

# Hydrogeology and Quality of Ground Water in Orange County, Florida

*By James C. Adamski and Edward R. German*

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## CONVERSION FACTORS AND VERTICAL DATUM

Multiply	By	To obtain
<b><i>Length</i></b>		
inch (in.)	2.54	centimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
<b><i>Area</i></b>		
acre	0.4047	hectare
square mile (mi <sup>2</sup> )	2.590	square kilometer
<b><i>Mass</i></b>		
pound (lb)	0.4536	kilogram
pound per acre per year (lb/acre)/yr	0.4536	kilograms per acre per year
<b><i>Flow Rate</i></b>		
cubic foot per second (ft <sup>3</sup> /s)	0.02832	cubic meter per second
gallon per day (gal/d)	0.04381	meter per day
gallon per minute (gal/min)	0.04381	meter per minute
million gallons per day (Mgal/d)	0.04381	cubic meter per second
inch per month (in/mo)	25.4	millimeter per month
inch per year (in/yr)	25.4	millimeter per year
<b><i>Hydraulic Conductivity</i></b>		
foot per day (ft/d)	0.3048	meter per day
<b><i>Transmissivity*</i></b>		
foot squared per day (ft <sup>2</sup> /d)	0.09290	meter squared per day
<b><i>Leakance</i></b>		
foot per day per foot (ft/d)/ft	1.0	meter per day per meter

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

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

Vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1929 (NGVD 29).

Horizontal coordinate information (latitude-longitude) is referenced to the North American Datum of 1927 (NAD 27).

### Acronyms and Abbreviations

ET	evapotranspiration	NOAA	National Oceanic and Atmospheric Administration
FEP	fluorinated ethylene propylene		
GMWL	Global Meteoric Water Line	pCi/L	picoCuries per liter
LOWESS	locally weighted scatterplot smoothing curve	PTFE	polytetrafluoroethylene
MCL	Maximum Contaminant Limit	RIBs	rapid infiltration basins
μg/L	micrograms per liter	RCID	Reedy Creek Improvement District
μm	micrometer	SFWMD	South Florida Water Management District
μS/cm	microsiemens per centimeter	SJRWMD	St. Johns River Water Management District
meq/L	milliequivalents per liter	TDS	total dissolved solids
mg/L	milligrams per liter	USGS	U.S. Geological Survey
		VSMOW	Vienna Standard Mean Ocean Water

# Hydrogeology and Quality of Ground Water in Orange County, Florida

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## ABSTRACT

Ground water is the main source of water supply in central Florida and is critical for aquatic habitats and human consumption. To provide a better understanding for the conservation, development, and management of the water resources of Orange County, Florida, a study of the hydrogeologic framework, water budget, and ground-water quality characteristics was conducted from 1998 through 2002. The study also included extensive analyses of the surface-water resources, published as a separate report.

An increase in population from about 264,000 in 1960 to 896,000 in 2000 and subsequent urban growth throughout this region has been accompanied by a substantial increase in water use. Total ground-water use in Orange County increased from about 82 million gallons per day in 1965 to about 287 million gallons per day in 2000. The hydrogeology of Orange County consists of three major hydrogeologic units: the surficial aquifer system, the intermediate confining unit, and the Floridan aquifer system. Data were compiled from 634 sites to construct hydrogeologic maps and sections of Orange County. Water-level elevations measured in 23 wells tapping the surficial aquifer system ranged from about 10.6 feet in eastern Orange County to 123.8 feet above NGVD 29 in northwestern Orange County from March 2000 through September 2001. Water levels also were measured in 14 wells tapping the Upper Floridan aquifer. Water levels fluctuate over time from seasonal and annual variations in rainfall; however, water levels in a number of wells tapping the Upper Floridan aquifer have declined over

time. Withdrawal of ground water from the aquifers by pumping probably is causing the declines because the average annual precipitation rate has not changed substantially in central Florida since the 1930s, although yearly rates can vary.

A generalized water budget was computed for Orange County from 1991 to 2000. Average rates for the 10-year period for the following budget components were computed based on reported measurements or estimates: precipitation was 53 inches per year (in/yr), runoff was 11 in/yr, spring discharge was 2 in/yr, and net lateral subsurface outflow and exported water was 1 in/yr. Evapotranspiration was 39 in/yr, which was calculated as the residual of the water-budget analysis, assuming changes in storage were negligible.

Water-quality samples were collected from April 1999 through May 2001 from a total of 26 wells tapping the surficial aquifer system, 1 well tapping the intermediate confining unit, 24 wells tapping the Upper Floridan aquifer, 2 springs issuing from the Upper Floridan aquifer, and 8 wells tapping the Lower Floridan aquifer. These data were supplemented with existing water-quality data collected by the U.S. Geological Survey and St. Johns River Water Management District.

Concentrations of total dissolved solids, sulfate, and chloride in samples from the surficial aquifer system generally were low. Concentrations of nitrate were higher in samples from the surficial aquifer system than in samples from the Upper Floridan or

Lower Floridan aquifers, probably as a result of agricultural and residential land use. Water type throughout most of the Upper Floridan and Lower Floridan aquifers was calcium or calcium-magnesium bicarbonate, probably as a result of dissolution of the carbonate rocks. Water type in both the surficial and Floridan aquifer systems in eastern Orange County is sodium chloride. Concentrations of total dissolved solids, sulfate, and chloride in the aquifers increase toward eastern Orange County.

Data from 16 of 24 wells in eastern Orange County with long-term water-quality records indicated distinct increases in concentrations of chloride over time. The increases probably are related to withdrawal of ground water at the Cocoa well field, causing an upwelling of deeper, more saline water. The most commonly detected trace elements were aluminum, barium, boron, iron, manganese, and strontium. In addition, arsenic was detected in 12 of 59 samples, and selenium was detected in 19 of 58 samples. Concentrations generally were low; no samples had concentrations that exceeded any of the Maximum Contaminant Levels. Radon was detected in all ground-water samples in concentrations ranging from 56 to 14,700 picoCuries per liter.

Pesticide compounds were detected in low concentrations in 8 of 16 ground-water samples from the surficial aquifer system and in 2 of 14 samples from the Upper Floridan aquifer. The most commonly detected compounds were atrazine and its degradate, deethyl atrazine. Pesticides were present in shallow ground water primarily in urban areas around metropolitan Orlando. The source of pesticide compounds in ground-water samples probably is lawn-care and other household products containing pesticides. Pesticide concentrations did not exceed any Maximum Contaminant Levels.

Data from this study indicate that ground water is an abundant resource in Orange County, Florida. The quality of ground water generally is within the Primary and Secondary Drinking Water Regulations established by the U.S. Environmental Protection Agency; however, water-quality samples for this study were collected under drought conditions. Additional study to document water quality during various hydrologic conditions would be beneficial to understanding the occurrence and distribution of constituents such as pesticides.

## INTRODUCTION

Ground water from the Floridan aquifer system is the main source of water supply in central Florida. Ground water from the surficial and Floridan aquifer systems discharges to surface-water bodies such as lakes, springs, and streams, which provide aquatic habitat and recreation. An understanding of the quantity and quality of ground-water resources is important because of the numerous uses of ground water and the effect of ground water on the aquatic environment in central Florida.

A comprehensive water-resources study of Orange County by the U.S. Geological Survey (USGS) was completed by Lichtler and others (1968). Land use in Orange County has changed substantially since the late 1960s as a result of rapidly increasing population. The increase in population and subsequent urban growth was accompanied by a substantial increase in water use. Therefore, a new study was needed to document current (2001) ground-water conditions and assess potential changes in the quantity and quality of the water resources within Orange County.

In 1998, the USGS in cooperation with the City of Orlando, Orange County Utilities, Orlando Utilities Commission, Reedy Creek Improvement District, St. Johns River Water Management District (SJRWMD), and South Florida Water Management District (SFWMD), began a 4-year study to evaluate the ground- and surface-water resources of Orange County. A summary of the surface-water investigations will be published in a separate report. The objectives of the ground-water portion of the study were to: (1) describe the current conditions of the ground-water resources of Orange County; (2) assess long-term trends in ground-water resources, particularly with respect to changes in land use and (or) increases in water use; and (3) determine natural and anthropogenic factors affecting ground-water resources. Data collected in and around Orange County by the USGS and numerous State and local agencies since 1968 were compiled and new data were collected to meet the objectives of the present study.

## Purpose and Scope

The purpose of this report is to present results from a comprehensive study of the ground-water resources that will be useful for the conservation, development, and management of the water resources

of Orange County. This report presents a description of the hydrogeology and the water quality of the surficial and Floridan aquifer systems. Climate, physiography, land use, population, and water use of Orange County, as well as a description of data-collection and analytical methods, are included. Current (2001) conditions of ground-water availability and water quality also are compared and contrasted to past conditions. Natural and anthropogenic factors that could be affecting the availability and quality of ground water are described.

The scope of the report includes a compilation of existing data and description of new data on the geology and ground-water hydrology of Orange County. Geologic and geophysical data from 634 sites were used to construct hydrogeologic maps and sections. An additional 18 new wells that tap the surficial aquifer system were installed. Slug tests were done on 4 existing and 16 newly installed wells to measure the hydraulic properties of the surficial aquifer system. Water levels in 37 wells were measured bimonthly from March 2000 through September 2001; four of the wells also were instrumented with transducers for continuous monitoring of water levels. Historical water-level data were statistically analyzed for trends. During the period from April 1999 through May 2001, water-quality samples were collected once from 26 wells tapping the surficial aquifer system, 1 well tapping the intermediate confining unit, 24 wells tapping the Upper Floridan aquifer, 2 springs discharging from the Upper Floridan aquifer, and 8 wells tapping the Lower Floridan aquifer. These data were combined with water-quality data collected from 1990 through 2000 to assess the water-quality conditions of the ground-water resources of Orange County. Limited historical (pre-1990) water-quality data also were available for statistical trend analysis.

## Previous Investigations

The water resources of Orange County have been studied for more than 60 years. Stringfield (1936) and Unklesbay (1944) described the geology of the Floridan aquifer system and documented water levels prior to extensive ground-water development.

Lichtler and others (1968) reported on both ground- and surface-water conditions in Orange County in the early-to-mid-1960s. Anderson and Joyner (1966) described the availability and quality of surface water. Lichtler and others (1976) investigated the hydrologic connection between ground water and

three lakes in the Orlando area. Phelps and German (1995), Smoot and Schiffer (1985), German (1983), Gaggiani and Lamonds (1977), and Pfischner (1968) described the hydrology and quality of water in selected Orange County lakes. Schiffer (1989) described the effects of urban runoff on the water quality of wetlands in the metropolitan Orlando area.

Tibbals and Frazee (1976) and Phelps and Schiffer (1996) described hydrogeologic and water-quality conditions at the Cocoa well field in east Orange County. Kimrey (1978) completed a preliminary appraisal of drainage wells in and around Orlando. The effects of drainage wells on the water quality of the Upper Floridan aquifer in the Orlando area were described by Schiner and German (1983) and Taylor (1993). Bradner (1991) described water quality in the Upper Floridan aquifer in the vicinity of drainage wells and delineated a hydrocarbon plume in the Upper Floridan aquifer in downtown Orlando, resulting from operation of a coal-gasification plant. A comprehensive inventory of drainage wells and their effects on recharge in Orange and Seminole Counties was completed by CH2M Hill (1997).

The effects of agricultural (citrus) and urban land uses on ground-water quality were studied by Rutledge (1987) and German (1996). Fate and transport of nutrients in ground water under a rapid-infiltration basin was studied by Sumner and Bradner (1996). A study of the water quality and isotope geochemistry of springs in central Florida included data from Rock and Wekiva Springs in Orange County (Toth, 1999).

A seismic-reflection and hydrogeologic study of Lake Apopka was completed by Locker and others (1988). A study by O'Reilly and others (2002) of the hydrogeology and water quality of the Lower Floridan aquifer included all of Orange County.

O'Reilly (1998), Murray and Halford (1996), and Tibbals (1990) developed ground-water flow models that included all or parts of Orange County. Ground-water flow and salt-water intrusion were modeled in Orange County (PB Water, 1999). A ground-water flow model developed for Seminole County also included Orange County (Spechler and Halford, 2001). A model of ground-water flow in peninsular Florida included all of Orange County (Sepúlveda, 2002). McGurk and Presley (2002) developed a model of ground-water flow in east-central Florida that included all of Orange County.

## Site-Numbering System

The USGS National Water Data Information System (NWIS) uses a 15-digit number (site identification number) based on latitude and longitude, to identify wells. The first six digits denote the degrees, minutes, and seconds of latitude; the next seven digits denote the degrees, minutes, and seconds of longitude; and the last two digits denote a sequential number for a site within a one-second grid. Well site identification numbers generally end in 01 or 02. For convenience, in this report wells and springs also are given a site number that refers to locations shown in the figures. Surface-water sites generally are designated by an 8-digit downstream-order number. Appendix 1 lists the site numbers and site identification numbers.

## Acknowledgments

The authors express their appreciation to various public officials of Orange County, the City of Orlando, the Orlando Utilities Commission, Reedy Creek Improvement District, St. Johns River Water Management District, and South Florida Water Management District, whose cooperation and knowledge greatly aided this investigation. The authors are particularly grateful for water-quality data provided by the City of Orlando and St. Johns River Water Management District. The authors also are grateful for access to land owned by the city of Orlando, Orange County, South Florida Water Management District, St. Johns River Water Management District, the State of Florida, and private land owners.

## DESCRIPTION OF THE STUDY AREA

Orange County is located in east-central Florida (fig. 1). The county is about 1,003 mi<sup>2</sup> in area, with about 916 mi<sup>2</sup> of land and about 87 mi<sup>2</sup> of water (Lichtler and others, 1968). The St. Johns River forms the boundary with Brevard County, directly to the east. Seminole and Lake Counties are north and west, respectively, of Orange County, and Osceola County is directly south. The northern and eastern parts of Orange County are contained within SJRWMD, whereas the south-central and southwestern parts of Orange County are contained within SFWMD.

Metropolitan Orlando is the major population center in the county. This urban area includes the city of Orlando as well as adjacent communities such as Apopka, Maitland, and Winter Park. Other communities in Orange County include Bithlo, Christmas, Oakland, Winter Garden, and Zellwood. Since 1971, the southwestern part of Orange County has become a major recreational resource with several large theme parks, hotel complexes, and golf courses, attracting large numbers of international and domestic tourists.

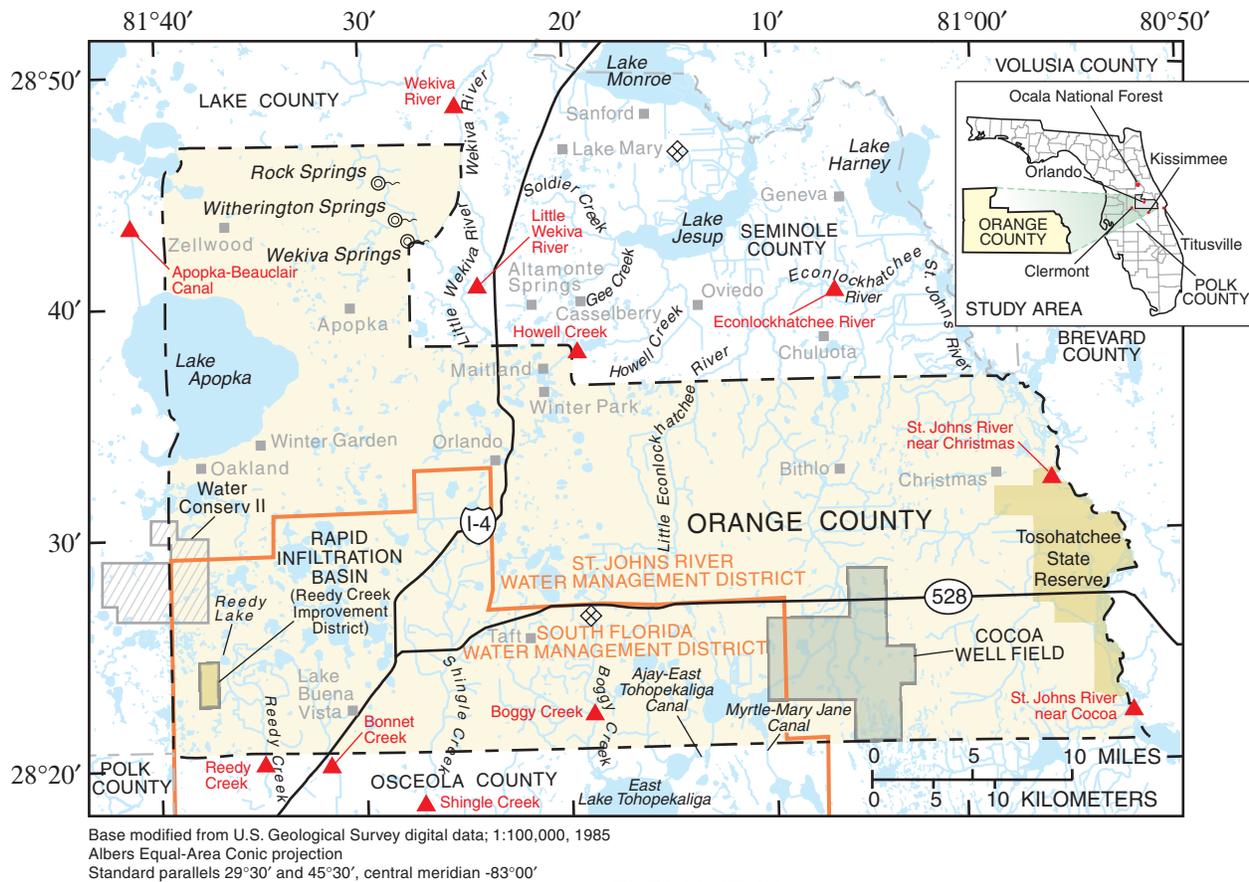
## Environmental Setting

Orange County has a subtropical climate with relatively short, warm winters, and long, hot summers. The average annual temperature at Orlando is 71.5 °F. The average air temperatures in January and July are 50 °F and 90 °F, respectively. Minimum air temperatures during the winter months occasionally drop below freezing, but rarely below 20 °F. Maximum air temperatures in the summer months commonly exceed 90 °F.

Records of annual precipitation were compiled for a National Oceanic and Atmospheric Administration (NOAA) rainfall station in south Orlando and Sanford, Florida. The periods of record for these stations are from 1931 to 2001. The mean annual rainfall for Orlando was 50 in., the minimum was 30.4 in. (2000), and the maximum was 68.7 in. (1960). The mean annual rainfall for Sanford was 52 in. (fig. 2).

The distribution of daily rainfall in Orlando probably is typical of all of Orange County. The maximum daily rainfall recorded at the Orlando station was 8.19 in. in July 1960. Days with low rainfall occur relatively frequently yet account for little of the annual accumulation. For example, 50 percent of the days with measurable rainfall had 0.2 in. or less total rainfall. These relatively low rainfall days accounted for only 8.4 percent of the total rainfall accumulation for the period of record. Conversely, higher daily rainfall events, though relatively infrequent, account for a large portion of the total rainfall accumulation. For example, rainfall totals exceeding 1 in. occurred on about 12 percent of the days with measurable rainfall, yet accounted for about half of the total rainfall accumulation.

Seasonally, the wettest month for the period 1931-2000 was July, with a maximum rainfall of 19.57 in. (in 1960) and a mean rainfall of nearly 8 in. Several months had less than 0.2 in. of rain, with the driest being December 1944 with no recorded rainfall. Most of the rainfall in Orange County occurs during the months of June



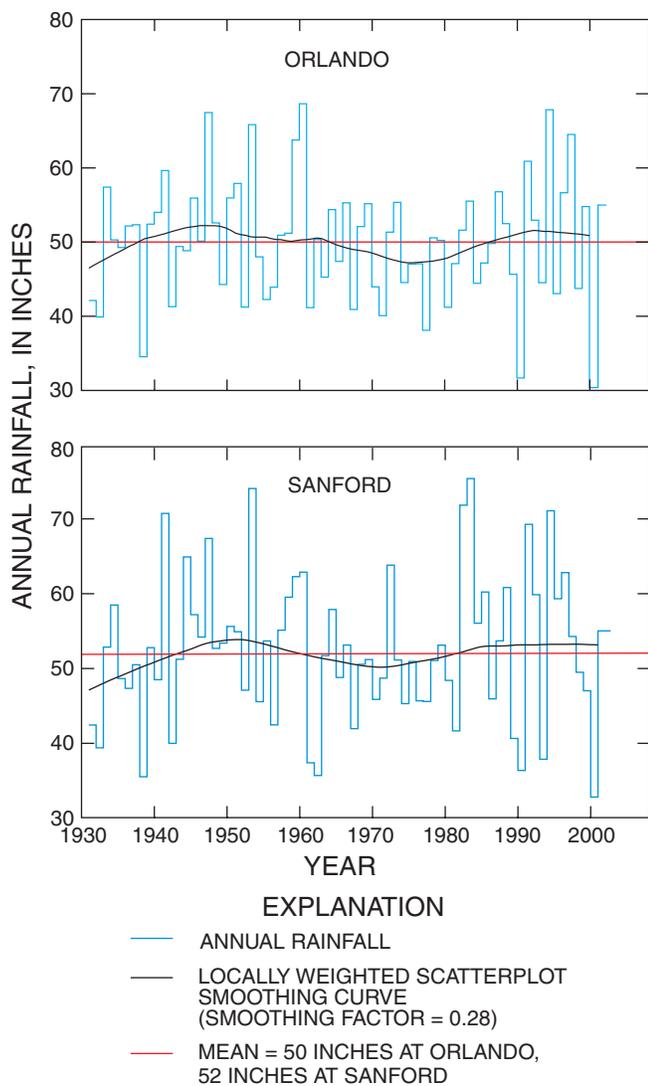
**EXPLANATION**

- ▲ Reedy Creek SURFACE WATER SITE AND NAME
- ◆ RAIN GAGE -- NOAA (National Oceanic Atmospheric Administration) at Orlando International airport and Sanford International airport

**Figure 1.** Location of Orange County, Florida.

through September (commonly referred to as the wet season). For each of these 4 months, the average rainfall for the 1931-2000 period exceeded 6 in./mo. The remaining 8 months had average rainfall totals of less than 4 in./mo (commonly referred to as the dry season). The average wet-season rainfall for 1931-2000 was 28.13 in., and the average dry-season rainfall was 21.84 in. Hence, more than half of the annual total rainfall generally falls during the wet season. Some dry seasons can be relatively wet, as in 1997, when total precipitation was 34.2 in., compared to only 30.3 in. during the wet season for that year. In 1997, a substantial portion of the total dry-season precipitation occurred in December (12.63 in.), a normally dry month with an average of 2.1 in. of rain. This pattern of occurrence indicates that the annual rainfall totals can be dominated by a few relatively extreme events.

A considerable amount of variation in annual rainfall occurs from year to year, making it difficult to determine whether annual rainfall rates have changed substantially over time. A cycle of wet and dry periods is present, as illustrated by the locally weighted scatterplot smoothing curve (LOWESS) in figure 2. Furthermore, the annual variability of rainfall totals at the Orlando and Sanford stations was lower during 1961 through about 1989 than during the years preceding or following this period. No consistent linear trend in annual rainfall rates is present for the period of record 1931-2001. Statistical analysis (Kendall tau) also indicates that no long-term trend in rainfall has occurred at the Orlando station during the period of record (E.R. German, U.S. Geological Survey, written commun., 2003).



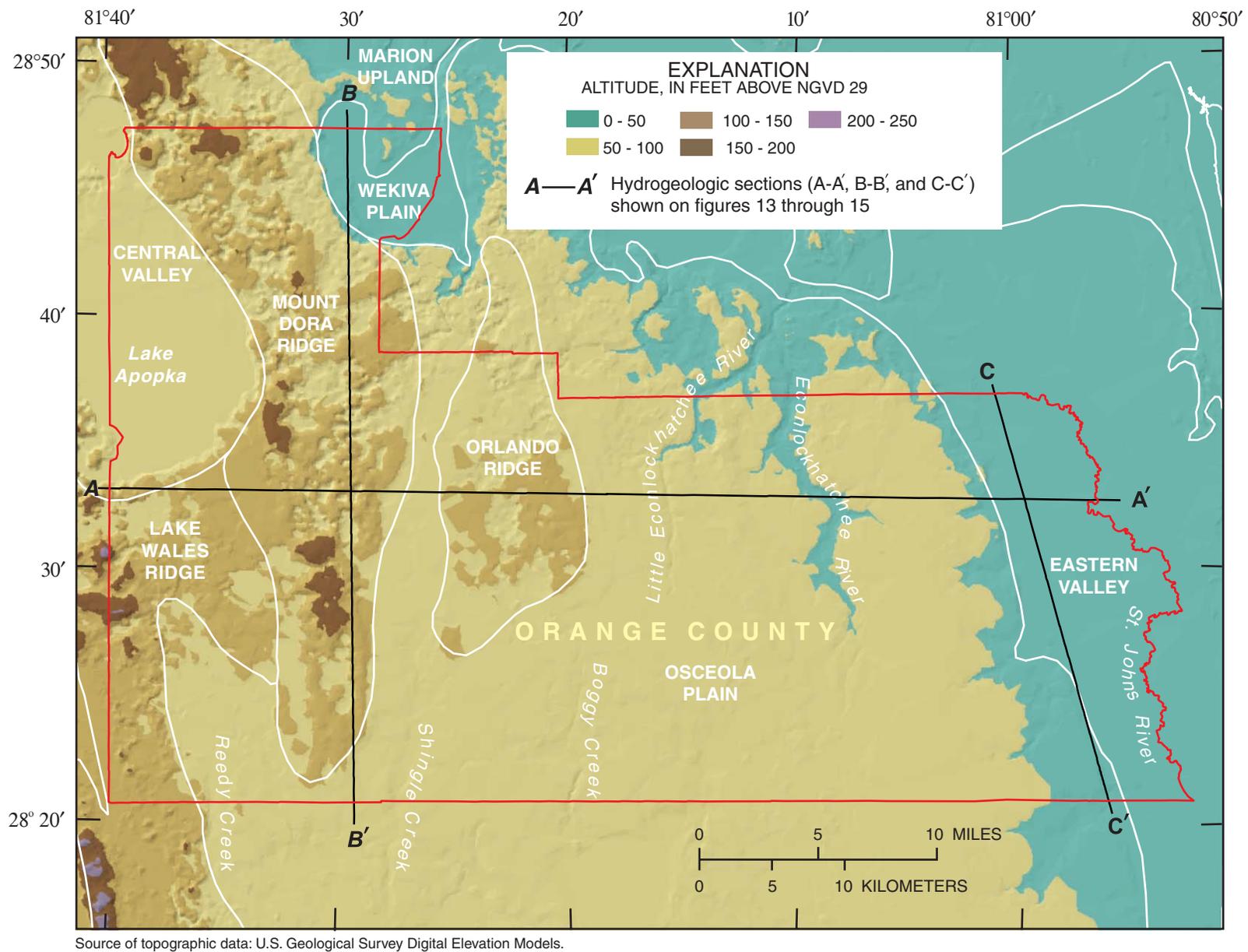
**Figure 2.** Annual rainfall at Orlando and Sanford, Florida, 1931-2001.

Land-surface altitudes in Orange County range from less than 5 ft above NGVD 29 near the St. Johns River to more than 200 ft above NGVD 29 in west-central Orange County; however, about 75 percent of the county has a land-surface altitude ranging between 70 and 120 ft above NGVD 29. The median altitude is about 90 ft above NGVD 29. Topography ranges from flat lying in eastern Orange County to gently rolling hills in northwestern and southwestern Orange County (fig. 3).

Parts of eight physiographic divisions are located in Orange County—the Central Valley, the Eastern Valley, the Lake Wales Ridge, the Marion Upland, the Mount Dora Ridge, the Orlando Ridge, the Osceola Plain, and the Wekiva Plain (White, 1970; fig. 3). The Central Valley, Eastern Valley, and Osceola Plain are characterized by relatively flat-lying land. The Central Valley contains Lake Apopka, one of the largest lakes in Florida. The Eastern Valley and Osceola Plain historically contained numerous wetlands, many of which were drained for development. Wetlands remain and (or) were restored in many parts of Orange County, including Tosohatchee State Reserve (fig. 1). The Lake Wales Ridge, Mount Dora Ridge, and Orlando Ridge contain gently rolling hills. These hills generally align to form ridges that trend in a northwest-southeast direction (White, 1970). The ridges also are characterized by numerous lakes, many of which are seepage lakes with no external drainage (fig. 3). The Wekiva Plain and Marion Upland are present in northwestern Orange County.

Orange County is drained by two major stream systems—the St. Johns and Kissimmee River systems. The St. Johns River flows along the eastern boundary of Orange County. Tributaries of the St. Johns River, primarily the Econlockhatchee River and Wekiva River, drain about 662 mi<sup>2</sup> of eastern and northern Orange County. Tributaries of the Kissimmee River—primarily Bonnett, Boggy, Reedy, and Shingle Creeks—drain about 341 mi<sup>2</sup> of south-central and southwestern Orange County (Lichtler and others, 1968) (fig. 1). Ground-water seepage provides most of the base flow to these streams. In addition, discharge from two large springs, Rock and Wekiva (fig. 1), form the headwaters of the Wekiva River.

The geology of Orange County consists of metamorphic rocks of Precambrian age overlain by a thick sequence of sedimentary rocks ranging from Paleozoic to Recent age (Arthur and others, 1994). The sedimentary rocks of Paleocene to Recent age are important with respect to the hydrogeology. The oldest rocks in this sequence are those of the Cedar Keys Formation of Paleocene age. This formation consists primarily of marine dolomite with abundant evaporites (gypsum and anhydrite). Overlying the Cedar Keys Formation is a thick sequence of marine limestones and dolomites of Eocene age that contain minor amounts of evaporites.



**Figure 3.** Physiography (modified from White, 1970) and locations of hydrogeologic sections (figures 13 through 15 of this report).

These rocks include the Oldsmar Formation, the Avon Park Formation, and the Ocala Limestone. The rocks of Eocene age can be more than 2,200 ft thick in Orange County. These units generally are fossiliferous and have undergone a considerable amount of fracturing and dissolution.

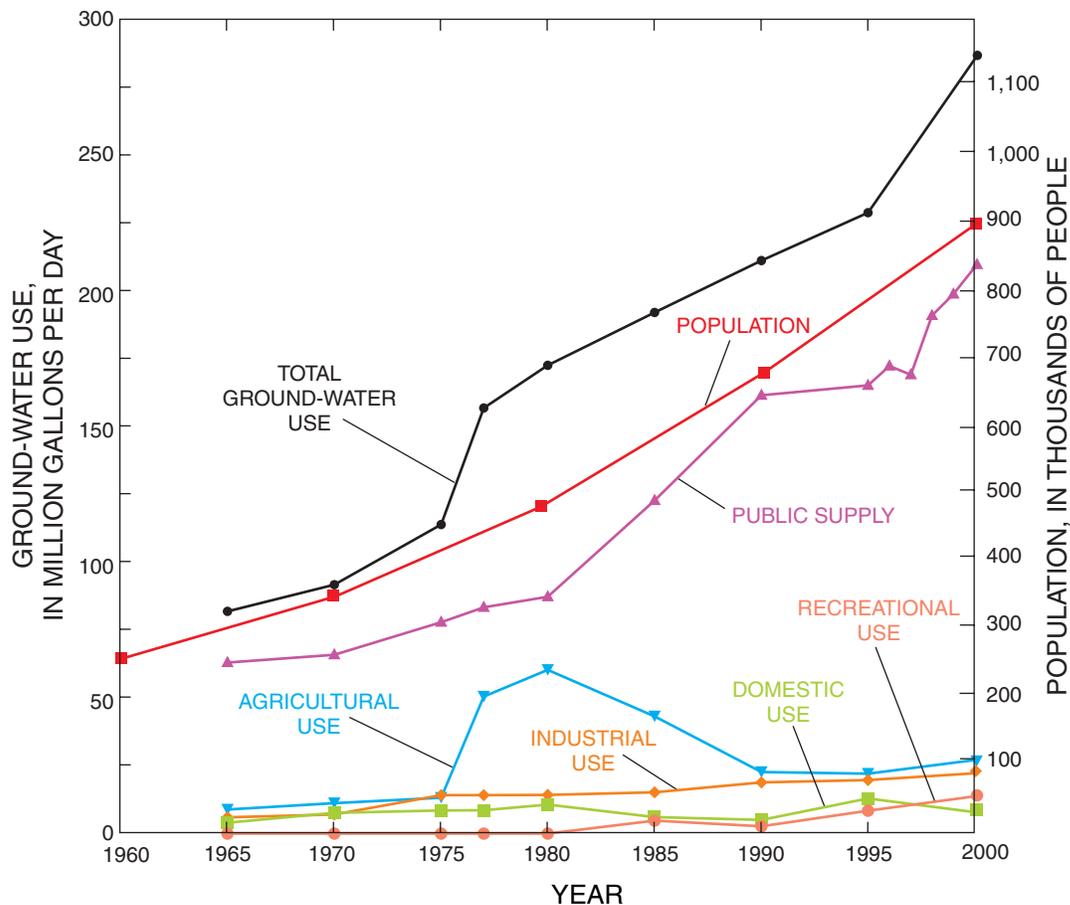
Dolomite, limestone, clay, and silt of the Miocene-age Hawthorn Group overlie the Ocala Limestone. The contact is an erosional unconformity. In general, the clay and silt layers have a distinctive gray to green color.

Sand, clay, silt, and shell layers of Pliocene through Recent age overlie the Hawthorn Group. Many such layers were deposited in beach or near-beach environments when sea levels were higher than under present conditions. The Lake Wales and Mount Dora Ridges, which are composed of sand, silt, and clay, represent ancient beach environments (Arthur and others, 1994).

Most of the above-mentioned geologic units are not exposed at the surface in Orange County. Surficial geology consists primarily of Pleistocene to Recent deposits. The Hawthorn Group is exposed in north-western Orange County near Rock Springs (Scott and others, 2001).

### Population, Land Use, and Water Use

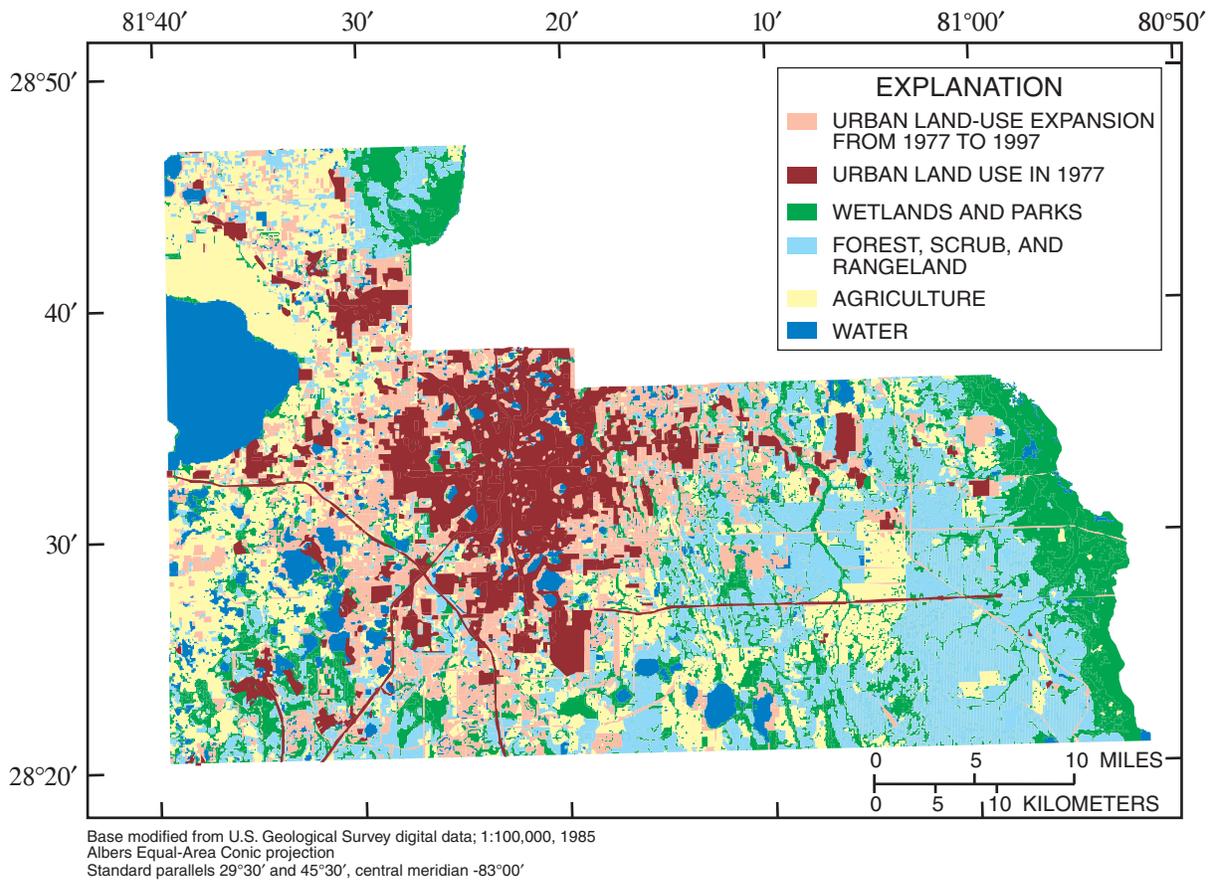
Orange County has experienced a large population increase since 1968, mostly as a result of an increase in the tourism industry. The population of Orange County in 1920 was less than 20,000; the population increased to more than 264,000 by 1960. The residential population in 2000 was about 896,000 (U.S. Census Bureau, 2002) (fig. 4). In addition to the residential population, about 744,000 tourists visit Orange County each week (Orlando Chamber of Commerce, written commun., July 1998).



**Figure 4.** Population (1960-2000; U.S. Census Bureau, 2002) and ground-water use (1965-2000; R.L. Marella, U.S. Geological Survey, written commun., 2002) in Orange County, Florida.

Land use has changed as a result of increased population. A comparison of the extent of urban land use in 1977 with the extent of urban land use in 1997 (fig. 5) shows that the amount of urban area increased considerably in all directions around the Orlando area and in the northwestern part of the county. Urban area increased from 142 mi<sup>2</sup> (14 percent) in 1977 to 221 mi<sup>2</sup> (22 percent) in 1997. The eastern third of the county has seen relatively little increase in urbanization between 1977 and 1997, especially in the southeast. The increase in urban land use has occurred in land previously used for range and agriculture. Citrus land use in 1970 accounted for about 65,960 acres, decreasing to 51,170 acres in 1978, and to about 8,400 acres in 1990 (Marella, 1992). A series of freezes in 1983, 1985, and 1989 destroyed most of the citrus groves, which were replaced by urban development as the population growth accelerated. Livestock production similarly has decreased in Orange County. The number of cattle decreased from

36,000 in 1969, to 19,000 in 1978, to 16,000 in 1997, and to 14,000 in 2002. The number of hogs decreased from 7,700 in 1969 to 790 in 1997 (Jeff Geuder, Florida Agricultural Statistics Service, written commun., 2002; Florida Agricultural Statistics Service, 2002). In addition, cropland decreased from 108,000 acres in 1969 to 30,000 acres in 1997 (Jeff Geuder, Florida Agricultural Statistics Service, written commun., 2002). Former row-crop agricultural land north of Lake Apopka recently was purchased by SJRWMD as part of the plan to restore the lake. Much of this land is being restored to more natural conditions, so present (2002) row-crop land use in Orange County is reduced greatly from 1997. Agricultural chemical (fertilizers and pesticides) use varies by crop and year. For example, the average fertilizer use for corn in the 1990s was 105 (lbs/acre)/yr for nitrogen, 97 (lbs/acre)/yr for phosphorus, and 200 (lbs/acre)/yr for potassium. The average fertilizer use for oranges in the



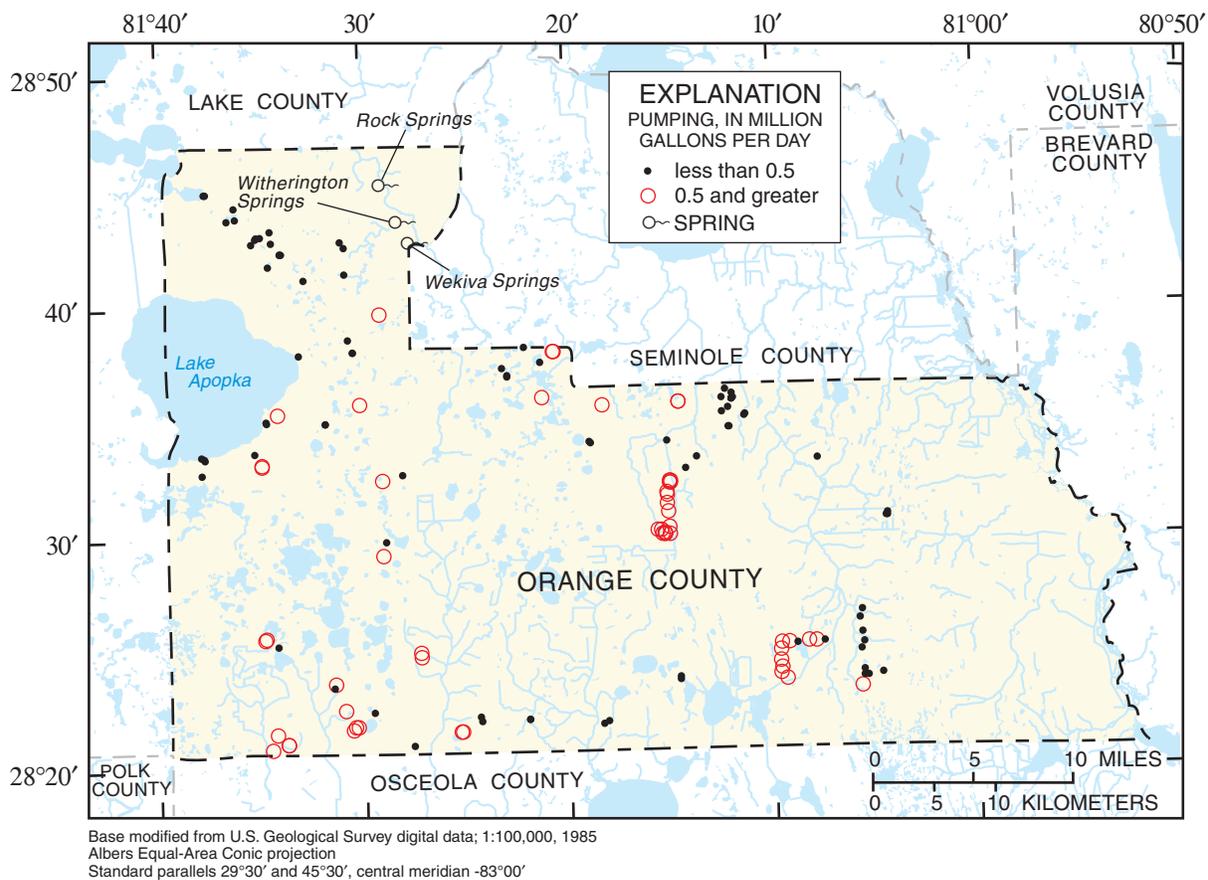
**Figure 5.** Generalized land use in Orange County, Florida, in 1997 (source: Orange County Growth Management Department), showing expansion of urban land use since 1977 (based on land-use classifications described by Anderson and others, 1976).

1990s was 198 (lbs/acre)/yr for nitrogen, 46 (lbs/acre)/yr for phosphorus, and 199 (lbs/acre)/yr for potassium. Atrazine, a broadleaf herbicide, is applied to corn fields at a rate between 1.2 and 1.7 (lbs/acre)/yr; atrazine is not used in citrus groves. These numbers are based on surveys of growers conducted by the Florida Agricultural Statistics Service (2002). Agricultural chemicals also are used in residential settings in maintaining lawns and gardens; however, pesticide usage is more highly variable depending on the homeowner.

Ground-water use has increased substantially in Orange County in the last 35 years. Most of the ground water used in Orange County is pumped from the Floridan aquifer system. Total ground-water use in Orange County was about 287 Mgal/d in 2000 (fig. 4). In comparison, total ground-water use in Orange County was 82 Mgal/d in 1965. A large percentage of ground water pumped in Orange County is used for public water supply, which increased from 63 Mgal/d in 1965 to 212 Mgal/d in 2000 (R.L. Marella, U.S. Geological

Survey, written commun., 2002) (figs. 6-7). Of the 212 Mgal/d of water withdrawn for public water supply, about 84 Mgal/d (40 percent) was withdrawn from the Upper Floridan aquifer, and 128 Mgal/d (60 percent) was withdrawn from the Lower Floridan aquifer. Most of the ground water pumped for public supply is consumed in Orange County; however, about 12 percent (26 Mgal/d) of the water pumped for public supply is transferred to Brevard County for consumption (R.L. Marella, U.S. Geological Survey, written commun., 2002).

The relatively large increase in public supply has been partially offset by a decline in agricultural use of ground water—from 60 Mgal/d in 1980 to 27 Mgal/d in 2000. The large increase in agricultural ground-water use from 1975 to 1980 represents changes in methods to estimate that use (R.L. Marella, U.S. Geological Survey, written commun., 2002). The decline in agricultural use after 1985 probably is related to changes in land use described previously.



**Figure 6.** Estimated pumping from public-supply wells tapping the Upper Floridan aquifer in 2000 (modified from Spechler and Halford, 2001, and Brian McGurk, St. Johns River Water Management District, written commun., 2002).

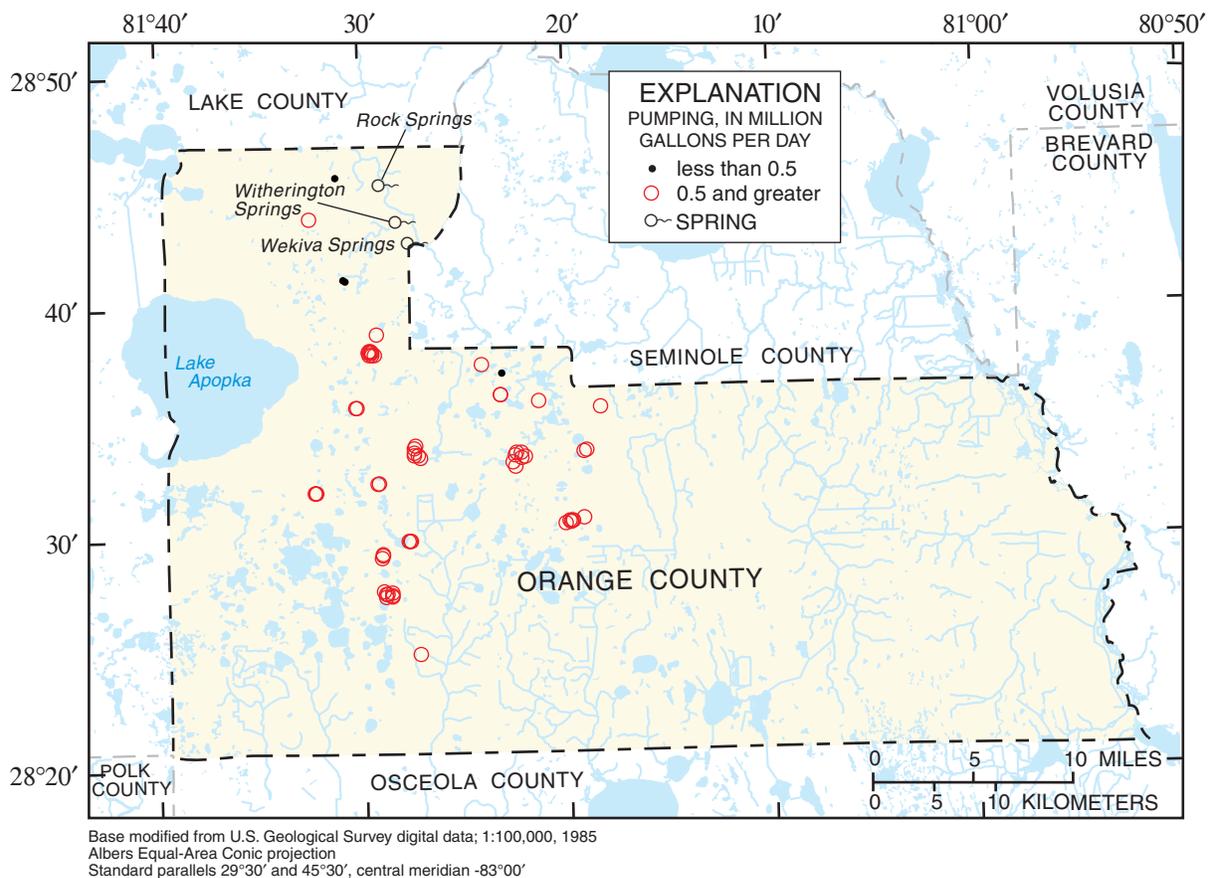
## DATA COLLECTION AND ANALYSIS

The ground-water resources of Orange County were analyzed by using existing data and new geologic, geophysical, water-level, and water-quality data. Existing data were obtained and compiled from various Federal, State, and local agencies. Collection of new data for this study began in 1999 and continued through 2001.

Geologic and geophysical information from 634 sites were used to construct hydrogeologic maps and sections. This information, obtained from USGS, SJRWMD, and the Florida Geological Survey, included borehole geophysical logs and lithologic descriptions of well cuttings by geologists and drillers. Analysis included quality assurance of the data and verification of well locations. Some wells had been assigned a different site identifier by the three agencies. Duplicate site information was removed. The reported

location of a well was checked to verify that the well plotted in a reasonable location, and that the latitude-longitude location corresponded with the township-range location. The reported land-surface altitude was checked against the actual altitude of the location. In addition, seven observation wells that tap the Upper Floridan aquifer were geophysically logged as part of this study (table 1). Geophysical logs included temperature, fluid resistivity, caliper, natural gamma, and electric.

Maps were constructed by determining the depth to geologic or hydrogeologic contacts at each well location. The top of the Upper Floridan aquifer was considered to be the contact between Eocene-age limestones (generally, the Ocala Limestone) and overlying Miocene-age sediments (primarily, the Hawthorn Group). The top of the intermediate confining unit was considered to be the top of the Hawthorn Group, and any overlying clay units of Pliocene or Pleistocene age, if present. These definitions are consistent with those



**Figure 7.** Estimated pumping from public-supply wells tapping the Lower Floridan aquifer in 2000 (modified from O'Reilly and others, 2002; Spechler and Halford, 2001; and Brian McGurk, St. Johns River Water Management District, written commun., 2002).

**Table 1.** Summary of borehole geophysical data collected from wells tapping the Upper Floridan aquifer

[--, no data; cal, caliper log; gam, natural gamma log; res, fluid resistivity; temp, water temperature; elec, electric logs including spontaneous potential and long- and short-normal resistivity; UF, Upper Floridan aquifer]

Site identifier	Site number	Site name	Elevation (feet above NGVD 29)	Casing length (feet)	Depth of well (feet below land surface)	Types of logs
282434081283102	45	Sea World Replacement	103.16	158	239	cal, gam, res
282640080565901	180	Tosohatchee UF well	22	--	203	gam
282739081054501	82	Cocoa F	67.29	200	375	cal, gam, res
282835081305201	86	Palm Lake well	152.00	161	235	temp, cal, gam, res, elec
283003081283901	101	Turkey Lake UF well	125	--	305	cal, gam
283253081283401	126	OR-47	81.71	328	350	temp, cal, gam, res
284529081301001	170	Rock Springs UF well	71.90	143	365	temp, cal, gam, res, elec

of previous hydrogeologic studies in central Florida (Murray and Halford, 1996; Spechler and Halford, 2001; Knowles and others, 2002).

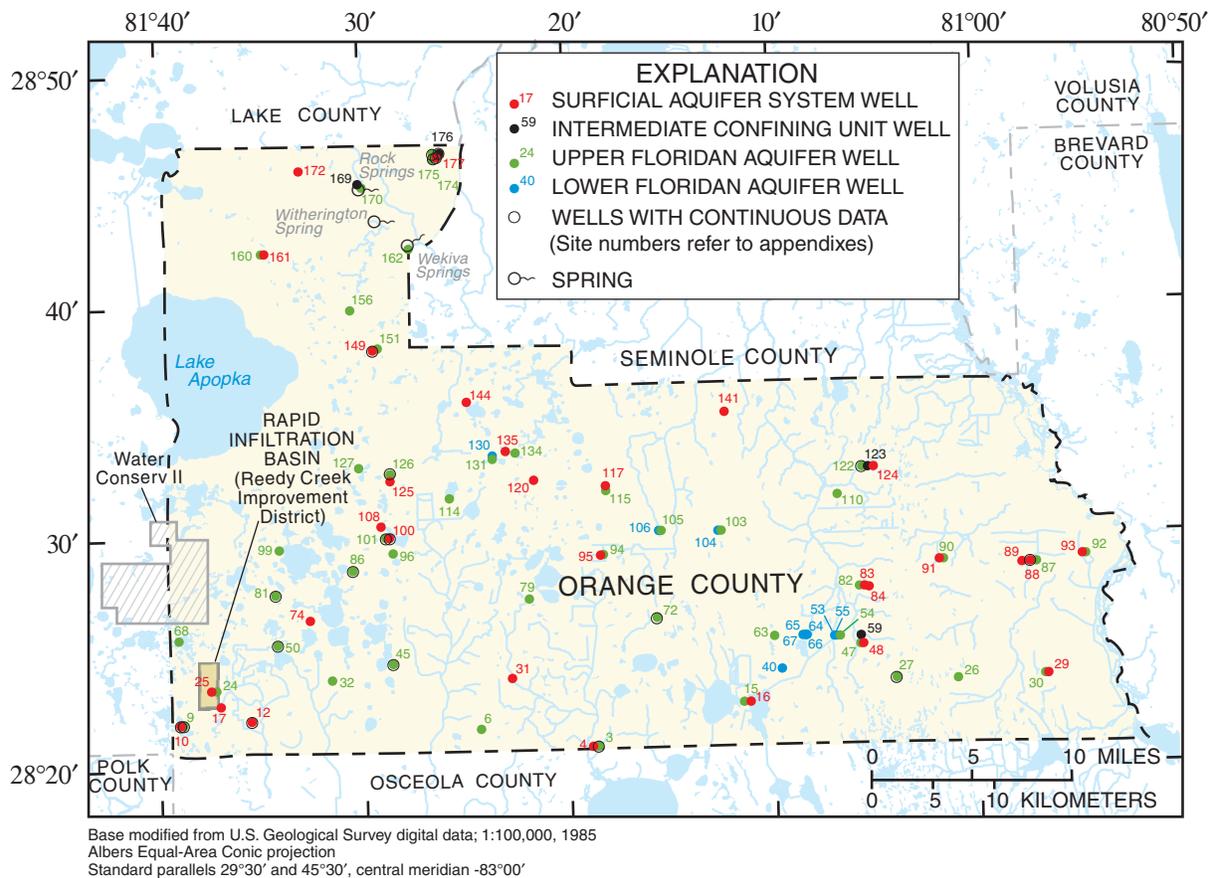
Natural gamma logs, which measure the natural radioactivity of rock units, were useful for determining these geologic contacts. The Hawthorn Group contains radioactive minerals that produce an inflection or spike in the natural-gamma log (Johnson, 1984; Keys, 1988). The beginning and end of this spike generally correspond to the upper and lower contacts, respectively, of the Hawthorn Group.

A total of 18 wells (app. 1) that tap the surficial aquifer system was installed throughout Orange County from August 1999 through February 2000. Twelve of the wells were installed near existing wells that tap the Upper Floridan aquifer to provide a comparison of water levels and water quality between the two aquifers. Thirteen of the wells were drilled with rotary mud methods, three of the wells were bored with hollow stem auger, and two wells were installed by using hand augers. At 13 sites, a test hole was drilled to the top of the intermediate confining unit, and split spoon samples were collected every 5 ft for lithologic analysis. In general, wells were completed with a 20/30 U.S. Standard Sieve size sand filter pack to about 5 ft above the top of the screen, followed by a 2-ft-thick bentonite seal, then the remaining annular space was grouted with type I Portland cement. Final depth of the wells tapping the surficial aquifer system ranged from 9 to 75 ft; screen length ranged from 5 to 20 ft. The newly installed wells were developed by pumping until the water became clear and (or) specific conductance stabilized.

From February through March 2001, slug tests were performed on 4 existing observation wells and 16 of the newly installed observation wells to measure the horizontal hydraulic conductivity of the surficial aquifer system. The slug tests consisted of rapidly inserting and (or) removing a slug from the water column in the well and measuring the change of water level in the well over time. The slug was a sand-filled polyvinyl chloride pipe lowered with a rope. The water level in the well would either fall or rise to return to pre-test levels, when the slug was inserted or removed, respectively. Two to six tests were performed at each well.

Water levels in 37 wells (23 wells tapping the surficial aquifer system, 2 wells tapping the intermediate confining unit, and 12 wells tapping the Upper Floridan aquifer) were measured bimonthly from March 2000 through September 2001. Three of the wells tapping the surficial aquifer system and one of the wells tapping the Upper Floridan aquifer also were instrumented with pressure transducers for the continuous monitoring of water levels. All wells in Orange County with water-level data are shown in figure 8.

Water samples collected from a total of 121 wells (fig. 9; table 2; apps. 2-4) were used to characterize ground-water quality in Orange County. These data, a subset of the total water-quality samples available, were selected to provide a relatively even geographic distribution of data. The large number of samples available around the Cocoa well field (apps. 1 and 2), for example, would statistically bias the results, and, hence, not all available data were used in the analyses.



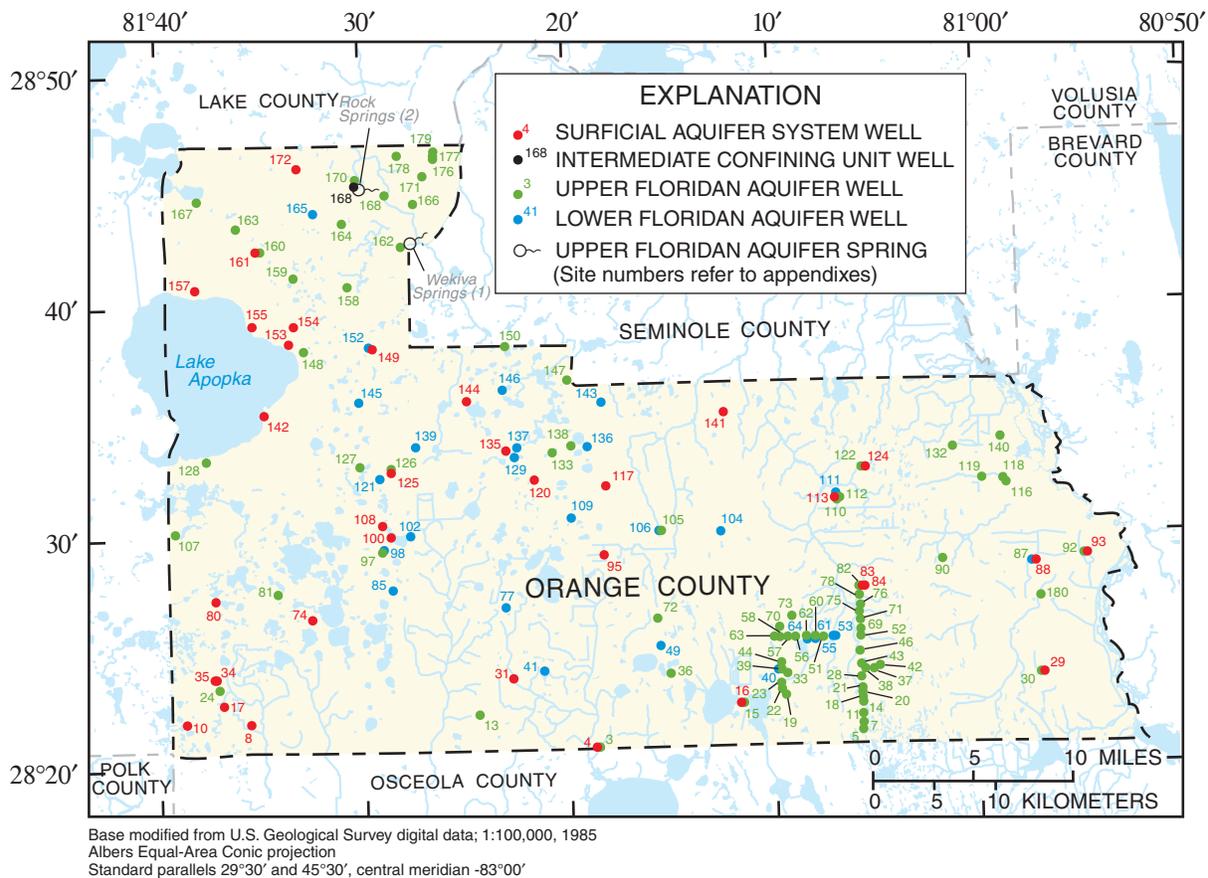
**Figure 8.** Locations of wells with periodic and continuous water-level data and geophysical data.

Water-quality samples were collected specifically for this project by the USGS from April 1999 through May 2001 (fig. 9; apps. 1-4). These samples were collected to: (1) assess the overall ground-water quality throughout Orange County; and (2) determine the occurrence and distribution of selected constituents such as nutrients and pesticides. Samples were collected once from 26 wells tapping the surficial aquifer system, 1 well tapping the intermediate confining unit, 24 wells tapping the Upper Floridan aquifer, and 8 wells tapping the Lower Floridan aquifer. In addition, samples were collected once from Wekiva Springs (site 1) and twice from Rock Springs (site 2).

Water samples were collected from wells by using either a permanently installed pump or a portable 2-in-diameter stainless steel pump equipped with fluorinated ethylene propylene (FEP) tubing. Samples from Rock Springs and Wekiva Springs were collected by using a pump equipped with a polytetrafluoroethylene (PTFE) diaphragm pump head and FEP tubing.

At Rock Springs, the tubing was inserted directly into the spring orifice; at Wekiva Springs, the water was collected directly from the main orifice using a FEP bailer, then composited into a churn splitter prior to processing. Field measurements (temperature, specific conductance, dissolved oxygen, and pH) of ground water were made at all well sites by using a flow-through chamber and following USGS protocols (Wilde and Radtke, 1998). Samples were collected after purging the well of at least three casing volumes and (or) stabilization of the field measurements. Field measurements were made at both spring sites by inserting the instrument probes directly into the spring orifice.

Samples were collected for laboratory analysis of alkalinity, major ions, silica, selected trace elements, radon, total organic carbon, and nutrients including nitrite as nitrogen, nitrite plus nitrate as nitrogen, ammonia as nitrogen, ammonia plus organic nitrogen as nitrogen (hereafter referred to as nitrite, nitrate,



**Figure 9.** Locations of wells and springs where water-quality data were collected from 1990 through 2001.

**Table 2.** Summary of well construction information, by aquifer, for wells with water-quality records

[Altitude, in feet above sea level; casing length in feet; well depth in feet below land surface]

	Number of wells	Minimum	Median	Maximum
Surficial aquifer system	34			
Land surface altitude		14	93	146
Casing length		3.7	20	54
Well depth		8.7	30	74
Upper Floridan aquifer	62			
Land surface altitude		14	71	152
Casing length		10	169	620
Well depth		40	357	840
Lower Floridan aquifer	25			
Land surface altitude		59	97	145
Casing length		602	1,060	1,428
Well depth		1,200	1,390	2,440

ammonia and ammonia plus organic nitrogen, respectively), phosphorus, and orthophosphate as phosphorus (hereafter referred to as phosphate) (table 3). Samples from selected sites were collected for analysis of stable isotopes (deuterium and oxygen-18) and (or) 46 pesticides and pesticide metabolites (app. 4) (Zaugg and others, 1995). All samples were processed according to USGS protocols (Wilde and others, 1999). Samples for major-ion, nutrient, and trace-element analyses were filtered with a 0.45- $\mu\text{m}$  pore-size disposable capsule filter. Samples for major-cation and trace-element analyses were acidified with 2 milliliters nitric acid to adjust sample pH to less than 2. Samples for pesticide analysis were filtered with a 0.7- $\mu\text{m}$  pore-size baked, glass-fiber filter in an aluminum filter plate because solid phase extraction of the sample is required for the low detection limits (Zaugg and others, 1995). Whole-water samples for low-level constituents such as trace elements and pesticide could have concentrations that

**Table 3.** Analytical methods and drinking water standards for inorganic analytes included in the study

[Abbreviations used for method of analysis: AA, atomic absorption spectrometry; C, colorimetry; G, residue evaporation at 180 degree Celsius; I, combustion-infrared method; IC, ion-exchange chromatography; ICP, induction-coupled argon plasma atomic emission spectrometry; ISE, ion-selective electrode; SC, scintillation; T, end-point titration. Abbreviations used for drinking water standards: MCL, Maximum Contaminant Limit (National Primary Drinking Water Regulations); SS, National Secondary Drinking Water Regulations; TT, Treatment Technology (National Primary Drinking Water Regulations). mg/L, milligrams per liter; µg/L, micrograms per liter; pCi/L, picoCuries per liter]

Constituent	Method of analysis <sup>a</sup>	Reporting limit <sup>a</sup>	Drinking water standards <sup>b</sup>
Calcium, mg/L	ICP	0.02	None
Magnesium, mg/L	ICP	.03	None
Sodium, mg/L	AA	.1	None
Potassium, mg/L	AA	.1	None
Alkalinity, mg/L	T	1.0	None
Sulfate, mg/L	IC	.2	250 (SS)
Chloride, mg/L	IC	.1	250 (SS)
Fluoride, mg/L	ISE	.1	4.0 (MCL), 2.0 (SS)
Bromide, mg/L	IC	.05	None
Silica, mg/L	ICP	.01	None
Total dissolved solids, mg/L	G	1.0	500 (SS)
Nitrite plus nitrate, as nitrogen, mg/L	C	.02	10 (MCL)
Nitrite, as nitrogen, mg/L	C	.01	1 (MCL)
Ammonia, as nitrogen, mg/L	C	.01	None
Ammonia plus organic nitrogen, as nitrogen, mg/L	C	.2	None
Phosphorus, mg/L	C	.02	None
Phosphorus, ortho, as phosphorus, mg/L	C	.01	None
Organic carbon, total, mg/L	I	.1	None
Aluminum, µg/L	ICP	3.0	50–200 (SS)
Arsenic, µg/L	ICP	1.0	50 (MCL) <sup>c</sup> ; 10 (MCL) <sup>d</sup>
Barium, µg/L	ICP	.5	2,000 (MCL)
Beryllium, µg/L	ICP	1.0	4 (MCL)
Boron, µg/L	ICP	2.0	None
Cadmium, µg/L	ICP	.5	5 (MCL)
Chromium, µg/L	ICP	1.0	100 (MCL)
Cobalt, µg/L	ICP	1.0	None
Iron, µg/L	ICP	2.0	300 (SS)
Lead, µg/L	ICP	2.0	15 (TT)
Lithium, µg/L	ICP	1.0	None
Manganese, µg/L	ICP	1.0	50 (SS)
Selenium, µg/L	ICP	1.0	50 (MCL)
Strontium, µg/L	ICP	.5	None
Vanadium, µg/L	ICP	1.0	None
Radon, pCi/L	SC	20.0	None

<sup>a</sup>Fishman and Friedman (1985) and Ocala Water Quality and Research Laboratory (2002).

<sup>b</sup>U.S. Environmental Protection Agency (2002).

<sup>c</sup>Current as of 2003.

<sup>d</sup>Effective January 23, 2006.

differ from filtered samples because some of these constituents will sorb onto sediment and colloids in the water. All samples were chilled to less than 4 °C and shipped overnight to USGS laboratories in Ocala, Fla., and Denver, Colo., for analysis.

Sampling equipment was washed with a nonphosphatic detergent and rinsed with deionized water to prevent cross contamination. Except for the stainless steel pump, equipment used for the collection and processing of trace-element samples also was rinsed with a 5-percent solution of laboratory-grade hydrochloric acid and rinsed with deionized water. Equipment used for the collection and processing of pesticide samples was rinsed with laboratory-grade, pesticide-free methanol and rinsed with laboratory-grade, pesticide-free water. A total of five field-blank and five replicate (sequential) samples was collected for quality assurance purposes. In addition, source-solution blank samples were submitted with field-blank samples to verify the quality of the blank water. Field-blank samples were analyzed for nutrients, trace elements, and pesticides. In general, concentrations of nearly all constituents were less than method detection limits in all field-blank samples. In one field-blank sample, manganese was detected at a concentration of 0.4 µg/L, and in a second field-blank sample, barium was detected at the method reporting limit of 0.2 µg/L. Ammonia also was detected in one field-blank sample, and phosphate was detected in two field-blank samples at low concentrations (0.02 and 0.03 mg/L), which is near the method reporting limit. However, ammonia and phosphate also were detected in the associated source-solution blank samples at similar concentrations, indicating the contamination was not a result of contamination from the sampling equipment.

Data for replicate samples from the same well were in good agreement. For example, replicate samples from a well (site 13, fig. 9) had similar concentrations of nutrients (ammonia was 0.19 mg/L in both samples), trace elements (barium was 12 µg/L and boron was 37 µg/L in both samples; iron was 850 and 865 µg/L, and lithium was 4.7 and 4.6 µg/L in the samples), and pesticides (all concentrations were below detection limits). Concentrations of radon, an inert radioactive gas, exhibited the largest differences between replicate samples. In the same well (site 13, fig. 9), replicate samples had radon concentrations of 175 and 167 pCi/L, a difference of 7 pCi/L, which represents less than a 5-percent error.

Water-quality data collected for this project were supplemented with data from 60 samples, primarily field measurements and concentrations of major ions and nutrients, compiled from the USGS and SJRWMD databases (apps. 1-4). The samples were collected from 1990 through 2000 and analyzed with a variety of methods, including the collection of whole-water samples. Some sites were sampled more than one time during the period of record, in which case only the most recent and most analytically complete sample was included in this report. Sites also were selected to establish an even spatial distribution in Orange County. Both whole-water and filtered analyses of major ions and nitrate were included in the summary because the differences between concentrations of those constituents in whole-water and filtered samples generally are very slight. Bicarbonate concentrations were calculated from alkalinity. Data reported as nitrite plus nitrate as nitrate were converted to concentrations as nitrogen, and were merged with the data collected during this study.

Regression analysis indicated that total dissolved solids (TDS) concentrations of ground-water samples were significantly correlated to specific conductance ( $r^2 > 0.99$ ) (fig. 10). If TDS concentrations were not available, TDS was calculated as a function of specific conductance by using the equation:

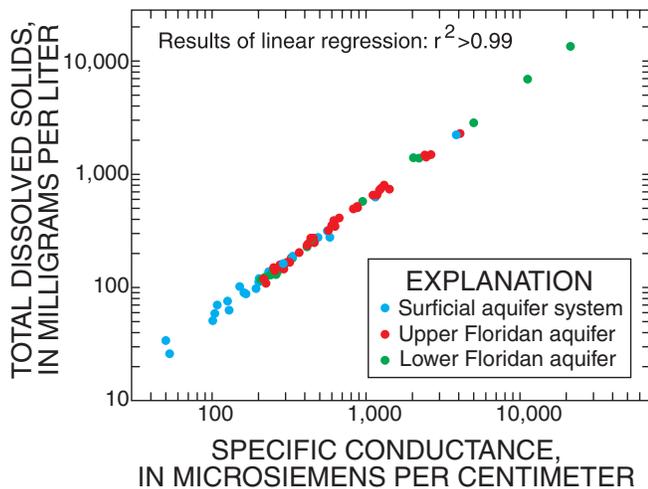
$$\log(\text{TDS}) = 1.02 * [\log(\text{specific conductance})] - 0.30, \quad (1)$$

where

TDS is in milligrams per liter, and  
specific conductance is in microiemens per centimeter.

This equation is valid, however, only for values of specific conductance greater than 2 µS/cm. The error is the result of the nonlinear relation between low values of specific conductance and TDS. The minimum value of specific conductance in this study was 50 µS/cm, with a TDS concentration of 34 and a predicted TDS concentration of 27 mg/L. Hence, for the range of values in this study, the equation to estimate TDS concentrations from specific conductance is acceptable.

Data were analyzed by using nonparametric statistical tests. The Mann-Kendall (Kendall's tau) test, a nonparametric correlation procedure, and locally weighted scatterplot smoothing (LOWESS) were used to analyze long-term data for temporal trends in rainfall, water levels in wells, and discharge from springs



**Figure 10.** Relation between specific conductance and total dissolved solids in ground-water samples collected from 1990 through 2001.

(Helsel and Hirsch, 1992). Spearman's rho, a rank-order correlation coefficient, was used to assess relations between chemical constituents. The Kruskal-Wallis test, a nonparametric analysis of variance performed after ranking the data (Helsel and Hirsch, 1992), was used to assess differences in concentrations of chemical constituents between aquifers. For all statistical tests, a probability level of 5 percent ( $p$ -value  $< 0.05$ ) was the criterion for statistical significance. A  $p$ -value  $< 0.05$  indicated that the probability of a correlation or difference occurring by chance is less than 5 percent.

Boxplots were used to illustrate the distribution of selected chemical concentrations in the aquifers. Maps were used to illustrate the spatial distribution of selected hydrogeologic properties and water-quality constituents. Water-quality data were compared to drinking water regulations established by the U.S. Environmental Protection Agency. National Primary Drinking Water Regulation are enforceable, health-based standards that limit the concentrations of certain chemical constituents (Maximum Contaminant Levels (MCL)) in drinking water. National Secondary Drinking Water Regulation (also referred to as secondary standards) are nonenforceable guidelines set for cosmetic or aesthetic reasons (U.S. Environmental Protection Agency, 2002).

## HYDROGEOLOGY

The geology of central Florida affects the occurrence and movement of ground water in Orange County. The area is underlain by about 6,500 ft of marine limestones and dolomites that were deposited on a basement complex of crystalline rock (Lichtler and others, 1968; Arthur and others, 1994). The upper 2,500 ft of sediments are important to the ground-water resources of the area.

### Hydrogeologic Setting

The geologic formations of interest in central Florida are, from oldest to youngest: the Cedar Keys Formation (of Paleocene age), the Oldsmar Formation, the Avon Park Formation, and the Ocala Limestone (all of Eocene age), the Hawthorn Group (of Miocene age) and undifferentiated post-Miocene sediments (fig. 11). Hydrogeologic units in the area include two aquifer systems (the Floridan aquifer system and the surficial aquifer system) and an intermediate confining unit. The Cedar Keys Formation forms the sub-Floridan confining unit.

Some differences are noted between the names of geologic units described by Lichtler and others (1968, table 2) and those used in this report (fig. 11). The unit previously called the Hawthorn Formation is now recognized by the Florida Geological Survey as the Hawthorn Group and the unit called the Ocala Group is now called the Ocala Limestone. Miller (1986) determined that there was no paleontological basis for differentiating the Avon Park and Lake City Limestones, so the thickness of the Avon Park Formation (fig. 11) includes the combined thickness of both units. Also, because dolomites are an important constituent, the unit should be called a formation rather than a limestone. Finally, thickness values for units shown in figure 11 may differ from values given by Lichtler and others (1968) because data from more recently drilled wells were incorporated.

Aquifer nomenclature also has been modified since the study by Lichtler and others (1968). The nonartesian and secondary artesian aquifers in previous studies are now considered to be part of the surficial aquifer system and the intermediate confining unit, respectively, which separates the surficial aquifer system from the Floridan aquifer system. The Floridan aquifer system has been divided into the Upper and Lower Floridan aquifers, separated by the middle semiconfining unit.

SYSTEM	SERIES	STRATIGRAPHIC UNIT	LITHOLOGY	HYDROGEOLOGIC UNIT	APPROXIMATE THICKNESS (feet)			
QUATERNARY	RECENT	UNDIFFERENTIATED DEPOSITS	Quartz sand, unconsolidated, locally can contain clay, chert shell, and limestone lenses.	SURFICIAL AQUIFER SYSTEM	LESS THAN* 50 - 200			
	PLEISTOCENE							
TERTIARY	PLIOCENE	HAWTHORN GROUP	Clay, green-gray color with phosphatic pebbles, silt, locally can contain sand and carbonate units.	INTERMEDIATE CONFINING UNIT	10 - GREATER THAN 200			
	MIOCENE							
	EOCENE	UPPER	OCALA LIMESTONE	Limestone, white, tan, or cream, fossiliferous, soft to hard, locally dolomitic, highly porous.	FLORIDAN AQUIFER SYSTEM	UPPER FLORIDAN AQUIFER	300 - 400	
		MIDDLE	AVON PARK FORMATION	Limestone, light brown to brown porous, fossiliferous, locally dolomitic and carbonaceous; intergranular gypsum and anhydrite; brown, crystalline dolomite.		MIDDLE SEMICONFINING UNIT	MIDDLE CONFINING UNIT	400 - 700
		LOWER	OLDSMAR FORMATION	Limestone, white to light brown, porous, fossiliferous, interbedded with dolomite, minor amounts of gypsum present.		LOWER FLORIDAN AQUIFER		
	PALEOCENE	CEDAR KEYS FORMATION	Dolomite, light gray, with significant amounts of gypsum and anhydrite.	SUB-FLORIDAN CONFINING UNIT	POORLY KNOWN			

\*Thickness includes saturated and unsaturated undifferentiated sedimentary deposits overlying the intermediate confining unit.

**Figure 11.** Geologic and hydrogeologic units in Orange County, Florida (modified from Tibbals, 1990, and O'Reilly and others, 2002).

In an area underlain primarily by carbonate (limestone and dolomite) rocks, sinkholes are common, resulting in a landform called karst. Rainfall is naturally acidic and, over long time periods, gradually dissolves the limestone, resulting in the formation of enlarged conduits and cavities. The cavities may subside either gradually or suddenly, forming dolines or sinkholes. Sinkholes generally form more rapidly in areas of active ground-water recharge because the acidity of the water (and thus its ability to dissolve limestone) is greatest when the water first enters the aquifer. Ground-water recharge can occur at rapid rates in areas where sediments overlying the limestone are thin or very permeable. Such conditions are present in Orange County, particularly in the western and northwestern

parts. Sinkholes frequently occur near the end of the dry season, when ground-water levels are low and withdrawals from the aquifers are at the annual peak rate. Sinkholes can be dry or water-filled, internally drained depressions. Most of the natural lakes and ponds in Orange County probably were formed by this process (Lichtler and others, 1968).

A large sinkhole formed in May 1981 in the city of Winter Park. The sinkhole was about 100 ft deep and nearly 300 ft across. Initially after the collapse of the sinkhole, its sides were steep and the water level in the sinkhole was at equilibrium with the water level in the underlying limestone. Under natural conditions, the bottoms of many sinkhole lakes eventually become covered with less permeable clay or silt, "plugging"

the sinkhole's direct connection to the underlying limestone. In the Winter Park sinkhole (as in other sinkholes that form in urban areas), fill was emplaced in the bottom of the sinkhole and after about 14 years, it resembled other sinkhole-formed lakes in Orange County (Schiffer, 1998).

The features apparent at land surface in central Florida are not the only manifestation of the karstification process. Because of the thick sequence of carbonate rocks, at numerous times during the geologic past the rocks that were at land surface at any given time were eroded into karst landforms. Numerous horizons of paleokarst features, such as fractures and large cavities, are evident when drilling into the subsurface formations. These features can cause the wide variations in hydraulic properties observed in the Floridan aquifer system.

## Surficial Aquifer System

The surficial aquifer system generally consists of unconsolidated sand ranging in age from Pliocene to Recent (fig. 11). Shell material is present in parts of the aquifer system in eastern Orange County and layers of silt or clay exist locally. A layer of peat was penetrated during well drilling in central Orlando, and hardpan also is present at some locations. Most of the surficial sediments were deposited in beach or nearshore environments when sea level was higher than at present and sediments may have been reworked as sea levels fluctuated during the geologic past.

The surficial aquifer system in Orange County ranges widely in thickness. Sediments composing the surficial aquifer system are less than 50 ft thick in many parts of southwestern and northwestern Orange County and more than 150 ft thick in parts of central and southeastern Orange County (figs. 12 through 15). Values shown on figure 12 represent the thickness of both saturated and unsaturated, undifferentiated sediments overlying the intermediate confining unit. The thickness of saturated sediments (and, thus, the surficial aquifer system) fluctuates as the water-table altitude fluctuates over time.

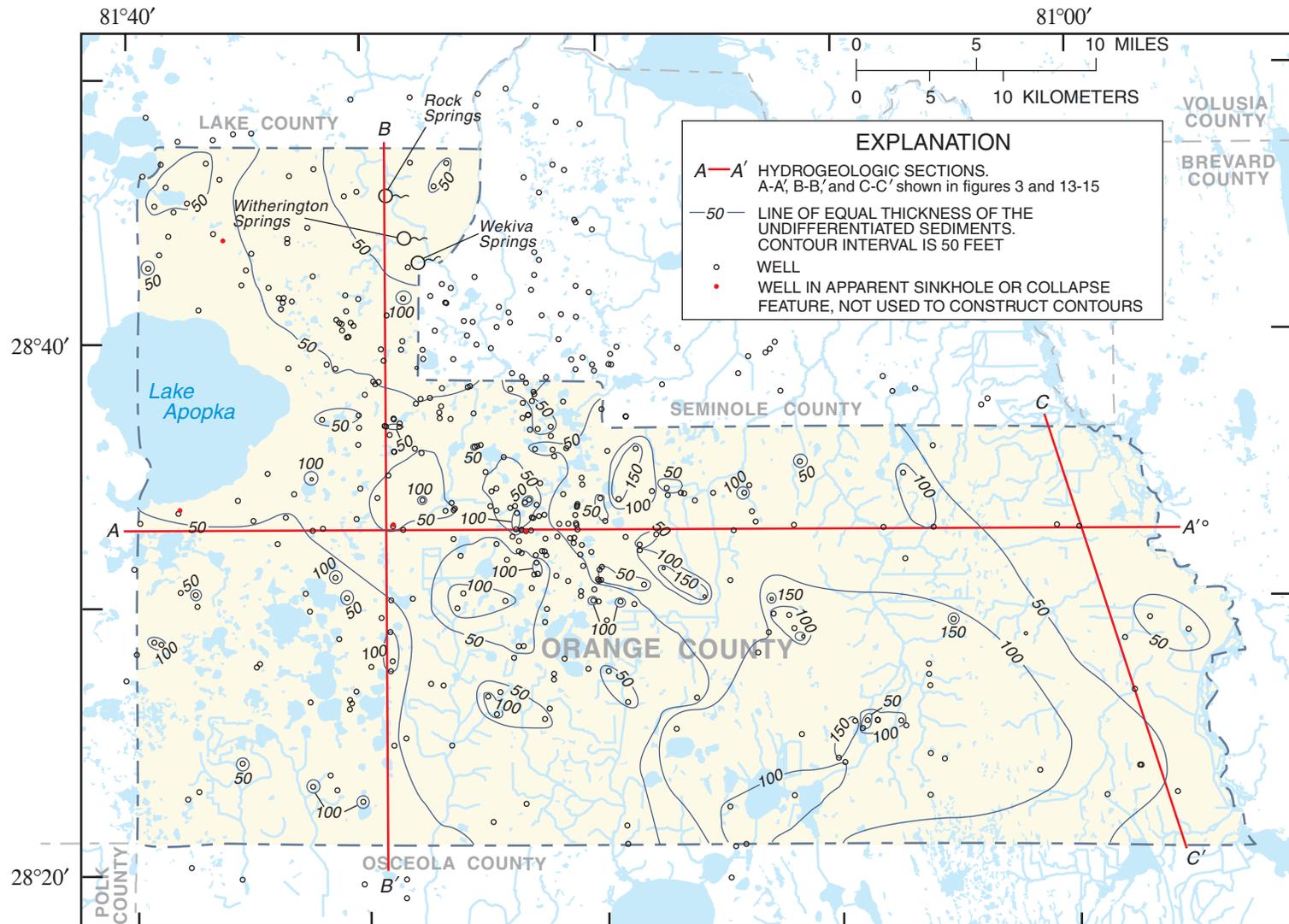
The thickness of the surficial aquifer system can vary widely over short areal distances; hence, the thickness shown in figure 12 is generalized. For example, in southeastern Orange County, thickness values range from about 35 to 170 ft in a distance of less than 5 mi.

Some wells, apparently drilled in sinkholes, indicate anomalously large thickness values and were not used to construct thickness contours, but are plotted on figure 12 to illustrate the variability in thickness.

The variability in thickness values probably results from the sediments originally being deposited upon an uneven paleokarst surface. Additionally, the presence of locally discontinuous clay lenses and the lithologic gradation of geologic units over short areal distances can cause the lower boundary of the surficial aquifer system to be at different depths in the stratigraphic section at different locations. For example, a sedimentary layer near the bottom of the surficial aquifer system could grade from sand at one location to clay at a nearby location. In this case, the layer would be included in the surficial aquifer system at the first location but considered to be part of the intermediate confining unit at the second location.

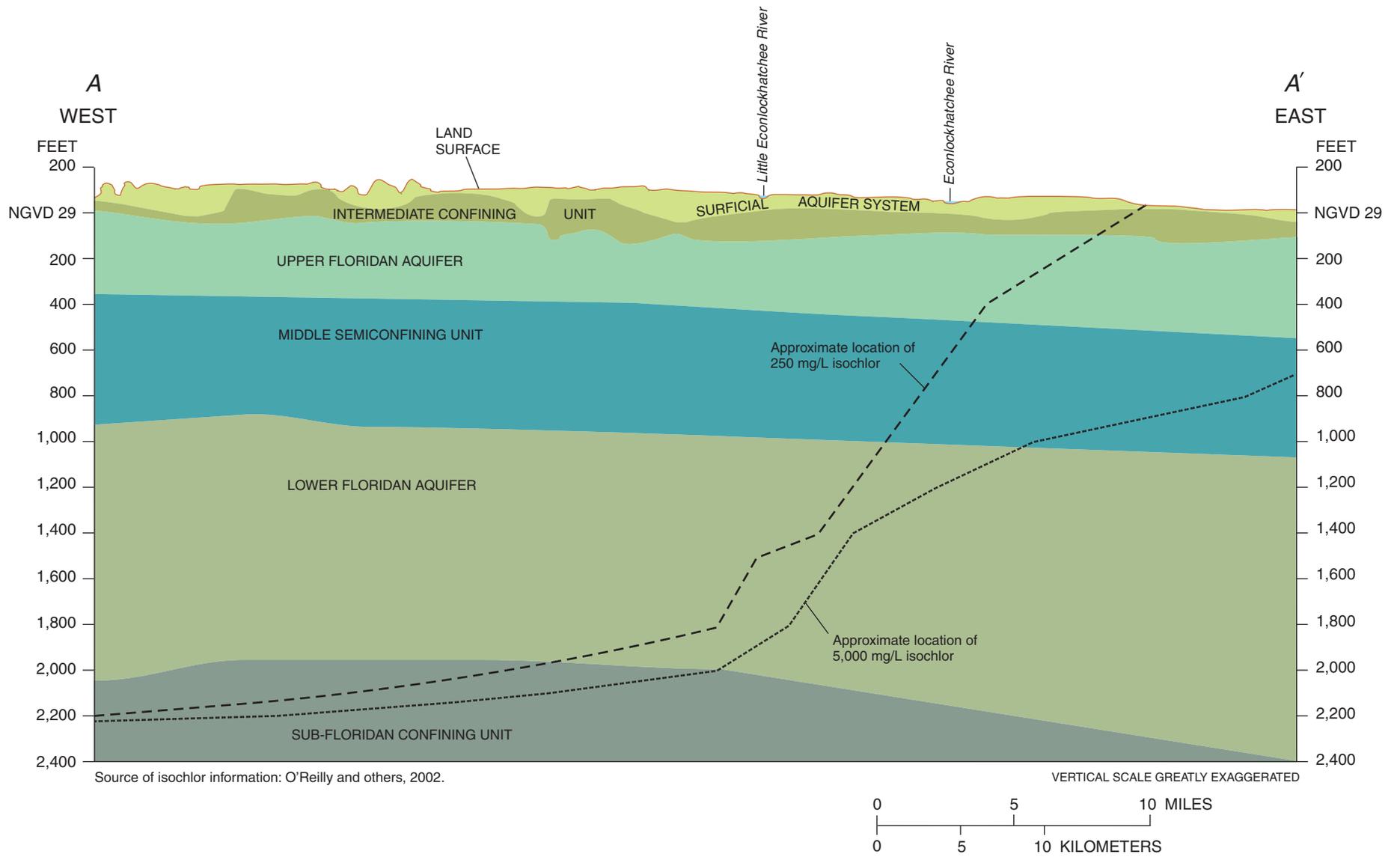
The horizontal hydraulic conductivity of the surficial aquifer system ranges from 0.05 to 30 ft/d, with a median of 3 ft/d (fig. 16 and table 4). These values are based on 20 slug tests made by the USGS (S. Kinnaman, U.S. Geological Survey, written commun., 2001) and 1 test made by SJRWMD (Wanielista and others, 1992) on 21 wells tapping the surficial aquifer system. The tests performed by the USGS were analyzed by using the Bouwer and Rice (1976) method. These values are in good agreement with estimates from other studies conducted in central Florida. Hydraulic conductivity values for the surficial aquifer system ranged from 0.5 to 40 ft/d, with a median of 5 ft/d in adjacent Seminole County (Spechler and Halford, 2001), and from 0.2 to 35 ft/d, with a median of 8 ft/d in adjacent Lake County and the nearby Ocala National Forest (Knowles and others, 2002). The wide range in values probably is the result of lithologic variations in the aquifer materials. Relatively high horizontal hydraulic conductivity values occur throughout Orange County, including 9 ft/d in the northwestern part of the county (site 161), 20 ft/d in southeastern Orange County (site 29), and 30 ft/d in central Orlando (site 120; fig. 16). The sites with the lowest values of horizontal hydraulic conductivity (0.05 ft/d at site 100 and 0.06 ft/d at site 172) are located in western and northwestern Orange County, respectively (fig. 16). The low values probably result from the lithology at the sites (primarily fine sand with silt and clay).

In general, water in the surficial aquifer system is unconfined, and the altitude of water levels in wells tapping the aquifer system represents the water table.

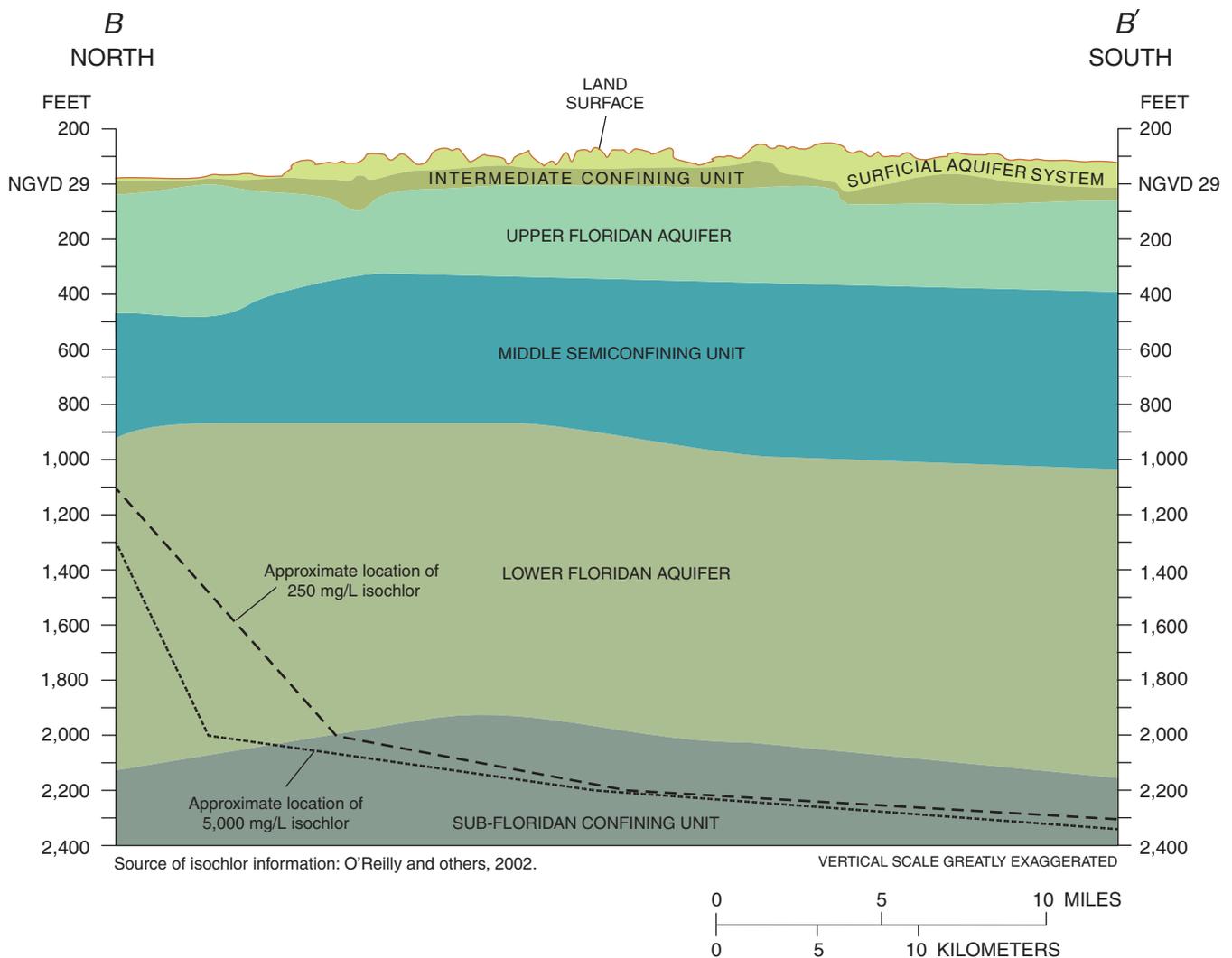


Sources of data: geophysical and geological information from the U.S. Geological survey, St. Johns River Water Management District, and Florida Geological Survey

**Figure 12.** Generalized thickness of undifferentiated sedimentary deposits overlying the intermediate confining unit.



**Figure 13.** Generalized hydrogeologic section A-A' (trace of section is shown on figures 3 and 12) (thickness of middle semiconfining unit and Lower Floridan aquifer modified from O'Reilly and others, 2002).



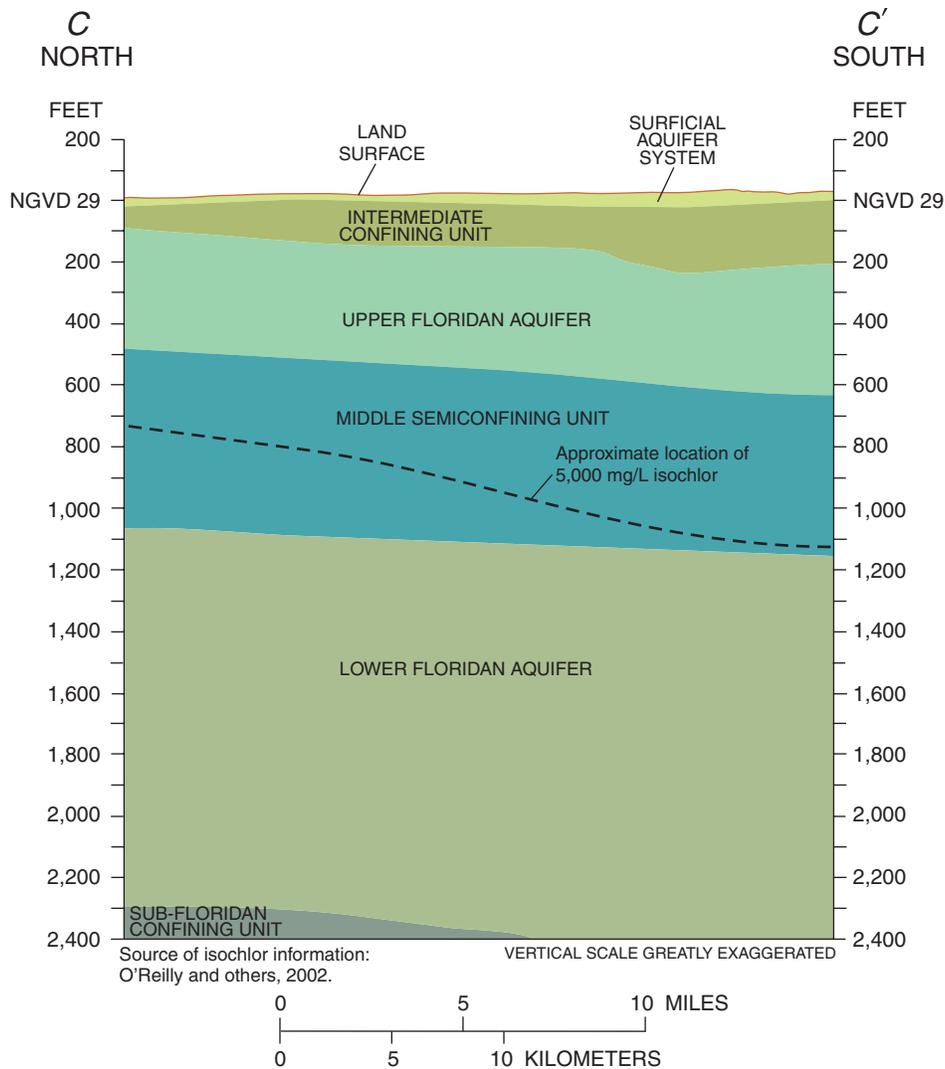
**Figure 14.** Generalized hydrogeologic section B-B' (trace of section is shown on figures 3 and 12) (thickness of middle semiconfining unit and Lower Floridan aquifer modified from O'Reilly and others, 2002).

Water-level altitudes during this study ranged from about 10.6 ft (site 93) in eastern Orange County to 123.8 ft above NGVD 29 (site 161) in northwestern Orange County. Water in the surficial aquifer system flows laterally from areas of higher altitude to discharge at lakes or streams in areas of lower elevation. The altitude of the water table generally mimics land surface and is higher beneath hilltops than in adjacent low-lying areas. At streams and lakes, the altitude of such features represents the altitude of the water table at those locations.

At some locations, flow at the water table of the surficial aquifer system can be complex. For example, the well at site 172, had water levels ranging from 82.5 to 89.6 ft above NGVD 29. Lake Lerla, about 1.8 mi

east of the well, has a surface altitude of about 61 ft above NGVD 29. Lake Smith, however, is about 1.2 mi west of the well and has a surface altitude of about 143 ft above NGVD 29 (fig. 16). The difference in hydraulic gradient between the well and the respective lakes could indicate that ground water in the area of Lake Smith is perched locally by a discontinuous impervious layer, such as a clay lens.

Ground water in the surficial aquifer system is recharged by precipitation throughout most of Orange County. In eastern Orange County, the surficial aquifer system also is recharged by upward leakage of water from the Floridan aquifer system. The surficial aquifer system is artificially recharged by inflow from septic

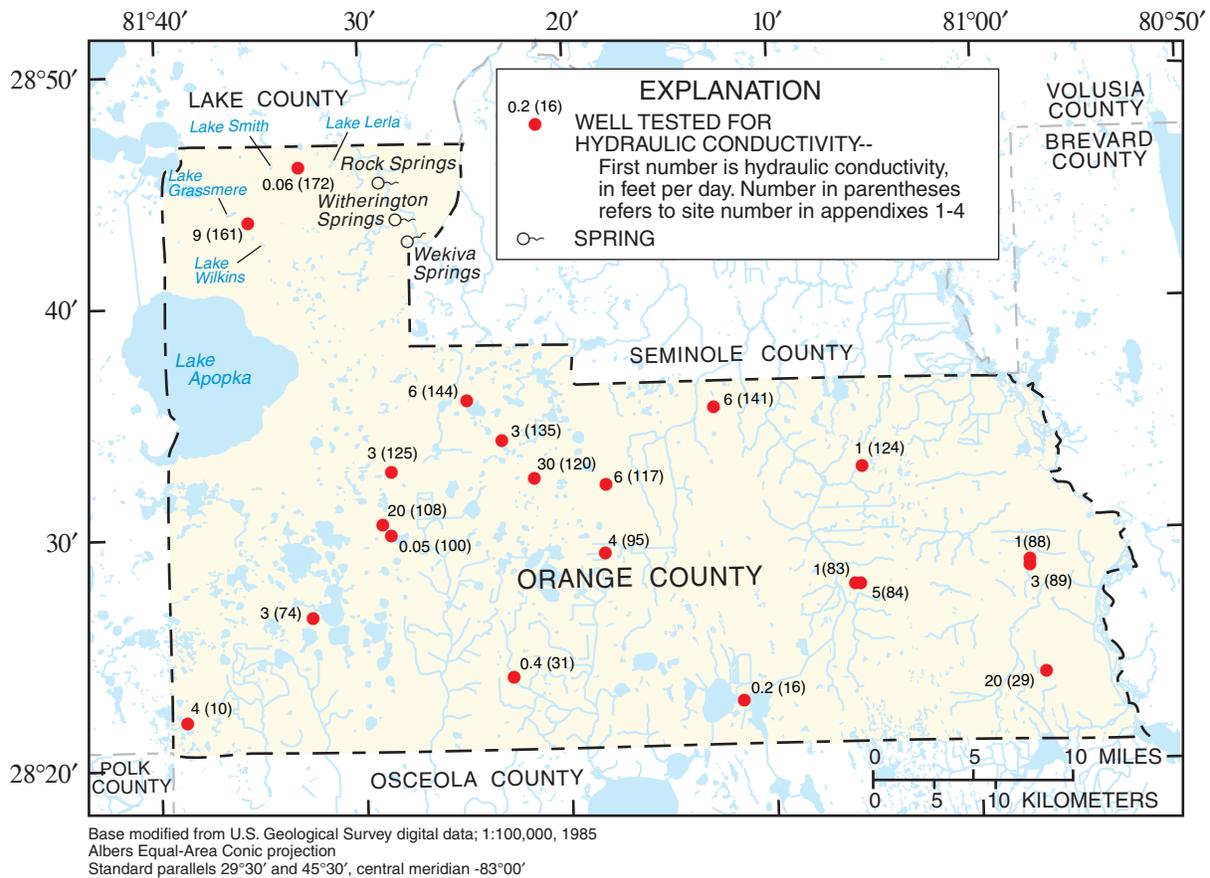


**Figure 15.** Generalized hydrogeologic section C-C' (trace of section is shown on figures 3 and 12) (thickness of middle semiconfining unit and Lower Floridan aquifer modified from O'Reilly and others, 2002).

systems and rapid infiltration basins (RIBs) used to dispose of treated wastewater effluent. The surficial aquifer system also is artificially recharged by irrigation of agricultural land or residential areas with either treated wastewater or water pumped from the Floridan aquifer system. Water discharges from the surficial aquifer system by evapotranspiration, lateral flow to lakes and streams, leakage downward to the Floridan aquifer system, and by withdrawals from wells.

The altitude of the water table in the surficial aquifer system varies seasonally, responding to variations in rates of recharge and discharge, and generally is highest after the wet season and lowest after the dry

season. The water-level fluctuations in some wells (sites 10 and 88; fig. 17) indicate that the water table in the surficial aquifer system generally rises rapidly, probably as a result of rainstorms. The difference in responses probably results from variations in depth to the water table and permeability and specific yield of the sediments. The water table is at or very near land surface at site 88, and within about 10 ft below land surface at site 10 (table 4). The horizontal hydraulic conductivity calculated from slug tests is 1 ft/d at site 88 and 4 ft/d at site 10 (fig. 16, table 4). Specific yield can vary with water-table depth (Duke, 1972) as well as the lithology of the sediments (Fetter, 1980).



**Figure 16.** Distribution of horizontal hydraulic conductivity values determined from slug tests in the surficial aquifer system.

## Intermediate Confining Unit

The intermediate confining unit consists primarily of clay, silt, and carbonate (limestone and dolomite) rocks of the Miocene-age Hawthorn Group (fig. 11). The intermediate confining unit also can include clay layers of early Pliocene age (Murray and Halford, 1996). Carbonate rocks, which are present primarily in the basal units of the Hawthorn Group, have been considered part of the intermediate confining unit in most studies (Miller, 1986; Murray and Halford, 1996; Spechler and Halford, 2001), but modeled as part of the Upper Floridan aquifer in at least one study (O'Reilly, 1998). For the purposes of this study, the basal carbonate units of the Hawthorn Group are considered to be part of the intermediate confining unit. The Hawthorn Group also is characterized by the presence of phos-

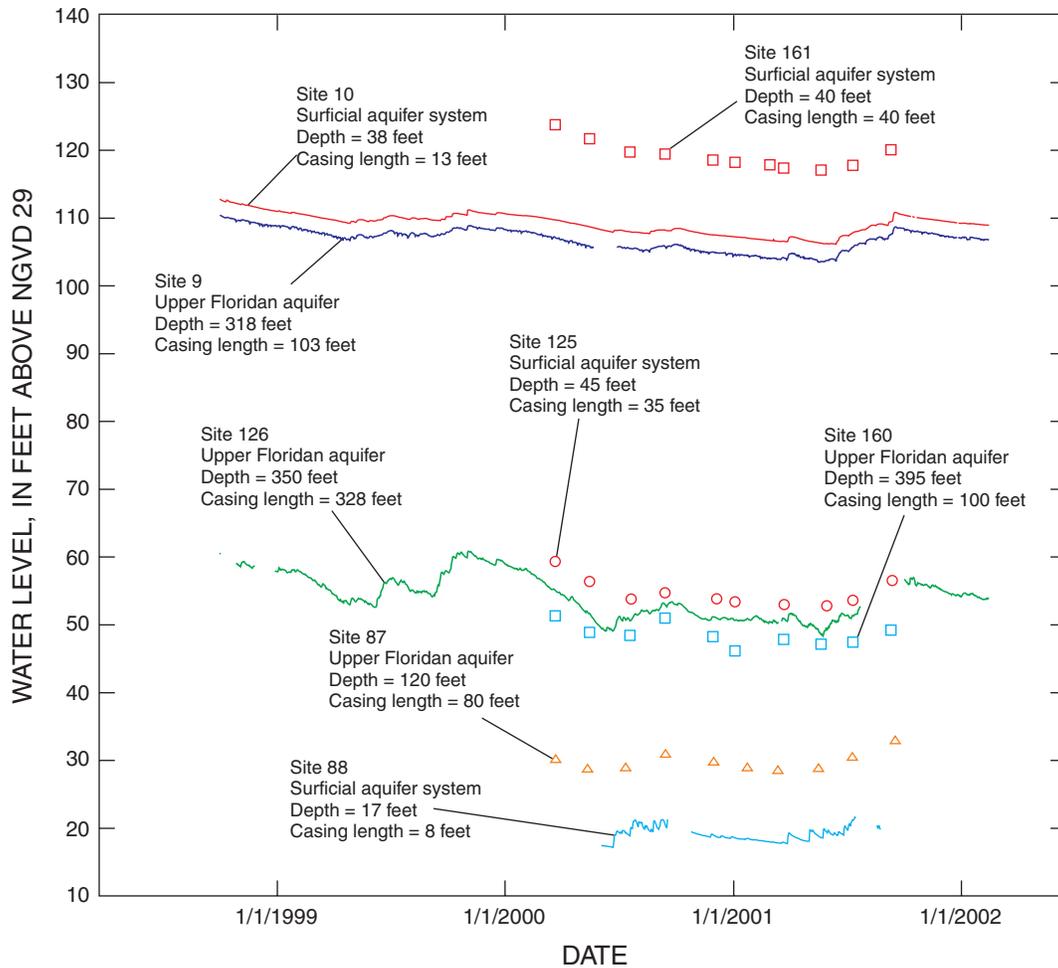
phatic sediments throughout its thickness, ranging in size from fine sand to gravel. These sediments include the apatite mineral francolite (Scott, 1988), which can contain uranium-238. Uranium-238 decays radioactively, forming radium and, eventually, radon-222 as one of the daughter products. Radon is an inert, radioactive gas that can be dissolved in ground water (Arthur and others, 1994).

The intermediate confining unit in Orange County ranges in thickness from about 10 to more than 200 ft, with a median thickness of about 100 ft (figs. 13-15 and 18). In general, the unit is thickest in southeastern Orange County, and thinnest in southwestern and northwestern Orange County. As with the surficial aquifer system, the thickness of the intermediate confining unit ranges widely over short spatial distances. The thickness of the unit ranges from less than 50 to more than 150 ft in and around Orlando.

**Table 4.** Well-construction information, aquifer information, and average horizontal hydraulic conductivity for the surficial aquifer system

[Source of data, U.S. Geological Survey and St. Johns River Water Management District; NA, not available. Well locations shown in figure 16]

Site number	Site identifier	Site name	Land surface altitude (feet)	Well depth (feet)	Depth to water (feet below land surface)	Saturated well penetration (feet)	Screen length (feet)	Saturated aquifer thickness (feet)	Average hydraulic conductivity (feet per day)	Lithology
10	282202081384602	Lake Oliver shallow well	117.06	38	12.58	25.42	5	50	4	NA
16	282214081112802	Moss Park shallow well	69.05	29	14.7	14.3	3	36	.2	Fine to medium sand, silt
29	282348080564301	OR0715	40.28	30	6.79	23.21	10	60	20	Shell, medium sand
31	282352081224401	S. Orange Park surficial well	83	29	7.5	21.5	10	28	.4	Medium sand
74	282631081323301	Tibet Butler surficial well	104	24	8.86	15.14	10	42	3	Fine to medium sand, silt
83	282739081054502	OR0714	66.68	30	5.36	24.64	10	49	1	Sand, shell
84	282739081054503	OR0727	66.67	30	5.34	24.66	10	49	5	Sand, shell
88	282838080572402	OR0713	21.6	17	5.09	11.91	10	26	1	Sand, silt, shell
89	282838080572403	OR0726	21.65	17	2.82	14.18	10	26	3	Sand, silt, shell
95	282912081181201	OR0722	97.82	30	11.03	18.97	10	34	4	Fine sand
100	283003081283801	Turkey Lake surficial well	125	54	30.09	23.91	10	30	.05	Fine to medium sand, clay
108	283033081290301	Turkey Lake surficial well	110	29	12.46	16.54	10	15	20	Fine to medium sand
117	283210081180401	OR0718	95.79	35	6.6	28.4	10	32	6	Fine to medium sand
120	283228081213501	OR0721	76.16	25	5.86	19.14	10	23	30	Sand
124	283249081053203	Bithlo-3	63.14	15	9.37	5.63	3	90	1	Very fine to fine sand, silt
125	283251081283501	OR0716	81.46	45	28.08	16.92	10	41	3	Fine to medium sand
135	283345081225701	OR0720	80	32	4.1	27.9	10	30	3	Fine sand
141	283517081121501	CFRP surficial well	75	15	NA	NA	10	10	6	Fine sand
144	283555081245101	OR0719	93	32	6.34	24.6	10	28	6	Sand, silt, minor clay
161	284230081345302	OR0107	146	40	30.87	9.13	9.13	9	9	NA
172	284604081330301	OR0717	135	75	45.4	29.6	20	35	.06	Sand, silt, clay



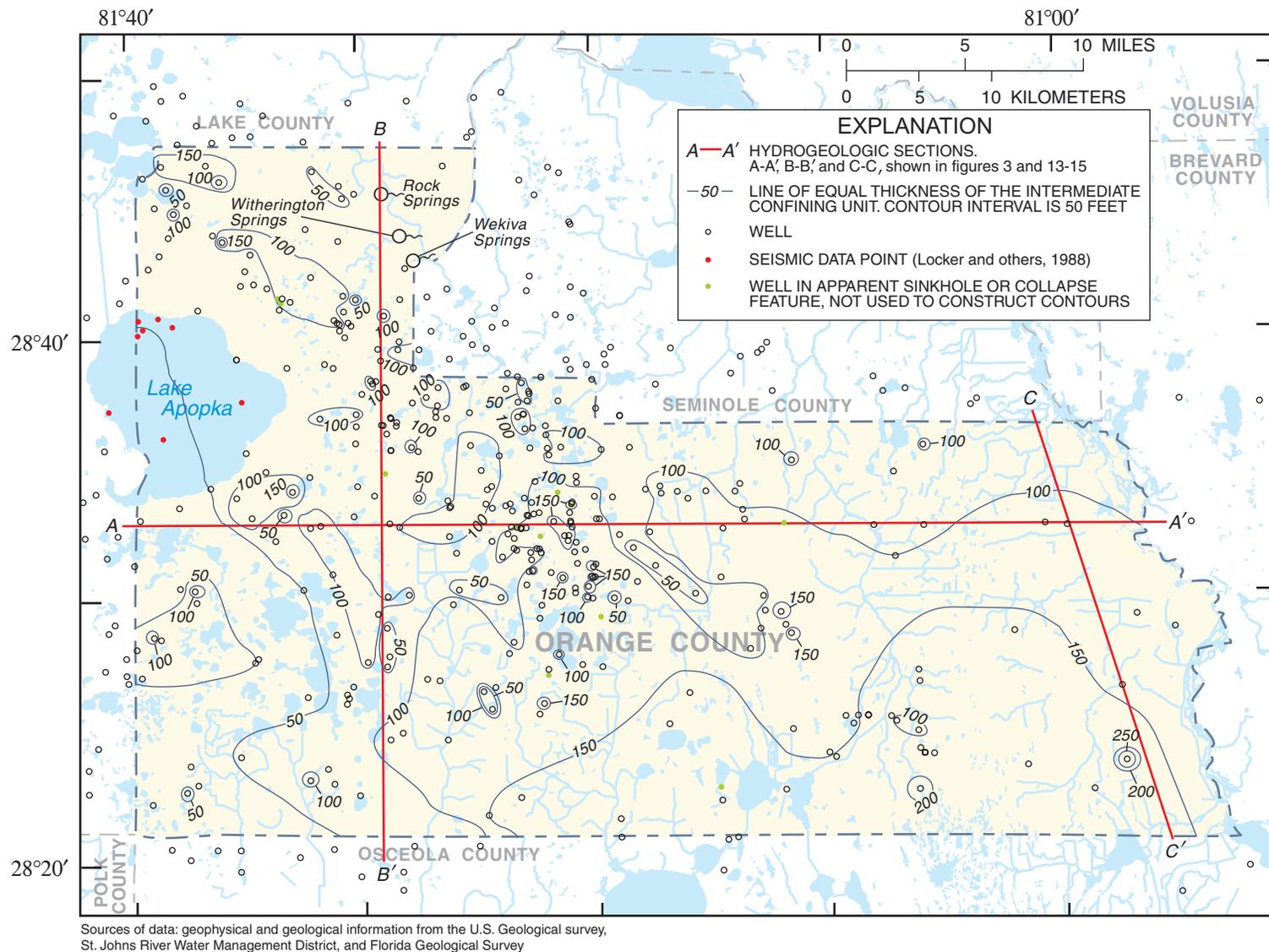
**Figure 17.** Continuous and periodic water levels in observation wells tapping the surficial aquifer system and the Upper Floridan aquifer (refer to figure 8 and appendixes for site numbers).

Many locations where the thickness of the intermediate confining unit is much more than 200 ft probably are anomalous points where sediments filled in paleosinkholes. Although shown on figure 18 to illustrate the variability in the thickness, these sinkhole locations were not used to construct the contours. Thus, the thickness of the intermediate confining unit shown in figure 18 is generalized.

The thickness of the intermediate confining unit also ranges widely because the contact of the Hawthorn Group with the underlying limestones of Eocene age is an erosional unconformity. Hence, the Hawthorn Group is thicker in places where the top of the limestone has been eroded, and thinner where the top of the limestone is higher. Furthermore, the Hawthorn Group often is identified by the presence of phosphatic pebbles and sand. Reworking of Hawthorn Group

sediments during Pliocene and Pleistocene time can make it difficult to determine the contact between the Hawthorn Group and overlying sediments. This reworking also can cause the inflection in the natural gamma log to occur above the top of the Hawthorn Group or can result in a gradual change in gamma counts rather than a sharp inflection, making it difficult to identify the contact depth.

Leakance of the intermediate confining unit ranges over several orders of magnitude. Values from aquifer tests range from  $1 \times 10^{-4}$  (ft/d)/ft in eastern Orange County to  $2 \times 10^{-2}$  (ft/d)/ft in northeastern Polk County (Tibbals, 1977; 1981). Leakance values obtained from calibrating a ground-water flow model in Orange County ranged from  $1 \times 10^{-5}$  to about  $8 \times 10^{-4}$  (ft/d)/ft (Murray and Halford, 1996).



**Figure 18.** Generalized thickness of the intermediate confining unit.

Leakance values were smallest in places where the intermediate confining unit was thickest, such as in southeastern Orange County, and largest in places where the intermediate confining unit was thin or absent, such as in southwestern and northwestern Orange County. Lithology of the intermediate confining unit also can affect the leakance values.

Few observation wells tap the intermediate confining unit, which contains permeable zones called the secondary artesian aquifer by Lichtler and others (1968). Only three observation wells [sites 59 and 123 (fig. 8, app. 1) and a well adjacent to site 48] have long-term water-level measurements. A hydrograph for the well at site 123 (fig. 19) indicates that the water level is intermediate between levels in the surficial aquifer system and the Upper Floridan aquifer. Water levels in the other two wells completed in the intermediate confining unit are greatly affected by nearby pumping of the Floridan aquifer system. The intermediate confining unit generally is not used as a source of water supply in Orange County.

## Floridan Aquifer System

The Floridan aquifer system consists of the Upper and Lower Floridan aquifers, separated by the middle semiconfining unit (and, in some areas the middle confining unit) (fig. 11). These hydrogeologic units consist primarily of carbonate rocks of Eocene age. The Upper Floridan aquifer consists of the Ocala Limestone and the upper one-third of the Avon Park Formation; the middle semiconfining unit consists of about the middle one-third of the Avon Park Formation; and the Lower Floridan aquifer consists of the lower one-third to one-half of the Avon Park Formation, all of the Oldsmar Formation, and the upper part of the Cedar Keys Formation (Miller, 1986; Murray and Halford, 1996; O'Reilly and others, 2002). The Floridan aquifer system is confined nearly everywhere in Orange County by the intermediate confining unit, although local breaches in the intermediate confining unit could exist. The sub-Floridan confining unit, which consists of anhydrite beds of the Cedar Keys Formation, underlies the Floridan aquifer system (fig. 11).

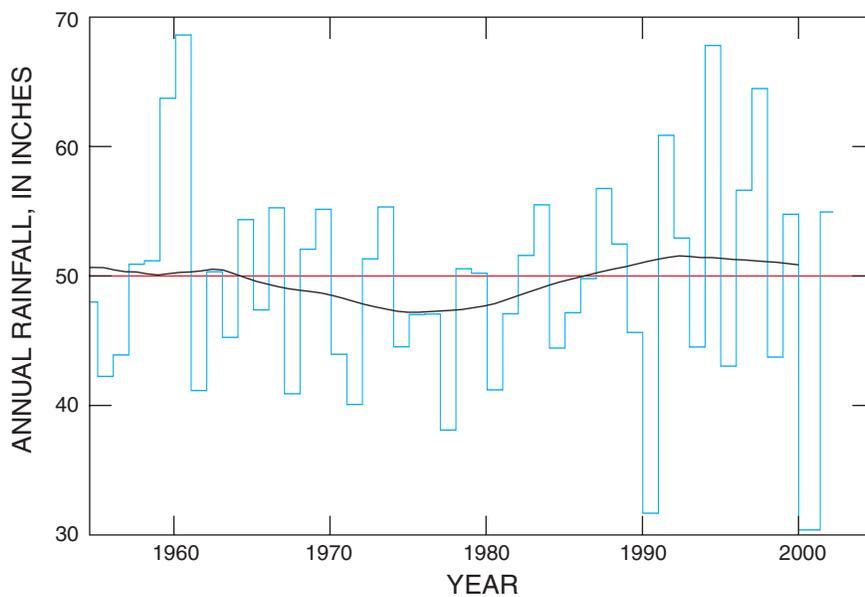
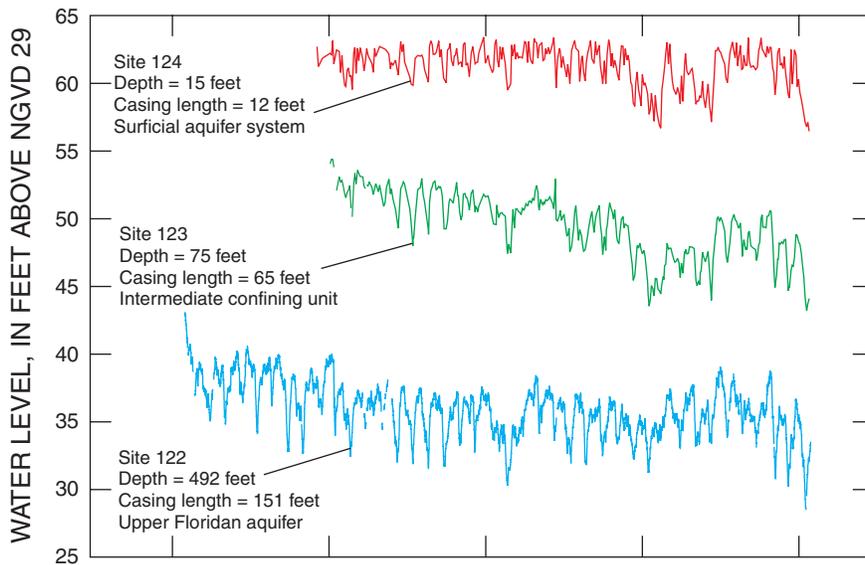
### Upper Floridan Aquifer

The structure contour map shown in figure 20 illustrates the surface of the Eocene-age carbonate rocks as it would appear if all overlying sediments were

removed. Elevation of this surface ranges from about 250 ft below to nearly 50 ft above NGVD 29, with a median of about 62 ft below NGVD 29. The altitude of the surface is highest in northwestern and southwestern Orange County and lowest in southeastern Orange County. In and around the city of Orlando, the altitude of the surface ranges greatly over small areal distances as a result of carbonate rock dissolution and subsequent formation of numerous cavities and sinkholes. At a few locations, the top of the Upper Floridan aquifer can be more than 250 to 300 ft below NGVD 29, probably as a result of the presence of a paleosinkhole. These anomalous points were not used to construct the contours shown in figure 20. Remnants of rock—peaks and pinnacles—remain between the sinkholes, imparting a hummocky appearance to the surface. Many of these geomorphic features are localized and not expressed in the land surface topography because the Hawthorn Group and overlying sediments are thicker over the sinkholes than over the peaks and pinnacles. This relation implies that the formation of many of the sinkholes predates the deposition of the Hawthorn Group and overlying sediments. Sinkholes still form at land surface in Orange County either by dissolution of the carbonate rocks and (or) by collapse of overlying sediments into existing cavities.

Thickness of the Upper Floridan aquifer ranges from about 300 to 400 ft throughout most of Orange County. The Upper Floridan aquifer in central Florida has been divided into two water-bearing zones, A and B (figs. 21-23) (Spechler and Halford, 2001). Zone A generally corresponds with the Ocala Limestone, whereas zone B corresponds to the upper one-third of the Avon Park Formation (O'Reilly and others, 2002). Zone B is the more productive of the two zones. Thickness of zone A ranges widely. Thickness of the Ocala Limestone, where present, ranges from less than 1 to more than 115 ft, with a median thickness of about 45 to 50 ft. The Ocala Limestone is absent, possibly as a result of erosion, in many parts of Orange County.

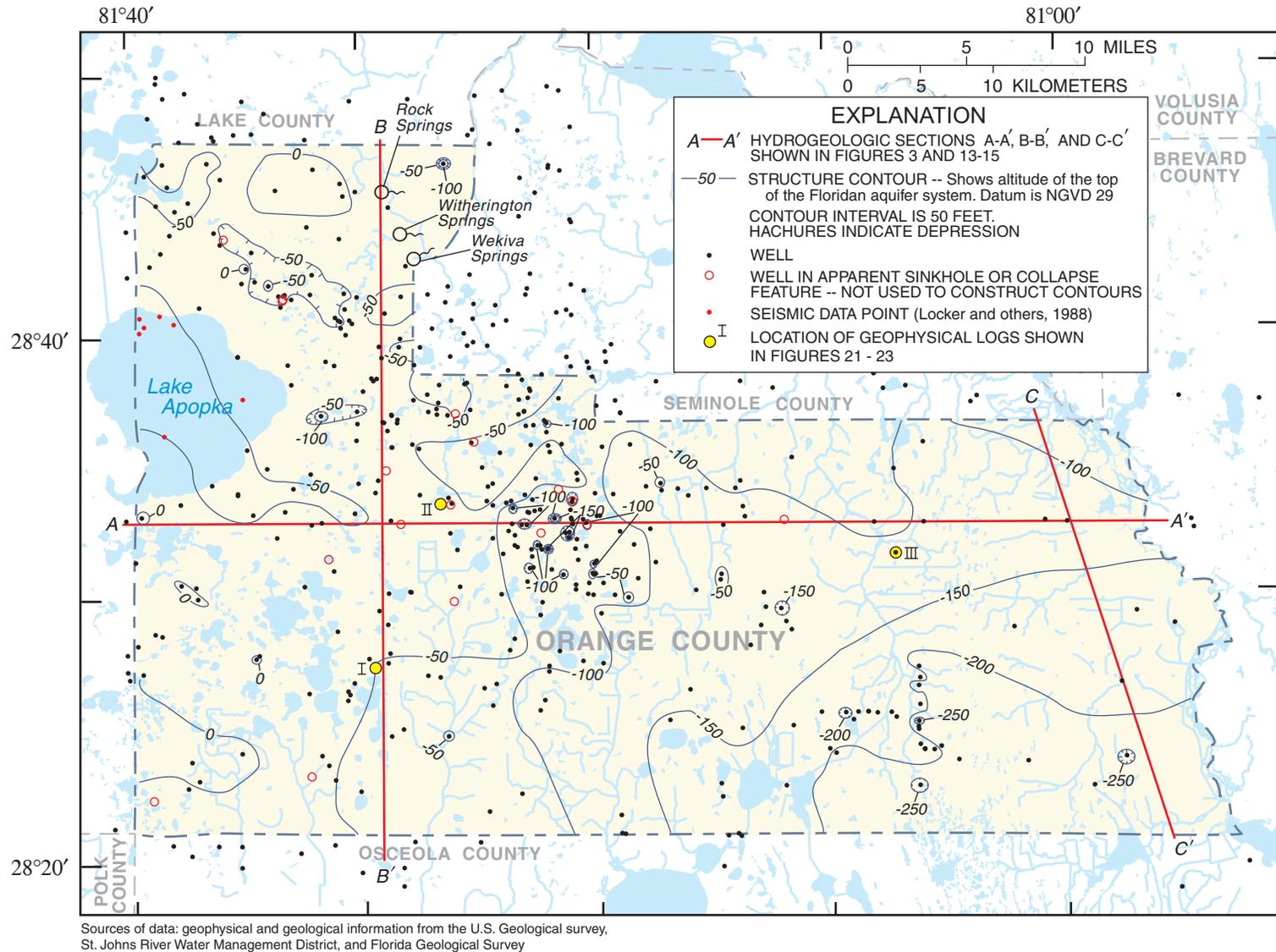
Much of the porosity of the Floridan aquifer system is secondary, resulting from fracturing and dissolution of the carbonate rocks. As a result, transmissivity of the aquifer can be high with a large range in values (fig. 24). Results from 20 aquifer tests in and around Orange County (fig. 24) indicate that transmissivity of the Upper Floridan aquifer ranges from about 4,000 to 550,000 ft<sup>2</sup>/d with a median of about 80,000 ft<sup>2</sup>/d.



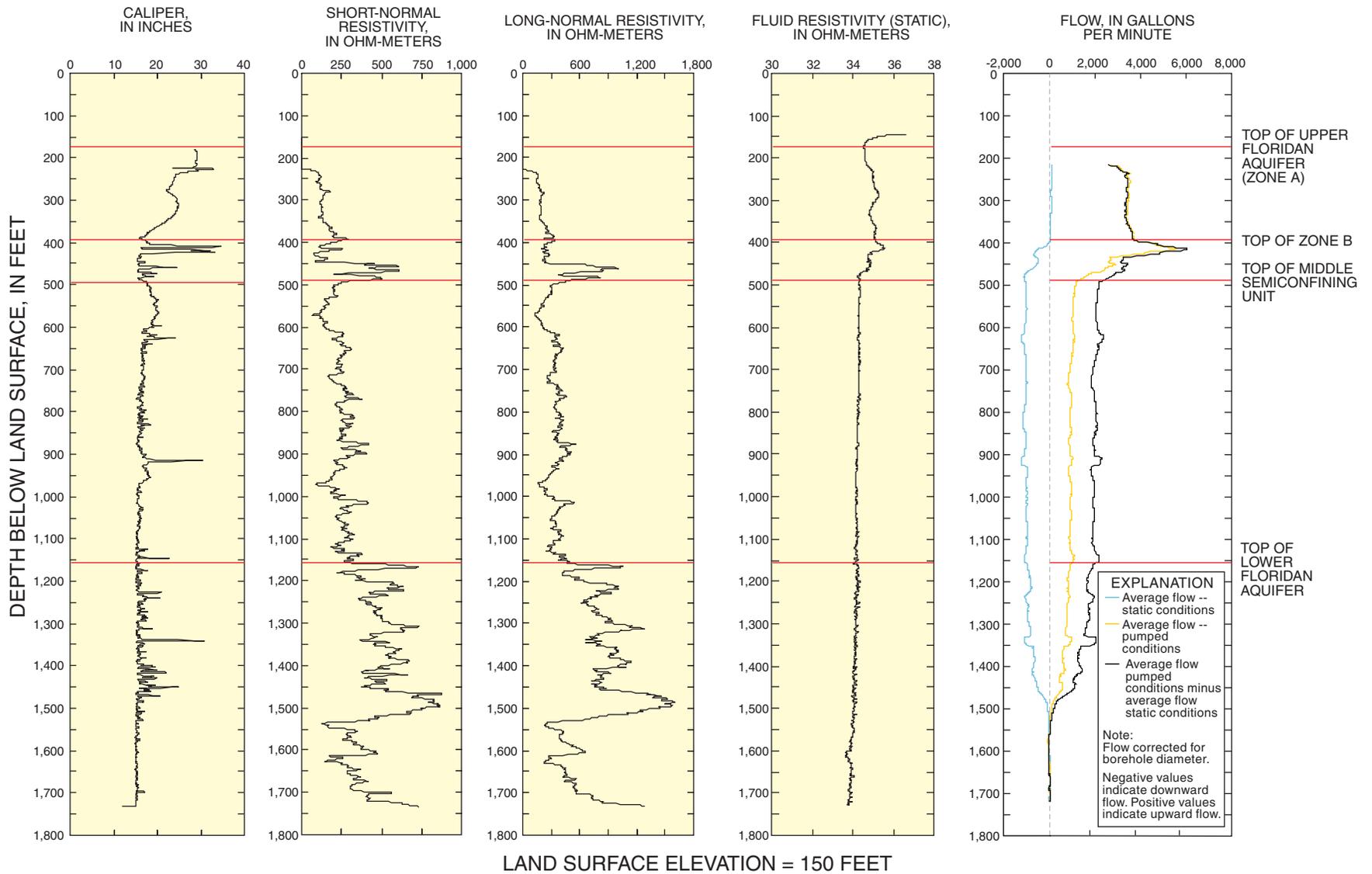
**EXPLANATION**

- ANNUAL RAINFALL
- LOCALLY WEIGHTED SCATTERPLOT SMOOTHING CURVE (SMOOTHING FACTOR = 0.28)
- MEAN ANNUAL RAINFALL (1935 - 2000 = 50 INCHES)

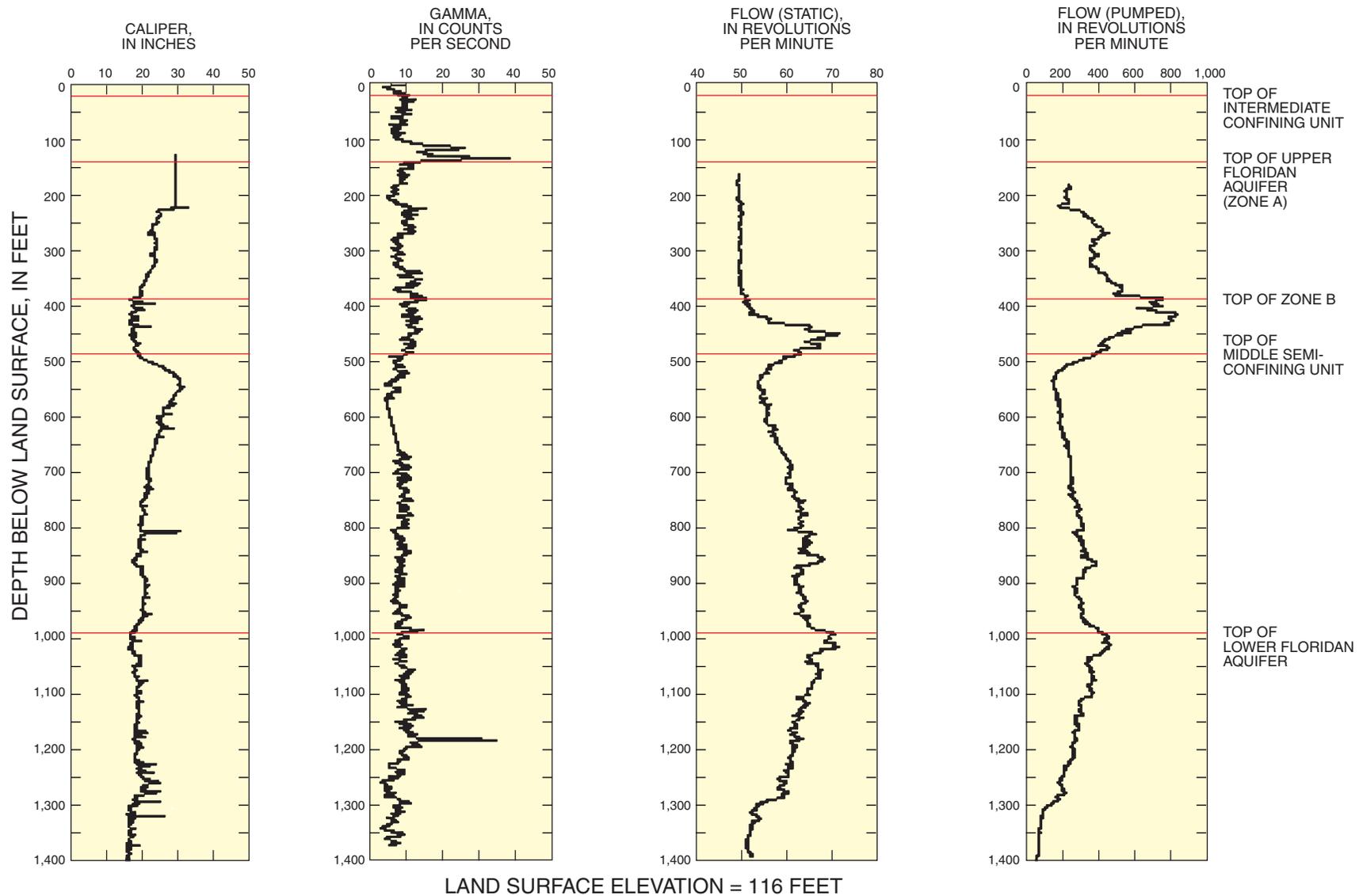
**Figure 19.** Water levels in three wells tapping the surficial aquifer system, the intermediate confining unit, and the Upper Floridan aquifer, and rainfall at Orlando, Florida.



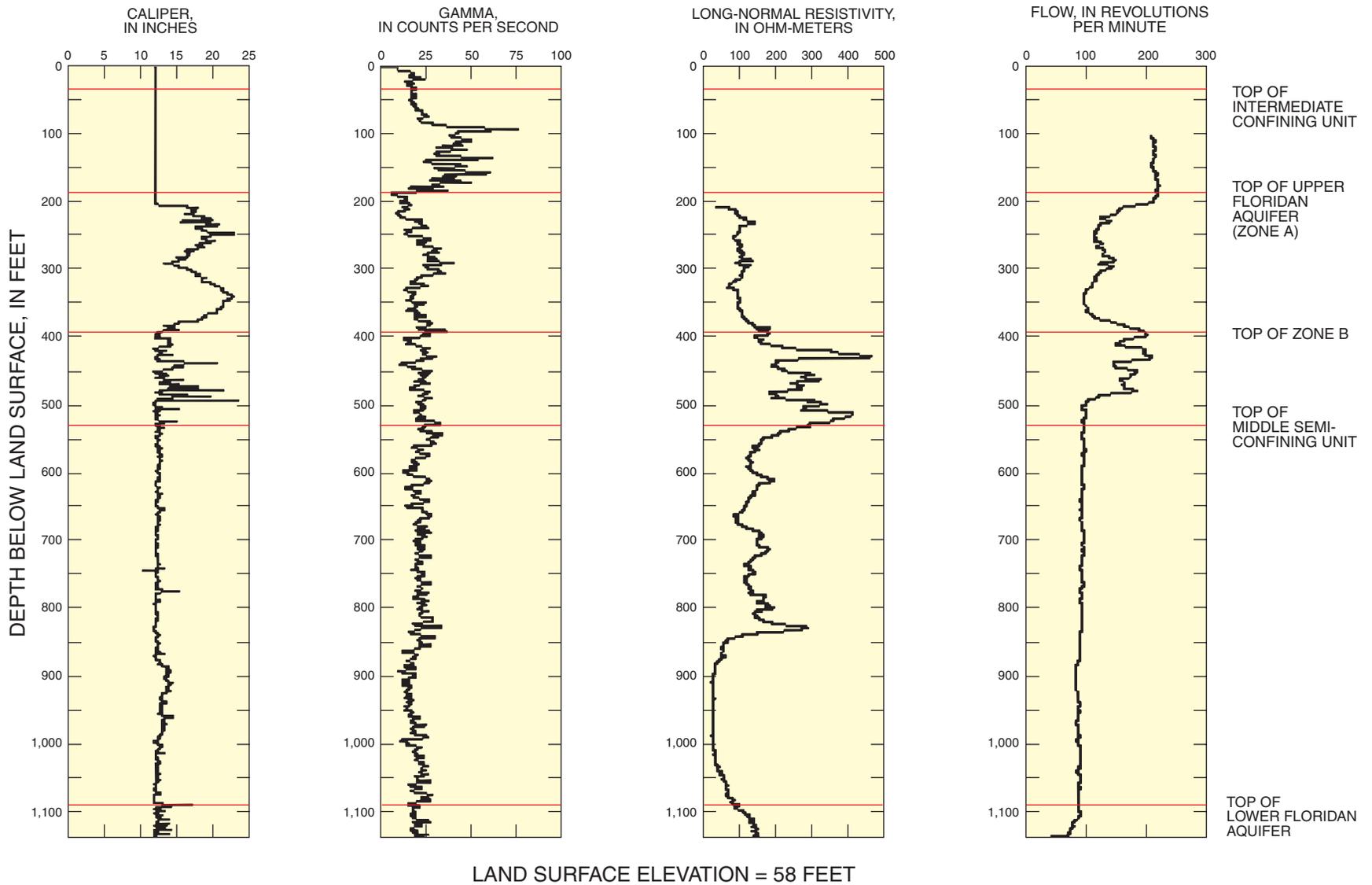
**Figure 20.** Generalized altitude of the top of the Upper Floridan aquifer.



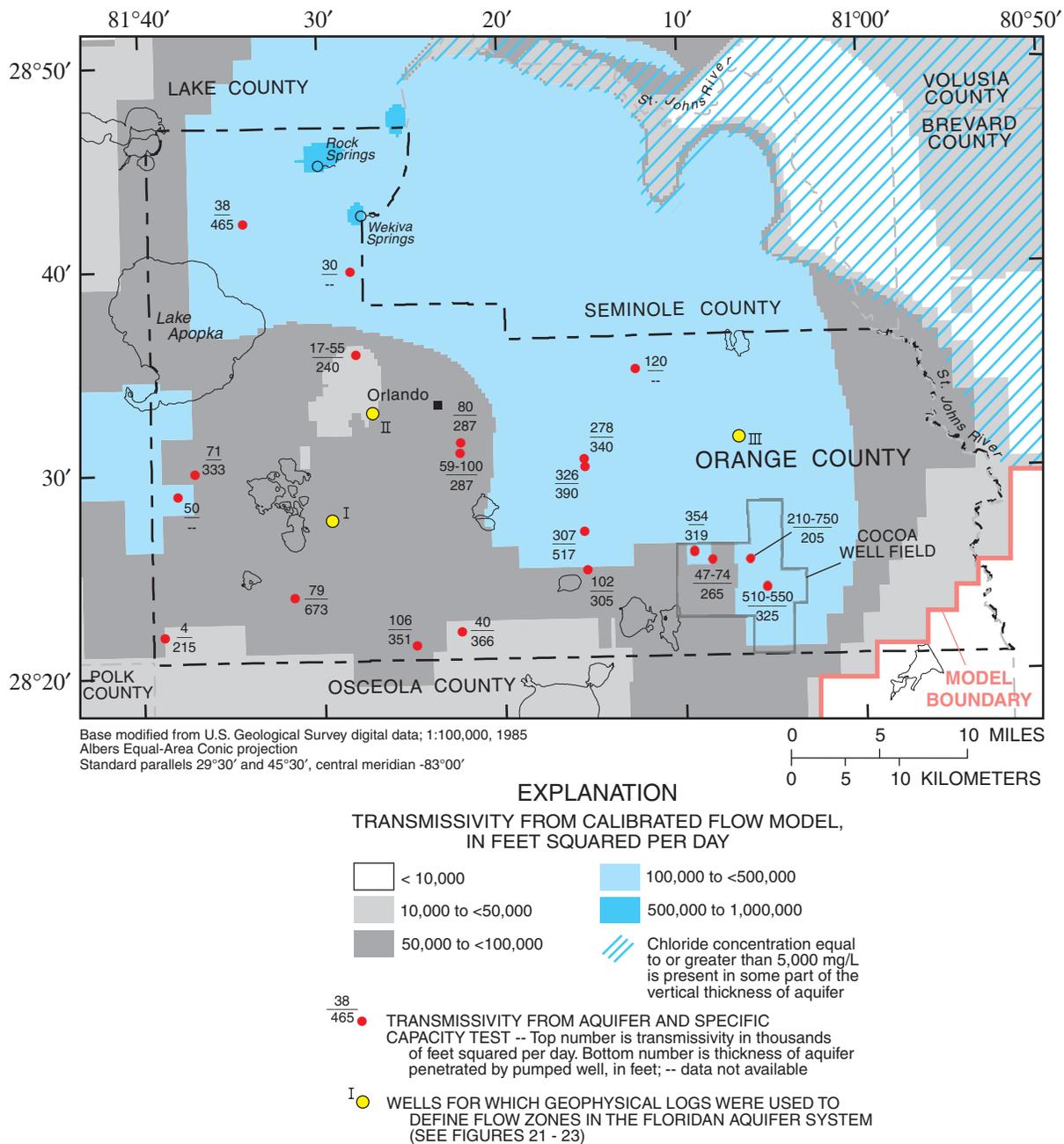
**Figure 21.** Selected geophysical logs showing hydrogeologic units for site I (refer to figure 20 for location), Orange County, Florida (modified from O'Reilly and others, 2002).



**Figure 22.** Selected geophysical logs showing hydrogeologic units for well OR0621, site II (refer to figure 20 for location), Orange County, Florida (A.M. O'Reilly, U.S. Geological Survey, written commun., 2002).



**Figure 23.** Selected geophysical logs showing hydrogeologic units for well OR0618, site III (refer to figure 20 for location), Orange County, Florida (A.M. O'Reilly, U.S. Geological Survey, written commun., 2002).



**Figure 24.** Location of aquifer tests and model-derived transmissivity values for the Upper Floridan aquifer (modified from Murray and Halford, 1996; PB Water, 1999; and Spechler and Halford, 2001).

Transmissivity values from calibrated ground-water flow models generally are greater than those calculated from aquifer tests because: (1) wells used for aquifer tests rarely penetrate the full thickness of the aquifer; and (2) transmissivity values calculated from aquifer tests are more likely to represent a point value rather than the more areally averaged value derived from a ground-water flow model. Model-calibrated transmissivity

determined for the Upper Floridan aquifer was less than 50,000 ft<sup>2</sup>/d along the St. Johns River in southern and southeastern Orange County (fig. 24; Spechler and Halford, 2001). Maximum values of transmissivity occur in a broad area extending from northwestern Orange County, through the city of Orlando, and around the Cocoa well field in southeastern Orange County (fig 24; Spechler and Halford, 2001).

## Middle Semiconfining Unit and Lower Floridan Aquifer

The middle semiconfining unit, which separates the Upper and Lower Floridan aquifers, is composed of less permeable carbonate units of the Avon Park Formation (fig. 11; O'Reilly and others, 2002). The contacts between the middle semiconfining unit and the Upper and Lower Floridan aquifers are based primarily on permeability (determined from geophysical logs) rather than lithology and stratigraphy. The middle semiconfining unit is composed of soft limestone, in which secondary porosity is less developed than the rest of the Floridan aquifer system. As a result, the middle semiconfining unit is identified on geophysical logs by lower apparent resistivity, smooth borehole walls as determined by caliper logs, and little increase in borehole flow (O'Reilly and others, 2002).

The top of the middle semiconfining unit ranges from about 330 ft below NGVD 29 in northwestern Orange County to about 485 ft below NGVD 29 in southeastern Orange County (O'Reilly and others, 2002). The thickness of the unit ranges from about 385 ft in southwestern Orange County to 635 ft in east-central Orange County (O'Reilly and others, 2002). A second confining unit, the middle confining unit, underlies the middle semiconfining unit in western Osceola County and southern Lake County (O'Reilly and others, 2002). This unit is composed primarily of anhydritic and gypsiferous dolomite and dolomitic limestone, and is much less permeable than the middle semiconfining unit (Miller, 1986). One well control point in southwestern Orange County indicates that the middle confining unit is present in that area (O'Reilly and others, 2002), but is not present throughout Orange County.

Few data are available describing the hydraulic properties of the middle semiconfining unit. Values of leakance of the middle semiconfining unit obtained from model simulations range from  $1 \times 10^{-5}$  (ft/d)/ft to  $2 \times 10^{-3}$  (ft/d)/ft (Murray and Halford, 1996; Sepúlveda, 2002). The vertical hydraulic conductivity of the middle semiconfining unit was estimated to be less than 0.05 ft/d based on results of aquifer tests at the Cocoa well field (Phelps and Schiffer, 1996).

The top of the Lower Floridan aquifer ranges from about 870 ft below NGVD 29 in northwestern Orange County to 1,120 ft below NGVD 29 in southeastern Orange County (O'Reilly and others, 2002). Only four wells in Orange County penetrate the full thickness of the Lower Floridan aquifer. Based on four

wells that penetrate the full thickness of the Floridan aquifer system in central and southern Orange County, the thickness of the Lower Floridan aquifer ranges from 1,023 to 1,180 ft (O'Reilly and others, 2002).

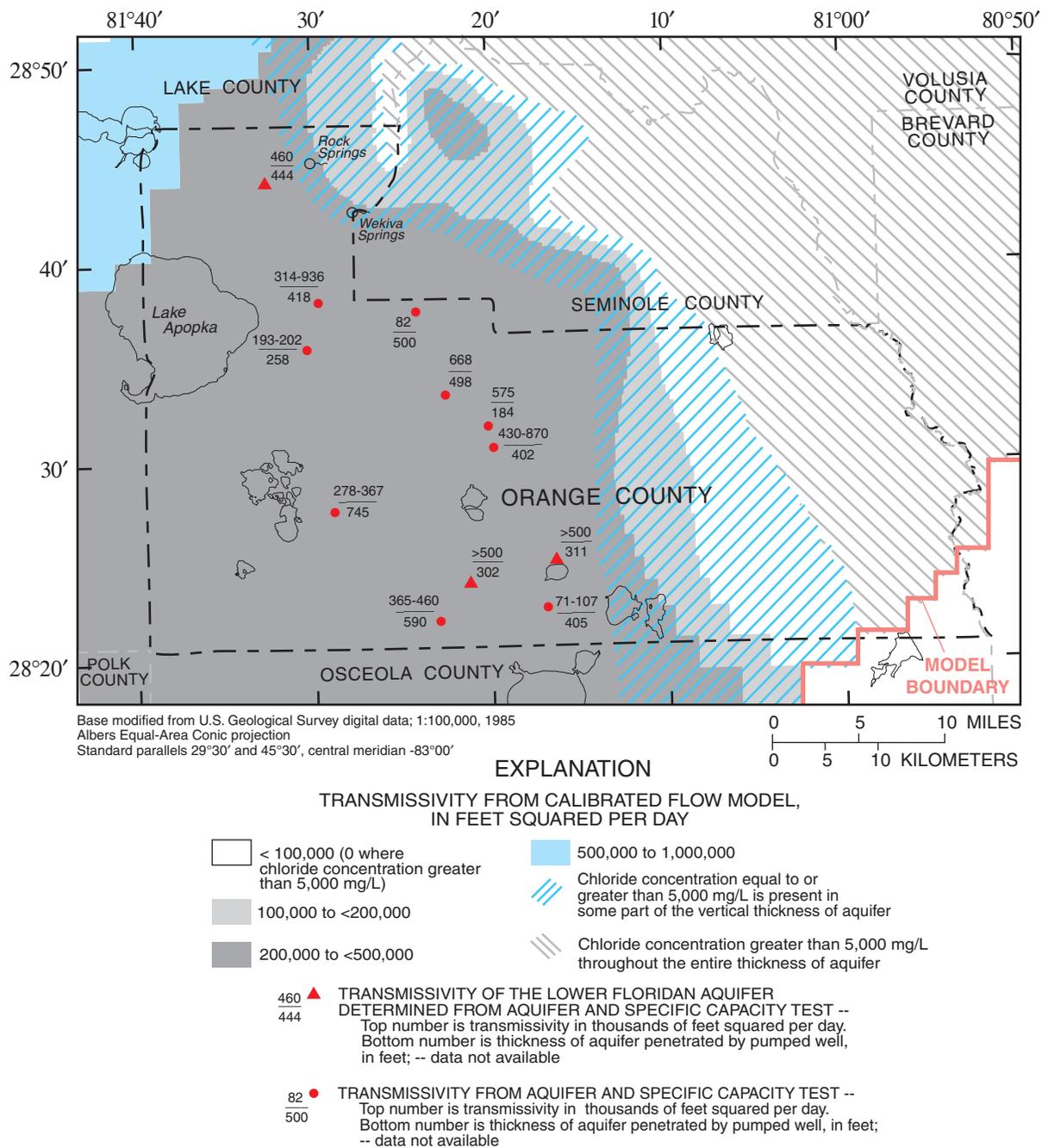
As in the Upper Floridan aquifer, transmissivity of the Lower Floridan aquifer is enhanced by secondary porosity features, which probably are the primary cause of high transmissivity zones (O'Reilly and others, 2002). Only 12 aquifer tests, however, were reported for wells tapping the Lower Floridan aquifer (fig. 25). Transmissivity values for these tests range from 82,000 to more than 900,000 ft<sup>2</sup>/d (O'Reilly and others, 2002). High values of transmissivity were calculated for a number of wells. Results of a test in Orlando indicated a transmissivity of about 500,000 ft<sup>2</sup>/d (Lichtler and others, 1968). Drawdown in the observation well (900 ft from the pumped well) was only about 1 in. after pumping the supply well at 3,200 gal/min for 10.5 hours. The small drawdown allowed only an estimation of the transmissivity (Lichtler and others, 1968). No tests were completed in eastern Orange County, where few wells tapping the Lower Floridan aquifer have been drilled (fig. 25).

Calibration of a model of Seminole County and surrounding areas, including Orange County, resulted in a large range of values for transmissivity of the Lower Floridan aquifer (fig. 25). Maximum values were in northwestern Orange County; minimum values were in eastern Orange County (fig. 25). More recent model-derived transmissivity values for the Lower Floridan aquifer in Orange County ranged from about 5,000 to 700,000 ft<sup>2</sup>/d (Sepúlveda, 2002).

## Recharge and Discharge

Recharge to the Floridan aquifer system occurs naturally from downward leakage of water from the surficial aquifer system, and directly from precipitation in places where the intermediate confining unit is missing. Recharge also can occur artificially from drainage wells and disposal of treated wastewater. Discharge occurs naturally by upward leakage of water to the surficial aquifer system, and directly to streams such as the Wekiva River. Discharge also occurs artificially from pumping wells.

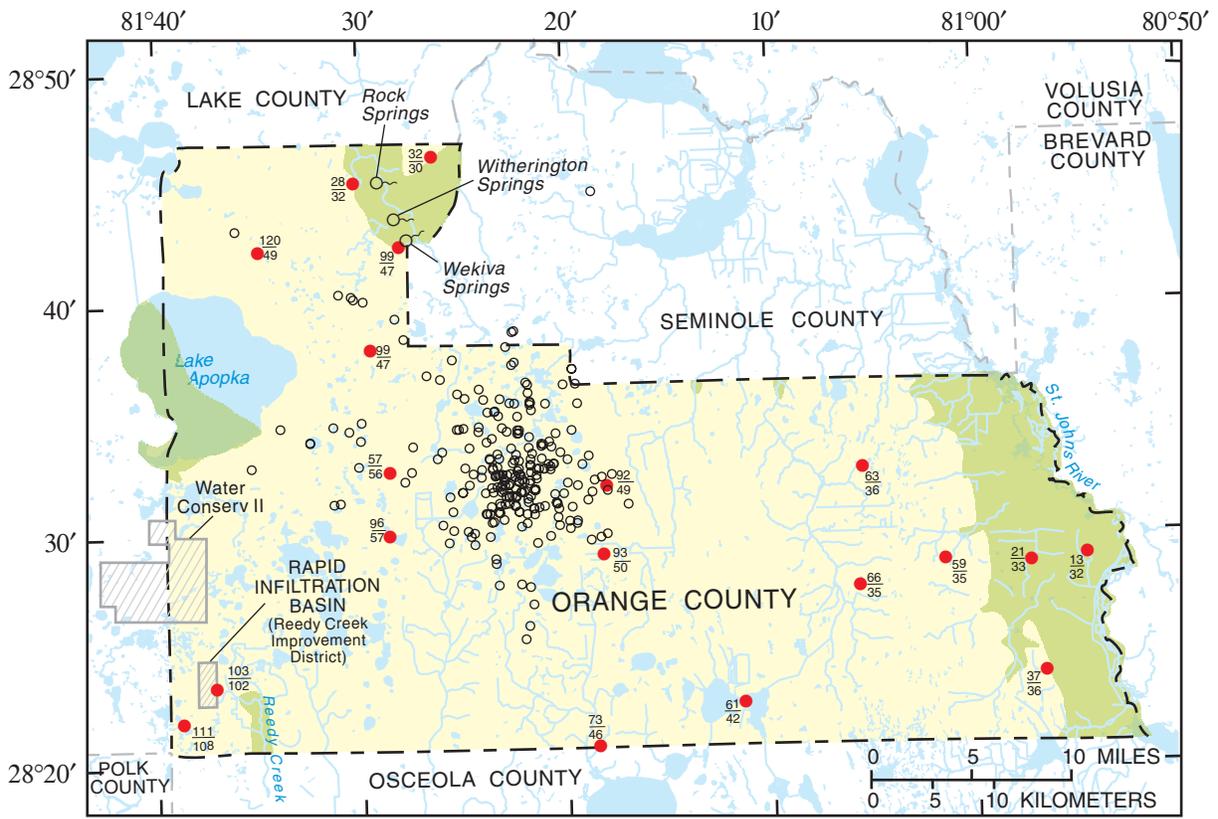
Recharge to the Upper Floridan aquifer can occur in areas where the altitude of the water table is higher than the altitude of the potentiometric surface of the Upper Floridan aquifer. At these locations, the potential exists for ground water to flow downward



**Figure 25.** Location of aquifer tests and model-derived transmissivity values for the Lower Floridan aquifer (modified from Spechler and Halford, 2001, and O'Reilly and others, 2002).

from the surficial aquifer system, through the intermediate confining unit, and recharge the Floridan aquifer system. Most of Orange County is designated as a potential recharge area, based on this criterion (fig. 26). In reality, this recharge occurs slowly, except in locations where the intermediate confining unit is thin or very permeable. Rates of recharge to the Upper Floridan

aquifer in Orange County were estimated with groundwater flow models (O'Reilly, 1998; Murray and Halford, 1996). In western Orange County, natural recharge rates can be as high as 25 in/yr, whereas in much of central Orange County, the rate is less than 10 in/yr (fig. 27). Recharge rates can exceed 25 in/yr in areas where significant artificial recharge occurs (such



Base modified from U.S. Geological Survey digital data; 1:100,000, 1985  
 Albers Equal-Area Conic projection  
 Standard parallels 29°30' and 45°30', central meridian -83°00'

**EXPLANATION**

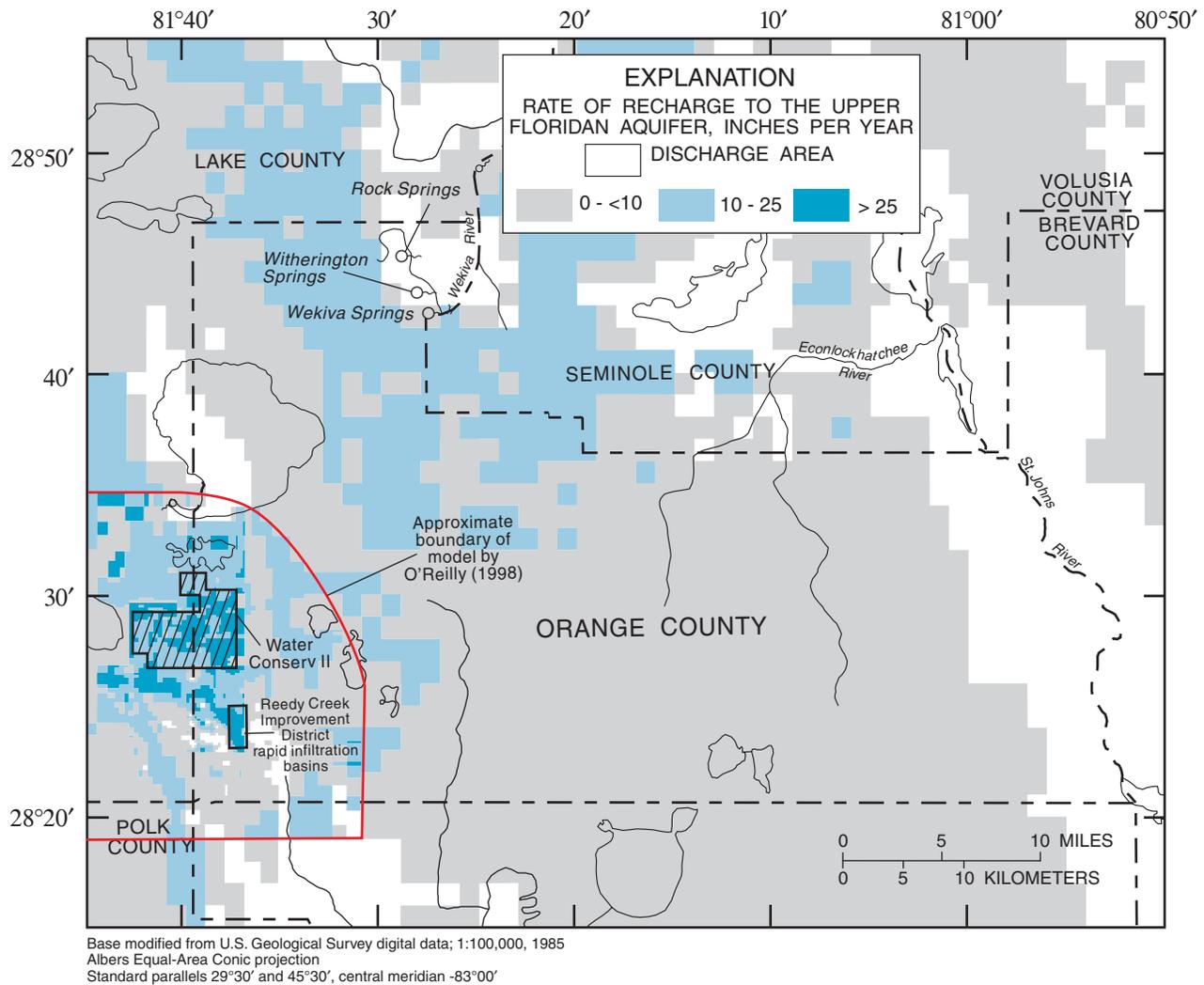
- RECHARGE AREA
- POTENTIAL DISCHARGE AREA
- UPPER FLORIDAN AQUIFER DRAINAGE WELL
- WELL PAIRS TAPPING THE SURFICIAL AQUIFER SYSTEM AND THE UPPER FLORIDAN AQUIFER -- Top number is water level in the surficial aquifer system and bottom number is water level in the Upper Floridan aquifer in September 2001, in feet above NGVD 29
- SPRING

**Figure 26.** Areas of potential recharge to and discharge from the Upper Floridan aquifer (modified from Boniol and others, 1993; CH2M Hill, 1997; and Murray and Halford, 1996).

as Water Conserv II and the RCID RIBs) or where the intermediate confining unit is very leaky (fig. 27). The thickness and lithology of the intermediate confining unit, which is less than 50 ft thick in many parts of western Orange County, but 100 to 150 ft thick in most of central and eastern Orange County, probably affects the recharge rate.

The Upper Floridan aquifer also receives recharge artificially from water flowing into drainage wells (fig. 26). Estimates for recharge rates from these

wells range from about 30 Mgal/d (Tibbals, 1990; Murray and Halford, 1996) to nearly 46 Mgal/d (Spechler and Halford, 2001). Actual recharge to the Upper Floridan aquifer from drainage wells can vary considerably because of seasonal and annual variations in precipitation and lake stages, but probably ranges from about 38 to 50 Mgal/d (CH2M Hill, 1997). In addition to drainage wells that receive storm runoff, the Upper Floridan aquifer historically received effluent from the disposal of both municipal and industrial



**Figure 27.** Simulated recharge rate to the Upper Floridan aquifer by leakage through the intermediate confining unit under average steady-state 1988 conditions (modified from Murray and Halford, 1996) and average steady-state 1995 conditions (modified from O'Reilly, 1998).

wastewater into so-called sanitary wells. At least 18 sanitary wells, with depths ranging from 231 to 863 ft, were located around the city of Orlando (Unklesbay, 1944). The use of sanitary wells was discontinued due to the risk of contamination of the Floridan aquifer system (Thomas L. Lothrop, city of Orlando, oral commun., 2003).

The hydrologic system in Orange County also receives artificial recharge from wastewater, including septic tanks, and from irrigation of citrus groves and lawns with treated wastewater (reclaimed water), as well as from land application of reclaimed water at RIBs in the western part of the county (fig. 1).

Recharge enters the surficial aquifer system and flows into the Upper Floridan aquifer in areas where the water table is higher than the potentiometric surface. Estimating the amount of artificial recharge requires some extrapolation from 1990 data, which indicate that more than 211,000 homes and residences were served by public sewers (U.S. Census Bureau, 2002). The total amount of treated wastewater discharged from public sewer systems in Orange County in 1990 was 91.67 Mgal/d (Marella, 1994) or 434 gal/d per household. In 2000, the number of housing units in Orange County was more than 361,000. Assuming the same amount of wastewater discharge per unit in 2000 as in 1990

(434 gal/d per household), then the estimated total amount of wastewater discharge (including public sewers and septic tanks) in 2000 would be about 157 Mgal/d. Of the total 157 Mgal/d, about 30 to 40 Mgal/d was discharged from a wastewater treatment plant directly to surface water either in the Little Econlockhatchee River or to wetlands that drain into the St. Johns River (fig. 1). The remainder of the wastewater ( $157 - 40 = 117$  Mgal/d) potentially contributes to the surficial aquifer system in Orange County through septic tanks, irrigation, or RIBs, although some reclaimed water is lost to evapotranspiration.

In a few locations, the altitude of the potentiometric surface of the Upper Floridan aquifer is higher than the water table in the surficial aquifer system, indicating areas of potential discharge from the Upper Floridan aquifer to the surficial aquifer system or to lakes and streams. These areas primarily are in eastern Orange County along the St. Johns River, in southwestern Orange County along Reedy Creek, in western Orange County beneath parts of Lake Apopka, and in northwestern Orange County (fig. 26). In areas of low land-surface altitude, artesian pressure causes water in wells to flow out of the top of the casing. Numerous flowing wells (sites 87, 92, 118, and 180; figs. 8 and 9) are present in eastern Orange County, most of which are capped to prevent water from discharging continuously. Natural discharge also occurs at springs such as Rock, Wekiva, and Witherington Springs in the northwestern part of the county (fig. 1). In southwestern Orange County, however, Reedy Creek would go dry periodically (zero discharge) prior to urban development in the basin, indicating that natural discharge of the Upper Floridan aquifer in that area probably was minimal.

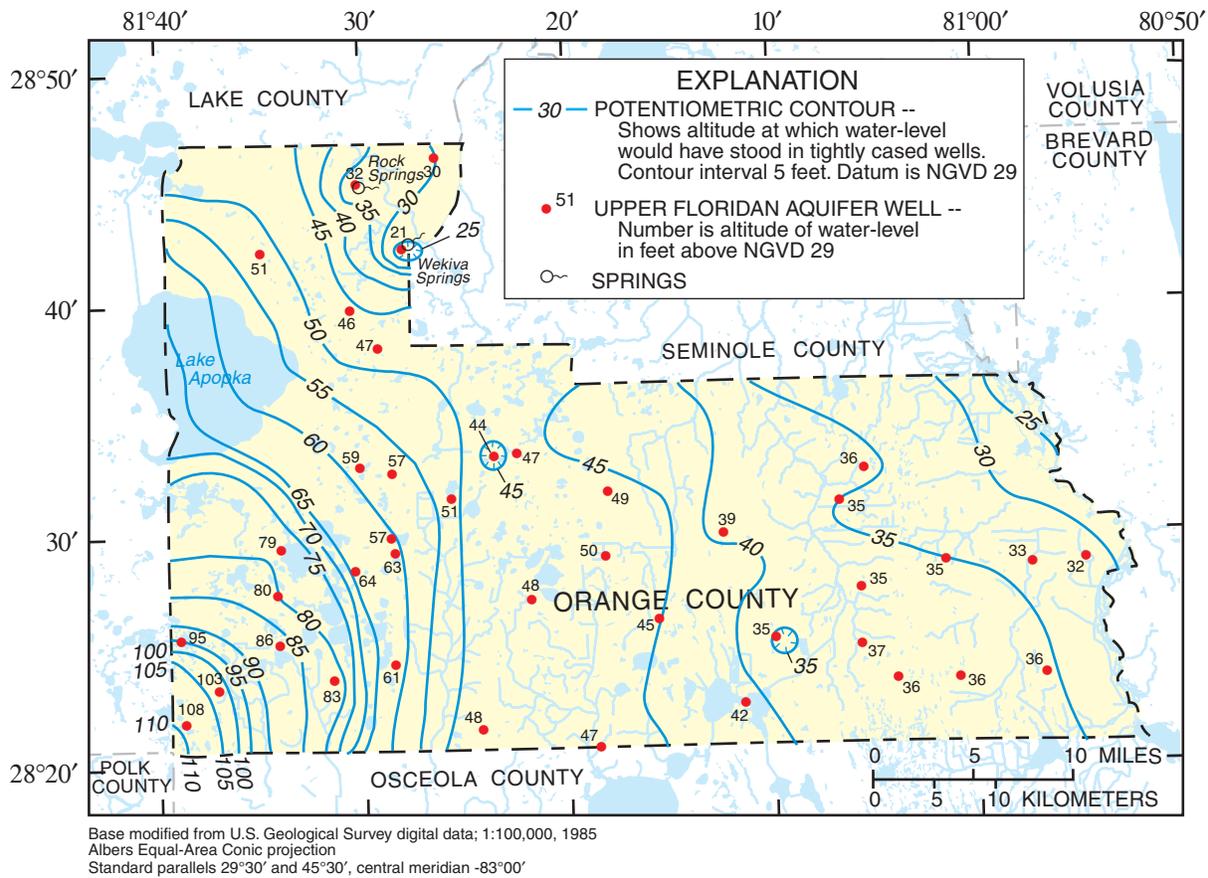
Ground-water discharge also occurs artificially as a result of withdrawal from wells throughout the county. In 2000, about 287 Mgal/d of ground water was withdrawn (R.L. Marella, U.S. Geological Survey, written commun., 2002), which is equivalent to about 6 in. of water for the year over the area of the county (1,003 mi<sup>2</sup>). Average rainfall in Orlando is about 50 in./yr; hence, an amount of ground water equivalent to about 12 percent of average rainfall was withdrawn from the aquifers in 2000. Furthermore, rainfall in 2000 was only 30.4 in.; the amount of ground water withdrawn was about 20 percent of the rainfall during that year.

## Potentiometric Surface and Ground-Water Flow Patterns

The potentiometric surface of the Upper Floridan aquifer ranges from about 110 ft above NGVD 29 in southwestern Orange County to less than 30 ft above NGVD 29 in eastern Orange County (fig. 28). These levels indicate lateral ground-water flow in the Upper Floridan aquifer in Orange County is from the southwest to the east-northeast. Local depressions in the potentiometric surface result from ground water pumping and from discharge of ground water at Wekiva Springs. The slope of the surface is steeper in southwestern Orange County and flattens in eastern Orange County, probably as a result of an increase in transmissivity from the southwest to the east.

The potentiometric surface of the Upper Floridan aquifer declined throughout much of Orange County from 1961 to 2001. Water levels in wells measured near the end of the wet season in September 2001 (fig. 28) were compared with water levels in wells measured in July 1961 (fig. 29), which, according to Lichtler and others (1968) represented relatively average conditions. Water-level measurements for both time periods were available for 15 wells. Water levels declined in all 15 wells, as a result of a general decline in the altitude of the potentiometric surface. Declines ranged from a minimum of 0.8 ft in southwestern Orange County to 16 ft in south-central Orange County, with a median decline of about 3 ft. Declines greater than 10 ft also were observed in central and west-central Orange County (fig. 30). Water-level declines in central Orange County roughly coincide with areas of urban land use (fig. 5) and locations of public-supply wells (figs. 6 and 7).

In southwestern Orange County, the altitude of the Upper Floridan aquifer potentiometric surface is affected by artificial recharge at RIBs. The water level in an observation well tapping the Upper Floridan aquifer (site 24) generally increased after 1990, about the same time the RIBs began receiving reclaimed water (fig. 31). The well is located adjacent to RIBs; hence, the water level in the well probably is affected by artificial recharge from the RIBs. A previous study indicated an increase ranging from 2 to 4 ft in the altitude of the potentiometric surface of the Upper Floridan aquifer in the vicinity of site 24 as a result of the effects of the RIBs (O'Reilly, 1998).



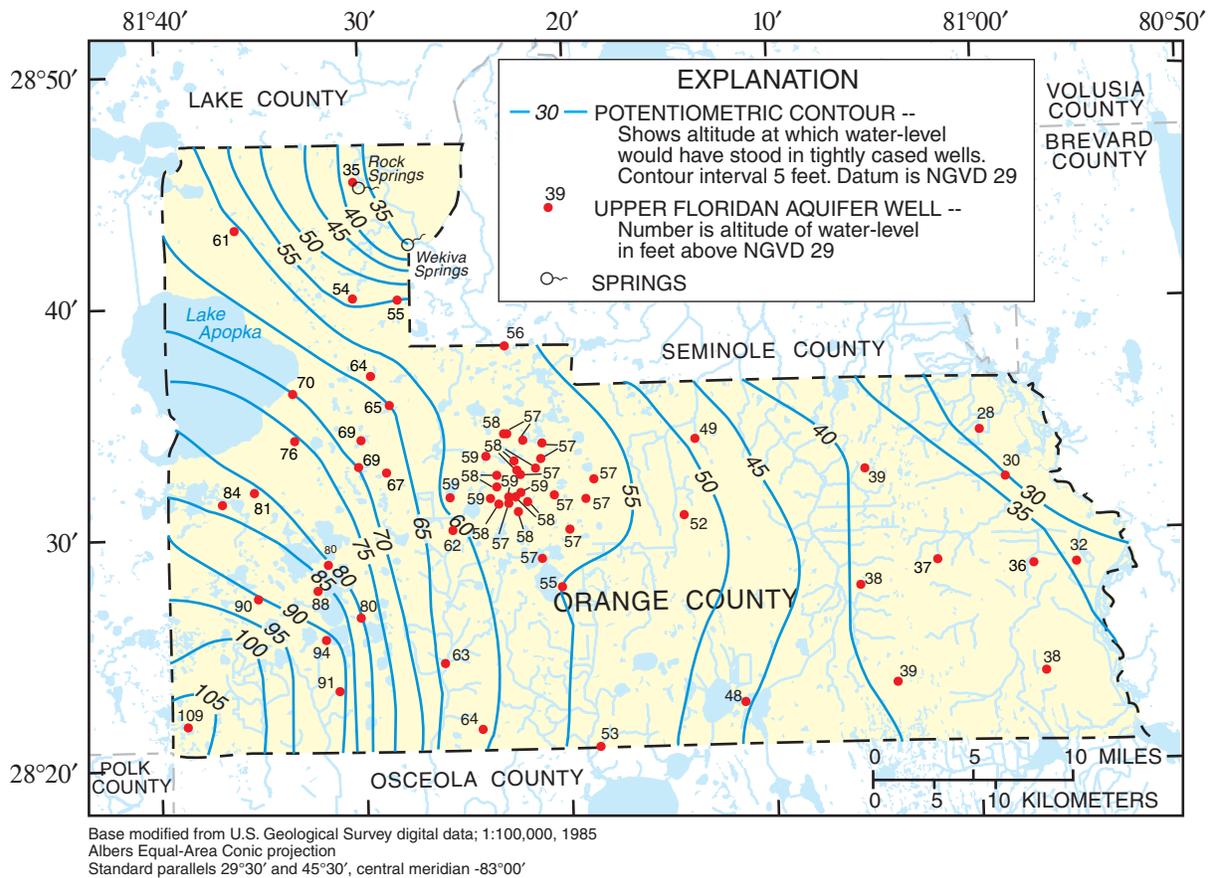
**Figure 28.** Potentiometric surface of the Upper Floridan aquifer, September 2001 (modified from Knowles and Kinnaman, 2002).

The potentiometric surface of the Lower Floridan aquifer generally mimics the potentiometric surface of the Upper Floridan aquifer, with water flowing laterally from southwestern Orange County to northeastern Orange County (fig. 32) (O'Reilly and others, 2002). Compared with the Upper Floridan aquifer, however, fewer wells are available for constructing potentiometric-surface maps of the Lower Floridan aquifer. No wells are available in southwestern or northeastern Orange County to evaluate the highest and lowest altitudes of the potentiometric surface. Water levels from four wells that were measured during the 1960s also are available for May 1999; the water level declined 9 ft in three of the wells and 12 ft in the other well.

The potential exists for ground water to flow vertically between the Upper Floridan and Lower Floridan aquifers. In six of seven well pairs in Orange County, the potentiometric surface of the Upper Floridan aquifer is higher than that of the Lower Floridan aquifer, indicating a potential for downward flow from

the Upper Floridan to the Lower Floridan aquifer. The difference between the two potentiometric surfaces ranged from 0.3 to 2.4 ft in May 1999 (O'Reilly and others, 2002). At one well pair (sites 105 and 106, fig. 8), the potentiometric surface of the Lower Floridan aquifer was as much as 0.9 ft higher than that of the Upper Floridan aquifer, indicating a potential for ground water to flow upward from the Lower Floridan to the Upper Floridan aquifer. This difference probably results from pumping of the Upper Floridan aquifer in the area, rather than being indicative of natural hydrogeologic conditions.

Continuous water levels in two wells that tap the Upper and Lower Floridan aquifers (sites 130 and 131, fig. 8) respond similarly to rainstorms (Lichtler and others, 1968, p. 97); however, flow between the two aquifers is difficult to quantify. The well at site 130 is cased only 600 ft, which indicates that the borehole is open not only to the Lower Floridan aquifer, but also open to about 300 ft of the middle semiconfining unit



**Figure 29.** Potentiometric surface of the Upper Floridan aquifer, July 1961 (modified from Lichtler and others, 1968).

(O'Reilly and others, 2002). Therefore, the water level in the well may not accurately indicate the water level in the Lower Floridan aquifer.

The low leakance values of the middle semiconfining unit noted earlier might preclude much groundwater flow between the two aquifers, at least in the eastern part of the county. Phelps and Schiffer (1996) determined that pumping from the Upper Floridan aquifer at the Cocoa well field (fig. 1) did not cause an observable effect on water levels in the Lower Floridan aquifer. Chemical and (or) isotopic analyses of water samples from both aquifers at the same site could be used to better estimate flow through the middle semiconfining unit.

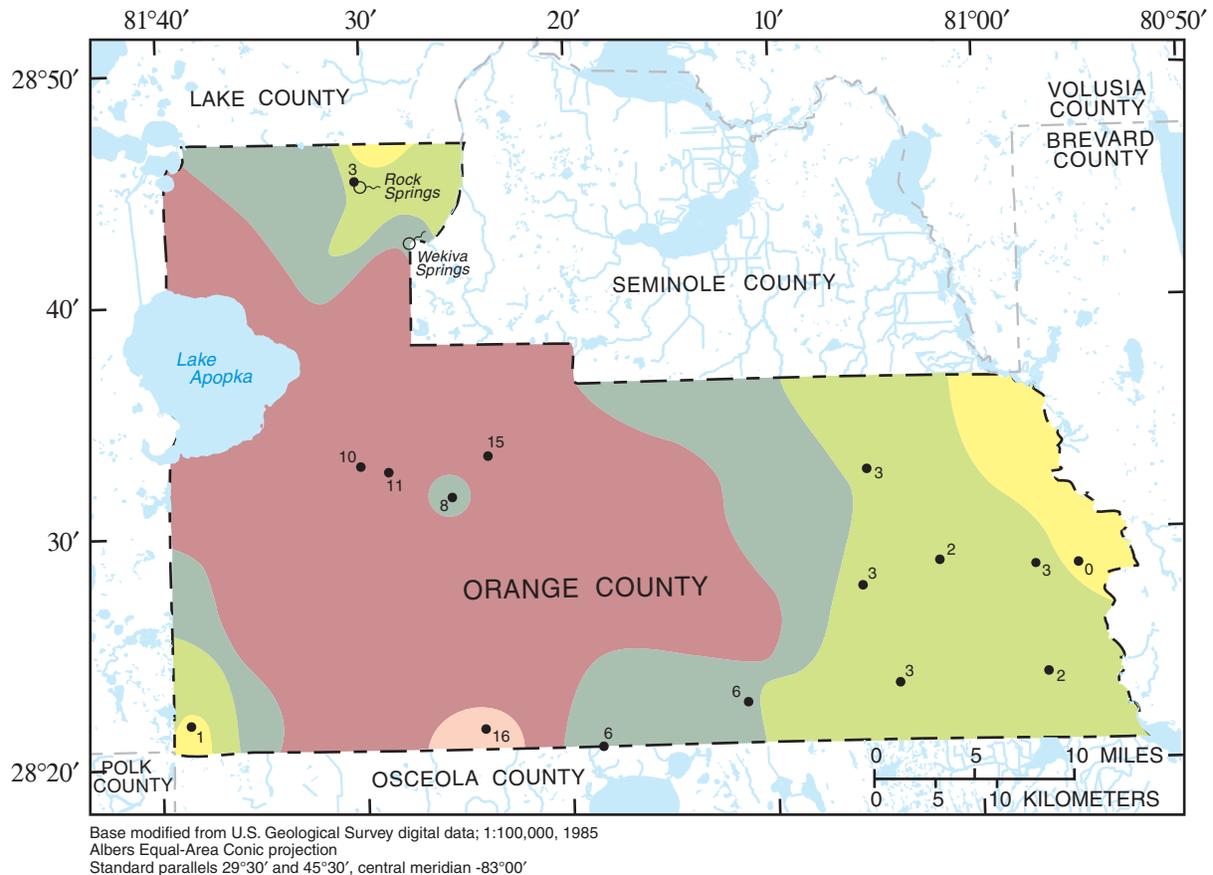
## Long-Term Trends in Water Levels

### Surficial Aquifer System

The Mann-Kendall test was used to analyze long-term water-level data for significant trends. Long-term data for the surficial aquifer system in Orange

County are sparse; however, more data are available for the Floridan aquifer system. Two observation wells tapping the surficial aquifer system (sites 10 and 12, fig. 33) had continuous water-level data for 30 or more years of record. Three additional wells (sites 48, 91, and 124) had monthly water-level measurements for more than 20 years (fig. 33; table 5). Results of the Mann-Kendall trend analysis indicate that water levels have not declined significantly in four of the wells (sites 10, 12, 48, and 91; fig. 33). Results also indicate that water-level altitudes in one well (site 124) declined during the period of record, but the trend is weak (fig. 33; table 5).

The results of the trend analysis is for the overall monotonic trend for the entire period of record. The LOWESS line for site 124 indicates that the decline is not constant over the period of record. The water level in the well (site 124) increased from the beginning of the record to about the early 1980s, declined sharply to



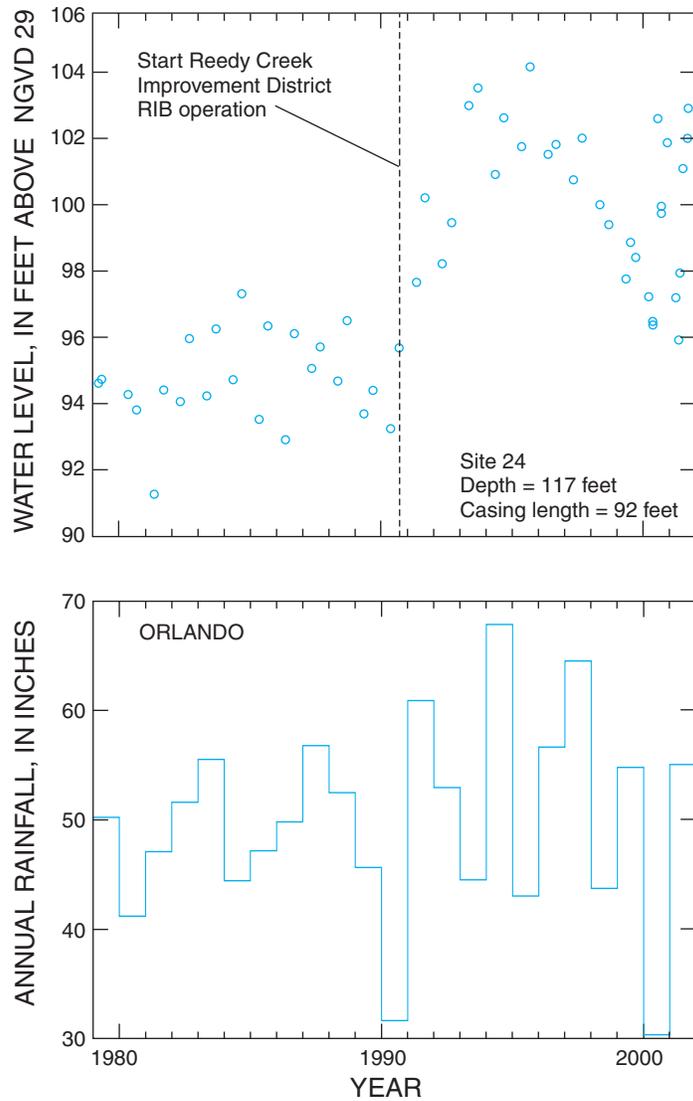
**Figure 30.** Decline in potentiometric surface of the Upper Floridan aquifer from July 1961 to September 2001.

the early 1990s, and then increased to the present (2002). The LOWESS lines for the other four wells also indicate periods of declining or increasing water levels. These oscillations in water levels probably are affected by the somewhat cyclic variations in rainfall over time (fig. 33).

Temporal trends in lake stage also can indicate changes in the water table. Lake water levels were statistically analyzed for trends using annual mean water levels for lakes with at least 15 years of record. Most of these lakes are around Orlando in central Orange County. The tests were done for the entire period of record and also for the period from 1967-2000. Of the

345 lakes in the lake water-level database, 70 lakes had 15 years or more of record since 1967 and 82 lakes had 15 years or more of record including all years.

From 1967 to 2000, significant trends were indicated in 27 (39 percent) of the 70 lakes tested. Eighteen lakes had increasing water levels and 9 lakes had decreasing water levels. For the entire period of record, trends were indicated in 32 (39 percent) of the 82 lakes tested. Of these 32 lakes, 13 had increasing water levels and 19 lakes had decreasing water levels. These results indicate no consistent overall trend or change in the altitude of the water table of the surficial aquifer system throughout Orange County. Any apparent water-level changes are localized, probably resulting from



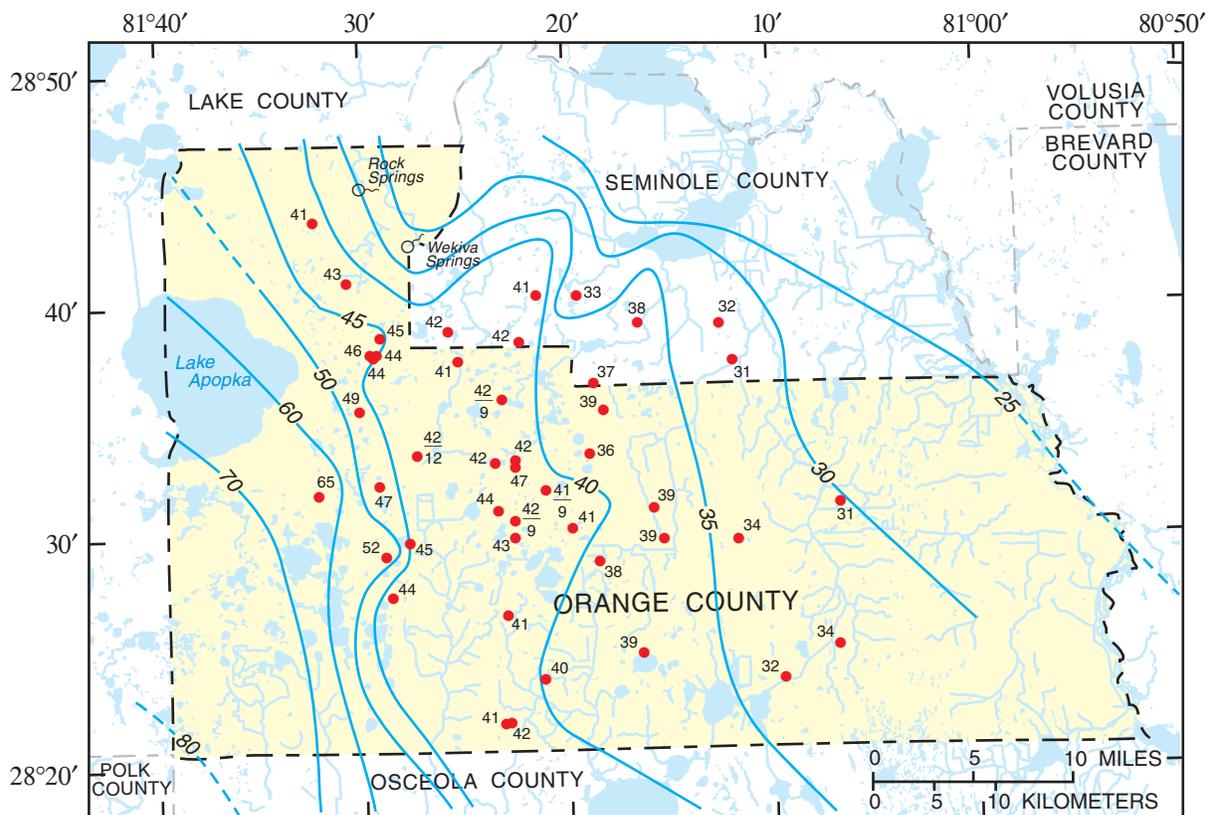
**Figure 31.** Long-term periodic water levels in an observation well tapping the Upper Floridan aquifer and annual rainfall at Orlando, Florida (refer to figure 8 and appendix 1 for site number).

such activities as drainage changes or ground-water pumping. Short-term variations in precipitation distribution probably also affect the water levels in the surficial aquifer system.

### Floridan Aquifer System

Water levels in the Upper Floridan aquifer generally fluctuate over time, increasing, sometimes rapidly, during the wet season (June through September), and decreasing during the rest of the year. For example, the water level in an Upper Floridan aquifer observation well in southwestern Orange County (site 9, fig. 8)

increased 5.1 ft during the wet season, from 103.6 ft above NGVD 29 on June 14, 2001, to 108.7 ft above NGVD 29 on September 16, 2001 (fig. 17). The water level in an observation well in eastern Orange County (site 87, fig. 8) increased 4 ft during that same period of time. The rise in water level in the first well (site 9) could reflect nearby recharge to the aquifer, which potentially could cause variations in water quality. Because the second well (site 87) is in a discharge area for the Floridan aquifer system, local recharge of the aquifer seems unlikely. The rise in water level in the well at site 87 probably results from recharge that



Base modified from U.S. Geological Survey digital data; 1:100,000, 1985  
 Albers Equal-Area Conic projection  
 Standard parallels 29°30' and 45°30', central meridian -83°00'

**EXPLANATION**

- 50 — POTENTIOMETRIC CONTOUR--Shows altitude at which water level would have stood in tightly cased wells. Dashed where approximate and estimated from Upper Floridan aquifer potentiometric surface maps. Contour interval 5 and 10 feet. Datum is NGVD 29
- <sup>42</sup>/<sub>9</sub> WELL -- Top number is water level in feet above NGVD 29 in May 1999. Bottom number is water level decline from the 1960s to May 1999
- SPRING

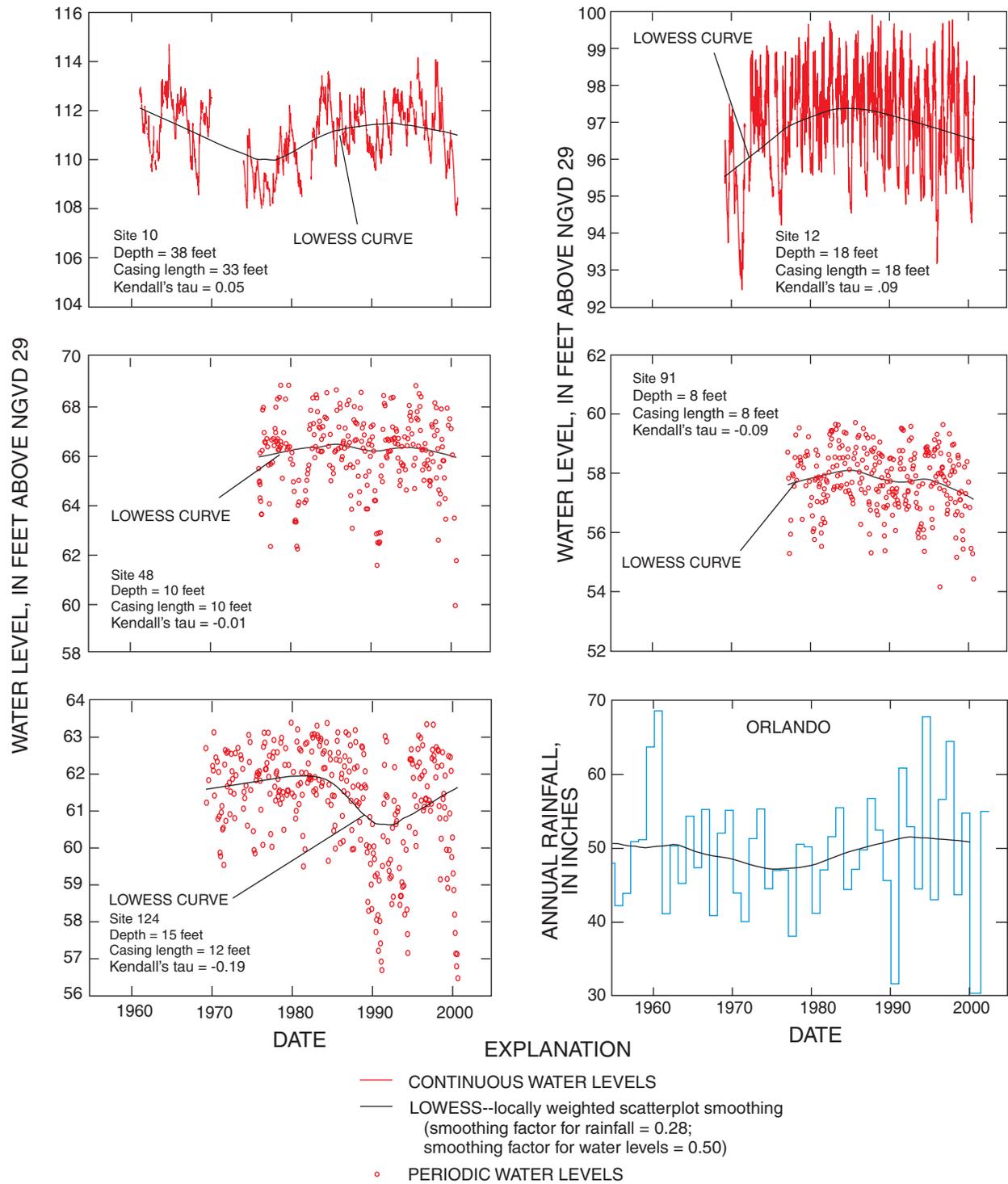
**Figure 32.** Generalized potentiometric surface of the Lower Floridan aquifer, May 1999 (modified from O'Reilly and others, 2002), and water-level decline since the 1960s.

occurs to the west, increasing pressure throughout the aquifer. The collection of ground-water samples for chemical and (or) isotopic analysis during the wet season would be useful in identifying areas of rapid recharge to the Upper Floridan aquifer.

Water levels in the Upper Floridan aquifer also can change from year to year as a result of climatic variations. The water levels in the two above-mentioned wells (sites 9 and 87) were each about 2 ft lower in September 2000 compared with September 2001 (fig. 17). Rainfall in June-September 2000 was about 21 in. (National Oceanic and Atmospheric

Administration, 2001) compared with 39 in. in June-September 2001 (National Oceanic and Atmospheric Administration, 2002).

Long-term water-level data from 13 observation wells tapping the Upper Floridan aquifer and 2 wells tapping the Lower Floridan aquifer were statistically analyzed for trends (table 5; figs. 8 and 34). The periods of record used for data analysis ranged from 27 to 58 years. These wells are not evenly distributed throughout Orange County; most of the wells are located in eastern Orange County, including seven wells located in and around the Cocoa well field (fig. 1).



**Figure 33.** Long-term continuous and periodic water levels in observation wells tapping the surficial aquifer system (refer to figure 8 and appendix 1 for site numbers) and annual rainfall at Orlando, Florida.

**Table 5.** Well construction data, period of record, and results of trend analysis for long-term observation wells tapping the surficial and Floridan aquifer systems

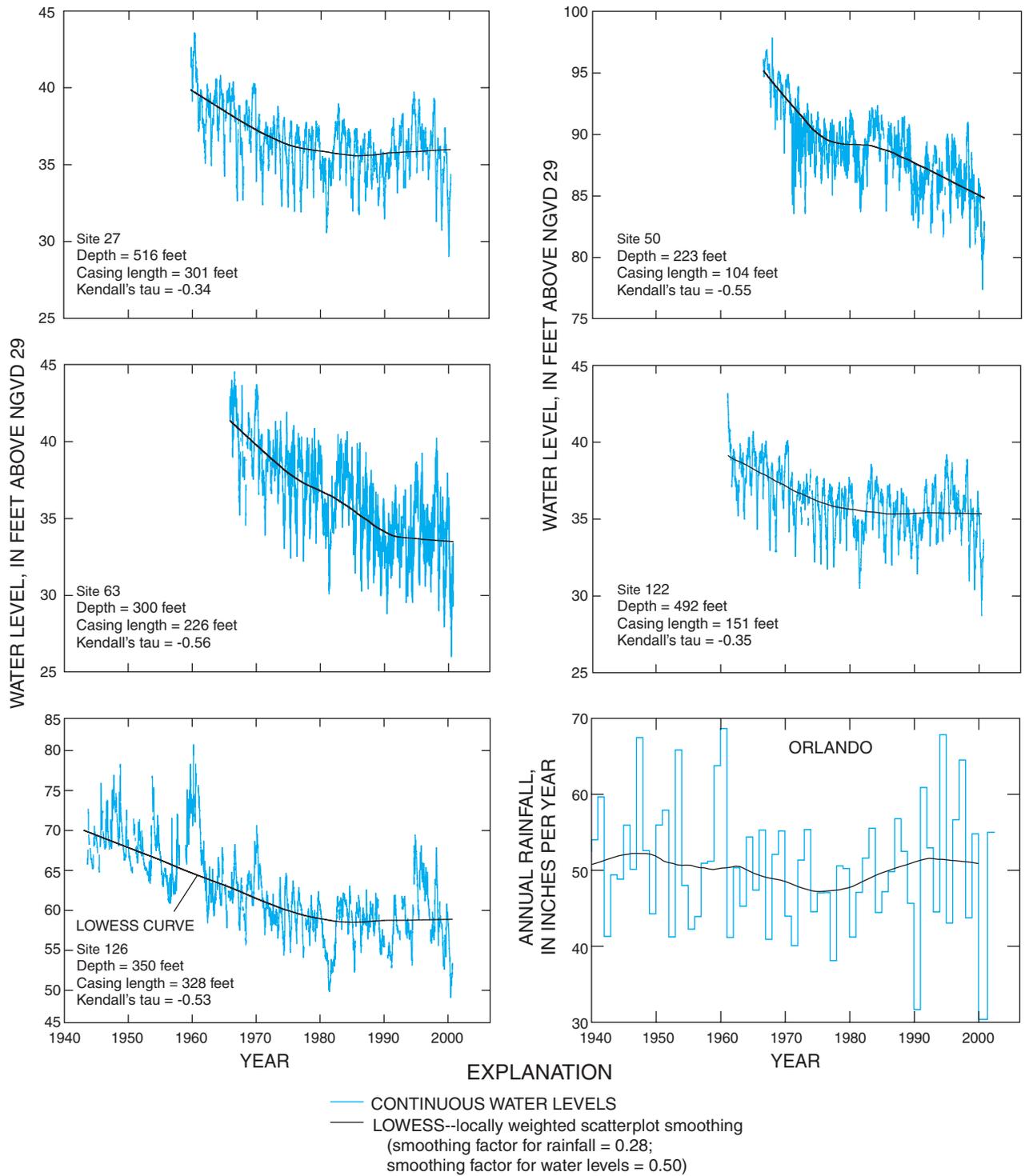
[Kendall's tau values shown in bold face were statistically significant at the 0.05 significance level]

Site number	Station identifier	Station name	Elevation (feet above NGVD 29)	Depth of well (feet below land surface)	Casing length (feet)	Period of record	Kendall's tau
<b>Surficial aquifer system</b>							
10	282202081384602	Lake Oliver surficial well	117.06	38	13	1960 to 1969, 1974 to 2001	0.05
12	282210081352601	Disney surficial well	99.44	18	18	1969 to 2001	.09
48	282510081054502	Cocoa-M well	70.81	10	10	1969 to 2001	-.005
91	282847081013702	Cocoa-K well	60	8	8	1968 to 2001	-.09
124	283249081053203	Bithlo-3 well	63.14	15	12	1960 to 2001	-.19
<b>Upper Floridan aquifer</b>							
9	282202081384601	Lake Oliver deep well	117.12	318	103	1959 to 1969, 1974 to 2001	-.06
27	282341081040101	Cocoa-A well	75.06	516	301	1960 to 2001	<b>-.34</b>
30	282348080564701	Palmetto well	40.62	381	245	1960 to 2001	-.06
50	282528081340901	Bay Lake deep well	97.1	223	104	1966 to 2001	<b>-.55</b>
63	282531081095701	Cocoa-D well	75.91	300	226	1965 to 2001	<b>-.56</b>
67	282533081082206	Cocoa-C (zone 5) well	63.72	1,004	248	1966 to 2001	<b>-.55</b>
72	282623081153801	Cocoa-P well	94.12	439	245	1971 to 2001	<b>-.33</b>
82	282739081054501	Cocoa-F well	67.29	375	200	1966 to 2001	-.07
90	282847081013701	Cocoa-H well	60	495	252	1971 to 2001	.09
122	283249081053201	Bithlo-1 well	63.58	492	151	1961 to 2001	<b>-.35</b>
126	283253081283401	OR-47 well	81.71	350	328	1943 to 2001	<b>-.53</b>
131	283333081233502	Lake Adair 10 well	80.4	400	105	1974 to 2001	-.19
170	284529081301001	Rock Springs deep well	71.9	365	143	1961 to 2001	-.21
<b>Lower Floridan aquifer</b>							
64	282533081082202	Cocoa-C (zone 1) well	63.71	1,357	1,351	1966 to 2001	<b>-.56</b>
130	283333081233501	Lake Adair 9 deep well	80.4	1,281	601	1974 to 2001	-.22

Results of the statistical analysis indicated that water-level altitudes declined in 11 of the 15 wells. Three of the wells (sites 130, 131, and 170) had weak declines in water levels (absolute value of tau <0.3; table 5). Seven wells tapping the Upper Floridan aquifer and one well tapping the Lower Floridan aquifer had statistically significant water-level declines (p-value <0.05) as indicated by strong (absolute value of tau >0.3) negative correlations with time (table 5). Five of these wells are located in or near the Cocoa well field, one well (site 50) is in southwestern Orange County, one well (site 122) is near the town of Bithlo, and one well (site 126) is in west-central Orlando (fig. 8). Four wells (sites 9, 30, 82, and 90; fig. 8 and app. 1) had no statistically significant water-level declines (p-value >0.05) (table 5).

Declines in water levels, based on the minimum and maximum values of the LOWESS curves (fig. 34), ranged from about 4 ft (site 27) to about 12 ft (site 126),

with a median of about 6 ft. The water-level decline in one well (site 126; fig 8) is particularly interesting. The water level in the well began declining from the beginning of the period of record to the early 1980s, and then stabilized. Prior to 1967, land-surface altitude at the site was 72.12 ft above NGVD 29. After 1967, the land-surface altitude increased to 81.71 ft, probably as a result of nearby construction. The water level in the well frequently was greater than 72.12 until the early 1960s, which would seem to indicate that the well flowed periodically. The well is not located in or near any discharge areas for the Upper Floridan aquifer (fig. 26). Unklesbay (1944) does not describe the well as flowing periodically; however, the original casing is recorded as being 10 ft above land surface (Unklesbay, 1944), which may have been installed to prevent flowing and to obtain accurate water-level measurements during high water.



**Figure 34.** Long-term continuous water levels in observation wells tapping the Upper Floridan aquifer and annual rainfall at Orlando, Florida (refer to figure 8 and appendix 1 for site numbers).

Declines in the altitude of the potentiometric surface of the Upper Floridan aquifer also have resulted in flow decreases from springs in the Orange County area. Discharge rates for Rock and Wekiva Springs (fig. 1) have decreased, based on LOWESS curves (fig. 35) generated for discharge measurements made during or immediately following the wet season (June-September).

Water-level declines generally are not continuous throughout the period of record. Although the overall water-level trend in the five wells presented in figure 34 is decreasing (table 5), water levels in some wells exhibit periods of stabilization or even increasing water levels. For example, the water level in one well (site 50) declined from the beginning of record until about the mid-1970s, then stabilized until about the early 1980s, and then declined until present (fig. 34). The water level in another well (site 63) has declined throughout most of the period of record, but the rate of decline decreased in the early 1990s (fig. 34). The cyclic pattern of rainfall over the period of record could be responsible for the brief periods of stabilization or the temporary increase of water levels in some of the wells. There seems to be no long-term trend in rainfall (fig. 35); therefore, long-term declines in water levels (table 5) likely are due primarily to long-term increases in ground-water withdrawals (fig. 4).

Changes in the distribution of pumping also could account for some variations in water-level trends. For example, the decline and stabilization of water levels in the well at site 126 could have resulted from changes in land use and, ultimately, pumping practices. In 1977, more than half of the land use surrounding the well (site 126) was agricultural; however, by 1997, a major portion of the land use around the well was urban (residential and commercial). After several freezing winters in the 1980s, many orange groves in Orange County were redeveloped as subdivisions. The displacement of agricultural land by urban land probably allowed for the abandonment of nearby irrigation wells, as indicated by the significant decrease in water use for agricultural purposes between 1980 and 1990.

## Water Budget

A water budget summarizes the inputs and outputs of a hydrologic system. In general, inputs to a natural system include precipitation and lateral inflow (either ground or surface water) from an adjacent area. Assuming that there is no change in storage, inputs are balanced by outputs, such as evapotranspiration, runoff,

lateral ground-water outflow, spring discharge and, in some areas, by exportation of water to adjacent watersheds or counties. A generalized water budget for Orange County, assuming changes in storage are negligible, can be described by the following equation:

$$P = ET + Q_R + Q_S + Q_O, \quad (2)$$

where

P is precipitation;

ET is evapotranspiration;

$Q_R$  is runoff (sum of overland runoff and ground-water seepage to streams);

$Q_S$  is spring discharge; and

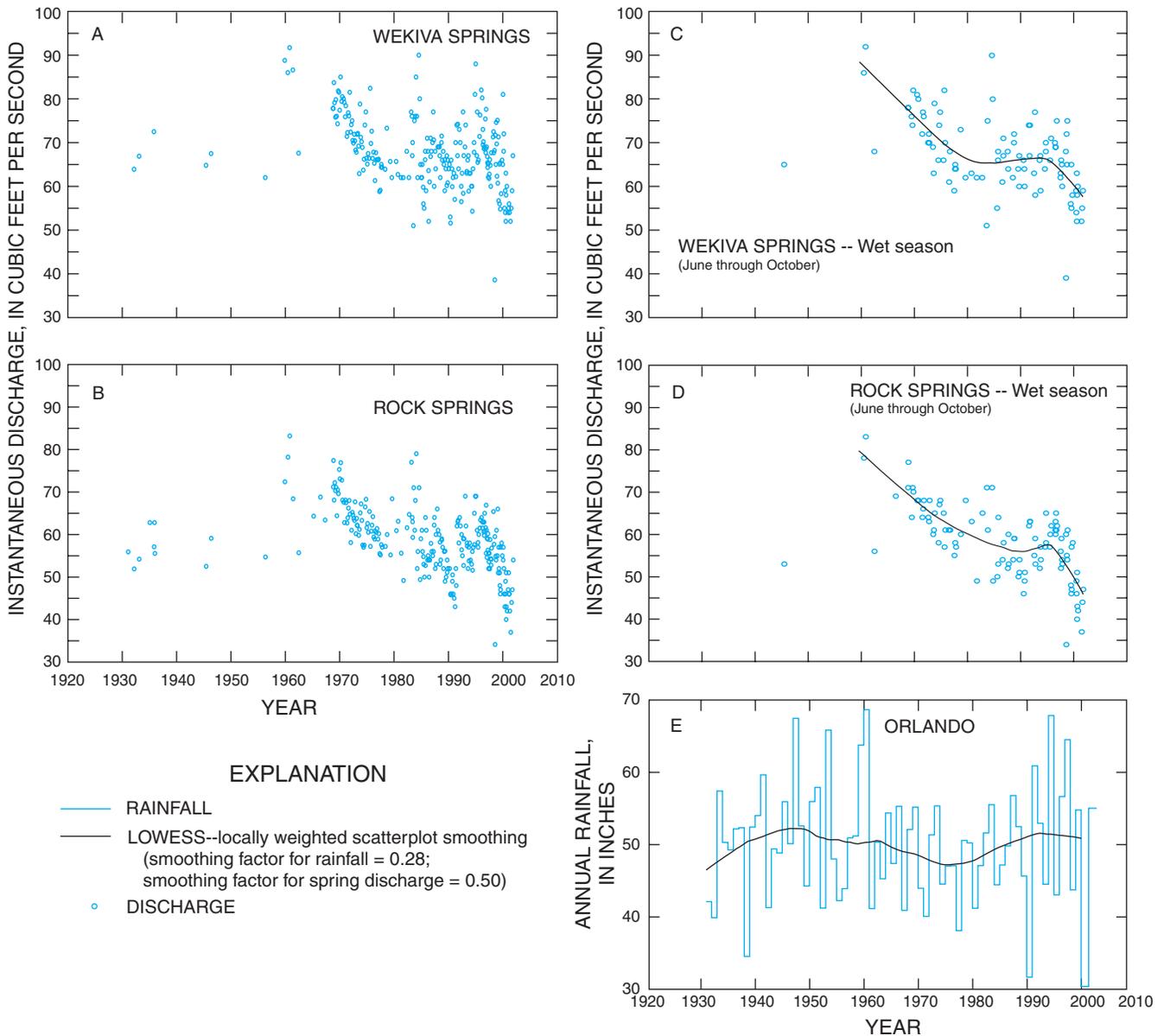
$Q_O$  is net lateral subsurface outflow plus exported water.

All units are in inches per year.

A generalized water budget was computed for Orange County from 1991 to 2000 (fig. 36). All values were rounded to the nearest whole number. A budget averaged over a 10-year period (as opposed to a single year's budget) is likely to be more representative of long-term conditions. Also, water released from or accumulated as storage within the surficial aquifer system, which is difficult to quantify, can be assumed to be negligible during a 10-year averaging period.

The major input to the system is precipitation, which averaged about 53 in/yr from 1991 to 2000 at five NOAA stations (Clermont, Kissimmee, Orlando, Sanford, and Titusville; fig. 1). Runoff from streams flowing into Orange County and lateral subsurface inflow are relatively minor inputs to the hydrologic system. These inputs are included in the computation of  $Q_R$  and  $Q_O$ , as described below.

Water leaving the county as surface-water runoff ( $Q_R$ ) averaged about 11 in/yr from 1991 to 2000, based on analyses of streamflow records at 10 USGS gaging sites that collect runoff from basins that lie entirely (or partially) within Orange County (fig. 1). These sites include: Econlockhatchee River near Chuluota (02233500); St. Johns River near Christmas (02232500); St. Johns River near Cocoa (02232400); Wekiva River near Sanford (02235000); Shingle Creek (02263800); Boggy Creek (02262900); Bonnet Creek (02264100); Apopka-Beauclair Canal (02237700); Reedy Creek (02266300); and Howell Creek (02234308). Estimated runoff from the Ajay-East Tohopekaliga Canal is included in the total (after subtracting the estimated runoff from the Myrtle-Mary Jane Canal). Flows in the Ajay-East Tohopekaliga



**Figure 35.** Discharge at Wekiva and Rock Springs for entire period of record (A and B) and for wet season (C and D), and annual rainfall at Orlando, Florida (E). (Spring locations are shown on figure 1.)

Canal and the Myrtle-Mary Jane Canal are not currently (2000) gaged but were estimated from measurements reported by Lichtler and others (1968). Runoff from these 11 sites ranged from 3.4 in/yr at the Econlockhatchee River near Chuluota to 0.1 in/yr at Howell Creek. At sites where runoff is combined from Orange County and an adjacent county, the amount of runoff contributed solely from Orange County was estimated by multiplying the total gaged discharge by the

percentage of the basin area contained within the county. Runoff from the eastern boundary of Orange County into the St. Johns River was calculated as the difference between discharge at the Cocoa and the Christmas sites, adjusted proportionately for the length of the river that forms the county boundary line.

Other calculated outflows include about 2 in/yr of spring discharge ( $Q_s$ ), which is based on the average discharge at Wekiva and Rock Springs from 1991 to

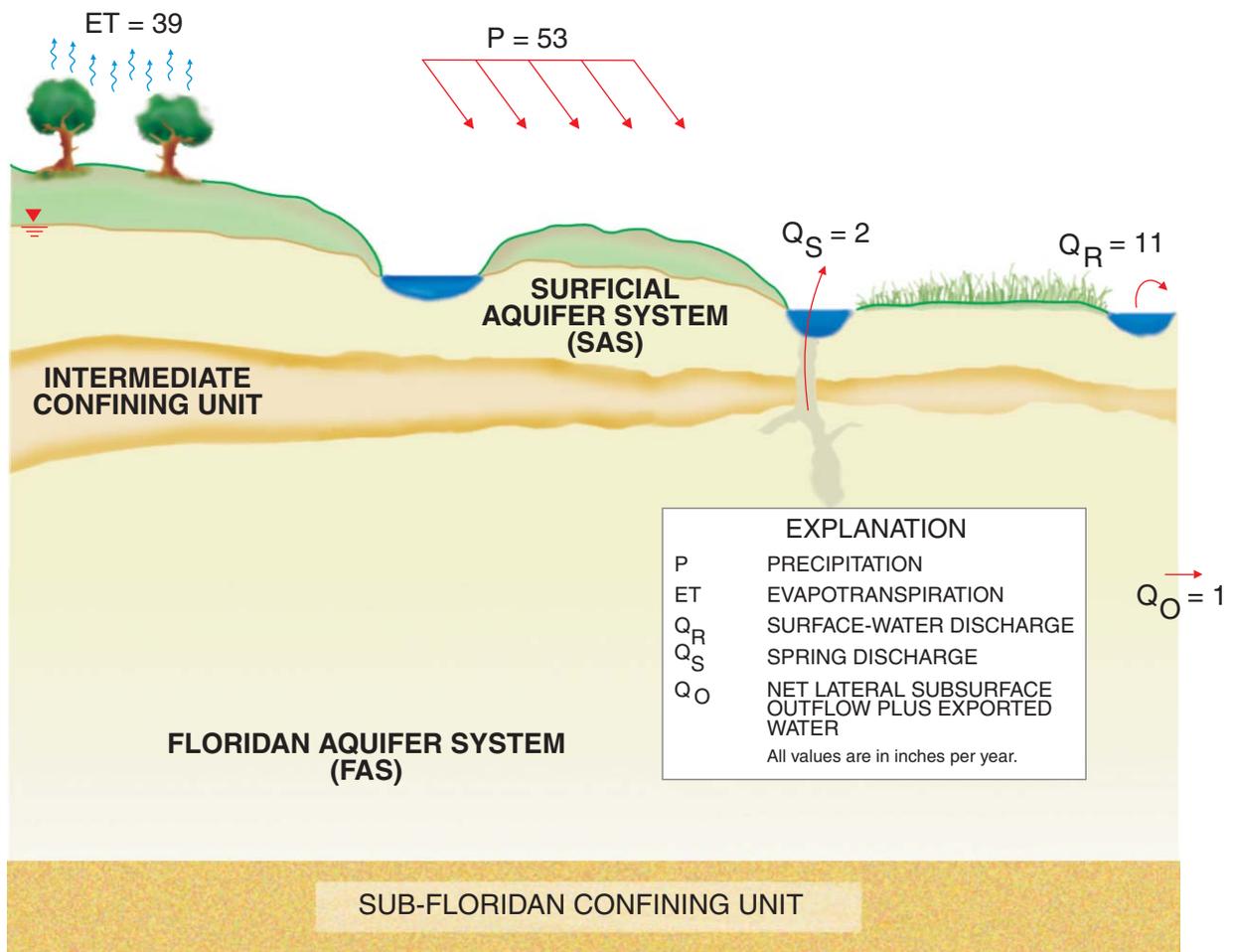


Figure 36. Water budget for Orange County, Florida, 1991-2000.

2000; 1 in/yr of net lateral subsurface outflow plus exported water ( $Q_O$ ), which includes: the net lateral (subsurface) outflow of ground water from the Floridan aquifer system as simulated by a USGS ground-water flow model (Sepúlveda, 2002); potable water pumped from the Cocoa wellfield to Brevard County from 1991 to 2000; and reclaimed water distributed by Water Conserv II for irrigation in Lake County. Net lateral subsurface outflow of water from the surficial aquifer system is assumed to be negligible. Evapotranspiration (ET) was calculated as the residual of equation 2 and accounted for about 39 in/yr of water removed from the system. This back-calculated value of ET is a reasonable estimate for Orange County, because it falls within the range of values documented in previous USGS studies; that is, the value is greater than the 27 in/yr reported for a well-drained, deep water-table ridge site

in western Orange County (Sumner, 1996), but is considerably less than the evaporation rate (56 in/yr) reported by Swancar and others (2000) for a 2-year period (August 1996-July 1998) at Lake Starr in east-central Polk County.

## WATER QUALITY

Ground water is an important resource in Orange County for consumption and recreation. Ground water also is important for aquatic habitat because it discharges into lakes and streams. The quality of ground water in the surficial and Floridan aquifer systems with respect to major ions and nutrients, trace elements, radon and stable isotopes, and pesticides is described in the following sections. Locations of the springs and wells sampled are shown in figure 9.

## Major Ions and Nutrients

Natural waters generally are classified according to the relative concentrations of major ions, also called water type, which can be indicative of the geochemical evolution of the water. Concentrations of major ions (calcium, magnesium, sodium, potassium, bicarbonate, sulfate, and chloride) in ground water generally result from water-rock interactions in the aquifer. Concentrations of major ions in ground water also can be affected by lateral and (or) vertical migration of saline water, such as modern or relict seawater (Hem, 1989). In addition, low concentrations of major ions are present in precipitation. In central Florida, the concentration of chloride in rain generally ranges between 0.5 and 1.0 mg/L (National Atmospheric Deposition Program, 2002). Major ions can be concentrated in ground water through evapotranspiration. Finally, land-use activities can affect concentrations of major ions in ground water. Anthropogenic sources of these constituents include irrigation with water from the Floridan aquifer system and disposal of wastewater (Adamski and Knowles, 2001; Hem, 1989; Sacks and others, 1998).

Concentrations of nutrients (nitrate, nitrite, ammonia, organic nitrogen, and phosphorus) in ground water can be derived from natural or anthropogenic sources. Nitrogen compounds in ground water can originate from decomposition of natural organic matter, but also can result from fertilizers and animal and human wastes (Hem, 1989; Fetter, 1980). Nitrogen oxides occur in precipitation as a result of natural chemical reactions and the combustion of fossil fuels (U.S. Geological Survey, 1999). In central Florida, the concentration of nitrate in rain generally is low, less than 1.0 mg/L (National Atmospheric Deposition Program, 2002). Phosphorus compounds in ground water similarly can originate from natural and anthropogenic sources including phosphatic sediments in the aquifer, fertilizers, and animal and human wastes.

Concentrations of some major ions and nutrients in drinking water can pose health or aesthetic concerns. Concentrations of nitrate greater than 10 mg/L as nitrogen can cause methemoglobinemia in small children (Hem, 1989). Concentrations of chloride greater than about 250 mg/L can impart an objectionable taste to water. High concentrations of sulfate in water can have a laxative effect (Fetter, 1980).

Current and historical data were used to assess the ground-water quality with respect to major ions and nutrients. Data from 34 samples collected from the surficial aquifer system, 62 samples from the Upper Floridan aquifer, and 25 samples from the

Lower Floridan aquifer were used to assess the current water-quality conditions (tables 2 and 6). These samples were collected from 1990 through 2001 by the USGS and SJRWMD. Data from 24 wells and 2 springs were used to assess water-quality trends of the Floridan aquifer system.

## Surficial Aquifer System

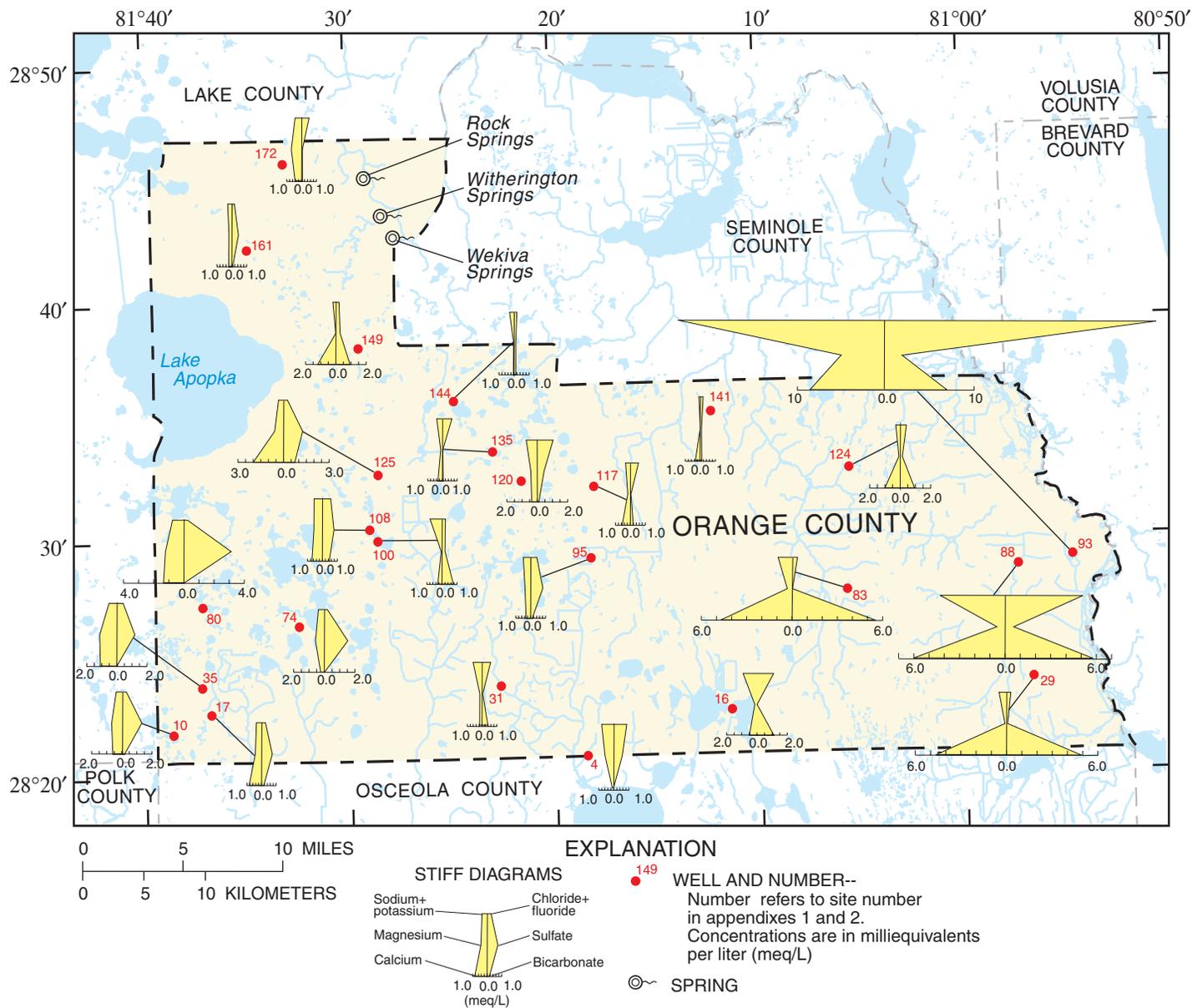
Concentrations of major ions and nutrients in the ground water of the surficial aquifer system are highly variable. This variation probably results from several factors including variability in the lithology of the sediments, interaction with the Upper Floridan aquifer including the upwelling of water with higher dissolved solids concentration, and effects of land use. Water type throughout the surficial aquifer system generally is mixed ion; however, samples from two wells tapping the surficial aquifer system (sites 29 and 83, fig. 37) in southeastern Orange County had calcium-bicarbonate type water, possibly as a result of dissolution of shell material in the aquifer. Water type in the well at site 93 was sodium chloride. Water type in samples from several wells (sites 10, 35, 74, and 80) in southwestern Orange County was calcium sulfate or mixed-cation sulfate (fig. 37).

Median concentrations of TDS, chloride, and sulfate generally were low (less than 250 mg/L for TDS and less than 50 mg/L for chloride and sulfate) in samples from the surficial aquifer system (table 6; figs. 38 and 39), but increased in eastern and southwestern Orange County. TDS concentrations exceeded the National Secondary Drinking Water Regulation (also referred to as secondary standards; U.S. Environmental Protection Agency, 2002) of 500 mg/L in two samples from eastern Orange County and in one sample near Lake Apopka (fig. 38). The secondary standard for chloride (250 mg/L) was exceeded in one sample from a well (site 93) in eastern Orange County (fig. 39). Maximum sulfate concentration in samples from the surficial aquifer system was 150 mg/L (table 6); the secondary standard for sulfate is 250 mg/L. The high TDS (greater than 500 mg/L) and chloride concentrations in eastern Orange (figs. 38 and 39, respectively) correspond with locations where the potentiometric surface of the Upper Floridan aquifer is higher than land surface (fig. 26), resulting in water with high TDS from the Upper Floridan aquifer discharging into the surficial aquifer system. Elevated concentrations of TDS and chloride in other parts of Orange County could result from land-use activities. For example, wells at sites 34 and 35 are adjacent to RIBs, which could be affecting water quality at those sites.

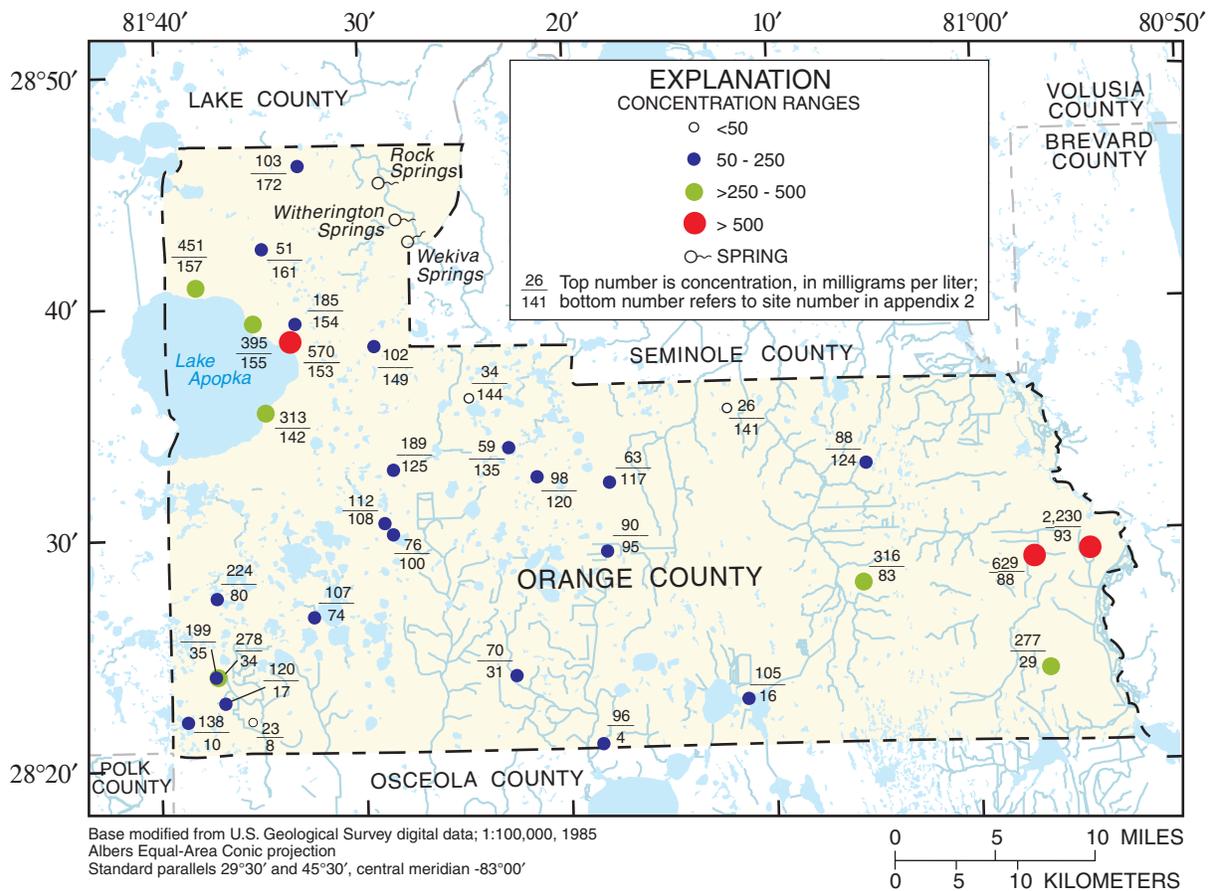
**Table 6.** Summary statistics of water-quality indicators, and major-ion and nutrient constituents in ground-water samples from the surficial and Floridan aquifer systems, 1990 through 2001

[Data source, U.S. Geological Survey and St. Johns River Water Management District; temperature, degrees Celsius (°C); specific conductance, microsiemens per centimeter at 25 °C; ph, standard units; all concentrations in milligrams per liter; No., number; <, less than; --, no data]

Constituent	Surficial aquifer system						Upper Floridan aquifer						Lower Floridan aquifer					
	No. of samples	Minimum	25th percentile	Median	75th percentile	Maximum	No. of samples	Minimum	25th percentile	Median	75th percentile	Maximum	No. of samples	Minimum	25th percentile	Median	75th percentile	Maximum
Temperature	32	20	24	24.6	25.1	28.5	54	22.3	23.8	24.2	24.7	29.8	24	24	24.6	25.2	26.7	28.8
Specific conductance	34	50	135	215	468	3,860	55	125	318	580	1,150	4,080	25	207	258	286	2,030	46,000
Dissolved oxygen	22	<.1	<.1	<.1	.7	6.7	28	<.1	<.1	<.1	<.1	.2	8	<.1	<.1	<.1	<.1	<.1
pH	33	3.9	5.4	5.9	6.8	9.9	52	5.1	7.5	7.7	7.8	8.3	23	7.3	7.7	7.8	7.9	8.1
Calcium	33	.9	6.1	19	49	170	48	6.0	43	77	110	180	24	26	33	39	133	678
Magnesium	33	.2	1.8	6.1	10	60	48	3.4	6.8	12	25	67	24	6.8	8.1	8.6	25	1,050
Sodium	33	1.9	5.1	8.4	18	540	48	3.8	8.4	28	110	610	24	3.8	5.6	7.1	105	9,300
Potassium	33	<.1	.9	2.3	9.8	26	48	.6	1.3	1.9	3.4	18	24	.6	.9	1.0	3.3	345
Bicarbonate	28	<1	7	18	58	455	48	7.3	133	180	259	400	25	49	129	142	150	321
Sulfate	32	<.2	3.8	17	36	150	56	<.2	14	44	150	300	25	1.7	5.5	14	440	3,700
Chloride	34	5	8.1	14	29	1,100	56	5.9	11	37	200	1,100	25	6.0	8.5	11	370	22,300
Fluoride	32	<.1	<.1	<.1	.22	1.0	48	<.1	.1	.2	.3	.8	25	<.1	.1	.2	.2	3.6
Bromide	25	<.05	<.05	.05	.08	3.2	31	<.05	<.05	.1	.7	17	22	<.05	<.05	<.05	.09	22
Silica	30	.7	4.9	8.9	11	39	48	1.5	10	14	21	31	24	1.3	9.7	11	12	25
Total dissolved solids	33	24	88	112	277	2,230	56	45	168	338	537	2,290	25	117	137	154	1,390	28,800
Nitrite plus nitrate, as nitrogen	32	<.02	<.02	.02	3.5	20	34	<.02	<.02	<.02	<.02	2	8	<.02	<.02	<.02	<.02	<.02
Nitrite, as nitrogen	26	<.01	<.01	<.01	<.01	.02	32	<.01	<.01	<.01	<.01	.01	8	<.01	<.01	<.01	<.01	.01
Ammonia, as nitrogen, dissolved	30	<.01	.02	.2	.41	6.2	32	<.01	.1	.3	.5	.8	8	.1	.2	.3	.4	.5
Ammonia plus organic nitrogen, as nitrogen, total	0	--	--	--	--	--	6	<.2	<.2	<.2	<.2	.4	0	--	--	--	--	--
Ammonia plus organic nitrogen, as nitrogen, dissolved	28	<.2	<.2	.3	.6	7.3	26	<.2	<.2	.3	.6	1	8	<.2	<.2	.3	.3	.6
Phosphorus, total	0	--	--	--	--	--	8	<.02	.03	.04	.09	.35	0	--	--	--	--	--
Phosphorus, dissolved	28	<.02	<.02	.04	.08	1.5	32	<.02	<.02	.05	.1	.34	8	.04	.05	.05	.05	.07
Phosphate, as phosphorus, dissolved	28	<.01	<.01	.03	.07	1.4	33	<.02	.02	.03	.08	.3	8	.03	.04	.05	.05	.05
Organic carbon, total	28	<.1	1.8	3.3	11	26	25	.6	1.2	2	3.3	11	8	.6	1.3	1.8	1.9	2.7



**Figure 37.** Concentrations of major cations and anions in water samples collected from wells tapping the surficial aquifer system, 1992 through 2001.



**Figure 38.** Concentrations of total dissolved solids in water samples collected from wells tapping the surficial aquifer system, 1990 through 2001.

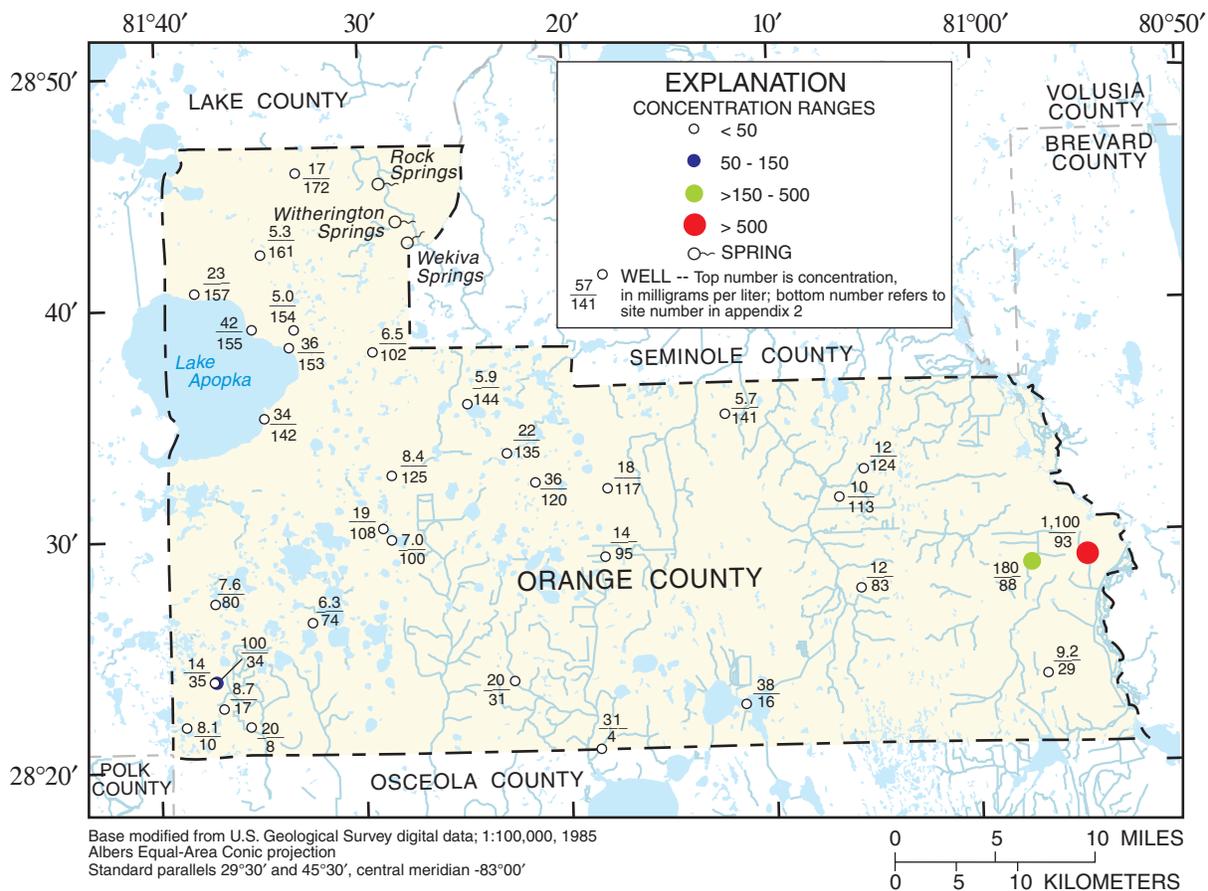
Concentrations of nutrients in the surficial aquifer system typically were low. About half of the samples had nitrate concentrations less than or equal to the method reporting limit of 0.02 mg/L as nitrogen; about half the samples had ammonia, ammonia plus organic nitrogen, phosphorus, and phosphate concentrations less than or equal to 0.2, 0.3, 0.04, and 0.03 mg/L, respectively (table 6; figs. 40 and 41).

Locally, the concentrations of nutrients in ground water from the surficial aquifer system can be much greater, possibly as a result of natural conditions and (or) land-use activities. One sample (site 35, fig. 9) had a nitrate concentration of 20 mg/L as nitrogen (table 6), exceeding the National Primary Drinking Water Regulation or MCL of 10 mg/L as nitrogen (U.S. Environmental Protection Agency, 2002). This well, located adjacent to a RIB, has a depth of 35 ft and a casing length of 33 ft. One sample (site 172) had a nitrate concentration of 10 mg/L (fig. 41). This well, completed in clean, sandy soil just downgradient from a citrus grove, had a depth of 74 ft and a casing length of 54 ft.

In addition, concentrations of nitrate exceeded 3.0 mg/L in samples from two wells near Lake Apopka (sites 142 and 154), one well in western Orlando (site 125), and four wells in southwestern Orange County (sites 10, 17, 35, and 80).

Elevated concentrations of nitrate indicate contamination of ground water, possibly from land-use practices such as using lawn fertilizers and septic systems. Concentrations of nitrate in ground water underlying pristine areas generally are low, indicating that natural sources of nitrate do not contribute significantly to concentrations in ground water in central Florida. For example, nitrate concentrations in 14 of 15 samples from the surficial aquifer system underlying the nearby Ocala National Forest (fig. 1) were less than 1.0 mg/L (Adamski and Knowles, 2001).

Three samples from the surficial aquifer system had ammonia concentrations greater than 1.0 mg/L (sites 153, 155, and 157, fig. 9), and five samples had ammonia plus organic nitrogen concentrations greater than 1.0 mg/L (sites 88, 93, 108, 154, and 157). Four



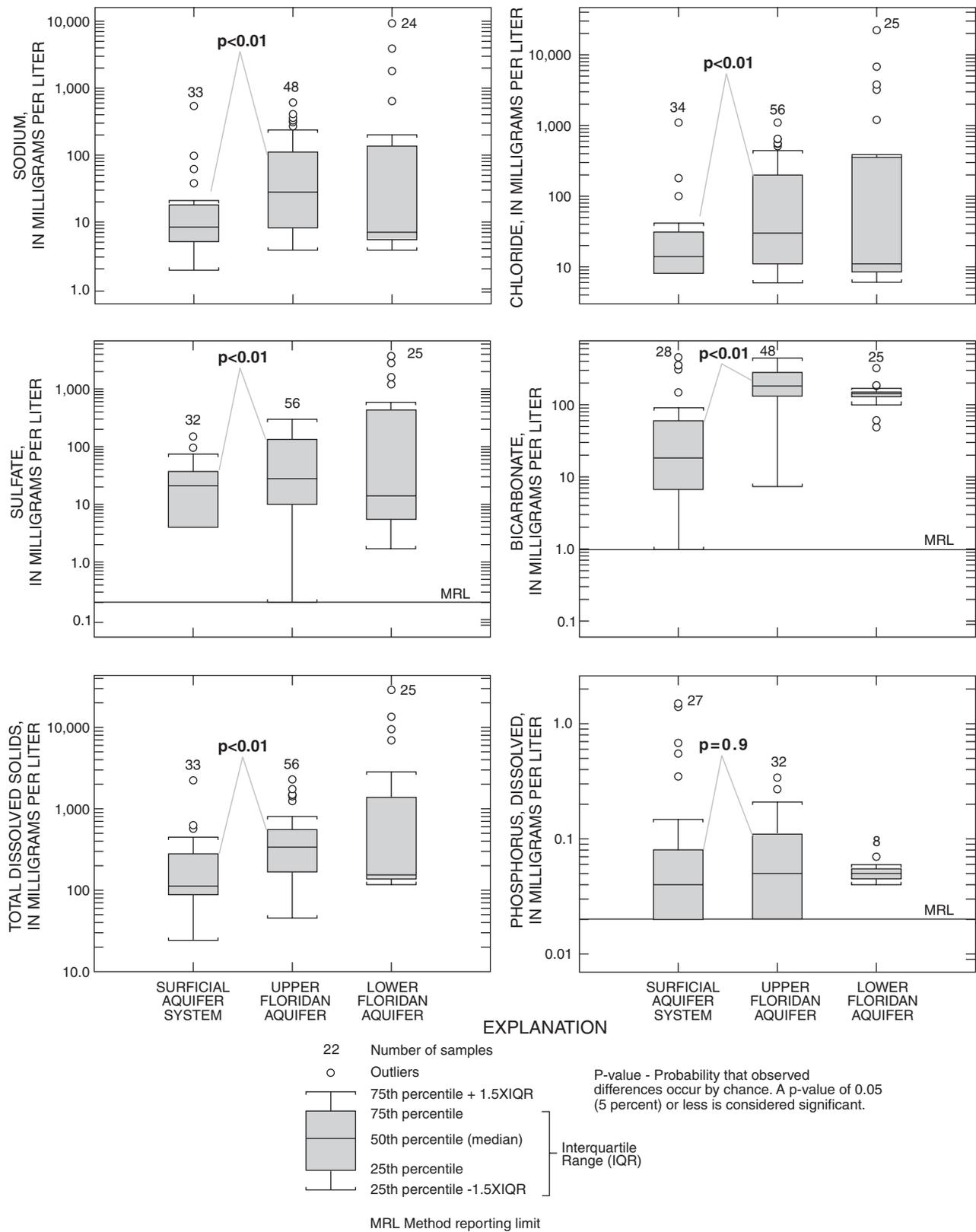
**Figure 39.** Concentrations of chloride in water samples collected from wells tapping the surficial aquifer system, 1990 through 2001.

of the wells are near the northern edge of Lake Apopka, near areas of former row-crop agriculture. The ammonia and organic nitrogen in the ground water at these locations possibly result from the long-term use of fertilizers on crops such as corn. Ammonia and organic nitrogen also could result from decomposition of natural organic material in the soils. Two of the wells are in the Tosohatchee State Reserve (fig. 1), a relatively pristine area. The ammonia plus organic nitrogen in these samples most likely are from organic-rich soils and decay of leaf litter.

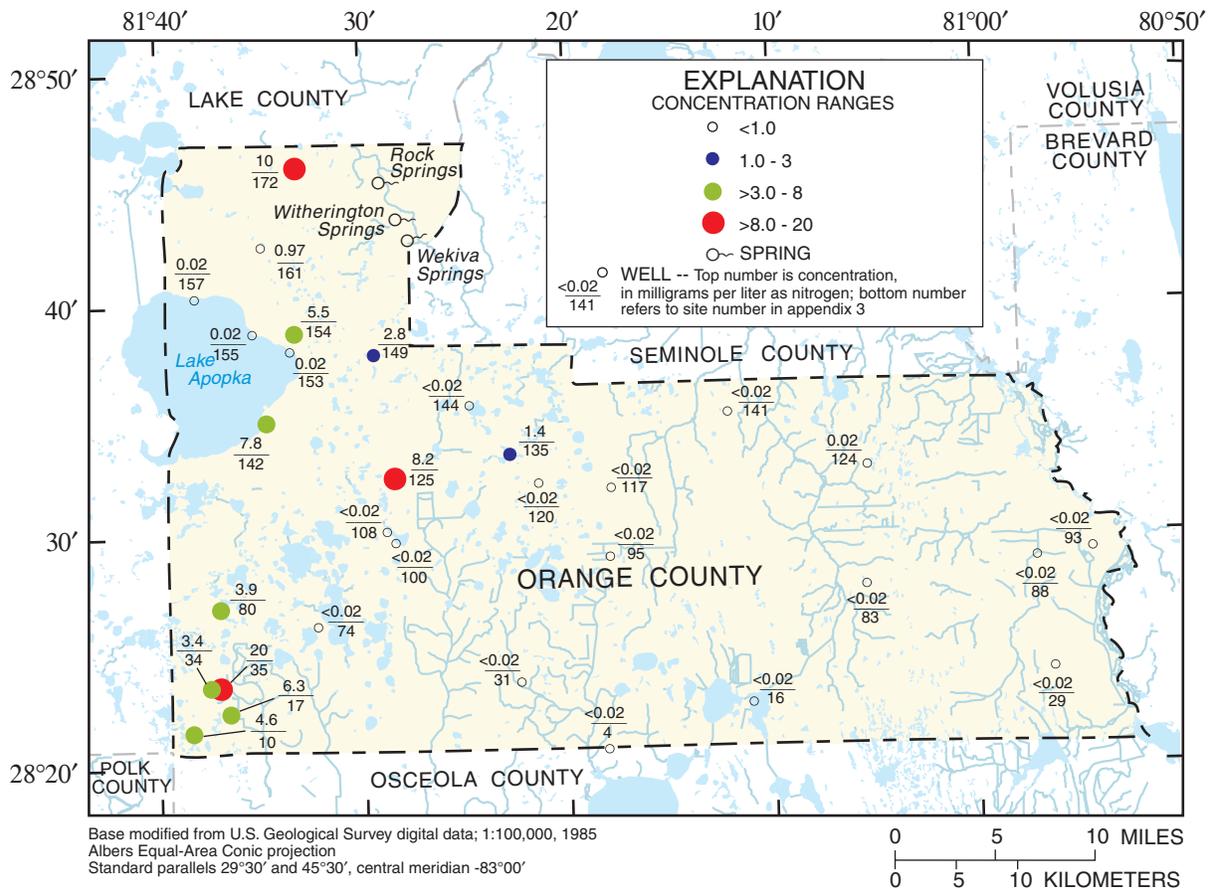
A total of seven samples had phosphorus and (or) phosphate concentrations greater than or equal to 0.1 mg/L as phosphorus. Two of the samples were from wells in the city of Orlando (sites 117 and 120, fig. 9), one sample was from a well located adjacent to a RIB (site 35), and four samples were from wells near Lake Apopka (sites 142, 153, 155, and 157). As with ammonia plus organic nitrogen, the potential sources of phosphorus in ground water could be natural (phosphatic sediments in the aquifer) or from local land use. During drilling of the two wells in the city of Orlando, cuttings

indicated no phosphatic sediments at one site (site 120), and phosphatic sediments at a depth of 44 ft at the second site (site 117). The borehole at the second site was backfilled and the final depth was only 35 ft. The source of phosphorus in ground water from these two wells probably is related to local land use, such as fertilizing residential lawns and gardens.

The maximum concentration of phosphorus is not regulated in drinking water; however, elevated concentrations of phosphorus in surface water can cause excessive growth of algae and cyanobacteria. Water samples from lakes in Orange County that had concentrations of phosphorus greater than 0.1 mg/L also had concentrations of chlorophyll-*a*, an indicator of the amount of algae and cyanobacteria in a water body, greater than 10 µg/L (E.R. German, U.S. Geological Survey, written commun., 2003). The concentration of phosphorus in the surficial aquifer system can have important consequences to algal growth in lakes because ground water from the surficial aquifer system discharges into lakes and streams.



**Figure 40.** Distribution of sodium, chloride, sulfate, bicarbonate, total dissolved solids, and phosphorus in water samples from the surficial aquifer system, the Upper Floridan aquifer, and the Lower Floridan aquifer, 1990 through 2001.



**Figure 41.** Concentrations of nitrite plus nitrate in water samples collected from wells tapping the surficial aquifer system, 1990 through 2001.

### Floridan Aquifer System

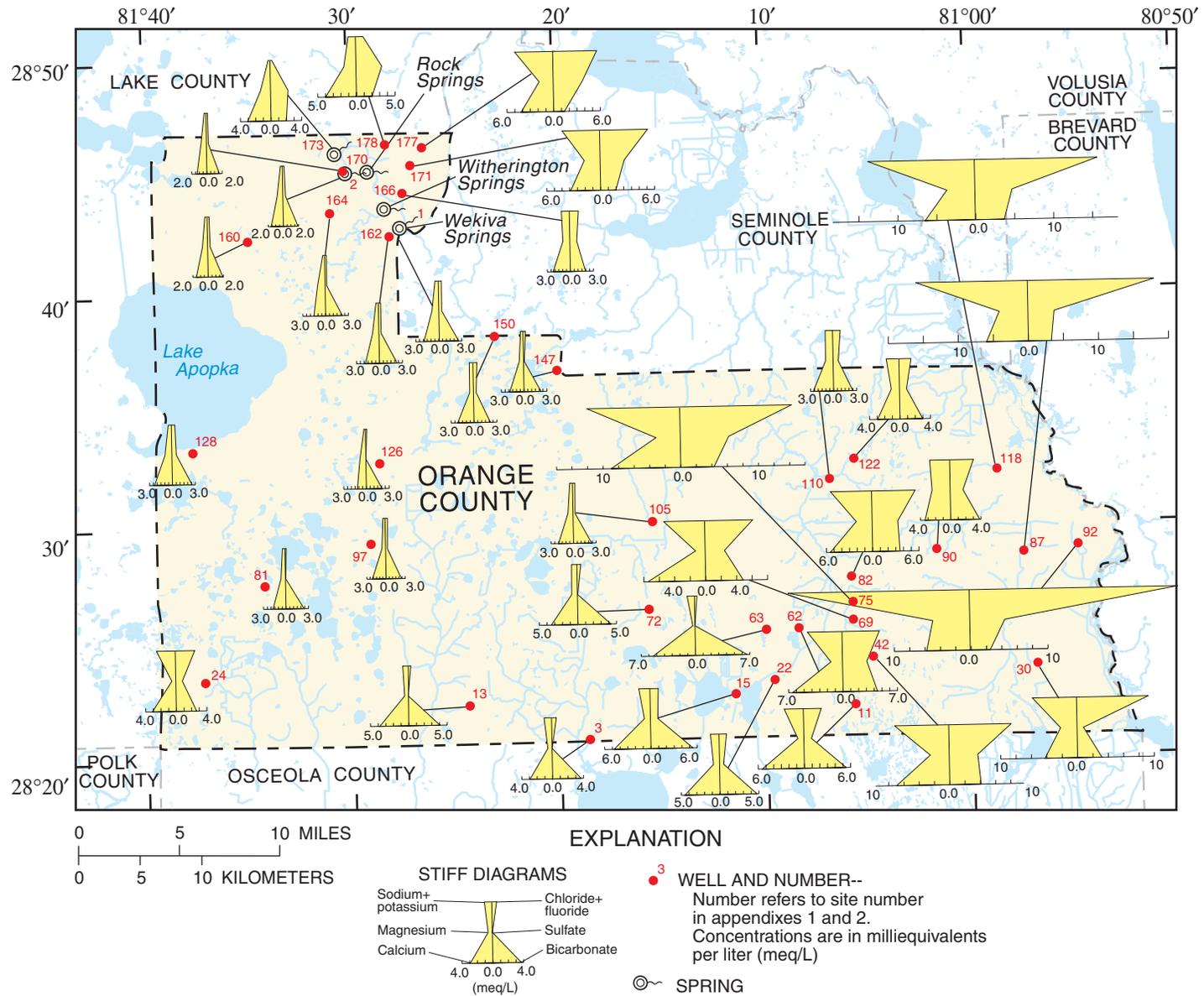
Water type in the Upper Floridan (fig. 42) and Lower Floridan aquifers throughout much of Orange County is calcium or calcium-magnesium bicarbonate as a result of the dissolution of limestone and dolomite. The lithology of the aquifer systems affects the concentrations of these constituents. Whereas the surficial aquifer system primarily is composed of relatively inert quartz sand, the Floridan aquifer system is composed of more soluble carbonate rocks (limestone and dolomite). Dissolution of calcium carbonate in these rocks by slightly acidic water (carbonic acid) results in an increase in the concentration of calcium and bicarbonate in the water by the following reaction (Drever, 1988):



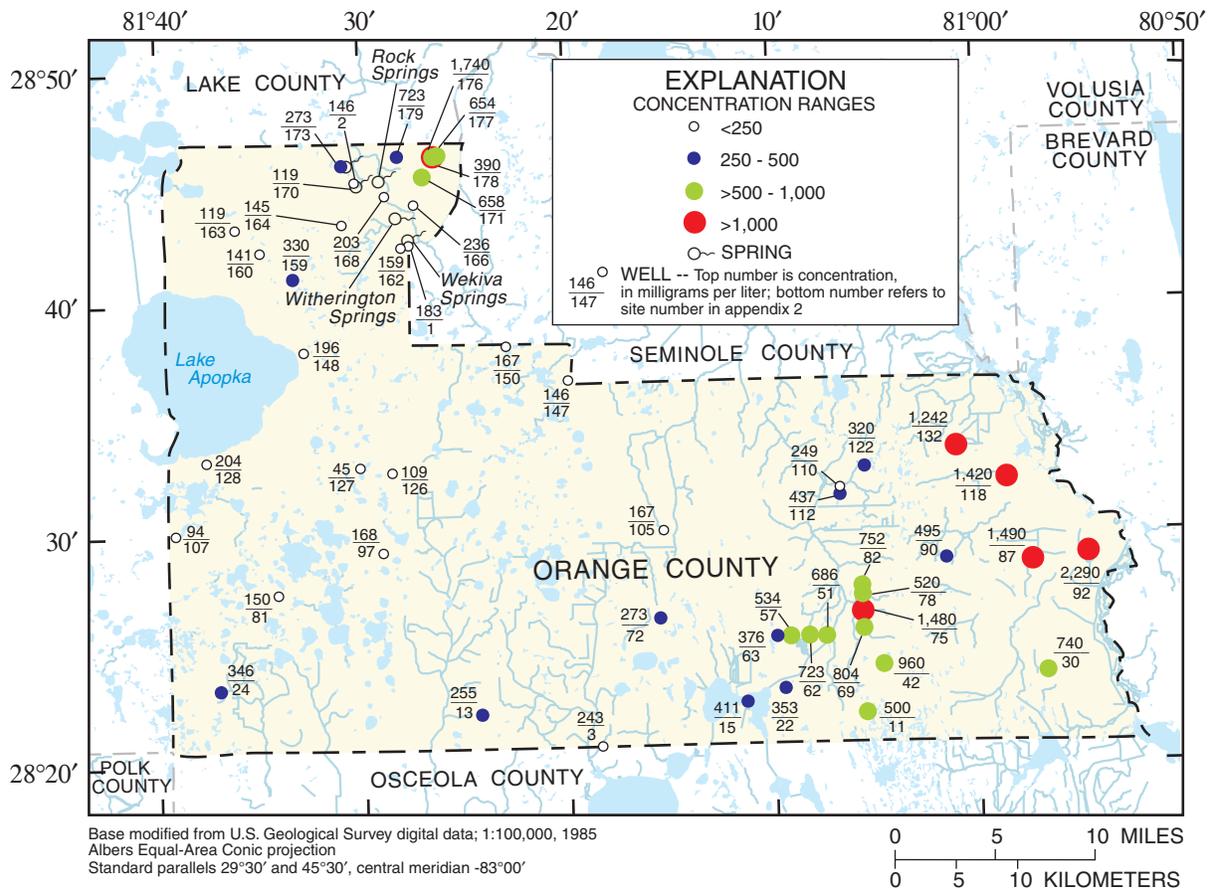
Concentrations of major ions and TDS typically were higher in samples from the Upper Floridan aquifer than in samples from the surficial aquifer system (table 6; fig. 40). Statistical analysis

using the Kruskal-Wallis test indicates that median concentrations of calcium, magnesium, sodium, bicarbonate, chloride, and TDS were significantly different ( $p < 0.05$ ) in samples from the surficial aquifer system than in samples from the Upper Floridan aquifer. The range of selected constituents is shown in figure 40. Statistical comparison of water quality from the Lower Floridan aquifer is difficult because of the limited available data.

Water type in the Upper Floridan aquifer in about the eastern one-third of Orange County is sodium chloride (fig. 42). Concentrations of TDS, chloride, and sulfate generally are low (less than 500 mg/L for TDS and less than 50 mg/L for chloride and sulfate) throughout the Upper Floridan aquifer in Orange County (figs. 43 through 45). Concentrations of TDS, chloride, and sulfate increase toward eastern and southeastern Orange County, and in northwestern Orange County near Rock Springs (figs. 43 through 45). In addition, the well at site 24 had relatively high concentrations of TDS, chloride, and sulfate. In the Upper



**Figure 42.** Concentrations of major cations and anions in water samples collected from springs and wells tapping the Upper Floridan aquifer, 1995 through 2001.

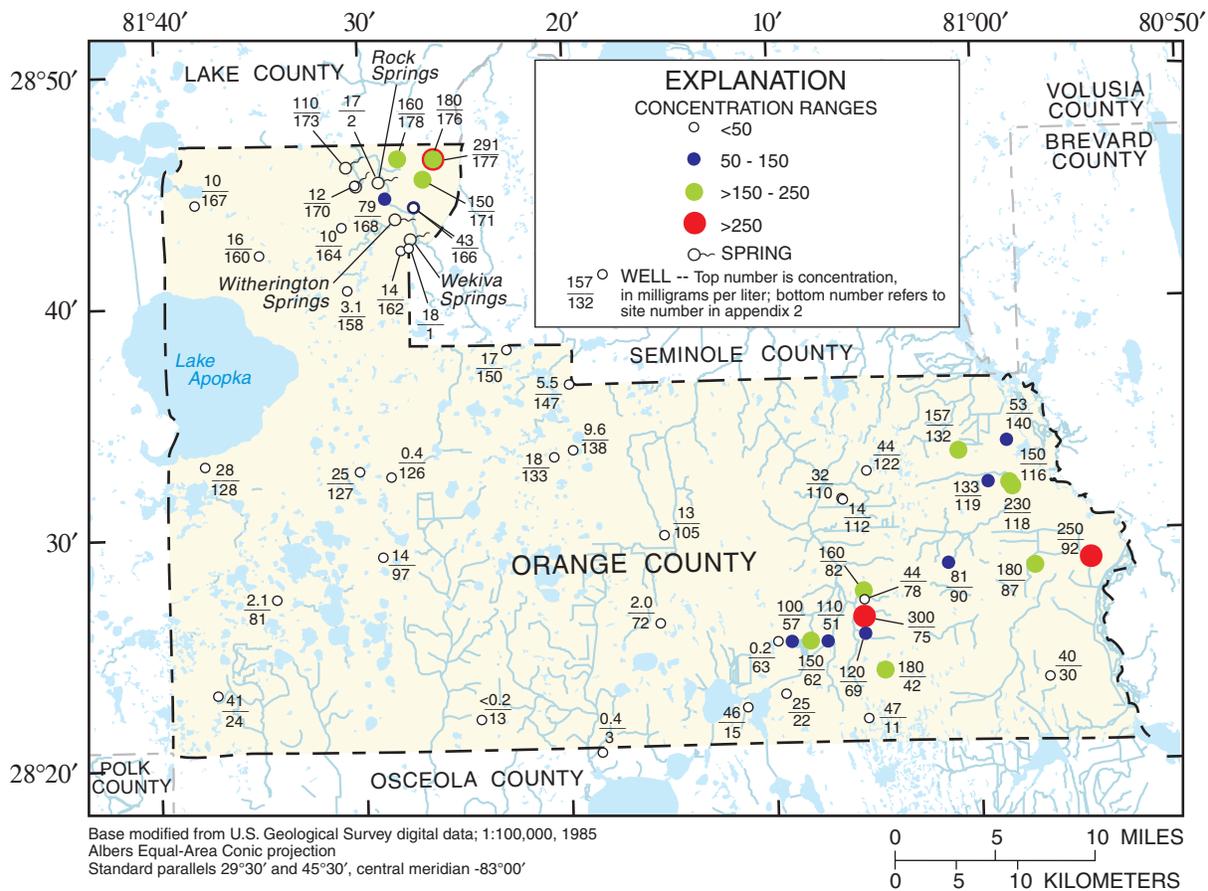


**Figure 43.** Concentrations of total dissolved solids in water samples collected from springs and wells tapping the Upper Floridan aquifer, 1990 through 2001.

Floridan aquifer, sulfate concentrations exceeded the secondary standard of 250 mg/L in 2 of 48 samples, chloride concentrations exceeded the secondary standard of 250 mg/L in 8 of 48 samples, and TDS concentrations exceeded the secondary standard of 500 mg/L in 15 of 56 samples. In the Lower Floridan aquifer, sulfate and chloride concentrations exceeded the secondary standards in 7 of 25 samples, and TDS concentrations exceeded the secondary standard in 8 of 25 samples. The distribution of sample locations, however, is much more limited for wells tapping the Lower Floridan aquifer (fig. 9); hence, these data may not accurately represent the water quality of the entire Lower Floridan aquifer throughout Orange County. A detailed discussion of the water quality of the Lower Floridan aquifer also is available in O'Reilly and others (2002).

At several locations in Orange County, samples from the Upper Floridan aquifer had mixed-ion or sodium-chloride type water and high concentrations of TDS. In eastern Orange County, samples from several

wells had sodium-chloride water type and concentrations of TDS greater than 1,000 mg/L (figs. 42 and 43, respectively). These wells coincide with an area where the potentiometric surface of the Upper Floridan aquifer is higher than land surface, indicating an area of possible discharge from the Upper Floridan aquifer and an upwelling of deeper ground water, possibly relict seawater. Similarly, in northwestern Orange County, near Rock Springs and along the Wekiva River, water type in the Upper Floridan aquifer is mixed ion and concentrations of TDS are greater than 500 mg/L. This also is an area of discharge from the Upper Floridan aquifer, as evidenced by the presence of Rock, Wekiva, and Witherington Springs, and could allow upwelling of deeper water, probably from the Lower Floridan aquifer, with higher concentrations of TDS. No wells tap the Lower Floridan aquifer at these two locations, so differences in water levels and water quality between the Upper and Lower Floridan aquifers cannot be quantified to confirm upwelling as a cause for the observed differences.



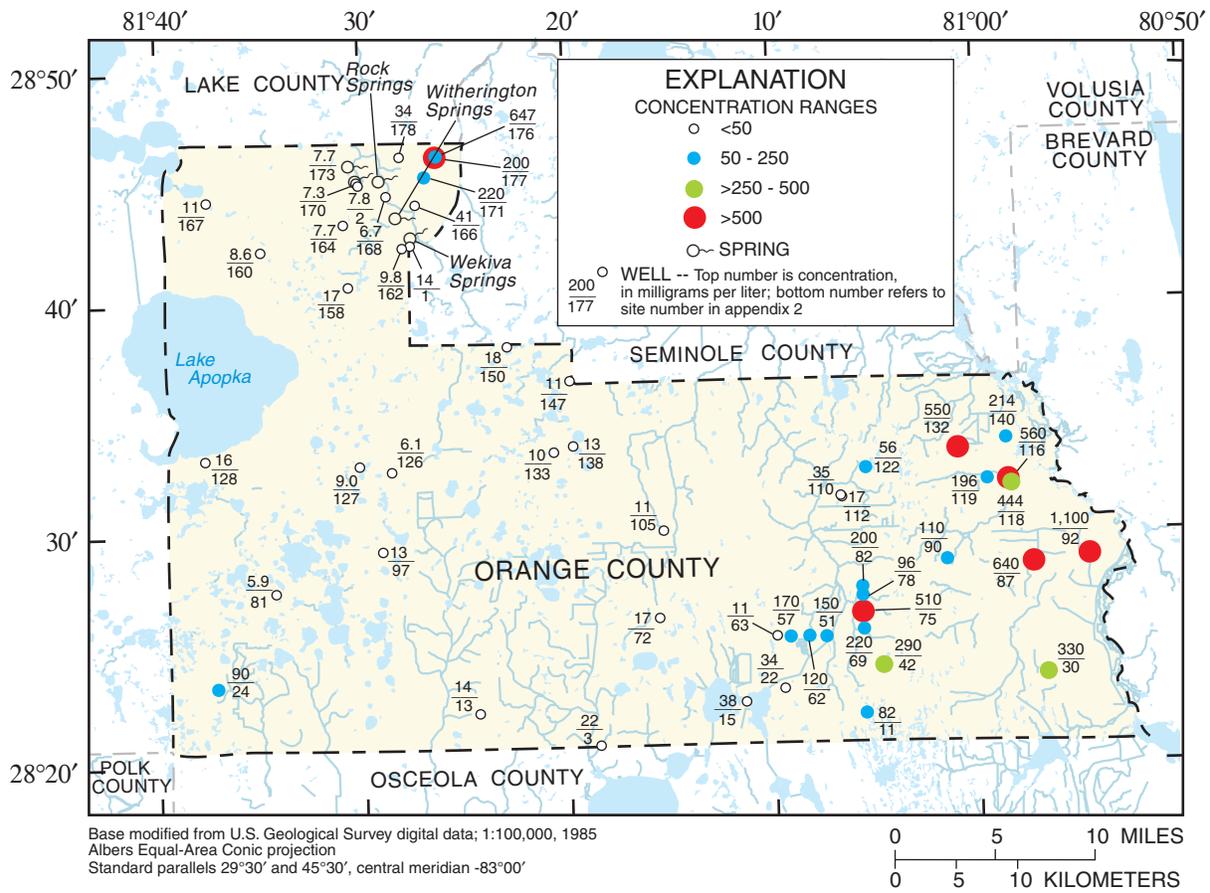
**Figure 44.** Concentrations of sulfate in water samples collected from springs and wells tapping the Upper Floridan aquifer, 1990 through 2001.

Water from many of the wells in and around the Cocoa well field in southeastern Orange County is sodium-chloride type with concentrations of TDS greater than 500 mg/L. Samples from two wells had TDS concentrations of 960 and more than 1,400 mg/L (fig. 43). The water quality of the Upper Floridan aquifer in this area probably is affected by pumping of the well field, causing the upwelling of deeper, saline water, possibly relict seawater. The migration of this water probably is vertical, rather than horizontal, through conduits and fractures in the aquifer. The majority of affected wells are aligned in a north-south orientation. A sample from a well east of the well field had a TDS concentration of 740 mg/L (fig. 43).

Constituent concentrations in samples from an observation well (site 24) in southwestern Orange County could indicate that reclaimed water from nearby RIBs is infiltrating into the Upper Floridan aquifer. Concentrations of sodium, chloride, and sulfate are relatively high (53, 90, and 41 mg/L, respectively)

and are in the range of concentrations for reclaimed water (table 7; Sumner and Bradner, 1996). As noted previously, water levels in this well have increased in response to the mounding of water beneath the RIBs. A sample collected from this well in 1979 prior to the installation of the RIBs had concentrations of chloride and sulfate of 4.0 and 28 mg/L, respectively (table 7). Hence, the concentrations of chloride and sulfate apparently have increased over time, probably as a result of infiltration of reclaimed water from the RIBs.

Changes in water quality of the Floridan aquifer system with respect to concentrations of major ions were assessed two ways. First, the historical areal (1960 through 1969) distribution of chloride concentrations (fig. 46) was compared to recent (1990 through 2001) distribution of chloride concentrations (fig. 45). A limitation to this method is that few wells were sampled both during the 1960s and the recent period. Many wells sampled in the 1960s have been abandoned or destroyed and other wells have been drilled. For a more



**Figure 45.** Concentrations of chloride in water samples collected from springs and wells tapping the Upper Floridan aquifer, 1990 through 2001

**Table 7.** Comparison of historical (1979) and recent (1999) water-quality data for site 24 with the range of quality of reclaimed water discharged to rapid infiltration basins in southwestern Orange County

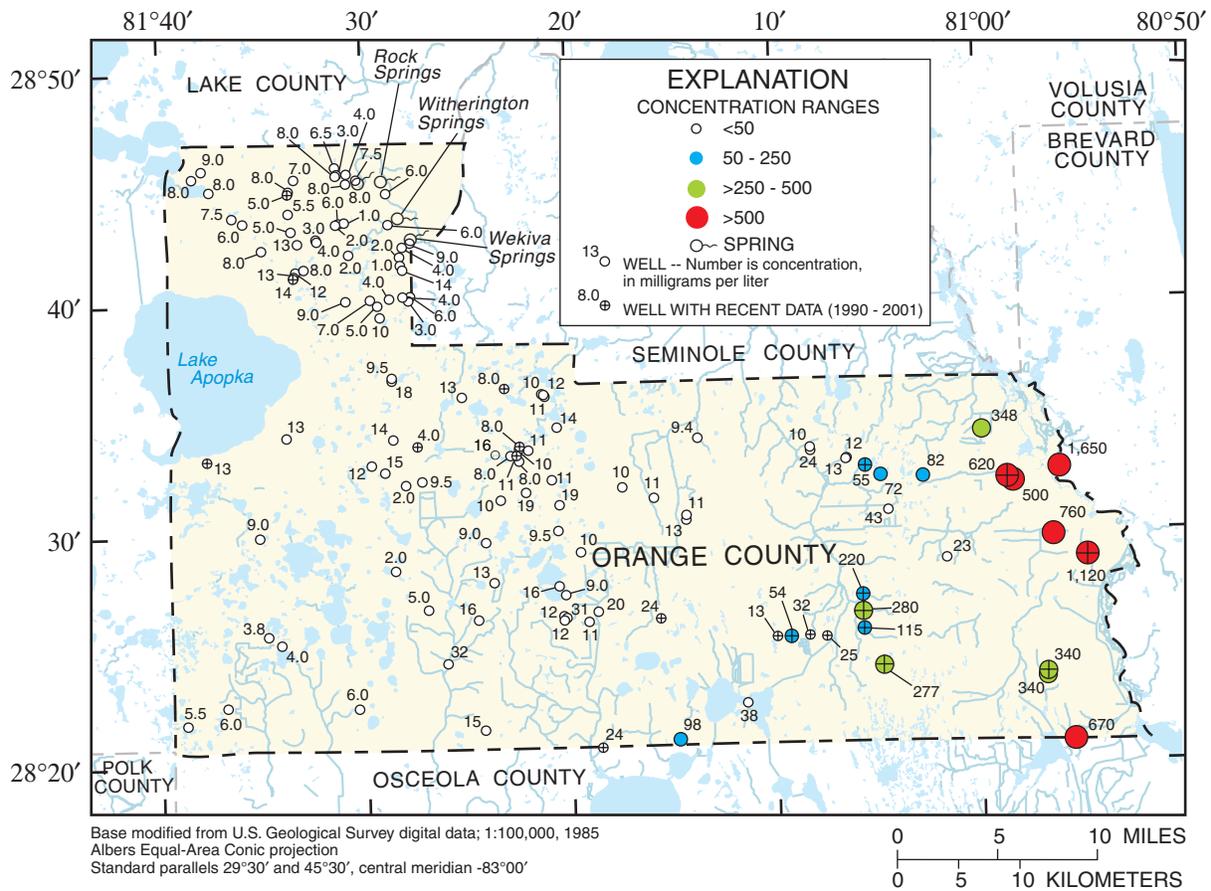
[All values in milligrams per liter, except specific conductance in microsiemens per centimeter at 25 °C, and pH in standard units; --, no data. Site 24 refers to figure 9 and appendix 2]

Constituent	Site 24		Reclaimed water <sup>a</sup>
	March 26, 1979	July 12, 1999	
Specific conductance	258	645	480 -550
pH	7.9	7.4	5.9 - 8.2
Calcium	37	63	25 - 35
Magnesium	4.7	6.3	5.0 - 10
Sodium	3.8	53	45 - 80
Bicarbonate	--	172	52 -150
Sulfate	28	41	--
Chloride	4	90	60 -155

<sup>a</sup>Data from Sumner and Bradner, 1996.

accurate assessment of changes in ground-water quality, data from the same sites should be compared. Second, wells with long-term data were analyzed for trends in water quality. Wells with long-term water-quality data primarily are located in and around the Cocoa well field; hence, areas in other parts of Orange County are not well represented with long-term data sites.

A comparison of historical (fig. 46) and recent (fig. 45) chloride concentrations indicates that concentrations in the Upper Floridan aquifer throughout most of Orange County do not appear to have changed significantly. For example, samples from two wells in eastern Orange County (sites 92 and 116) had chloride concentrations of 1,120 and 620 mg/L in the 1960s and 1,100 and 560 mg/L in recent years (figs. 45 and 46). Samples from central, western, and northwestern Orange County also have similar chloride concentrations in the 1960s and in recent years. Historic and recent samples from the same wells in southwestern Orange County are not available, and, therefore,



**Figure 46.** Concentrations of chloride in water samples collected from springs and wells tapping the Upper Floridan aquifer, 1960 through 1969.

changes are difficult to assess. Nonetheless, chloride concentrations in samples collected recently in southwestern Orange County generally are within the range of concentrations in samples collected in the 1960s. In southeastern Orange County, however, chloride concentrations apparently have increased, especially in the vicinity of the Cocoa well field. For example, chloride concentration at the well at site 75 increased from 280 mg/L in 1966 to 510 mg/L in 1999 (figs. 45 and 46).

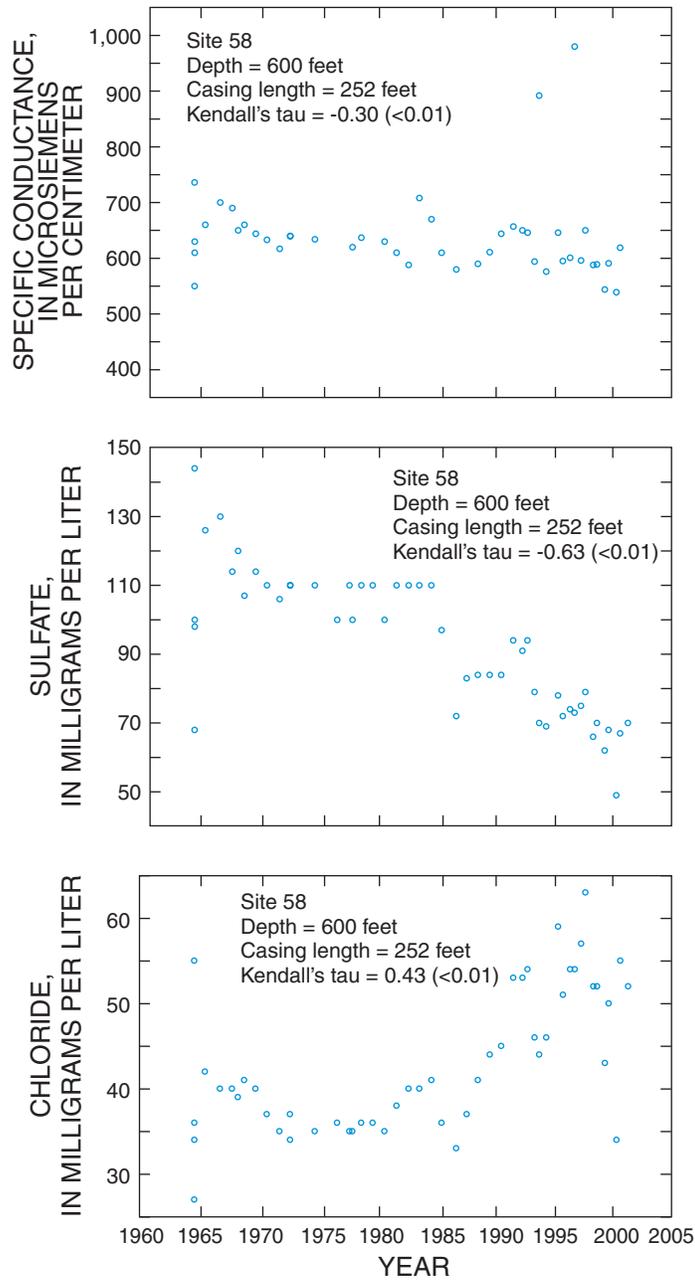
Long-term data were analyzed to determine if the increase in chloride concentrations were statistically significant. A total of 24 wells, each of which had more than 20 samples collected during at least a 20-year period, was included in the trend analysis (table 8). Four of the wells are nested in a single borehole (sites 64 through 67). All of the wells are in eastern Orange County, and all but two of the wells are in and around the Cocoa well field. Two wells (sites 64 and 65) exclusively tap the Lower Floridan aquifer, 1 well taps the middle semiconfining unit (site 66),

1 well is open to the Upper Floridan aquifer and the middle semiconfining unit (site 67), and the remaining 20 wells tap the Upper Floridan aquifer. In addition, the long-term data are limited primarily to major-ion concentrations; trend analysis was limited to specific conductance, chloride, and sulfate. Data from 14 wells indicated a statistically significant increase in specific conductance, whereas data from 2 wells indicated a decrease in specific conductance over time. Data from 16 of the wells indicated a statistically significant increase in chloride concentrations during the period of record, whereas data from 2 of the wells indicated a decrease in chloride concentrations during the period of record. Data from 13 wells indicated a statistically significant increase in sulfate concentrations, whereas data from 5 wells indicated a decrease in sulfate concentrations over time (table 8). In one well (site 58), sulfate concentration decreased while chloride concentration increased (table 8; fig. 47).

**Table 8.** Evaluation of trends in specific conductance, chloride, and sulfate for wells having 20 or more years of record

[Site numbers refer to appendixes 1 and 2. Kendall's tau values shown in boldface were statistically significant at the 0.05 significance level. Well depth, in feet below land surface;  $\mu\text{S}/\text{cm}$ , microsiemens per centimeter at 25 °C; mg/L, milligrams per liter; <, less than]

Site number	Site identifier	Well depth	Period of record	Kendall's tau		
				Specific conductance ( $\mu\text{S}/\text{cm}$ )	Chloride (mg/L)	Sulfate (mg/L)
28	282344081054201	580	1962 - 2001	<b>0.73</b>	<b>0.77</b>	<b>0.74</b>
37	282404081050501	519	1962 - 2000	.11	.05	.12
38	282405081053002	527	1972 - 2001	<b>.59</b>	<b>.67</b>	<b>.7</b>
42	282412081044701	600	1963 - 2000	.23	<b>.3</b>	<b>.39</b>
43	282416081054101	524	1964 - 2001	-.13	.04	<b>-.26</b>
51	282529081073201	710	1962 - 2001	<b>.49</b>	<b>.58</b>	<b>.56</b>
52	282530081054201	490	1957 - 2000	-.19	-.23	<b>-.32</b>
56	282530081084501	702	1965 - 2000	<b>.59</b>	<b>.54</b>	<b>.32</b>
57	282830081091701	600	1964 - 2001	<b>.24</b>	<b>.35</b>	<b>-.32</b>
58	282530081094001	600	1964 - 2001	<b>-.30</b>	<b>.43</b>	<b>-.63</b>
60	282531081075601	509	1963 - 2001	<b>.85</b>	<b>.88</b>	<b>.78</b>
62	282531081082201	761	1966 - 2001	<b>.75</b>	<b>.86</b>	<b>.79</b>
64	282533081082202	1,360	1966 - 2001	<b>.77</b>	<b>.89</b>	<b>.77</b>
65	282533081082204	1,220	1966 - 2001	<b>.13</b>	-.04	<b>.29</b>
66	282533081082205	1,050	1966 - 2001	<b>-.10</b>	<b>-.4</b>	<b>-.31</b>
67	282533081082206	1,000	1966 - 2000	<b>.46</b>	<b>.62</b>	<b>.45</b>
69	282548081054201	496	1957 - 2001	.08	.07	.02
71	282612081054201	617	1966 - 2001	<b>.26</b>	<b>.27</b>	<b>.26</b>
75	282632081054501	640	1966 - 2000	<b>.53</b>	<b>.54</b>	<b>.48</b>
76	282650081054201	525	1957 - 2001	.23	<b>.24</b>	<b>.24</b>
78	282716081054501	506	1964 - 2001	-.07	-.16	-.17
90	282847081013701	495	1961 - 2001	<b>.37</b>	<b>.33</b>	.13
118	283214080583501	200	1953 - 1999	-.28	<b>-.36</b>	-.27
122	283249081053201	492	1960 - 2000	<b>.34</b>	<b>.3</b>	-.07



**EXPLANATION**

(<0.01) Number in parenthesis is p-value, or probability that trend occurs by chance. A probability less than 5 percent (<0.05) is considered significant

**Figure 47.** Changes in specific conductance and in concentrations of sulfate and chloride in well at site 58 tapping the Upper Floridan aquifer (site number refers to figure 9 and appendix 1).

Twelve of the wells with increasing chloride concentrations are in or in close proximity to the Cocoa well field, indicating that pumping from the well field probably is causing upwelling of deeper, more saline water (Phelps and Schiffer, 1996). The water apparently is migrating preferentially through conduits and fractures in the rock. Data from the four zones at the nested well (sites 64 through 67) illustrate this preferential movement. The increase in chloride concentrations is evident in samples from the shallow (site 67) and deep wells (site 64), but not from the intermediate wells (table 8; fig. 48).

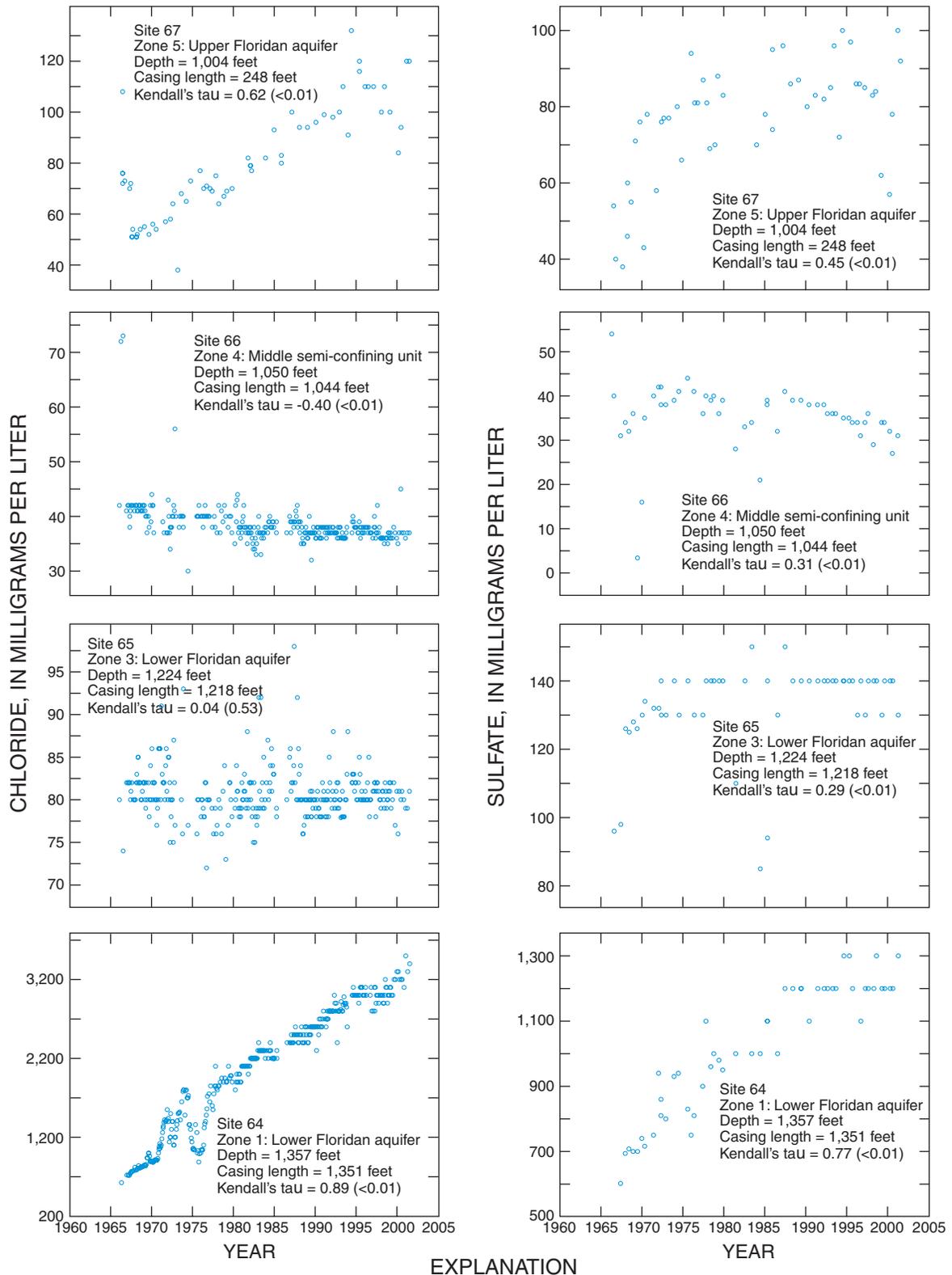
Limited historical data also are available for Wekiva Springs and Rock Springs. Data are limited primarily to specific conductance and concentrations of sulfate and chloride. Values of specific conductance, and probably TDS, have increased in samples from both springs since about the mid-1960s (fig. 49). These results are in agreement with previous studies (Murray and Halford, 1996). Discharge at both springs (fig. 35) and water levels in an observation well (site 170, fig. 9) that taps the Upper Floridan aquifer near Rock Springs have declined over the same period of time (Kendall's  $\tau = -0.21$ ,  $p < 0.01$ ). The increase in specific conductance at Wekiva Springs does not seem to be related to upwelling of deeper, saline water. Three observations wells (site 162) tapping the surficial aquifer system (well depth = 60 ft), the Upper Floridan aquifer (well depth = 155 ft), and the middle semiconfining unit (well depth = 645 ft) are near Wekiva Springs. The median values of specific conductance, in samples collected from 1993 through 1998, were 278  $\mu\text{S}/\text{cm}$  for the surficial aquifer system, 291  $\mu\text{S}/\text{cm}$  for the Upper Floridan aquifer, and 240  $\mu\text{S}/\text{cm}$  for the middle semiconfining unit. Also, chloride concentrations in the water from the Upper Floridan aquifer in the area of Wekiva and Rock Springs do not seem to have increased since the 1960s (figs. 45 and 46).

As with the surficial aquifer system, nutrient concentrations in the Floridan aquifer system generally are low. Twenty-nine of 31 recent samples from the Upper Floridan aquifer have nitrate concentrations less than or equal to the reporting limit of 0.02 mg/L. None of the samples from the Lower Floridan aquifer had detectable concentrations of nitrate (table 6). A sample from one well tapping the Upper Floridan aquifer (site 127, fig. 9) had a nitrate concentration of 2.0 mg/L as nitrogen. The well, located in west-central Orlando, is a drainage well for a lake. Water artificially recharging the aquifer from the lake could be the source of nitrate and possibly other

constituents. The sample from the well also had a TDS concentration of 45 mg/L, less than half of the concentration in a sample from a nearby well (site 126, fig. 9), possibly indicating that the well received lake water prior to being sampled. Similarly, other drainage wells on lakes and streets (fig. 26) may allow contaminants to be transported to the Upper Floridan aquifer.

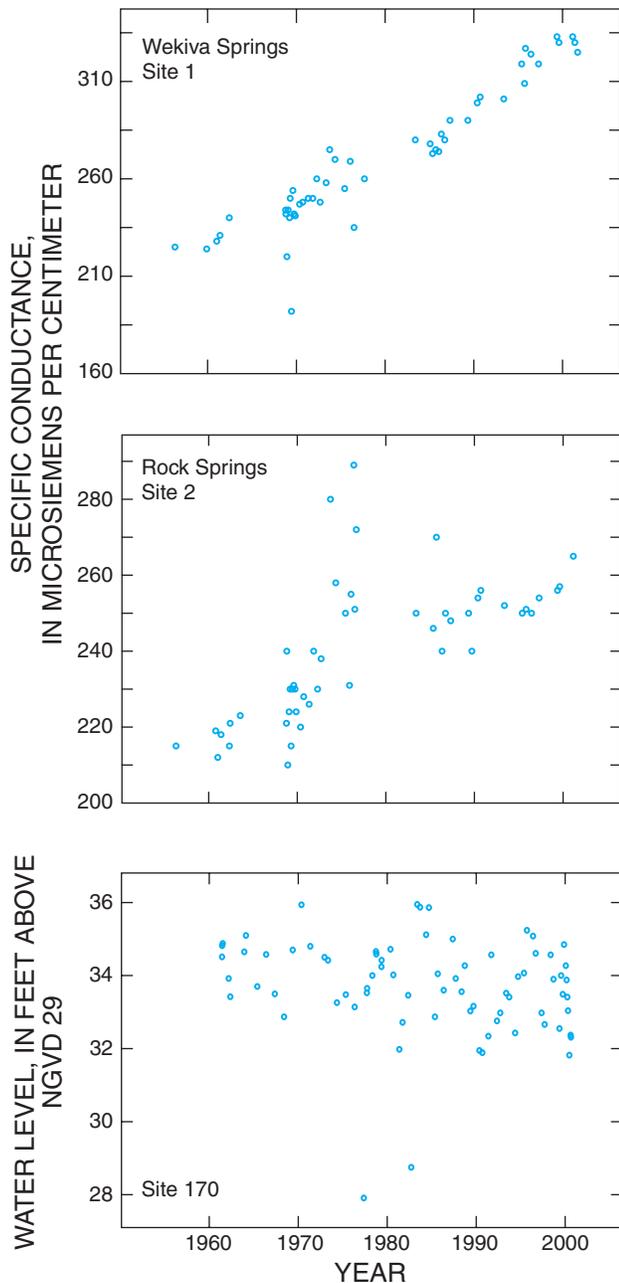
Concentrations of nitrate in water from Wekiva and Rock Springs have generally increased with time (Spechler and Halford, 2001), although the most recent values are somewhat lower than historic maximums. In Wekiva Spring, nitrate values ranged from less than 0.02 mg/L in the 1950s and 1960s to a maximum of 1.98 mg/L in 1988; the concentration was 0.98 mg/L in 2001. In Rock Springs, values ranged from less than 0.02 mg/L in 1956 to 1.81 mg/L in 1993; the concentration was 1.4 mg/L in 1999. Increases in specific conductance from these springs could be related to the effects of fertilizer or septic-tank leachate on localized recharge water into the springs. Toth (1999) investigated the isotopic geochemistry in selected springs to determine sources of nitrates. The ratio of  $^{15}\text{N}/^{14}\text{N}$  of nitrate from synthetic fertilizers ranges from about -5 to +8 per mil, whereas the ratio of  $^{15}\text{N}/^{14}\text{N}$  of nitrate from animal wastes or sewage is about +8 to more than 20 per mil (Heaton, 1986). Results from Toth (1999) indicated the ratio of  $^{15}\text{N}/^{14}\text{N}$  was +5.8 and +8.6 per mil for Rock and Wekiva Springs, respectively, values that are roughly between the ranges for synthetic fertilizer and wastewater sources. These values could be indicative of the change of land use, from agriculture to residential, and hence, reflect the change of the source of nitrate from synthetic fertilizers to wastewater. Toth (1999), using isotopes to date water from Rock and Wekiva Springs, indicated that at least a fraction of the water discharging from both springs was young (post-1953). Additional dating of spring water would be useful in understanding the sources of nitrates, given the rapid changes in land-use occurring in Orange County.

Ammonia and ammonia plus organic nitrogen were present in about half of the ground-water samples from the Floridan aquifer system. Ammonia plus organic nitrogen concentrations were greater than 0.5 mg/L as nitrogen in 11 of 26 samples from the Upper Floridan aquifer. Most of these samples were from wells in eastern Orange County. Concentrations of ammonia plus organic nitrogen in samples from three flowing wells (sites 87, 92, and 118) were 0.65, 0.64, and 0.63 mg/L as nitrogen, respectively.



(<0.01) Number in parenthesis is p-value, or probability that trend occurs by chance. A probability less than 5 percent (<0.05) is considered significant

**Figure 48.** Concentrations of chloride and sulfate in water samples from wells tapping the Floridan aquifer system (site numbers refer to appendix 1).



**Figure 49.** Specific conductance in ground-water samples collected from Wekiva Springs (site 1) and Rock Springs (site 2), and water levels in nearby observation well tapping the Upper Floridan aquifer (site 170). (Site numbers shown on figure 9.)

Because these wells are located in a discharge area for the Upper Floridan aquifer, the source of ammonia plus organic nitrogen in these samples probably is natural constituents in the aquifer. Only one of eight samples from the Lower Floridan aquifer had a concentration of ammonia plus organic nitrogen greater than 0.5 mg/L as

nitrogen. Because of the depth and location of the well (site 53 in the Cocoa well field, fig. 9), the source of the ammonia plus organic nitrogen also probably is natural.

Phosphorus concentrations generally were low in ground-water samples from the Floridan aquifer system (table 6). Phosphorus was present in all eight samples from the Lower Floridan aquifer, but the maximum concentration was only 0.07 mg/L as phosphorus. Phosphate concentrations were greater than 0.1 mg/L as phosphorus in 7 of 33 samples (sites 1, 15, 97, 147, 159, 160, and 162, fig. 9) from the Upper Floridan aquifer, including Wekiva Springs and one sample from a public-supply well (site 97). The source of phosphorus could either be from land-use practices or from the leaching of phosphatic sediments in the Hawthorn Group by recharging ground water. The median concentration of phosphorus was not significantly different between samples from the surficial aquifer system and the Upper Floridan aquifer. This result could indicate the Hawthorn Group is the source of phosphorus.

### Trace Elements, Radon, and Stable Isotopes

Trace elements are metallic and nonmetallic constituents that occur naturally in water in low concentrations, generally just a few parts per billion or micrograms per liter. The source of many of these constituents is from water-rock interactions in the aquifer. Some trace elements (table 9) also have industrial and agricultural uses. As a result, the occurrence of these trace elements in concentrations elevated above natural levels can result from and be indicative of anthropogenic sources. The occurrence of some trace elements in water also can pose health or aesthetic problems. Trace elements such as arsenic and lead are toxic and have National Primary Drinking Water Regulations established to limit their consumption in drinking water (U.S. Environmental Protection Agency, 2002). Elements such as cadmium and selenium can accumulate in vegetation, and ultimately in people or animals that consume the vegetation (Hem, 1989). Iron can impart an objectionable taste to water and stain plumbing fixtures. Trace elements generally occur as charged ions that readily sorb onto sediment and colloids in the water; hence, the concentrations in the filtered samples collected during this study could be less than concentrations in whole water.

**Table 9.** Summary statistics for selected trace elements and radon in ground-water samples from the surficial and Floridan aquifer systems, 1990 through 2001

[Source of data, U.S. Geological Survey and St. Johns River Water Management District; all concentrations dissolved, in micrograms per liter, except where noted; &lt;, less than; No., number]

Constituent	Surficial aquifer system							Upper Floridan aquifer							Lower Floridan aquifer						
	No. of samples	No. of detections	Minimum	25th percentile	Median	75th percentile	Maximum	No. of samples	No. of detections	Minimum	25th percentile	Median	75th percentile	Maximum	No. of samples	No. of detections	Minimum	25th percentile	Median	75th percentile	Maximum
Aluminum	24	22	<3.0	20	60	265	1,800	22	4	<3.0	<3.0	<3.0	<3.0	10	3	3	7.6		8.1		8.7
Arsenic	25	7	<2.0	<2.0	<2.0	2	6.5	26	4	<2.0	<2.0	<2.0	<2.0	4.1	8	1	<2.0	<2.0	<2.0	<2.0	2.4
Barium	24	24	2	7	19	36	410	26	25	6	9	15	29	120	8	8	9	15	29	54	99
Beryllium	24	2	<.5	<.5	<.5	<.5	.5	26	1	<.5	<.5	<.5	<.5	1	8	0	<.5	<.5	<.5	<.5	<.5
Boron	24	24	8.7	16	24	39	95	23	22	13	20	29	52	170	3	3	34		34		100
Cadmium	24	3	<.5	<.5	<.5	<.5	1.2	26	0	<.5	<.5	<.5	<.5	<.5	8	0	<.5	<.5	<.5	<.5	<.5
Chromium	12	4	<1.0	<1.0	<1.0	1.4	4	4	0	<1.0	<1.0	<1.0	<1.0	<1.0	2	0	<1.0	<1.0	<1.0	<1.0	<1.0
Cobalt	24	4	<1.0	<1.0	<1.0	<1.0	1.9	26	0	<1.0	<1.0	<1.0	<1.0	<1.0	8	0	<1.0	<1.0	<1.0	<1.0	<1.0
Iron, total								6	6	21	46	163	320	3,600							
Iron, dissolved	25	25	3.2	95	399	2,100	26,000	34	33	<2	23	38	140	2,000	22	22	4.4	6.8	8.5	19	1,500
Lead	24	2	<2.0	<2.0	<2.0	<2.0	4.9	26	0	<2.0	<2.0	<2.0	<2.0	<2.0	8	0	<2.0	<2.0	<2.0	<2.0	<2.0
Lithium	24	13	<.5	<.5	.7	1.4	12	23	20	<.5	1	3.2	7.7	14	3	3	1.4		2.2		8.7
Manganese	25	24	<1.0	7.6	26	58	270	26	24	<1.0	2.9	5.1	13	44	19	9	<1.0	<1.0	<1.0	1.4	6.1
Selenium	24	8	<2.0	<2.0	<2.0	2.1	8	26	9	<2.0	<2.0	<2.0	2.2	6.2	8	2	<2.0	<2.0	<2.0	<2.0	3.1
Strontium	24	24	8	25	51	95	5,200	38	38	34	140	710	2,000	10,200	23	23	57	190	620	1,060	13,800
Vanadium	24	14	<1.0	<1.0	1	3	4	26	3	<1.0	<1.0	<1.0	<1.0	2	8	0	<1.0	<1.0	<1.0	<1.0	<1.0
Radon, in picoCuries per liter	22	22	71	513	913	2,250	14,700	22	22	56	153	344	975	1,600	8	8	59	90	107	132	174

Data from water samples collected for this study (1999 through 2001) indicate that the most commonly detected trace elements in Orange County were aluminum, barium, boron, iron, manganese, and strontium. These constituents were detected in nearly every sample collected from the surficial aquifer system, the Upper Floridan aquifer, and the Lower Floridan aquifer (table 9). Of these constituents, only aluminum, iron, and manganese have standards for drinking water (table 3). Aluminum has a secondary standard of 200 µg/L, iron has a secondary standard of 300 µg/L, and manganese has a secondary standard of 50 µg/L (U.S. Environmental Protection Agency, 2002). The secondary standards for aluminum and manganese were exceeded in more than 25 percent of the samples from the surficial aquifer system. The secondary standard for iron was exceeded in more than 50 percent of the filtered samples from the surficial aquifer system, but only in about 13 percent of the filtered samples from the Upper Floridan aquifer, and about 9 percent of filtered samples from the Lower Floridan aquifer. Iron concentrations were higher in whole-water samples than in filtered samples (table 9).

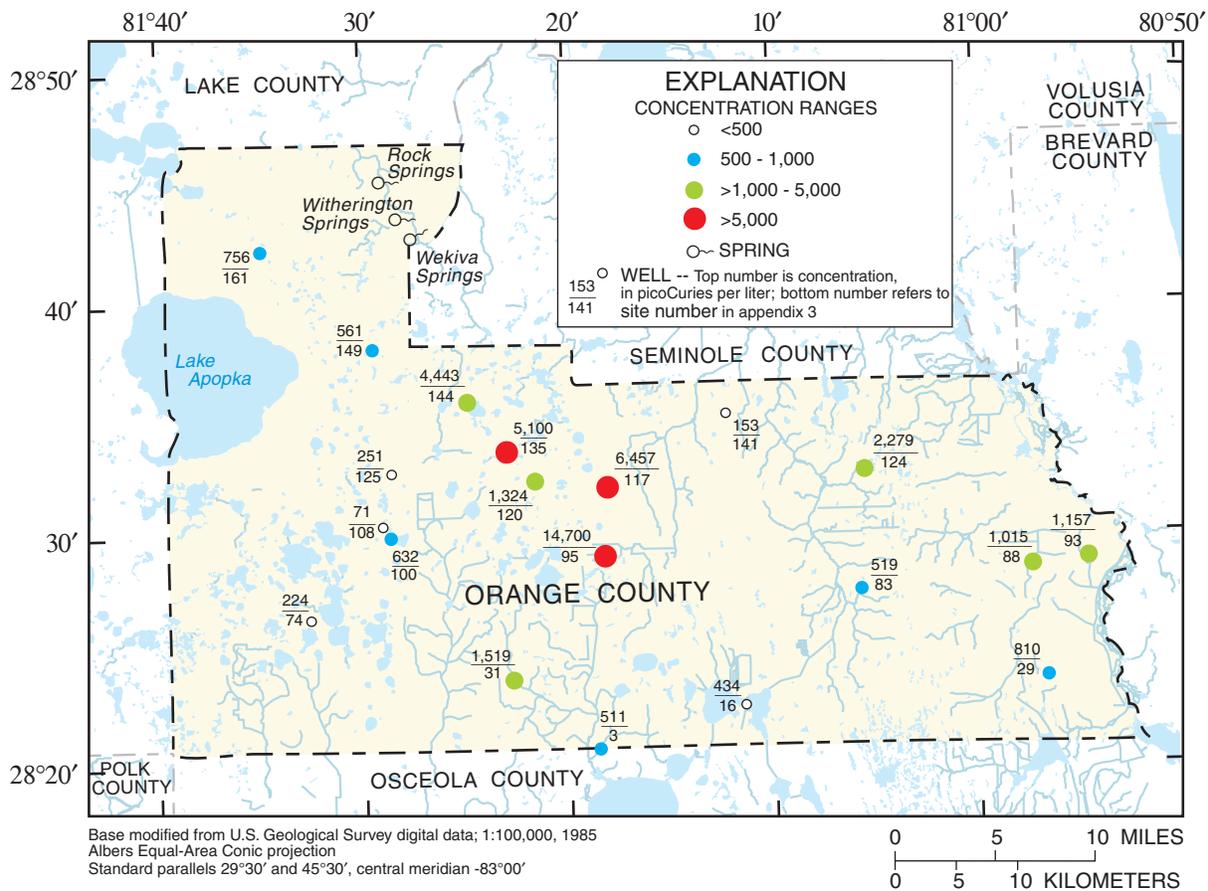
Other trace elements were detected less frequently in ground-water samples. Lithium was detected in 36 of 50 samples (72 percent). Vanadium was detected in 17 of 58 samples (29 percent). No drinking water standards are set for these two constituents. Arsenic was detected in 7 of 25 samples from the surficial aquifer system, in 4 of 26 samples from the Upper Floridan aquifer, and in 1 of 8 samples from the Lower Floridan aquifer. Beryllium was detected in 2 of 24 samples from the surficial aquifer system and 1 of 26 samples from the Upper Floridan aquifer, but no samples from the Lower Floridan aquifer contained beryllium. Selenium was detected in 8 of 24 samples from the surficial aquifer system, in 9 of 26 samples from the Upper Floridan aquifer, and in 2 of 8 samples from the Lower Floridan aquifer (table 9). Of 24 samples collected from the surficial aquifer system, cadmium was detected in 3, cobalt in 4, and lead in 2, but none of these trace elements were detected in any samples from the Floridan aquifer system. The drinking-water MCLs for these trace elements are: arsenic, 10 µg/L; beryllium, 4 µg/L; cadmium, 5 µg/L; chromium, 100 µg/L; lead, 15 µg/L; and selenium, 50 µg/L (U.S. Environmental Protection Agency, 2002). None of these trace elements exceeded the MCL standard in ground-water samples collected in Orange County (tables 3 and 9).

Sources of these trace elements probably are both natural and anthropogenic. Aluminum, iron, and manganese are common constituents in rocks and soil. Strontium can substitute for calcium in calcite, the major mineral present in limestone, and is present in ground water after dissolution of limestone. Arsenic is present in rocks, but also has many commercial and industrial uses, such as an ingredient in pesticides and as a wood preservative. The occurrence of arsenic in the surficial aquifer system could be anthropogenic; however, the occurrence of arsenic in the Lower Floridan aquifer most likely is natural because the aquifer generally is not directly affected by surface contamination. The occurrence of cadmium, chromium, cobalt, and lead in samples from the surficial aquifer system but not in samples from the Floridan aquifer system indicates a possible anthropogenic source for these constituents. These constituents have many industrial uses; however, the concentrations detected in the samples are within ranges of natural waters (Hem, 1989).

Radon, an inert, radioactive gas, is part of the uranium decay series, and results from the radioactive decay of radium through the emission of an alpha particle. Radon decays to polonium. Radium, radon, and alpha particles can cause cancer (Otton and others, 1995). National Primary Drinking Water Regulations have been established for radium (5 pCi/L) and alpha particles (15 pCi/L), but not for radon (U.S. Environmental Protection Agency, 2002).

A total of 52 samples was collected from 1999 through 2001 and analyzed for radon as part of this study. Radon was detected in every sample and concentrations ranged from 56 to 14,700 pCi/L (table 9). Radon concentrations generally had no apparent pattern of geographic distribution in the Upper Floridan aquifer, but high concentrations of radon in the surficial aquifer system were somewhat more prevalent in the central part of Orange County (figs. 50 and 51). Radon concentrations also were significantly higher in samples from the surficial aquifer system than in samples from the Upper Floridan or Lower Floridan aquifers (fig. 52).

The primary source of radon in ground water in Orange County probably is the uranium-bearing phosphate minerals in the Hawthorn Group. The concentrations of radon are highest in the surficial aquifer system either because the gas dissipates upward to the aquifer or because reworking of Hawthorn Group sediments distributed the phosphate minerals during deposition of sediments that form the surficial aquifer system.



**Figure 50.** Concentrations of radon in water samples collected from wells tapping the surficial aquifer system, 1999 through 2000.

Because radon has a half life of only 3.8 days, the gas generally is not transported far from its source, which probably explains the relatively low concentrations in the Floridan aquifer system.

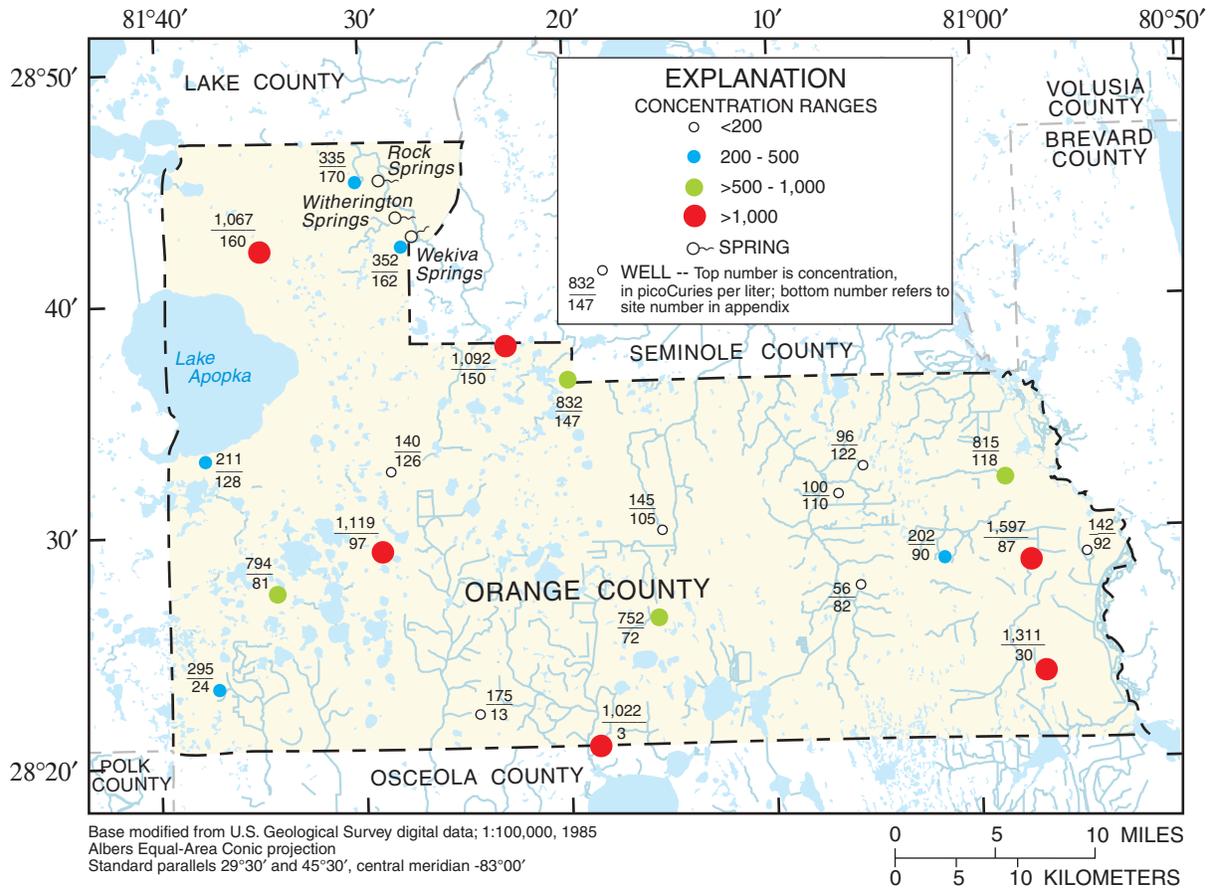
As part of this study, 46 water samples also were collected from 1999 through 2000 for the analysis of deuterium and oxygen-18, naturally occurring stable isotopes of hydrogen and oxygen, respectively. The results are reported as relative abundances or ratios to a standard, the Vienna Standard Mean Ocean Water (VSMOW), which can be useful in determining the source of ground water. Negative values indicate that the sample was lighter or depleted in these two isotopes with respect to the VSMOW. Precipitation becomes depleted relative to the VSMOW during evaporation. As a result, deuterium and oxygen-18 in meteoric water are strongly correlated and generally fall along a straight line (global meteoric line), which has the following equation:

$$\text{Deuterium} = 8 (\text{oxygen-18}) + 10 \text{ (Craig, 1961)}. \quad (4)$$

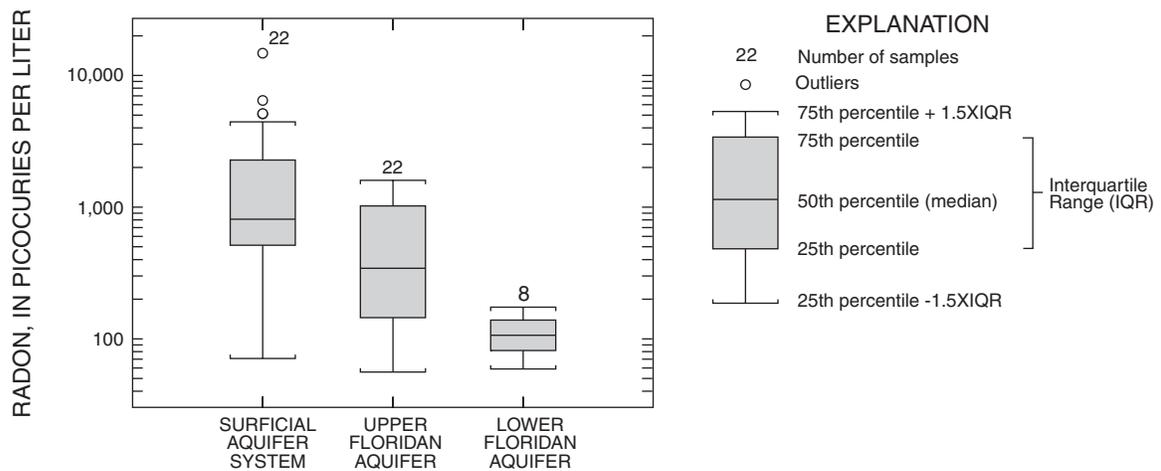
Locally, the data, and, therefore, the local meteoric lines, can vary depending on the latitude and distance from the ocean. Linear regression indicated that deuterium and oxygen-18 in ground-water samples from Orange County (fig. 53) were related with the following equation:

$$\text{Deuterium} = 5.64 (\text{oxygen-18}) + 2.70. \quad (5)$$

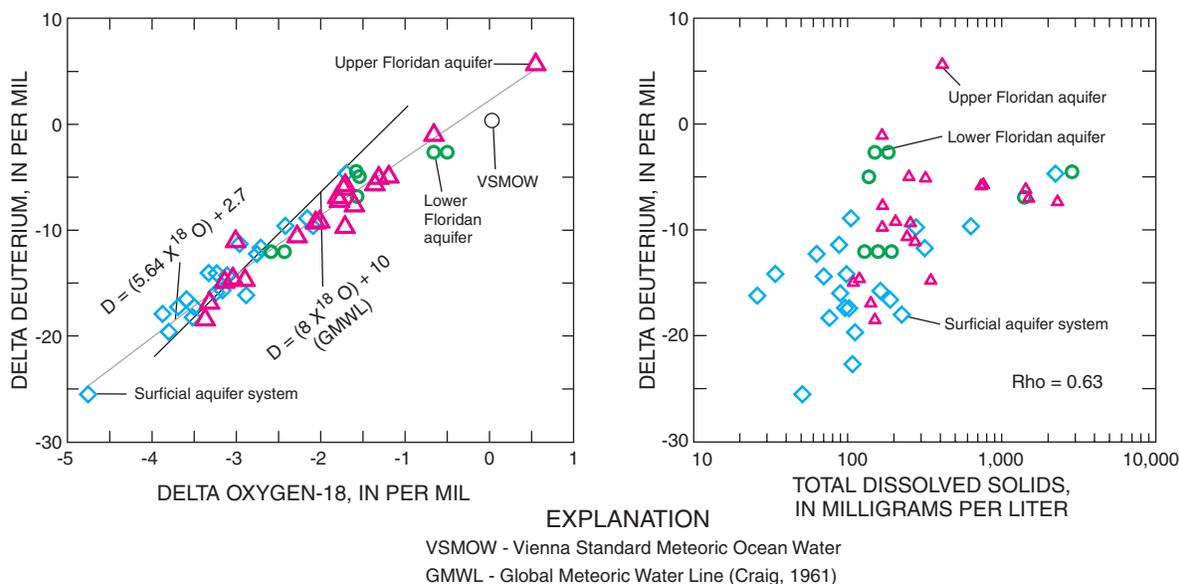
The data plot along a line that is roughly parallel to the global meteoric line, indicating that the ground water in Orange County generally is of meteoric origin. However, samples from the Upper and Lower Floridan aquifers generally are heavier (less depleted) than samples from the surficial aquifer system (fig. 53). In addition, deuterium is significantly correlated to TDS (Spearmans's rho=0.63; fig. 53). These relations probably result from mixing of a small amount of relict



**Figure 51.** Concentrations of radon in water samples collected from wells tapping the Upper Floridan aquifer, 1999 through 2000.



**Figure 52.** Distribution of radon in water samples from the surficial aquifer system, the Upper Floridan aquifer, and the Lower Floridan aquifer, 1999 through 2000.



**Figure 53.** Relations between deuterium and oxygen-18, and deuterium and total dissolved solids in ground-water samples collected from the surficial aquifer system, the Upper Floridan aquifer, and the Lower Floridan aquifer, 1999 through 2000.

seawater with the meteoric water. As noted previously, concentrations of TDS, sulfate, and chloride in the Upper Floridan aquifer increase in eastern Orange County possibly as a result of upwelling of water from deeper zones of the aquifer. Assuming it is similar to modern seawater, this relict seawater probably is isotopically similar to the VSMOW, and, therefore, heavier than precipitation. Hence, mixing with relict seawater would impart a heavier ratio than present in modern meteoric water, which is represented by the values of the surficial aquifer system.

## Pesticides

Pesticides are synthetic, organic compounds used to control unwanted plants, insects, and fungi. The presence of pesticides in ground water and surface water indicates anthropogenic sources, and can pose a health or ecological risk. Many of the compounds have multiple uses, including agriculture and residential pest control, aquatic vegetation control, mosquito control, and maintenance of road and utility rights-of-way (Shahane, 1999). For example, in Florida, atrazine is used to control broadleaf weeds in corn and sugarcane fields, and also is used to control weeds in residential lawns. Furthermore, pesticides can volatilize after application and be transported in the atmosphere.

Atrazine and other pesticide compounds commonly are detected in precipitation in midwestern and northeastern states, but few data are available on the concentrations of pesticides in precipitation in Florida (Majewski and Capel, 1995). As a result of their widespread use and transport, pesticides commonly are detected in ground water (Barbash and Resek, 1996), even in areas considered relatively pristine (Adamski, 1997).

As part of this study, 34 ground-water samples were collected in Orange County from 1999 through 2000 and analyzed for 47 pesticides and pesticide degradates (app. 4). Sixteen samples were collected from wells tapping the surficial aquifer system, 14 samples from wells tapping the Upper Floridan aquifer, and 4 samples from wells tapping the Lower Floridan aquifer.

Results indicate that some pesticides and degradates are present locally in low concentrations in the surficial aquifer system and the Upper Floridan aquifer. Pesticides were detected in samples from eight wells tapping the surficial aquifer system and from two wells tapping the Upper Floridan aquifer (table 10). Pesticides were not detected in samples from the Lower Floridan aquifer. A total of 10 compounds was detected, including six herbicides, two insecticides, and two metabolites. The maximum number of compounds in any single sample was three. The most commonly

**Table 10.** Well, date of sample collection, and number of pesticide compounds detected in each sample

Site number	Site identifier	Well name	Date of collection	Number of compounds detected
Surficial aquifer system				
74	282631081323301	Tibet-Butler well	12/2/1999	1
80	282722081371701	Conserv II well	6/23/1999	2
95	282912081181201	OR0722	2/15/2000	1
108	283033081290301	Turkey Lake well	2/16/2000	1
117	283210081180401	Englewood Park well	10/26/1999	2
120	283228081213501	Langford Park well	10/26/1999	1
125	283251081283501	OR0716	8/26/1999	1
135	283345081225701	Ivanhoe Park well	10/28/1999	2
Upper Floridan aquifer				
126	283253081283401	OR47	7/15/1999	2
147	283646081195401	Bradner well	9/1/1999	3

detected pesticide compounds were atrazine and deethyl atrazine, a metabolite of atrazine. The maximum concentration of any compound detected was 0.417 µg/L for simazine (table 11), which was from a well tapping the surficial aquifer system in southwestern Orange County. Of the 10 compounds detected, only atrazine and simazine have National Primary Drinking Water Regulations, which were not exceeded in any of the ground-water samples. Eight of the 10 compounds have target levels for cleanup of ground water and surface water in brownfields (Florida Department of Environmental Protection, 1999). None of the concentrations in any of the ground-water samples exceeded the guidance levels for ground-water cleanup, but concentrations of chlorpyrifos and diazinon exceeded the guidance levels for surface-water cleanup (table 11).

Some of the pesticide compounds also have ecological effects. For example, chlorpyrifos, diazinon, and trifluralin are highly toxic to aquatic organisms, and chlorpyrifos and diazinon also are highly toxic to birds. DDE, a metabolite of DDT, is thought to cause the thinning of egg shells of birds (EXTOXNET, 2002). Finally, concentrations of atrazine as low as 0.1 µg/L in water has recently been shown to disrupt the endocrine systems of male frogs, causing demasculinization (Hayes and others, 2002).

The source of pesticides in these ground-water samples is difficult to assess because of the many uses of the compounds. In Orange County, the current land uses associated with pesticide use include agriculture and urban (commercial and residential). Row-crop agriculture, such as corn, has not been an important land use since 2000; however, some pesticides and metabolites are persistent in the environment. Atrazine, chlorpyrifos, DCPA, diazinon, prometon, and simazine are commonly used to control pests in residential and urban areas. Eight (6 samples from the surficial aquifer system and 2 samples from the Upper Floridan aquifer) of 10 samples with pesticides detected were collected from wells in the metropolitan Orlando area; 5 of the samples were collected from residential sites that were constructed prior to 1977. Therefore, the source of pesticides in these samples likely is from lawn maintenance and other household uses. Because DDT was banned in 1972, the source of DDE likely is not from recent use. Benfluralin and trifluralin, detected in a single sample (app. 4), could result from residential use, as both of these pesticides are available for residential use. Benfluralin also is used for peanut production in Florida, and trifluralin is applied to cabbage, corn, cotton, and soybeans; however, none of these crops are currently grown commercially in Orange County (Shahane, 1999). The well from which

**Table 11.** Pesticides detected in ground-water samples, environmental regulations, and associated health guidance concentrations

[µg/L, micrograms per liter; estimated values are shown in boldface]

Pesticide compound	Type	Number of detections	Observed range in concentrations (µg/L)	National Primary Drinking Water Regulation <sup>a</sup> (µg/L)	Florida health guidance concentrations <sup>b</sup>	
					Ground water (µg/L)	Surface water (µg/L)
Atrazine	herbicide	3	<b>0.003</b> - 0.029	3	3	1.8
Benfluralin	herbicide	1	<b>0.001</b>	none	none	none
Chlorpyrifos	insecticide	1	.005	none	21	.002
DCPA	herbicide	1	.008	none	70	310
Deethyl atrazine	metabolite	3	<b>.002</b> - <b>.003</b>	none	none	none
Diazinon	insecticide	1	.005	none	.63	.002
DDE, <i>p,p'</i>	metabolite	2	<b>.001</b> - <b>.003</b>	none	.1	.0006
Prometon	herbicide	2	.025 - .028	none	105	600
Simazine	herbicide	1	.417	4	4	5.8
Trifluralin	herbicide	1	<b>.001</b>	none	.78	.78

<sup>a</sup>U.S. Environmental Protection Agency, 2002.

<sup>b</sup>Brownfield Cleanup Targets, Florida Department of Environmental Protection, 1999.

the sample was collected was located in a city park surrounded by a residential area that was established prior to 1977. Pesticides were not detected in any samples from wells in relatively pristine areas, but atrazine was detected in one sample from a lake in Tosohatchee State Reserve (E.R. German, U.S. Geological Survey, written commun., 2003).

The results of this study should not be interpreted as a comprehensive investigation of the occurrence and distribution of pesticides in ground water of Orange County. Many more pesticide compounds are used in the county than were investigated by this study. For example, as many as 30 different herbicides and insecticides are registered for use in orange groves. Of these 30 compounds, only 4 herbicides and 5 insecticides were included in these analyses. Similarly, many more pesticides are registered for residential pest control than could be included in the analyses of this study. Finally, the constraints of this study allowed only one sample to be collected from each of the 34 wells, limiting inferences on both temporal and spatial variability of pesticide concentrations in ground water. The effects of seasonal application rates and rainfall variations are not known. Additional study would be beneficial to better understand the occurrence, distribution, and temporal variations of pesticides in ground water of Orange County.

## SUMMARY

A study of the hydrogeologic framework and ground-water quality characteristics was conducted from 1998 through 2002 for the surficial aquifer and Floridan aquifer systems underlying Orange County, Florida. Ground water is an abundant resource in central Florida and the primary source of water for aquatic habitats and human consumption. The quality of ground water generally is within the Primary and Secondary Drinking Water Regulations established by the U.S. Environmental Protection Agency. However, ground-water levels, spring flows, and ground-water quality have declined in some areas since 1968, probably as a result of withdrawal by pumping and an increase in urban land use. The population of Orange County increased from about 344,000 in 1970 to 896,000 in 2000. Ground-water use also increased from about 82 million gallons per day (Mgal/d) in 1965 to about 287 Mgal/d in 2000.

The hydrogeology of Orange County consists of three major hydrogeologic units—the surficial aquifer system, the intermediate confining unit, and the Floridan aquifer system—which together are as much as 2,500 feet (ft) thick in Orange County. The Floridan

aquifer system consists of the Upper and Lower Floridan aquifers, which are separated by the middle semiconfining unit and are underlain by the sub-Floridan confining unit.

The surficial aquifer system consists mostly of unconsolidated sand with interbedded silt, clay, and shell of Pliocene to Recent age. The surficial aquifer system generally is between 50 and 100 ft thick throughout most of Orange County. The thickness can vary widely over small spatial distances because of deposition of sediments on a highly eroded surface and lateral gradation of units from sand to clay. The hydraulic conductivity of the surficial aquifer system, based on slug tests on 21 wells, ranges from about 0.05 to 30 feet per day (ft/d) with a median of about 3 ft/d. The two lowest values of hydraulic conductivity were measured in wells located in western Orange County.

In general, the surficial aquifer system is unconfined, and the altitude of the water levels in wells represents the water table. Ground water in the surficial aquifer system is recharged mostly by precipitation, but also artificially by septic systems and rapid infiltration basins used for the disposal of treated wastewater (reclaimed water). The water table of the surficial aquifer system generally is higher beneath hilltops than beneath valleys. Water-level altitudes measured in wells tapping the surficial aquifer system ranged from about 10.6 ft in eastern Orange to 123.8 ft above NGVD 29 in northwestern Orange County.

In most locations in Orange County, the altitude of the water table of the surficial aquifer system is higher than the altitude of the potentiometric surface of the Upper Floridan aquifer, indicating that ground water from the surficial aquifer system potentially can flow downward to recharge the Upper Floridan aquifer. Water from the surficial aquifer system also flows laterally and discharges to lakes and streams.

The intermediate confining unit consists of clay, silt, limestone, and dolomite of Miocene age, and can include overlying clay layers of Pliocene age. Thickness of the unit ranges from about 10 to more than 200 ft, with a median thickness of about 100 ft. In general, the thickest part of the intermediate confining unit is in southeastern Orange County, and the thinnest parts are in southwestern and northwestern Orange County.

The Floridan aquifer system consists primarily of limestone and dolomite of Eocene age. The Upper Floridan aquifer consists primarily of the Ocala Limestone (zone A) and about the upper one-third of the Avon Park Formation (zone B); the middle semiconfin-

ing unit consists of about the middle one-third of the Avon Park Formation; and the Lower Floridan aquifer consists of the lower one-third to one-half of the Avon Park Formation and the Oldsmar Formation. The contacts between the Upper Floridan aquifer, middle semiconfining unit, and Lower Floridan aquifer are based primarily on permeability rather than stratigraphy and lithology. Much of the porosity of the Floridan aquifer system is secondary as a result of dissolution of the carbonate rock.

The altitude of the top of the rock forming the Upper Floridan aquifer ranges from about 250 ft below to 38 ft above NGVD 29 with a median of about 62 ft below NGVD 29. In general, the altitude is highest in northwestern Orange County and lowest in southeastern Orange County, but can range widely over short spatial distances, resulting from the dissolution of the carbonate rocks and formation of numerous sinkholes. Thickness of the Upper Floridan aquifer is about 300 to 400 ft throughout most of Orange County.

The thickness of the middle semiconfining unit ranges from about 385 to 635 ft. The top of the rock forming the Lower Floridan aquifer ranges from about 870 to 1,120 ft below NGVD 29. Thickness of the Lower Floridan aquifer ranges from about 1,023 to 1,180 ft.

Water recharges the Upper Floridan aquifer throughout most of Orange County either by slow leakage from the surficial aquifer system through the intermediate confining unit or artificially through drainage wells and rapid-infiltration basins. Recharge through drainage wells is estimated to be about 38 to 50 Mgal/d on average.

Discharge from the Upper Floridan aquifer occurs naturally at springs in northwestern Orange County, and artificially as a result of withdrawal from wells throughout the county. In a few locations, the altitude of the potentiometric surface is higher than the water table of the surficial aquifer system, indicating places of potential ground-water discharge from the Upper Floridan aquifer to the surficial aquifer system. The potentiometric surface of the Upper Floridan aquifer ranges from about 110 ft above NGVD 29 in southwestern Orange County to less than 30 ft above NGVD 29 in eastern Orange County. Water levels measured in observation wells in July 1961 and September 2001 indicate the altitude of the potentiometric surface of the Upper Floridan aquifer has declined 0.8 to 16 ft, with a median of 3 ft. In general, the potentiometric surface of the Lower Floridan aquifer mimics that of the Upper

Floridan aquifer, but, in places where pairs of wells tap each aquifer, water-level altitudes in the Lower Floridan aquifer generally are lower than those of the Upper Floridan aquifer.

Long-term water-level data in the surficial aquifer system are available in only five wells. Trend analysis indicates that water levels have not declined significantly in four of the wells. Trend analysis on long-term data collected from 15 wells tapping the Floridan aquifer system indicates statistically significant declines in water-level altitudes in seven wells tapping the Upper Floridan aquifer and one well tapping the Lower Floridan aquifer. Declines range from about 4 ft in southeastern Orange County to 12 ft in west-central Orlando, with a median of about 6 ft. Although the overall trend in these wells is decreasing water levels, the data indicate the declines are discontinuous, with intermittent periods of stabilization and (or) increasing water levels. The long-term declines probably are related to pumping of the aquifer rather than climatic changes. Declines in the potentiometric surface of the Upper Floridan aquifer also have resulted in decreased discharge from Rock and Wekiva Springs.

A generalized water budget was computed for Orange County from 1991 to 2000. Average rates for the 10-year period for the following budget components were computed based on reported measurements or estimates: precipitation was 53 inches per year (in/yr), runoff was 11 in/yr, spring discharge was 2 in/yr, and net lateral subsurface outflow and exported water was 1 in/yr. Evapotranspiration was 39 in/yr, which was calculated as the residual of the water-budget analysis, assuming changes in storage were negligible.

Water quality of the surficial aquifer system is highly variable, as a result of lithology of the sediments, natural and artificial recharge from the Upper Floridan aquifer, and effects of land use. Water type generally is mixed ion with low concentrations of total dissolved solids (TDS), sulfate, and chloride. The National Secondary Drinking Water Regulation for TDS (500 mg/L) was exceeded in only 3 of 33 samples from the surficial aquifer system. The National Secondary Drinking Water Regulation for chloride of 250 milligrams per liter (mg/L) was exceeded in only 1 of 31 samples from the surficial aquifer system. In general, nutrient concentrations also were low in samples from the surficial aquifer system. About half of the samples had nitrate concentrations less than or equal to the method reporting limit of 0.02 mg/L. Two samples had

concentrations greater than or equal to the Maximum Contaminant Level of 10 mg/L. The source of nutrients in the surficial aquifer system probably is local agricultural and urban land use.

Water type in the Floridan aquifer system generally is calcium or calcium-magnesium bicarbonate, resulting from the dissolution of the carbonate rocks, with low concentrations of TDS (less than 500 mg/L). Water in the Upper Floridan aquifer becomes sodium-chloride type with higher concentrations of TDS in eastern Orange County, possibly as a result of upwelling of deeper, more saline ground water. The National Secondary Drinking Water Regulation for TDS was exceeded in 15 of 56 samples.

Recent (1999) water samples from an observation well in southwestern Orange County had relatively high concentrations of sodium (53 mg/L), chloride (90 mg/L), and sulfate (41 mg/L), possibly as a result of reclaimed water from nearby rapid infiltration basins recharging the Upper Floridan aquifer. One sample collected from the same well prior to the installation of the rapid infiltration basins (1979) had lower concentrations of chloride (4 mg/L) and sulfate (28 mg/L).

A total of 24 wells that tap the Floridan aquifer system had historical water-quality data (1953-2001). All wells were located in eastern Orange County, mostly in and around the Cocoa well field. Data indicated statistically significant increases in sulfate and chloride concentrations over time in 13 and 16 wells, respectively, which probably relate to pumping, especially from the Cocoa well field where upward migration of deep saline water occurs. The migration appears to move through conduits and fractures, rather than diffusely through the aquifer medium, as indicated by increases of chloride and sulfate in samples from shallow and deep zones in nested observation wells, but not in samples from the two intermediate zones.

Specific conductance and TDS concentrations have increased in water samples from Rock and Wekiva Springs since about the mid-1960s. Based on data from nearby wells, the cause is likely related to the effects of fertilizer or septic-tank leachate on localized recharge water into the springs rather than upwelling of saline water from deeper zones of the aquifer.

Concentrations of nitrate and total organic carbon generally were low in samples from the Upper and Lower Floridan aquifers. A total of 29 of 31 samples collected from the Upper Floridan aquifer had concentrations of nitrate less than or equal to the reporting limit of 0.02 mg/L. Concentrations of nitrate in

samples from Rock and Wekiva Springs, which issue from the Upper Floridan aquifer, were 1.4 and 0.98 mg/L as nitrogen, respectively, which could be a result of the agricultural and (or) residential land use in the recharge basins.

The most commonly detected trace elements in ground-water samples from Orange County were aluminum, barium, boron, iron, manganese, and strontium. Arsenic was detected in 7 of 25 samples from the surficial aquifer system, 4 of 26 samples from the Upper Floridan aquifer, and 1 of 8 samples from the Lower Floridan aquifer. Selenium was detected in 8 of 24 samples from the surficial aquifer system, 9 of 26 samples from the Upper Floridan aquifer, and 2 of 8 samples from the Lower Floridan aquifer. These elements have many commercial and industrial uses; however, the low concentrations in ground water in Orange County do not exceed Maximum Contaminant Levels established by the U.S. Environmental Protection Agency and are within ranges of natural concentrations.

Radon was detected in every ground-water sample, and concentrations ranged from 56 to 14,700 picoCuries per liter. Radon concentrations generally had no apparent pattern of geographic distribution, but were substantially higher in samples from the surficial aquifer system than in samples from either the Upper or Lower Floridan aquifer. Radon is a naturally occurring radioactive gas generated by the decay of radium. The source of radon probably is uranium-bearing phosphate minerals present in the intermediate confining unit. No Maximum Contaminant Level has been established for radon in drinking water.

Ratios of stable isotopes of hydrogen (deuterium) and oxygen (oxygen-18) indicate that ground water in the surficial aquifer system and Floridan aquifer system is meteoric in origin, falling along a line parallel to the global meteoric water line. In general, samples from the Floridan aquifer system are slightly heavier (less depleted) with respect to the Vienna Standard Mean Ocean Water than are samples from the surficial aquifer system, indicating that deep saline water, possibly relict seawater, is migrating upward and mixing in places with water in the Floridan aquifer system.

Pesticides were present in low concentrations in 8 of 16 samples from the surficial aquifer system and in 2 of 14 samples from the Upper Floridan aquifer; no pesticides were found in the 4 samples from the Lower Floridan aquifer. The most commonly detected pesticide

compounds were atrazine and deethyl atrazine. The maximum number of compounds detected in any one sample was three. The maximum detected concentration of any compound was 0.417 micrograms per liter for simazine. No pesticide concentration exceeded a Maximum Contaminant Level. The source of pesticides is difficult to assess, but detections in urban areas could originate from commercial and residential use of pesticides. Pesticides are present in shallow ground water primarily in urban areas around metropolitan Orlando.

Water-quality samples for this project were collected during drought conditions when leaching from lawns and runoff from roads was minimal. Additional sample collection during other hydrologic conditions would be beneficial to assess the variable ground-water quality, particularly the occurrence and distribution of pesticides. Furthermore, an increase in data collection, including continuation of water-level measurements in surficial aquifer system wells and periodic collection of water-quality samples from both the surficial aquifer and Floridan aquifer systems, would be useful in documenting future trends.

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