft below land surface (fig. 29). In the interval from 1,110 to 1,388 ft, chloride concentrations increased from 169 to 1,210 mg/L (Yovaish Engineering Sciences, Inc., 1994, p. F-1). From 1,388 ft to the bottom of the hole (1,607 ft), chloride concentrations increased slightly to 1,290 mg/L; however, a water sample obtained after a high capacity test pump was installed produced a chloride concentration of 6,410 mg/L. This rather large discrepancy in chloride concentrations seems to be a result of the method used in obtaining water samples while the well was being drilled (reverse air), which resulted in some mixing and dilution of the formational waters. According to Yovaish Engineering Sciences, Inc. (1994), because of the mixing with the overlying fresher waters, water samples collected from 1,380 to 1,607 ft during drilling (fig. 29) probably represent a chloride concentration that is too low.

At the Yankee Lake site (fig. 29), a test well was drilled to a depth of 2,260 ft below land surface (W. Osburn, SJRWMD, written commun., 1998). From the top of the Upper Floridan aquifer to a depth of 435 ft, chloride concentrations remained below 25 mg/L. Chloride concentrations ranged from 32 to 74 mg/L from about 466 to 605 ft. Chloride concentrations increased sharply to 656 mg/L at about 615 ft. In the interval between 615 and 1,352 ft, chloride concentrations varied from 644 to 4,300 mg/L. At 1,383 ft, chloride concentrations increased to 6,080 mg/L. Another sharp increase to 9,600 mg/L was observed at 1,443 ft. From 1,443 to 1,695 ft, chloride concentrations varied from 9,080 to 10,740 mg/L. At 1,727 ft, chloride concentrations increased to 15,000 mg/L. In the interval between 1,759 ft and the bottom of the hole at 2,260 ft, chloride concentrations ranged from 16,600 to 18,000 mg/L (W. Osburn, SJRWMD, written commun., 1998).

In 1999, the Lake Mary monitoring well was completed to a depth of 1,390 ft below land surface. Chloride concentrations were 25 mg/L or less from a depth of 84 to 1,141 ft (W. Osburn, SJRWMD, written commun., 1999). In the interval between 1,204 to 1,329 ft, chloride concentrations ranged from 125 to 308 mg/L. Chloride concentrations increased sharply to 3,560 mg/L at about 1,345 ft and to 4,400 mg/L at 1,390 ft.

Data from numerous wells were used to estimate the depth to the 250 and 5,000 mg/L chloride isochlors in the Floridan aquifer system (figs. 30 and 31, respectively). The maps are based primarily on chloride concentrations of samples collected from monitoring wells and test drilling in Seminole and adjacent counties (McGurk and others, 1998, and B. McGurk, SJRWMD, written commun, 1999). Time domain electromagnetic measurements collected by the SJRWMD in the mid to late 1980ís were also used to interpolate between data points. The 250- mg/L isochlor is important because it represents the threshold for potable water. The 5,000-mg/L isochlor represents the base of the freshwater flow system.

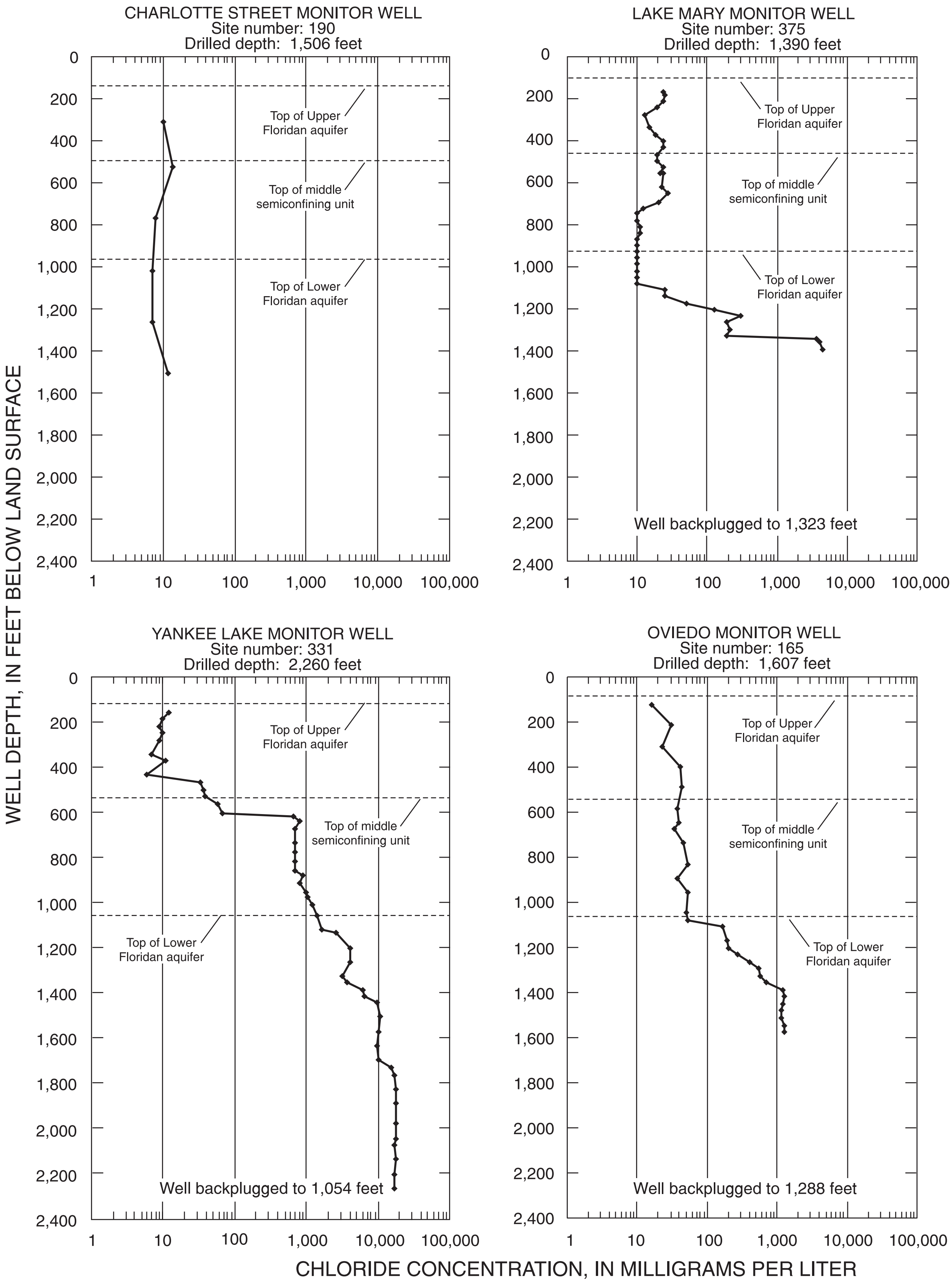


Figure 29. Chloride concentrations in water samples obtained through the drill stem during drilling of monitoring wells (modified from Yovaish Engineering Sciences, Inc., 1994; Ardman and Associates, 1993; and from the files of SJRWMD). Well locations shown in figure 3.

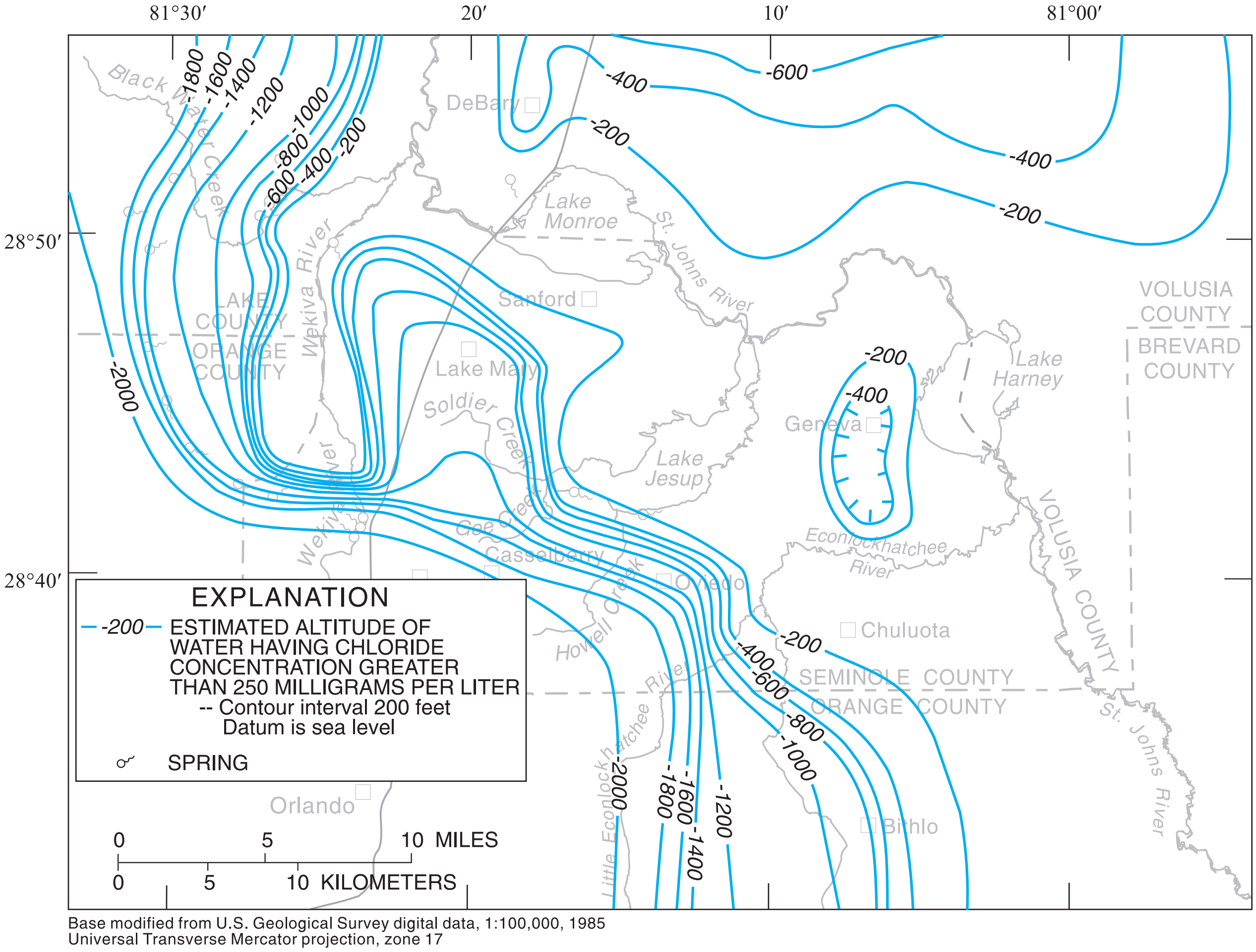


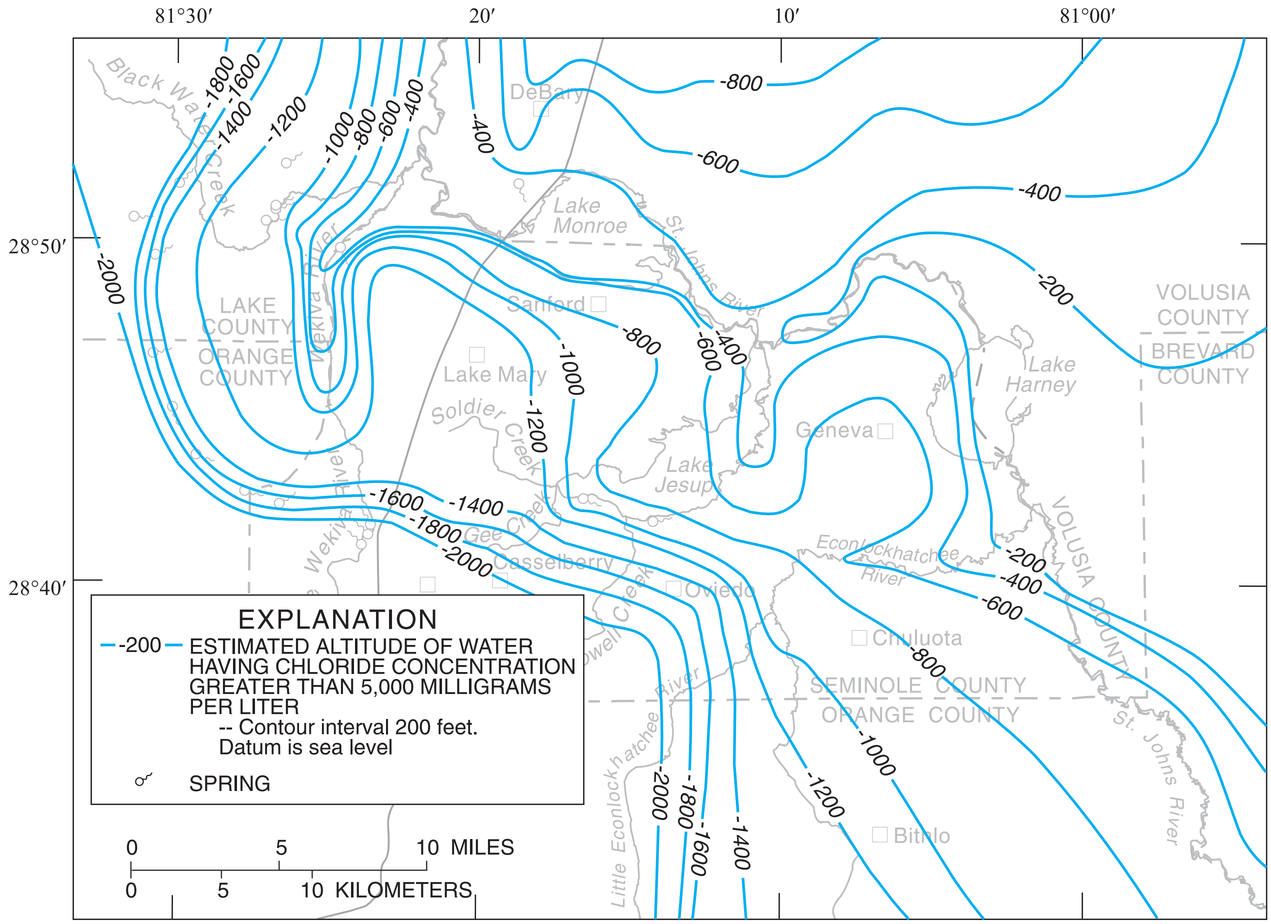
Figure 30. Estimated altitude of water in the Floridan aquifer system having chloride concentrations greater than 250 milligrams per liter (from McGurk and others, 1998; and B. McGurk, SJRWMD, written commun., 1999).

The altitude of the top of the transition zone (250-mg/L isochlor) is variable throughout Seminole County. The estimated position of the 250-mg/L isochlor is less than 200 ft below sea level in much of the eastern part of Seminole County (with the exception of the area around Geneva), near Lake Monroe, and along parts of the Wekiva River. The thickest section of freshwater in Seminole County is located in the extreme southwestern part of the county. The altitude of the 250-mg/L isochlor in this area is more than 2,000 ft below sea level. In general, the shape of the 5,000-mg/L isochlor (fig. 31) is similar to that of the 250-mg/L isochlor (fig. 30). The estimated altitude of the 5,000-mg/L isochlor ranges from less than 200 ft along the St. Johns River in eastern Seminole County to more than 2,000 ft below sea level in the southwestern part of the county.

Long-Term Trends

Monitoring chloride concentrations in ground water as an indicator of saltwater intrusion has been used to some degree since the 1950ís in a few wells tapping the Upper Floridan aquifer. Detection of chloride-concentration trends in water from wells in the Upper Floridan aquifer is essential to water-resources management, especially in areas that are experiencing rapid population growth and that are near the transition zones.

The frequency of water-quality monitoring varies from well to well. In the early to mid 1950ís and again in the early 1970ís, many wells were sampled throughout Seminole County. Since then, however, water samples have been collected intermittently. In addition, some of the monitoring wells have been destroyed or plugged, providing fewer wells for long-term observation.



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

Figure 31. Estimated altitude of water in the Floridan aquifer system having chloride concentrations greater than 5,000 milligrams per liter (from McGurk and others, 1998; and B. McGurk, SJRWMD, written commun., 1999).

In an effort to evaluate long-term water-quality changes in Seminole County, 14 wells sampled by Tibbals (1977) during the period from 1973-74 were located and resampled in 1995-96. Based on a limited number of water samples (two to three per well), it seems that chloride concentrations in water from these wells and other wells in the Upper Floridan aquifer have not changed significantly in Seminole County during the period from 1973-96, and probably not since the mid 1950ís. Tibbals (1977) reported that there was no significant change in chloride concentration of water from the Upper Floridan aquifer in Seminole County from the early 1950ís to the early 1970ís. Toth and others (1989) also found little change in chloride concentrations for wells sampled in the Wekiva River basin during 1973 and 1986. As water use continues to increase, however, water levels in the Upper Floridan are likely to decline further. Well fields located near the transitions zones risk the possibility of saline water intruding into the fresher water-bearing zones as freshwater heads are reduced. Heavy pumping could lower the head in a freshwater well enough to cause the transition zone to move upward and cause wells open within that zone to yield saltier water.

Recent water-quality data show that the upward movement of saline water is occurring in some well fields in the Oviedo area, which is near the transition zone (D. Hearn, Yovaish Engineering Sciences, Inc., written commun., 1999). Graphs showing chloride concentrations of water from seven public supply wells in the Oviedo area (four of which are shown in figure 32) indicate that chloride concentrations are increasing with time. Initial chloride concentrations in several of the wells were greater than 30 mg/L, indicating that the wells had already penetrated the transition zone.

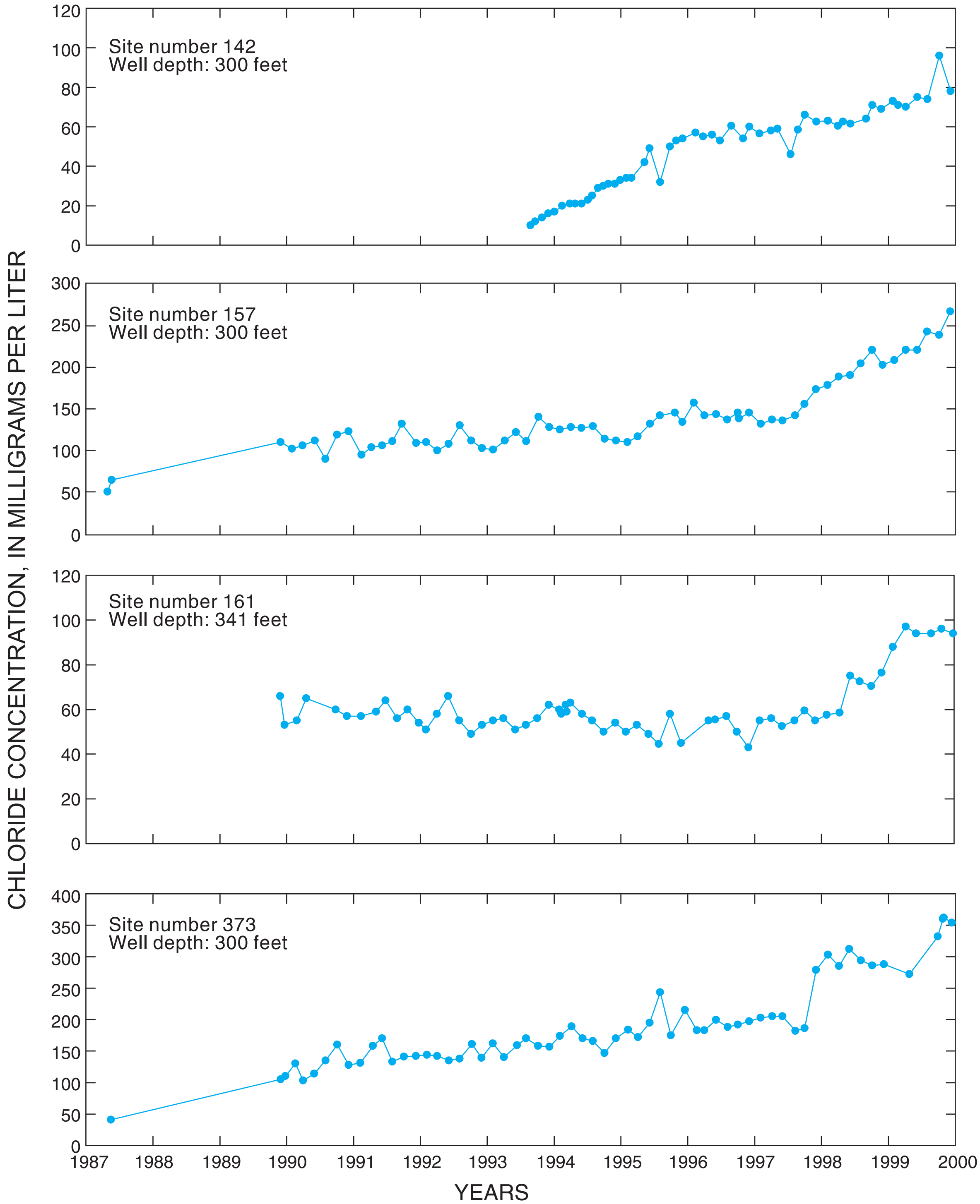


Figure 32. Chloride concentrations of water from four wells tapping the Upper Floridan aquifer near Oviedo, Florida.

The chemical quality of water has been monitored by the USGS at selected springs in the study area since about the mid 1950ís. In some Upper Floridan aquifer springs, water gradually has become more mineralized (fig. 33). Increases in specific conductance were observed at several of the springs where long-term water-quality data were available, including Wekiva, Sanlando, Starbuck, and Palm Springs. At Wekiva Springs, specific conductance of discharged water increased from about 225 µS/cm in 1956 to 319 µS/cm in 1997, whereas at Sanlando Springs, specific conductance increased from about 229 to 352 µS/cm during the same period of time.

Increases in major cations and anions, such as chloride and sulfate, also were observed in many of these springs. Chloride and sulfate concentration trends for samples collected between 1956 and 1998 from Wekiva and Sanlando Springs are shown in figure 34.

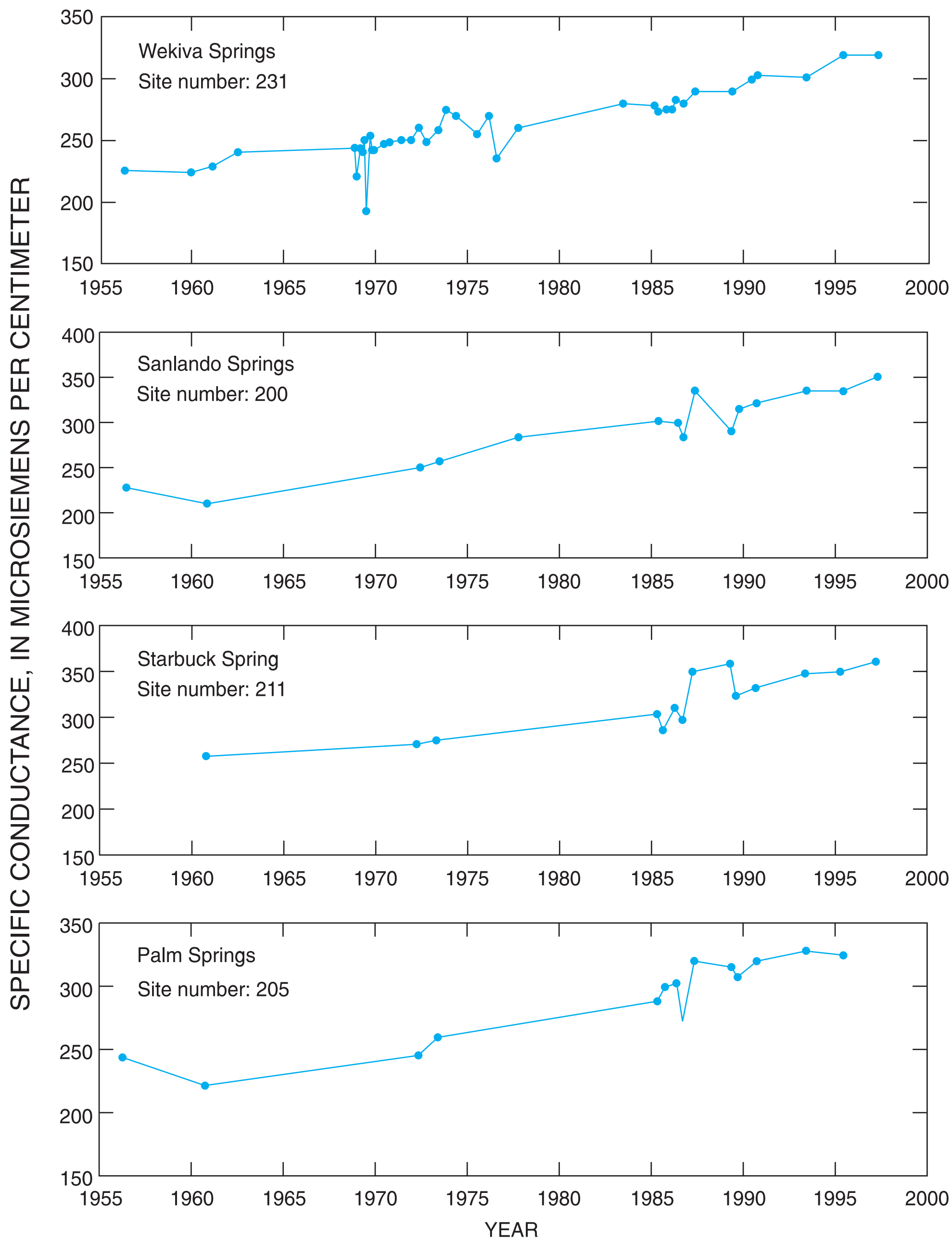


Figure 33. Specific conductance in water from selected springs discharging from the Upper Floridan aquifer (spring locations shown in figure 3).

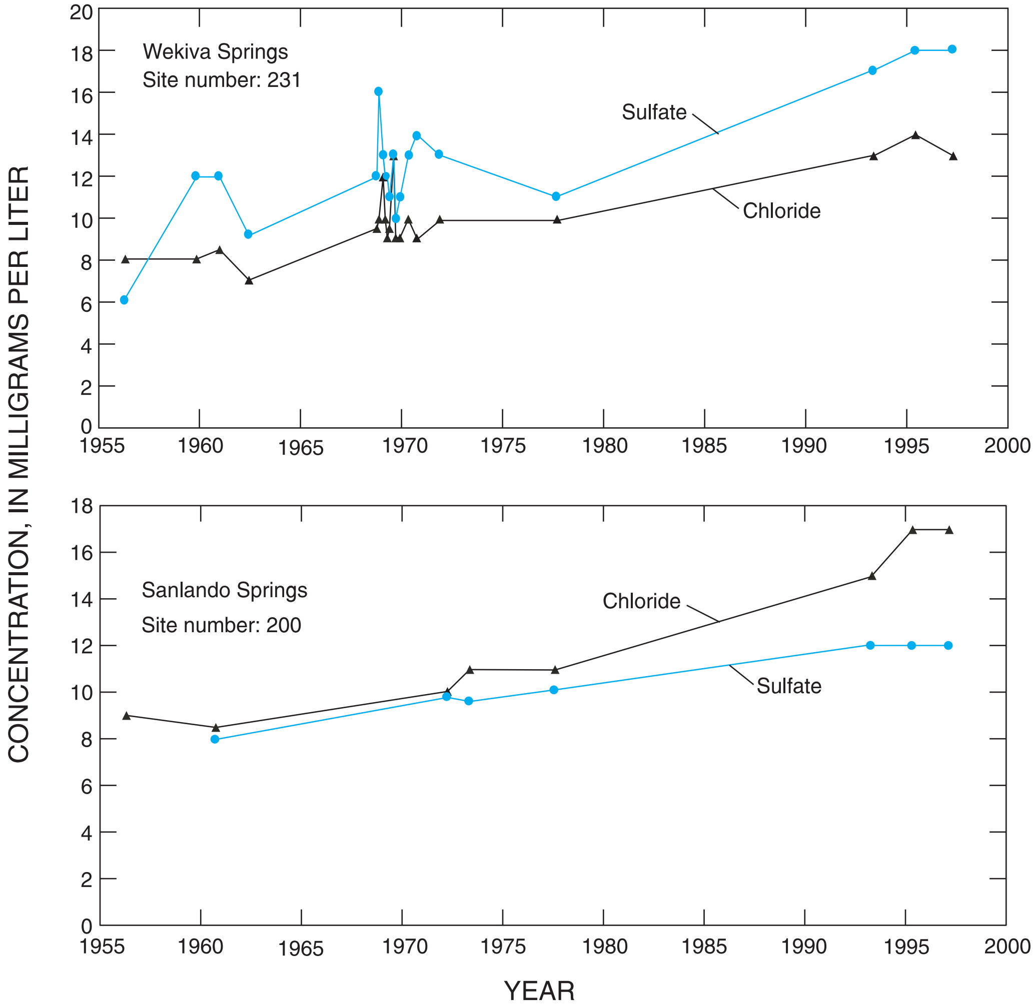


Figure 34. Chloride and sulfate concentrations in water from Wekiva and Sanlando Springs (spring locations shown in figure 3).

At Wekiva Springs, chloride concentration increased from 8 to 13 mg/L and at Sanlando Springs, chloride concentrations increased from 9 to 17 mg/L. Sulfate concentration in water from Wekiva Springs increased from 6 to 18 mg/L and at Sanlando from 8 to 12 mg/L.

There are two possible explanations for the observed increase in mineralization of spring water. The first is the upward movement of saltwater into fresher water-bearing zones within the Upper Floridan aquifer. If upconing were occurring, then the transition zone between fresh and saltwater would be moving upward, and chloride concentrations would be expected to increase with depth. However, data from two wells indicate otherwise. An examination of the water quality of an Upper and Lower Floridan aquifer well near Wekiva Springs shows that less mineralized (and older) Lower Floridan aquifer water underlies more mineralized Upper Floridan aquifer water (Toth, 1999, p. 24, 60). Therefore, the observed increase in mineralization of spring water near Wekiva Springs (and other nearby springs experiencing increasing mineralization) is likely from a shallower source and not from deeper zones of the aquifer.

The second possible explanation for the increase in the mineralization of spring water could be related to the observed increase in the total nitrate-plus-nitrite as nitrogen concentrations since the mid 1970ís. Increasing total nitrate-plus-nitrite as nitrogen concentrations have been observed at seven springs in the study area having long-term observations (Wekiva, Rock, Sanlando, Starbuck, Palm, Seminole, and Gemini (Toth, 1999)), six of which are shown in figure 35. Total

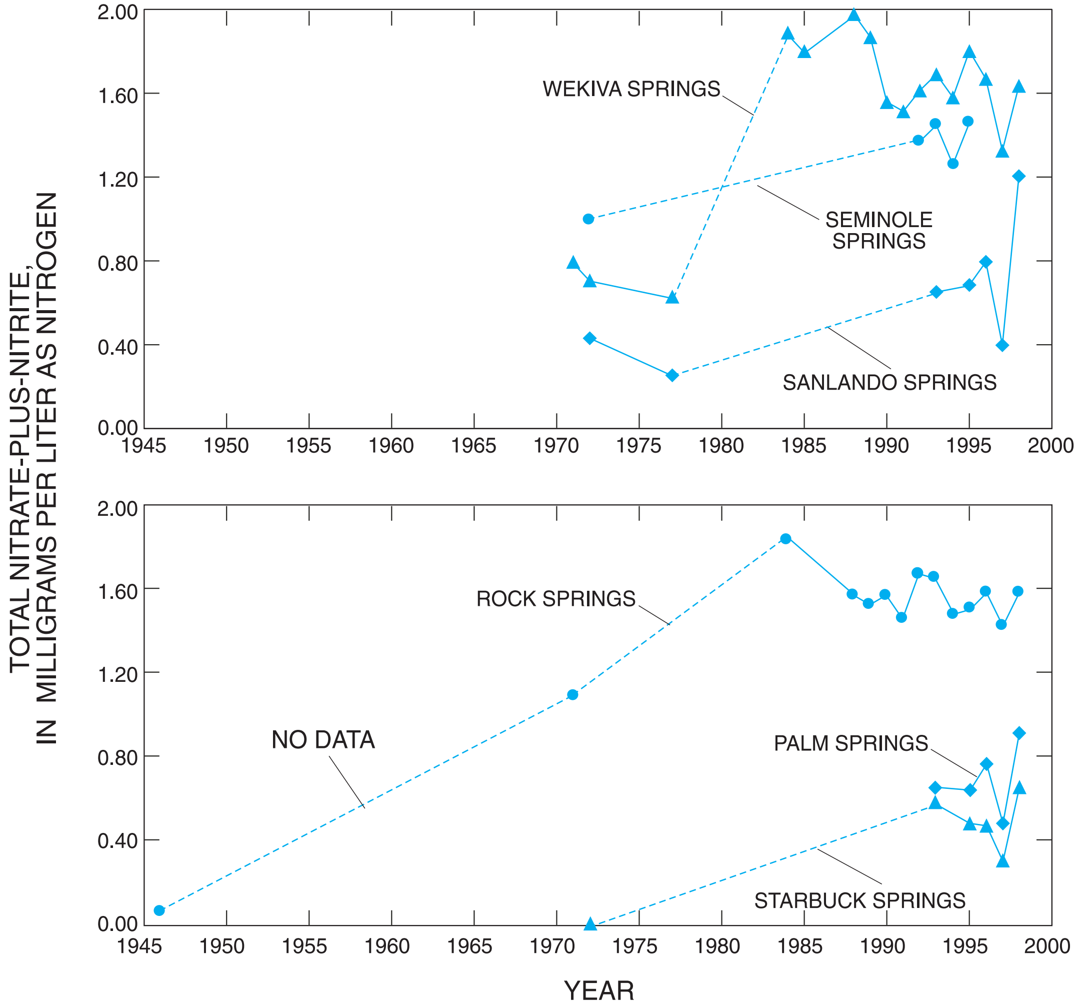


Figure 35. Average annual total nitrate-plus-nitrite as nitrogen concentrations in selected Upper Floridan aquifer springs (spring locations shown in figure 3) (D. Toth, SJRWMD, written commun., 1999).

nitrate-plus-nitrite as nitrogen concentrations exceed 0.2 mg/L at all of these springs, with concentrations exceeding 1.60 mg/L at Wekiva and Rock Springs (D. Toth, SJRWMD, written commun., 1999). The primary drinking water standard for nitrate-nitrogen is 10 mg/L as nitrogen (Florida Department of State, 1989).

The presence of elevated levels of nitrate-plus-nitrite in spring water could be an indication of contamination from fertilizers, animal waste, or septic tanks. These sources also can contain chloride and sulfate, which could account for the increase in specific conductance and chloride and sulfate concentrations. Recharge water containing these constituents can enter the Upper Floridan through breaches in the intermediate confining unit caused by sinkholes or where the confining unit is thin or missing. Nitrates are readily transported in water and are stable over a considerable range of conditions (Hem, 1986, p. 124). The presence of elevated levels of nitrate-plus-nitrite in spring water suggests a significant contribution to spring discharge from shallow to intermediate flow paths (Toth, 1999, p. 23).

WATER BUDGET

A water budget accounts for the total amount of water within the study area and can be used to provide limits for recharge rates estimated during model calibration. A long-term water budget (1970-96) for the study area is shown in figure 36 and can be described by the following equations:

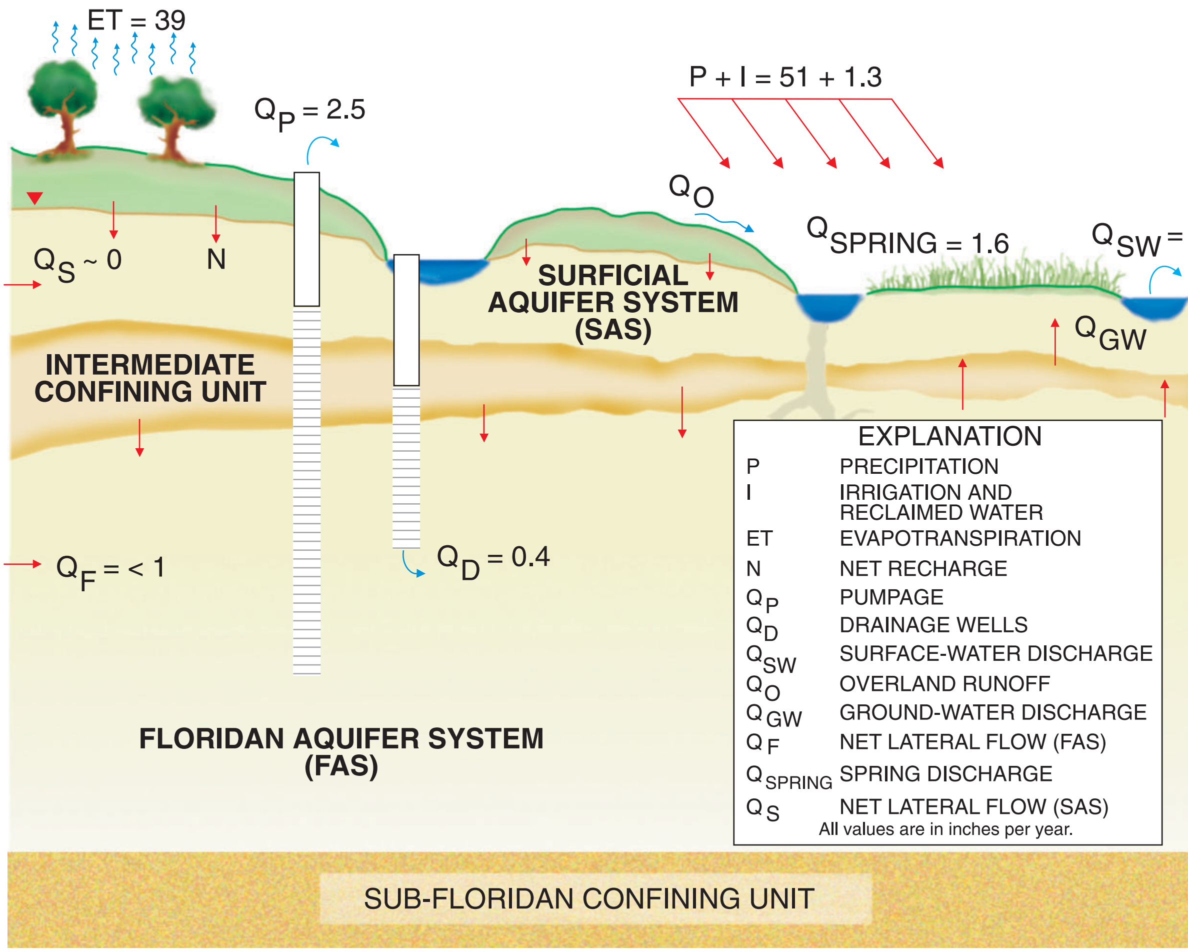


Figure 36. The long-term water budget and its components in the study area.

$$(P + I + Q_F + Q_S) \text{ ñ } (Q_{SW} + Q_P + ET) = \Delta S \cong 0, \quad (1)$$

$$Q_{sw} = Qo + Qspring + Q_{GW}\text{, and} \quad (2)$$

$$P + I = N + ET + Qo + Q_D\text{,} \quad (3)$$

where

- P is precipitation, in inches per year;
- I is irrigation and reclaimed water, in inches per year;
- N is net recharge to the water table, in inches per year;
- Q_D is inflow to drainage wells, which is a subcomponent of precipitation and irrigation;
- Q_{SW} is surface-water discharge, in inches per year;
- Q_O is overland runoff, which is a subcomponent of Q_{SW};
- Q_{SPRING} is spring discharge, which is a subcomponent of Q_{SW};
- Q_{GW} is ground-water discharge, which is a subcomponent of Q_{SW};
- Q_P is pumpage from the Floridan aquifer system, in inches per year;
- Q_S is lateral flow (net) in the surficial aquifer system that flows into the study area and is assumed to be negligible, in inches per year;
- Q_F is lateral flow (net) in the Floridan aquifer that flows into the study area, in inches per year;
- ET is evapotranspiration, in inches per year; and
- ΔS is change in storage, in inches per year, and is assumed to be negligible over the period used to estimate a long-term water budget (1970-96).

Inflows to the study area include precipitation, irrigation, and reclaimed water (fig. 36). Precipitation is the dominant and most variable source of water. Mean annual rainfall for the study area from 1970-97 was about 51 in/yr, and from September 1996 through August 1997 was about 52 in/yr. The application of irrigation water pumped from the Floridan aquifer system adds about 1.3 in/yr to the surficial aquifer system in the study area, but because of the localized nature of irrigation, application rates at individual sites are considerably higher than the average rate. Drainage wells redirect about 0.4 in/yr from precipitation and irrigation to the Upper Floridan aquifer.

Outflows from the study area include surface-water discharge, pumpage, lateral flow through the Floridan aquifer system, and evapotranspiration (fig. 36). Surface-water discharge removed an average of 11 in/yr between 1970-96. Pumpage removed an average of 2.5 in/yr from 1970-96 and 3.4 in/yr in 1996-97. Lateral flow (net) through the Floridan aquifer in the study area is less than 1 in/yr (Murray and Halford, 1996). In order to balance the water budget, evapotranspiration was estimated to be about 39 in/yr (fig. 36).

Discharge per unit area from the four major surface-water basins that drain the study area is spatially variable. The long-term average unit discharges from the Ocklawaha, Kissimmee, St. Johns River, and Coastal basins (fig. 1) are 3, 6, 14, and 12 in/yr, respectively. The Ocklawaha and upper Kissimmee basins are topographically high basins with extensive internally drained areas. The relatively low unit discharges from the Ocklawaha and upper Kissimmee basins suggest that most precipitation infiltrates and leaves the basins as lateral flow through the Floridan aquifer system. The relatively high unit discharge from the St. Johns River basin could be caused both by reduced infiltration and the discharge of ground water that originated in other basins. The Coastal basin covers only 4 percent of the study area and is not important to the overall water budget.

Separation and identification of many of the components in the water budget are difficult because many subcomponents are intertwined within each measurable component. Evapotranspiration removes water from plant canopies, depression storage, soil moisture, the saturated ground-water system, and surface-water features. Surface-water discharge is the sum of overland runoff and ground-water discharge minus evapotranspiration losses from stream and riparian areas. Drainage wells receive water from precipitation, irrigation, overland runoff, and ground-water discharge from the surficial aquifer system.

Recharge to the water table (N) is the subcomponent of the water budget that drives ground-water flow through the surficial and Floridan aquifer systems (fig. 36), and cannot be defined easily from equation 1. The surficial aquifer system is recharged when the amount of applied water exceeds evapotranspiration losses and overcomes capillary effects in the unsaturated zone. Overland runoff (Q_O) occurs when the infiltration capacity of the soil is exceeded and additional precipitation or applied irrigation water drains directly to local streams or depressions without infiltrating the subsurface, or when the water table intercepts land surface in topographically low areas. Of the applied water that reaches the water table, recharge (N) is the fraction that is not immediately extracted by evapotranspiration and moves downgradient. Natural discharge from the surficial and Floridan aquifer systems occurs as evapotranspiration or flow to streams.

Recharge usually is indirectly estimated as a calibration parameter in a ground-water flow model because of the complexity and interdependence of the processes that control it. Recharge rates have been estimated in this manner at the former Orlando Naval Training Center and for the Reedy Creek area (fig. 1), about 5 and 25 miles south of Seminole County, respectively. Average recharge rates were estimated to be 19 in/yr in the former Orlando Naval Training Center (Halford, 1998a) and 5 to 25 in/yr for the Reedy Creek area (OíReilly, 1998). These estimates are for areas without artificial recharge sites, where locally induced rates can exceed 1,000 in/yr.

The water-budget analysis provides a general idea of how much water passes through the surficial and Floridan aquifer systems, but cannot indicate what fraction of flow passes through each individual aquifer. The direction and rate of the movement of water also cannot be determined through a water-budget analysis. A ground-water flow model can help address these more specific questions.

SIMULATION OF GROUND-WATER FLOW IN THE SURFICIAL AND FLORIDAN AQUIFER SYSTEMS

The conceptual model and hydrologic data discussed in the previous sections were used to construct a three-dimensional numerical ground-water flow model of the surficial and Floridan aquifer systems. The McDonald and Harbaugh (1988) modular finite-difference model (MODFLOW) was used to simulate flow in the surficial and Floridan aquifer systems and to solve the governing equation:

$$\nabla \cdot (Kb\nabla h) + q + N = S\frac{\partial h}{\partial t}, \qquad (4)$$

where

- ∇ is del, the vector differential operator;
- K is hydraulic conductivity, in feet per day;
- b is saturated thickness, in feet;
- h is hydraulic head, in feet;
- q is a source or sink, in feet per day;
- N is the net recharge, in feet per day;
- S is storage coefficient in confined aquifers and the specific yield in unconfined aquifers, dimensionless; and
- t is time, in days.

A steady-state numerical model of the ground-water flow system was constructed and calibrated to time-average data for the period September 1996 through August 1997. Time-averaged data were used in the calibration because data needed to define long-term historical changes in ground-water levels, pumpage, and recharge within the study area were not available. The September 1996 through August 1997 period was used because most of the water-level and water-use data were collected in the study area during this time.

Estimates of all model-parameter values, fluxes, and boundary conditions were made to construct the initial model. A systematic sensitivity analysis of model response to changes in each parameter value and boundary conditions was then made. Calibration of the model consisted of making changes to parameters and boundary conditions and focusing on the most sensitive parameters until the best fit between model-simulated and measured ground-water levels and fluxes was obtained.

Description of the Ground-Water Flow Model

To implement a finite-difference model, the study area was discretized into a rectangular grid of cells by row and column. The active model grid covered an area of about 2,500 mi^2 and was divided into 137 rows of 195 columns (fig. 37). The model cells ranged in area from 0.034 to 9.8 mi^2 and the largest cells were in peripheral areas away from Seminole County. Seminole County was discretized into uniform square cells of a 1,000 ft on a side. Of the 80,145 model cells, 13,321 cells were inactive outside the study area.

The grid was oriented along a north-south axis. Neither a majority of known stresses nor boundary conditions were aligned along any particular axis. No measurements of anisotropy were available and a lateral anisotropy ratio of 1:1 was used for simulation. Values of aquifer and confining-unit hydraulic properties were assigned to the center of each cell, defined as a node, by interpolation from observed point values.

The model was vertically discretized into three active layers to simulate the surficial (layer 1), Upper Floridan (layer 2), and Lower Floridan (layer 3) aquifers (fig. 9). Vertical impedance to flow between aquifers was simulated by assigning leakance values at each cell between model layers. The leakance represented the average vertical hydraulic conductivity of the confining unit material between layers divided by the thickness of the confining unit and was in units of feet per day per foot (1/d).

Previous models (Tibbals, 1990; Murray and Halford, 1996) have treated the Upper Floridan aquifer as a single active layer. More recent hydrogeologic information suggests that the Upper Floridan aquifer may be better simulated by two layers to better approximate the hydraulic conductivity contrast between zones A and B. Assigning the appropriate open interval for many of the observation and production wells that are classified as Upper Floridan, however, is difficult because the top and bottom of the open interval are unknown. Also, the middle semiconfining unit could be simulated as an active layer because the hydraulic properties of the middle semiconfining unit are similar to zone A of the Upper Floridan aquifer.

Hydraulic Properties

The hydraulic conductivity distribution of the surficial aquifer system (layer 1) was defined by an eastern area and a western area. The divide between the two areas generally was based on the eastern extent of the Mt. Dora Ridge (fig. 37). A uniform hydraulic conductivity of 5 ft/d was assigned to the eastern area and was estimated from the geometric mean of 21 slug tests conducted in Seminole County during the study (table 1). A uniform hydraulic conductivity of 30 ft/d was assigned to the western area based on estimates from OíReilly (1998). The estimates of OíReilly (1998) were for the area south of Lake Apopka. The initial hydraulic conductivity distribution was not changed throughout model calibration because the data were insufficient to identify spatial trends and could not be correlated to mappable features such as land cover, lithology, or topography.

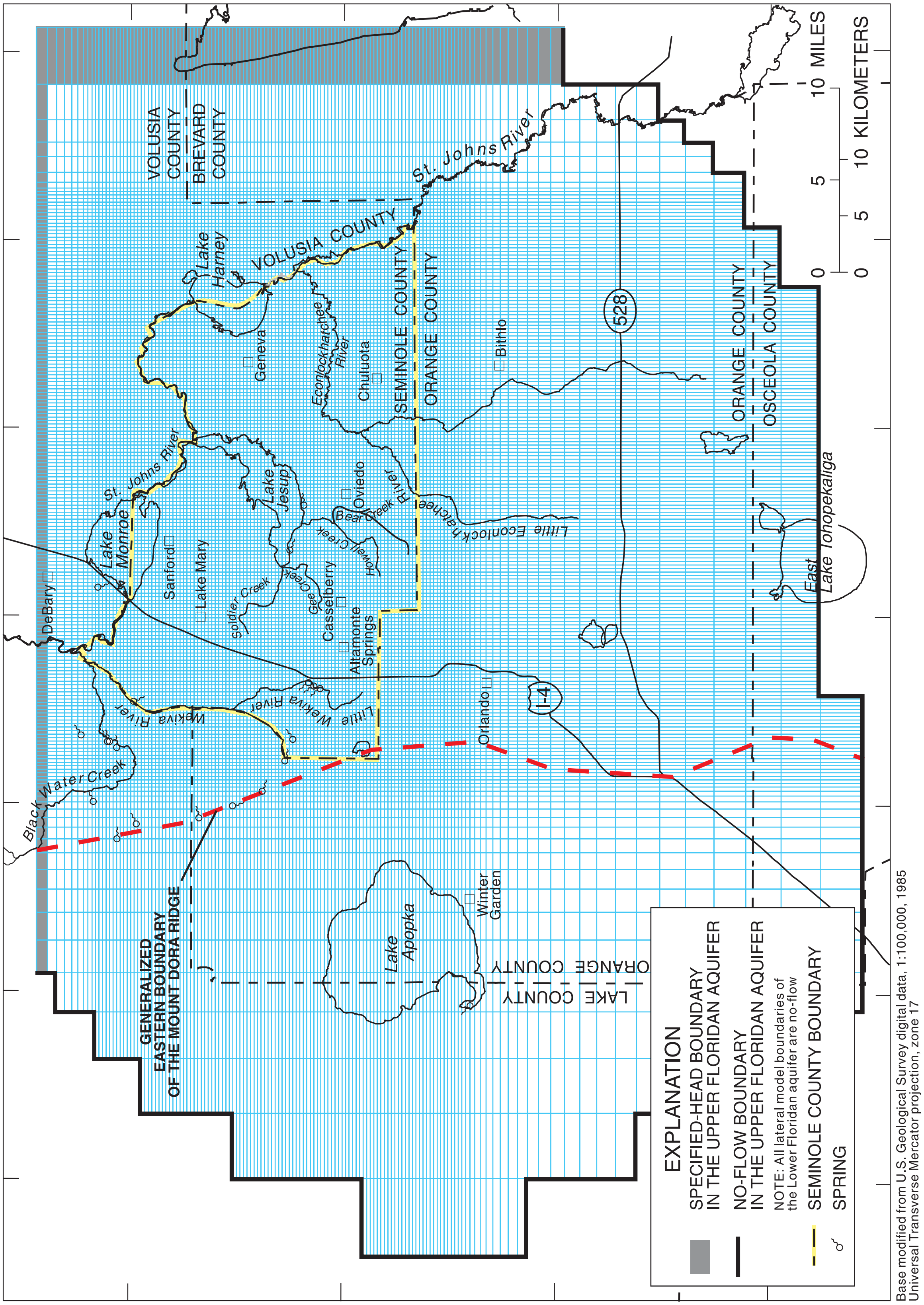


Figure 37. Maximum extent of finite-difference grid and lateral model boundaries.

Transmissivity estimates for the Upper Floridan aquifer were converted to horizontal hydraulic conductivity to make use of the numerous partially penetrating aquifer tests. Transmissivity estimates from aquifer tests with a producing well that penetrated 65 percent or less of the Upper Floridan aquifer were assumed to be estimates for zone A. Results from other Upper Floridan aquifer tests were assumed to be estimates for zones A and B. Based on available flow logs, the hydraulic conductivity of zone B was estimated to be 10 times greater than the hydraulic conductivity of zone A. The 1:10 hydraulic conductivity ratio and the 65 and 35 percent division of total thickness between zones A and B were assumed to exist throughout the study area. The thickness of the Upper Floridan aquifer was defined to be the difference between the altitudes of the top of the Upper Floridan aquifer (fig. 16) and the top of the middle semiconfining unit (Miller, 1986).

Estimation of horizontal hydraulic conductivity from aquifer tests for the Upper Floridan aquifer is best illustrated by example. A transmissivity value of 17,000 ft^2/d was estimated at site 278 from an aquifer test of a well that was open to about 18 percent of the 380 ft thickness of the Upper Floridan aquifer. A horizontal hydraulic conductivity value of 69 ft/d was estimated for zone A by dividing 17,000 ft^2/d by 247 ft (65 percent of 380 ft). A transmissivity value of 168,000 ft^2/d was estimated near site 135 from an aquifer test of a well that was open to the entire 360 ft thickness of the Upper Floridan aquifer. Transmissivity estimates of 26,000 and 142,000 ft^2/d were estimated for zones A and B, respectively, because of the 1:10 hydraulic conductivity ratio and the fact that zone A makes up 65 percent and zone B 35 percent of the total thickness of the Upper Floridan aquifer. Horizontal hydraulic conductivity values of 113 and 1,130 ft/d were estimated by dividing transmissivity estimates by the thickness of zones A (234 ft) and B (126 ft), respectively.

Additional transmissivity estimates for the Upper Floridan aquifer were made by applying the Thiem equation to Island, Rock, Sanlando, Seminole, and Wekiva Springs. The springs were assumed to be fully penetrating wells with radii that ranged from 2 to 20 ft for the purposes of estimating transmissivity. The head loss from the spring pool was assumed to range from about 0 to 1 ft. The maximum transmissivity estimate for each spring ranged from three to five times the minimum estimate. For example, the transmissivity estimates for Wekiva Spring ranged from 300,000 to 1,300,000 ft^2/d, and were assumed to be for zones A and B, respectively.

Despite the range of uncertainty, estimates of transmissivity from springs were useful because they were consistently greater than estimates interpolated from aquifer tests for springs with discharges in excess of 5 ft^3/s. Interpolated transmissivity estimates from aquifer tests ranged from about 15,000 to 70,000 ft^2/d at the springs. Transmissivity estimates from the Thiem analyses were proportional to spring discharges within the range of uncertainty and were extrapolated to the springs with discharges greater than 0.5 ft^3/s (table 3). The assigned transmissivity estimates for the springs ranged from 18,000 (Palm Spring in Lake County) to 800,000 ft^2/d (Wekiva Spring).

The initial transmissivity estimates of the Upper Floridan aquifer for the model were generated in steps to account for observed lithologic and water-quality changes. Horizontal hydraulic conductivity values for zones A and B were estimated by inverse-distance weighted interpolation from the point estimates of log (K). The transmissivity of each zone was then calculated to be the product of the horizontal hydraulic conductivity multiplied by the zone thickness. In the part of the Upper Floridan aquifer that contains freshwater (layer 2), the transmissivity was thus the sum of zones A and B transmissivities. Freshwater was defined as water containing less than 5,000 mg/L chloride concentration. The part of the aquifer containing salt water (greater than 5,000 mg/L chloride concentration) is not considered to be part of the flow system in this study as has been done in previous investigations (Tibbals, 1990). Thus, transmissivity is lower than would be the case if the entire Upper Floridan aquifer contained freshwater.

The initial transmissivity distribution of the Lower Floridan aquifer (layer 3) was defined as the thickness of the aquifer in areas where the aquifer contained water with a chloride concentration of less than 5,000 mg/L multiplied by a uniform horizontal hydraulic conductivity of 400 ft/d. The thickness of the Lower Floridan aquifer containing water with a chloride concentration less than 5,000 mg/L is about 1,000 ft throughout the western half of the study area and thins to 0 ft in a 5- to15-mile-wide band in the middle of the study area (fig. 18). The horizontal hydraulic conductivity estimates for the Lower Floridan aquifer ranged from 200 to 900 ft/d, assuming an aquifer thickness of 1,000 ft. A uniform value was assumed for the model because no spatial trend could be inferred from the tests, and the range of horizontal hydraulic conductivity estimates at individual sites was similar to the range of estimates over the study area (fig. 18).

The initial areal distribution of leakance between layers 1 and 2 was calculated by dividing a preliminary estimate of vertical hydraulic conductivity of the intermediate confining unit (0.01 ft/d) by the estimated thickness of the unit (fig. 14). The initial areal distribution of leakance between layers 2 and 3 was calculated by multiplying the thickness of the middle semiconfining unit (Miller, 1986) by a vertical hydraulic conductivity value of 0.5 ft/d estimated from aquifer tests (Boyle Engineering Corporation, 1995).

Surface-Water Features

The distribution and altitude of surface-water features control the direction and rate of ground-water flow in the surficial and Floridan aquifer systems. Ground-water movement through the surficial aquifer system clearly is affected by surface-water features at a horizontal scale of less than the highest resolution (smallest grid node) simulated (1,000 ft). Ground-water movement through the Floridan aquifer system is affected predominantly by a few major surface-water features such as the St. Johns River and Lake Apopka.

Lakes, streams, and wetlands in Seminole County and parts of adjacent Orange County were simulated explicitly. Only streams that appeared on 1:100,000 scale maps and lakes with areas that were greater than half of the area of the smallest model cell (500,000 ft^2) were simulated (fig. 38). The elevations of the lakes and streams were determined from lake stage data, river gaging sites, and 1:24,000 scale U.S. Geological Survey topographic quadrangle sheets.

Interaction between the surficial aquifer system and lakes, streams, and wetlands was simulated by using the RIVER package of MODFLOW. The simulated flow rate in or out of the aquifer at a RIVER node was defined by:

$$Q_B = C_{RB}(H_{RIVER} - H_{AQUIFER}), \qquad (5)$$

where

Q_B is the discharge rate, in cubic feet per day;
C_{RB} is the hydraulic conductance of the riverbed or lakebed, in feet squared per day;
H_{RIVER} is the stage of the river or lake, in feet; and
$H_{AQUIFER}$ is the head in the aquifer beneath the river or lake, in feet.

Equation 5 applies only if $H_{AQUIFER}$ is greater than or equal to the assigned elevation of the bottom of the surface-water feature.

The river nodes were assigned as specified heads and were used primarily to facilitate record keeping. A riverbed hydraulic conductance of 100 times the river-reach length per cell was used for all river nodes. The results of model simulations of similar aquifer conditions at Cecil Field Naval Air Station near Jacksonville (Halford, 1998b) indicated that model results would not be sensitive to changes in riverbed conductance. The ground-water flow model constructed for the Cecil Field Naval Air Station was insensitive to increasing riverbed conductance. Estimates of riverbed conductance were highly correlated with estimates of horizontal hydraulic conductivity of the surficial aquifer system, a more sensitive parameter than the riverbed conductance. This implies that the interaction between surface water and the surficial aquifer system is controlled by the hydraulic conductivity of the surficial aquifer system, rather than by the riverbed conductance.

A total of 4,092 RIVER nodes was assigned to layer 1, of which, 1,743 nodes simulated lakes within the study area. The river-bottom elevation for all streams was set equal to the river stage to ensure that all simulated reaches were either gaining flow or were inactive. This constraint was imposed because digitized reaches in the headwaters of a stream may represent a dry channel. For lakes, the lake bottom was set far below the elevation of the water surface so that water could be gained or lost from these features.

Closed-basin lakes with measured stages were simulated as RIVER nodes during model calibration because the stage was known with more certainty than the lake water budget. The water budget of a closed-basin lake is affected by precipitation, overland runoff, and evaporation, in addition to ground-water interaction. A closed-basin lake is expected to be a net source of recharge to the surficial aquifer system because precipitation usually exceeds evaporation within the study area, and all overland runoff discharges to the lake.

Closed-basin lakes were converted to active lakes in the calibrated model. An active lake is an area with a specified flux at the water table and high lateral hydraulic conductance values within the lake that allows for the simulation of lake-level changes in response to variations in projected ground-water pumpage. The conversion from RIVER nodes to active lakes was accomplished by removing the RIVER nodes within a lake, specifying high hydraulic conductance values among all of the nodes within a lake, and specifying the ground-water flux across the lakebeds to be equal to rates estimated during model calibration. The hydraulic conductance values among all of the nodes within an active lake were set to 100,000 times the values estimated from the calibration runs by using the VAR1 package (Halford, 1998c).

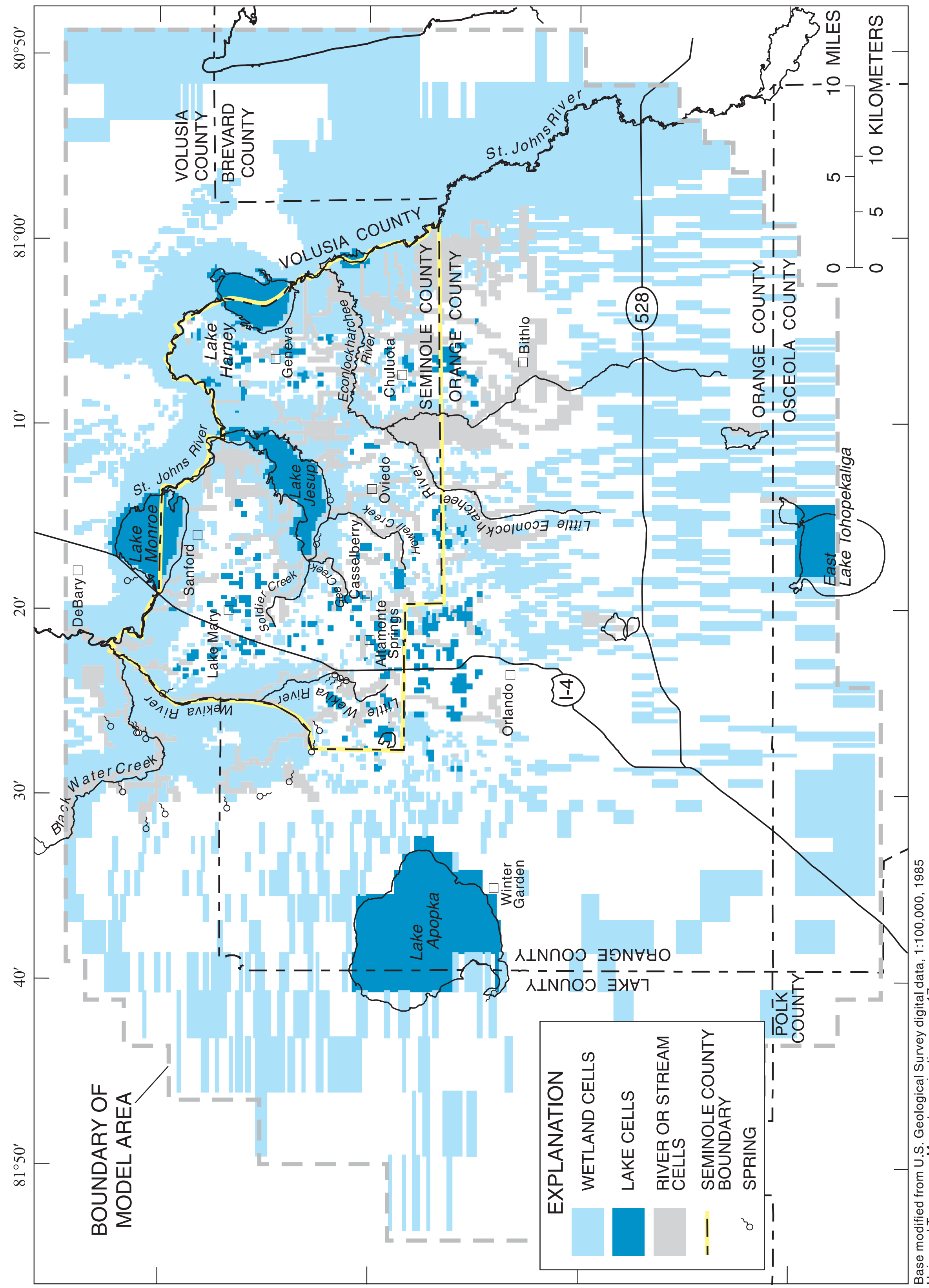


Figure 38. Location of river, lake, and wetland cells.

All areas that were not simulated as a lake or stream were assigned drains with high conductance values and outlet heads set at a specified water-table elevation. The specified elevation of the water table was approximated by using a multilinear regression among the measured levels in surficial aquifer system wells, land surface elevation, and the ìminimum water tableî (N. Sepulveda, USGS, written commun., 2000). The ìminimum water-tableî surface was generated by interpolating between measured and estimated stages of lakes and streams. Land surface elevations were estimated from digital hypsography provided by the SJRWMD. The root-mean-square residual between measured and linearly regressed water-table elevations was 4.05 ft.

If the simulated water table rises to the regressed surface, the drains behave as specified heads and simulate the removal of water from the surficial aquifer system (layer 1); otherwise no water is removed from the surficial aquifer system. Conceptually, active drain nodes simulate the effects of either limited recharge, net evapotranspirative losses, or ground-water discharge to surface-water features where the water table is within a few feet of land surface. Elsewhere, the drains are a means of estimating the net recharge while constraining the water table. The St. Johns River and adjacent wetlands were simulated with drains because that area is a broad ground-water discharge area with little variation in topography (fig. 38).

The net recharge to the calibrated model was estimated by subtracting the drain discharge from the applied recharge and was set to 0 where drain discharge exceeded applied recharge. Only drains that discharged at rates in excess of the applied recharge rate and were in locations of ground-water discharge were retained in the calibrated model. For example, a site with 25 in/yr of applied recharge and 15 in/yr of water discharged to a drain would be assigned a net recharge of 10 in/yr and the drain would be removed from the calibrated model. Another site with 25 in/yr of applied recharge and 35 in/yr of water discharged to a drain would be assigned a net recharge of 0 in/yr and the drain would be retained in the calibrated model.

Pumpage and Spring Discharge

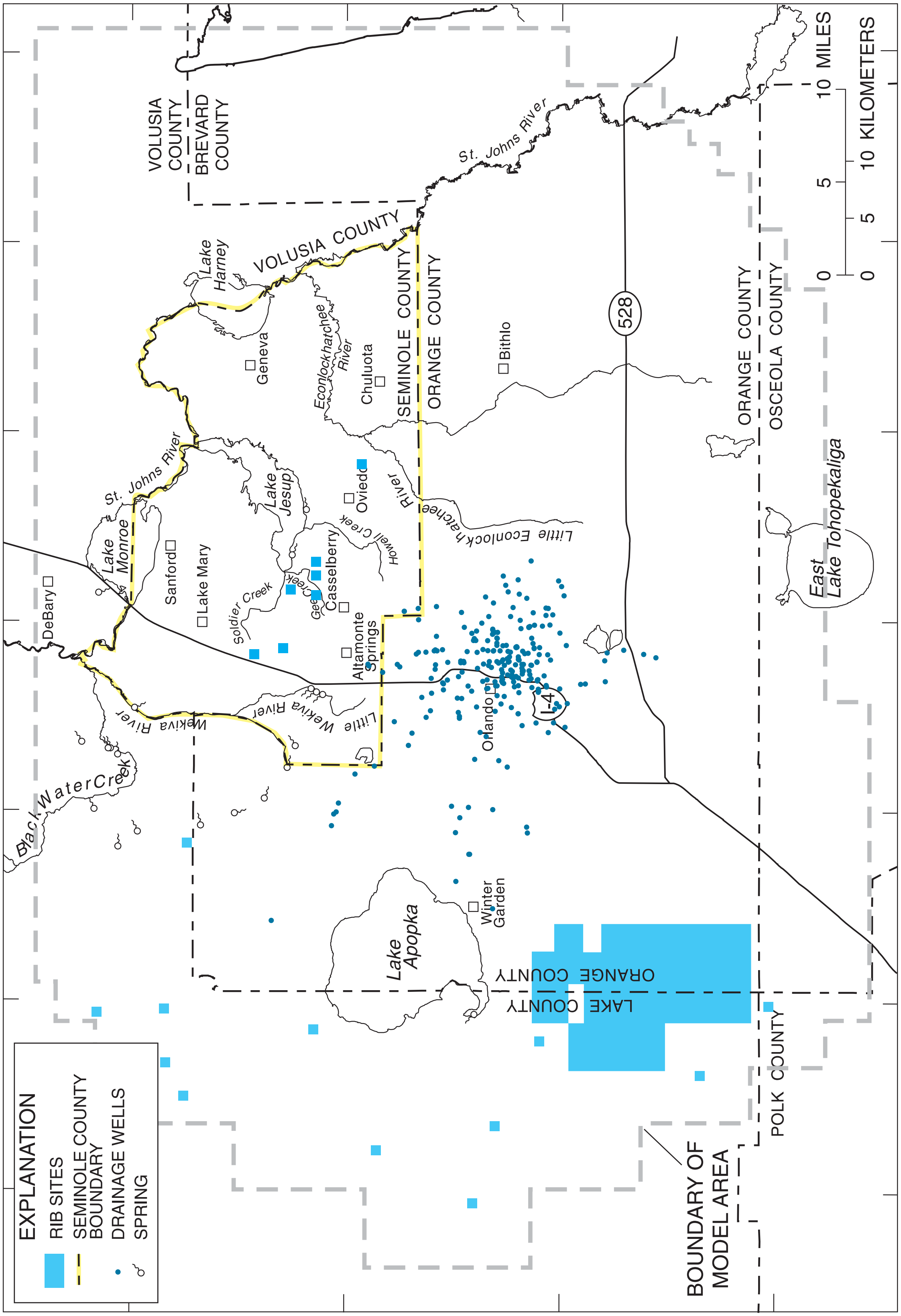
Pumpage and spring discharge are highly focused stresses that remove water directly from the Upper Floridan and Lower Floridan aquifers. The discharge from wells that is pumped at rates greater than 0.1 Mgal/d (0.16 ft^3/s) and springs that typically flow at rates greater than 0.65 Mgal/d (1 ft^3/s) were either measured or estimated during the study period. The cumulative discharge from these wells and springs was estimated to be 578 Mgal/d (894 ft^3/s). The combined discharge from springs and wells that exceeded 0.5 Mgal/d was 428 Mgal/d (662 ft^3/s), which represents 74 percent of the total pumpage and spring discharge within the study area. Pumpage from all sites shown in figures 7 and 8 was simulated as specified discharges.

A few wells in the study area are open to both the Upper Floridan and Lower Floridan aquifers. In the model, pumpage from these wells was apportioned equally from each aquifer without regard to transmissivity or water-level differences. Due to the water-level differences that can exist between producing zones, the flow contribution from each zone is not necessarily proportional to the transmissivity of each zone (Bennett and others, 1982). For example, if a well is screened through two aquifers with identical transmissivities, a higher potentiometric surface in one aquifer can cause more water to be contributed from that aquifer than from the other. The water-level differences between aquifers can induce cross flow between aquifers even when there is no discharge from the well, as occurs between the Upper Floridan and Lower Floridan aquifers. The error resulting from this distribution of pumpage probably did not greatly affect model calibration because the pumpage from these wells (15 Mgal/d) was small relative to the total pumpage (386 Mgal/d).

The rates of spring discharge from the Upper Floridan aquifer are generally well known. Thus, springs were simulated as specified discharges using the drain package. Simulated water levels in the Upper Floridan aquifer were constrained to be greater than 1 ft above the spring pool elevation to ensure discharge to the drain cell. The drain conductance was estimated for each spring cell by dividing the known discharge for the spring by the difference between the spring pool elevation and the simulated head in the Upper Floridan aquifer (initially, this was estimated to be 1 ft).

Reclaimed Water and Drainage Wells

Reclaimed water is distributed to RIB sites and spray irrigation fields in the study area. All of the 48.5 Mgal/d (75 ft^3/s) of reclaimed water that was applied to RIB sites in Seminole, Orange, and Lake Counties (fig. 39) during the simulation period was assumed to be direct recharge to the surficial aquifer system (layer 1). Reclaimed water that was used as spray irrigation was assumed to affect recharge rates to the surficial aquifer system and is simulated by higher recharge rate estimates. The spray irrigation was not simulated directly and the locations of these sites are not shown in figure 39.



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

Figure 39. Location of rapid infiltration basin (RIB) sites and drainage wells in the Upper Floridan aquifer.

An effort was made during preliminary model calibration to estimate the maximum recharge rate in spray irrigation areas in Seminole County, independently from the maximum natural recharge rate throughout the rest of the model domain. This approach was abandoned because the model was not very sensitive to the zones where recharge was potentially affected by spray irrigation. The lack of sensitivity was due both to a relative lack of surficial observation wells and the coarse (1,000 ft by 1,000 ft) discretization of the surficial aquifer system.

Drainage wells were estimated to add 45.6 Mgal/d (70.6 ft^3/s) directly to the Upper Floridan aquifer in Orange and Seminole Counties. The injection of water from drainage wells was simulated as specified inflows at the locations shown in figure 39.

Boundary Conditions

Proper representation of model boundary conditions is one of the most important aspects in the simulation of an aquifer system. Model boundaries are assigned to represent the actual hydrologic boundaries as accurately as possible. If model boundaries are generalized, they are placed far enough away from the influence of hydrologic stresses in the model area to minimize their influence on simulation results.

The upper boundary of the model is the water table. At lakes, streams, and wetlands, this upper boundary was simulated using the RIVER package, as described previously. In the remaining areas of the model, the upper boundary was simulated in one of two ways because of different needs and constraints during calibration and prediction. For calibration, water-table elevations generally were specified to be values obtained from regression analysis of measured water-table elevations. Measured water levels for the surficial aquifer were too few to constrain model calibration, and the regressed water levels were believed to better represent the water-table surface. For predictive scenarios, the water table was simulated as a free surface with recharge rates estimated during the calibration simulations.

Water-table nodes were constrained to the regressed water-table elevations by using drain nodes during model calibration. A spatially uniform maximum recharge rate of 25 in/yr, except at RIB sites, was applied to this boundary in all calibration simulations. The maximum rate was estimated to be the difference between precipitation (52 in/yr) and an assumed minimum evapotranspiration rate (27 in/yr; Sumner, 1996). The applied recharge rate represented the maximum rate for the study area because water was rejected at nodes where the water table was near or at the regressed water-table surface.

Net recharge rates estimated from the calibrated model were applied to the water-table nodes as specified fluxes for all of the predictive simulations. Net recharge rates were estimated by subtracting the drain discharge rate from the applied recharge rate and was set to 0 where drain discharge exceeded applied recharge. Only drains that discharged in excess of the applied recharge rate and that were in areas of ground-water discharge were retained in the predictive models.

The lateral boundary of the surficial aquifer system (layer 1) was simulated as a no-flow boundary because the distance from any ground-water divide to a surface-water feature in the surficial aquifer system is typically less than 1 mile. Because all of Seminole County lies more than 1 mile from the model edges, errors in the lateral boundary of the surficial aquifer system would be damped by an intervening surface-water feature and, therefore, would not affect simulated results in Seminole County.

The lateral model boundaries of the Upper Floridan aquifer (layer 2) were no-flow boundaries along the southern and western edges and specified-heads along the northern and eastern edges (fig. 37). The southern and western edges of the Upper Floridan aquifer were simulated as no-flow boundaries because a regional potentiometric-surface high exists in the southwestern corner of the study area, and the potentiometric surface of the Upper Floridan aquifer indicated that flow was nearly parallel to the boundaries (fig. 21). Flow did not cross these boundaries because no hydraulic gradient exists transverse to the boundaries. The northern and eastern edges of the Upper Floridan aquifer were simulated as specified heads because no natural boundary could be defined conveniently near the study area. The specified water-levels were an average of estimates along the boundary from September 1996 and May 1997 potentiometric surfaces.

The lateral model boundaries of the Lower Floridan aquifer (layer 3) were no-flow. The potentiometric surface of the Lower Floridan aquifer was assumed to be similar to the potentiometric surface of the Upper Floridan aquifer and similar lateral flow directions exist in both aquifers. The southern and western edges of the Lower Floridan aquifer also were simulated as no-flow boundaries because no hydraulic gradient was assumed to exist transverse to the boundaries.

The eastern boundary was assumed to be no-flow because it coincides with the freshwater/saltwater interface where the chloride concentration in water beneath the freshwater zone exceeds 5,000 mg/L.

The lower model boundary is simulated as a no-flow boundary throughout the study area, and is defined by water-quality constraints or the base of the Floridan aquifer system. In the eastern half of the study area, where chloride concentrations in water at the top of the Lower Floridan aquifer exceeds 5,000 mg/L, the bottom of the Upper Floridan aquifer (layer 2) was defined as the lower model boundary (figs. 17 and 18). In the middle of the study area, the lower model boundary was defined as the contact in the Lower Floridan aquifer where chloride concentrations exceed 5,000 mg/L. In the western half of the study area, the bottom of the Lower Floridan aquifer was the lower model boundary and was assumed to occur at about 2,000 ft below sea level.

Model Calibration

Calibration is the attempt to reduce the difference between model results and measured data by adjusting model input. Calibration was accomplished in this study by adjusting input values of recharge, transmissivity, and vertical leakance until an acceptable calibration criterion was achieved. The ì goodnessî or improvement of the calibration is based on the differences between simulated and measured ground-water levels and stream discharges. Simulated water levels and discharges from a calibrated, deterministic ground-water model commonly depart from measured water levels and discharges, even after a diligent calibration effort. The discrepancy between model results and measurements (model error) commonly is the cumulative result of simplification of the conceptual model, grid scale, and the difficulty in obtaining sufficient measurements to account for all of the spatial variation in hydraulic properties and recharge throughout the model area.

A steady-state, ground-water flow model was calibrated to time-averaged water-level data for the period September 1996 through August 1997. Water-level measurement frequency was either monthly or twice a year. Although water levels fluctuated about 4 ft during the course of the study period, the net change in storage was assumed to be small because the difference between beginning and ending water levels was about 0.5 ft. A uniform 0.5-ft water-level decline over the study period would result in water being released from storage at a rate of 1 in/yr if the specific yield was 0.2.

Calibration improvement was determined by decreases in the sum-of-squares (SS) error between simulated and measured water levels, which is defined by:

$$SS(x) = \sum_{i=1}^{nobs} (f(x)_i)^2 , \qquad (6)$$

$$f(x)_i = (\hat{h}(x)_i - h_i) , \qquad (7)$$

where

x is the vector of parameters being simulated;

nobs is the number of simulated and measured observations that are compared; and

$f(x)_i$ is the $i^{\underline{th}}$ residual which is the difference between the $i^{\underline{th}}$ simulated head ($\hat{h}(x)_i$) and the $i^{\underline{th}}$ measured head (h_i).

Although the sum-of-squares error serves as the objective function, the root-mean-square (RMS) error is reported instead because RMS error is more directly comparable to actual values and serves as a composite of the average and the standard deviation of a set. Root-mean-square error is related to the sum-of-squares error by

$$RMS = \sqrt{\frac{SS}{nobs}} . \qquad (8)$$

Observations

Water levels, water-level differences between aquifers, and ground-water discharge rates to streams and springs were compared. Only water-level values were included, however, in the objective function (eq. 6). Water-level differences between aquifers and ground-water discharge were compared qualitatively after model calibration.

A total of 290 water-level measurements were used to calibrate the model. Water levels in the surficial, Upper Floridan, and Lower Floridan aquifers were compared at 103, 146, and 41 locations, respectively. Measurements obtained from the supplementary surficial aquifer system wells listed in appendix 3 and from wells used by OíReilly (1998) were among the 290 measurements used. Because measured water levels rarely coincide with the center of a cell, simulated water levels were linearly interpolated laterally to points of measurement from the centers of surrounding cells. Simulated water levels were interpolated because they were assumed to be part of a continuous distribution. Vertical interpolation was not considered because of the uncertainty in the open interval of some of the observation wells and because of possible inconsistencies between the conceptual model and actual geohydrologic conditions.

Twenty-nine pairs of water-level differences between aquifers also were compared qualitatively to constrain leakance estimates. Eighteen pairs of water-level differences, mostly in Seminole County, were compared between the surficial and Upper Floridan aquifers. The remaining 11 pairs of water-level differences, located in Orange and Seminole Counties, were compared between the Upper Floridan and Lower Floridan aquifers.

Ground-water discharge, which was compared to measured stream-discharge, was simulated by summing the discharge from river, drain, and well nodes within a basin. The simulated discharge rates from all river nodes and from the wells that simulated spring discharge were summed in their entirety. Because drain nodes also simulate evapotranspiration losses, only discharge from drain nodes in excess of the applied recharge rate was assumed to be ground-water discharge. For example, a site with 25 in/yr of applied recharge and 15 in/yr of water discharged to a drain would be interpreted to have a net recharge of 10 in/yr and no ground-water discharge. Another site with 25 in/yr of applied recharge and 35 in/yr of water discharged to a drain would be interpreted to have no net recharge and a ground-water discharge of 10 in/yr.

Baseflow frequently is not equivalent to ground-water discharge because other hydrologic phenomena can significantly affect stream discharge during recession periods. The quantification of ground-water discharge by using stream-discharge records was ambiguous because drainage from bank storage, wetlands, surface-water bodies, and soils also decreased exponentially during recession periods. These hydrologic phenomena, as well as evapotranspiration, have been shown to affect stream discharge more than ground-water discharge during recession periods at sites in central and northeastern Florida (Halford and Mayer, 2000).

The range of ground-water discharge was estimated for each site with surface-water discharge records. The minimum ground-water discharge was the surface-water discharge during winter recession periods when riparian evapotranspiration was at a minimum. The minimum ground-water discharge estimate was recognized to be less than the expected minimum ground-water discharge because riparian evapotranspiration losses occur during the winter. The maximum ground-water discharge was estimated to be two to three times greater than the minimum ground-water discharge that was not supplied by springs. The ratios of maximum to minimum ground-water discharge (two to three) were estimated with the hydraulic properties of the surficial aquifer and recharge frequency (Halford and Mayer, 2000). These ratios (two to three) were subjectively increased to a single ratio of four to account for potential underestimation of the minimum ground-water discharge.

Comparisons between simulated and estimated ground-water discharges were performed differently from water-level comparisons because of the large uncertainty associated with the discharge estimates. At 14 gaged basins, minimum and maximum ground-water discharges were identified. Model calibration was affected only by simulated discharges that were less than the measured minimum discharge or greater than the measured maximum discharge. The residual was 0 if simulated discharge was within the range of the measured minimum discharge and maximum discharge.

Parameter Estimation

Model calibration was facilitated by a parameter estimation program (Halford, 1992). The parameter estimation process is initialized by using the model to establish the initial differences between simulated and measured observations. These differences, or residuals, are then minimized by the parameter estimation program. The sensitivity coefficients (the derivatives of simulated water-level change with respect to parameter change) are calculated by the influence coefficient method using the initial model results (Yeh, 1986) to implement parameter estimation. Each parameter is changed a small amount, and MODFLOW is used to compute new water levels for each perturbed parameter. The current arrays of sensitivity coefficients and residuals are used by a quasi-Newton procedure

(Gill and others, 1981, p. 137) to compute parameter changes that should improve the model. The model is updated to reflect the latest parameter estimates and a new set of residuals is calculated. The entire process of changing a parameter in the model, calculating new residuals, and computing a new value for the parameter is continued iteratively until model error or model-error change is reduced to a specified level or until a specified number of iterations are made.

A total of 11 parameters were defined relating to the vertical hydraulic conductivity of the confining layers, transmissivity or horizontal hydraulic conductivity of the aquifers, and surficial aquifer recharge arrays in the calibrated model (table 4). Values for 4 of the 11 parameters were specified *a priori* and were not estimated by model calibration. The parameters were used as global multipliers to change the hydraulic conductivity, transmissivity, and recharge estimates by fixed amounts throughout the study area. The vertical hydraulic conductivity of the intermediate confining unit and middle semiconfining unit were divided into multiple zones that were estimated with independent parameters. Final parameter estimates of most of the hydraulic properties were not dependent on initial parameter estimates.

The vertical hydraulic conductivity of the intermediate confining unit was divided into four broad areas based on the thickness of the intermediate confining unit: less than 50 ft thick, less than 50 ft with karstification, 50 to 100 ft thick, and greater than 100 ft (fig. 40). The area with an intermediate confining unit thickness of less than 50 ft was subdivided into an eastern and western area because the western area is generally more karstic than the eastern area. The average vertical hydraulic conductivity is expected to be greater in areas where the intermediate confining unit is less thick. The small-scale erosional and karstic features that are not represented in the smoothed thickness distribution (fig. 14) tend to disproportionately increase the leakance where the intermediate confining unit is thinner. The vertical leakance of the middle semiconfining unit was divided into two areas based on the presence or absence of evaporites (fig. 41).

Table 4. Initial and calibrated values of parameters estimated to calibrate the model

Parameter description	Parameter	Initial value	Constrained	Calibrated value	Including areas of Upper Floridan containing saltwater
Recharge rate, inches per year	N-Maximum	25	yes	25	25
Lateral hydraulic conductivity of surficial aquifer, feet per day	Keast	5	yes	5	5
	Kwest	30	yes	30	30
Vertical hydraulic conductivity of intermediate confining unit, feet per day	IC-Thin-East	0.005	no	0.0072	0.0067
	IC-Thin-West	.05	yes	.05	.05
	IC_50-100	.005	no	.0067	.007
	IC> 100	.005	no	.001	.0011
Transmissivity multiplier of Upper Floridan aquifer, dimensionless	K-UF	1	no	1.44	1.43
Vertical hydraulic conductivity of middle semiconfining unit (evaporites absent), feet per day	Mels	.5	no	.99	1.06
Vertical hydraulic conductivity of middle semiconfining unit (evaporites present), feet per day	Manh	.5	no	.01	.01
Lateral hydraulic conductivity of Lower Floridan aquifer, feet per day	K-LF	400	no	250	260
RMS ERROR, IN FEET		**7.73**		**5.28**	**5.24**

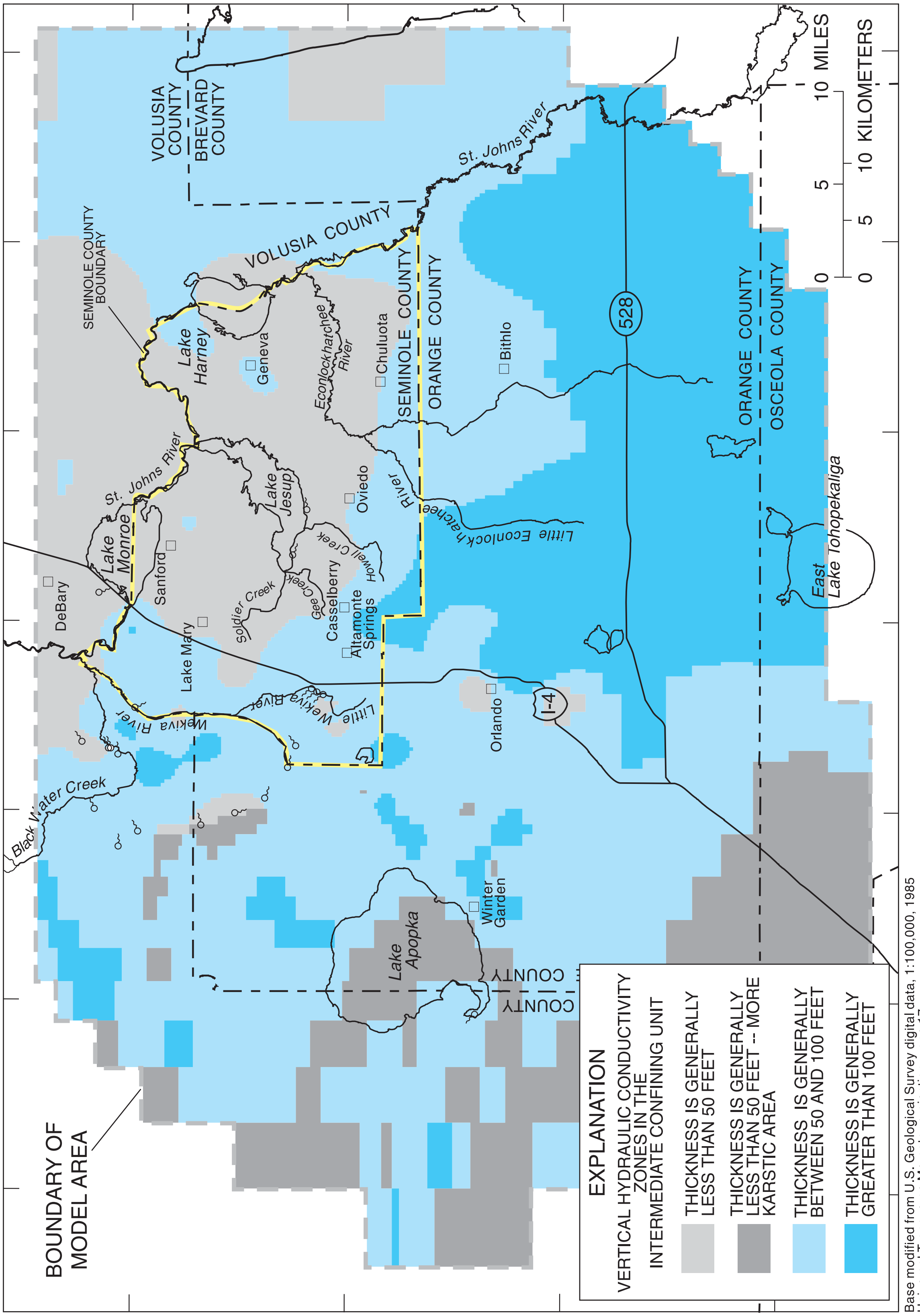


Figure 40. Vertical hydraulic conductivity zones in the intermediate confining unit.

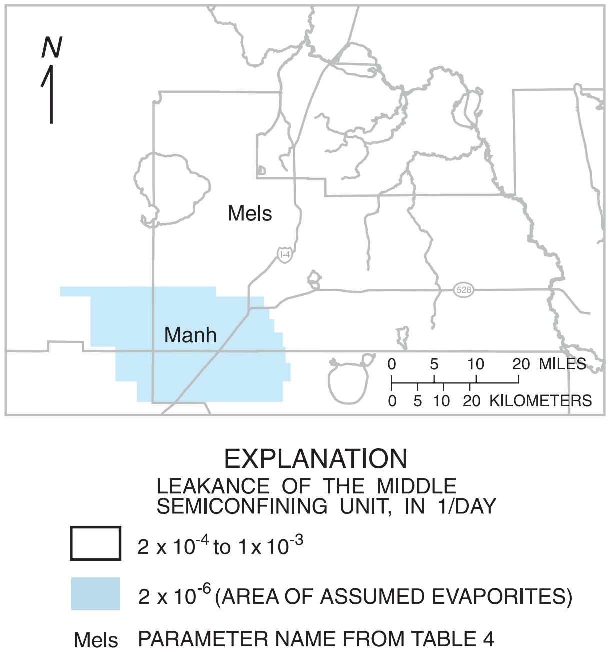


Figure 41. Leakance of the middle semiconfining unit.

The leakance of the intermediate confining unit was defined with four parameters in the calibrated model. The vertical hydraulic conductivity estimate for the IC-Thin-West area (table 4) was constrained to 0.05 ft/d, based on previous estimates (OíReilly, 1998). Final estimates of leakance of the intermediate confining unit ranged from $5x10^{-6}$ to $7x10^{-3}$ 1/d (fig. 42). Areas of higher leakance generally occur where the intermediate confining unit is thin. The highest leakance occurred along the western edge of the study area where the intermediate confining unit was estimated to be less than 50-ft thick.

Final estimates of the transmissivity of the Upper Floridan aquifer were about 1.4 times greater than the initial estimate, ranging from 2,000 to 1,000,000 ft^2/d (fig. 17). Lower transmissivity generally occurs in the southwestern and northeastern parts of the study area. The highest transmissivities are found near Rock and Wekiva Springs. The hydraulic conductivity estimate of the Lower Floridan aquifer (table 4) was reduced to about 60 percent of the initial estimate during model calibration.

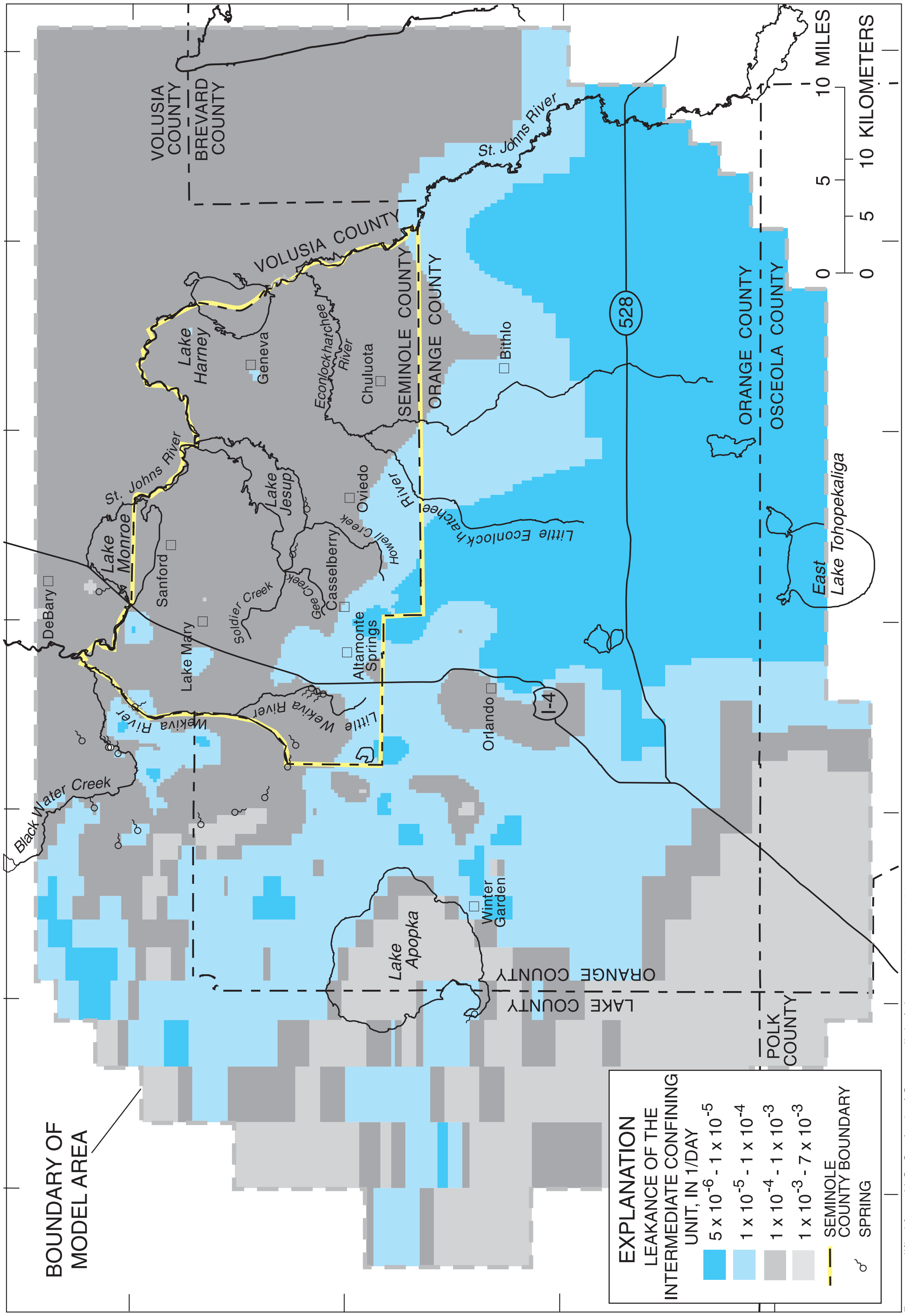
The minimum, maximum, average, and RMS water-level errors of the calibrated model were -23.70, 16.66, -1.04, and 5.28 ft, respectively. The water-level residuals for the surficial, Upper Floridan, and Lower Floridan aquifers are shown in figures 43, 44, and 45, respectively. The simulated potentiometric surfaces and water-level residuals represent average conditions during the study period.

The simulated water levels approximated the measured levels throughout the 120-ft range of measured levels observed in the study area (fig. 46). The range in measured water levels (9 to 129 ft above sea level) is similar to the range in simulated water levels (10 to 118 ft above sea level) in the surficial and Floridan aquifer systems. The distribution of water-level residuals was skewed, as indicated by the fact that more than 50 percent (specifically, 55 percent) were less than 0 ft. Overall, 68 percent of the simulated water levels were within 5 ft of the measured water levels.

The discrepancy between simulated and measured water levels could not be compared throughout the entire model domain because of data limitations. The veracity of the water-table simulation beyond Seminole County is limited because of the lack of water-level observations. Likewise, the difference between simulated and measured water levels in the Lower Floridan aquifer is not known along the western and northern extents of the model domain because of the lack of water-level observations.

The water table is not as well known as the residuals suggest (fig. 43). The RMS error of the 103 water-level observations in the surficial aquifer system (layer 1) is 5.8 ft. This comparison is somewhat meaningless because 87 percent of the water-table values were specified by the regressed water-table surface, which was constructed with the 103 water levels that were used for model calibration.

Simulated water-level differences between the surficial aquifer system and the Upper Floridan aquifer approximated the measured differences throughout the range observed in the study area (fig. 47). The measured water-level differences ranged from -17 to 68 ft, a slightly greater range than for the simulated water-level differences, which ranged from -23 to 51 ft. The general pattern of simulated differences agrees with the measured differences (fig. 48). Discrepancies between simulated and measured water-level differences could not be compared throughout the entire model domain because of limitations in the spatial availability of water-level data.



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

Figure 42. Calibrated leakance of the intermediate confining unit.

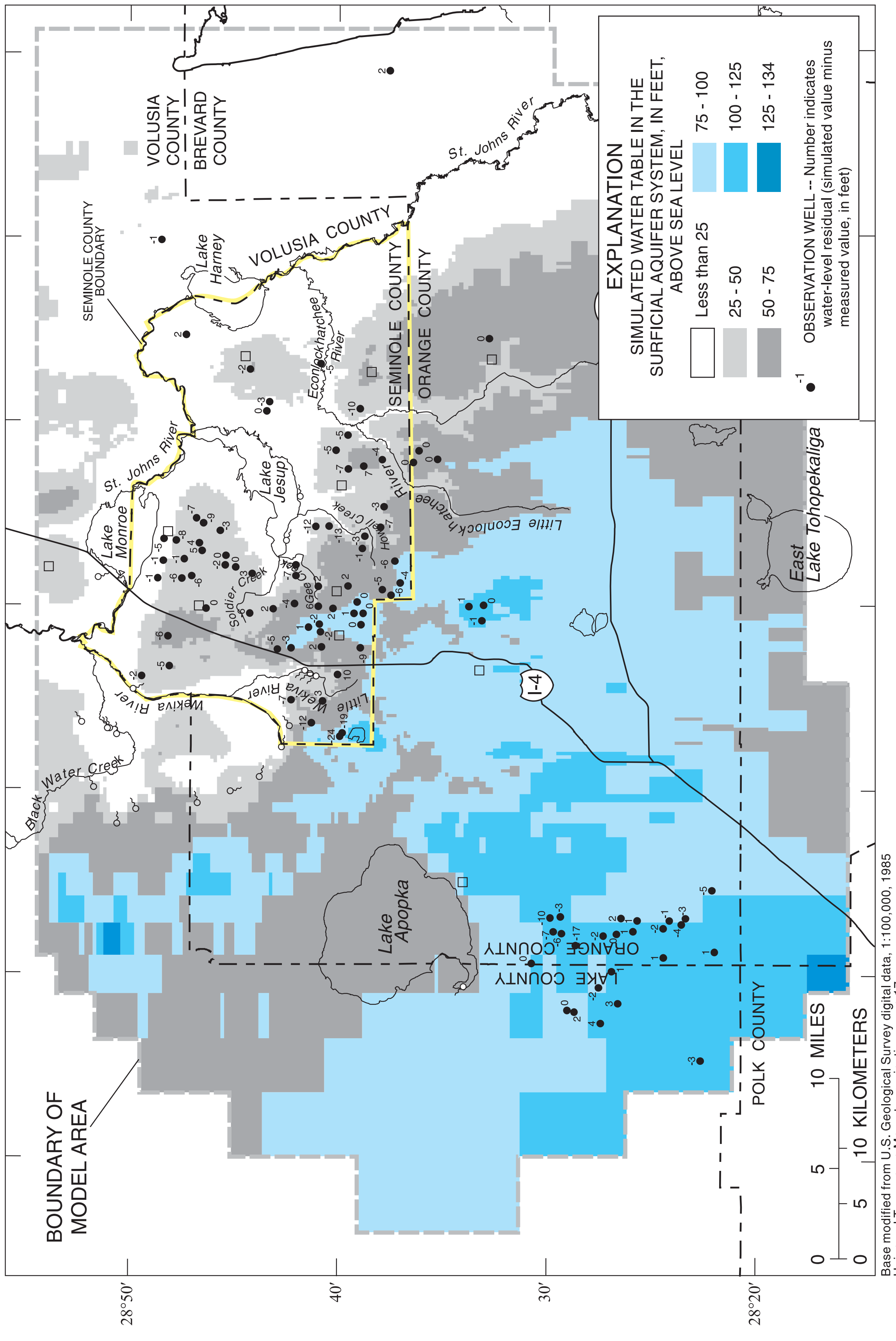


Figure 43. Simulated water-table and water-level residuals for the surficial aquifer system (layer 1), September 1996 through August 1997.

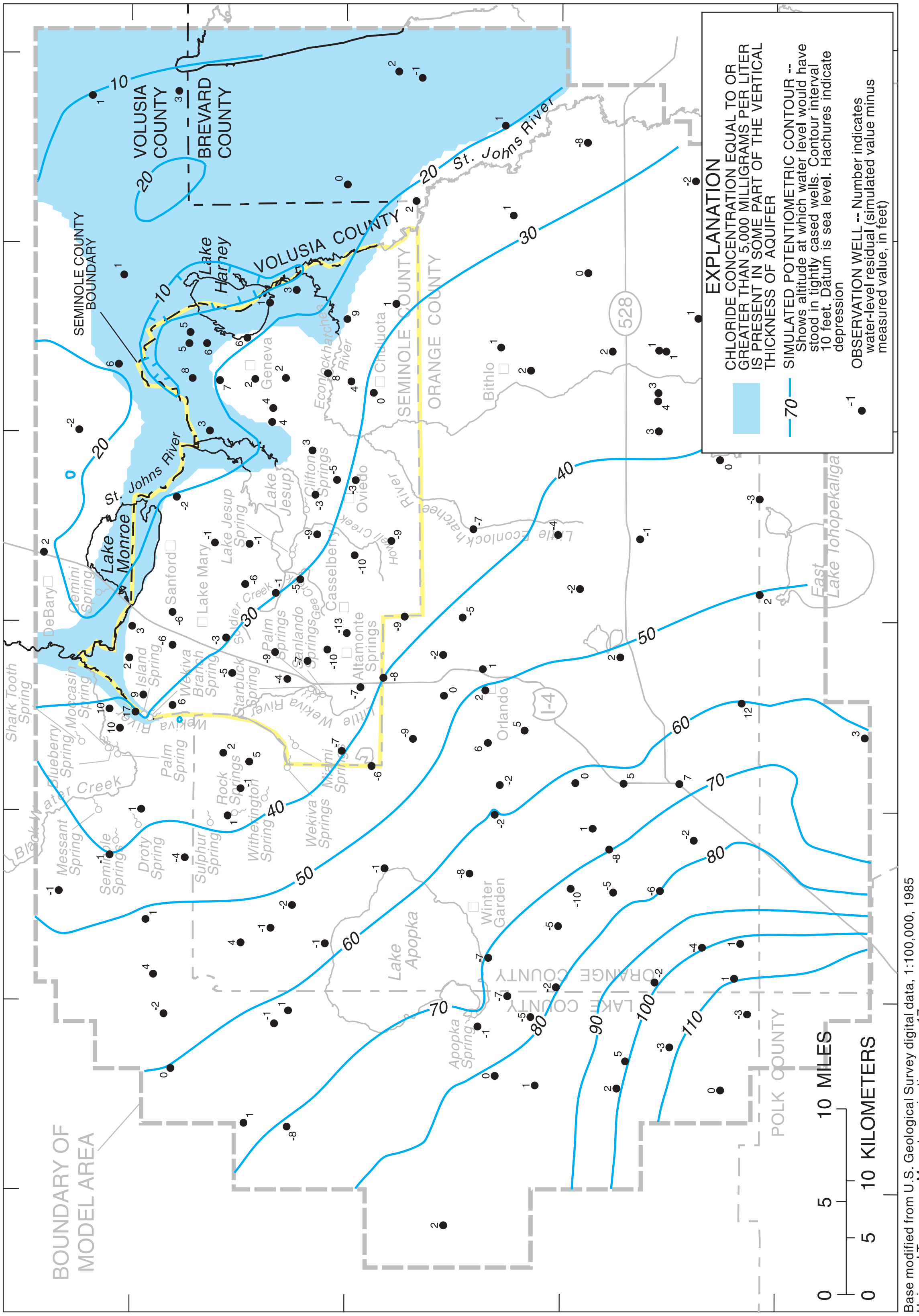


Figure 44. Simulated potentiometric surface and water-level residuals for the Upper Floridan aquifer (layer 2), September 1996 through August 1997.

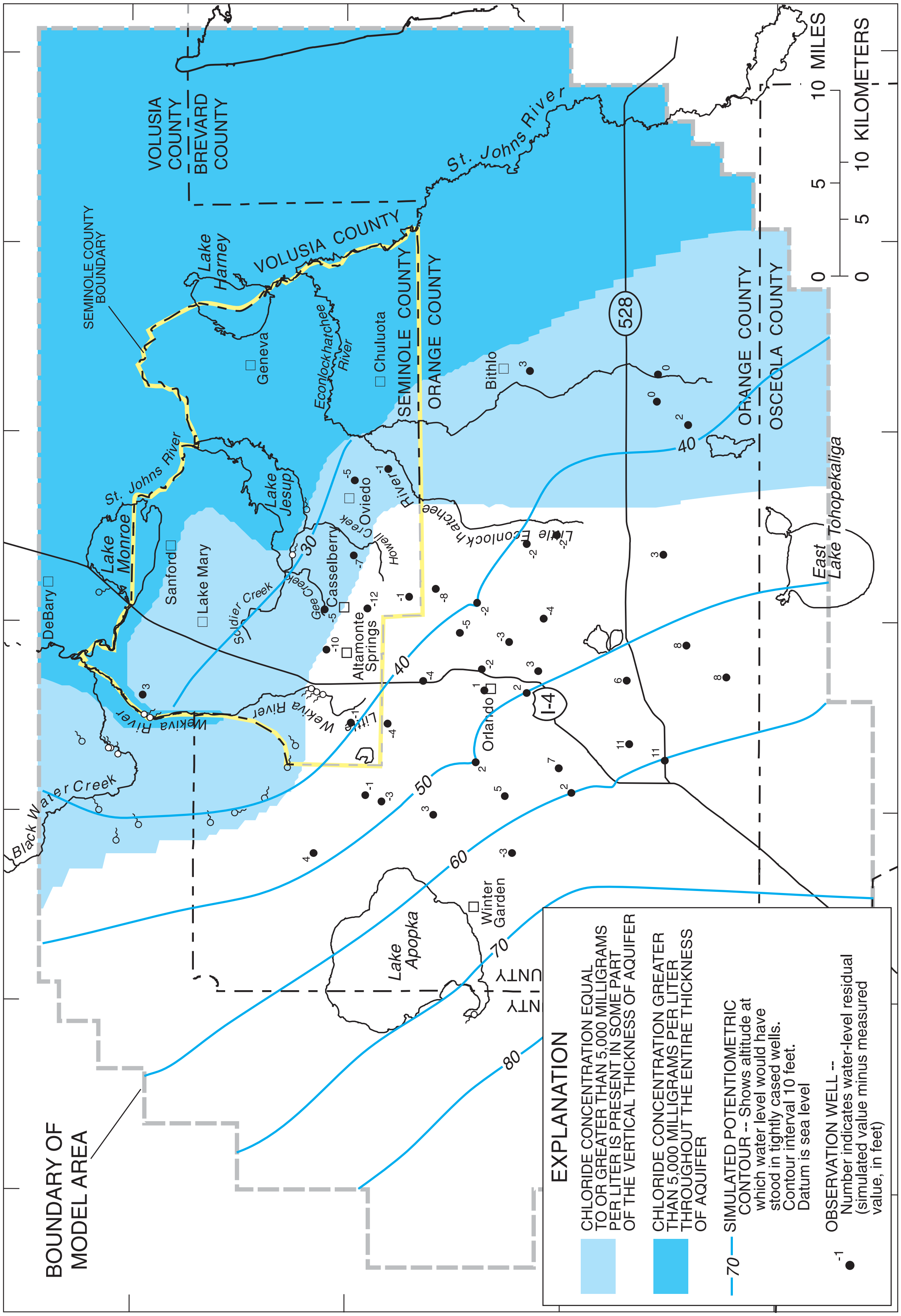


Figure 45. Simulated potentiometric surface and water-level residuals for the Lower Floridan aquifer (layer 3), September 1996 through August 1997.

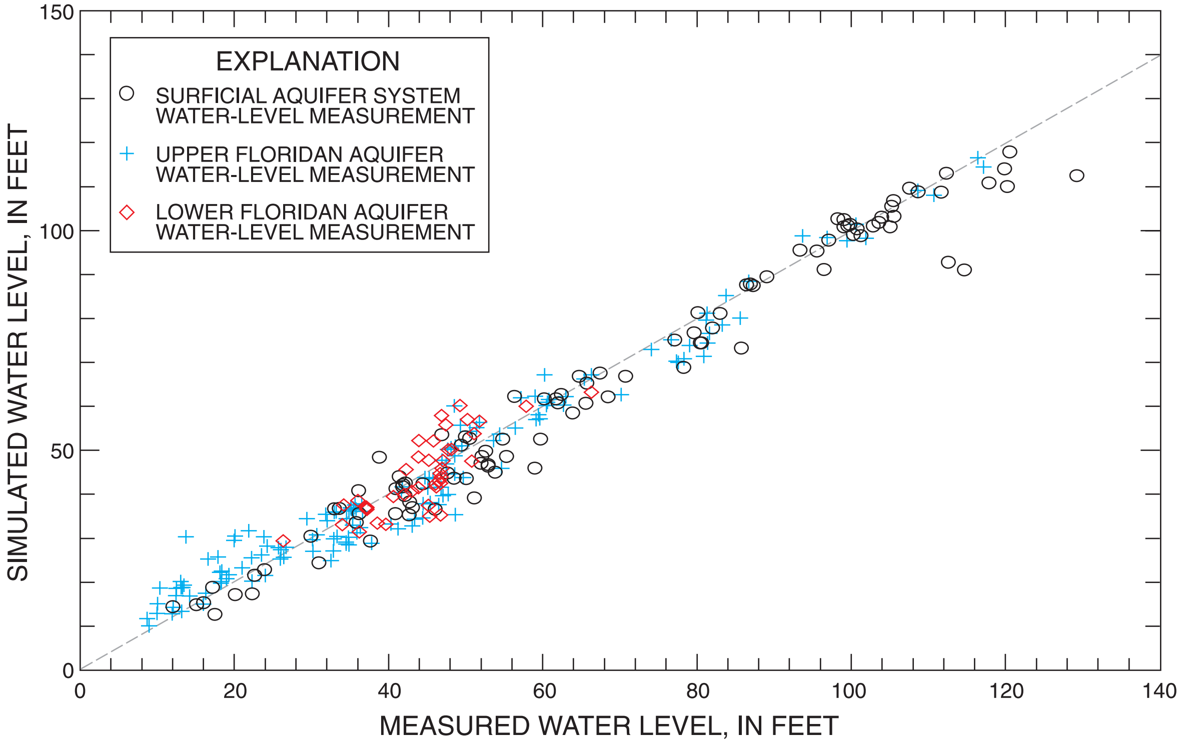


Figure 46. Comparison of simulated heads to measured water levels for the calibrated model.

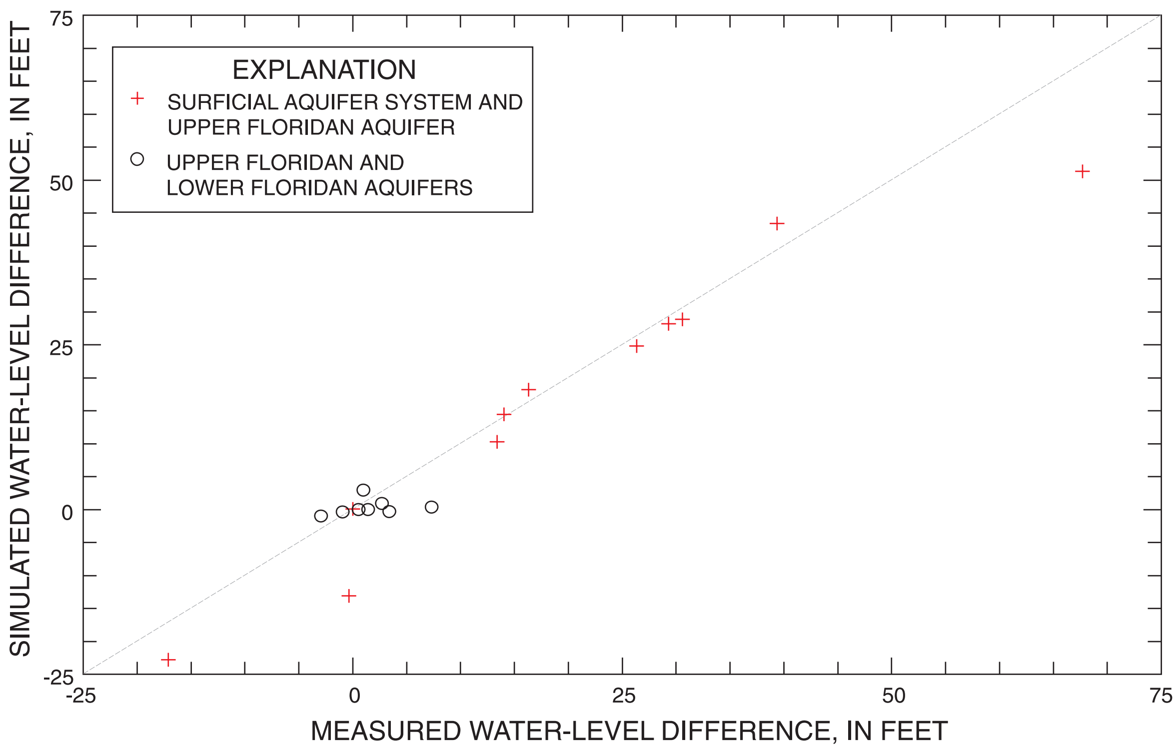
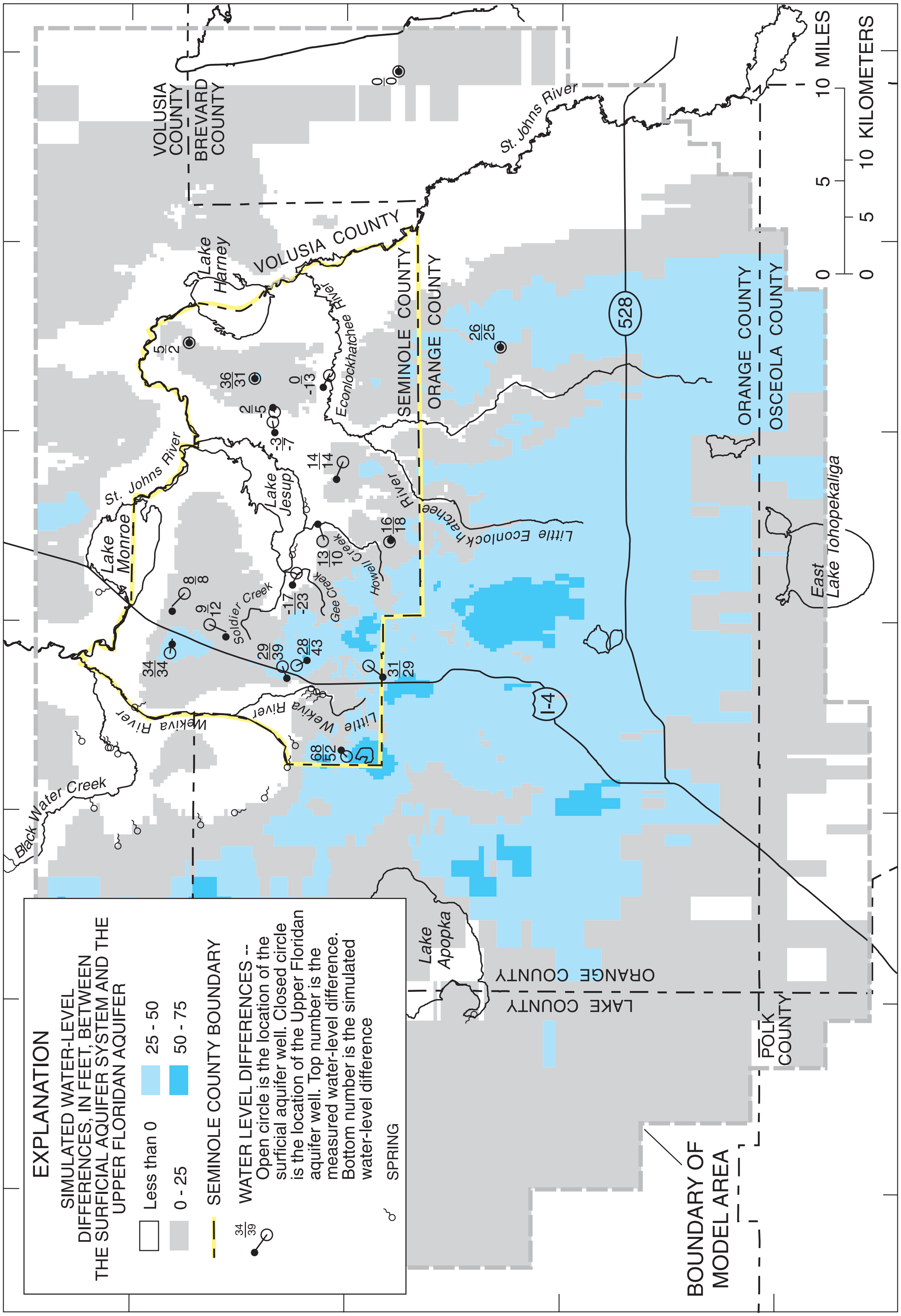


Figure 47. Comparison of simulated to measured water-level differences for the calibrated model.



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

Figure 48. Simulated water-level differences between the surficial aquifer system (layer 1) and the Upper Floridan aquifer (layer 2), September 1996 through August 1997.

Simulated water-level differences between the Upper Floridan and Lower Floridan aquifers did not compare as well with the measured differences (fig. 49). The measured water-level differences range from -6.4 to 7.3 ft, which is about three times greater than the simulated water-level differences, which range from -1.6 to 2.9 ft. The relatively small range of simulated water-level differences suggest that the vertical hydraulic conductivity of the middle semiconfining unit may have been overestimated. This estimate could have been improved by incorporating the measured water-level differences between the Upper Floridan and Lower Floridan aquifers in the objective function (eq. 6) during parameter estimation.

Most of the 14 ground-water discharge rates simulated were within the range of the estimated minimum and maximum discharges (fig. 50) for the 1996-97 calibration period. The simulated discharge was less than the estimated minimum at 5 of the 14 sites (table 5). The coarser discretization of the model in the upstream reaches of these basins may have caused the simulated discharges to be lower.

Although the model can simulate the ground-water flow system of the surficial and Floridan aquifer systems beneath Seminole County fairly well, there are a few areas where model results may be deficient. The simulated potentiometric surface of the Upper Floridan aquifer ranges from 9 to 17 ft higher than measured water levels just southwest of the confluence of the Wekiva River and Black Water Creek (fig. 44), probably because the observation wells are open only to the top few feet of the Upper Floridan aquifer. Vertical head differences within the Upper Floridan aquifer were not simulated, and vertical head differences near Wekiva Spring have been observed to differ by as much as 26 ft over a 400 ft interval from the top of the Upper Floridan aquifer (well 228) to the top of the middle semiconfining unit (well 227). The simulated potentiometric surface of the Upper Floridan aquifer is about 9 ft less than the measured surface near Lake Jesup (fig. 44).

Sensitivity Analysis

A sensitivity analysis was performed by independently varying the estimated parameters from 0.2 to 5 times their calibrated value to determine how parameter estimates affected simulation results. Model sensitivity was described in terms of RMS error. The sensitivity of model results to changing one parameter while all others were held at their calibrated values is shown in figure 51. The minimum for each sensitivity curve did not always correspond with the calibrated parameter estimate because ground-water discharges and minimum water levels at springs were used to calibrate the model but were not included in the computation of RMS error.

Table 5. Simulated and estimated ground-water discharge for the calibrated model

[Map numbers refer to fig. 4]

Map number	Site name	Simulated discharge, cubic feet per second	Estimated ground-water discharge, cubic feet per second		Residual
			Minimum	Maximum	
S1	Little Econlockhatchee near Union Park	6	5	20	0
S32	Little Econlockhatchee River at SR 434	33	40	160	-7
S44	Howell Creek near Altamonte Springs	1	2	8	-1
S57	Howell Creek near Slavia	2	3	12	-1
S74	Econlockhatchee River near Chuluota	25	30	120	-5
S79	Little Wekiva River near Altamonte Springs	11	5	20	0
S89	Little Wekiva River near Longwood	53	40	60	0
S90	Gee Creek near Longwood	3	1	4	0
S95	Wekiva River near Apopka	144	130	160	0
S96	St. Johns River above Lake Harney	71	100	300	-29
S100	Soldier Creek near Longwood	5	2	8	0
S134	Wekiva River at Old Railroad Crossing near Sanford	218	170	220	0
S138	Wekiva River near Sanford	240	210	270	0
S140	St. Johns River near Sanford	224	200	600	0

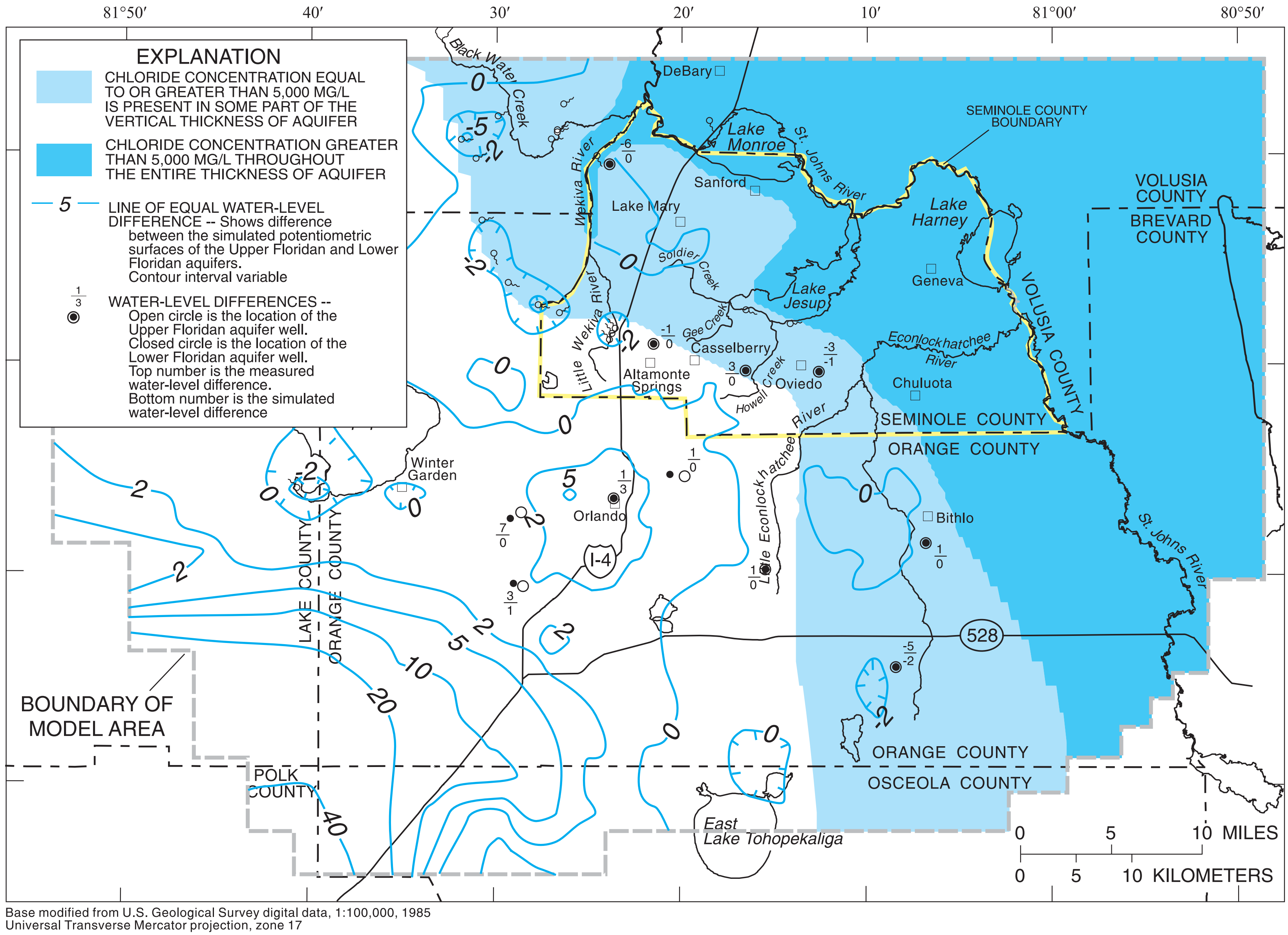


Figure 49. Simulated water-level differences between the Upper Floridan aquifer (layer 2) and the Lower Floridan aquifer (layer 3), September 1996 through August 1997.

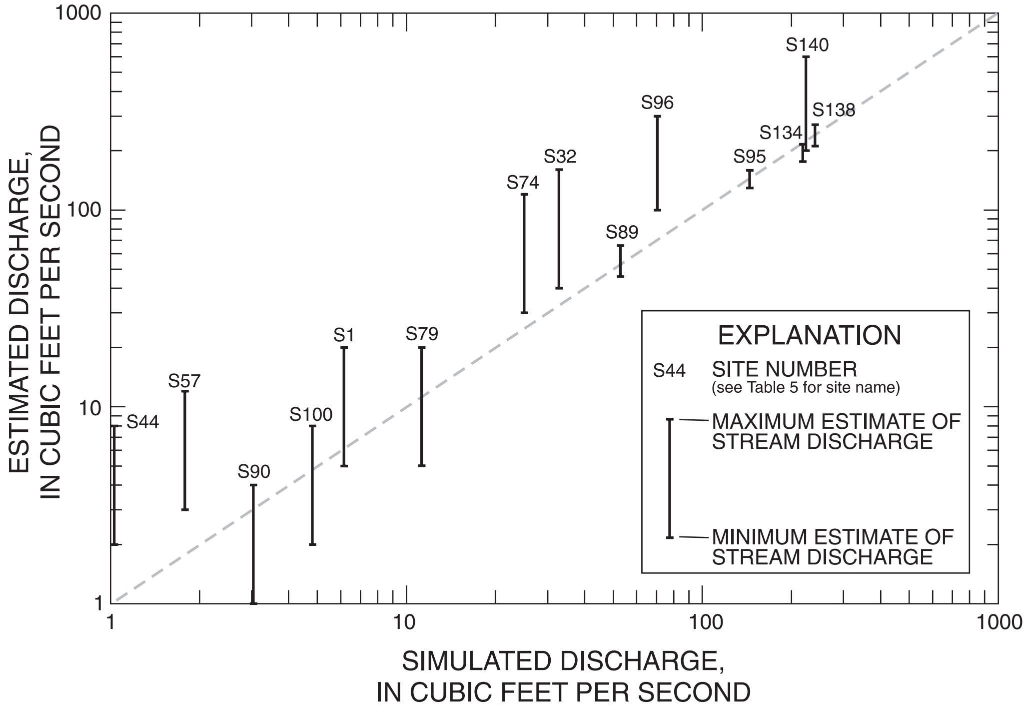


Figure 50. Comparison of simulated to estimated stream discharge for the calibrated model, September 1996 through August 1997.

The recharge rate (N-Maximum) and the vertical leakance of the intermediate confining unit across zone IC_50-100 were the two most sensitive parameters. The model was very sensitive to these two parameters because they control the availability of water for the Floridan aquifer system, and they are areally extensive parameters that directly affect the most observations. Model sensitivity to changes in recharge rates was asymmetric about the calibrated value because water-table elevations were constrained at or below the regressed water-table surface. Water levels and flow rates declined proportionately with decreases in recharge but became constrained once the recharge rate was sufficient that the water table intercepted the regressed water-table surface. Model sensitivity to changes in horizontal hydraulic conductivity of the surficial aquifer system was asymmetric about the calibrated value for the same reasons that affect recharge, except decreases in the calibrated estimates were constrained. The model was least sensitive to the vertical leakance of the middle semiconfining unit across zone Manh (fig. 51).

The effect of truncating the salt-water volume of the Upper Floridan aquifer on parameter estimates and model calibration was tested. The transmissivity array for the Upper Floridan aquifer (layer 2) in the calibrated model was replaced with an alternative array that added the transmissivity in the salt-water volume to the existing initial transmissivity array. The alternative model was calibrated with the parameter estimates for the calibrated model as initial values. Model calibration to water levels and flow rates in the study area did little to determine if the salt-water volume of the Upper Floridan aquifer should be included or excluded from the model domain. Inclusion of the part of the Upper Floridan aquifer containing salt water had little effect on parameter estimates or the RMS error (table 4). The maximum change was a 7-percent reduction of the vertical leakance of the intermediate confining unit in the IC-Thin-East zone from 0.0072 to 0.0067 ft/d. The RMS error of the alternative model was 5.24 ft, slightly less than the 5.28 ft RMS error of the calibrated model.

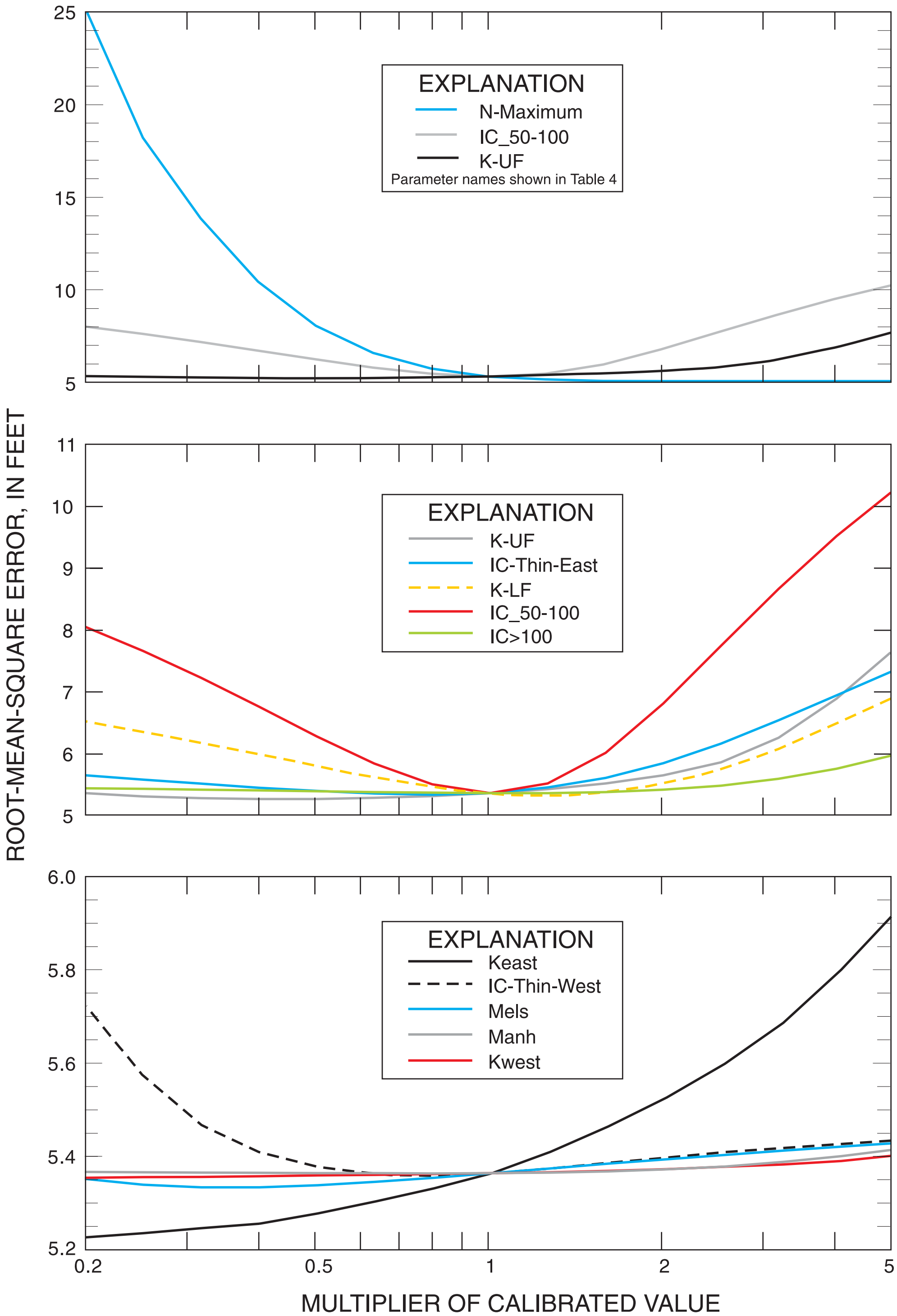


Figure 51. Model sensitivity to independent changes in selected model calibration parameters.

Ground-Water Flow During the Calibration Period

The water-table configuration is strongly influenced by surface drainage features. The simulated lateral flow direction in the surficial aquifer system commonly is perpendicular to the nearest drainage feature. The drainage features in western Orange and Seminole Counties include many closed-basin lakes and sinks that are directly connected to the Upper Floridan aquifer. The simulated potentiometric surfaces of the Upper Floridan and Lower Floridan aquifers are, therefore, strongly influenced by large surface-water features such as the St. Johns River, as well as by pumping and spring discharge.

Recharge supplied 1,251 ft^3/s of the 1,438 ft^3/s simulated flow in the study area through the surficial and Floridan aquifer systems (fig. 52). Drainage wells and RIBís supplied 10 percent (146 ft^3/s) of the total flow. Specified-heads in the Upper Floridan aquifer supplied the remaining 3 percent (41 ft^3/s) of the total flow simulated during the calibration period.

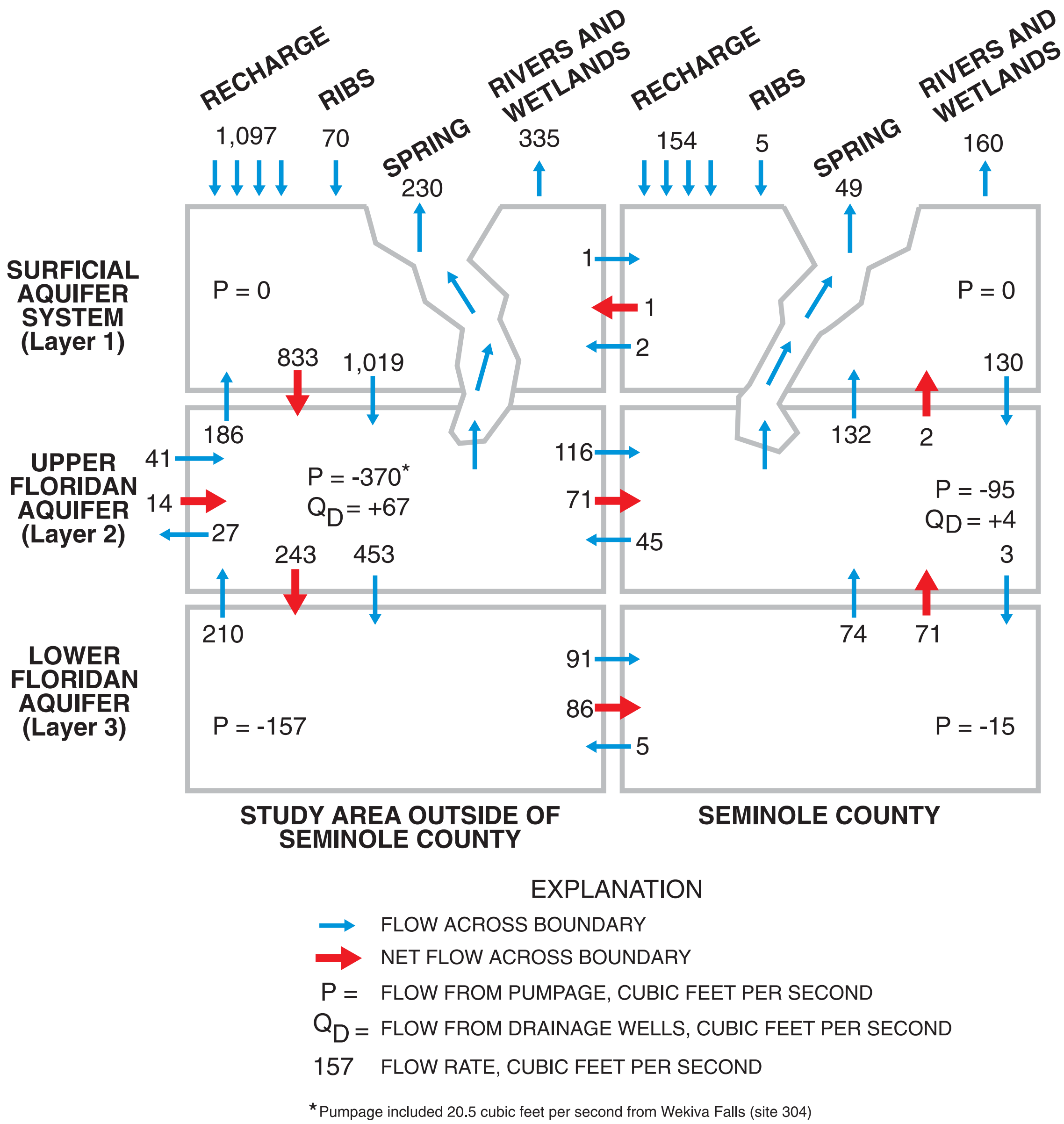


Figure 52. Simulated volumetric flow budget for the calibrated period, September 1996 through August 1997.

Pumpage was about 44 percent (637 ft^3/s) of the total flow and was the largest flow component that removed water from the ground-water system (fig. 52). Simulated discharge to rivers and wetlands was the second largest component and accounted for about 34 percent (495 ft^3/s) of the total flow. The simulated spring discharge was 279 ft^3/s, which is 19 percent of the ground-water discharge in the study area. About 2 percent (27 ft^3/s) of the simulated flow exited through specified heads in the Upper Floridan aquifer (layer 2) along the northern and eastern boundaries.

The simulated water budget for Seminole County differs from the water budget of the study area because 56 percent (207 ft^3/s) of the budget is supplied by lateral inflow through the Upper Floridan and Lower Floridan aquifers. Recharge supplied 154 ft^3/s of the 367 ft^3/s flow that was simulated through the surficial and Floridan aquifer systems in Seminole County (fig. 52). Drainage wells and RIB sites in Seminole County supplied about 2 percent (9 ft^3/s) of the total flow through the county.

Simulated discharge to rivers and wetlands was about 44 percent (160 ft^3/s) of the total flow through Seminole County and was the largest flow component that removed water from the ground-water system in the county (fig. 52). Net lateral flow through the Upper Floridan and Lower Floridan aquifers (157 ft^3/s) transports about 1.5 times the amount of water that is discharged from Seminole County as pumpage (110 ft^3/s). The simulated spring discharge was 49 ft^3/s, which is 13 percent of the total ground-water discharge from Seminole County and about 18 percent of the spring discharge within the entire study area.

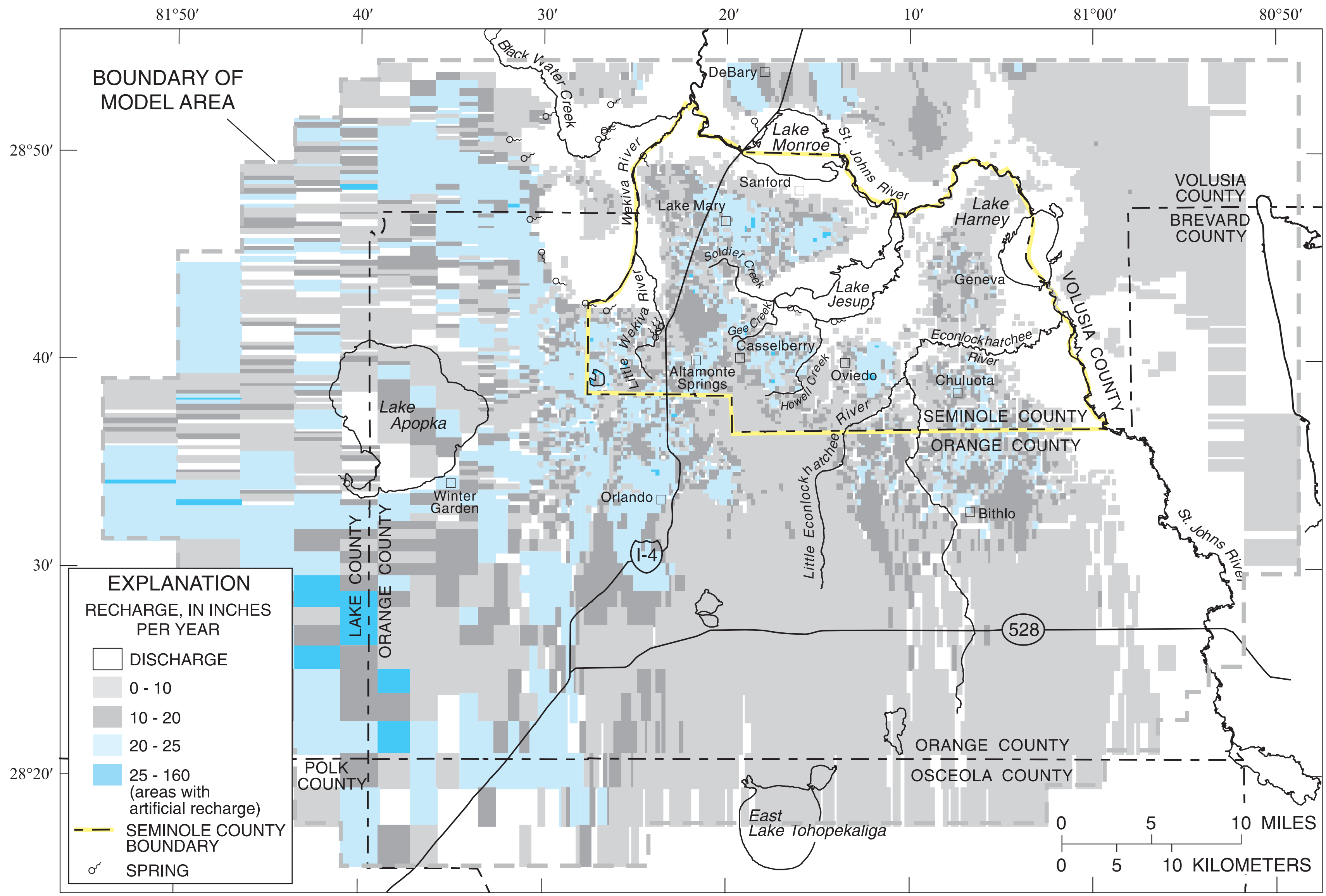
Net flux to the water table is the sum of applied recharge, artificial recharge, and leakage from lakes minus the amount of water rejected at drains or discharged to rivers and lakes. Where artificial recharge, rivers, and lakes were absent, the net recharge rates in the study area ranged from 0 to 25 in/yr and were highest in western Orange and Seminole Counties (fig. 53). The highest rates occurred where the vertical leakance of the intermediate confining unit was greatest, and all of the applied recharge entered the ground-water flow system. Ground-water discharge occurred mostly in the St. Johns, Econlockhatchee, and Wekiva Rivers and the adjacent wetlands.

The distribution of leakage from the surficial aquifer system to the Upper Floridan aquifer (fig. 54) is similar to the distribution of net recharge to the water table because the predominant flow direction in the surficial aquifer system is vertical. The surficial aquifer system collects about 7.2 in/yr of water from sporadic recharge events and continually discharges this water to surface-water features (1.0 in/yr) and to the Upper Floridan aquifer (6.2 in/yr). Most of the lateral ground water movement in the study area passes through the Floridan aquifer system because the aquifer system is about 1,000 times more transmissive than the surficial aquifer system.

Water supply for the Sanford and Oviedo well fields was of interest because projections for population and water use in 2020 indicate proportionately greater increases near these well fields than in the rest of Seminole County. The Sanford well field has 26 wells that pumped 5.6 Mgal/d (8.7 ft^3/s) in 1996-97, and the Oviedo well field has 7 wells that pumped 3.6 Mgal/d (5.6 ft^3/s) in 1996-97. Pumpage from the two well fields was simulated with 14 well nodes because several of the wells were within 1,000 ft of one another.

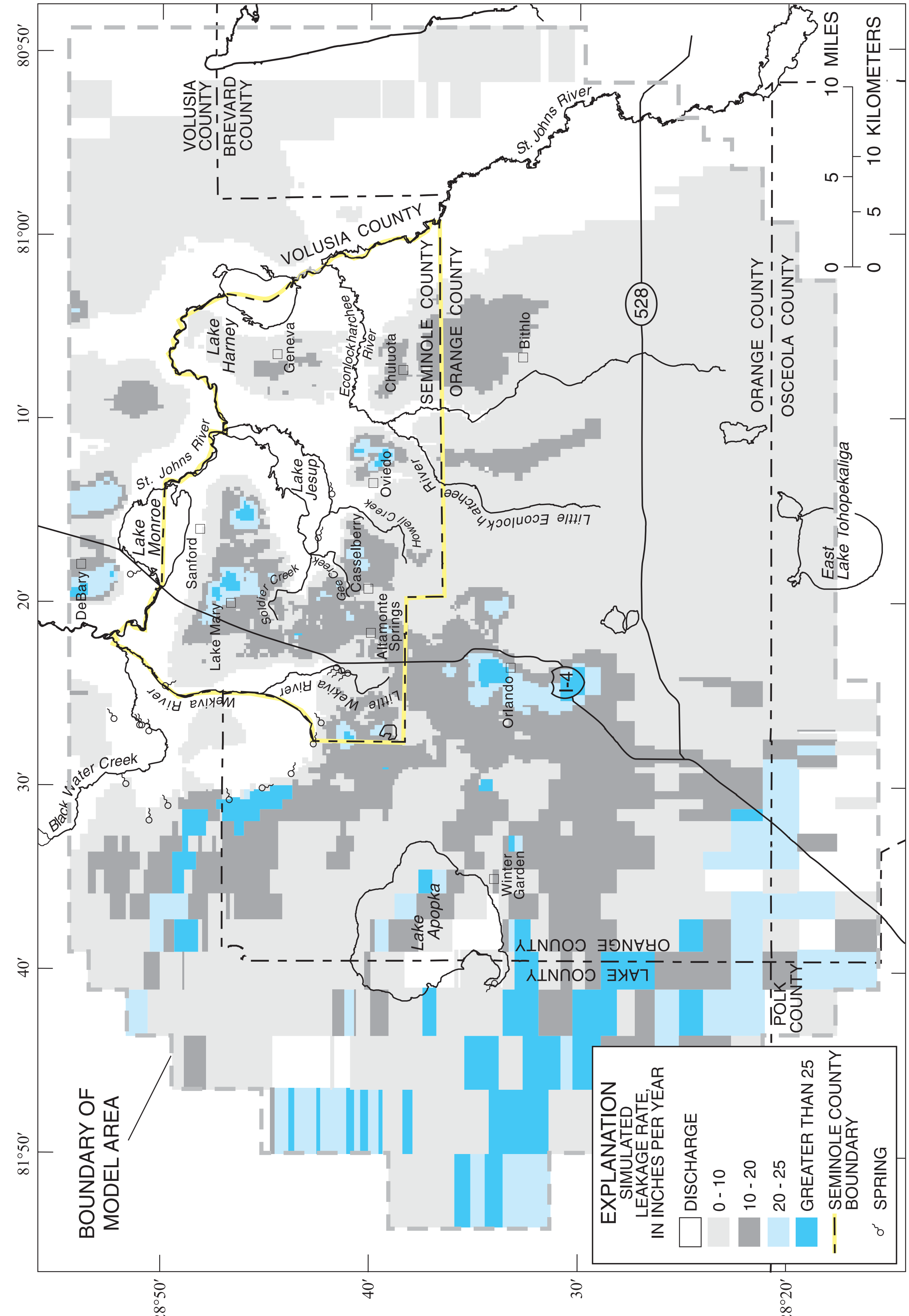
The source areas for the Sanford and Oviedo well fields were estimated by backtracking particles from individual well nodes to the water table using MODPATH (Pollock, 1994). Particles were applied uniformly to the four lateral faces of the 14 well nodes that simulated the 33 wells. The number of particles that was applied to each well node was proportional to the pumpage. For example, 200, 400, and 800 particles were applied to nodes that produced 1, 2, and 4 Mgal/d, respectively. Particle tracking was performed for both the current (1996-97) and projected (2020) pumpage conditions.

The primary source areas for the Sanford well fields for 1996-97 were two areas that extended about 8 miles south-southwest of the production wells (fig. 55). The southern source areas were deflected to the east because of the influence of Palm, Sanlando, and Starbuck Springs. The primary source areas for the Oviedo well field extended about 6 miles southwest of the production wells. The source areas were separated near Oviedo because of local ground-water discharge to Bear Creek between the two source areas. Relatively little water may be contributed from distant source areas in Lake and southwestern Orange Counties. This water would likely travel along deeper flow paths before discharging at the well fields.



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

Figure 53. Net recharge to the water table, September 1996 through August 1997.



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

Figure 54. Simulated leakage rates between the surficial aquifer system (layer 1) and the Upper Floridan aquifer (layer 2), September 1996 through August 1997.

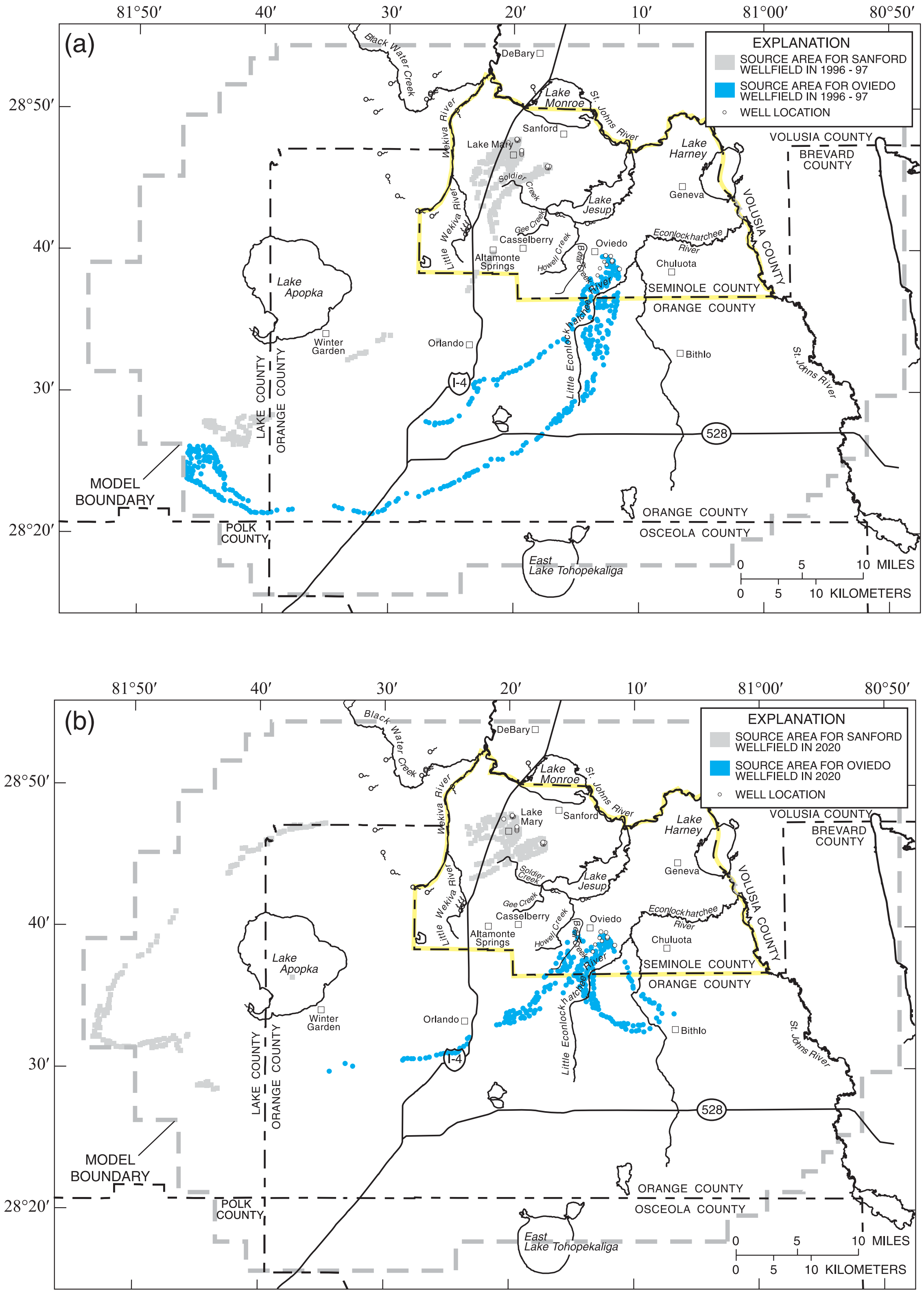


Figure 55. Simulated source areas for the Sanford and Oviedo well fields with (a) 1996-97 pumpage and (b) projected 2020 pumpage.

Simulation of Projected 2020 Withdrawals

Pumpage in the study area has been projected to increase from 412 Mgal/d (637 ft^3/s) in 1996-97 to 591 Mgal/d (915 ft^3/s) in 2020. Projected pumpage increases from public-supply and commercial sources account for all of the change from the calibration period to 2020. Pumpage from agricultural and recreational wells was assumed to remain at 1995 rates. All free-flowing wells in the study area were assumed to have been plugged by 2020. The areal distributions of projected ground-water withdrawals from the Upper and Lower Floridan aquifers in 2020 are shown in figures 56 and 57, respectively.

Potential changes in the specified-heads in the Upper Floridan aquifer (layer 2) along the northern and eastern boundaries were estimated from a larger regional model (B. McGurk, SJRWMD, written commun., 2000). Specified heads for projected 2020 conditions were estimated by subtracting drawdown estimates from the regional model for the period 1995-2020 from the specified heads for the calibrated model for 1996-97. The additional drawdown generally was less than 2 ft except for an area with a 2-mile radius near DeBary in Volusia County. The maximum drawdown in this area was about 18 ft.

Because of the manner in which the calibrated model converts the recharge rate and specified water-table drains to a net recharge rate, additional recharge cannot be induced as the simulated water table is lowered. This causes predicted drawdowns in the Floridan aquifer system (particularly in the Upper Floridan aquifer) to be greater than if the recharge mechanism had not been changed. The limited recharge increases in the predictive simulations originated from increased leakage from lakes that were simulated with river nodes.

Net recharge rates used in the steady-state model were assumed to have the appropriate spatial distribution. Evapotranspiration was neglected in the hypothetical projections because little is know about the quantitative effects of large temporal changes in the depth to the water table and about how much evapotranspiration rates would be reduced for a given decline in water-table altitude. In addition, the discharge of ground-water by evapotranspiration is difficult to predict because the roots of established plants may, to a limited extent, keep pace with a declining water level, especially if the change occurs slowly (Durbin, 1978).

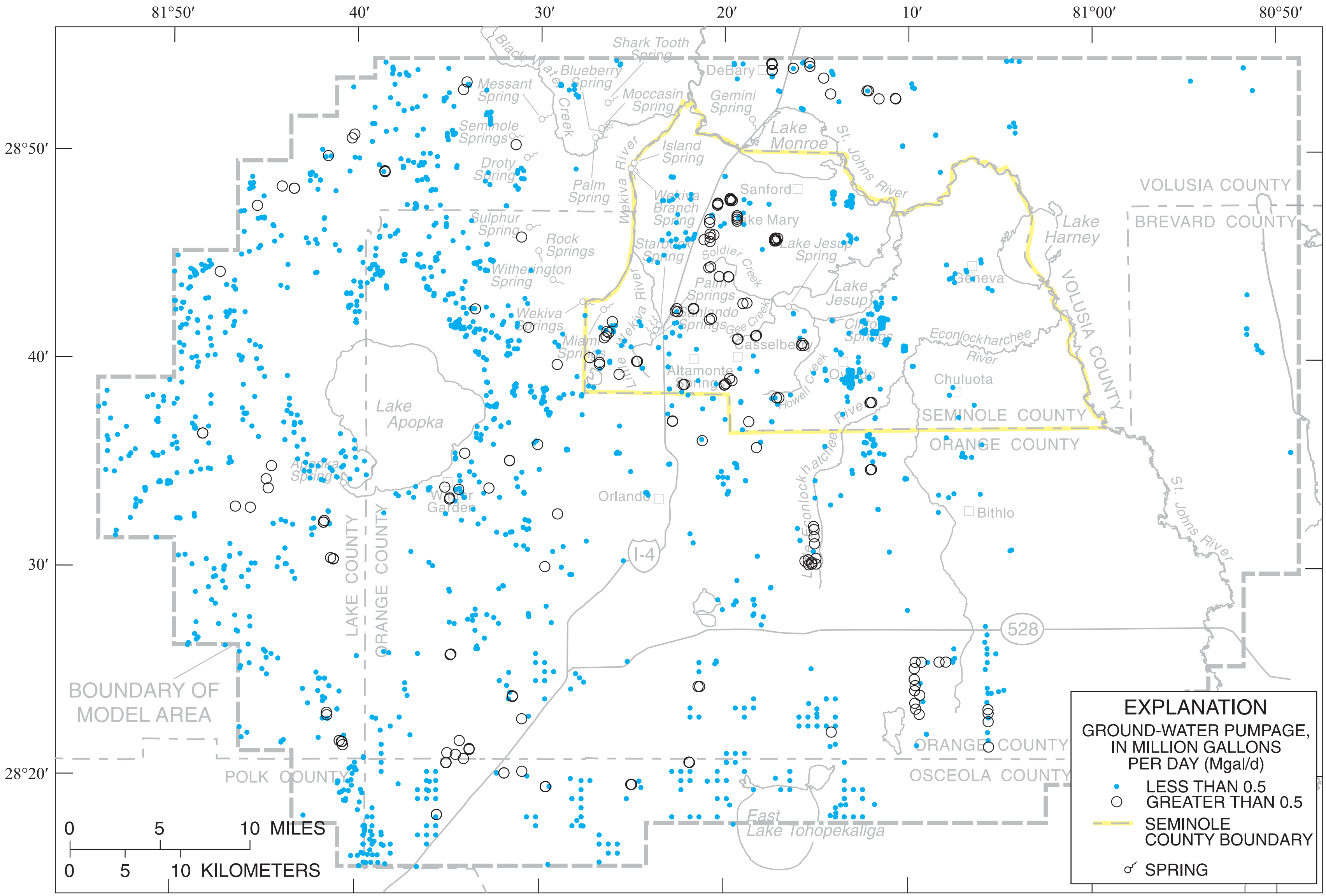
The projected 2020 pumpage reduced simulated water levels from 1996-97 conditions by as much as 16 ft in the surficial aquifer system and 18 ft in both the Upper and Lower Floridan aquifers (figs. 58-60). The greatest declines from 1996-97 to 2020 occurred primarily near projected new pumping centers in central Orange County.

Declines of greater than 5 ft in the surficial aquifer system generally occurred in the southern part of the modeled area (fig. 58). The maximum decline in the surficial aquifer system was about 16 ft, which occurred in an area northwest of East Lake Tohopekaliga. Declines in the active lakes averaged 4.8 ft and ranged from 0.4 to 10.9 ft. Recharge to the water table and leakage to the Upper Floridan aquifer increased slightly (35 ft^3/s).

Declines of more than 5 ft in the surficial aquifer system (fig. 58) were induced by nearby pumpage and high leakance across karstic areas. The area near the Polk-Orange County lines was affected mostly by nearby pumpage increases in the Upper Floridan aquifer. The areas in southern Seminole and central Orange Counties were affected by general water-level declines in the Upper Floridan aquifer being transmitted through a leakier intermediate confining unit within internally drained, karstic areas.

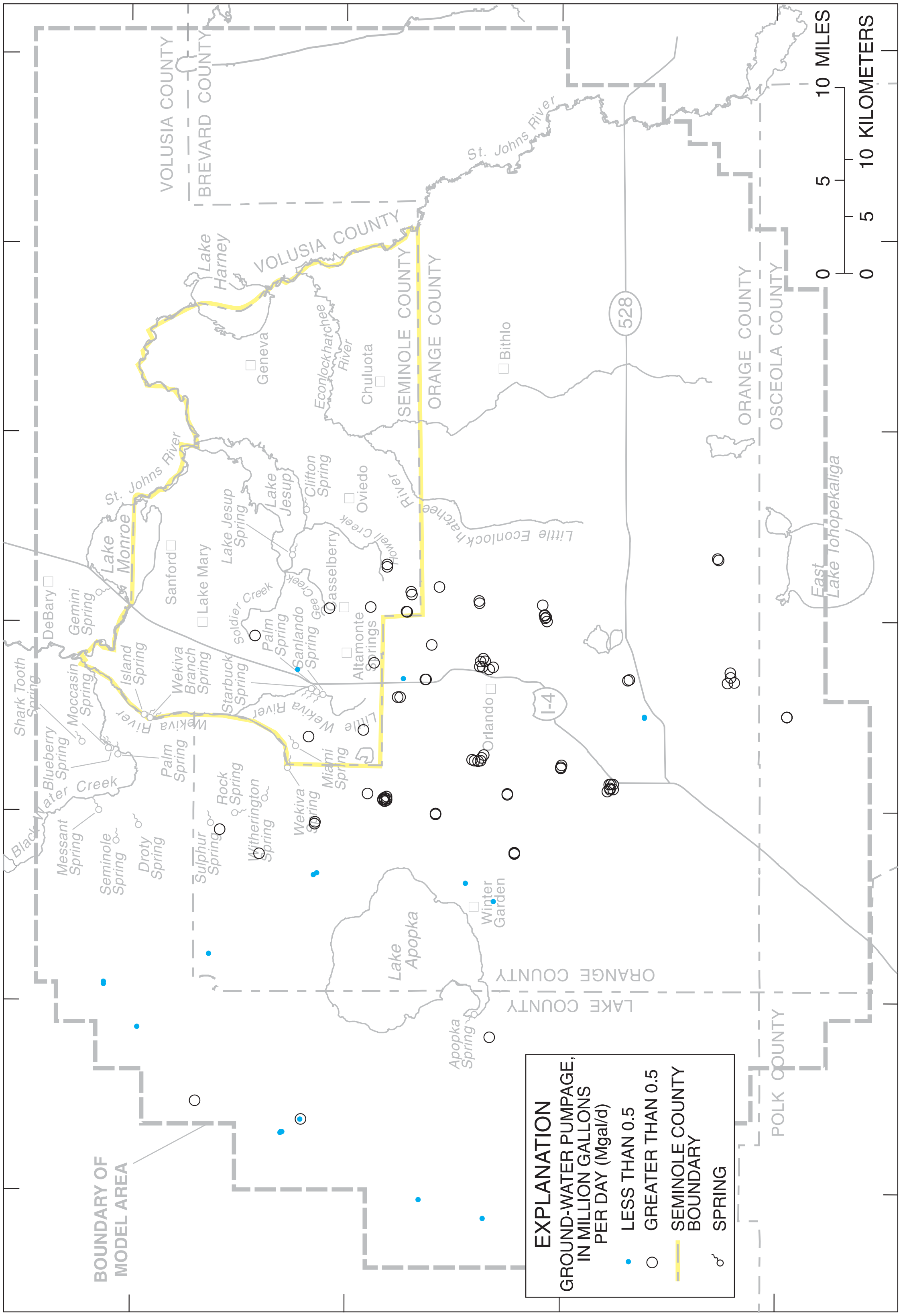
Projected increases in pumpage from the Floridan aquifer system in Orange and Osceola Counties from 1996-97 through 2020 affected simulated water levels in Seminole County. Simulated water levels in the Upper and Lower Floridan aquifers were reduced by about 9 ft in the southwestern part of Seminole County (figs. 59 and 60, respectively). Declines of less than 2 ft in the Upper Floridan aquifer occurred primarily in the northeastern part of Seminole County and along the St. Johns River. Declines of greater than 14 ft in the Upper and Lower Floridan aquifers generally occurred in the south-central part of the modeled area, with the greatest declines of more than 18 feet occurring in an area just northwest of East Lake Tohopekaliga.

Recharge supplied 1,286 ft^3/s of the 1,486 ft^3/s flow through the study area that was simulated through the surficial and Floridan aquifer systems (fig. 61). Drainage wells and RIB sites supplied 10 percent (146 ft^3/s) of the total flow. Specified-heads in the Upper Floridan aquifer supplied the remaining 4 percent (54 ft^3/s) of the simulated flow.



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

Figure 56. Distribution of projected 2020 Upper Floridan aquifer pumpage.



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

Figure 57. Distribution of projected 2020 Lower Floridan aquifer pumpage.

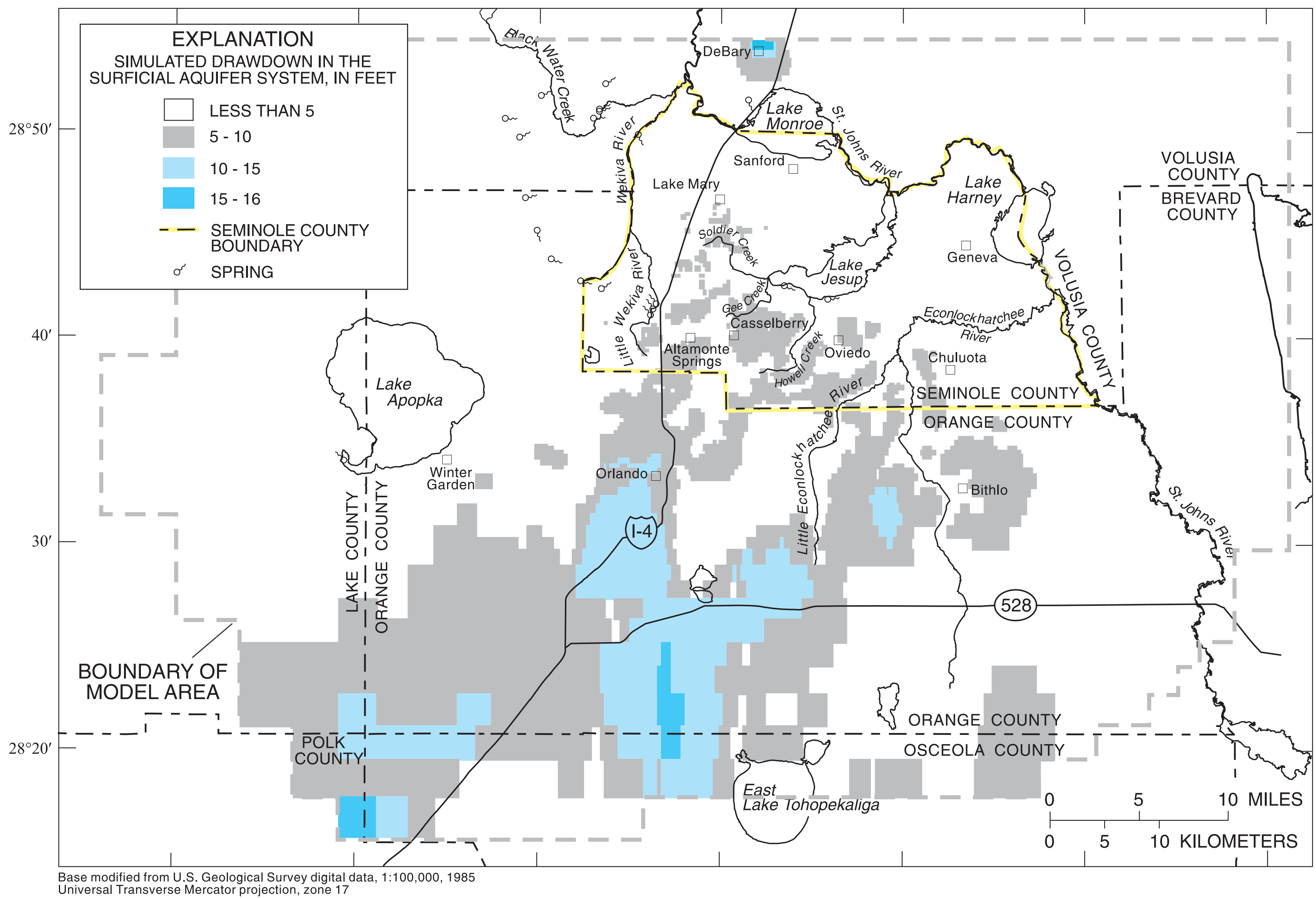


Figure 58. Simulated steady-state drawdowns in the surficial aquifer system (layer 1) from 1996-97 conditions resulting from projected 2020 pumpage.

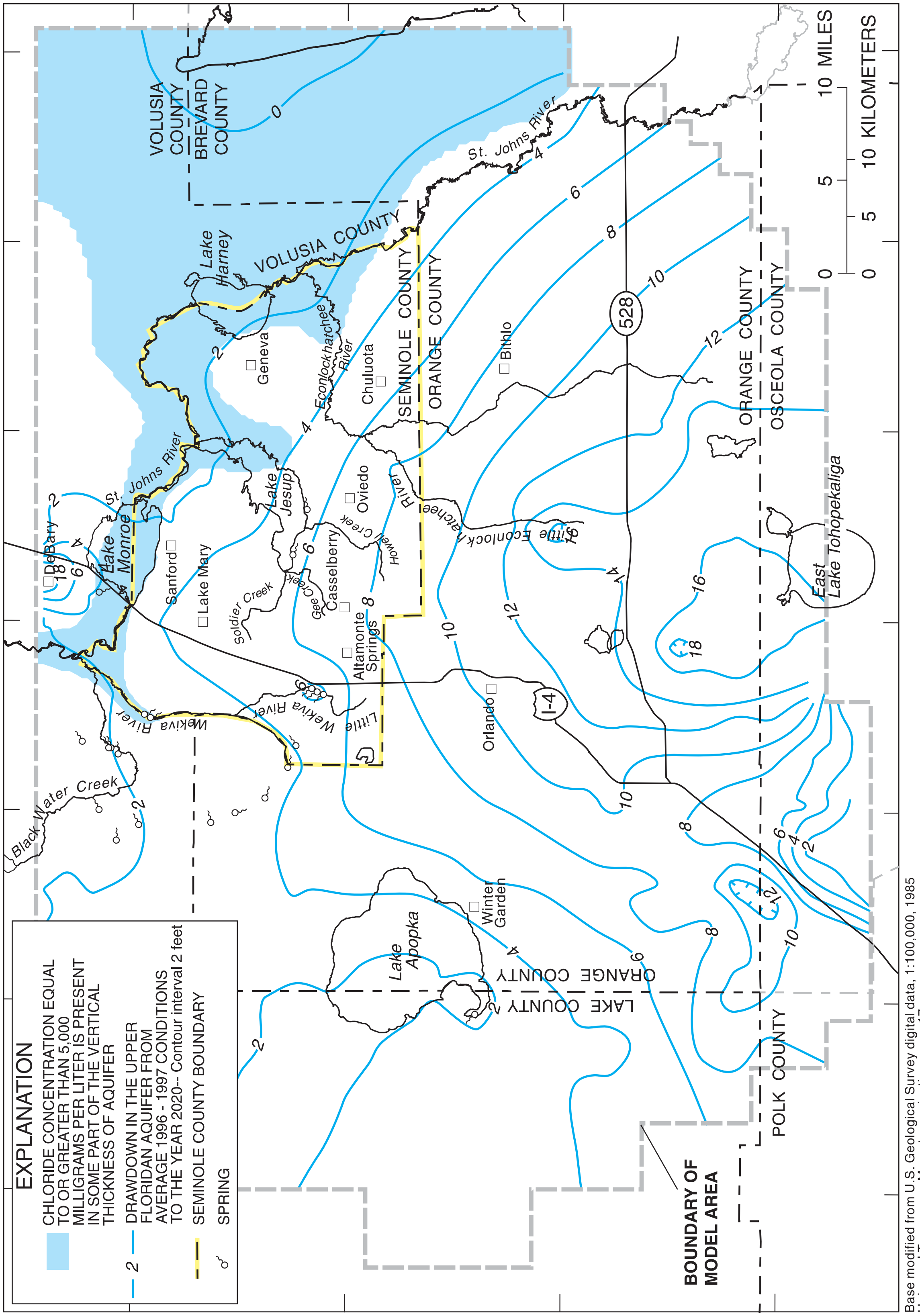


Figure 59. Simulated steady-state drawdowns in the Upper Floridan aquifer (layer 2) from 1996-97 conditions resulting from projected 2020 pumpage.

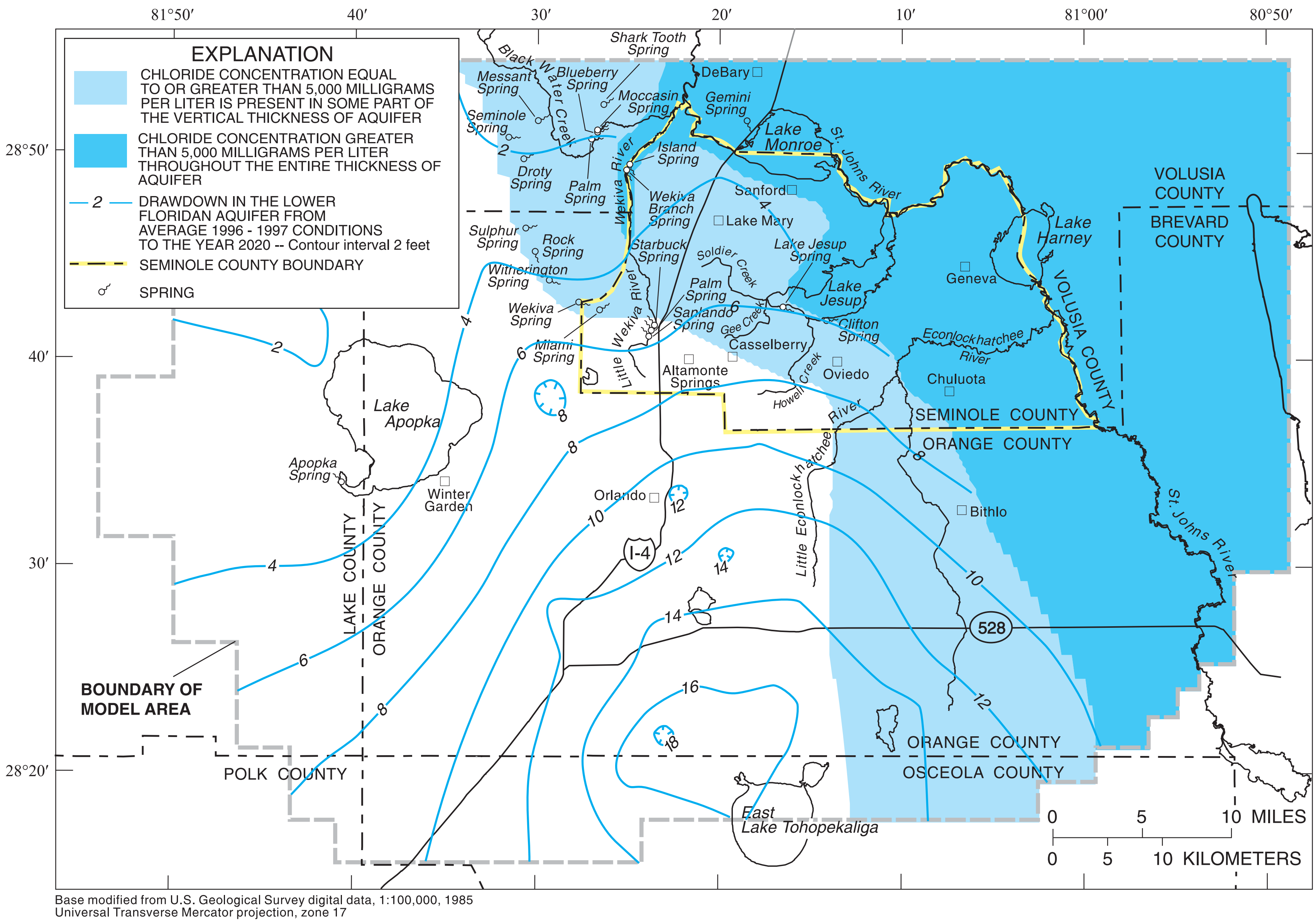


Figure 60. Simulated steady-state drawdowns in the Lower Floridan aquifer (layer 3) from 1996-97 conditions resulting from projected 2020 pumpage.

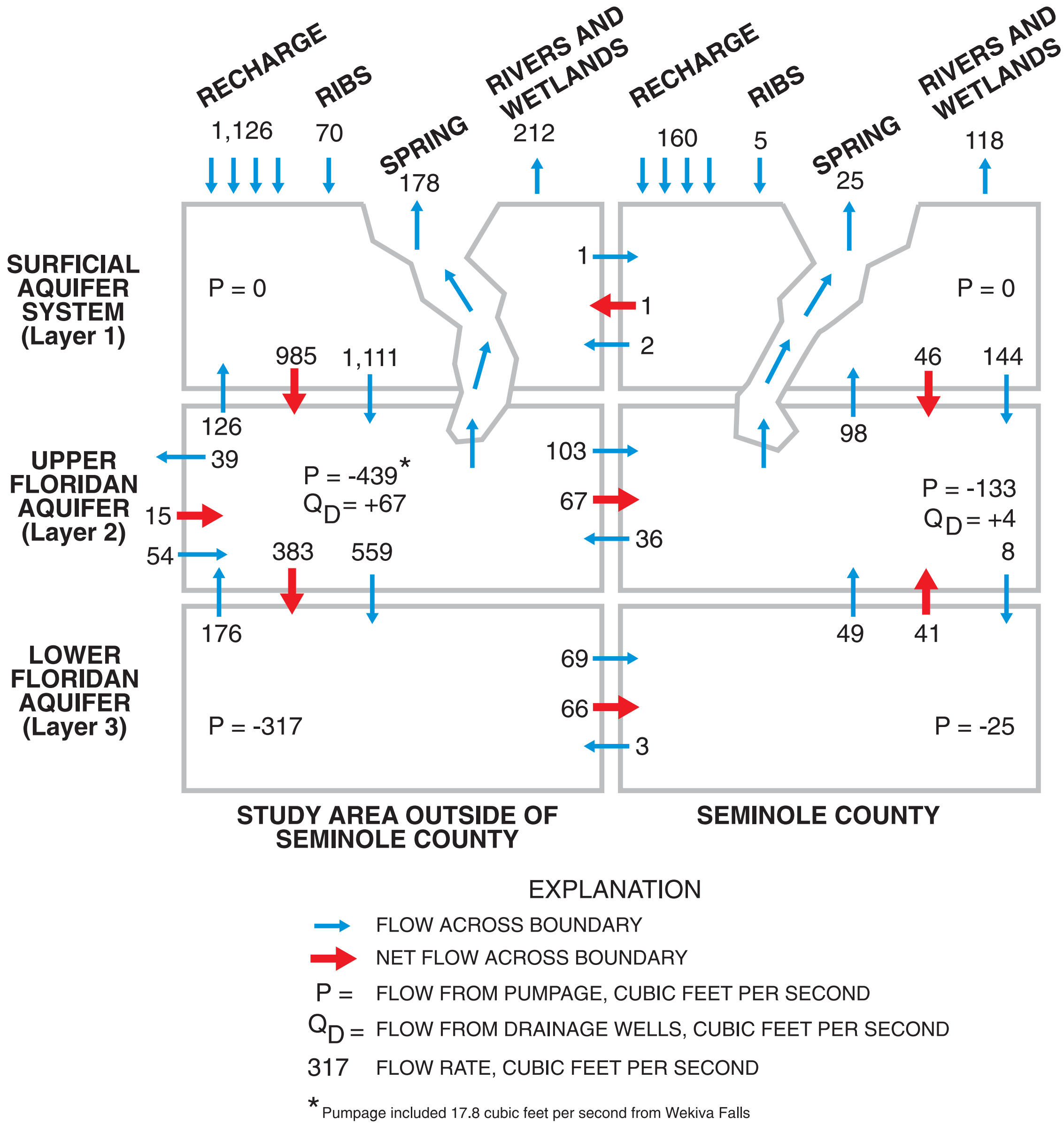


Figure 61. Simulated volumetric flow budget for projected 2020 pumpage.

In the simulations for 2020, projected pumpage was the largest flow component, removing 914 ft^3/s (fig. 61). Simulated discharge to rivers and wetlands was about 22 percent (330 ft^3/s) of the total flow, a reduction of 165 ft^3/s from 1996-97. The simulated spring discharge was 203 ft^3/s, which was 14 percent of the ground-water discharge in the study area. About 3 percent (39 ft^3/s) of the simulated flow exited through specified heads in the Upper Floridan aquifer (layer 2) along the northern and eastern boundaries.

The simulated flow through Seminole County in 2020 was 338 ft^3/s, which is 31 ft^3/s less than in 1996-97. Increased pumpage in Orange and Osceola Counties caused a reduction of lateral inflow to Seminole County through the Upper Floridan and Lower Floridan aquifers to 172 ft^3/s (fig. 61). Recharge supplied 160 ft^3/s to Seminole County in 2020, which was 6 ft^3/s greater than the recharge simulated in 1996-97. Drainage wells and RIB sites in Seminole County were assumed to supply water at the 1996-97 rate, which was 9 ft^3/s.

Projected pumpage from Seminole County in 2020 was 158 ft^3/s, which is 44 percent greater than pumpage in 1996-97 (fig. 61). Simulated discharge to rivers and wetlands was about 35 percent (118 ft^3/s) of the total flow through Seminole County and was the second largest flow component that removed water from the ground-water system in Seminole County. Simulated lateral discharge from Seminole County through the Upper Floridan and Lower Floridan aquifers in 2020 was 39 ft^3/s, a decline of 22 percent from 1996-97 rates. The simulated spring discharge in 2020 was 25 ft^3/s, which is about 8 percent of the ground-water discharge from Seminole County and about 12 percent of the spring discharge within the study area.

Projected pumpage increases in 2020 affected discharge from springs in Seminole County. Simulated spring discharge in Seminole County declined 50 percent, whereas spring discharge in the study area declined 27 percent. Sanlando Spring was affected more than any other spring in the study area, and the simulated discharge decreased by 68 percent from 21.1 ft^3/s in 1996-97 to 6.7 ft^3/s in 2020 (table 3). Discharge from Palm (Seminole County) and Starbuck Springs accounts for 41 percent of the spring discharge in Seminole County, and the discharges from these springs were both reduced by 42 percent.

The simulated source areas for the Sanford and Oviedo well fields were affected by the increased pumpage from 1996-97 to 2020 (fig. 55). Pumpage from the Sanford well field was projected to increase pumpage by 5.5 Mgal/d (8.5 ft^3/s) to a total of 11.1 Mgal/d (17.2 ft^3/s) from their existing 26 wells. The Oviedo well field was projected to increase pumpage by 1.8 Mgal/d (2.8 ft^3/s) to a total of 5.4 Mgal/d (8.4 ft^3/s) from their existing seven wells and six new wells. Projected 2020 pumpage from the two well fields was simulated with 21 well nodes because several of the wells were within 1,000 ft of one another.

The contributing areas for the Sanford well fields expanded primarily to the west in 2020 probably as a result of increased pumpage from both Orange and Seminole Counties (fig. 55). The source areas for the Oviedo well field in 2020 expanded to the south and east of the source areas in 1996-97. New wells and increased pumpage from the Oviedo well field decreased simulated ground-water discharge to Bear Creek and adjacent wetlands from 3.6 to 1.5 ft^3/s between 1996-97 and 2020.

Simulation of a Drought in 2020

Projected pumpage increases from 1996-97 to 2020 will increase the range of seasonal water-level changes and ground-water discharges to rivers, wetlands, and springs. The effects of pumpage increases will be most pronounced during the dry season (November-May). Water levels in the surficial aquifer system have been observed to decline steadily during this period, with minimal recharge reaching the water table (OíReilly, 1998).

The ground-water system is further stressed during the dry season because pumpage tends to increase during periods of little precipitation. Ground-water withdrawals during May 1997 were 25 percent greater than the average withdrawals during 1997 and 50 percent greater than the September 1997 withdrawals.

The effects of an extreme drought were investigated using a transient model of the study area. Transient flow in the surficial and Floridan aquifer systems was simulated with a 180-day stress period with no recharge. The projected 2020 pumpage was increased by 50 percent during the drought period. The specific yields of the surficial aquifer system and the active lakes were assumed to be 0.2 and 1.0, respectively. Storage coefficients of the Upper Floridan and Lower Floridan aquifers were both assumed to be a uniform value of 0.0005 throughout the study area. The initial water levels for the transient simulation were the steady-state water levels that were simulated with the average 2020 pumpage. All drainage wells were assumed to have stopped flowing at the start of the 180-day drought.

The effects of an extreme drought caused water levels in the surficial aquifer system to decline more than 2 ft in the western part of the study area, in western Seminole County, and around the Seminole-Orange County line near the Econlockhatchee River (fig. 62).The maximum simulated drawdown in the surficial aquifer system was about 8 ft, which occurred just south of Orlando. Simulated water levels declined by as much as 20 ft in the Upper Floridan aquifer and 24 ft in the Lower Floridan aquifer. Simulated water-level declines in the active lakes averaged 0.4 ft and ranged from 0 to 1.8 ft at the end of the 180-day drought.

Storage was the primary source of water at the end of the 180-day drought. Storage supplied 1,557 ft^3/s of the 1,721 ft^3/s simulated through the surficial and Floridan aquifer systems in the study area (fig. 63). RIB sites supplied 4 percent (75 ft^3/s) of the total flow. Specified-heads in the Upper Floridan aquifer supplied the remaining 5 percent (89 ft^3/s) of the total flow that was simulated during the 180-day drought.

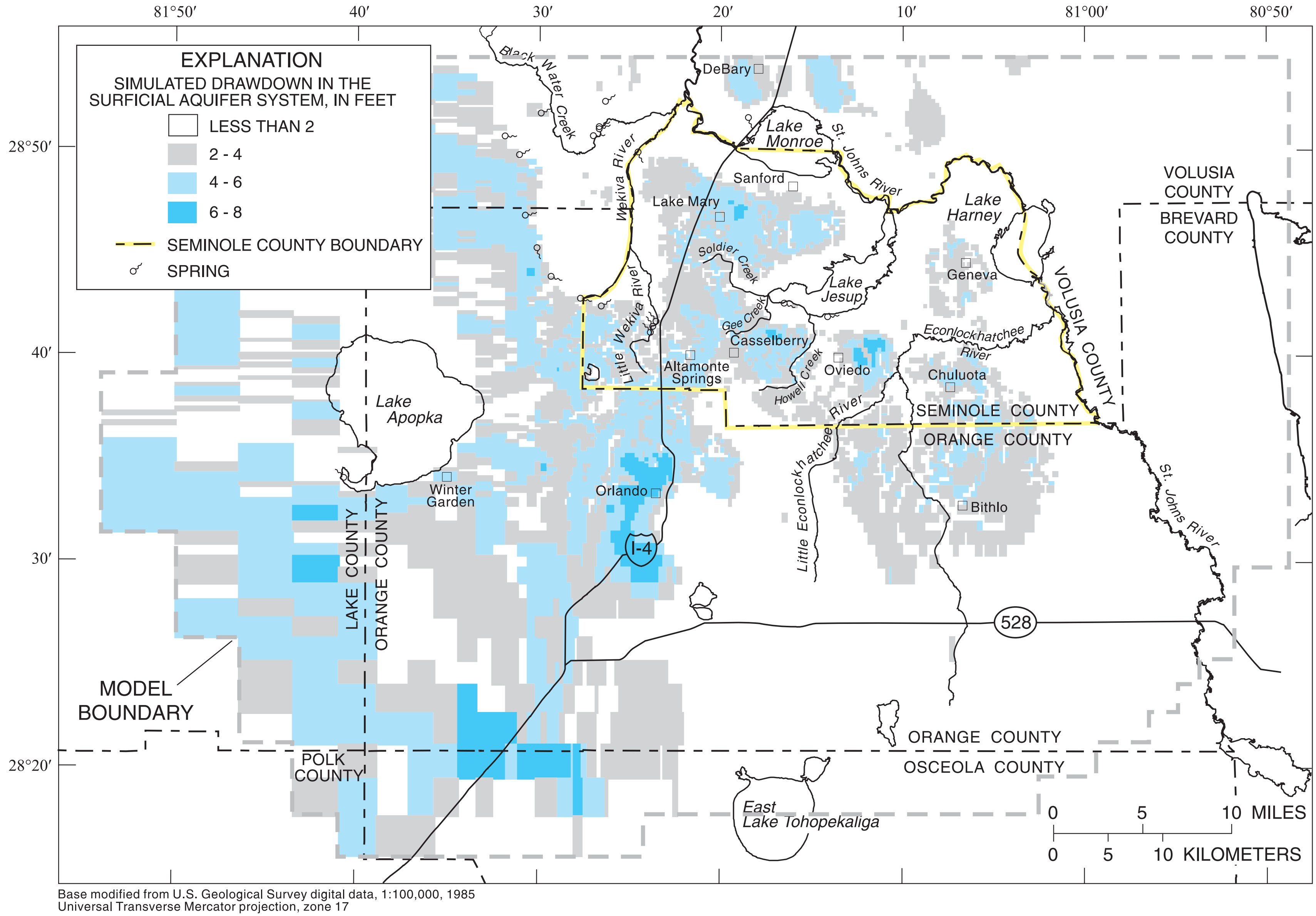


Figure 62. Simulated drawdowns from average projected 2020 conditions to the end of the 180-day transient drought simulation in the surficial aquifer system (layer 1).

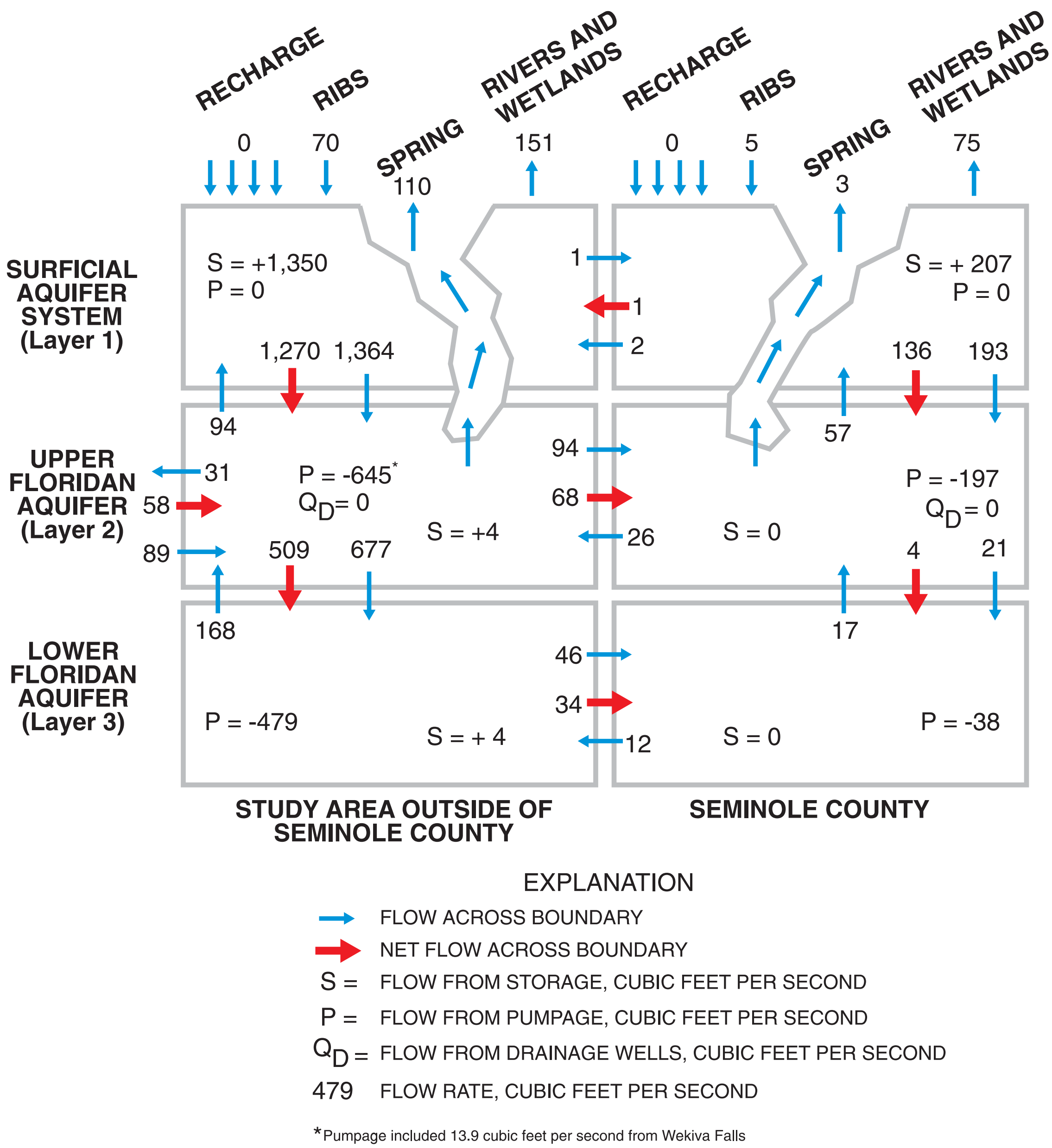


Figure 63. Simulated volumetric flow budget for the end of the 180-day transient drought simulation with 2020 pumpage increased by 50 percent.

Pumpage at the end of the 180-day drought was about 79 percent (1,359 ft^3/s) of the total flow, and was the largest flow component that removed water from the ground-water system (fig. 63). Simulated discharge to rivers and wetlands was the second largest flow component and removed 226 ft^3/s, a reduction of 32 percent from average 2020 conditions. The simulated spring discharge was 113 ft^3/s, which was a 45 percent reduction from average 2020 discharge rates. About 2 percent (31 ft^3/s) of the simulated flow exited through specified heads in the Upper Floridan aquifer (layer 2) along the northern and eastern boundaries.

The simulated flow through Seminole County at the end of the 180-day drought was 353 ft^3/s, which is 23 ft^3/s more than the flow with average 2020 pumpage conditions. Greater pumping rates in Orange and Osceola Counties reduced lateral inflow to Seminole County through the Upper Floridan and Lower Floridan aquifers to 140 ft^3/s (fig. 63). Storage supplied 207 ft^3/s to Seminole County in 2020, which was 29 percent greater than the average 2020 recharge rate (160 ft^3/s).

Pumpage from Seminole County at the end of the 180-day drought was 235 ft^3/s, and was the largest flow component that removed water from the ground-water system in Seminole County (fig. 63). Simulated discharge to rivers and wetlands was about 21 percent (75 ft^3/s) of the total flow through Seminole County, a 36 percent reduction from average 2020 discharge rates. Simulated lateral discharge from Seminole County through the Upper Floridan and Lower Floridan aquifers at the end of the 180-day drought period was 38 ft^3/s, which was similar to average 2020 rates. Simulated spring discharge at the end of the 180-day drought declined 86 percent in Seminole County and 45 percent in the study area. Palm, Sanlando, and Starbuck Springs were affected more than any other springs in Seminole County, and ceased to flow before the end of the 180-day drought period (table 3).

Model Limitations

The flow model addresses questions about ground-water flow and water-level changes in the surficial and Floridan aquifer systems beneath Seminole and surrounding counties fairly well, but it cannot mimic exactly the true system. This model, or any other model, is limited by simplification of the conceptual model, discretization effects, difficulty in obtaining sufficient measurements to justify all of the spatial variation in hydraulic properties throughout the model area, and limitations in the accuracy of land surface altitude measurements.

The use of net recharge rates estimated for the 1996-97 calibration for predictive simulations tends to underestimate the amount of water available for recharge as water levels decline. Reduction of water-table elevations from 1996-97 conditions would expand the area that can capture recharge. Unfortunately, the magnitude and extent of these changes are poorly understood. A more conservative approach was adopted for the predictive simulations because of insufficient knowledge about how much additional water would be captured by lower water-table elevations.

The boundary conditions in the Upper Floridan and Lower Floridan aquifers limit the predictive utility of the calibrated model. Specified water levels in the Upper Floridan aquifer along the northeastern edge of the study area constrain water-level changes near this boundary in the Upper Floridan and Lower Floridan aquifers. Drawdown estimates near the northeastern edge will be underestimated when the simulated stresses are greater than the stresses observed in 1996-97 because the specified water levels cannot decline. No-flow boundaries along the southern and western edges of the study area will cause drawdown estimates to be overestimated near these boundaries.

The Upper Floridan aquifer was truncated beneath the St. Johns and Wekiva Rivers where chloride concentrations were greater than 5,000 mg/L to avoid the effects of variable water density. The truncated boundary of the Upper Floridan aquifer was approximated by a no-flow boundary along the current freshwater/saltwater interface, which was established during the last 10,000 years (Lane, 1994). This is a reasonable simulation approach if the water-quality and potentiometric distributions are in equilibrium and are expected to remain so for all predictive simulations. However, the water-quality and potentiometric distributions within the study area probably were not in equilibrium in 1996-97 and cannot be expected to be so during the predictive simulations. Over the last 100 years, pumpage within the study area has gone from negligible rates to 412 Mgal/d (637 ft^3/s) in 1996-97, and has been projected to increase to 591 Mgal/d (915 ft^3/s) in 2020. Not simulating the areas with chloride concentrations of more than 5,000 mg/L may result in underestimating the potential for the degradation of water quality due to the encroachment and upconing of saline waters.

Another limitation of the model is that the vertical discretization of the hydrogeology was overly generalized. Results from flow logs indicated that the Upper Floridan aquifer can be discretized into at least two layers to simulate the prevailing order-of-magnitude contrast in hydraulic conductivity between the top two-thirds and bottom one-third of the Upper Floridan aquifer. In addition, the middle semiconfining unit probably could be simulated as an aquifer. The coarse vertical discretization used in this model affected comparisons between simulated and measured water levels in areas with large vertical water-level gradients. Thus, in future models the Floridan aquifer system probably should be simulated with a minimum of four layers in the Seminole County area; however, current data limitations prohibit the construction and calibration of such a model.

Lateral discretization of the study area into a rectangular grid of cells and vertical discretization into layers forced an averaging of hydraulic properties. Each cell represents a homogeneous block or some volumetric average of the aquifer medium.

Discretization errors occurred in even the smallest model cells, which were 1,000 ft on a side and about 20 ft thick, because the permeable zones in the aquifers are sand lenses, solution features, or fractures that are considerably smaller in one or two dimensions than the model cells. Due to the averaging of the hydraulic properties, the model cannot simulate the local effects on flow caused by aquifer heterogeneity.

The model of a heterogeneous aquifer system was simplified further by the methods used to describe the spatial variability of the hydraulic conductivity distributions. The uniform areas of lateral hydraulic conductivity in the surficial aquifer system and the Upper and Lower Floridan aquifers provide estimates of the average values but not variations within the areas. The vertical hydraulic conductivity distributions of the intermediate confining unit and middle semiconfining unit also were estimated with broad averages of poorly defined areas. The lack of sufficient measurements to account for all of the spatial variation in hydraulic properties throughout the model area necessitated these simplifications. Simplifying the model to this degree does not invalidate the model results, but does mean that model results should be interpreted at scales larger than the representative elemental volume of hydraulic conductivity.

Alternative Models

More than a dozen alternative models were constructed using estimates of recharge and hydraulic properties that were different than those presented in this report. These alternative models generally explained the observed water levels, water-level differences, ground-water discharges, and closed-basin recharges slightly better than the final model. Best fits of water levels had RMS errors of about 4.0 ftó not all that different from the 5.3 ft RMS error for the calibrated model. Recharge estimates from the alternative models ranged from 1,300 to 1,900 ft^3/s, which is within the range of uncertainty in ground-water discharge estimates that ranged from 900 to 1,900 ft^3/s. The alternative models were rejected, however, because many more parameters were used than could be supported by the data.

The alternative spatial distributions of recharge, hydraulic conductivity of the surficial aquifer system, vertical leakance of the intermediate confining unit, and transmissivity of the Upper Floridan aquifer that were tested are described by the general approaches applied to each particular distribution. The same spatial distributions of vertical leakance of the middle semiconfining unit and transmissivity of the Lower Floridan aquifer were used in all models because insufficient data exist to suggest alternative distributions. Each alternative model is not described because many were permutations from combining the general approaches.

The applied recharge rate distribution was subdivided into as many as three zones that roughly encompassed the areas of Seminole County, west of Seminole County, and south of Seminole County. The Seminole County area was separated from the rest of the model area because the discretization was finer, allowing for better simulation of flow in the surficial aquifer system. Maximum recharge rates in the more coarsely discretized areas were expected to be lower than they would have been where the discretization was finer. Recharge rates west of Seminole County were expected to be higher than anywhere else in the model area because that area is very karstic. Although simulated recharge estimates for the three recharge zones agreed with the expected patterns, the additional complexity did not seem warranted by a minimal reduction in RMS error.

The upper boundary of the surficial aquifer system (layer 1) was constrained with land surface altitude instead of a regressed water-table surface in many of the alternative models. Simulated water-table elevations tended to be higher, maximum recharge rates were lower, and areas where recharge was not constrained by the upper surface tended to be greater than results from the calibrated model. These alternative models typically were biased above measured water levels and had average errors of 0.5 to 1.5 ft, whereas the average error of the calibrated model is -1 ft. Using land surface as an upper boundary was rejected because the simulated water-table elevations were too high and the maximum recharge rates were too low.

The hydraulic conductivity of the surficial aquifer system was alternatively defined by inverse-distance weighted interpolation from the point estimates of log (K) and by arbitrary zones. The calibrated and alternative models were not sensitive to variations in the hydraulic conductivity of the surficial aquifer. Dividing the surficial aquifer system into multiple arbitrary zones made the alternative models less sensitive to any single parameter used to estimate the hydraulic conductivity of the surficial aquifer because the areally less extensive zones were not affected directly by as many water-level observations. Simulated water levels in layer 1 were influenced more by changes in the vertical leakance of the intermediate confining unit than by changes in the horizontal hydraulic conductivity of the surficial aquifer.

Alternative definitions of the vertical leakance of the intermediate confining unit were based on the addition of areas where geologic controls were suggested by the presence of highly karstified closed basins, subsurface structures, and water-quality anomalies in the Upper Floridan aquifer. The addition of these areas locally improved the fit of water levels and closed-basin recharge rates, but did not greatly reduce the overall RMS error of the model. The use of these additional areas ultimately was rejected because the lateral extents were poorly defined, and the model generally was insensitive to vertical leakance change in many of these areas.

Variations in transmissivity of the Upper Floridan aquifer was defined by two zonation methods. One method assumed that transmissivity estimates from aquifer tests could be applied to 3-mile-diameter circles around each test site and the unspecified areas could be subdivided and estimated independently. The other method was to arbitrarily divide the transmissivity distribution into many areas. Neither approach worked well because transmissivity changes in the majority of areas did little to alter the simulated water levels.

SUMMARY AND CONCLUSION

The study area covers about 2,500 square miles of east-central Florida and includes all of Seminole and Orange Counties and parts of Brevard, Lake, Osceola, Polk, and Volusia Counties. Rapid increases in population during the past 30 years have occurred throughout the area. From 1965 to 1995, the population of Seminole County increased from about 73,000 to 324,000. During the same period, Orange County, one of the most populous counties in the state, increased from about 309,000 to 759,000. The population in Seminole and Orange Counties is projected to reach about 509,000 and 1,236,000, respectively, by the year 2020.

The Floridan aquifer system is the major source of water supply in the study area. In 1965, withdrawals from the Floridan aquifer system in Seminole County were about 11 million gallons per day (Mgal/d). In 1995, withdrawals totaled about 69 Mgal/d. Ground-water withdrawals from the Floridan aquifer in adjacent Orange County, increased from 82 Mgal/d in 1965 to about 229 Mgal/d in 1995.

The principal water-bearing units in the study area are the surficial aquifer and the Floridan aquifer systems. The two aquifer systems are separated by the intermediate confining unit, which contains beds of lower permeability sediments that confine the water in the Floridan aquifer system.

The surficial aquifer system is unconfined and consists mainly of lenses of fine-to-medium quartz sand and varying amounts of shell and clay. The deposits generally are discontinuous, and the lithology and texture of the deposits can vary considerably over short distances both vertically and laterally. Thickness of the surficial aquifer system in the study area is highly variable, ranging from about 10 feet (ft) to more than 150 ft. The water table in the surficial aquifer system fluctuates about 2 to 5 ft seasonally. The water-bearing properties of the surficial aquifer system vary considerably from location to location. Field hydraulic conductivities determined from slug tests performed on 21 surficial aquifer system wells in Seminole County range from 0.5 to 40 ft/d. Recharge to the surficial aquifer system is chiefly by the infiltration of rainfall. The surficial aquifer system provides small amounts of water for lawn irrigation and domestic use.

The intermediate confining unit consists of interbedded, locally highly phosphatic, clay, silt, sand, limestone, and dolomite. Throughout most of the study area, the intermediate confining unit serves as a confining layer (except where breached by sinkholes) that restricts the vertical movement of water between the surficial aquifer system and the Upper Floridan aquifer. Thickness of the intermediate confining unit is highly variable due to past erosional processes and sinkhole formation and ranges from less than 25 ft in parts of Seminole and southern Volusia Counties to more than 200 ft in southeastern Orange County. Sinkholes, which are common in western Seminole, western Orange, and eastern Lake Counties, provide avenues for water from the surficial aquifer system to recharge the underlying Upper Floridan aquifer.

The Floridan aquifer system is subdivided into two major aquifers, the Upper and the Lower Floridan aquifers, separated by the less permeable middle semi-confining unit. The Upper Floridan aquifer can be further subdivided into two separate zones of different permeabilities. The Floridan aquifer system consists primarily of limestone and dolomite of Eocene age. The altitude of the top of the Floridan aquifer ranges from about 50 ft above sea level in the southwestern part of the study area to more than 250 ft below sea level in southeastern Orange County. In Seminole County, the altitude at the top of the aquifer ranges from more than 100 feet below sea level in the northwestern part of the county to less than 50 feet below sea level in much of the eastern, western, and southern parts of the County. The surface of the Upper Floridan aquifer is irregular and paleokarstic.

Ground water in the Upper Floridan aquifer moves regionally in a southwest-to-northeast direction across the study area. In May 1997, the potentiometric surface of the Upper Floridan aquifer ranged from about 120 ft above sea level in extreme northeastern Polk County to about 8 ft above sea level in southern Volusia County. Depressions in the potentiometric surface of the Upper Floridan aquifer in various parts of the study area result from pumping, diffuse upward leakage, and spring discharge.

Upper Floridan aquifer water levels and spring flow have been affected by ground-water development. Hydrographs of three wells tapping the Upper Floridan aquifer show a general downward trend from about 1960-90. The water-level declines are caused predominantly by increased pumpage and cumulative below-average rainfall. From 1990-97, water levels have risen slightly, a trend that can be explained by the cumulative above average rainfall. Decreases in spring discharge also have been observed in some springs.

Concentrations of chemical constituents in water in the Floridan aquifer system vary both areally and with depth. The chemical quality of water in the Upper Floridan aquifer generally varies with proximity to recharge and discharge areas.

The quality of water in the Upper Floridan aquifer varies considerably in Seminole County. Specific conductance ranges from 210 to about 14,700 microsiemens per centimeter (μS/cm) at 25° C. Chloride concentrations range from 6.2 to 5,300 milligrams per liter (mg/L) and sulfate concentrations range from 0 to 760 mg/L. Chloride concentrations are lowest in the recharge areas of the Floridan aquifer system in the western part of Seminole County and around Geneva. The most highly mineralized water occurs adjacent to the Wekiva River in northwest Seminole County and in the area around the eastern part of Lake Jesup and along the Econlockhatchee and St. Johns River in eastern Seminole County. The thickest section of freshwater in Seminole County is located in the extreme southwestern part of the county. Depth to water having chloride concentrations greater than 250 mg/L in this area is more than 2,000 ft below land surface. With the exception of the Geneva area, depth to the 250-mg/L isochlor is less than 200 ft in most of the eastern part of Seminole County and around the Wekiva River.

Analysis of limited long-term water-quality data indicates that the chloride concentrations of water for most wells in the Floridan aquifer system in Seminole County have not changed significantly in the 20-year period from 1976 to 1996, and probably not since the mid 1950ís. Analysis of water samples collected from some Upper Floridan aquifer springs, however, indicates that the water has become more mineralized during recent years. Increases in specific conductance and major cations and anions, such as chloride and sulfate, were observed at many of the springs in the study area where long-term water-quality data were available. Associated with these increases in the mineralization of spring water has been an observed increase in total nitrate and nitrite concentrations. The presence of elevated nitrate concentrations in spring water could be an indication of contamination from fertilizers, animal waste, or sewage.

A three-dimensional ground-water flow model of the study area was constructed and used to simulate ground-water flow in the surficial and Floridan aquifer systems. The active model grid covered an area of about 2,500 square miles (mi^2) and was divided into 137 rows of 195 columns. The model was vertically discretized into three active layers to simulate the surficial aquifer system (layer 1), the Upper Floridan aquifer (layer 2), and the Lower Floridan aquifer (layer 3). A steady-state ground-water flow model was calibrated to water-level data that were averaged over a 1-year period from September 1996 through August 1997. Model calibration was facilitated by using a parameter-estimation program. The calibrated model generally produced simulated water levels in reasonable agreement with measured water levels, and was used to simulate the effects of expected increases in ground-water withdrawals on the water levels in the surficial aquifer system and the potentiometric surface of the Upper and Lower Floridan aquifers in the study area.

The calibrated flow model was used to simulate the possible effects of increased pumpage from the Floridan aquifer system in the year 2020. Pumpage in the study area has been projected to increase from 412 Mgal/d (637 ft^3/s) in 1996-97 to 591 Mgal/d (915 ft^3/s) in 2020. The projected 2020 pumpage reduced simulated water levels from 1996-97 conditions in much of the modeled area in the surficial aquifer system and in the Upper and Lower Floridan aquifers. The greatest simulated drawdowns from 1996-97 to 2020 generally occurred near projected new pumping centers in central Orange County.

Simulated drawdowns of greater than 5 ft in the surficial aquifer system generally occurred in the southern part of the modeled area. The maximum simulated drawdown in the surficial aquifer system was about 16 ft. Simulated water-level declines in the active lakes averaged 4.8 ft and ranged from 0.4 to 10.9 ft.

Projected pumpage increases from the Floridan aquifer system in Orange and Osceola Counties from 1996-97 through 2020 affected simulated water levels in Seminole County. Simulated water levels in the Upper and Lower Floridan aquifers declined about 9 ft in the southwestern part of Seminole County. Simulated drawdowns of less than 2 ft in the Upper Floridan aquifer occurred primarily in the northeastern part of Seminole County and along the St. Johns River. Simulated drawdowns of greater than 14 ft in the Upper and Lower Floridan aquifers generally occurred in the south-central part of the modeled area. Projected 2020 pumpage also affected discharge from springs. Simulated spring discharge declined 50 percent in Seminole County and 27 percent in the entire study area.

The effects of an extreme drought were investigated with a transient model of the study area. The transient flow fields of the surficial and Floridan aquifer systems were simulated using a 180-day stress period with no recharge. The projected 2020 pumpage was increased by 50 percent during the drought period. Drawdowns of 2 ft or more in the surficial aquifer system generally occurred in the western part of the study area, in western Seminole County, and around the Seminole-Orange County line near the Econlockhatchee River. The maximum simulated drawdown in the surficial aquifer system was about 8 ft. Simulated water levels declined by as much as 20 ft in the Upper Floridan aquifer and 24 ft in the Lower Floridan aquifer. Simulated water-level declines in the active lakes averaged 0.4 ft and ranged from 0 to 1.8 ft at the end of the 180-day drought. Simulated spring discharge declined 86 percent in Seminole County and 45 percent in the study area.

Results derived from this study were based primarily on ground-water flow model simulations. This model, or any other model, however, is limited by simplification of the conceptual model, discretization effects, difficulty in obtaining sufficient measurements to account for all spatial variation in hydraulic properties throughout the model area, and limitations in the accuracy of land surface altitude measurements.

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APPENDIXES

Appendix 1. Well and spring data-collection sites

[--, no data; na, not applicable. Abbreviations for aquifer: S, surficial aquifer system; ICU, intermediate confining unit; UF, Upper Floridan aquifer; MSCU, middle semiconfining unit; LF, Lower Floridan aquifer; SFCU, sub Floridan confining unit. Abbreviations for data type: qw, water-quality sample; Q, spring discharge; wl, ground-water level. Abbreviations for source of data: SJRWMD, St. Johns River Water Management District; USGS, U.S. Geological Survey. Site locations shown in figure 3]

Site number	USGS site identification number	Station name	Aquifer	Bottom of casing (feet)	Depth of well (feet)	Data type	Source of data	County
1	281506081194601	OSF-70	UF	130	470	wl	USGS	Osceola
2	281511081393101	815139342 26S26E01	UF	358	447	wl	USGS	Osceola
3	281532081345001	Loughman Deep	UF	85	247	wl	USGS	Osceola
4	281532081493001	815149233 25S25E32	UF	--	231	wl	USGS	Polk
5	281536081324801	Florida Power	UF	63	261	wl	USGS	Osceola
6	281559081260701	Shingle Creek	UF	--	200	wl	USGS	Osceola
7	281630080591001	TH-3 Lake Poinsetta SW	UF	245	377	wl	USGS	Osceola
8	281630081024401	TH-9 Nova Road West	UF	288	405	wl	USGS	Osceola
9	281632080515001	DSR-38	UF	--	253	wl	USGS	Osceola
10	281714081093001	Lake Joel	UF	394	750	wl	USGS	Osceola
11	281937081245901	Bermuda OSF-9	UF/MSCU/LF	280	1,200	wl	USGS	Osceola
12	282051081133201	Lake Ajay Village	UF	373	470	wl	USGS	Osceola
13	282051081183401	Boggy Creek Road	UF	199	400	wl	USGS	Orange
14	282126081403901	821140	UF	--	--	wl	USGS	Lake
15	282141081241701	US 441 Phone Relay	UF	317	435	wl	USGS	Orange
16	282145081365601	Hartzog Road 4" Britt Groves	UF	--	--	wl	USGS	Orange
17	282202081384601	Lake Oliver Deep	UF	103	318	wl	USGS	Orange
18	282204080514301	Lake Poinsett	UF	--	553	wl	USGS	Orange
19	282215081230001	OCU SRWF, MW2A	SFCU	2,050	2,467	wl	USGS	Lake
20	282220081225401	OCU SRWF, MW1A	LF	1,160	1,705	wl	USGS	Orange
21	282241081112801	Moss Park	UF	240	480	wl	USGS	Orange
22	282241081443901	L-0051	UF	85	115	wl	SJRWMD	Lake
23	282245081492601	Eva Deep	UF	105	192	wl	USGS	Lake
24	282331081370801	Hartzog Road	UF	68	166	wl	USGS	Orange
25	282341081040101	Cocoa A	UF	301	516	wl	USGS	Orange
26	282348080564701	Palmetto Well	UF	245	381	wl	USGS	Orange
27	282354081313001	RCID Observation Well #1	UF	145	281	wl	USGS	Orange
28	282406081093602	Cocoa R	LF	1,098	1,205	wl	USGS	Orange
29	282411081211301	OUC Orange Test Well	LF	1,098	1,424	wl	USGS	Orange
30	282434081283102	Sea World Replacement Well	UF	158	239	wl	USGS	Orange
31	282502081422301	Lykes Brothers Replacement Well	UF	--	--	wl	USGS	Lake
32	282510081054501	Cocoa 1	UF	316	710	wl	USGS	Orange
33	282511081271701	OCU Orangewood #4	LF	1,100	1,250	wl	USGS	Orange
34	282515081162601	OUC SE Test Well	LF	1,090	1,399	wl	USGS	Orange
35	282528081340901	Bay Lake Deep	UF	104	223	wl	USGS	Orange
36	282530081054201	Cocoa 7	UF	285	490	wl	USGS	Orange
37	282530081065601	Cocoa S, OR0614	LF	1,170	1,250	wl	USGS	Orange
38	282530081065602	Cocoa S, OR0615	MSCU	900	1,050	wl	USGS	Orange
39	282530081065603	Cocoa S, OR0613, Interface Well	LF	1,428	1,500	wl	USGS	Orange
40	282531081095701	Cocoa D	UF	226	300	wl	USGS	Orange
41	282532081075601	Cocoa B	UF	235	515	wl	USGS	Orange
42	282532081511801	Barry	UF	125	232	wl	USGS	Lake
43	282533081082204	Cocoa C, Zone 3	LF	1,218	1,224	wl	USGS	Orange
44	282533081082206	Cocoa C, Zone 5, OR0024	UF/MSCU	248	1,004	wl	USGS	Orange
45	282543081385801	82513801	UF	--	--	wl	USGS	Orange
46	282623081153801	Cocoa P	UF	245	439	wl	USGS	Orange

Appendix 1. Well and spring data-collection sites--Continued

[--, no data; na, not applicable. Abbreviations for aquifer: S, surficial aquifer system; ICU, intermediate confining unit; UF, Upper Floridan aquifer; MSCU, middle semiconfining unit; LF, Lower Floridan aquifer; SFCU, sub Floridan confining unit. Abbreviations for data type: qw, water-quality sample; Q, spring discharge; wl, ground-water level. Abbreviations for source of data: SJRWMD, St. Johns River Water Management District; USGS, U.S. Geological Survey. Site locations shown in figure 3]

Site number	USGS site identification number	Station name	Aquifer	Bottom of casing (feet)	Depth of well (feet)	Data type	Source of data	County
47	282650081262502	Sand Lake Road	LF	2,005	2,030	wl	USGS	Orange
48	282657081230401	OUC Sky Lake #2	LF	960	1,390	wl	USGS	Orange
49	282705081430701	Trout Lake	UF	--	--	wl	USGS	Lake
50	282709081283001	USGS Well NR I-4 and 528A	UF	68	205	wl	USGS	Orange
51	282718081405601	Conserv II 4W3	UF/MSCU	157	1,000	wl	USGS	Orange
52	282718081215101	Pinecastle Post Office	UF	--	--	wl	USGS	Orange
53	282729081443301	Lake Louisa State Park, L-0053	UF	70	85	wl	USGS	Lake
54	282738081341401	Lake Sawyer Well	UF	103	178	wl	USGS	Orange
55	282739081054501	Cocoa F	UF	200	375	wl	USGS	Orange
56	282749081315801	82713101	UF	120	347	wl	USGS	Orange
57	282758081392801	Conserv II 1W-2	UF/MSCU/LF	146	1,402	wl	USGS	Orange
58	282823081500401	Gaffney	UF	96	390	wl	USGS	Lake
59	282833081544201	Brown	UF	86	324	wl	USGS	Lake
60	282835081305201	Palm Lake Drive	UF	161	235	wl	USGS	Orange
61	282847081013701	Cocoa H	UF	252	495	wl	USGS	Orange
62	282848080544501	Tosohatchee Game Preserve	UF	152	335	wl	USGS	Orange
63	282910081181301	OCU Conway #3	UF	148	700	wl	USGS	Orange
64	282923081282801	Ivey	UF	168	337	wl	USGS	Orange
65	282931081285901	OCU Hidden Springs #4	LF	1,250	1,400	wl	USGS	Orange
66	282936081340201	Ross	UF	180	280	wl	USGS	Orange
67	283006081274101	OUC #33 Kirkman #3	LF	983	1,400	wl	USGS	Orange
68	283011081152401	OCU Eastern Regional Wellfield	LF	1,100	1,385	wl	USGS	Orange
69	283012081152301	OCU Eastern Regional Wellfield	UF	210	550	wl	USGS	Orange
70	283011081360002	West Orange Country Club	UF	100	260	wl	USGS	Orange
71	283017081391301	Davenport Road 4"	UF	--	--	wl	USGS	Orange
72	283048081194801	OUC #24 Conway #3	LF	1,063	1,350	wl	USGS	Orange
73	283102081223401	OUC #10 Kuhl #1	LF	953	1,283	wl	USGS	Orange
74	283111081502001	Defrene	UF	123	329	wl	USGS	Lake
75	283116081442301	Rings Pond	UF	--	--	wl	USGS	Orange
76	283126081064501	OR0617	UF	210	550	wl	SJRWMD	Orange
77	283126081064502	Long Branch OR0618	LF	1,140	1,280	wl	SJRWMD	Orange
78	283128081404701	Johns Lake Well, L-0052	UF	73	155	wl	USGS	Lake
79	283135081155201	OCU Rio Pinar	LF	1,000	1,120	wl	USGS	Orange
80	283135081234301	Layne Atlantic	LF	1,170	1,230	wl	USGS	Orange
81	283144081254201	Lake Mann Drainage Well, OR0174	UF	137	400	wl	USGS	Orange
82	283204081544901	Mascotte Deep	UF	66	160	wl	USGS	Lake
83	283214080583501	Department of Transportation	UF	--	200	qw, wl	USGS	Orange
84	283215081321201	Ocoee So #2	LF	810	1,450	wl	USGS	Orange
85	283224081210201	OUC #9 Primrose #2	LF	993	1,150	wl	USGS	Orange
86	283232081394101	Edgewater Beach	UF	--	--	wl	USGS	Lake
87	283236080535101	Titusville SW TP	UF	--	247	wl	USGS	Brevard
88	283236081290901	OCU Oak Meadows #4	MSCU/LF	707	1,260	wl	USGS	Orange
89	283249081053201	Bithlo 1, OR0007	UF	151	492	qw, wl	USGS/SJRWMD	Orange
90	283249081053203	Bithlo 3	S	12	15	wl	USGS	Orange
91	283253081283401	OR0047	UF	328	350	wl	USGS	Orange
92	283307081300801	Sherwood Drain	UF	118	450	wl	USGS	Orange
93	283307081435301	Jacks Lake	UF	--	--	wl	USGS	Lake

Appendix 1. Well and spring data-collection sites--Continued

[--, no data; na, not applicable. Abbreviations for aquifer: S, surficial aquifer system; ICU, intermediate confining unit; UF, Upper Floridan aquifer; MSCU, middle semiconfining unit; LF, Lower Floridan aquifer; SFCU, sub Floridan confining unit. Abbreviations for data type: qw, water-quality sample; Q, spring discharge; wl, ground-water level. Abbreviations for source of data: SJRWMD, St. Johns River Water Management District; USGS, U.S. Geological Survey. Site locations shown in figure 3]

Site number	USGS site identification number	Station name	Aquifer	Bottom of casing (feet)	Depth of well (feet)	Data type	Source of data	County
94	283325081374001	City of Oakland #2	UF	148	370	wl	USGS	Orange
95	283326081262101	Lake Lawne Drainage Well	UF	84	109	wl	USGS	Orange
96	283327081223201	OUC Highland Well #7	LF	943	1,415	wl	USGS	Orange
97	283333081233501	Lake Adair 9, OR0009	MSCU/LF	601	1,281	wl	USGS	Orange
98	283333081233502	Lake Adair 10	UF	105	400	wl	USGS	Orange
99	283340081222801	Lake Ivanhoe Interface Well, OR0465	LF	2,060	2,089	wl	USGS	Orange
100	283340081222802	Lake Ivanhoe LF, OR0467	LF	1,300	1,350	wl	USGS	Orange
101	283340081222803	Lake Ivanhoe, OR0468	UF	189	450	wl	USGS	Orange
102	283353081185801	OUC #22, Navy	LF	1,080	1,370	wl	USGS	Orange
103	283355081411701	L-0199 Turnpike	UF	110	146	wl	USGS	Lake
104	283357081272201	OUC #8 Pine Hills #1	LF	1,000	1,414	wl	USGS	Orange
105	283400081405100	Apopka Spring	UF	na	na	Q	USGS	Lake
106	283406081150601	Union Park	UF	--	--	qw, wl	USGS	Orange
107	283417081331401	Ocoee SR 438 Drainage Well	UF	--	500	wl	USGS	Orange
108	283436081194501	Lake Speir Drainage Well	UF	--	--	wl	USGS	Orange
109	283441081203301	Glenridge Deep	LF	1,210	1,300	wl	USGS	Orange
110	283517081120501	CFRP-Research Pkwy MW5	S	10	15	wl	SJRWMD	Orange
111	283528081235201	Lake Fairview Drainage Well	UF	176	745	wl	USGS	Orange
112	283530081214301	Lake Midget Drainage Well	UF	170	372	wl	USGS	Orange
113	283530081514501	Lake Lucy	UF	73	141	wl	USGS	Lake
114	283548081181401	Winter Park, FTU Blvd Deep	MSCU/LF	700	1,354	wl	USGS	Orange
115	283555081300801	Ocoee Forest Oaks #3	LF	1,192	1,450	wl	USGS	Orange
116	283610081113701	UCF Oak Hammock MW3	S	6	11	wl	SJRWMD	Orange
117	283623081230501	Wymore and Lee Roads	LF	1,160	1,270	wl	USGS	Orange
118	283626081121501	UCF Pond MW2	S	2.5	7.5	wl	SJRWMD	Orange
119	283627080512001	BR0001	UF	132	136	wl	SJRWMD	Brevard
120	283644080574901	BR0660	UF	98	247	qw, wl	SJRWMD	Brevard
121	283644080574903	Silver Lake, BR1526	UF	235	300	wl	USGS	Brevard
122	283646081195401	Bradner	UF	120	150	qw, wl	USGS	Orange
123	283654081260801	Lake Davis Drainage Well	UF	250	365	wl	USGS	Orange
124	283702081183901	Casselberry South S-2	MSCU/LF	600	1,200	wl	USGS	Seminole
125	283717081194202	Phillips	UF	85	290	wl	USGS	Seminole
126	283719081173601	Eastbrook Elementary	S	14	24	wl	USGS	Seminole
127	283732080510001	BR0585	UF	132	195	wl	USGS	Brevard
128	283732080510002	BR1469	S	19	29	wl	SJRWMD	Brevard
129	283740081031401	Lee	UF	84	273	qw, wl	USGS	Seminole
130	283754081154301	Woods	UF	--	131	qw, wl	USGS	Seminole
131	283758081120401	Seminole County Lake Hayes 2	UF	232	435	qw	USGS	Seminole
132	283800081115501	Lake Hayes, S-1215	LF	582	904	wl	USGS	Seminole
133	283800081154601	Tuskawilla Middle School	S	29	39	wl	USGS	Seminole
134	283802081252001	OCU Riverside #4	MSCU/LF	502	1,231	wl	USGS	Orange
135	283810081172401	Seminole County Consumers 1	UF	168	595	qw	USGS	Seminole
136	283813081292101	OCU Western Regional TP-2	LF	1,037	1,455	wl	USGS	Orange
137	283813081325701	State Foliage Research	UF	--	200	wl	USGS	Orange
138	283816081225501	Lake Charity Well	UF	325	374	wl	USGS	Orange
139	283818081291201	OCU Western Regional wellfield LF-1	LF	1,031	1,580	wl	USGS	Orange
140	283819081292601	OCU Western Regional wellfield TP-1	LF	1,032	1,450	wl	USGS	Orange

Appendix 1. Well and spring data-collection sites--Continued

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Site number	USGS site identification number	Station name	Aquifer	Bottom of casing (feet)	Depth of well (feet)	Data type	Source of data	County
141	283821081074401	Southern States Chuluota 1	UF	122	240	qw	USGS	Seminole
142	283837081113001	City of Oviedo 205	UF	100	300	qw	USGS	Seminole
143	283843081075501	Green	UF	95	107	qw, wl	USGS	Seminole
144	283844081200101	Seminole County Indian Hills 1	UF	200	470	qw	USGS	Seminole
145	283848081122702	Canterbury Road MW7	S	8	13	wl	SJRWMD	Seminole
146	283849081273401	Ecological Utilities Corp	UF	--	105	wl	USGS	Seminole
147	283850081202601	English Estate Elementary	S	9	19	wl	USGS	Seminole
148	283851081221101	Altamonte Springs WP 2 Well 4	UF	184	495	qw	USGS	Seminole
149	283852081165501	Red Bug Elementary	S	25	35	wl	USGS	Seminole
150	283853081060301	Jacobs	UF	80	137	qw	USGS	Seminole
151	283854081134701	Stanko	UF	110	190	qw	USGS	Seminole
152	283858081092001	Partin Elementary	S	4	14	wl	USGS	Seminole
153	283858081191601	F2400 Florida Power	MSCU/LF	600	1,200	wl	USGS	Seminole
154	283858081221801	Lake Orienta Elementary	S	25	35	wl	USGS	Seminole
155	283901081135901	Jacobson	UF	85	132	qw	USGS	Seminole
156	283906081290001	Sheeler Oaks	MSCU/LF	600	1,200	wl	USGS	Orange
157	283908081120701	City of Oviedo 203	UF	160	300	qw	USGS	Seminole
158	283912081095601	Steinmatz	UF	--	120	qw	USGS	Seminole
159	283918081254301	Altamonte Springs Plant 5 Well 7	UF	310	520	qw	USGS	Seminole
160	283920081232501	Spanish Trace Apts.	UF	--	250	wl	USGS	Seminole
161	283925081124201	City of Oviedo 101	UF	258	341	qw	USGS	Seminole
162	283932081123601	Oviedo WTP, S-1211	S	20	30	wl	USGS	Seminole
163	283933081123102	Oviedo WTP, S-1189	UF	500	600	wl	USGS	Seminole
164	283933081123103	Oviedo WTP, S-1193	UF	87	220	wl	USGS	Seminole
165	283933081123105	Oviedo WTP, S-1078	LF	1,230	1,288	wl	USGS	Seminole
166	283933081185701	Casselberry Elementary	S	12	22	wl	USGS	Seminole
167	283936081162801	Citrus Road, S-1056	UF	156	365	wl	USGS	Seminole
168	283936081162804	Citrus Road, S-1329	LF	1,050	1,150	wl	USGS	Seminole
169	283944081251701	Deep South	MSCU/LF	577	1,205	wl	USGS	Seminole
170	283945081071901	Brown	UF	--	190	wl	USGS	Seminole
171	283955080565701	Plastic	UF	--	97	wl	USGS	Brevard
172	283956081040201	Yarborough	UF	--	71	qw, wl	USGS	Seminole
173	283957081270601	Bear Lake Elementary	S	27	37	wl	USGS	Seminole
174	283958081203401	840-120-02	UF	--	101	wl	USGS	Seminole
175	284006081272001	Seminole County Bel Aire 1	UF	150	250	qw	USGS	Seminole
176	284007081113501	Jackson Heights	S	7	17	wl	USGS	Seminole
177	284012081264601	Benton	UF	--	--	wl	USGS	Seminole
178	284025081072401	S-0285	UF	--	--	qw	SJRWMD	Seminole
179	284025081123001	Arie	UF	85	282	qw, wl	USGS	Seminole
180	284033081052701	Yarborough	UF	--	100	qw	USGS	Seminole
181	284043081054401	Yarborough	UF	--	78	qw	USGS	Seminole
182	284043081154001	Winter Springs East 3	UF	190	395	qw	USGS	Seminole
183	284043081154601	Winter Springs East 1	UF	105	290	qw	USGS	Seminole
184	284049081221501	Altamonte Springs Elementary	S	30	40	wl	USGS	Seminole
185	284050081065301	Snow Hill Road, S-1200	UF	500	600	wl	USGS	Seminole
186	284050081065302	Snow Hill Road, S-1201	UF	100	140	wl	USGS	Seminole
187	284050081065303	Snow Hill Road, S-1300	S	8	18	wl	USGS	Seminole
188	284052081212601	Charlotte St., S-1014	UF	142	300	qw, wl	SJRWMD	Seminole

Appendix 1. Well and spring data-collection sites--Continued

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Site number	USGS site identification number	Station name	Aquifer	Bottom of casing (feet)	Depth of well (feet)	Data type	Source of data	County
189	284052081212602	Charlotte St., S-1015	S	40	50	wl	SJRWMD	Seminole
190	284052081212605	Charlotte St., S-1024	LF	1,246	1,506	wl	SJRWMD	Seminole
191	284056081234401	Sanlando Softball Complex MW3	S	37	52	wl	USGS	Seminole
192	284057081191901	Casselberry North N2400	MSCU/LF	600	1,200	wl	USGS	Seminole
193	284058081200301	Tenneco Well MW2	S	5	15	wl	USGS	Seminole
194	284059081365401	DPC Testwell	UF	132	215	wl	USGS	Orange
195	284105081154301	Keeth Elementary	S	14	24	wl	USGS	Seminole
196	284111081063401	Yarborough	UF	--	90	qw	USGS	Seminole
197	284112081181801	Winter Springs Plant 3, Well 4	UF	97	423	qw	USGS	Seminole
198	284116080514001	Mims	UF	--	173	wl	USGS	Brevard
199	284118081262201	Wekiva Elementary	S	28	38	wl	USGS	Seminole
200	02234991	Sanlando Springs	UF	na	na	qw, Q	USGS	Seminole
201	284119081244801	Southern States Meredith Manor 1	UF	83	400	qw	USGS	Seminole
202	284120081152201	Bouillon	UF	--	185	qw, wl	USGS	Seminole
203	284122081534401	Groveland Tower Deep, L-0095	UF	148	368	wl	USGS	Lake
204	284125081131701	Mann	UF	80	90	qw, wl	USGS	Seminole
205	02234996	Palm Springs	UF	na	na	qw, Q	USGS	Seminole
206	284128081320901	Apopka Grossenbacher #4, OR0554	MSCU/LF	660	1,400	wl	USGS	Orange
207	284133081085501	McNair	UF	--	230	qw	USGS	Seminole
208	284133081105701	Florida Avenue	UF	--	na	qw, wl	USGS	Seminole
209	284139081255401	Seminole County Lake Brantley 1	UF	--	--	qw	USGS	Seminole
210	284147081220201	Seminole 125	UF	63	146	wl	USGS	Seminole
211	02234997	Starbuck Spring	UF	na	na	qw, Q	USGS	Seminole
212	284156081141400	Clifton Springs	UF	na	na	qw, Q	USGS	Seminole
213	284159081101701	S-1067	UF	--	53	qw	SJRWMD	Seminole
214	284201081102601	S-1128	UF	--	85	qw	SJRWMD	Seminole
215	284206081195401	Longwood Elementary	S	14	24	wl	USGS	Seminole
216	284207081174401	Neely	UF	--	90	qw, wl	USGS	Seminole
217	284216081221801	Rock Lake Middle School	S	30	40	wl	USGS	Seminole
218	284216081250701	Sabal Point Elementary	S	13	23	wl	USGS	Seminole
219	284217081023001	Kilbee #3, S-0025	UF	58	154	qw, wl	USGS/SJRWMD	Seminole
220	284217081172501	Transportation Dept.	S	19	29	wl	USGS	Seminole
221	284230081345301	Plymouth Towers	UF	100	395	wl	USGS	Orange
222	284232081110201	S-0983	UF	--	58	qw	SJRWMD	Seminole
223	284232081533001	Citrus Properies	UF	100	593	wl	USGS	Lake
224	284233081045202	S-0042	UF	107	140	qw	SJRWMD	Seminole
225	02234650	Miami Springs	UF	na	na	qw, Q	USGS	Seminole
226	284237081190201	Winter Springs WP 2, Well 3	UF	123	491	qw	USGS	Seminole
227	284238081275802	OR0547	MSCU	440	645	wl	SJRWMD	Orange
228	284238081275803	OR0548	UF	100	155	qw, wl	USGS/SJRWMD	Orange
229	284241081402601	Keen Ranch	UF	90	94	wl	USGS	Lake
230	284243081225901	Boyles	UF	--	158	qw, wl	USGS	Seminole
231	02234600	Wekiva Springs	UF	na	na	qw, Q	USGS	Orange
232	284244081234901	Clouser	UF	--	118	qw	USGS	Seminole
233	284245081463302	Number 2	UF	192	331	wl	USGS	Lake
234	284247081070801	S-0001	UF	95	204	qw, wl	SJRWMD	Seminole
235	284255081222201	Woodlands Elementary	S	28	38	wl	USGS	Seminole

Appendix 1. Well and spring data-collection sites--Continued

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Site number	USGS site identification number	Station name	Aquifer	Bottom of casing (feet)	Depth of well (feet)	Data type	Source of data	County
236	284305081261601	S-0867	UF	--	--	qw	SJRWMD	Seminole
237	284306081101701	S-0051	UF	119	122	qw	SJRWMD	Seminole
238	284315081182702	S-0829	UF	85	180	qw, wl	USGS/SJRWMD	Seminole
239	284317081085701	Cockran Road, S-0045	S	27	37	wl	USGS	Seminole
240	284317081213401	Principe	UF	--	--	qw, wl	USGS	Seminole
241	284320081410701	Apopka Beauclair Canal Deep	UF	575	650	wl	USGS	Lake
242	284322081084301	Cockran Forest E., S-0028	UF	90	203	qw, wl	USGS/SJRWMD	Seminole
243	284325081092701	Cockran Forest W. Dp, S-0038	UF	56	165	qw, wl	USGS/SJRWMD	Seminole
244	284325081092702	Cockran Forest W. Sh, S-0035	S	32	35	wl	USGS	Seminole
245	284330081360501	World Foilage Resource	UF	127	403	wl	USGS	Orange
246	284331081031001	Pecor	UF	--	117	qw, wl	USGS	Seminole
247	284339081184601	S-1127	UF	--	148	qw	USGS	Seminole
248	284341081254901	S-0866	UF	--	49	qw	SJRWMD	Seminole
249	02234620	Witherington Springs	UF	na	na	Q	USGS	Orange
250	284401081194701	Seminole County Country Club 2	UF	167	350	qw	USGS	Seminole
251	284412081071102	Geneva, S-1253	UF	132	280	wl	USGS	Seminole
252	284412081071103	Geneva, S-1288	S	20	30	wl	USGS	Seminole
253	284414081202501	Greenwood Lakes	S	14	24	wl	USGS	Seminole
254	284421081251701	S-0865	UF	--	38	qw	SJRWMD	Seminole
255	284428081072603	Avenue C	UF	117	353	qw	USGS	Seminole
256	284428081155201	Largent	UF	--	--	qw, wl	USGS	Seminole
257	284429081204601	Seminole Co. Greenwood Lk 1	UF	165	480	qw	USGS	Seminole
258	284429081272001	Old Railroad Camp	UF	--	--	qw, wl	USGS	Orange
259	284432081151501	S-0638	UF	109	134	qw, wl	USGS	Seminole
260	284434081050101	Lake Harney	UF	--	60	qw, wl	USGS	Seminole
261	284440081175901	Seminole County	UF	75	250	qw, wl	USGS	Seminole
262	284442081052401	S-0034	UF	51	200	qw	SJRWMD	Seminole
263	284445081462101	Lake Yale Groves Well	UF	112	200	wl	USGS	Lake
264	284453081284401	Wekiva Springs State Park Fireplace Well	UF	--	40	qw, wl	USGS	Orange
265	284453081365101	Sadler Road	UF	--	325	wl	USGS	Orange
266	284456081145901	Ceresoli	UF	100	150	qw	USGS	Seminole
267	284458081250801	S-0863	ICU/UF	--	27	--	SJRWMD	Seminole
268	284516081224001	Griffin	UF	--	--	qw, wl	USGS	Seminole
269	284519081081801	Rotundo	UF	70	100	qw	USGS	Seminole
270	284522081174901	Utilities Inc. Park Ridge 1	UF	252	355	qw	USGS	Seminole
271	02234610	Rock Springs	UF	na	na	qw, Q	USGS	Orange
272	284529081301001	Rock Springs Deep	UF	143	365	wl	USGS	Orange
273	284533081204801	Forest	UF		471	wl	USGS	Seminole
274	284535081245701	S-0860	UF	--	--	qw	SJRWMD	Seminole
275	284541081265201	Anderson, OR0068	UF	90	95	qw, wl	USGS	Orange
276	284542081133001	S-0980	UF	105	335	qw	SJRWMD	Seminole
277	284549081214301	Seminole County Heathrow 4	UF	171	400	qw	USGS	Seminole
278	284550081071501	Cameron Brothers	UF	77	126	qw, wl	USGS	Seminole
279	284553081171901	City of Sanford WF1, Well 10	UF	122	302	qw	City of Sanford	Seminole
280	284553081204801	S-0972	UF	162	500	qw	SJRWMD	Seminole
281	284602081230101	Seminole Co. Hanover Woods 1	UF	147	361	qw	USGS	Seminole
282	284604081154801	Palm Way	UF	--	--	wl	USGS	Seminole

Appendix 1. Well and spring data-collection sites--Continued

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Site number	USGS site identification number	Station name	Aquifer	Bottom of casing (feet)	Depth of well (feet)	Data type	Source of data	County
283	284606081110901	S-0810	UF	--	--	qw	SJRWMD	Seminole
284	284612081303400	Sulphur Springs	UF	na	na	Q	USGS	Orange
285	284618081095401	Wight	UF	--	63	qw, wl	USGS	Seminole
286	284618081200901	Lake Dawson P-3	S	12	22	wl	USGS	Seminole
287	284619081200901	Lake Dawson P-1	S	6	16	wl	USGS	Seminole
288	284626081051801	Settlers Loop Road, S-0026	UF	83	200	qw, wl	USGS/SJRWMD	Seminole
289	284630081170101	Lakeview Middle School	S	20	30	wl	USGS	Seminole
290	284634081245401	S-0854	UF	--	--	qw	SJRWMD	Seminole
291	284635081280601	Hidden Well Near Rock Springs	UF	--	96	qw	USGS	Orange
292	284638081185701	Utilities Inc. Phillips 1	UF	92	250	qw	USGS	Seminole
293	284653081122601	S-1006	UF	--	105	qw	USGS	Seminole
294	284700081182301	Lake DeForest P3	S	5	15	wl	USGS	Seminole
295	284706081070801	Thrasher	UF	99	178	qw, wl	USGS	Seminole
296	284712081044301	Seminole County	UF	70	141	qw, wl	USGS	Seminole
297	284715081051801	S-0266 Landfill	S	9	14	wl	SJRWMD	Seminole
298	284715081051802	Osceola Landfill, S-0086	UF	70	225	qw, wl	USGS/SJRWMD	Seminole
299	284715081051803	S-0200	UF	500	550	wl	SJRWMD	Seminole
300	284722081130201	S-1106	UF	105	200	qw	USGS	Seminole
301	284722081181301	Utilities Inc. Ravena Park 2	UF	148	460	qw	USGS	Seminole
302	284728081183101	Idyllwilde Elementary	S	10	20	wl	USGS	Seminole
303	284728081322201	Lake Sorrento	UF	60	400	wl	USGS	Lake
304	284740081251700	Wekiva Falls	UF	--	120	qw	USGS	Lake
305	284743080520101	V-0520	UF	--	197	wl	USGS/SJRWMD	Volusia
306	284744081162701	Sanford Middle School	S	8	18	wl	USGS	Seminole
307	284750081132301	Seminole 257	UF	--	206	qw, wl	USGS/SJRWMD	Seminole
308	284753081144801	S-1195	UF	--	--	qw	USGS	Seminole
309	284757081144401	S-1196	UF	96	148	qw	USGS	Seminole
310	284802081192701	Jordan Baptist Church	UF	70	120	qw, wl	USGS	Seminole
311	284802081211101	Hartstock Wilson Ave.	UF	81	147	qw, wl	USGS	Seminole
312	284802081242101	Via Hermosa	UF	--	--	qw, wl	USGS	Seminole
313	284804081231601	Lake Sylvan MW1	S	6	16	wl	USGS	Seminole
314	284808081213901	Wilson Elementary	S	15	25	wl	USGS	Seminole
315	284808081432801	Taveras #3	UF	98	223	wl	USGS	Lake
316	284809081121301	S-0666	UF	--	--	qw	SJRWMD	Seminole
317	284825081000901	Harney Road, V-1034	S	--	21	wl	USGS	Volusia
318	284827081403501	Bartholow	UF	192	271	wl	USGS	Lake
319	284829081245901	S-0091	UF	75	160	qw	SJRWMD	Seminole
320	284835081155301	S-0672	UF	--	--	qw	SJRWMD	Seminole
321	284835081244302	S-0092	UF	80	120	qw	SJRWMD	Seminole
322	284837081182001	S-1084	UF	--	105	qw	SJRWMD	Seminole
323	284842081533001	College Street	UF	90	245	wl	USGS	Lake
324	284850081195501	Seminole County Lake Monroe 1	UF	96	223	qw	USGS	Seminole
325	284855081520401	Herlong Park	UF	100	105	wl	USGS	Lake
326	284856081383001	Mt. Dora Deep City Well #3	UF	155	752	wl	USGS	Lake
327	284902081112001	Beck	UF	--	--	qw	USGS	Volusia
328	284903081250800	Wekiva Branch Spring	UF	na	na	qw, Q	USGS	Seminole
329	284917081353701	Rickey and Reed	UF	--	--	wl	USGS	Lake

Appendix 1. Well and spring data-collection sites--Continued

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Site number	USGS site identification number	Station name	Aquifer	Bottom of casing (feet)	Depth of well (feet)	Data type	Source of data	County
330	284922081250300	Island Spring	UF	na	na	qw, Q	USGS	Seminole
331	284923081234801	Yankee Lake, S-1225	LF	950	1,054	wl	USGS	Seminole
332	284923081234802	Yankee Lake, S-1230	UF	122	403	wl	USGS	Seminole
333	284923081234803	Yankee Lake, S-1310	S	25	35	wl	USGS	Seminole
334	284929081294901	L-0201	UF	--	--	qw, wl	USGS	Lake
335	284933081255801	L-0038	ICU/UF	78	92	qw, wl	SJRWMD	Lake
336	284934081474801	Lake Sumter JC	UF	218	366	wl	USGS	Lake
337	284940081303800	Droty Spring	UF	na	na	qw, Q	USGS	Lake
338	284945081244201	Fernandez	ICU/UF	--	41	qw, wl	USGS	Seminole
339	284946081194301	Port of Sanford Industrial Park	UF	--	--	qw	USGS	Seminole
340	284954081201101	Anderson	UF	128	228	qw, wl	USGS	Seminole
341	285001081242301	S-0097	UF	110	120	qw	SJRWMD	Seminole
342	285002081215101	Cain	UF	--	--	qw, wl	USGS	Seminole
343	285016081014101	V-0103	UF	102	107	qw, wl	USGS	Volusia
344	285028081253301	Seminole State Forest L-0037	UF	102	364	qw, wl	USGS/SJRWMD	Lake
345	285031081062301	V-0165	UF	58	255	qw, wl	SJRWMD	Volusia
346	285038081270100	Palm Spring	UF	na	na	Q	USGS	Lake
347	285043081192201	V-0696	UF	--	130	qw	SJRWMD	Volusia
348	285044081094901	Osteen Convenience Store	UF	--	220	qw	USGS	Volusia
349	02235250	Seminole Springs	UF	na	na	qw, Q	USGS	Lake
350	285057081243201	L-0032	UF	96	120	qw, wl	SJRWMD	Lake
351	285057081321301	New Heindrick	UF	--	--	wl	USGS	Lake
352	285102081263900	Blueberry Spring	UF	na	na	Q	USGS	Lake
353	285105081263800	Moccasin Spring	UF	na	na	Q	USGS	Lake
354	02235255	Messant Spring	UF	na	na	qw, Q	USGS	Lake
355	285129081541002	City of Fruitland Pk #2	UF	144	300	wl	USGS	Lake
356	285135081205902	V-691	UF	--	145	qw	SJRWMD	Volusia
357	285143080521401	Loomis Nursery Well	UF	--	120	wl	USGS	Volusia
358	285144081183900	Gemini Spring	UF	na	na	qw, Q	USGS	Volusia
359	285153081144201	V-0240	UF	197	243	qw	SJRWMD	Volusia
360	285221081095002	USGS Test Well G-2	UF	74	92	wl	USGS	Volusia
361	285224081262400	Shark Tooth Spring	UF	na	na	Q	USGS	Lake
362	285230081242201	Lower Wekiva 2-in South	UF	102	109	qw	USGS	Lake
363	285257081434201	Eichelburger	UF	108	297	wl	USGS	Lake
364	285318081340601	Eustis Sand Co.	UF	--	350	wl	USGS	Lake
365	285359081161701	Deltona Corp Diamond Street #3	UF	76	250	qw, wl	USGS	Volusia
366	285426081380901	Marshall	UF	--	125	wl	USGS	Lake
367	285442081181401	Orange City Tower, V-0196	UF	88	234	wl	USGS	Volusia
368	285442081181402	Orange City Tower, V-0780	LF	710	800	wl	USGS	Volusia
369	285452080551801	Buerger	UF	--	148	wl	USGS	Volusia
370	285454081241201	Lower Wekiva 2-in	UF	--	65	qw	USGS	Lake
371	285524081132401	Galaxy MS, V-0774	LF	740	780	wl	USGS/SJRWMD	Volusia
372	285539081262901	Pine Lake	UF	155	200	wl	USGS	Lake
373	283913081120501	City of Oviedo 204	UF	160	300	qw	City of Oviedo	Seminole
374	284236081160500	Lake Jesup Spring	UF	na	na	Q	USGS	Seminole
375	284407081215501	Lake Mary monitor well	LF	1,260	1,323	qw	SJRWMD	Seminole

Appendix 2. Lake and stream data-collection sites

[Abbreviations for data type: L, lake stage; S, stream stage and discharge. Abbreviations for source of data: OC, Orange County; SC, Seminole County; SJRWMD, St. Johns River Water Management District; T, estimated from U.S. Geological Survey topographic map; USGS, U.S. Geological Survey. Site locations shown in figure 4]

Site number	USGS site identification number	Station name	Data type	Source of data	County	Simulated as active lake
S1	02233200	Little Econlockhatchee near Union Park	S	USGS	Orange	no
S2	02232500	St. Johns River near Christmas	S	USGS	Orange	no
S3		Lake Sue	L	OC	Orange	no
S4		Lake Spier	L	T	Orange	yes
S5		Lake Silver	L	OC	Orange	yes
S6		Lake Daniel	L	OC	Orange	no
S7		Lake Sarah	L	OC	Orange	no
S8		Lake Berry	L	OC	Orange	no
S9		Lake Virginia	L	OC	Orange	no
S10		Bay Lake	L	OC	Orange	yes
S11		Little Lake Fairview	L	OC	Orange	yes
S12		Lake Mizell	L	OC	Orange	no
S13		Lake Fairview	L	OC	Orange	yes
S14		Crooked Lake	L	OC	Orange	no
S15		Horseshoe Lake	L	OC	Orange	no
S16		Lake Price	L	OC	Orange	no
S17		Lake Orlando	L	OC	Orange	no
S18		unnamed lake 178	L	T	Orange	yes
S19		Lake Killarney	L	OC	Orange	no
S20		unnamed lake 174	L	T	Orange	yes
S21		Lake Waunatta	L	OC	Orange	no
S22		Lake Pickett	L	SC	Seminole	no
S23		Lake Osceola	L	OC	Orange	no
S24		Lake Georgia	L	OC	Orange	yes
S25		Lake Bell	L	OC	Orange	no
S26		Deep Lake	L	SC	Seminole	no
S27		Little Lake Georgia	L	SC	Seminole	no
S28		Park Lake	L	OC	Orange	no
S29		unnamed lake 154	L	T	Orange	yes
S30		Lake Maitland	L	OC	Orange	no
S31		Long Lake	L	OC	Orange	yes
S32	02233475	Little Econlockhatchee River at State Road 434	S	USGS	Seminole	no
S33		Hungerford Lake	L	T	Orange	yes
S34		Lake Shadow	L	T	Orange	yes
S35		unnamed lake 146	L	T	Orange	yes
S36		Bear Gully Lake	L	SC/SJRWMD	Seminole	no
S37		Lake Gandy	L	OC	Orange	no
S38		Lake Sybelia	L	OC	Orange	yes
S39		Lake Ann	L	SC	Seminole	no
S40		Garden Lake	L	SC	Seminole	no
S41		Lake Florence	L	SC	Seminole	yes
S42		Lake Minnehaha	L	OC	Orange	no
S43		Lake Hayes	L	SC	Seminole	no
S44	02234308	Howell Creek near Altamonte Springs	S	USGS	Seminole	no
S45		Mills Lake	L	SC	Seminole	no
S46		Horseshoe Lake	L	SC	Seminole	no
S47		Lake Bosse	L	OC	Orange	no

Appendix 2. Lake and stream data-collection sites--Continued

[Abbreviations for data type: L, lake stage; S, stream stage and discharge. Abbreviations for source of data: OC, Orange County; SC, Seminole County; SJRWMD, St. Johns River Water Management District; T, estimated from U.S. Geological Survey topographic map; USGS, U.S. Geological Survey. Site locations shown in figure 4]

Site number	USGS site identification number	Station name	Data type	Source of data	County	Simulated as active lake
S48		Lake Destiny	L	SC	Seminole	yes
S49		Lake Howell	L	SC	Seminole	yes
S50		Lake Catherine	L	SC	Seminole	no
S51		Lake Seminary	L	SC	Seminole	yes
S52		Lake of the Woods	L	SC	Seminole	no
S53		Little Bear Lake	L	SC	Seminole	no
S54		Lake Eva	L	T	Seminole	yes
S55	283847081270101	Bear Lake	L	SC/SJRWMD	Seminole	no
S56		Cub Lake	L	SC	Seminole	no
S57	02234324	Howell Creek near Slavia	S	USGS	Seminole	no
S58		Lake Lotus	L	SC	Seminole	no
S59		Spring Lake	L	SC	Seminole	no
S60		Red Bug Lake	L	SC	Seminole	no
S61		Lake Orienta	L	SC	Seminole	yes
S62		Lake Nixon	L	T	Seminole	yes
S63		Prairie Lake	L	SC	Seminole	yes
S64		Queens Mirror Lake	L	SC	Seminole	no
S65		Long Lake	L	T	Seminole	no
S66		Crystal Bowl Lake	L	SC	Seminole	no
S67		Crains Roost	L	SC	Seminole	no
S68		Mirror Lake	L	SC	Seminole	no
S69		Lost Lake	L	SC	Seminole	no
S70		Border Lake	L	T	Orange	yes
S71		Lake Yvonne	L	SC	Seminole	no
S72		Triplet Lake	L	SC	Seminole	no
S73		Lake Concord	L	SC	Seminole	no
S74	02233500	Econlockhatchee River near Chuluota	S	USGS	Seminole	no
S75	2234428	Lake Charm	L	USGS	Seminole	yes
S76		Trout Lake	L	SC	Seminole	no
S77		Lake Kathryn	L	SC	Seminole	no
S78		Sand Lake	L	SC	Seminole	yes
S79	02234990	Little Wekiva River near Altamonte Springs	S	USGS	Seminole	no
S80		Lake Fairy	L	SC	Seminole	no
S81	284134081253201	Lake Brantley	L	SJRWMD	Seminole	no
S82		Lake Irene	L	SC	Seminole	yes
S83		Lake Wildmere	L	SC	Seminole	no
S84		unnamed lake 78	L	T	Seminole	yes
S85		Lake Talmo	L	SC	Seminole	no
S86		unnamed lake 203	L	T	Seminole	yes
S87		Rock Lake	L	SC	Seminole	yes
S88		Twin Lakes	L	T	Seminole	yes
S89	02234998	Little Wekiva River near Longwood	S	USGS	Seminole	no
S90	02234400	Gee Creek near Longwood	S	USGS	Seminole	no
S91		East Lake	L	SC	Seminole	no
S92		Boat Lake	L	SC	Seminole	no
S93		West Lake	L	SC	Seminole	yes
S94	2842430810725	Buck Lake	L	SJRWMD	Seminole	no
S95	02234635	Wekiva River near Apopka	S	USGS	Seminole	no
S96	02234000	St. Johns River above Lake Harney	S	USGS	Seminole	no

Appendix 2. Lake and stream data-collection sites--Continued

[Abbreviations for data type: L, lake stage; S, stream stage and discharge. Abbreviations for source of data: OC, Orange County; SC, Seminole County; SJRWMD, St. Johns River Water Management District; T, estimated from U.S. Geological Survey topographic map; USGS, U.S. Geological Survey. Site locations shown in figure 4]

Site number	USGS site identification number	Station name	Data type	Source of data	County	Simulated as active lake
S97		Lake Ruth	L	SC	Seminole	no
S98		Lake Alma	L	T	Seminole	yes
S99		Grace Lake	L	SC	Seminole	yes
S100	02234384	Soldier Creek near Longwood	S	USGS	Seminole	no
S101		Island Pond	L	T	Seminole	yes
S102		Lake Myrtle	L	SC	Seminole	yes
S103		Lake Proctor	L	SC	Seminole	yes
S104		Lake Bingham	L	SC	Seminole	yes
S105		Lake Geneva	L	SC	Seminole	yes
S106		Rice Lake	L	SC	Seminole	no
S107		Lake Minnie	L	SC	Seminole	yes
S108		Lake Mary	L	SC	Seminole	yes
S109		Linden Lake	L	SC	Seminole	no
S110	284533081210101	Lake Emma	L	SC/SJRWMD	Seminole	yes
S111	284541081200301	Crystal Lake	L	SC/SJRWMD	Seminole	no
S112		Silver Lake	L	SC	Seminole	yes
S113		Lake Loch Low	L	T	Seminole	yes
S114		Lake Onora	L	SC	Seminole	no
S115		Golden Lake	L	SC	Seminole	no
S116		Lake Ada	L	SC	Seminole	yes
S117		Crystal Lake, East	L	SC	Seminole	no
S118		Island Lake, South	L	SC	Seminole	no
S119		Lake Marietta	L	SC	Seminole	no
S120		Island Lake	L	SC	Seminole	no
S121		BelAir Lake	L	SC	Seminole	no
S122		DeForest Lake	L	SC	Seminole	yes
S123		Reservoir Lake	L	SC	Seminole	no
S124		Banana Lake	L	SC	Seminole	no
S125		Lake Como	L	T	Seminole	yes
S126		Amory Lake	L	SC	Seminole	no
S127		Sawyer Lake	L	SC	Seminole	no
S128	02234435	Lake Jesup outlet near Sanford	S	USGS	Seminole	no
S129		unnamed lake 209	L	T	Seminole	yes
S130		Twin Lakes,West	L	T	Seminole	yes
S131		Mullet Lake	L	SC	Seminole	no
S132		Twin Lakes, East	L	SC	Seminole	yes
S133		Lake Irish	L	T	Seminole	yes
S134	022349993	Wekiva River at Old Railroad Crossing near Sanford	S	USGS	Seminole	no
S135		Lake Sten	L	T	Seminole	yes
S136		Sylvan Lake	L	SC	Seminole	no
S137		Ross Lake	L	T	Seminole	yes
S138	02235000	Wekiva River near Sanford	S	USGS	Seminole	no
S139		unnamed lake 5	L	T	Seminole	yes
S140	02234500	St. Johns River near Sanford	S	USGS	Seminole	no

Appendix 3. Supplementary surficial aquifer system wells in Seminole County, Florida

[--, no data. Source of data: Florida Department of Environmental Protection. Site locations shown in figure 5]

Site number	Latitude/ Longitude	Station name	Bottom of casing (feet)	Depth of well (feet)
SP1	283704 0811847	Texaco Service Station	--	--
SP2	283730 0811927	Chevron Service Station	3	13
SP3	283750 0811439	Oviedo Maintenance Facility	1	11
SP4	283755 0811206	Lake Hayes Treatment Plant	5	10
SP5	283755 0811909	BP Oil Co.	5	15
SP6	283845 0811615	Texaco Service Station	--	--
SP7	283856 0812103	7-11 Store	--	--
SP8	283907 0811949	Aamco Transmission	5	15
SP9	283916 0812026	Cumberland Farms	--	--
SP10	283933 0811046	Exxon Service Station	--	--
SP11	283942 0812328	Exxon Service Station	--	--
SP12	283950 0812655	Lynwood Water Treatment Plant	5	10
SP13	284003 0812345	Tri-City Electrical Contractors, Inc.	--	39
SP14	284016 0812010	Casselberry, City of	5	20
SP15	284027 0811542	7-11 Store	--	20
SP16	284046 0812511	7-11 Store	25	30
SP17	284055 0812101	Browning-Ferres Facility	1	11
SP18	284058 0811858	Casselberry, City of	22	27
SP19	284126 0812111	UPS, Longwood Center	10	15
SP20	284202 0811748	Cumberland Farms	--	--
SP21	284202 0811823	City of Winter Springs Fire Dept.	2	12
SP22	284307 0812011	Former School Bus Maintenance Facility	10	15
SP23	284407 0811816	Bob Dance Dodge	5	15
SP24	284454 0811755	Seminole County, Five Points Fueling Facility	10	20
SP25	284522 0811717	Cumberland Farms	2	12
SP26	284524 0811748	Cumberland Farms	20	25
SP27	284538 0811556	Barry's Appliance	10	15
SP28	284626 0811531	Central Florida Regional Airport	10	12
SP29	284638 0811636	Sanford Auto Mall	4	14
SP30	284646 0811515	Central Florida Regional Airport	5	15
SP31	284721 0811728	Sunlight Foods Facility	--	--
SP32	284819 0811622	Sanford Police Dept.	--	--
SP33	284821 0811733	CSX Transportation Railroad Facility	5	10
SP34	284837 0811830	M&M Auto Parts and Salvage	2	12

Appendix 4. Chemical and physical data for water from Upper Floridan aquifer wells in Seminole, and parts of adjacent Brevard, Lake, Orange, and Volusia Counties, Florida

[Source of data: USGS, U.S. Geological Survey, SJRWMD, St. Johns River Water Management District. Samples analyzed by the USGS are dissolved; SJRWMD samples are dissolved or total; in ground water, dissolved and total constituents are comparable if particulate matter is negligible. °C, degrees Celsius; µS/cm, microsiemens per centimeter at 25 °C; mg/L, milligrams per liter; µg/L, micrograms per liter; --, not analyzed; <, less than. Site numbers are from Appendix 1; locations shown in figure 3]

Map number	USGS site identification number	Source of data	Date	Water temperature (°C)	Specific conductance (µS/cm)	pH (standard units)	Hardness, total (mg/L as $CaCO_3$)	Silica, (mg/L as SiO_2)	Calcium, (mg/L as Ca)	Magnesium, (mg/L as Mg)	Sodium, (mg/L as Na)	Potassium, (mg/L as K)	Strontium, (µg/L as Sr)	Chloride, (mg/L as Cl)	Sulfate, (mg/L as SO_4)	Fluoride, (mg/L as F)	Alkalinity (mg/L as $CaCO_3$)
Seminole County																	
129	283740081031401	USGS	5/9/95	23.7	735	7.6	260	17	83	13	54	2.4	1,600	96	46	0.20	182
130	283754081154301	USGS	5/15/95	24.0	210	7.9	94	11	32	3.4	6.0	0.70	140	6.2	5.0	.30	88
131	283758081120401	USGS	4/27/95	24.0	378	7.6	150	11	44	8.7	13	1.2	180	23	4.0	.20	135
135	283810081172401	USGS	4/27/95	23.6	305	7.5	130	10	40	7.9	6.3	.80	100	10	3.6	.20	124
141	283821081074401	USGS	5/1/95	24.2	870	7.7	220	13	64	15	92	3.8	640	160	30	.10	157
142	283837081113001	USGS	5/1/95	23.1	450	7.6	190	12	70	4.5	18	1.3	190	36	2.6	.20	169
143	283843081075501	USGS	5/9/95	--	460	--	210	14	80	3.2	7.6	.70	520	8.6	0.30	<.10	226
144	283844081200101	USGS	4/27/95	24.9	255	8.1	110	10	32	8.2	5.4	.70	140	8.0	4.9	.20	105
148	283851081221101	USGS	5/3/95	24.4	250	7.3	110	8.1	33	7.5	6.2	.80	90	11	8.4	.10	100
150	283853081060301	USGS	6/27/95	25.5	235	--	96	12	36	1.3	7.0	1.2	210	9.6	.40	<.10	105
151	283854081134701	USGS	6/27/95	25.2	265	--	--	--	--	--	--	--	--	--	--	--	--
155	283901081135901	USGS	6/27/95	23.8	300	--	110	9.8	32	7.7	14	1.0	160	22	6.3	.20	116
157	283908081120701	USGS	5/1/95	24.2	655	7.9	160	10	50	9.6	61	2.6	260	110	17	.20	113
158	283912081095601	USGS	6/26/95	23.0	870	--	170	9.8	44	14	100	3.8	380	180	28	.20	125
159	283918081254301	USGS	5/3/95	23.6	268	7.9	130	9.0	39	8.8	4.8	.70	60	7.8	.80	.20	127
161	283925081124201	USGS	5/1/95	24.4	420	7.4	140	10	42	8.6	28	1.5	190	50	10	.20	116
172	283956081040201	USGS	5/9/95	22.8	2,680	7.8	410	12	91	44	360	12	2,600	690	160	.20	139
175	284006081272001	USGS	4/28/95	23.8	290	7.1	130	8.7	38	9.4	5.8	1.4	80	11	8.7	.20	118
178	284025081072401	SJRWMD	6/16/92	--	--	--	--	--	--	--	--	--	--	1,270	200	--	--
179	284025081123001	USGS	5/9/95	24.4	352	7.7	130	9.1	36	9.5	17	1.2	130	32	7.0	.10	119
180	284033081052701	USGS	6/29/95	23.9	1,360	--	--	--	--	--	--	--	--	270	42	--	--
181	284043081054401	USGS	6/29/95	23.1	7,160	--	730	11	110	110	1,200	49	2,600	2,200	330	.10	192
182	284043081154001	USGS	5/2/95	25.2	724	8.0	--	--	--	--	--	--	--	130	42	--	--
183	284043081154601	USGS	5/2/95	24.3	430	7.6	160	11	47	10	25	1.4	210	46	17	.20	123
188	284052081212601	SJRWMD	5/16/95	22.9	389	7.9	--	--	95	12	7.0	3.5	210	11	1.0	.20	251
196	284111081063401	USGS	6/28/95	23.3	460	--	190	18	64	8.3	14	1.7	670	19	2.0	.20	217
197	284112081181801	USGS	5/2/95	24.1	303	7.8	140	11	43	8.5	5.9	.80	140	9.8	1.6	.20	134
201	284119081244801	USGS	5/1/95	24.0	268	7.9	120	9.8	33	8.3	6.8	.90	230	12	7.0	.20	104
202	284120081152201	USGS	5/10/95	22.7	295	7.9	130	9.9	39	7.4	8.2	.90	160	13	3.1	.20	130
204	284125081131701	USGS	5/10/95	23.7	610	7.5	170	11	46	13	55	2.4	300	100	23	.20	113
207	284133081085501	USGS	6/26/95	23.9	6,550	--	730	11	110	110	1,100	38	2,400	1,900	280	.10	123
208	284133081105701	USGS	5/9/95	23.9	895	7.9	170	9.1	46	14	95	3.3	350	180	27	.20	110
209	284139081255401	USGS	5/1/95	24.1	243	7.5	120	11	32	8.5	4.6	.80	190	6.4	2.2	.20	112

Appendix 4. Chemical and physical data for water from Upper Floridan aquifer wells in Seminole, and parts of adjacent Brevard, Lake, Orange, and Volusia Counties, Florida--Continued

[Source of data: USGS, U.S. Geological Survey, SJRWMD, St. Johns River Water Management District. Samples analyzed by the USGS are dissolved; SJRWMD samples are dissolved or total; in ground water, dissolved and total constituents are comparable if particulate matter is negligible. °C, degrees Celsius; µS/cm, microsiemens per centimeter at 25 °C; mg/L, milligrams per liter; µg/L, micrograms per liter; --, not analyzed; <, less than. Site numbers are from Appendix 1; locations shown in figure 3]

Map number	USGS site identification number	Source of data	Date	Water temperature (°C)	Specific conductance (µS/cm)	pH (standard units)	Hardness, total (mg/L as $CaCO_3$)	Silica, (mg/L as SiO_2)	Calcium, (mg/L as Ca)	Magnesium, (mg/L as Mg)	Sodium, (mg/L as Na)	Potassium, (mg/L as K)	Strontium, (µg/L as Sr)	Chloride, (mg/L as Cl)	Sulfate, (mg/L as SO_4)	Fluoride, (mg/L as F)	Alkalinity (mg/L as $CaCO_3$)
213	284159081101701	USGS	8/1/95	--	3,300	--	--	--	--	--	--	--	--	1,000	140	--	--
214	284201081102601	USGS	8/8/95	--	3,350	--	--	--	--	--	--	--	--	1,100	160	--	--
216	284207081174401	USGS	5/10/95	23.0	300	7.2	130	9.1	39	8.4	5.9	.70	100	9.1	1.6	.20	136
219	284217081023001	SJRWMD	5/22/95	22.4	12,400	7.0	--	--	37	290	2,500	92	7,600	5,300	760	.20	141
222	284232081110201	SJRWMD	2/23/93	--	--	--	--	--	--	--	--	--	--	1,470	190	--	--
224	284233081045202	SJRWMD	5/22/95	22.7	2,560	7.0	--	--	61	54	460	24	1,600	720	170	.20	234
226	284237081190201	USGS	5/2/95	23.9	283	7.8	140	10	43	7.8	5.7	.80	130	9.0	2.9	.20	129
230	284243081225901	USGS	4/24/97	24.5	623	--	--	--	--	--	--	--	--	80	89	--	--
232	284244081234901	USGS	5/11/95	24.3	710	7.4	190	9.0	54	14	55	2.3	1,400	94	98	.20	97
234	284247081070801	SJRWMD	5/24/95	22.6	327	7.2	--	--	58	2.5	6.0	1.0	180	11	0	<.10	162
236	284305081261601	SJRWMD	1/22/91	--	--	--	--	--	--	--	--	--	--	123	146	--	--
237	284306081101701	SJRWMD	11/7/86	--	--	--	--	--	--	--	--	--	--	1,555	229	--	--
238	284315081182702	SJRWMD	8/5/93	22.7	263	7.9	120	11	33	8.3	7.9	.90	160	12	2.8	.20	--
240	284317081213401	USGS	5/11/95	--	255	--	--	--	--	--	--	--	--	13	11	--	--
242	284322081084301	SJRWMD	4/11/95	22.7	330	7.2	--	--	52	2.2	11	1.8	1,200	13	5.0	<.04	132
243	284325081092701	SJRWMD	4/12/94	22.4	4,280	7.6	--	--	90	75	680	24	--	1,200	180	.20	--
246	284331081031001	USGS	5/8/95	23.4	14,700	7.6	1,500	11	220	230	2,600	26	5,900	4,400	710	.10	138
247	284339081184601	USGS	7/31/95	--	250	--	--	--	--	--	--	--	--	12	3.8	--	--
248	284341081254901	SJRWMD	1/22/91	--	--	--	--	--	--	--	--	--	--	179	230	--	--
250	284401081194701	USGS	4/27/95	24.5	265	7.2	120	10	34	7.9	5.6	.80	130	8.1	2.1	.20	114
254	284421081251701	SJRWMD	1/22/91	--	--	--	--	--	--	--	--	--	--	530	460	--	--
255	284428081072603	USGS	5/15/95	24.8	215	8.0	95	14	36	1.1	6.3	.70	400	8.5	2.8	<.10	88
256	284428081155201	USGS	5/10/95	24.2	2,660	7.9	360	10	66	46	380	14	960	680	110	.10	114
257	284429081204601	USGS	4/27/95	23.5	305	7.6	140	11	42	8.5	5.4	.80	130	8.2	1.5	.10	133
259	284432081151501	USGS	6/14/95	--	3,120	--	--	--	--	--	--	--	--	830	130	--	--
260	284434081050101	USGS	5/8/95	21.9	1,460	7.7	280	9.7	73	23	160	6.4	1,000	310	39	<.10	176
261	284440081175901	USGS	5/10/95	--	430	--	--	--	--	--	--	--	--	11	25	--	--
262	284442081052401	SJRWMD	1/11/95	22.0	403	7.1	--	--	75	1.7	7.0	.70	330	12	0	.50	191
266	284456081145901	USGS	6/27/95	25.3	2,380	--	340	11	76	35	340	10	1,100	630	86	.20	117
267	284458081250801	SJRWMD	3/10/92	--	--	--	--	--	--	--	--	--	--	516	444	--	--
268	284516081224001	USGS	5/11/95	--	455	--	--	--	--	--	--	--	--	20	.20	--	--
269	284519081081801	USGS	6/28/95	24.3	445	--	--	--	--	--	--	--	--	9.9	.20	--	--
270	284522081174901	USGS	5/2/95	23.9	418	7.4	150	9.6	46	7.9	26	1.4	170	47	6.9	.10	131
274	284535081245701	SJRWMD	1/22/91	--	--	--	--	--	--	--	--	--	--	758	429	--	--
276	284542081133001	SJRWMD	11/9/92	--	--	--	--	--	--	--	--	--	--	889	130	--	--

Appendix 4. Chemical and physical data for water from Upper Floridan aquifer wells in Seminole, and parts of adjacent Brevard, Lake, Orange, and Volusia Counties, Florida--Continued

[Source of data: USGS, U.S. Geological Survey, SJRWMD, St. Johns River Water Management District. Samples analyzed by the USGS are dissolved; SJRWMD samples are dissolved or total; in ground water, dissolved and total constituents are comparable if particulate matter is negligible. °C, degrees Celsius; µS/cm, microsiemens per centimeter at 25 °C; mg/L, milligrams per liter; µg/L, micrograms per liter; --, not analyzed; <, less than. Site numbers are from Appendix 1; locations shown in figure 3]

Map number	USGS site identification number	Source of data	Date	Water temperature (°C)	Specific conductance (µS/cm)	pH (standard units)	Hardness, total (mg/L as $CaCO_3$)	Silica, (mg/L as SiO_2)	Calcium, (mg/L as Ca)	Magnesium, (mg/L as Mg)	Sodium, (mg/L as Na)	Potassium, (mg/L as K)	Strontium, (µg/L as Sr)	Chloride, (mg/L as Cl)	Sulfate, (mg/L as SO_4)	Fluoride, (mg/L as F)	Alkalinity (mg/L as $CaCO_3$)
277	284549081214301	USGS	4/27/95	24.0	290	7.3	140	8.4	42	7.6	4.2	.80	40	6.6	5.9	.10	128
278	284550081071501	USGS	5/8/95	22.6	479	7.5	200	30	71	5.2	16	1.3	380	25	.20	<.10	196
279	284553081171901	City of Sanford	2/15/95	--	--	7.7	160	--	--	--	--	--	--	49	--	.10	140
280	284553081204801	SJRWMD	11/1/93	23.3	260	7.7	110	8.4	38	4.2	4.4	.70	56	8.2	5.1	.10	--
281	284602081230101	USGS	4/27/95	23.0	335	7.2	160	10	50	8.3	5.4	.60	50	9.5	2.2	.10	152
283	284606081110901	SJRWMD	5/6/91	--	--	--	--	--	--	--	--	--	--	832	92	--	--
285	284618081095401	USGS	5/8/95	23.6	4,900	7.6	680	8.2	160	68	740	18	3,100	1,400	200	.10	121
288	284626081051801	SJRWMD	9/1/93	24.3	699	7.0	--	20	91	22	16	1.2	790	30	.20	.20	--
290	284634081245401	SJRWMD	1/22/91	--	--	--	--	--	--	--	--	--	--	100	28	--	--
292	284638081185701	USGS	5/2/95	23.3	355	7.6	170	8.8	57	5.5	8.3	2.2	70	16	25	<.10	132
293	284653081122601	USGS	7/18/95	--	2,580	--	--	--	--	--	--	--	--	720	110	--	--
295	284706081070801	USGS	5/8/95	23.6	665	7.2	310	18	110	8.0	16	1.6	730	25	.60	<.10	309
296	284712081044301	USGS	5/8/95	26.3	2,350	7.0	500	17	130	41	240	4.5	3,700	600	33	.10	202
298	284715081051802	SJRWMD	1/9/95	22.0	659	6.9	--	--	120	3.4	20	1.2	580	35	2.0	<.10	289
300	284722081130201	USGS	6/27/95	--	2,220	--	--	--	--	--	--	--	--	540	86	--	--
301	284722081181301	USGS	5/2/95	23.4	340	7.7	160	9.7	52	6.9	8.0	.90	140	14	3.9	.10	144
307	284750081132301	SJRWMD	9/2/93	25.1	2,130	8.0	310	9.8	72	31	275	8.8	1,100	530	80	.20	--
308	284753081144801	USGS	6/28/95	23.8	1,800	--	300	11	79	25	230	6.2	1,200	420	68	.20	134
309	284757081144401	USGS	7/11/95	--	1,590	--	--	--	--	--	--	--	--	400	70	--	--
310	284802081192701	USGS	5/11/95	24.2	410	--	--	--	--	--	--	--	--	19	2.3	--	--
311	284802081211101	USGS	5/11/95	23.3	265	7.8	--	--	--	--	--	--	--	7.9	.20	--	--
312	284802081242101	USGS	5/11/95	--	510	--	160	9.7	46	10	24	1.2	230	47	29	.20	123
316	284809081121301	SJRWMD	2/8/93	--	--	--	--	--	--	--	--	--	--	504	78	--	--
319	284829081245901	SJRWMD	10/21/93	24.3	660	7.1	--	--	55	17	45	1.5	670	87	44	.30	134
320	284835081155301	SJRWMD	1/14/89	--	--	--	--	--	--	--	--	--	--	462	97	--	--
321	284835081244302	SJRWMD	8/7/95	23.7	252	6.7	--	--	32	8.3	8.0	1.0	140	11	6.0	.30	115
322	284837081182001	SJRWMD	6/27/95	--	1,310	--	--	--	--	--	--	--	--	270	60	--	--
324	284850081195501	USGS	4/27/95	22.9	322	7.3	130	9.6	40	8.0	9.1	.80	280	16	2.9	.20	125
338	284945081244201	USGS	5/11/95	22.3	4,800	7.5	830	9.6	200	78	730	15	4,300	1,300	370	.20	136
339	284946081194301	USGS	6/29/95	23.2	392	--	130	8.7	38	8.8	22	1.2	590	42	7.6	.20	124
340	284954081201101	USGS	5/11/95	23.4	1,220	7.5	250	8.6	65	21	120	4.2	900	250	69	.20	116
341	285001081242301	SJRWMD	8/8/95	23.0	5,260	7.0	--	--	270	110	960	25	5,800	1,770	550	.20	138
342	285002081215101	USGS	5/10/95	23.0	545	8.0	150	8.8	45	9.7	43	1.8	460	80	20	.20	122
Brevard County																	
120	283644080574901	SJRWMD	6/12/95	22.9	5,460	6.1	--	--	180	110	840	27	7,200	2,000	410	.20	121

Appendix 4. Chemical and physical data for water from Upper Floridan aquifer wells in Seminole, and parts of adjacent Brevard, Lake, Orange, and Volusia Counties, Florida--Continued

[Source of data: USGS, U.S. Geological Survey, SJRWMD, St. Johns River Water Management District. Samples analyzed by the USGS are dissolved; SJRWMD samples are dissolved or total; in ground water, dissolved and total constituents are comparable if particulate matter is negligible. °C, degrees Celsius; µS/cm, microsiemens per centimeter at 25 °C; mg/L, milligrams per liter; µg/L, micrograms per liter; --, not analyzed; <, less than. Site numbers are from Appendix 1; locations shown in figure 3]

Map number	USGS site identification number	Source of data	Date	Water temperature (°C)	Specific conductance (µS/cm)	pH (standard units)	Hardness, total (mg/L as $CaCO_3$)	Silica, (mg/L as SiO_2)	Calcium, (mg/L as Ca)	Magnesium, (mg/L as Mg)	Sodium, (mg/L as Na)	Potassium, (mg/L as K)	Strontium, (µg/L as Sr)	Chloride, (mg/L as Cl)	Sulfate, (mg/L as SO_4)	Fluoride, (mg/L as F)	Alkalinity (mg/L as $CaCO_3$)
Lake County																	
304	284740081251700	USGS	6/10/97	23.7	1,920	7.5	430	11	110	38	210	5.4	2,900	400	230	.30	109
334	284929081294901	USGS	11/22/96	22.9	341	7.8	110	9.6	41	2.3	5.1	.60	--	7.5	58	.30	100
335	284933081255801	SJRWMD	8/21/95	22.6	321	7.7	--	--	58	4.6	6.0	1.3	280	4.0	1.0	.30	169
344	285028081253301	SJRWMD	4/20/95	22.7	1,873	6.8	--	--	160	43	240	8.7	3,100	460	320	.20	191
350	285057081243201	SJRWMD	4/20/95	21.8	2,460	7.2	--	--	94	50	380	12	2,500	760	250	.20	101
362	285230081242201	USGS	1/8/97	22.7	1,275	7.3	320	10	94	21	120	4.3	1,200	240	100	.20	175
370	285454081241201	USGS	1/8/97	22.7	960	7.5	270	9.2	78	17	80	2.9	970	150	71	.10	178
Orange County																	
83	283214080583501	USGS	5/16/95	23.1	2,600	--	--	--	--	--	--	--	--	600	240	--	--
89	283249081053201	SJRWMD	5/24/95	23.6	530	6.9	--	--	58	13	32	2.0	1,100	55	42	.20	162
106	283406081150601	USGS	5/17/95	24.3	315	--	--	--	--	--	--	--	--	9.8	1.0	--	--
122	283646081195401	USGS	5/18/95	24.2	282	--	--	--	--	--	--	--	--	13	3.6	--	--
228	284238081275803	SJRWMD	5/17/95	23.2	258	7.7	--	--	44	11	6.0	2.8	210	10	16	.20	121
258	284429081272001	USGS	5/16/95	22.4	435	7.7	160	11	45	11	23	1.2	770	41	43	.30	99
264	284453081284401	USGS	5/16/95	22.3	370	--	--	--	--	--	--	--	--	6.7	79	--	--
275	284541081265201	USGS	5/16/95	24.0	1,220	7.4	310	11	82	25	110	3.3	1,700	230	150	.30	99
291	284635081280601	USGS	5/16/95	24.1	660	7.9	280	12	80	19	21	1.4	1,600	34	160	.10	101
Volusia County																	
327	284902081112001	USGS	5/22/95	23.0	2,780	7.5	--	--	--	--	--	--	--	690	150	--	--
343	285016081014101	USGS	5/23/95	--	790	--	--	--	--	--	--	--	--	48	.20	--	--
345	285031081062301	SJRWMD	5/22/95	22.1	589	6.6	--	--	140	4.7	15	1.0	810	35	1.0	.10	325
347	285043081192201	SJRWMD	1/14/93	--	--	--	--	--	--	--	--	--	--	494	127	--	--
348	285044081094901	USGS	5/22/95	--	235	--	--	--	--	--	--	--	--	11	5.1	--	--
356	285135081205902	SJRWMD	1/19/93	--	--	--	--	--	--	--	--	--	--	1,200	63	--	--
359	285153081144201	SJRWMD	6/13/95	23.2	2,030	6.0	--	--	71	26	290	8.8	530	500	56	.10	178
365	285359081161701	USGS	5/22/95	23.4	335	7.5	--	--	--	--	--	--	--	12	2.9	--	--

Appendix 5. Chemical and physical data for water from Upper Floridan aquifer springs in Seminole, Lake, Orange, and Volusia Counties, Florida

[° C, degrees Celsius; µS/cm, microsiemens per centimater at 25 ° C; mg/L, milligrams per liter; µg/L, micrograms per liter; --, not analyzed; <, less than. All concentrations are dissolved. Source of data: U.S. Geological Survey. Site numbers are from Appendix 1; locations shown in figure 3]

Map number	USGS site identification number	Spring name	Date	Water temperature (° C)	Specific conductance (µS/cm)	pH (standard units)	Hardness, total (mg/L as $CaCO_3$)	Silica, (mg/L as SiO_2)	Calcium, (mg/L as Ca)	Magnesium, (mg/L as Mg)	Sodium, (mg/L as Na)	Potassium, (mg/L as K)	Strontium, (ug/L as Sr)	Chloride, (mg/L as Cl)	Sulfate, (mg/L as SO_4)	Fluoride, (mg/L as F)	Alkalinity (mg/L as $CaCO_3$)
Seminole County																	
200	284119081234500	Sanlando Springs	5/25/95	24.5	336	--	160	8.6	43	12	9.5	1.6	80	17	12	0.20	134
205	284127081233400	Palm Springs	5/25/95	24.5	325	--	140	17	38	10	8.6	1.0	360	15	23	.20	118
211	02234997	Starbuck Spring	5/25/95	24.2	350	--	160	8.9	44	11	11	1.4	300	21	24	.20	122
212	284156081141400	Clifton Springs	11/7/95	23.7	710	7.5	180	10	46	15	64	2.9	450	130	37	.20	113
225	02234650	Miami Springs	5/26/95	24.4	263	--	110	8.0	32	8.0	6.2	0.80	240	11	8.5	.20	108
328	284903081250800	Wekiva Branch Spring	8/16/96	22.9	3350	--	650	11	160	60	470	11	3,200	830	350	.20	116
330	284922081250300	Island Spring	8/12/96	24.0	5,850	--	970	11	220	100	1,000	26	4,700	1,900	510	.20	126
Lake County																	
337	284940081303800	Droty Spring	6/17/97	23.9	305	7.5	150	10	41	11	5.0	.80	410	7.1	32	.20	117
349	02235250	Seminole Springs	5/24/95	24.3	335	7.9	160	8.5	45	11	5.0	.80	550	8.6	64	.20	84
354	02235255	Messant Spring	5/24/95	25.3	700	7.8	340	12	100	22	7.1	1.0	2,400	10	240	.20	104
Orange County																	
231	02234600	Wekiva Springs	5/25/95	23.8	319	--	140	9.1	40	10	8.7	1.5	130	14	18	.10	115
271	02234610	Rock Springs	5/25/95	23.8	250	--	110	9.4	32	8.0	5.1	1.2	170	8.2	20	.10	88
Volusia County																	
358	285144081183900	Gemini Spring	6/23/95	23.0	2,400	--	370	8.6	90	36	340	8.2	1,500	620	110	.10	125

U.S. Department of the Interior
U.S. Geological Survey
227 North Bronough Street
Suite 3015
Tallahassee, FL 32301-1372

R.M. Spechler and K.J. Halford ó Hydrogeology, Water Quality, and Simulated Effects of Ground-Water Withdrawals from the Floridan Aquifer System, Seminole County, Floridaó U.S. Geological Survey WRIR 01ñ4182

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