HYDROLOGY OF THE FLORIDAN AQUIFER SYSTEM IN EAST-CENTRAL FLORIDA

REGIONAL AQUIFER-SYSTEM ANALYSIS

U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1403-E

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Hydrology of the Floridan Aquifer System in East-Central Florida

By C.H. TIBBALS

REGIONAL AQUIFER SYSTEM ANALYSIS—FLORIDAN AQUIFER SYSTEM

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FOREWORD

THE REGIONAL AQUIFER-SYSTEM ANALYSIS PROGRAM

The Regional Aquifer-System Analysis (RASA) Program was started in 1978 following a congressional mandate to develop quantitative appraisals of the major ground-water systems of the United States. The RASA Program represents a systematic effort to study a number of the Nation's most important aquifer systems, which in aggregate underlie much of the country and which represent an important component of the Nation's total water supply. In general, the boundaries of these studies are identified by the hydrologic extent of each system and accordingly transcend the political subdivisions to which investigations have often arbitrarily been limited in the past. The broad objective for each study is to assemble geologic, hydrologic, and geochemical information, to analyze and develop an understanding of the system, and to develop predictive capabilities that will contribute to the effective management of the system. The use of computer simulation is an important element of the RASA studies, both to develop an understanding of the natural, undisturbed hydrologic system and the changes brought about in it by human activities, and to provide a means of predicting the regional effects of future pumping or other stresses.

The final interpretive results of the RASA Program are presented in a series of U.S. Geological Survey Professional Papers that describe the geology, hydrology, and geochemistry of each regional aquifer system. Each study within the RASA Program is assigned a single Professional Paper number, and where the volume of interpretive material warrants, separate topical chapters that consider the principal elements of the investigation may be published. The series of RASA interpretive reports begins with Professional Paper 1400 and thereafter will continue in numerical sequence as the interpretive products of subsequent studies become available.

Dallas L. Peck
Director

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METRIC CONVERSION FACTORS

For readers who wish to convert measurements from the inch-poound system of units to the metric system of units, the conversion factors are listed below:

Multiply inch-pound units	*By*	*To obtain metric units*
	Length	
inch (in)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	0.4047	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
gallon (gal)	3.785	liter (L)
	0.003785	cubic meter (m^3)
cubic foot (ft^3)	28.32	liter (L)
	0.02832	cubic meter (m^3)
million gallons (Mgal)	3,785	cubic meter (m^3)
	Flow	
gallon per minute (gal/min)	0.06309	liter per second (L/s)
	0.00006309	cubic meter per second (m^3/s)
inch per year (in/yr)	25.4	millimeter per year (mm/yr)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
	Specific capacity	
gallon per minute per foot [(gal/min)/ft]	0.2070	liter per second per meter [(L/s)/m]
	Transmissivity	
foot squared per day (ft^2/d)	0.09290	meter squared per day (m^2/d)
	Hydraulic conductivity	
foot per day (ft/d)	0.3048	meter per day (m/d)
	Leakance	
foot per day per foot [(ft/d)/ft]	1.000	meter per day per meter [(m/d)/m]

Temperature in degrees Fahrenheit (°F) can be converted to degrees Celsius (°C) as follows: °C=(°F−32)÷1.8.

ALTITUDE DATUM

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

HYDROLOGY OF THE FLORIDAN AQUIFER SYSTEM IN EAST-CENTRAL FLORIDA

By C.H. Tibbals

ABSTRACT

The fresh-ground-water flow system of east-central Florida consists of a thin surficial sand aquifer underlain by the thick, highly productive carbonate rocks of the Floridan aquifer system. On the basis of permeability, this system is divided into the Upper and Lower Floridan aquifers, which are separated by a less permeable limestone sequence referred to as the "middle semiconfining unit." The transmissivity of the Upper Floridan ranges from about 10,000 to 400,000 feet squared per day based on field aquifer tests, but simulation suggests an average value of 120,000 feet squared per day. The transmissivity of the Lower Floridan is less well known, but simulation suggests values in the range of 30,000 to 130,000 feet squared per day. Storage coefficients of both the Upper and Lower Floridan aquifers are about 0.001. Leakage coefficients of the confining bed that overlies the Upper Floridan range from 0.000001 per day to about 0.0006 per day. The leakage coefficient of the middle semiconfining unit is about 0.00005 per day.

The chemical quality of the water in the Upper Floridan aquifer varies according to proximity to recharge and discharge areas. Low concentrations of dissolved solids (less than 250 milligrams per liter) generally occur in recharge areas. However, in the discharge areas along the Atlantic Coast and along the St. Johns River, the dissolved-solids concentration is generally more than 1,000 milligrams per liter, and in places exceeds 25,000 milligrams per liter. The quality of water in the Lower Floridan is not well defined, but in east-central Florida, water in the Lower Floridan is probably more mineralized than water in the Upper Floridan.

The hydraulics of the Floridan aquifer system under predevelopment conditions involve mostly recharge to the Upper Floridan (by way of leakage from the surficial aquifer), lateral movement through the Upper Floridan for short distances, and discharge by way of springs and seepage to streams. Relatively small amounts of discharge occur along the coast, and small amounts move into and out of the underlying Lower Floridan. Thus, there is a vigorous flow system locally in the Upper Floridan and, except in west Orange County and southeast Lake County, a relatively sluggish flow system in the Lower Floridan.

The essential features of the predevelopment steady-state flow system are as follows:

- The highest rates of recharge to the Floridan are in four areas: the west flank of the Volusia County potentiometric surface "high"; the Putnam-Alachua County potentiometric surface "high"; the topographically high ridge areas of mid-Polk and Highlands Counties; and the northeast flank of the central Florida potentiometric surface "high" in Lake and Orange Counties and extending into east Marion County.
- Most discharge from Upper Floridan (about 68 percent of the total) occurs as point discharge to springs and streams located within 25 miles of recharge areas.
- The highest rates of diffuse upward leakage from the Upper Floridan (about 27 percent of the total discharge) occur near areas where the downward leakage rates are also high. Thus, it is inferred that thin or very leaky confining beds are common to the areas of high upward leakage and to the nearby areas of high downward leakage.
- Lateral boundary outflow from the Upper Floridan aquifer (principally occurring along the Atlantic Coast) is about 4 percent of the total discharge. Lateral flow to the south is about 1 percent of the total discharge.
- Interchange between the Upper and Lower Floridan aquifer layers is relatively small (about 290 cubic feet per second) compared with the flow within the Upper Floridan (about 1,950 cubic feet per second).
- The model-derived transmissivities are considered to have more regional significance than transmissivity values derived from individual aquifer tests.

The imposition of pumping has altered the flow system, but not to a great degree. The simulated effects of 1978 pumpage (about 560 million gallons per day) on the predevelopment Floridan aquifer system flow regime are summarized as follows:

- An average areal drawdown of about 4 feet has occurred in the Upper Floridan aquifer.
- Downward leakage to the Floridan from the overlying surficial aquifer has increased by about 600 cubic feet per second (from about 1,900 to about 2,500 cubic feet per second).
- Upward leakage from the Floridan to the surficial aquifer has decreased about 150 cubic feet per second (from about 530 to about 380 cubic feet per second).
- Spring flow has decreased about 90 cubic feet per second (from about 1,330 to 1,240 cubic feet per second).
- Lateral outflow at boundaries has increased in some areas and decreased in other areas, resulting in a net increase of about 15 cubic feet per second.

Simulation was used to investigate the effects of hypothetical development, as follows:

- Doubling the 1978 municipal pumpage would cause relatively small increases in drawdown, with 10 feet or more increase only near the centers of pumping and 20 feet or more only near Orlando.
- Raising elevations of spring pools would cause Upper Floridan head buildup near springs but little change in spring discharge when steady-state conditions are reached.

- Floridan pumpage tends to induce leakage from the overlying surficial aquifer system and to reduce upward discharge to it, thereby lowering the water table.
- Hydrologic analysis of Floridan aquifer system discharge led to the discovery and measurement of two hitherto undocumented springs.

INTRODUCTION

BACKGROUND

The Floridan aquifer system is one of the most areally extensive and widely used sources of ground-water supplies in the Southeastern United States (Cederstrom and others, 1979). The Floridan underlies about 100,000 mi^2, including all of Florida, south Georgia, southwest Alabama, and extreme south South Carolina. More than 3 billion gallons of water are pumped daily from the aquifer system, making it a major source of municipal, rural, industrial, and agricultural water supply in most of Florida and south Georgia, and in small parts of Alabama and South Carolina.

In October 1978, the U.S. Geological Survey began a study to provide a complete and detailed hydrogeologic description of the Floridan aquifer system, including its geology, geochemistry, and flow system. That investigation is herein referred to as the "Floridan aquifer system RASA" (Regional Aquifer-System Analysis), or "RASA." Early in the investigation and in some of the interim reports, the investigation was variously referred to as the "Southeastern Limestone RASA" or the "Tertiary Limestone RASA."

The Floridan aquifer system RASA was a 5-yr effort that included (1) synthesis of all existing data and presentation of a series of regional hydrogeologic and geochemical maps, (2) gathering of new hydrologic data to fill data voids, and (3) design and calibration of a large-scale, coarse-grid regional digital computer model of the aquifer system and four more detailed subregional models of selected areas of the Floridan aquifer system (fig. 1).

The results of the Floridan RASA study are presented in nine chapters in U.S. Geological Survey Professional Paper 1403. Professional Paper (PP) 1403–A summarizes the overall hydrology of the Floridan aquifer system. PP 1403–B describes the regional hydrogeologic framework. PP 1403–C describes the regional ground-water flow system, hydraulics, and ground-water development. PP 1403–D, –E, –F, and –H are detailed hydrologic descriptions that include computer simulation of the Floridan aquifer flow system in subregional areas: south Georgia, south South Carolina, and northeast Florida (PP 1403–D), east-central Florida (PP 1403–E), west-central Florida (PP 1403–F), and southwest Georgia and northwest Florida (PP 1403–H). PP 1403–G describes the hydrogeology and geochemistry of the saline ground-water flow system of south Florida. PP 1403–I describes the regional Floridan aquifer system ground-water chemistry.

The development and calibration of the regional model and of three of the four subregional models took place in two phases. The first phase consisted of assembling and calibrating models that simulated flow in the aquifer system prior to its development. The models that resulted from phase 1 are reported in the U.S. Geological Survey Water-Resources Investigations Report series and cover (1) the regional aquifer system (Bush, 1982), (2) east-central Florida (Tibbals, 1981), (3) west-central Florida (Ryder, 1982), and (4) northeast Florida and coastal parts of Georgia and South Carolina (Krause, 1982).

The second phase consisted of assembling and calibrating computer models that simulated flow in the aquifer system under pumping stresses. The models were also used to evaluate the effects of large future increases in ground-water pumpage in selected areas.

Prior to this RASA study, the U.S. Geological Survey had constructed two computer models to simulate Floridan aquifer ground-water flow in the east-central Florida area. Those models (Bush, 1978, and Grubb and Rutledge, 1979) simulated ground-water conditions in central Volusia County and in the Green Swamp area, respectively. General information and data from those models are incorporated in the RASA model described herein.

PURPOSE AND SCOPE

This report describes the hydrogeologic framework and ground-water flow in the Floridan aquifer system in east-central Florida, quantifies the amounts and determines the locations of recharge and discharge areas of the Floridan, and determines the effects that pumping stresses have had on hydraulic heads in the system.

Although Floridan aquifer system geology and ground-water chemistry are briefly described in this report, the reader is referred to PP 1403–B (Miller, 1986) and –I (Sprinkle, in press) for more complete discussions.

PREVIOUS INVESTIGATIONS

Many investigators have studied the Floridan aquifer system ground-water resource in east-central Florida. Among the more notable pioneer studies are those by Brown (1925, 1937), Cooke (1939, 1945), Fuller (1904, 1905), Matson and Sanford (1913), Sellards (1908), Stringfield (1933, 1936a, 1936b, 1938), Stringfield and

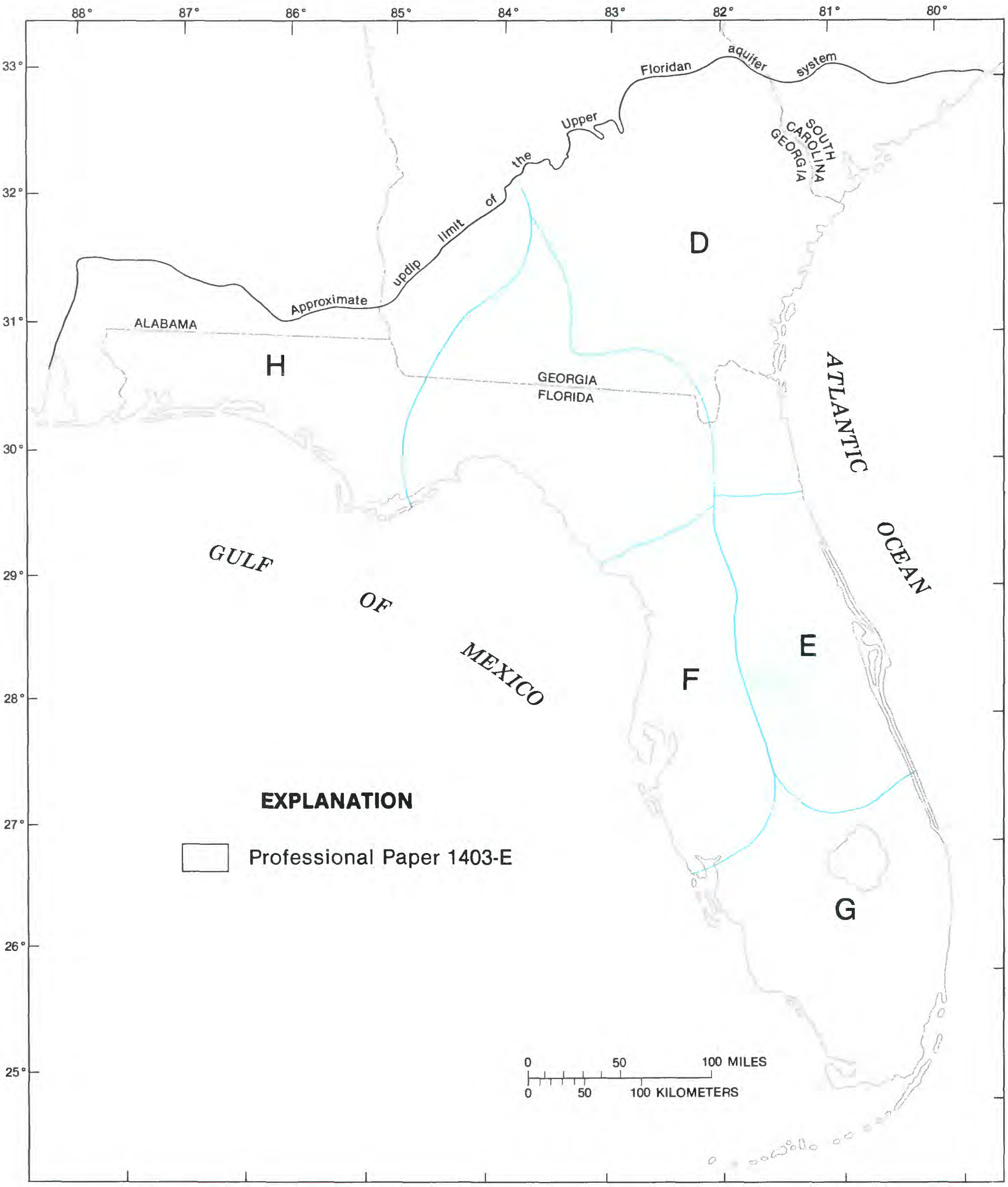

FIGURE 1.—Location of Floridan RASA subregional study areas.

Westendick (1935), Thompson and Stringfield (1931), and Unklesbay (1944).

Later, important areal hydrogeologic studies were conducted by Back (1963), Bermes and others (1963), Brown and Reece (1979), Cederstrom and others (1979), Clark and others (1964), Cooper and others (1953), Cooper and Stringfield (1950), Crain and others (1975), Faulkner (1973), Ferguson and others (1947), Frazee (1980), Johnston and others (1980), Klein (1975), Klein and others (1964), Knochenmus (1971), Knochenmus and Beard (1971), Knochenmus and Hughes (1976), Kohout (1959), Kohout and others (1977), Lichtler (1960, 1972), Lichtler and others (1968), Manheim (1967), McGuinness (1963), Miller (1982a, b, c, d, e), Parker and others (1955), Pascale (1975), Pride and others (1966), Rosenau and others (1977), Shampine (1975a, b, c, d), Snell and Anderson (1970), H.G. Stewart, Jr. (1966), J.W. Stewart (1980), Stringfield (1966), Tibbals (1975b, 1977), White (1958, 1970), and Wyrick (1960).

Investigations that included computer simulations of ground-water flow were conducted by Bush (1978, 1982), Grubb and Rutledge (1979), Krause (1982), Ryder (1982), and Tibbals (1981).

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The author expresses his appreciation to Douglas Munch (St. Johns River Water Management District) and to Abe Kreitman (South Florida Water Management District) and their respective staffs for their contributions of data and helpful information. Special thanks are due Breck Johnson, Umatilla, Fla., for the loan of special diving equipment and for his active participation in the documentation and measurement of Croaker Hole Spring.

WELL-NUMBERING SYSTEM

Well data used in this study were taken from files and publications of various sources. Each source has a unique well-numbering system or site identifier. Therefore, to attain a consistent well-numbering system the wells used in this study were assigned reference numbers in sequential format. Well locations are shown in figure 2. Appendix A contains an index to wells used in this study.

DESCRIPTION OF THE AREA

The east-central Florida RASA study area (fig. 3) consists of about 13,700 mi^2 and includes the counties of Brevard, Flagler, Indian River, Orange, Osceola, Putnam, Seminole, and Volusia and parts of the counties of Alachua, Clay, Glades, Highlands, Lake, Marion, Okeechobee, Polk, St. Johns, and St. Lucie.

The principal industries are tourism, agriculture, space research, and light manufacturing. Agricultural products include citrus products, cattle, dairy products, vegetables, ornamental plants, poultry, timber, and pulpwood.

TOPOGRAPHY

The topography ranges from rolling highlands in the northwest, west-central, and southwest parts of the study area to flat, swampy lowlands along the east coast and along the St. Johns River flood plain (fig. 3). Land-surface altitudes in the rolling highlands generally range from 100 to 200 ft above sea level and rise to as much as 310 ft just west of Lake Apopka in southeast Lake County. In the north-central and south-central parts, the land surface is moderately rolling to flat and altitudes range from 35 to 100 ft. In the coastal areas and along the St. Johns River, altitudes are generally less than 35 ft and, except for the coastal dune ridges, the terrain is generally flat and swampy.

DRAINAGE

The north and southeast part of the study area is drained by the northward-flowing St. Johns River and its major tributary, the Oklawaha River (fig. 3). The southwest part is drained by the southward-flowing Kissimmee River and its tributaries. Parts of the extreme west part of the study area are drained by the Withlacoochee River and the Peace River. The extreme east part drains into the coastal basin. Runoff (unaugmented by sewage, spring flow, or irrigation return flow) to streams ranges from virtually nil in the rolling sandhills to as much as 18 to 20 in/yr in the areas where the surface drainage system is well developed (Lichtler, 1972, p. 9).

CLIMATE

The climate of the study area is classified as subtropical humid and is characterized by warm, relatively wet summers and mild, relatively dry winters. The average air temperature ranges from about 69 °F in the north to about 73 °F in the south. Most years have a few days of freezing temperatures, but the minimum temperature rarely falls below 20 °F. The maximum temperature frequently rises to 90 °F but only occasionally exceeds 100 °F.

Rainfall is unevenly distributed during the year. About 55 percent of the annual rainfall occurs during four summer months, June, July, August, and September

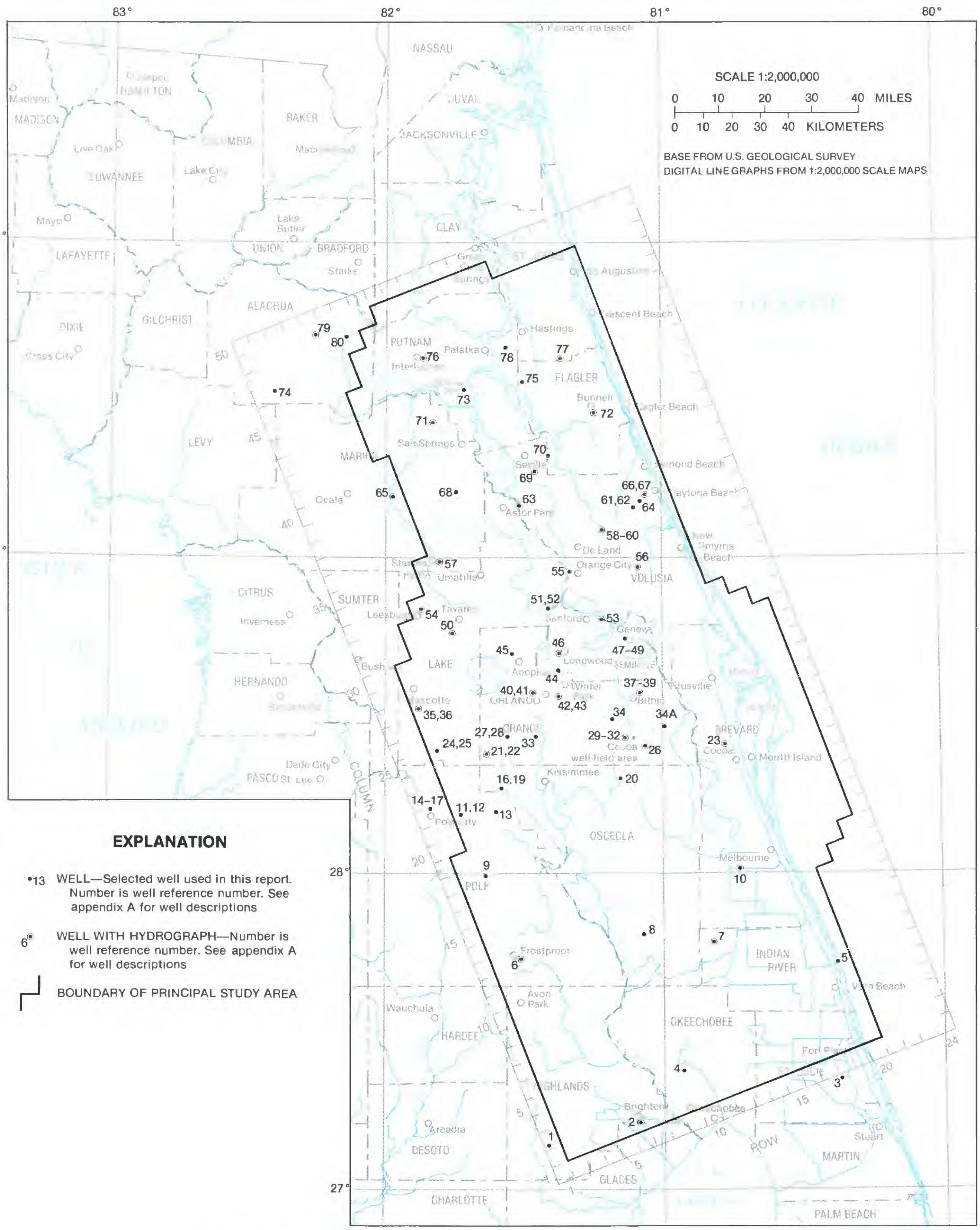


FIGURE 2.—Location of wells, other than drainage wells, used in this study.

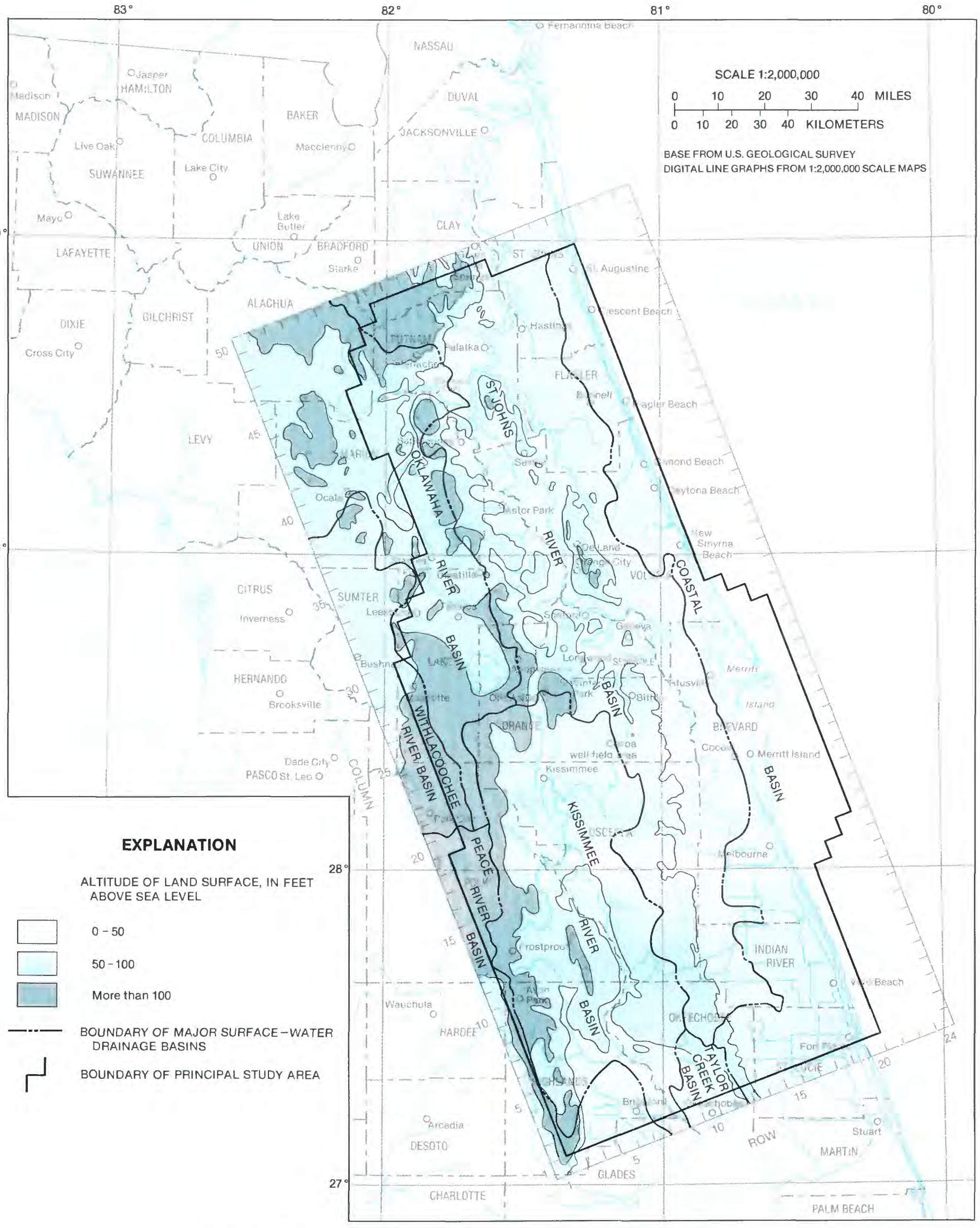


FIGURE 3.—Location of study area, generalized topography, and major surface drainage basins.

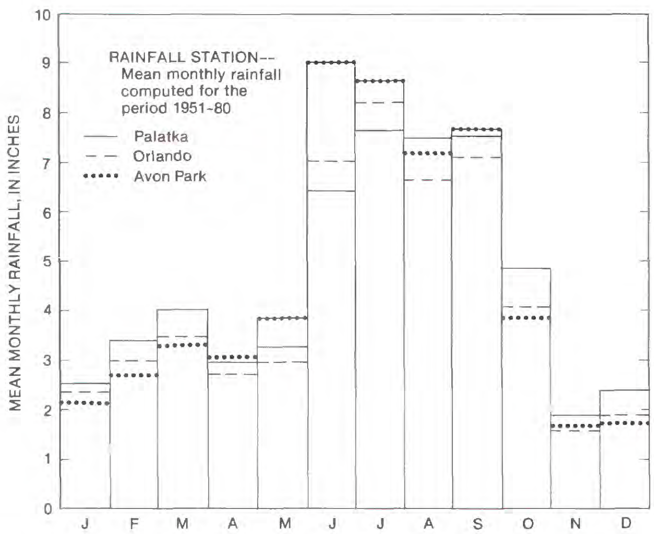


FIGURE 4.—Mean monthly rainfall at Palatka, Orlando, and Avon Park (National Oceanic and Atmospheric Administration, 1951–80).

(fig. 4). The rainfall is usually unevenly distributed throughout the area, especially during the summer. This is because most of the summer rainfall is derived from local showers or thunderstorms that occur randomly. The normal summer rainfall can be substantially augmented by tropical storms and hurricanes that pass through or near the Florida peninsula from time to time.

Winter rainfall generally results from large cold fronts that move from northwest to southeast and cause the warm, resident airmasses to lose their moisture. The precipitation is almost always in the form of rain, but it occasionally occurs as hail or, on extremely rare occasions, as snow. Winter rainfall generally occurs over wide areas and thus is not as spotty as is summer rainfall. The average annual rainfall is as high as 55 inches in the north and as high as 59 inches in the extreme southeast but generally is about 52 in over most of the study area (fig. 5).

LONG-TERM VARIABILITY OF RAINFALL

The short-term random nature of rainfall is obvious. Rainfall varies from place to place as well as from day to day and year to year. However, within these random occurrences and on an annual basis there are cycles of dry seasons and wet seasons.

Long-term, multiyear cycles, if they exist, are difficult to discern, primarily because of the relatively short length of rainfall record available. The longest rainfall record available in or near the study area is that of Jacksonville in northeast Florida. That record begins in 1867 (fig. 6). The next longest period of record common to several rainfall stations in and near the study area begins in 1903 and is that of Palatka, Orlando, and Avon Park. Figure 6 shows graphs of cumulative departure from average rainfall at Jacksonville from 1867 to 1981 and at Jacksonville, Palatka, Orlando, and Avon Park from 1903 to 1981. The vertical positions of the graphs are not as diagnostic as are the slopes of the graphs or the changes in position of the graphs from one year to the next. A rising line slope indicates above-average rainfall whereas a declining line slope shows below-average rainfall. For example, the long-term record at Jacksonville shows that from 1867 to 1888 there was a total excess (that which is above average) of about 105 in, an average excess of about 4.75 in/yr. However, from 1888 to about 1931 a drought of record proportions occurred. During that 43-yr period, the rainfall deficiency totaled about 192 in, an average deficiency of about 4.5 in/yr. From 1931 to 1943 there is no discernible trend; this indicates that, during that period, rainfall tended to be about average, with alternating short periods of wet and dry years.

The rainfall data for Palatka, Orlando, and Avon Park for the period 1903–81 can be analyzed similarly to that of Jacksonville for 1867–1981. For comparative purposes, the 1903–81 rainfall data for Jacksonville are included in figure 6. The records for Jacksonville and for two of the three east-central Florida stations show similarities. For example, the record for Jacksonville, Palatka, and Avon Park shows a dry period from about 1905 to about 1917–18. The record for Orlando shows the dry period ending in about 1911, after which a sustained period of generally above-average rainfall began that ended in about 1961. All four rainfall stations show the drought that extended through 1981. That sustained dry period began earlier at some stations than at others. At Orlando, the drought began in about 1961, at Avon Park, in 1969, at Jacksonville, in 1973, and at Palatka, in 1976. During the period 1976–81 the rainfall deficiency for the four stations averaged about 5.5 in/yr. Though severe, that drought, at this writing (1982), has been going on a relatively short time and, aside from the effects of increased pumping, is probably not affecting the hydrologic regimen as did the drought of 1888 to 1931. The significance of the 1888–1931 drought on ground-water levels is discussed in a later section.

EVAPOTRANSPIRATION

It is difficult to quantify evapotranspiration, but the upper and lower limits of annual evapotranspiration rates can be estimated. The upper limit of evapotranspiration is approximately equal to the rate at which water can evaporate from a free-water surface (such as a lake) under natural conditions. The maximum potential evaporation ranges from about 46 in/yr in the northeast part

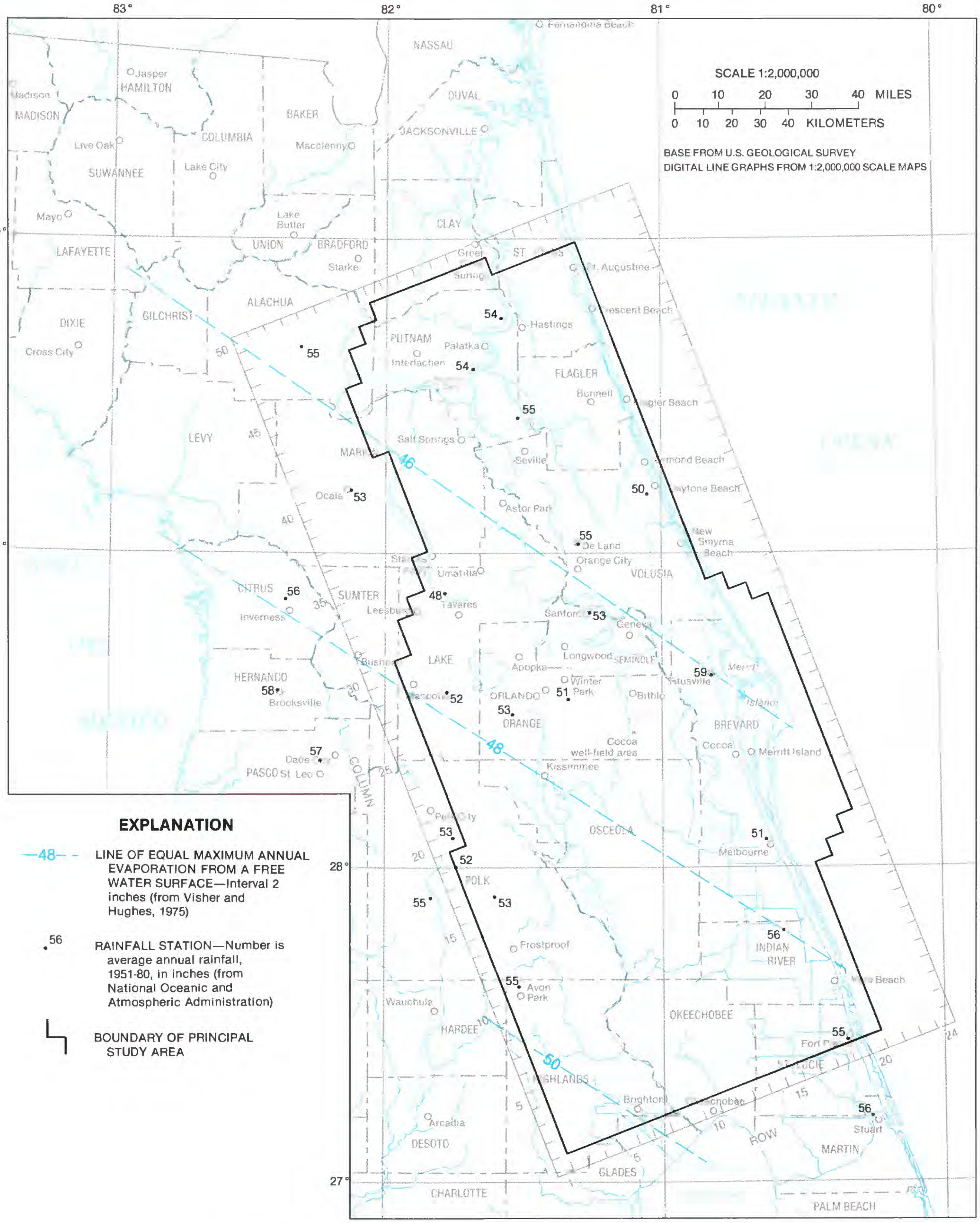


FIGURE 5.—Average annual rainfall and maximum potential evaporation.

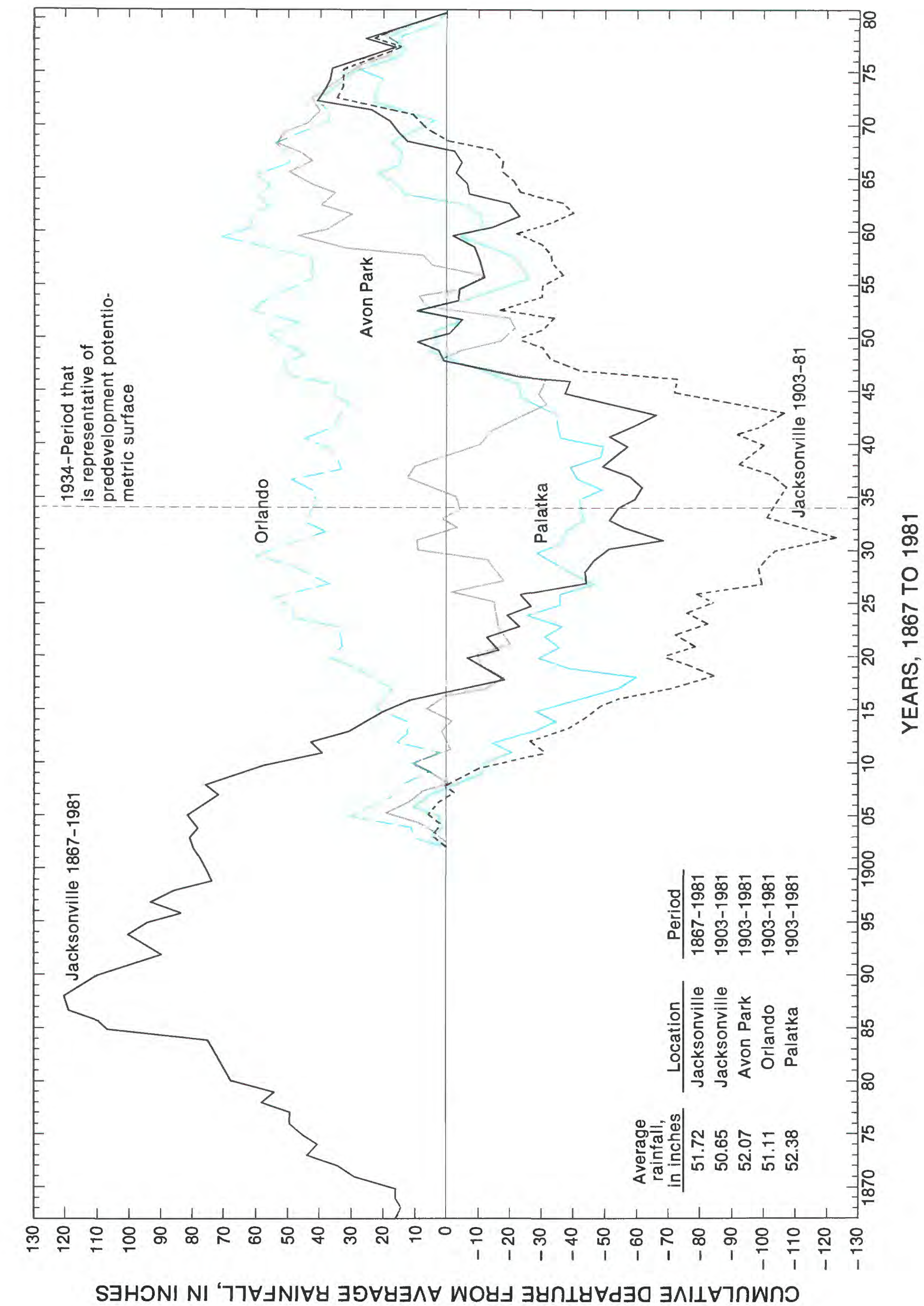


FIGURE 6.—Cumulative departure from average rainfall at Jacksonville (1867–1981) and at Jacksonville, Palatka, Orlando, and Avon Park (1903–81).

of the study area (fig. 5) to about 50 in/yr in the southwest part (Visher and Hughes, 1975).

The lowest rates of evapotranspiration probably occur in those parts of the study area that have deep, well-drained soils and a deep water table. In those areas, the land surface tends to be pocked by sinkholes and there is little or no surface runoff. In several spring areas, almost all drainage is derived from vertical percolation to the water table in the surficial aquifer and, thence, to the Upper Floridan aquifer, from which, in turn, it is discharged by the springs. The water that is discharged by the springs is all that remains of the rain that fell on the springs' ground-water basins; the remainder of the water ran off, was returned to the atmosphere by evapotranspiration, or was pumped by wells. Evapotranspiration, then, is equal to rainfall minus spring flow, runoff, and pumpage. Various investigators have estimated the minimum rate of evapotranspiration to range from 25 to 35 in/yr (Warren Anderson, oral commun., October 13, 1975; Knochenmus and Hughes, 1976; Tibbals, 1978).

It is probable that, in east-central Florida, the best indicator of annual rates of evapotranspiration is depth to water table. If the water table is deep, say, more than 10 to 15 ft below land surface, it is likely that the surface soils are well drained and that the water table is below the principal root zone of most plants. It follows, then, that evapotranspiration rates in areas where the water table is deep would be lower than they would be in areas where the water table is at or near land surface. Tibbals (1978) constructed a curve that describes an estimated relation of evapotranspiration rate to water-table depth in east-central Florida (fig. 7). The maximum evapotranspiration rate, 48 in/yr, occurs in areas where the water table is at or near land surface. The minimum rate, about 30 in/yr, occurs in areas where the water table is at depths of about 13 ft and greater. At those depths, little or no evapotranspiration occurs from the surface of the water table. Thus, evapotranspiration varies from about 48 to about 30 in/yr and occurs in the depth interval 0 to 13 ft.

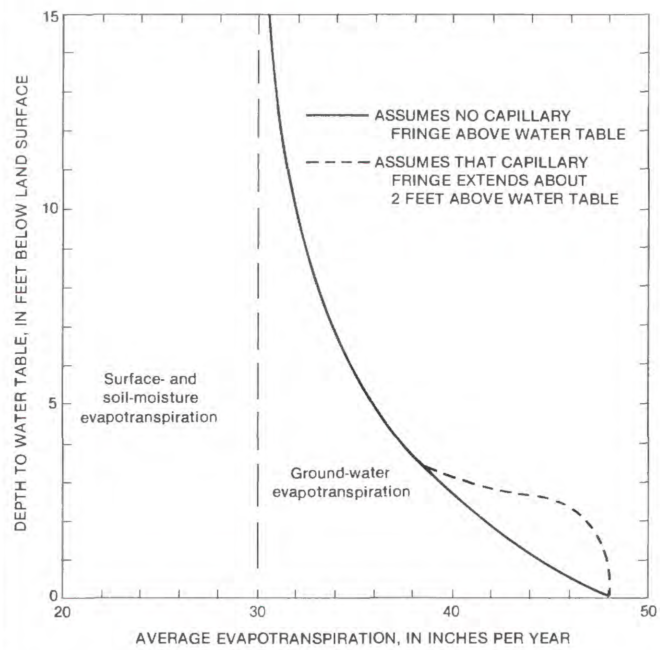


FIGURE 7.—Estimated relation of evapotranspiration to water-table depth in east-central Florida (modified from Tibbals, 1978).

HYDROGEOLOGY

The geology of the study area has been described wholly or in part by many investigators, including Matson and Sanford (1913), Applin and Applin (1944), Cooke (1939, 1945), Puri and Vernon (1959), Stringfield (1966), and White (1958, 1970). The most recent comprehensive descriptions of the geology of the Floridan aquifer system are by Miller (1982a, b, c, d, e) and by Miller (1986) in chapter B of this Professional Paper series.

The occurrence, movement, availability, quality, and quantity of ground water are related to the geology. The study area is underlain mostly by sand, limestone, dolomite, gypsum, anhydrite, and shale which together range in thickness from about 5,500 to 12,000 ft. Below those depths are the rocks that make up the basement complex (fig. 8).

In this report, discussion of geology and structure is limited to a brief description of the hydrogeologic framework of the Floridan aquifer system and related geologic units. This includes the permeable sequence of limestones that constitute the Floridan aquifer system and the hydraulically pertinent formations above and immediately below the Floridan to depths ranging from about 1,800 to 3,500 ft. Figure 8 summarizes the hydrogeology by describing the geologic and hydrogeologic units and showing their conceptual relations to the ground-water flow model described in a later section. The aquifers and confining units that make up the Floridan aquifer system have different nomenclature from place to place throughout the RASA study area. Figure 9 shows these differences in the various subregional study areas and how those differences are reconciled in the regional study area.

SURFICIAL AQUIFER

The uppermost water-bearing formation is the surficial aquifer. Throughout most of the study area, the surficial aquifer generally consists of fine to medium quartz sands that contain varying amounts of silt, clay, and loose shell. In some coastal areas the surficial aquifer also contains beds of cemented shell (coquina). Water in the surficial aquifer is unconfined. In the swampy lowlands and flatlands, the water table is generally at or near land surface throughout most of the year. In the rolling highlands, the water table is generally a subdued reflection of the topography (fig. 3) but can be several tens of feet below land surface. At depths usually less than 75 ft below the water table, the sands of the surficial aquifer generally grade into less permeable clayey or silty sands that act as the overlying confining unit for the limestones that constitute the Floridan aquifer system.

The surficial aquifer is recharged by local rainfall, irrigation, some lakes, ditches, and streams, septic tank effluent, sewage or stormwater holding pond effluent, and, in areas where the potentiometric surface of the Upper Floridan aquifer is above the water table, upward leakage from the Upper Floridan. Water leaves the surficial aquifer by seepage to some lakes, ditches, and streams, by evapotranspiration where the water table is near land surface, by pumpage, and, where the potentiometric surface of the Upper Floridan aquifer is below the water table, by downward leakage to the Floridan. The surficial aquifer system is used for potable supplies only in coastal areas where the Floridan contains brackish water. In the remainder of the study area, the most important function of the surficial aquifer is to store water, some of which recharges the Upper Floridan aquifer. The surficial aquifer is little used as a source of water supply because, relative to the Floridan aquifer system, its permeability is low, resulting in relatively low yields to wells. Also, water from the surficial aquifer often contains high concentrations of dissolved iron and is sometimes highly colored.

FLORIDAN AQUIFER SYSTEM

The Floridan aquifer system is composed of a sequence of limestone and dolomitic limestone that ranges in thickness from about 1,500 ft in the northwest part of the study area to about 3,300 ft in the extreme southwest part (fig. 10). The top of the Floridan is defined as the first occurrence of vertically persistent, permeable, consolidated, carbonate rocks. The top of the Floridan aquifer system is highest in east Marion, Lake, central Volusia, west Orange, west Seminole, and north Polk Counties (fig. 11). In those areas the top is at or slightly above sea level. The top of the aquifer system dips to about 100 ft below sea level to the northwest, to about 200 ft below sea level to the northeast, and to about 500 ft below sea level at the south end of the study area. The aquifer system does not outcrop in the study area.

The faults shown on the top of the Floridan aquifer system in figure 11 have little vertical displacement and, except for the fault in the vicinity of Blue Spring, probably extend only into the Upper Floridan (J.A. Miller, U.S. Geological Survey, written commun., January 1980). It should be noted that the faults shown are probably not all that exist. Small faults are not mappable on a regional basis. Significantly, the faults tend to be aligned with major surface-water features such as the St. Johns River, the Kissimmee River, and the Indian River. The effects of faulting on the Floridan aquifer system and its ground-water quality are discussed in a later section.

In addition to the relief on the top of the Floridan caused by faults, considerable relief is caused by subsurface subsidence. The surface expression of such subsidence is often in the form of closed or nearly closed topographic depressions that, in some instances, contain lakes. Subsurface subsidence is caused by the gradual dissolution of limestone and the collapse of the overlying sediments into the volume previously occupied by the limestone. The collapse of the overlying sediments can be subtle, affect large areas, and occur over a long period of time, or it can be quite pronounced, affect relatively small areas, and occur suddenly. A sudden subsidence is generally referred to as "sinkhole collapse." Almost all modern-day occurrences of sinkholes are in areas of the Floridan aquifer system where recharge rates are high and, generally, where the depth to the top of the Floridan is less than 200 ft.

The base of the Floridan aquifer system is defined as the first occurrence of vertically persistent beds of anhydrite or, in their absence, the top of the transition of the generally permeable carbonate sequence of rocks to the much less permeable gypsiferous and anhydritic carbonate beds. These beds have very low permeability and serve as the hydraulic base of the Floridan aquifer system. In the study area, the base of the Floridan ranges from about 1,700 ft below sea level in the northwest to about 3,800 ft below sea level in the extreme southwest (fig. 12).

The geologic formations (fig. 8) that make up the Floridan aquifer system in east-central Florida are, from top to bottom, Eocene rocks comprising the Suwannee Limestone (where present), the Ocala Limestone (where present), the Avon Park Formation, and, in some areas, all or part of the Oldsmar Formation. Paleocene rocks of the Cedar Keys Formation generally form the base of the Floridan aquifer system except in areas where the upper part of the Cedar Keys is permeable. In some areas the basal parts of the Oldsmar Formation are relatively impermeable.

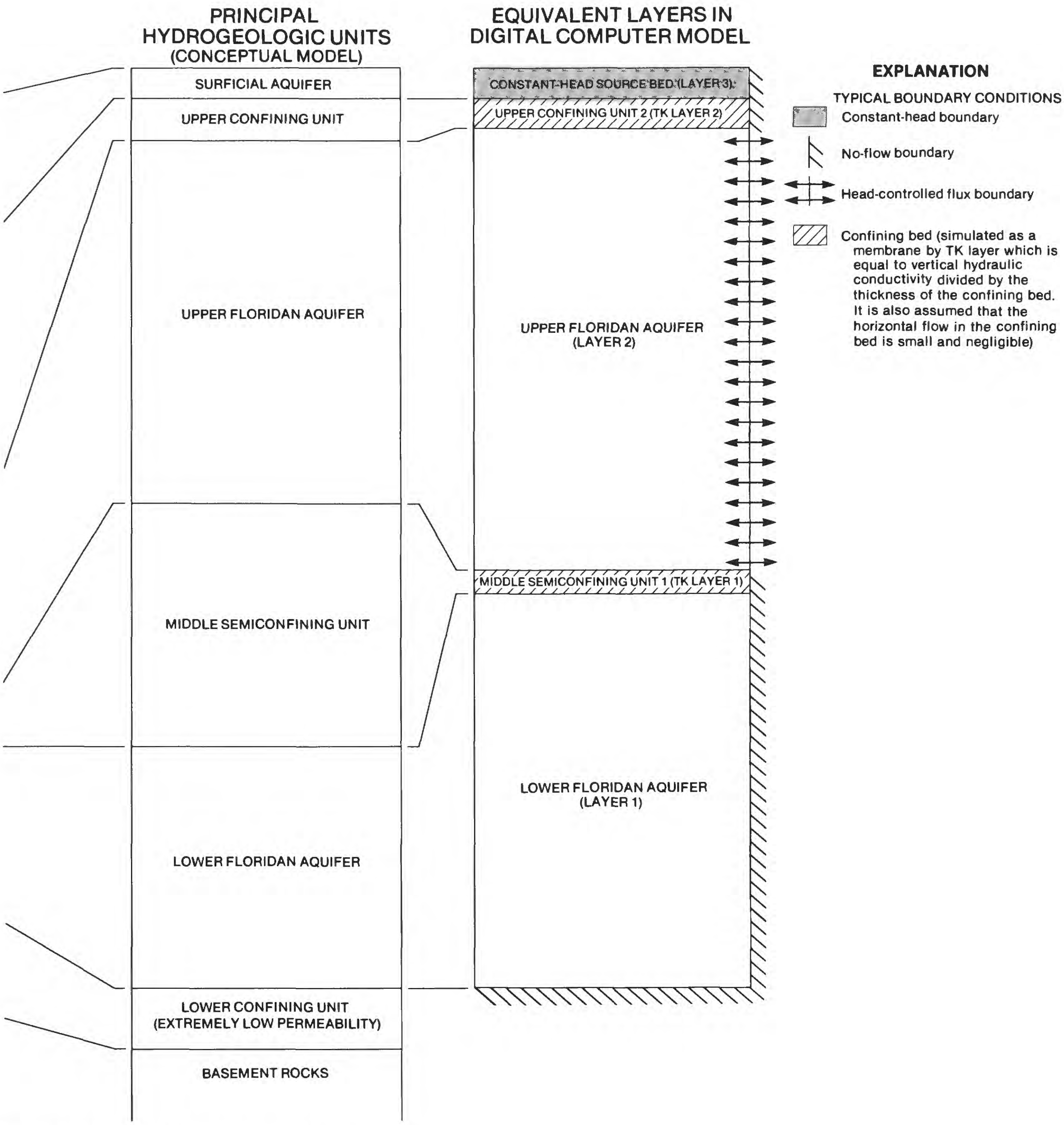
The Ocala Limestone constitutes the top of the Floridan aquifer system over most of the study area (Miller, 1982c). The Ocala Limestone is absent and the Avon Park Formation constitutes the top of the Floridan in southwest Volusia, north Seminole, and extreme north-

GEOLOGIC UNITS
(ADAPTED FROM FAULKNER, 1973, FIG. 2)

Era	System		Series		Stratigraphic unit	Thickness (feet)	Lithology	Aquifer (From CHAPTER B)
CENOZOIC	QUATERNARY		Holocene		Unnamed alluvial, lake, and windblown deposits	0-75	Alluvium, freshwater marl, peats and muds in stream and lake bottoms. Also, some dunes and other windblown sand.	SURFICIAL AQUIFER
							unconformity	
CENOZOIC	QUATERNARY		Pleistocene		Pamlico Formation and marine and estuarine terrace deposits	0-75	Mostly marine quartz sand, unconsolidated and generally well graded. Also, some fluviatile and lacustrine sand, clay, marl, and peat deposits.	SURFICIAL AQUIFER
							unconformity	
CENOZOIC	TERTIARY	UPPER	Pliocene		Jackson Bluff Formation	0-75 ±	Marine sands, argillaceous, carbonaceous; and sandy shell marl. Some phosphatic limestone.	
CENOZOIC	TERTIARY	UPPER	Pliocene		Alachua Formation	0-100 ±	Nonmarine interbedded deposits of clay, sand, and sandy clay; much of unit is phosphatic, base characterized by rubble of phosphate rock and silicified limestone residuum in a gray and green phosphatic clay matrix.	
CENOZOIC	TERTIARY	UPPER	Miocene		Fort Preston[1] Formation	0-100 ±	Nonmarine fluviatile sand, white to gray, variegated orange, purple and red in upper part, fine- to coarse-grained to pebbly, clayey, crossbedded.	
CENOZOIC	TERTIARY	UPPER	Miocene		Hawthorn Formation	0-300 ±	Marine interbedded sand, cream, white, and gray, phosphatic, often clayey; clay, green to gray and white, phosphatic, often sandy; dolomite, cream to white and gray, phosphatic, sandy, clayey; and some limestone, hard, dense, in part sandy and phosphatic. Tends to be sandy in upper part and dolomitic and limy in lower part.	
							unconformity	
CENOZOIC	TERTIARY	LOWER	Oligocene		Suwannee Limestone	0-150	Marine limestone, very pale orange, finely crystalline, small amounts of silt and clay.	FLORIDAN AQUIFER SYSTEM
							unconformity	
CENOZOIC	TERTIARY	LOWER	Eocene	Upper	[2]Ocala Limestone: Upper[3] member	0-325	Marine limestone, cream to white, soft, granular, highly porous, coquinal; often consists almost entirely of tests of foraminifers; cherty in places.	FLORIDAN AQUIFER SYSTEM
CENOZOIC	TERTIARY	LOWER	Eocene	Upper	[2]Ocala Limestone: Lower[4] member		Marine limestone, cream to tan and brown, granular, soft to firm, porous, highly fossiliferous; lower part at places is dolomite, gray and brown, crystalline, saccharoidal, porous.	FLORIDAN AQUIFER SYSTEM
							unconformity	
CENOZOIC	TERTIARY	LOWER	Eocene	Middle	Avon Park Formation	600-1600	Marine limestone, light brown to brown, finely fragmental, poor to good porosity, highly fossiliferous (mostly foraminifers); and dolomite, brown to dark brown, slightly porous to good porosity, crystalline, saccharoidal; both limestone and dolomite are carbonaceous or peaty; gypsum is present in small amounts. Marine limestone, light brown to brown, fragmental, highly fossiliferous, slightly carbonaceous or peaty and cherty; and dolomite, brown to dark brown with very minor amounts of gypsum and anhydrite. Unit is slightly porous to porous.	FLORIDAN AQUIFER SYSTEM
CENOZOIC	TERTIARY	LOWER	Eocene	Lower	Oldsmar Formation	300-1350	Marine limestone, light brown to chalky, white, porous, fossiliferous, with interbedded brown, porous, crystalline dolomite; minor amounts of anhydrite and gypsum.	
CENOZOIC	TERTIARY	LOWER	Paleocene		Cedar Keys Formation	500-2200	Marine dolomite, light gray, hard, slightly porous to porous, crystalline, in part fossiliferous, with considerable anhydrite and gypsum, some limestone.	
							unconformity	
MESOZOIC	CRETACEOUS		Upper and Lower Cretaceous			1500-?	Mostly marine Upper Cretaceous carbonate and evaporite rocks, sands and shales; thin Lower Cretaceous clastic section in some of area.	
							Coastal Plain Bedrock	
(?) PALEOZOIC and PRE-CAMBRIAN			DEVONIAN to PRECAMBRIAN (?)			Basement rocks	Marine Devonian, Silurian, and Ordovician quartzose sandstone and dark shale; lower Paleozoic (?) or Precambrian (?) rhyolite, tuff, and agglomerate.	

[1]Usage of Bureau of Geology, Florida Department of Natural Resources
[2]Ocala Group of Bureau of Geology, Florida Department of Natural Resources.
[3]Crystal River Formation of Ocala Group
[4]Inglis Formation and Williston Formation (older to younger) of Ocala Group.

FIGURE 8.—Geologic units, hydrogeologic units,



and equivalent layers used in computer model.

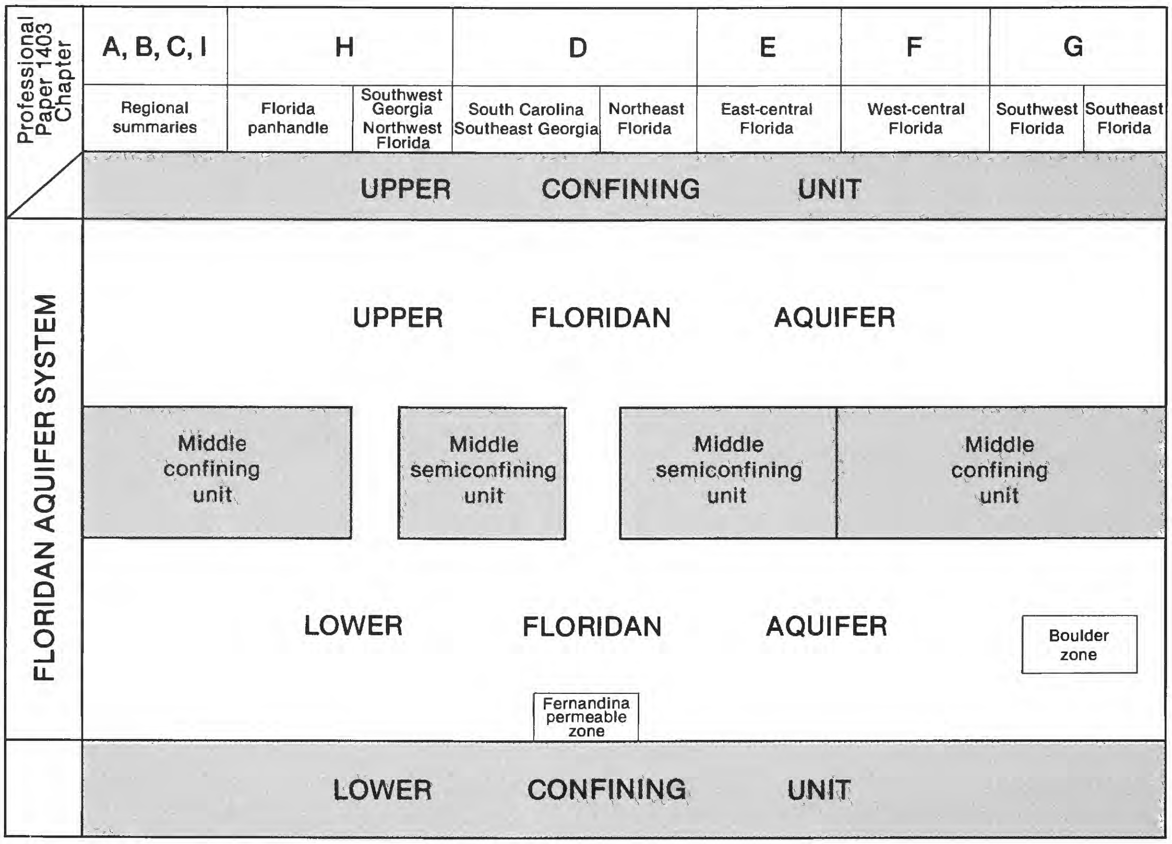


FIGURE 9.—Aquifers and confining units of the Floridan aquifer system.

east Lake Counties. The Suwannee Limestone constitutes the top of the Floridan aquifer system in the Highlands County area.

The Floridan aquifer system is divided on the basis of the vertical occurrence of two zones of relatively high permeability. Hereinafter, these zones are referred to as the "Upper Floridan" and "Lower Floridan" aquifers. The Upper and Lower Floridan are separated by a less permeable, soft, chalky limestone and dolomitic limestone sequence referred to as the "middle semiconfining unit." The unit is thin or absent in the west part of the study area, but is as much as 600 to 800 ft thick in east Orange County and in Okeechobee and west St. Lucie Counties (fig. 13). The depth to the middle semiconfining unit ranges from about 200 ft in Marion County to about 1,100 ft in St. Lucie County. The middle semiconfining unit is leaky, and the hydraulic connection between the Upper and Lower Floridan aquifers varies from place to place.

Figures 14–18 show the locations and geologic sections that generally describe the geology in the east-central Florida area.

In the extreme west part of the study area there is a separate and distinct confining unit composed primarily of intergranular anhydritic and gypsiferous limestone (figs. 17, 18). This unit is considerably less permeable than the middle semiconfining unit that is found in most of the study area. Because of its small areal extent, the anhydritic and gypsiferous confining bed is of only minor importance to the Floridan aquifer system in east-central Florida. However, in west-central Florida, this unit functions hydraulically as the base of the Floridan flow system.

In the extreme south part of the study area and beneath the Lower Floridan aquifer, there exists the northernmost extremity of a highly permeable cavernous zone generally referred to as the "Boulder Zone" (fig. 15). This zone, though important in south Florida from

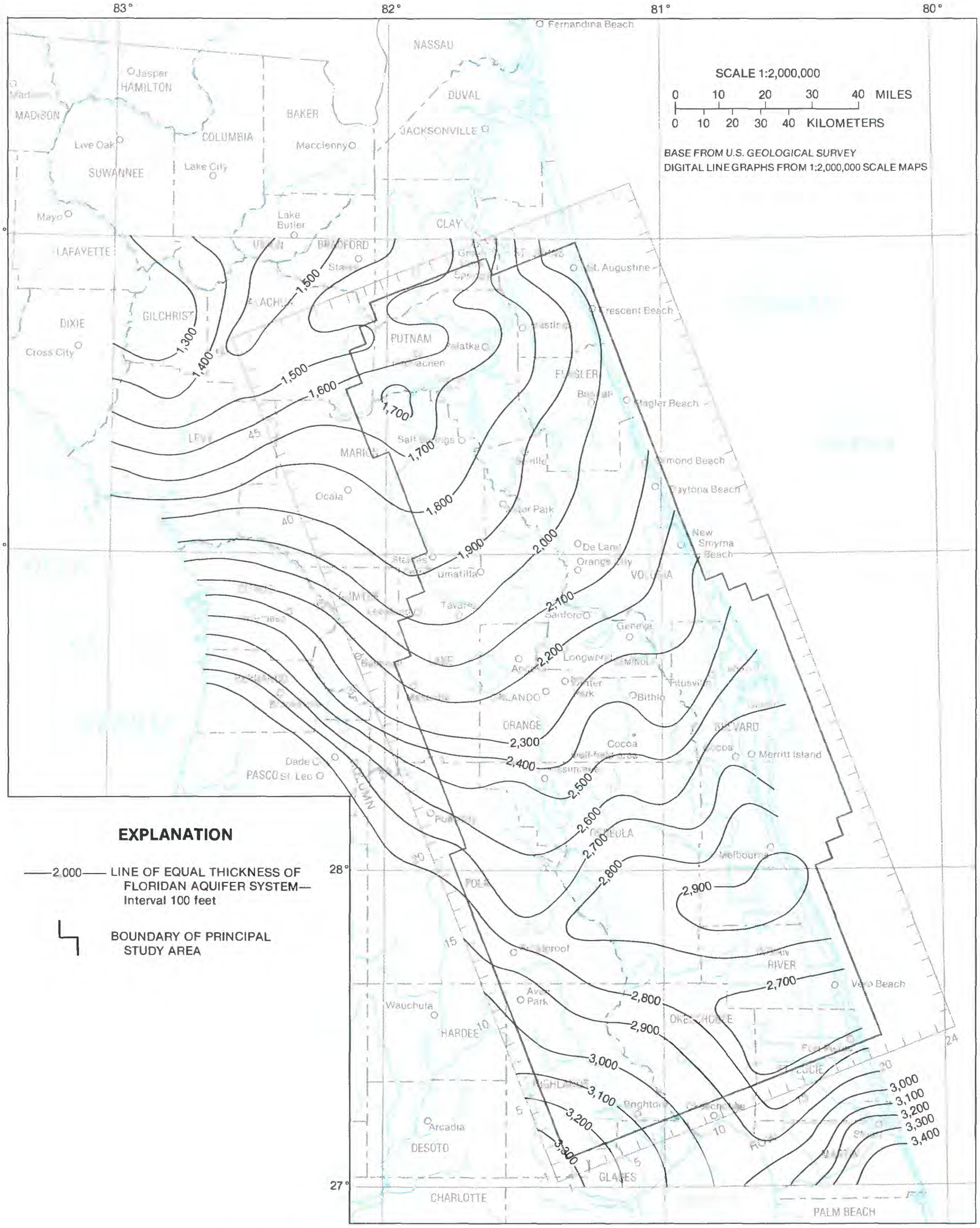


FIGURE 10.—Thickness of Floridan aquifer system (adapted from Miller, 1982d).

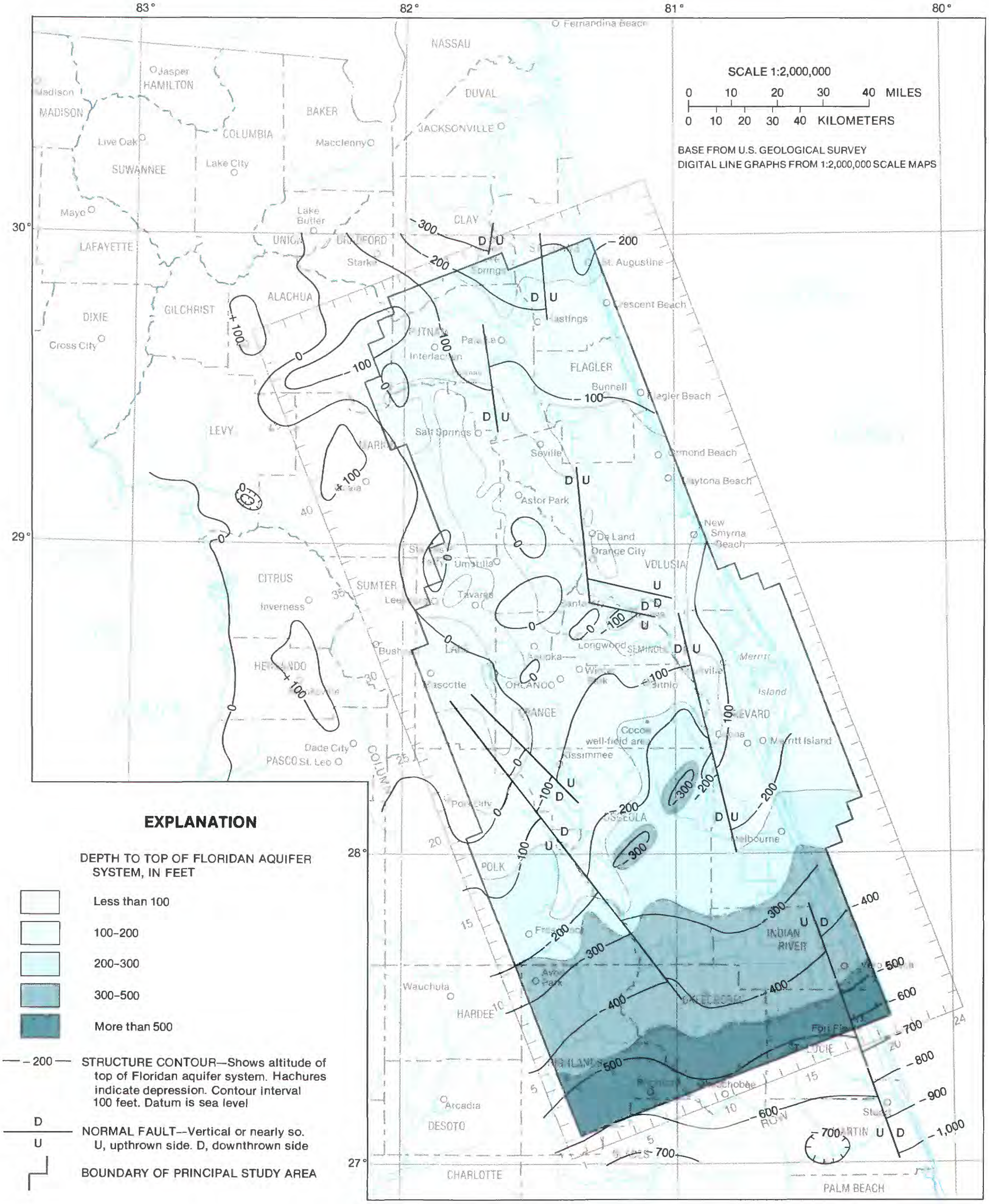


FIGURE 11.—Altitude and depth to top of Floridan aquifer system (adapted from Miller, 1982c).

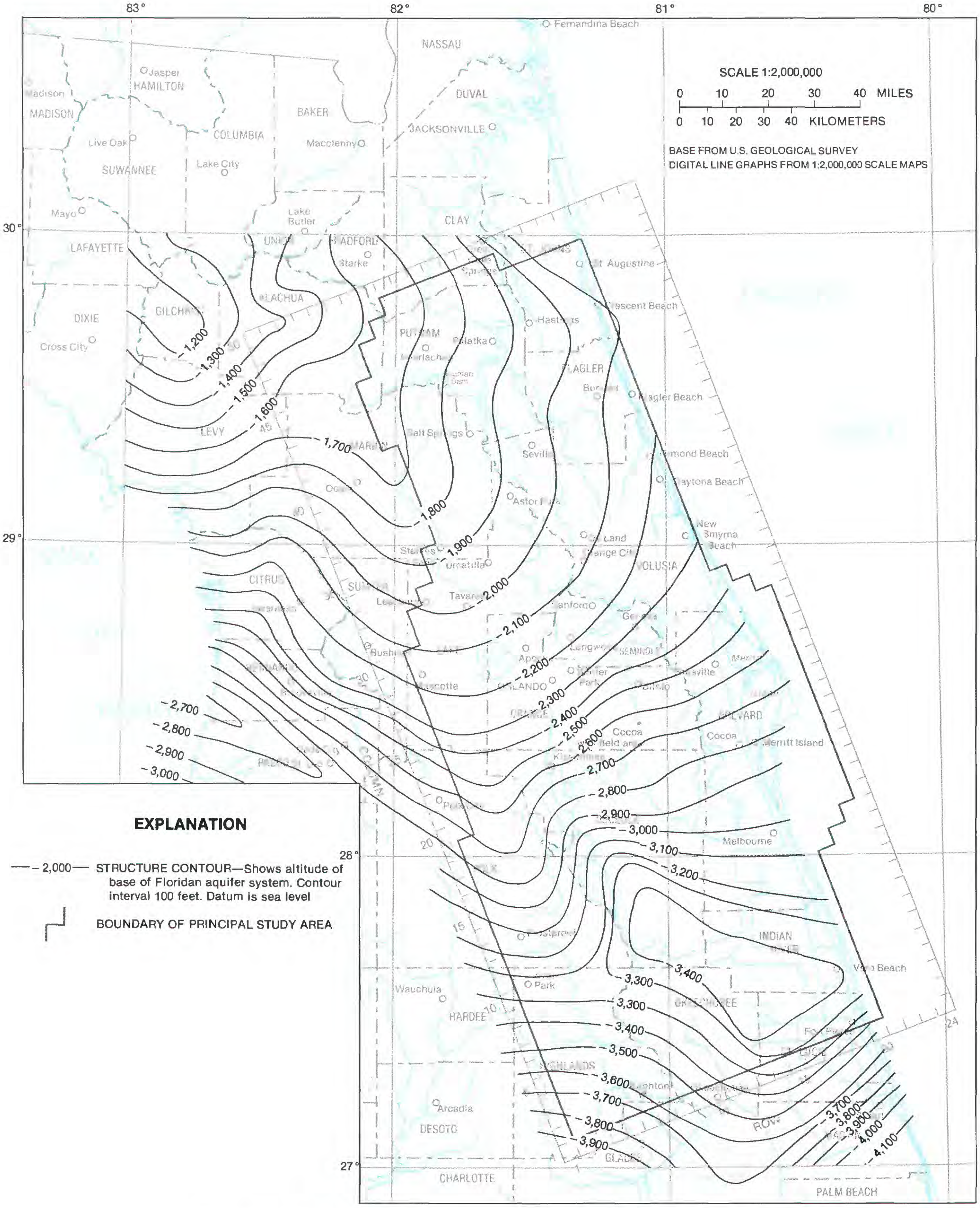


FIGURE 12.—Altitude of base of Floridan aquifer system (adapted from Miller, 1982b).

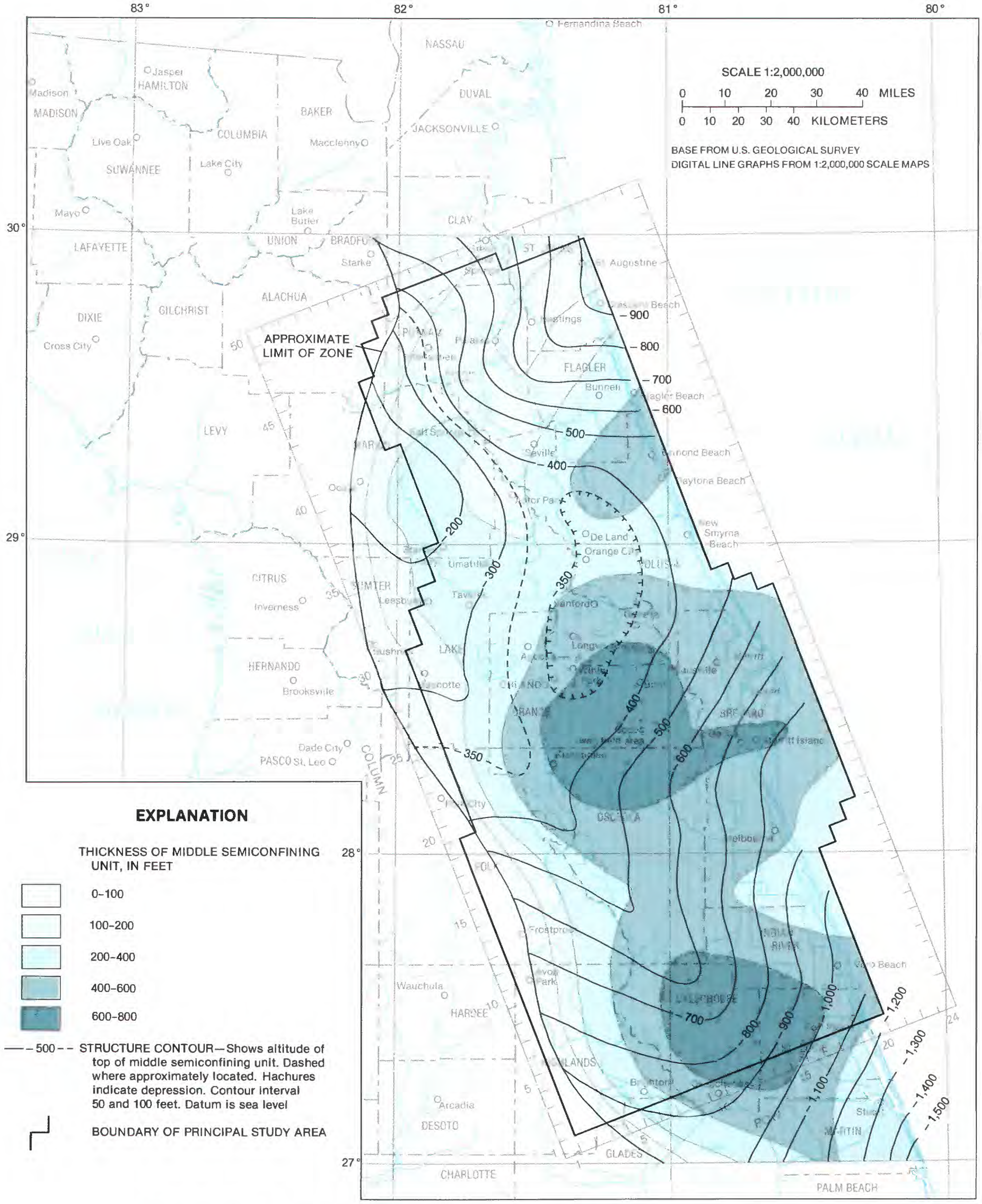


FIGURE 13.—Altitude of top and thickness of middle semiconfining unit (modified from Miller, 1982a).

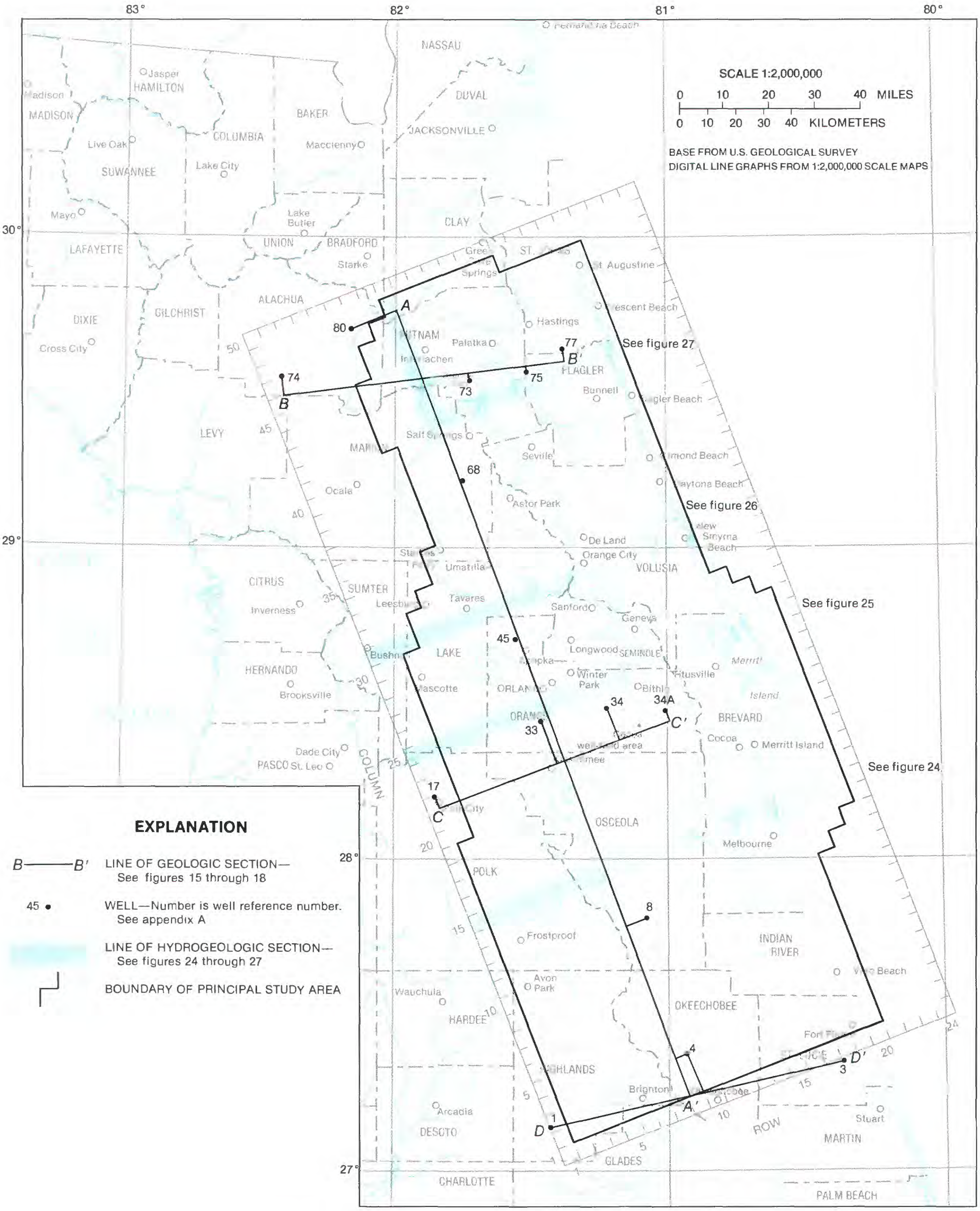


FIGURE 14.—Location of geologic and hydrogeologic sections.

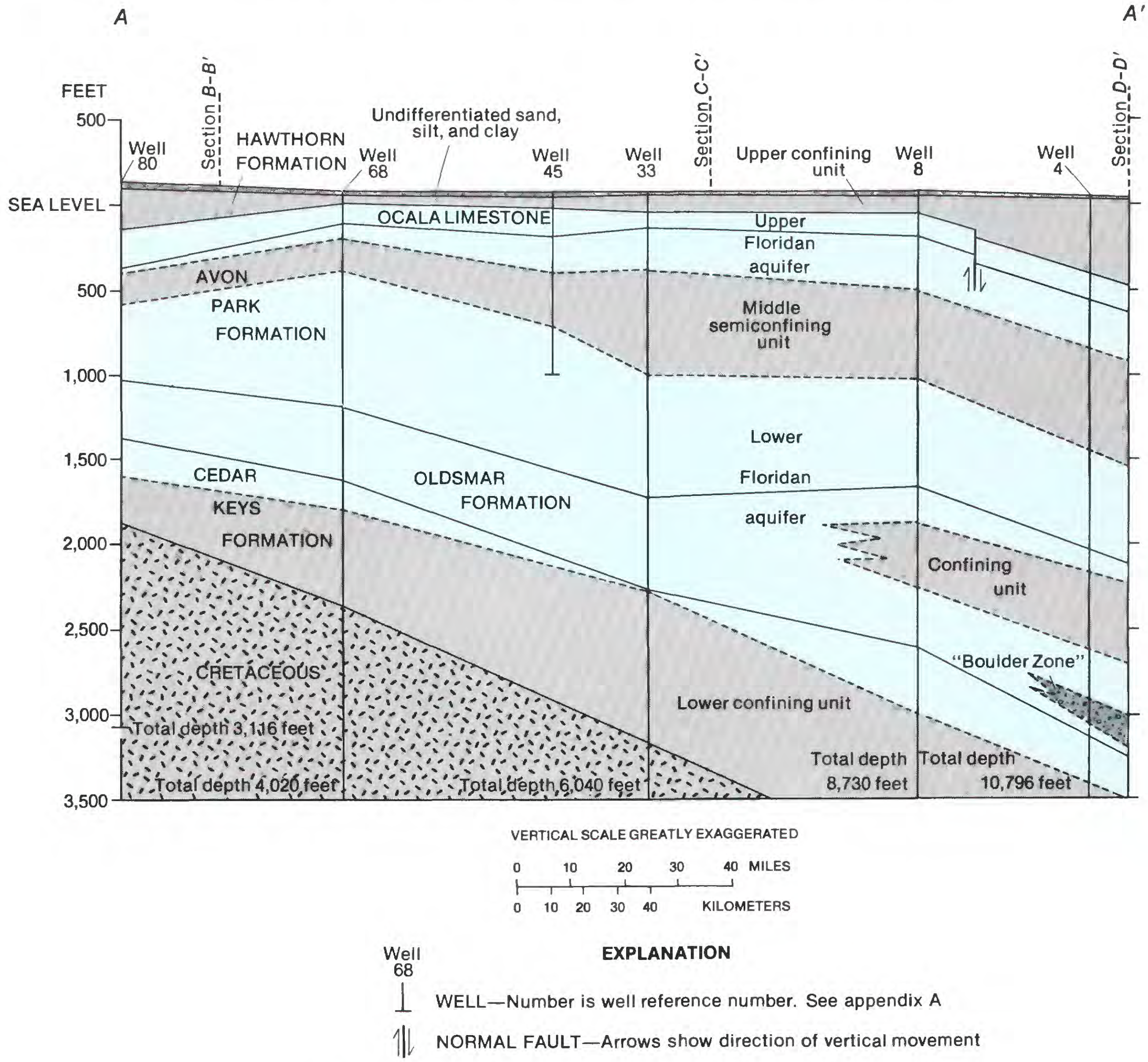


FIGURE 15.—Geologic section *A–A'* (adapted from Miller, 1986).

the standpoint of disposal of wastewaters through injection wells, does not significantly affect the Floridan aquifer system in east-central Florida.

POTENTIOMETRIC SURFACE

The earliest known Upper Floridan aquifer potentiometric surface map for Florida was prepared by Gunter and Ponton (1929), who used water-level data collected in 1928. That map represented only the north and north coastal parts of peninsular Florida from about Hillsborough County northward on the west coast and from mid-Brevard County northward on the east coast. The general configuration of the contours on the map resemble contours on more recent maps.

The first map of the Upper Floridan aquifer potentiometric surface throughout peninsular Florida was prepared by Stringfield (1936a), who used water levels from wells measured during 1933–35. Many countywide or even multicounty potentiometric surface maps have since been constructed, but the next statewide potentiometric surface map was prepared by Healy (1962), who used data from more than 600 wells measured during a 12-day period in July 1961.

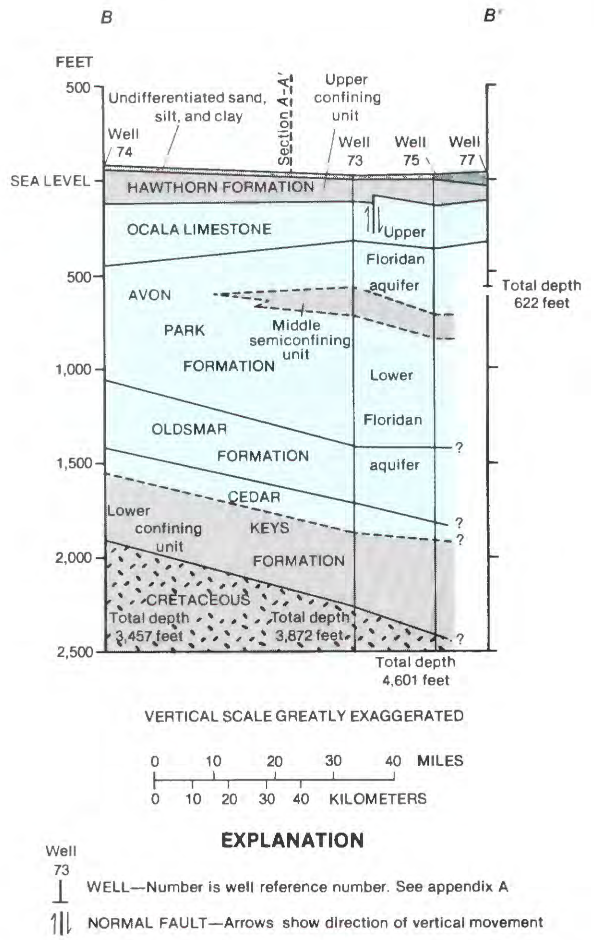


FIGURE 16.—Geologic section *B–B′* (adapted from Miller, 1986).

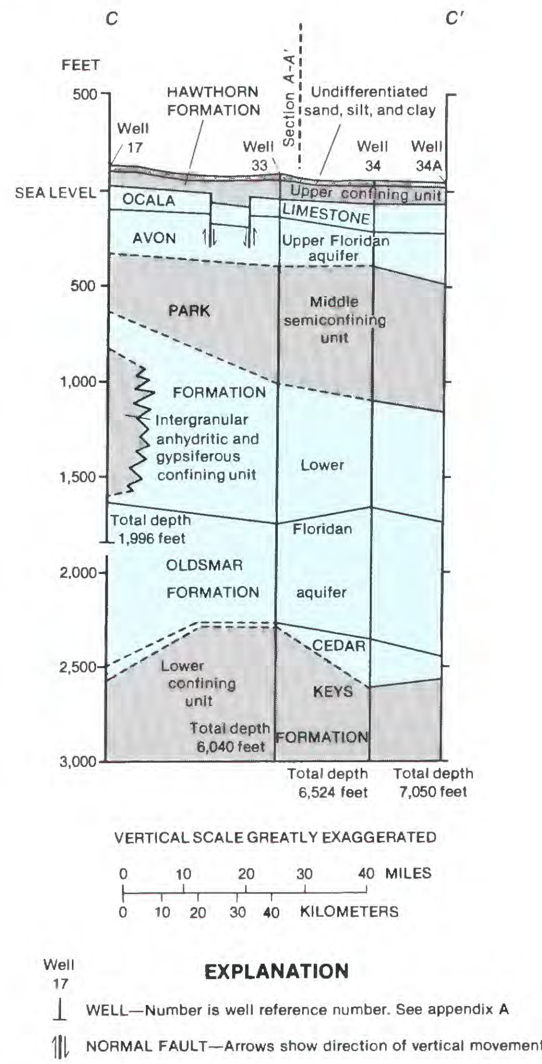


FIGURE 17.—Geologic section *C–C′* (adapted from Miller, 1986).

Currently, Upper Floridan potentiometric surface maps of central and north Florida are made on an annual or semiannual basis by the U.S. Geological Survey in cooperation with various State agencies and State water-management districts. However, these recent maps portray the potentiometric surface of only the Upper Floridan aquifer. Area-wide potentiometric surface maps of the Lower Floridan aquifer are not compiled because there are few wells that are deep enough to tap the Lower Floridan and that are hydraulically isolated from the Upper Floridan by well casing. Lichtler and others (1968) constructed a June 1962 potentiometric surface map of the Lower Floridan in the Orlando area using 11 public supply wells that are drilled and cased to the Lower Floridan.

A hydrograph of water levels in a well that taps the Lower Floridan in the Orlando area (well 42, fig. 19) shows that its water level is generally only 1 to 2 ft below the level in nearby well 43, open only to the Upper Floridan. Well 42 is 1,281 ft deep but is cased to a depth of only 601 ft. The casing extends into the middle semiconfining unit about 150 ft. In the Orlando area the middle semiconfining unit is about 600 ft thick. Therefore, the water levels measured in well 42 may not be the same as water levels in a well cased completely through the middle semiconfining unit and open only to the Lower Floridan. A well open only to the Lower Floridan would have a water level lower than that of well 42. Head measurements in a Lower Floridan aquifer monitor tube (open from 2,005 to 2,030 ft) in well 33 showed that, from February to April 1977, the head in the Lower Floridan was about 6 ft lower than that measured in the Upper Floridan (Geraghty and Miller, Inc., 1977, fig. 3).

At the beginning of this RASA study in October 1978, one of the first tasks was to construct a map of the

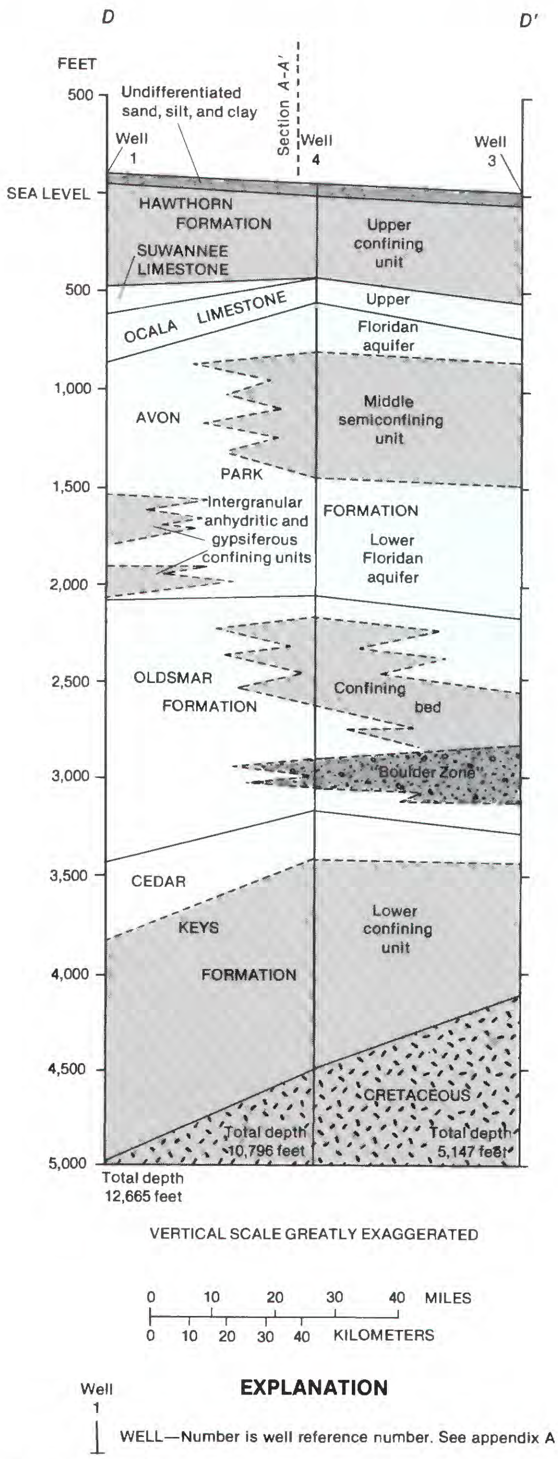


FIGURE 18.—Geologic section *D–D'* (adapted from Miller, 1986).

estimated potentiometric surface of the entire Upper Floridan aquifer system that portrayed the potentiometric surface prior to development (by pumping). That predevelopment potentiometric map, by Johnston and others (1980), is a composite of many other maps: recent potentiometric surface maps in areas where pumping has been light, and older maps or modifications of them where ground-water development has been extensive. The predevelopment potentiometric map shows the best estimate of the configuration of the average predevelopment potentiometric surface of the Upper Floridan aquifer. The east-central Florida part of the predevelopment potentiometric map is shown in figure 20.

The "predevelopment" potentiometric surface was not static. Rather, it fluctuated seasonally in response to changes in rates of recharge during wet and dry seasons and to changes in rates of natural discharge. Also, the predevelopment potentiometric surface underwent longer term fluctuations in response to prolonged periods of above- or below-normal rainfall such as the wet period that ended in 1888 and the drought (as measured at Jacksonville) that lasted from 1888 to about 1931 (fig. 6). Most of the water-level data used in constructing the predevelopment potentiometric surface in Florida were collected in the late 1920's and early 1930's. It is probable that the potentiometric contours shown in figure 20 represent "drought" rather than "average" predevelopment conditions in the north part of the study area.

The most recent potentiometric surface map of the entire Upper Floridan aquifer system was compiled by Johnston and others (1981) and represents the potentiometric surface in May 1980. The east-central Florida part of that map is shown in figure 21.

In general, the Upper Floridan potentiometric surface has declined from predevelopment levels measured in the 1930's. In a few areas, where little ground-water development has occurred, the potentiometric surface has remained virtually unchanged since predevelopment conditions. These areas are primarily in east Marion County and in east Polk County in the area immediately west of the Kissimmee River, in northeast Highlands County, and in south-central Volusia County. The areas of most decline in the potentiometric surface are in and near areas of heavy pumping from the Floridan aquifer system. These areas are in north-central Orange County (Orlando-Winter Park area), southeast Orange County (Cocoa well-field area), central Polk County, east Volusia County (Ormond Beach-Daytona Beach-New Smyrna Beach well fields), the potato-farming areas of south St. Johns County, and the citrus-growing areas of south Brevard, Indian River, and St. Lucie Counties.

Long-term hydrographs for wells in selected parts of the study area (fig. 2) are shown in appendix B.

The decline in the potentiometric surface from predevelopment conditions is due mostly to pumping. As mentioned in the section on long-term variability of rainfall, the predevelopment Upper Floridan aquifer

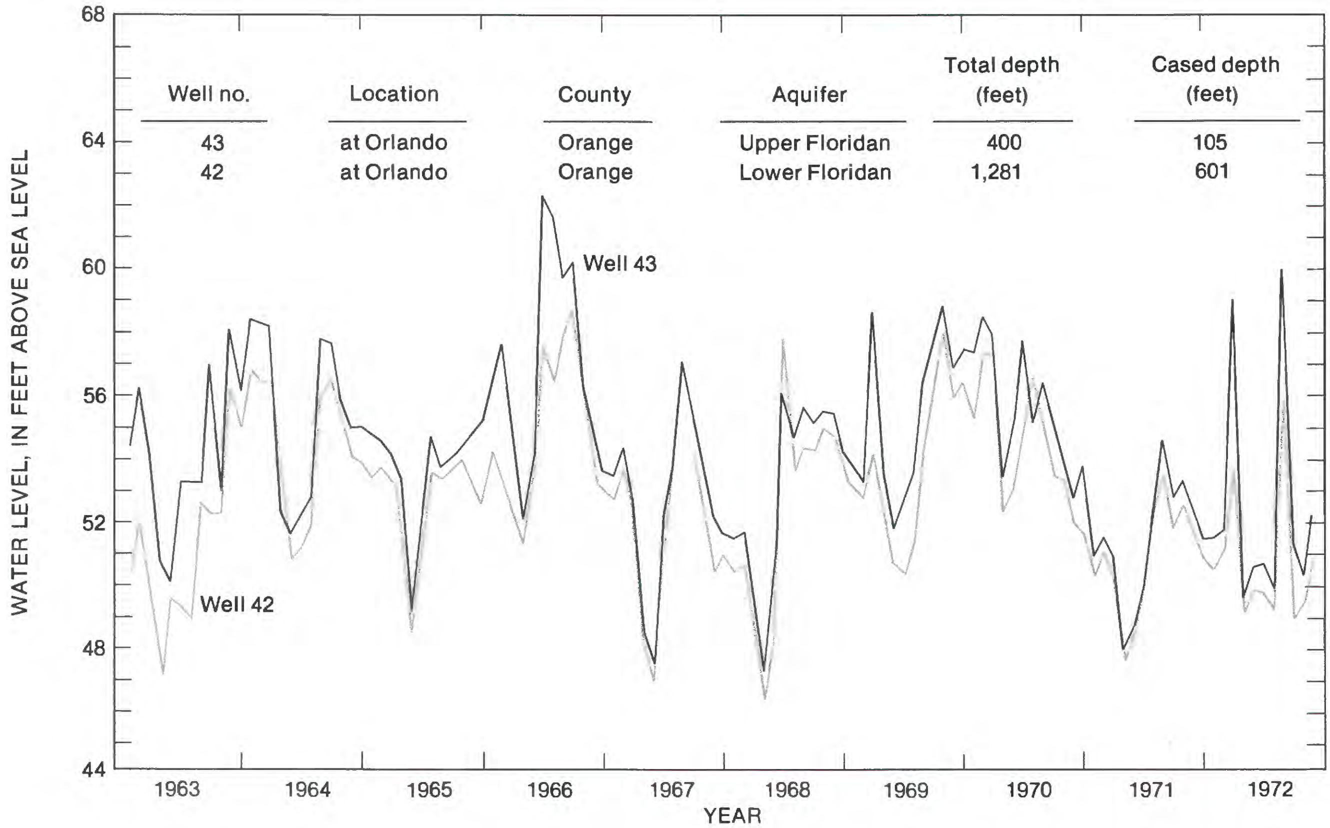


FIGURE 19.—Monthly average water levels in wells 43 (Upper Floridan aquifer) and 42 (Lower Floridan aquifer), 1963–72.

potentiometric surface map was based on water-level measurements made during a relatively dry period in the north part of the study area and a relatively wet period in the central and south parts (fig. 6). However, long-term declines were at a fairly steady rate even during the relatively wet period from about 1945 to about 1960 (appendix B). This indicates that increased ground-water development tended to offset the effects of greater than normal rainfall. Subsequent droughts, including that of 1976–81, combined with the effects of pumping, generally caused steeper declines of the potentiometric surface. The drawdown effects of pumping, by category, are discussed in a later section.

RECHARGE AND DISCHARGE

The following discussion of recharge and discharge is based largely on computer-based model simulation. Only spring flow and Upper Floridan ground-water discharge to some streams have been measured. Rates of recharge and areal discharge as diffuse upward leakage are derived from a digital computer model of the Floridan aquifer system. The computer model is described in a later section.

Water enters, or recharges, the Floridan aquifer system in east-central Florida by downward leakage from the surficial aquifer system to the Upper Floridan, by inflow from drainage wells, and by lateral inflow from areas adjacent to the study area.

In the aquifer recharge areas, water leaks downward from the surficial aquifer system, through the confining beds, and into the Upper Floridan (fig. 21). There, the water table in the surficial aquifer system is above the potentiometric surface of the Upper Floridan. The rate of recharge depends on the difference between the surficial aquifer system and the Upper Floridan and on the thickness and permeability of the confining beds. Recharge rates are proportional to head difference and confining bed permeability and are inversely proportional to confining bed thickness. In east-central Florida, simulation indicates that, areally, Upper Floridan aquifer recharge rates are as high as 14 in/yr (fig. 22). It is probable that, locally, recharge rates are as high as

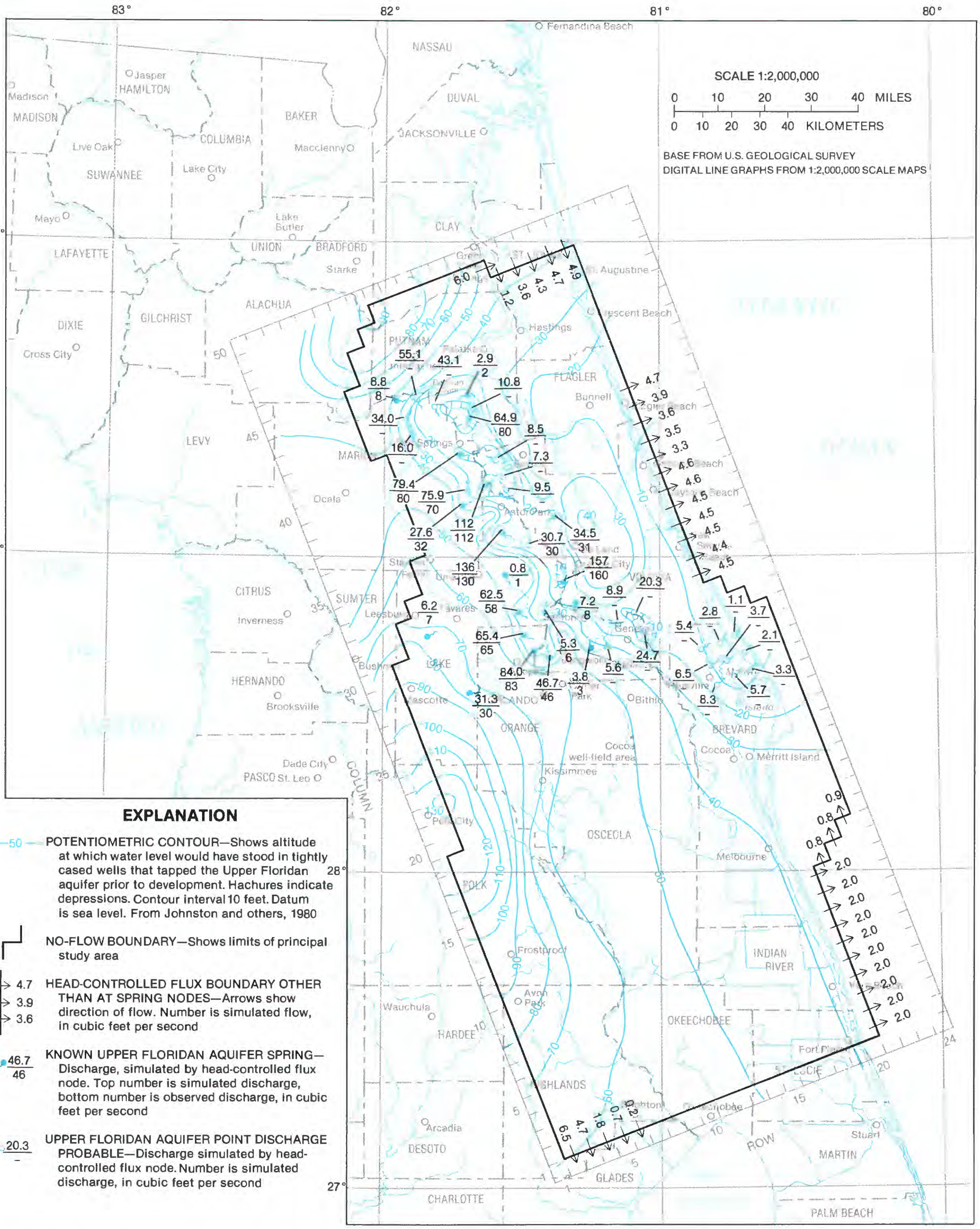


FIGURE 20.—Potentiometric surface of the Upper Floridan aquifer prior to development, spring discharge, and model boundary conditions for the Upper Floridan (revised from Tibbals, 1981).

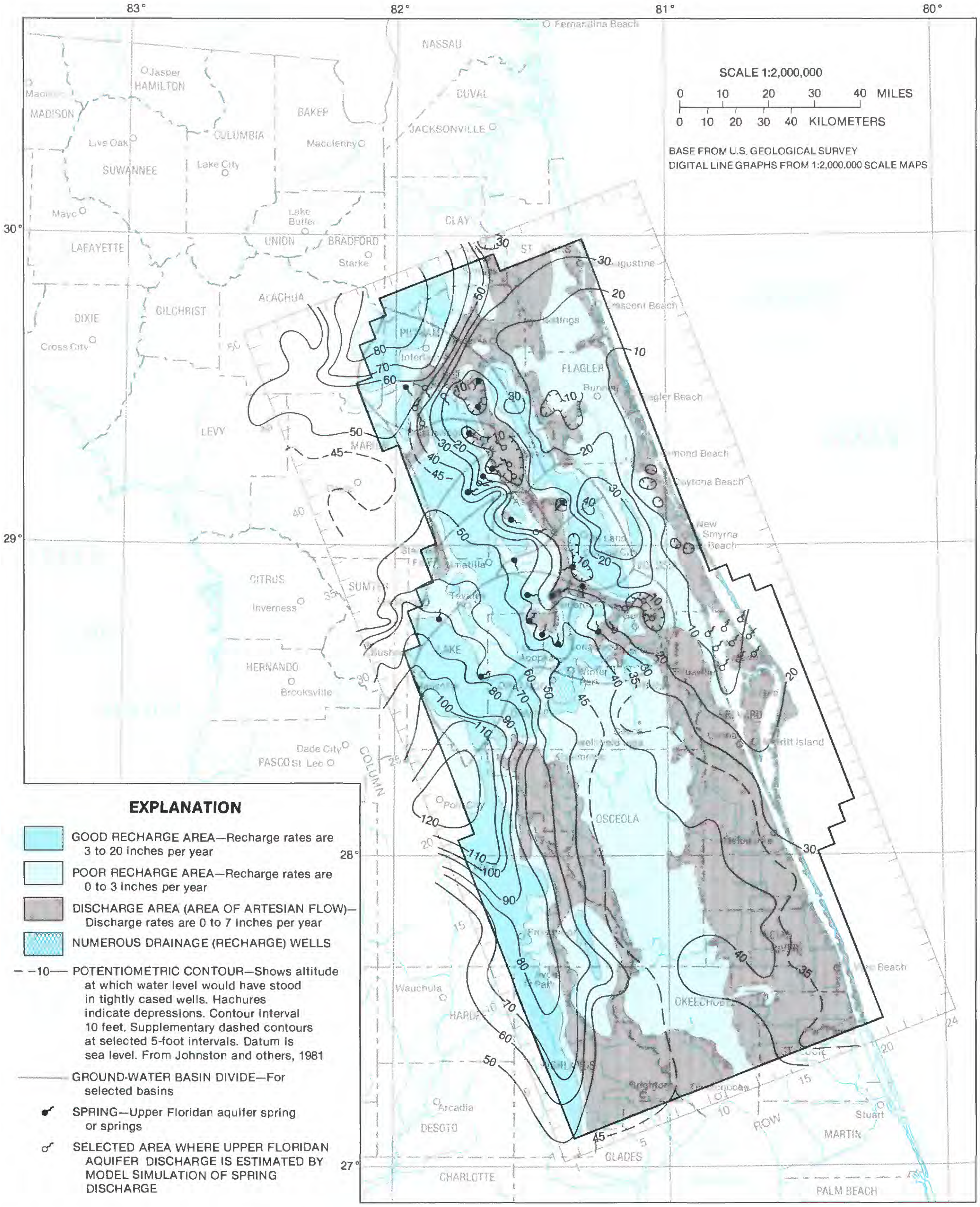


FIGURE 21.—Upper Floridan aquifer recharge and discharge areas; potentiometric surface of the Upper Floridan, May 1980; and selected ground-water basins.

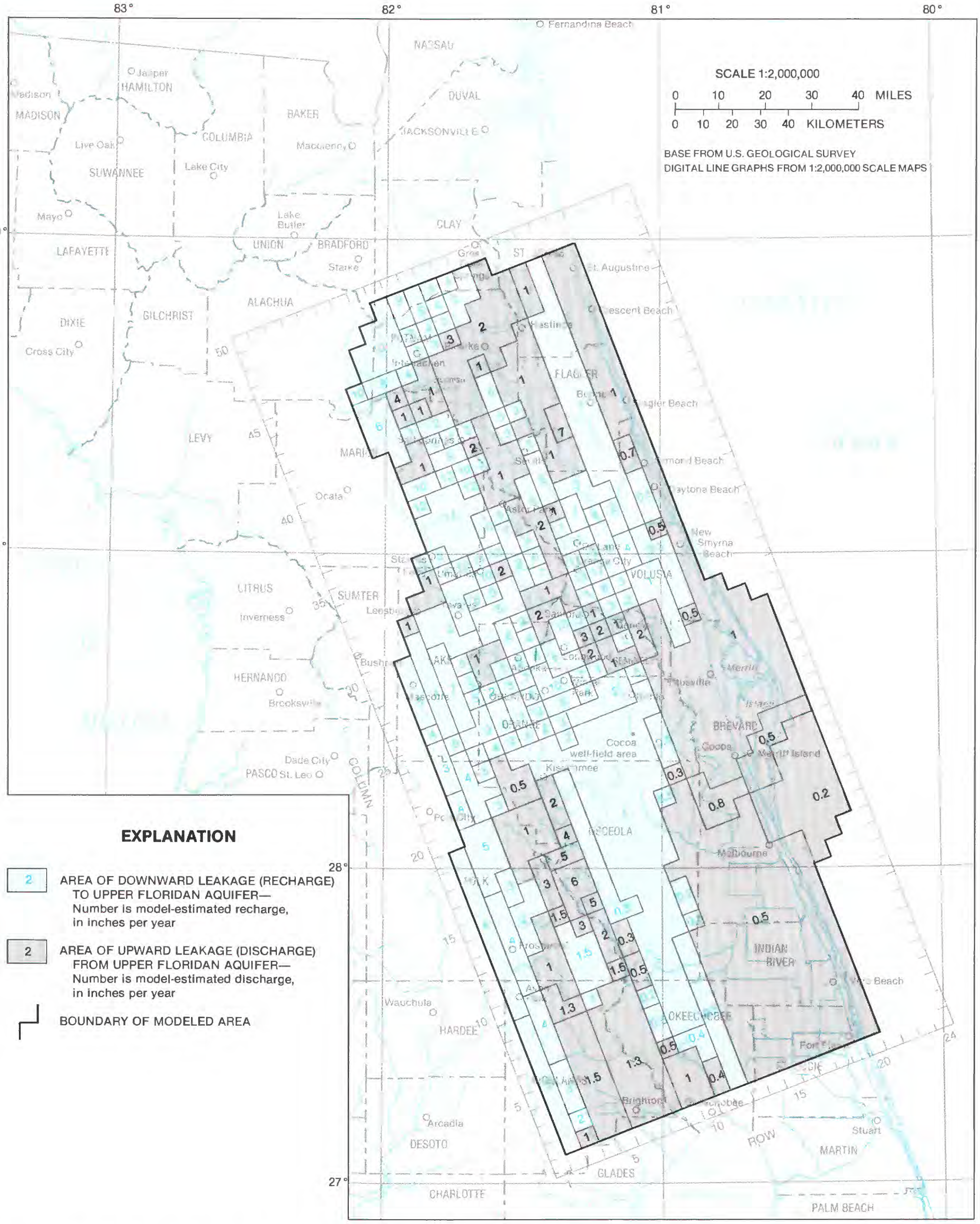


FIGURE 22.—Model-derived rates of recharge and discharge to and from the Upper Floridan aquifer through the upper confining unit.

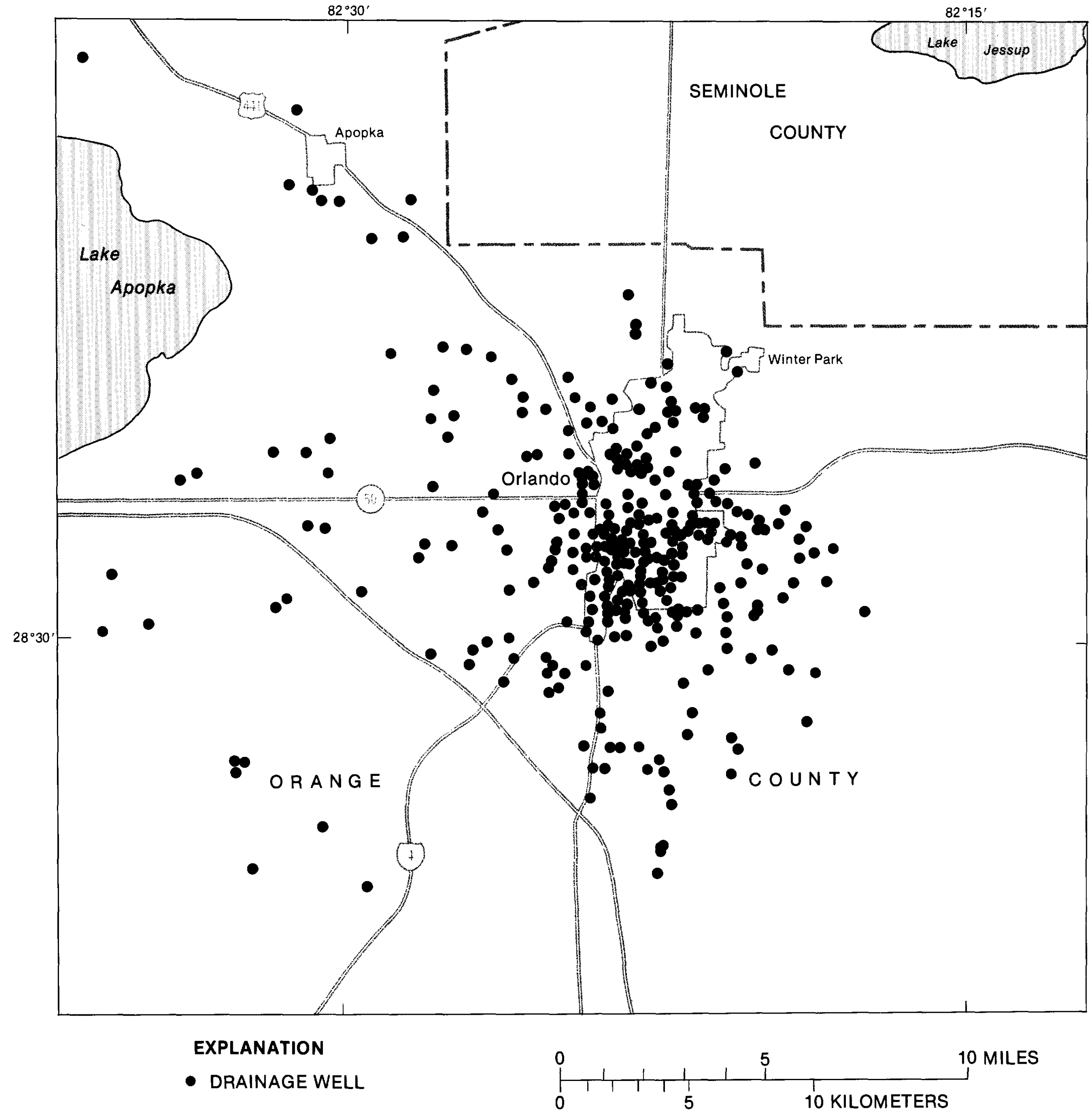


FIGURE 23.—Location of drainage wells that recharge the Upper Floridan aquifer in the Orlando area (modified from Kimrey, 1978).

20 in/yr. Recharge areas (fig. 21) are classified as good (3–20 in/yr) or poor (0–3 in/yr).

In addition to natural downward leakage, recharge also occurs through about 400 drainage wells in the Orlando area (fig. 23). These wells are constructed similarly to wells used for withdrawal; that is, they are cased to the top of the Upper Floridan aquifer and then drilled open-hole into the Upper Floridan. Drainage wells now (1982) are generally used to control lake levels and to dispose of street runoff from storm sewers, but in the past they were used to drain wetlands, to dispose of surplus effluent from industrial sites, and to receive effluent from septic tanks (Kimrey, 1978; Kimrey and Fayard, 1982). Additional construction of drainage wells is now prohibited by the Florida Department of Environmental Regulation.

The quantity of water that recharges the Upper Floridan by drainage wells in the Orlando area can only be approximated. Kimrey (1978, p. 15) states that recharge by drainage wells may be as much as 50 Mgal/d. However, during this study, drainage-well recharge was estimated at about 33 Mgal/d. The reason for this lower estimate is discussed in a later section.

Lateral inflow from adjacent areas under predevelopment conditions is estimated at about 19 ft^3/s (0.02 in/yr); it occurs primarily at the extreme east part of the north boundary of the study area (fig. 20). As is discussed in a later section, modern-day pumping stresses to the north of the study area have caused that lateral inflow to decrease.

Discharge from the Floridan aquifer system in the east-central Florida area occurs by diffuse upward leakage in discharge areas (fig. 21), areas where the potentiometric surface is above the water table, by pumping or flowing wells, by springs (fig. 20), and by lateral outflow to the Atlantic Ocean and at other places around the boundary of the study area. In areas where the Upper Floridan aquifer potentiometric surface is above land surface, wells that tap the Upper Floridan flow at the surface. Those areas are called areas of artesian flow. Simulation indicates that discharge by diffuse upward leakage from the Upper Floridan to the surficial aquifer ranges from 0 to about 7 in/yr (fig. 22).

Boundary flows are further discussed in a later section.

Twenty-nine named Upper Floridan springs in the study area (fig. 20, table 1) have discharges of 1 ft^3/s or more. Other sites of naturally occurring Upper Floridan discharge are confirmed by estimates based on low-flow stream-gaging measurements and water-quality analyses. The stream-gaging measurements indicate the amount of increase in flow between measurement sites. The water-quality analyses are used to help determine if the origin of the increase in flow is upward leakage (or spring flow) from the Upper Floridan or is seepage from the surficial aquifer. If the hardness of the inflow water is greater than about 20 mg/L as $CaCO_3$, or if the chloride concentration is more than about 10 mg/L, the inflow is attributed to the Upper Floridan aquifer. All the stream-gaging measurement sites and water-quality sampling sites are in areas of artesian flow where the potential for upward leakage exists.

Appendix C includes the results of the low-flow measurements and discussions of two newly documented springs—Island Spring and Croaker Hole Spring.

In several areas, depressions in the potentiometric surface of the Upper Floridan (figs. 20, 21) indicate relatively large ground-water discharges by other than known springs. These areas include the vicinity of the lower reaches of the Oklawaha River (in and near what is now Rodman Reservoir); generally, the St. Johns River from about Palatka to Lake Harney and, specifically, the St. Johns River between the mouth of the Oklawaha River and south to Little Lake George, Lake George, Lake Jessup, and Lake Harney; the Kissimmee River from the south part of Lake Tohopekaliga south to Lake Kissimmee; central Flagler County; and the coastline from Flagler Beach south to the north part of Merritt Island.

Stream-gaging records along the lower Oklawaha River during the spring low-flow seasons of 1945–50 show an increase of about 150 ft^3/s, all of which was discharge from the Upper Floridan aquifer. Of the 150 ft^3/s, about 8 ft^3/s was from Orange Spring.

It is possible that channel dredging in the St. Johns River has, in places, breached or partially breached the confining unit overlying the Upper Floridan aquifer, and thus allowed the Upper Floridan to discharge into the river. Barraclough (1962, p. 35) described two instances in which relatively shallow excavations in Seminole County caused the development of Upper Floridan springs. One spring was near Lake Jessup, whose outlet is the St. Johns River, and the other was near the Wekiva River, a tributary to the St. Johns. The writer has observed "sand boils" discharging water from the Upper Floridan at a recently excavated boat ramp in Lake County on Alexander Spring Creek, a tributary to the St. Johns River. Other springs and "sand boils" are known to have occurred as a result of dredging or excavation.

The U.S. Army Corps of Engineers maintains a navigation channel in the St. Johns River that is 34 ft deep and 400 to 900 ft wide from the river mouth to Jacksonville, 13 ft deep and 200 ft wide between Jacksonville and Palatka, 12 ft deep and 100 ft wide between Palatka and Sanford, and 5 ft deep and 100 ft wide between Sanford and Lake Harney (Anderson and Goolsby, 1973, p. 20). From about Palatka to Lake Harney, the configuration of the Upper Floridan potentiometric surface indicates discharge from the Upper Floridan. There are several known Upper Floridan springs along this reach. All along the reach, Upper Floridan heads are above the river level; therefore, the potential exists for leakage from the Upper Floridan. The presence of the known springs implies that, in the vicinity of the springs, the Upper Floridan overlying confining bed is relatively thin. It is possible that the dredged channel does not actually incise the Upper Floridan aquifer but, rather, incises shell beds or other permeable layers in the overlying confining unit that are hydraulically connected to the Upper Floridan.

The depression in the Upper Floridan potentiometric surface between the mouth of the Oklawaha River and south to Little Lake George is attributed to the 80-ft^3/s discharge of Croaker Hole Spring. Croaker Hole Spring was undocumented prior to this study and is discussed further in appendix C.

The configuration of the potentiometric surface in the vicinity of Lake George suggests that the Upper Floridan discharges near the east side of Lake George (figs.

20, 21). Tibbals (1981) simulated hypothetical spring discharge in Lake George as about 25 ft^3/s (table 1, fig. 20). Rutledge (1982, fig. 28, table 2) computed about 16 ft^3/s lateral Upper Floridan flow westward from Volusia County toward Lake George, presumably to be discharged there by either upward leakage or spring flow.

The configuration of the potentiometric surface in the vicinity of Lake Jessup (figs. 20, 21) indicates that the Upper Floridan is discharging into Lake Jessup. Tibbals (1981, fig. 4) simulated a hypothetical spring discharge of about 6 ft^3/s into Lake Jessup in addition to about 4 ft^3/s from Clifton Spring and Lake Jessup Spring.

Along the St. Johns River, from State Highway 50 downstream to State Highway 46, the increase in flow of the St. Johns River is attributed to inflow from the Econlockhatchee River (fig. 78). Thus, the Upper Floridan probably does not discharge large amounts into the St. Johns River along that reach. Stream-gaging measurements to detect Upper Floridan discharge along the St. Johns River downstream from State Highway 46 are virtually meaningless because wind action on Lake Monroe and Lake Harney combined with an extremely flat stream gradient can cause water to move upstream for several days at a time, especially during periods of low flow.

Figures 20 and 21 show a cone of depression on the potentiometric surface of the Upper Floridan aquifer in the Lake Harney area. Simulated hypothetical spring discharge (table 1) in the Lake Harney area and in the St. Johns River below Lake Harney and upstream from the mouth of Lake Jessup outlet is about 54 ft^3/s.

Lichtler and others (1968, fig. 23) documented the occurrence of highly mineralized water in the St. Johns River above State Highway 50. Upstream from State Highway 50, flow in the St. Johns River during extended dry periods consists mostly of upward leakage from the Upper Floridan aquifer and return flow from irrigated farms. The total inflow is not known. Stream-gaging techniques are not adequate to quantify the increase in flow during dry periods because errors in estimating evaporation from the large water surfaces can mask measured increase in flow. For example, on April 30, 1974, the measured flow at State Highway 50 was about 86 ft^3/s but the estimated evaporation from the approximately 11,000 acres of lakes upstream from State Highway 50 is estimated at about 90 ft^3/s on that day.

The relatively closely spaced potentiometric contours west of Lake Tohopekaliga and Lake Kissimmee along the Kissimmee River (figs. 20, 21) imply a reduction in transmissivity of the Upper Floridan aquifer or discharge from the Upper Floridan or both. Fault displacement in that area (fig. 11) is minor and evidence of low transmissivity is lacking. Also, there is little pumping from the Upper Floridan in that area. A water-budget calculation for Lake Kissimmee (Warren Anderson, U.S. Geological Survey, written commun., July 1980) suggested that, during the period July 15–28, 1956, the Upper Floridan was discharging about 35 ft^3/s into Lake Kissimmee.

The depression in the potentiometric surface of the Upper Floridan aquifer in central and west Flagler County was first discussed by Bermes and others (1963, p. 61) and was attributed to diffuse upward leakage and springs in the Haw Creek basin. A subsequent investigation (Anthony Navoy, U.S. Geological Survey, written commun., July 1980) found no springs and no appreciable discharge by wells in the Haw Creek area, but the potentiometric depression was confirmed. Therefore, the depression is probably caused by diffuse upward leakage in the Haw Creek basin and, possibly, by discharge from unconfirmed submerged springs near the southeast side of nearby Crescent Lake. Simulation suggests that the rate of diffuse upward leakage in the area is about 16 ft^3/s (Tibbals, 1981).

Along the coast from about Flagler Beach south to Merritt Island the potentiometric surface of the Upper Floridan aquifer was depressed under predevelopment conditions (fig. 20) owing to discharge by either diffuse upward leakage or by springs. The 1980 potentiometric surface (fig. 21) has further declined in response to pumping, especially in Volusia County. Tibbals (1981, fig. 4) indirectly simulated this discharge as about 50 ft^3/s flowing laterally from the northeast model boundary between Flagler Beach and the Oak Hill area of south Volusia County (north part of east boundary) and as about 36 ft^3/s of hypothetical spring flow in the area of north Merritt Island (Banana River, Mosquito Lagoon). The predevelopment figures are revised upward to 51 ft^3/s and 39 ft^3/s, respectively, in this report (fig. 20, table 1).

Off the coast of Volusia County and in the north Merritt Island area, the top of the Floridan aquifer is about 80 to 100 ft below sea level and the sea bottom is at a depth of about 60 ft. Therefore, the materials that overlie the Floridan are as thin as 20 ft. There, conditions are favorable for spring formation or, if the overlying materials are sufficiently permeable, for high rates of diffuse upward leakage. Stringfield (1936a, p. 152) mentioned that a large spring was reported about 16 mi east of the south Volusia County–north Brevard County area. The existence of this spring is not confirmed.

Several investigators have confirmed a submarine spring about 2.5 mi east of Crescent Beach, Flagler County (Stringfield and Cooper, 1951; Brooks, 1961). Brooks described the spring and took water samples.

Upper Floridan lateral outflow occurs along the north and south parts of the east boundary and along the west part of the south boundary. Under predevelopment conditions, Tibbals (1981, fig. 4) simulated these flows at

TABLE 1.—*Ground-water discharge from the Upper Floridan aquifer: Spring flow; simulated discharge to rivers, lakes, lagoons, and the Atlantic Ocean; and lateral flow at model boundaries*

[Negative numbers indicate flow into model area. ft^3/s, cubic feet per second. Dashes indicate that no data are available]

Model node		Name of discharging water body or location of discharge	Predevelopment, steady-state conditions			"Dry period," May 1978, transient conditions		Change in flow (ft^3/s)		
			Flow (ft^3/s)[1]		Percent error	Flow (ft^3/s)				
Row	Column		Observed[2] (A)	Simulated (B)	$\left(\frac{(B)-(A)}{(A)}\times 100\right)$	Observed[2] (C)	Simulated (D)	(C)−(D)	(D)−(B)	(C)−(A)
2	2	West part of south boundary	------	6.5	------	------	−1.7	------	−8.2	------
3	2	do.	------	4.7	------	------	−2.5	------	−8.2	------
4	2	do.	------	1.8	------	------	−1.7	------	−3.5	------
5	2	do.	------	0.7	------	------	−2.7	------	−3.4	------
5	31	Blue Spring+Holiday Springs[3]	3+4=7	6.2	−11.3	------	2.6	------	−3.6	------
6	2	West part of south boundary	------	0.2	------	------	−1.7	------	−1.9	------
6	27	Apopka Spring[3]	30	31.3	4.3	------	11.7	------	−19.6	------
8	42	Oklawaha River pickup	(10)	16.0	------	------	15.8	------	−0.2	------
8	43	do.	(30)	33.6	------	------	29.2	------	−4.4	------
8	44	Orange Spring[3]	8	8.8	10.0	------	8.6	------	−0.2	------
9	44	Oklawaha River pickup	(50)	55.1	------	------	41.8	------	−13.3	------
10	28	Wekiva Springs+Witherington Spring[3,4]+Miami Spring	74+4+5=83	84.0	1.2	64+(4)+5=73	70.5	2.5	−13.5	−10
10	29	Rock Springs[3,4]	65	65.4	0.6	57	44.8	12.2	−20.6	−8
10	31	Seminole Spring+Messant Springs[3]	20+36=56	62.5	11.6	------	46.5	------	−16.0	------
10	33	Camp La-No-Che Spring[3]	1	0.8	−20.0	------	0.7	------	−0.1	------
10	37	Juniper Springs+Fern Hammock Springs[3]	16+16=32	27.6	−13.8	------	26.0	------	−1.6	------
10	38	Juniper Creek pickup above State Highway 19[3]+Sweetwater Spring	58+12=70	75.9	8.4	------	75.1	------	−0.8	------
10	40	Salt Springs[3]	80	79.4	−0.8	------	78.1	------	−1.3	------
10	43	Oklawaha River pickup	(50)	43.1	------	------	41.1	------	−2.0	------
11	28	Sanlando Springs+Palm Springs+Starbuck Spring[3,4]	19+10+17=46	46.7	1.5	15+8+14=37	33.3	3.7	−13.4	−9
11	35	Alexander Springs+Alexander Spring Creek pickup above State Highway 455[3]	100+30=130	136	4.6	------	133	------	−3.0	------
11	38	Silver Glen Springs[3]	112	112	0.0	------	111	------	−1.0	------
11	42	Croaker Hole Spring[3]	80	64.9	−18.9	------	61.8	------	−3.0	------
12	30	Island Spring[3]	6	5.3	−11.7	------	4.4	------	−0.9	------
12	34	Alexander Spring Creek pickup below State Highway 455	(30)	30.7	------	------	29.6	------	−1.1	------
12	37	Lake George	(7)	9.5	------	------	9.0	------	−0.5	------
12	38	do.	(7)	7.3	------	------	6.6	------	−0.7	------
12	39	do.	(7)	8.5	------	------	7.5	------	−1.0	------
12	42	Beecher Spring[3]	9	10.8	20.0	------	9.5	------	−1.3	------
12	43	Satsuma Spring[3]	2	2.9	45.0	------	2.4	------	−0.5	------
13	27	Clifton Spring+Lake Jessup Spring[3]	2+1=3	3.8	26.7	------	2.2	------	−1.6	------
13	30	Gemini Spring[3]	8	7.2	−10.0	------	5.6	------	−1.6	------
13	31	Blue Spring[3,4]	160	157	−1.9	[5](150)	144	6	−13.0	−10.0
14	27	Lake Jessup	------	5.6	------	------	3.5	------	−2.1	------
14	35	Ponce De Leon Springs[3,4]	31	34.5	11.3	27	31.8	−4.8	−2.7	−4.0
15	28	St. Johns River below Lake Harney	------	8.9	------	------	6.8	------	−2.1	------
15	49	East end of north boundary	------	6.0	------	------	−3.0	------	−9.0	------
16	27	Lake Harney	------	24.7	------	------	19.6	------	−5.1	------
16	28	do.	------	20.3	------	------	16.9	------	−3.4	------
16	48	East part of north boundary	------	−1.2	------	------	−6.4	------	−5.2	------
17	48	do.	------	−3.6	------	------	−8.5	------	−4.9	------
18	48	do.	------	−4.3	------	------	−7.7	------	−3.4	------
19	48	do.	------	−4.7	------	------	−7.9	------	−3.2	------
20	2	South part of east boundary	------	2.0	------	------	1.2	------	−0.8	------
20	3	do.	------	2.0	------	------	1.2	------	−0.8	------

Footnotes at end of table.

TABLE 1.—*Ground-water discharge from the Upper Floridan aquifer: Spring flow; simulated discharge to rivers, lakes, lagoons, and the Atlantic Ocean; and lateral flow at model boundaries*—Continued

[Negative numbers indicate flow into model area. ft³/s, cubic feet per second. Dashes indicate that no data are available]

Model node		Name of discharging water body or location of discharge	Predevelopment, steady-state conditions			"Dry period," May 1978, transient conditions		Change in flow (ft³/s)		
			Flow (ft³/s)[1]		Percent error	Flow (ft³/s)				
Row	Column		Observed[2] (A)	Simulated (B)	$\left(\frac{(B)-(A)}{(A)}\times 100\right)$	Observed[2] (C)	Simulated (D)	(C)−(D)	(D)−(B)	(C)−(A)
20	4	South part of east boundary	------	2.0	------	------	1.2	------	−0.8	------
20	5	do.	------	2.0	------	------	1.2	------	−0.8	------
20	6	do.	------	2.0	------	------	1.2	------	−0.8	------
20	7	do.	------	2.0	------	------	1.3	------	−0.7	------
20	8	do.	------	2.0	------	------	1.3	------	−0.7	------
20	9	do.	------	2.0	------	------	1.4	------	−0.6	------
20	10	do.	------	2.0	------	------	1.5	------	−0.5	------
20	11	do.	------	2.0	------	------	1.6	------	−0.4	------
20	29	North part of east boundary	------	4.5	------	------	3.1	------	−1.4	------
20	30	do.	------	4.4	------	------	2.6	------	−1.8	------
20	31	do.	------	4.5	------	------	2.7	------	−1.8	------
20	32	do.	------	4.5	------	------	2.6	------	−1.9	------
20	33	do.	------	4.5	------	------	1.9	------	−2.6	------
20	34	do.	------	4.6	------	------	1.1	------	−3.5	------
20	35	do.	------	4.6	------	------	1.5	------	−3.1	------
20	36	do.	------	3.3	------	------	1.8	------	−1.5	------
20	37	do.	------	3.5	------	------	2.4	------	−1.1	------
20	38	do.	------	3.6	------	------	2.8	------	−0.8	------
20	39	do.	------	3.9	------	------	3.1	------	−0.8	------
20	40	do.	------	4.7	------	------	3.8	------	−0.9	------
20	48	East part of north boundary	------	−4.9	------	------	−7.6	------	−2.7	------
21	12	South part of east boundary	------	−0.8	------	------	−3.1	------	−2.3	------
22	13	do.	------	−0.8	------	------	−2.5	------	−1.7	------
23	14	do.	------	−0.9	------	------	−3.1	------	−2.2	------
19	23	Banana River, Mosquito Lagoon	------	8.3	------	------	6.5	------	−1.8	------
19	24	do.	------	6.5	------	------	5.1	------	−1.4	------
19	25	do.	------	5.4	------	------	4.5	------	−0.9	------
20	23	do.	------	5.7	------	------	4.7	------	−1.0	------
20	24	do.	------	3.7	------	------	3.1	------	−0.6	------
20	25	do.	------	2.8	------	------	2.4	------	−0.4	------
21	23	do.	------	3.3	------	------	2.8	------	−0.5	------
21	24	do.	------	2.1	------	------	1.8	------	−0.3	------
21	25	do.	------	1.1	------	------	0.9	------	−0.2	------
Total				1,394.5			1,145.2		−250.2	

Predevelopment steady-state conditions (ft³/s):
Total observed discharge of key springs: 1,019
Total computed discharge of key springs: 1,023

May 1978 transient conditions (ft³/s):
Total computed discharge of key springs: 904
Total observed discharge of selected springs: 344
Total computed discharge of selected springs: 323

[1] Revised from Tibbals (1981).
[2] Numbers in parentheses are estimated discharges; others are observed discharges.
[3] Key spring used in evaluation of predevelopment, steady-state model calibration.
[4] Selected spring used in evaluation of May 1978 non-steady-state model calibration.
[5] Average of discharges measured 1–10–78, 2–28–78, 4–20–78, and 5–30–78. Backwater from St. Johns River influences spring discharge by changing altitude of head at spring pool.

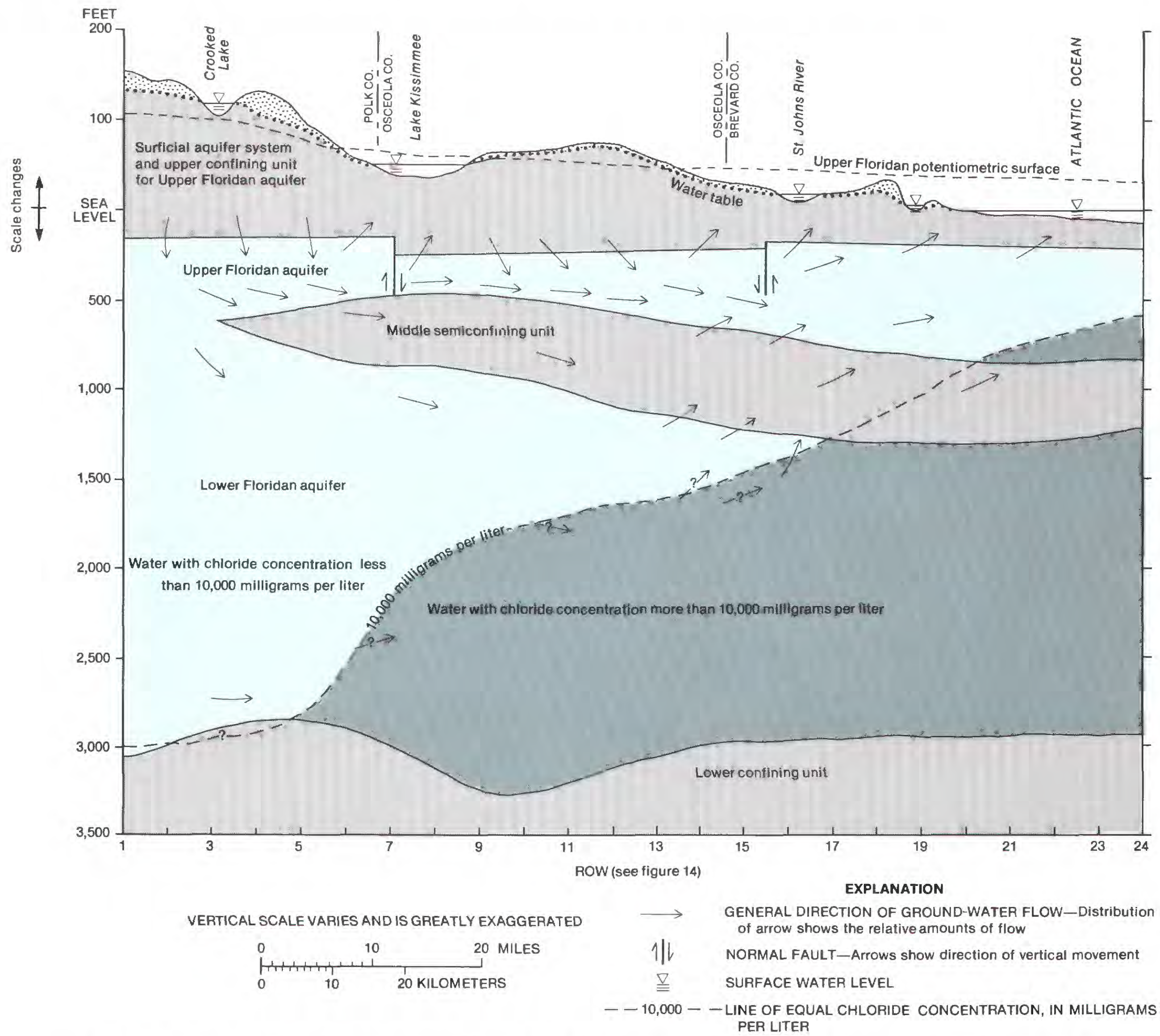


FIGURE 24.—Hydrogeologic units and ground-water flow along model column 15. Trace of section shown in figure 14.

about 52 ft^3/s, 10 ft^3/s, and about 14 ft^3/s, respectively. Subsequent revision to the predevelopment steady-state model resulted in computed flows of about 51 ft^3/s and 20 ft^3/s, respectively, for the north and south parts of the east boundary (fig. 20). Pumping stresses in 1978 tended to reduce boundary outflows in the southeast and southwest and to induce boundary outflow along the south part of the west boundary. The flow to the west is induced by heavy pumping in the phosphate mining and citrus growing areas primarily in Polk County. Boundary outflow to the west is estimated at about 78 ft^3/s.

Hydrogeologic sections (figs. 24–27) show the generalized Floridan aquifer flow system along typical flow paths, that is, at right angles to potentiometric contours (figs. 20, 21) and in the direction of decreasing head. These sections are aligned along rows and columns of the grid used for the digital flow model (see later discussion and fig. 42).

The flow arrows shown in the Upper and Lower Floridan indicate the general direction of flow, and the distribution of the arrows shows the relative amounts of flow. Typically, the Upper Floridan has the more vigorous flow system.

HYDRAULIC CHARACTERISTICS

The hydraulic characteristics of the Floridan aquifer system are described in terms of transmissivity and storage coefficient of the aquifer and leakage coefficients of both the upper confining unit and the middle semiconfining unit.

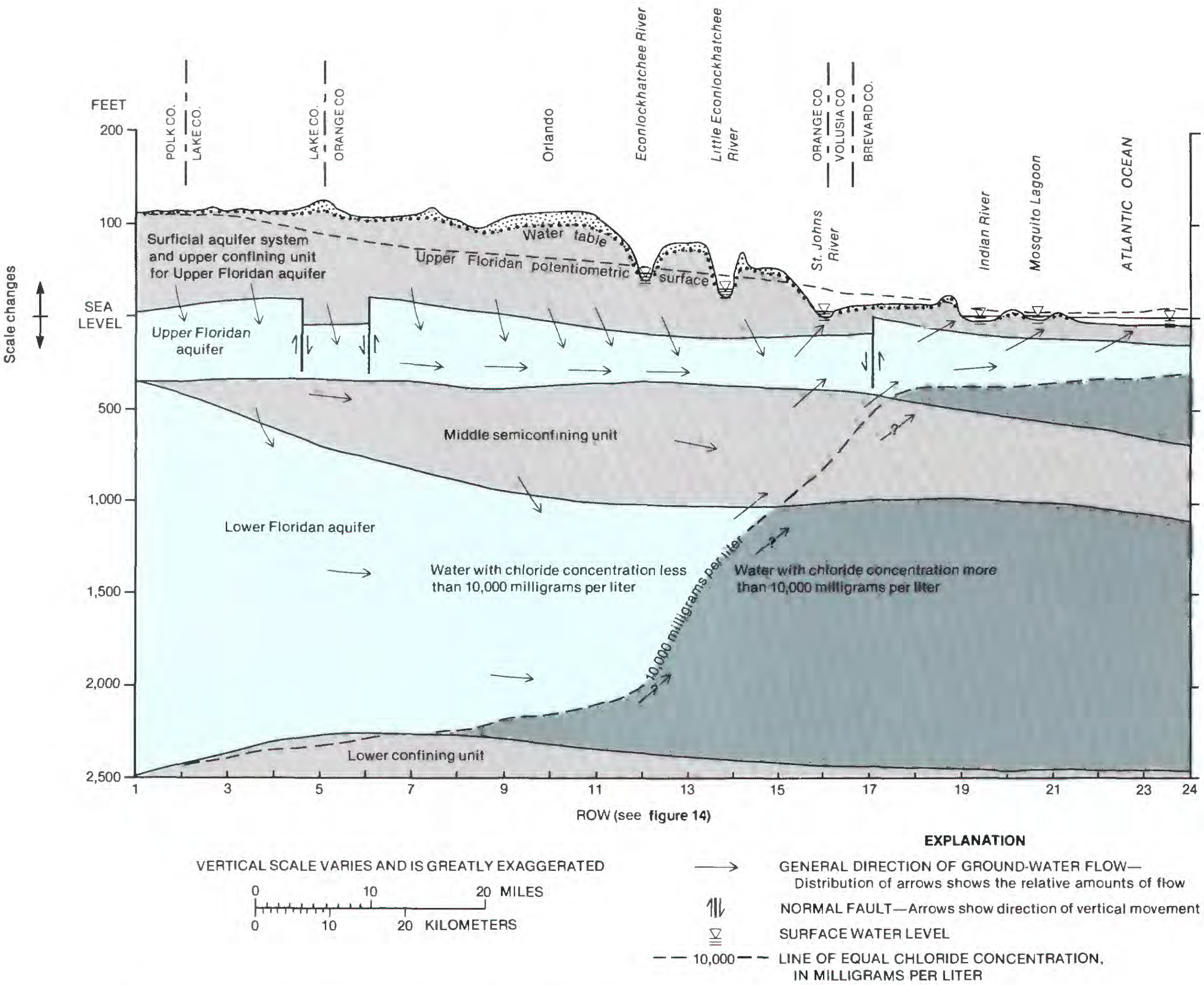


FIGURE 25.—Hydrogeologic units and ground-water flow along model column 25. Trace of section shown in figure 14.

The transmissivity of the Upper and Lower Floridan varies throughout the model area. Figures 28 and 29 show a comparison of field values of transmissivity derived from aquifer tests and transmissivity values obtained in the development and calibration of the predevelopment steady-state computer model (Tibbals, 1981). The average of model-derived transmissivity values for the Upper Floridan is about 120,000 ft^2/d; the range is from about 10,000 to about 400,000 ft^2/d. The highest transmissivities are generally near springs. The transmissivity values obtained by aquifer test analyses do not always agree with the model-derived values. Generally, the model-derived transmissivities are higher than those obtained from aquifer tests. This is mainly because the wells used in the aquifer tests generally tap less than the full thickness of the Upper Floridan. Such partial penetration plus the highly heterogeneous and anisotropic nature of the cavernous limestone aquifer system make the application of standard methods of aquifer test analysis uncertain and the results questionable. For example, in east Orange County, three aquifer test sites within an area of about 16 mi^2 (fig. 28) has transmissivity values of 74,000, 210,000, and 510,000 ft^2/d, respectively. Furthermore, counter to what would be expected, the test that had the most penetration of the aquifer had the lowest transmissivity. The transmissivity range obtained from model calibration in the same 16-mi^2 area, about 100,000 to 200,000 ft^2/d, is considered to have more regional significance than the individual test values. In general, however, the aquifer test values for transmissivity of the Upper Floridan are within the range of values determined by computer simulation of the Floridan aquifer system.

The transmissivity of the Lower Floridan (fig. 29) is less well known than that of the Upper Floridan. Only one aquifer test is known to have been conducted in the

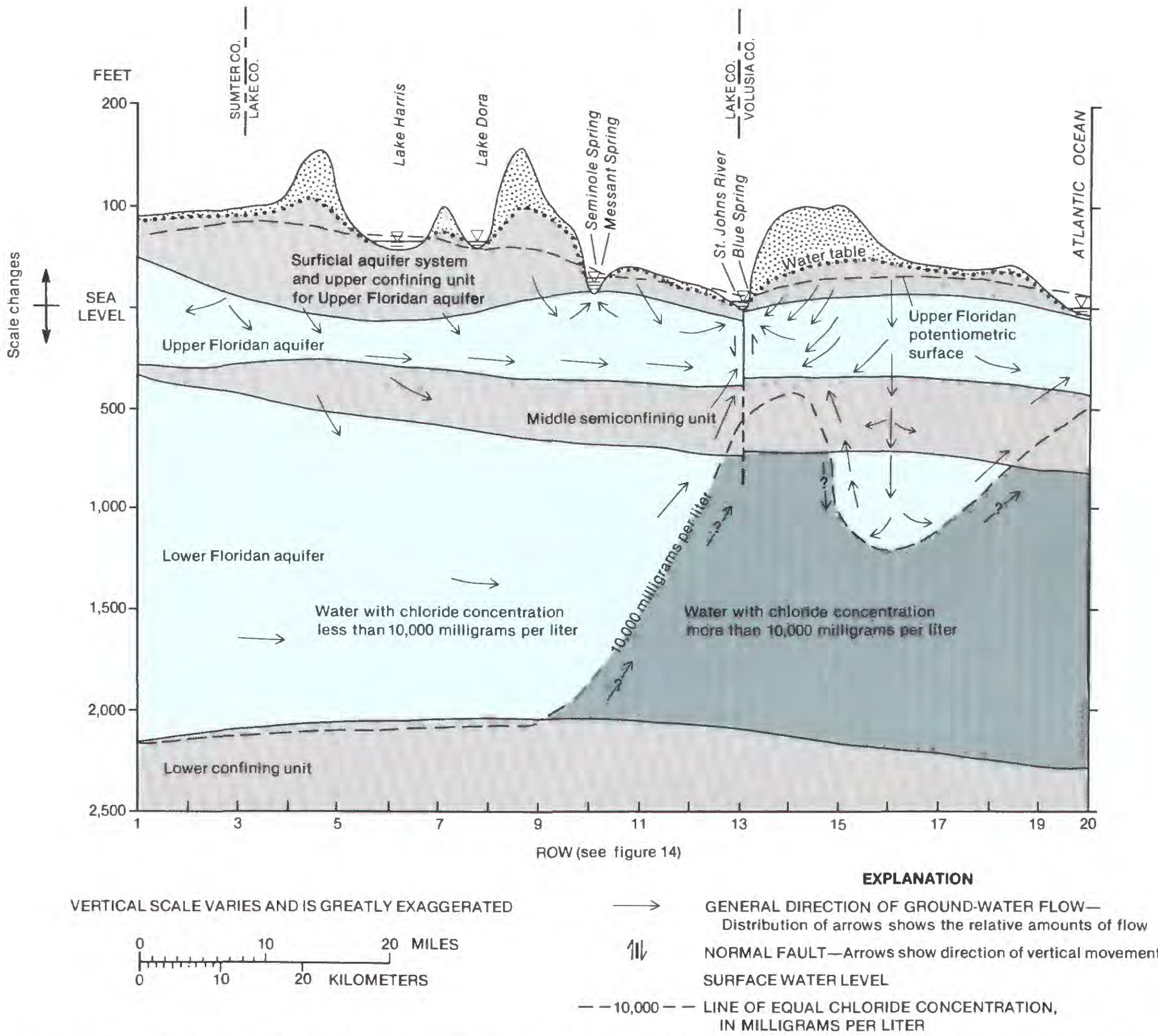


FIGURE 26.—Hydrogeologic units and ground-water flow along model column 31. Trace of section shown in figure 14.

Lower Floridan (Lichtler and others, 1968). Transmissivity values for the Lower Floridan obtained by model calibration (Tibbals, 1981) range from about 30,000 ft^2/d to about 130,000 ft^2/d; the highest values are in central and west Orange County. It is possible that transmissivities there are higher than 130,000 ft^2/d. Lichtler and others (1968) reported an apparent transmissivity of about 570,000 ft^2/d. Owing to the lack of model calibration for the Lower Floridan, the transmissivities derived from model simulation should be viewed as qualitative rather than quantitative.

The determination of values for storage coefficient from aquifer test analyses poses problems similar to those of obtaining values for transmissivity. Values for storage coefficient obtained during various investigations in the study area typically range from 5×10^{-4} to 1×10^{-3} for the Upper Floridan. Estimates of storage coefficient for the Lower Floridan are not reliable, but it is probable that the storage coefficient of the Lower Floridan is similar to that of the Upper Floridan.

The leakage coefficient of the confining unit that overlies the Upper Floridan (fig. 30) ranges from about 1×10^{-6} per day to about 6×10^{-4} per day. The highest values occur where aquifer diffuse recharge and discharge rates are highest (fig. 22)—areas where the confining beds are relatively thin or permeable. The lowest values occur where diffuse recharge and discharge rates are low—areas where confining beds are relatively thick or have low permeability.

No data are available to determine the leakage coefficient of the middle semiconfining unit that separates the Upper and Lower Floridan aquifers. Calibration of the steady-state predevelopment model (Tibbals, 1981) was done using a leakage coefficient of about 5×10^{-5} per day everywhere except the Blue Spring area. There, the leakage coefficient of the middle semiconfining unit is

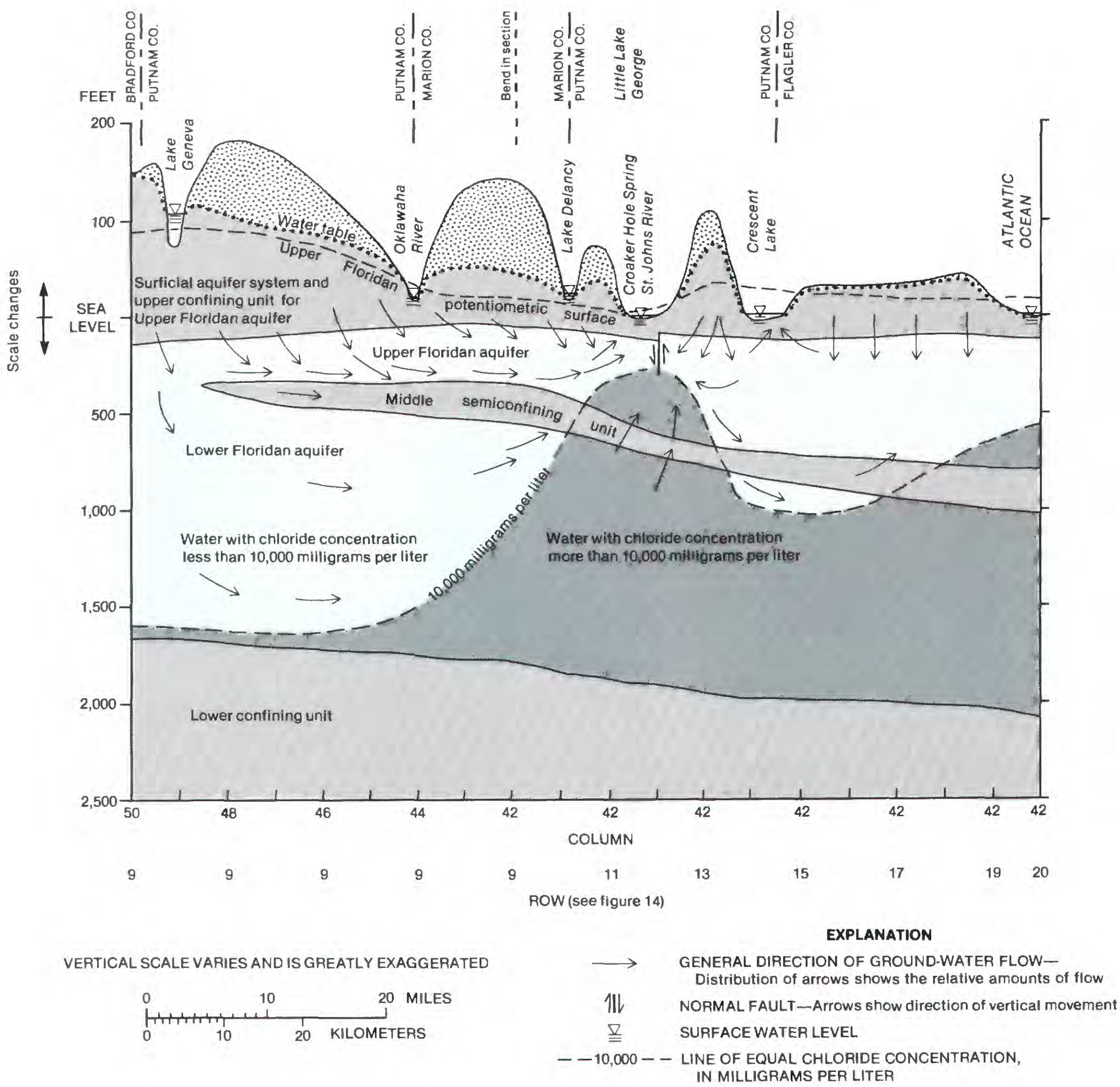


FIGURE 27.—Hydrogeologic units and ground-water flow along row 9, columns 50–42, and along model column 42, rows 9–20. Trace of section shown in figure 14.

probably very high because of a geologic fault that provides good hydraulic connection between the Upper and Lower Floridan.

WATER QUALITY

The quality of water in the Floridan aquifer system in east-central Florida varies from place to place but, in most areas, remains fairly constant with time. Seasonal water-quality variations occur mostly in areas where there is a lateral or vertical transition from fresh to brackish water, near drainage wells, or where some sinkholes provide a direct or near-direct surface hydraulic connection to the Floridan.

Geology is a major factor affecting the natural quality of water in the Floridan. As water moves downgradient through the aquifer system it tends to become more highly mineralized because of the gradual dissolution of the rock materials it contacts.

A second major factor affecting the quality of water in the Floridan aquifer system is the mixing and chemical reaction of freshwater with highly mineralized water that is in the aquifer at depth, along the Atlantic Coast, and along the St. Johns River valley.

Few data are available on the quality of water in the Lower Floridan aquifer. However, in east-central Florida the water in the Lower Floridan is probably more highly mineralized than that in the Upper Floridan.

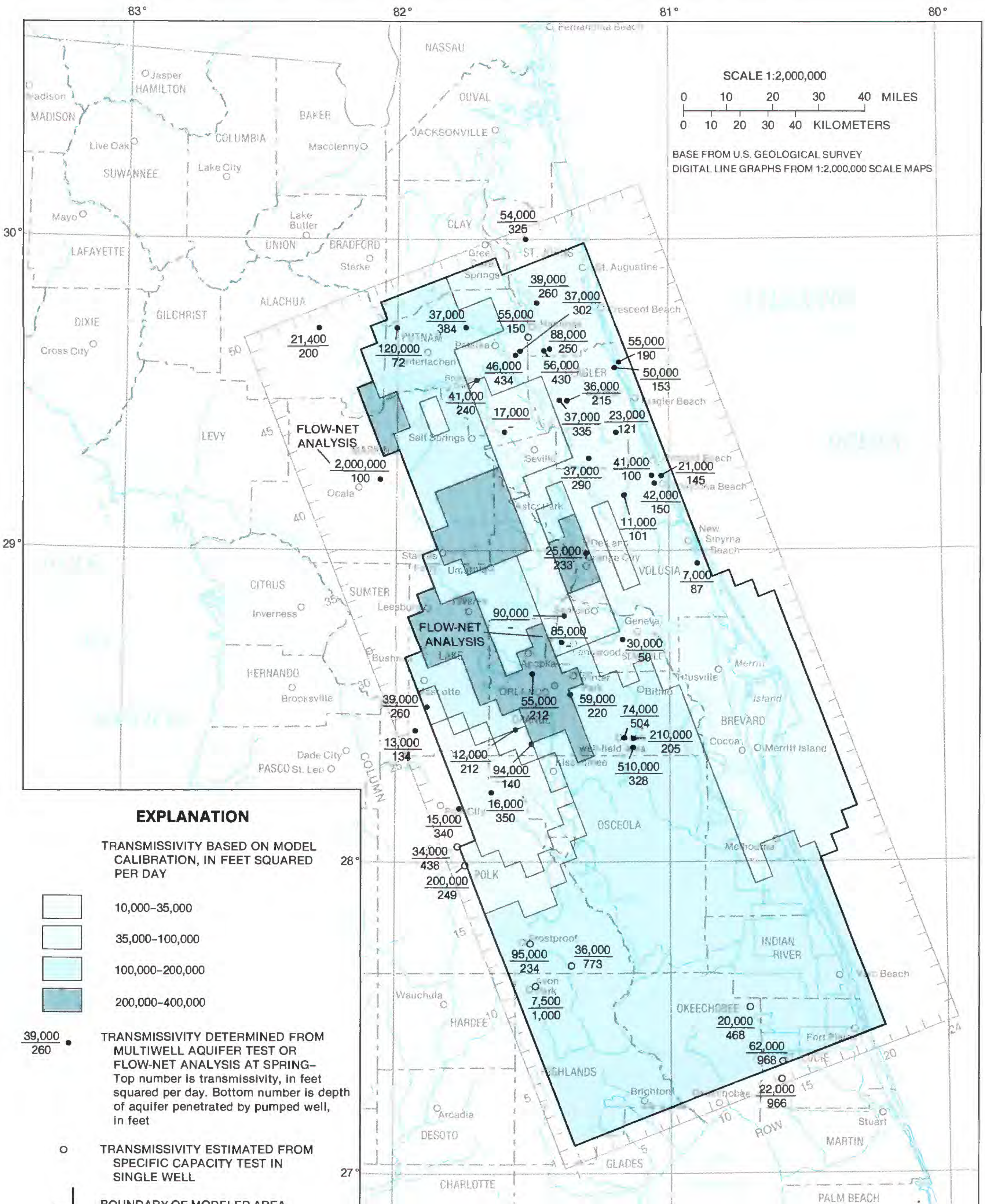


FIGURE 28.—Model-derived transmissivity of the Upper Floridan aquifer and locations of selected aquifer test sites (from Tibbals, 1981).

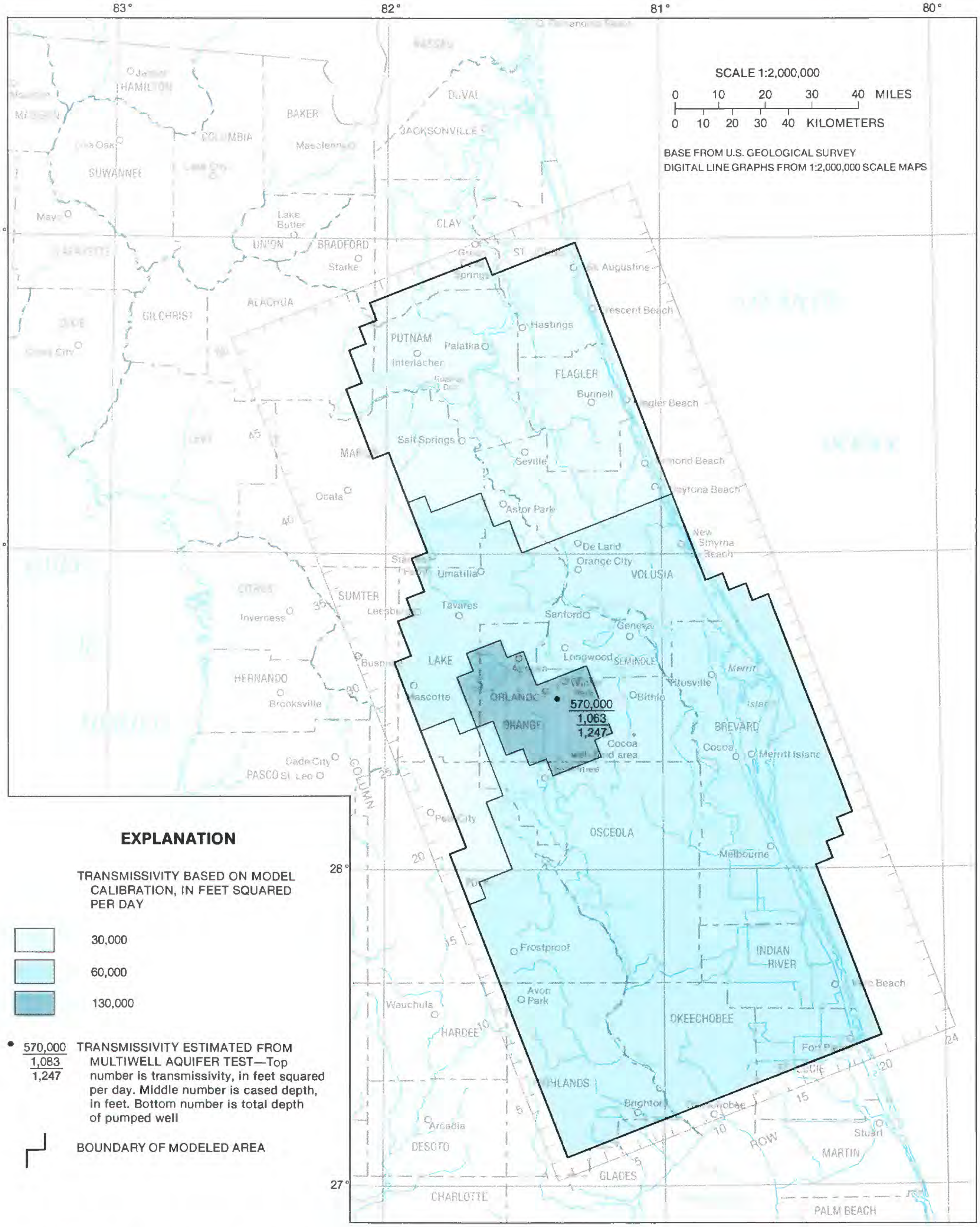


FIGURE 29.—Model-derived transmissivity of the Lower Floridan aquifer and location of aquifer test site (from Tibbals, 1981).

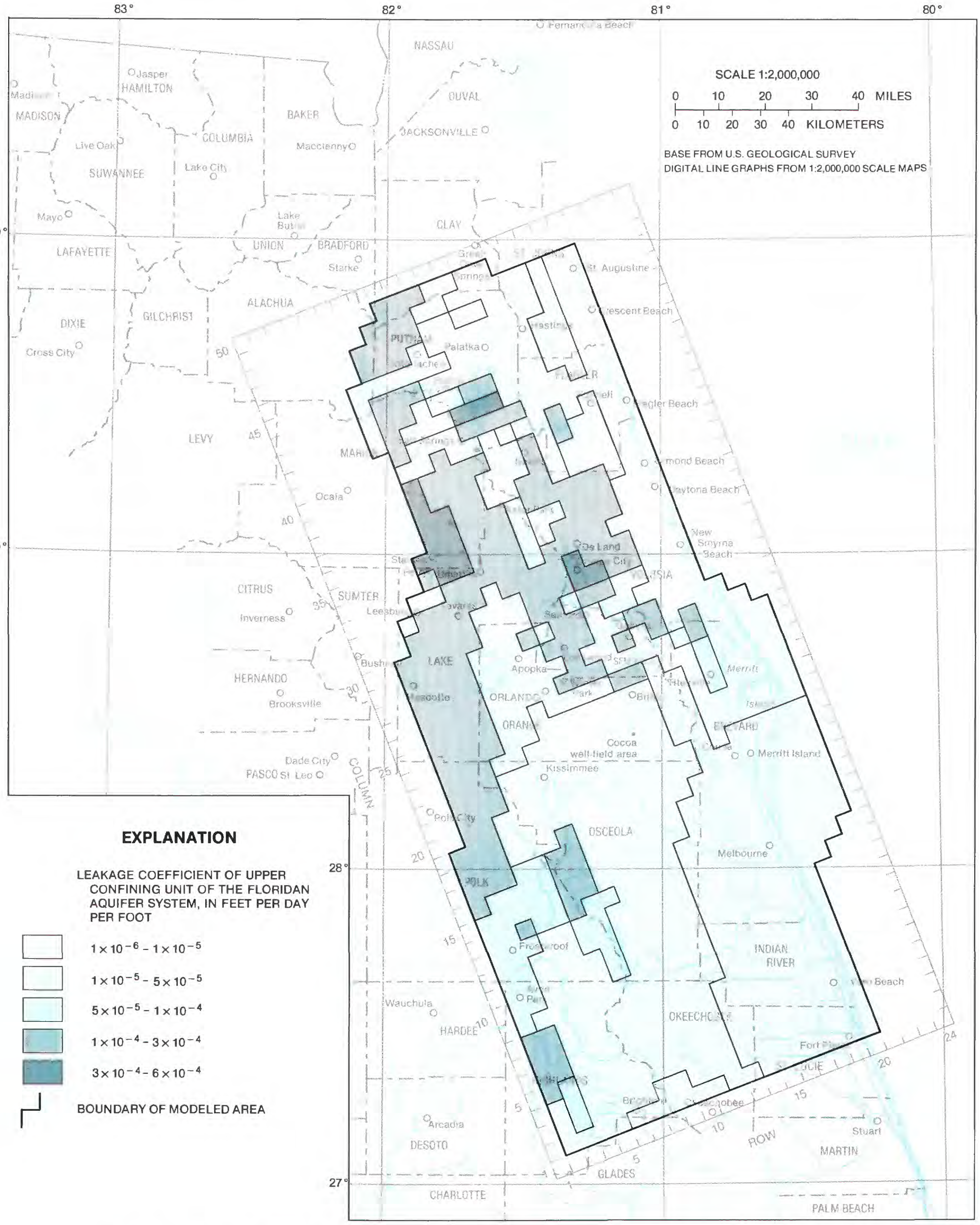


FIGURE 30.—Model-derived leakage coefficient of the upper confining unit of the Floridan aquifer system.

The concentration of dissolved solids, hardness, sulfate, and chloride shown in figures 31 through 34 are estimated as average concentrations that occur in the full thickness of the Upper Floridan. Concentrations of these constituents are generally less in water at the top of the Upper Floridan than in water at the bottom of the Upper Floridan; hence, the concentrations shown in figures 31 through 34 are termed "average" for the Upper Floridan. Figure 35 shows the average chloride concentration in water in the upper 100 ft of the Upper Floridan.

The extent to which the water in the Upper Floridan is mineralized is best described by its concentration of dissolved solids. In east-central Florida, the highest concentrations of dissolved solids occur near the Atlantic Coast and in the vicinity of the St. Johns River. Most of the highly mineralized water in the Upper Floridan in the study area is probably a mixture of freshwater and relict seawater that entered the aquifer system during a higher stand of the sea in past geologic time. In places, flushing of the ancient seawater is incomplete and the Floridan contains water that is brackish. Table 2 shows typical concentrations of dissolved solids, hardness, sulfate, and chloride in freshwater, brackish water, and seawater. The term "saline" is often used to describe the mineralization of water. Hem (1973, p. 219) defined various levels of salinity in terms of dissolved-solids concentration. The slightly modified definitions used in this report are as follows:

Salinity	*Dissolved-solids concentration (mg/L)*
Fresh	<1,000
Slightly saline	1,000– 3,000
Moderately saline	3,000–10,000
Very saline	10,000–35,000
Briny	>35,000

In Floridan aquifer system water, the dominant cations are calcium (Ca^{+2}), magnesium (Mg^{+2}), sodium (Na^{+}), and potassium (K^{+}). The dominant anions are bicarbonate (HCO_3^{-}), chloride (Cl^{-}), and sulfate (SO_4^{-2}). Locally, smaller amounts of dissolved iron, manganese, nitrate, phosphate, fluoride, strontium, sulfide, and silica may contribute to the dissolved-solids concentration.

In about 40 percent of the area the dissolved-solids concentration in water in the Upper Floridan is less than 250 mg/L (fig. 31). The areas of relatively low concentrations of dissolved solids generally correspond with the good recharge areas of the Upper Floridan aquifer (fig. 21). In the discharge areas along the Atlantic Coast and along the St. Johns River, the dissolved-solids concentration is generally more than 1,000 mg/L and ranges to more than 25,000 mg/L. Insofar as is known, nowhere in east-central Florida does the dissolved-solids concentration in water in the Upper Floridan equal that in seawater.

TABLE 2.—*Typical concentrations of dissolved solids, hardness, sulfate, and chloride in freshwater, brackish water, and seawater*
[mg/L, milligram per liter]

Constituent	Freshwater (mg/L)	Brackish water (mg/L)	Seawater (mg/L)
Dissolved solids	<1,000	1,000–35,000	35,000
Hardness as $CaCO_3$	<400	400–6,600	6,600
Sulfate	<250	250–2,700	2,700
Chloride	<250	250–19,000	19,000

"Hardness" is a term that has long been used to describe the resistance of water to produce a lather from soap. The U.S. Geological Survey (Hem, 1973, p. 225) classifies water on the basis of hardness as follows:

Hardness range (mg/L of $CaCO_3$)	*Description*
0–60	Soft
61–120	Moderately hard
121–180	Hard
>180	Very hard

Though water that is very hard may be unsuitable for many industrial uses (because of boiler scaling problems, for example), it may be satisfactory for domestic purposes.

Recent studies (Schroeder, 1966; Sauer, 1974; Marier and others, 1979) have found a statistically significant correlation between increased levels of hardness in drinking water and decreased risk of cardiovascular disease.

In east-central Florida, hardness concentrations in water in the Upper Floridan aquifer range from 61 to 120 mg/L in parts of the good Upper Floridan recharge areas (fig. 21) to several thousand milligrams per liter in and near the Upper Floridan discharge areas along the St. Johns River and near the Atlantic Coast (fig. 32).

Sulfate concentrations in water in the Upper Floridan aquifer (fig. 33) range from virtually zero in the good Upper Floridan recharge areas (fig. 21) to as much as 900 mg/L in discharge areas near the St. Johns River and along the Atlantic Coast. A bacterial process in which sulfate is reduced to bisulfide causes hydrogen sulfide gas to form. It is this gas that causes the characteristic "rotten egg" odor of water from some wells and springs in the Upper Floridan.

Chloride is the predominant anion in seawater and is responsible for its salty taste. Chloride concentration is the single most important indicator of the presence of brackish water. Figure 34 shows the average chloride concentration of water estimated to occur in the full thickness of the Upper Floridan, whereas figure 35

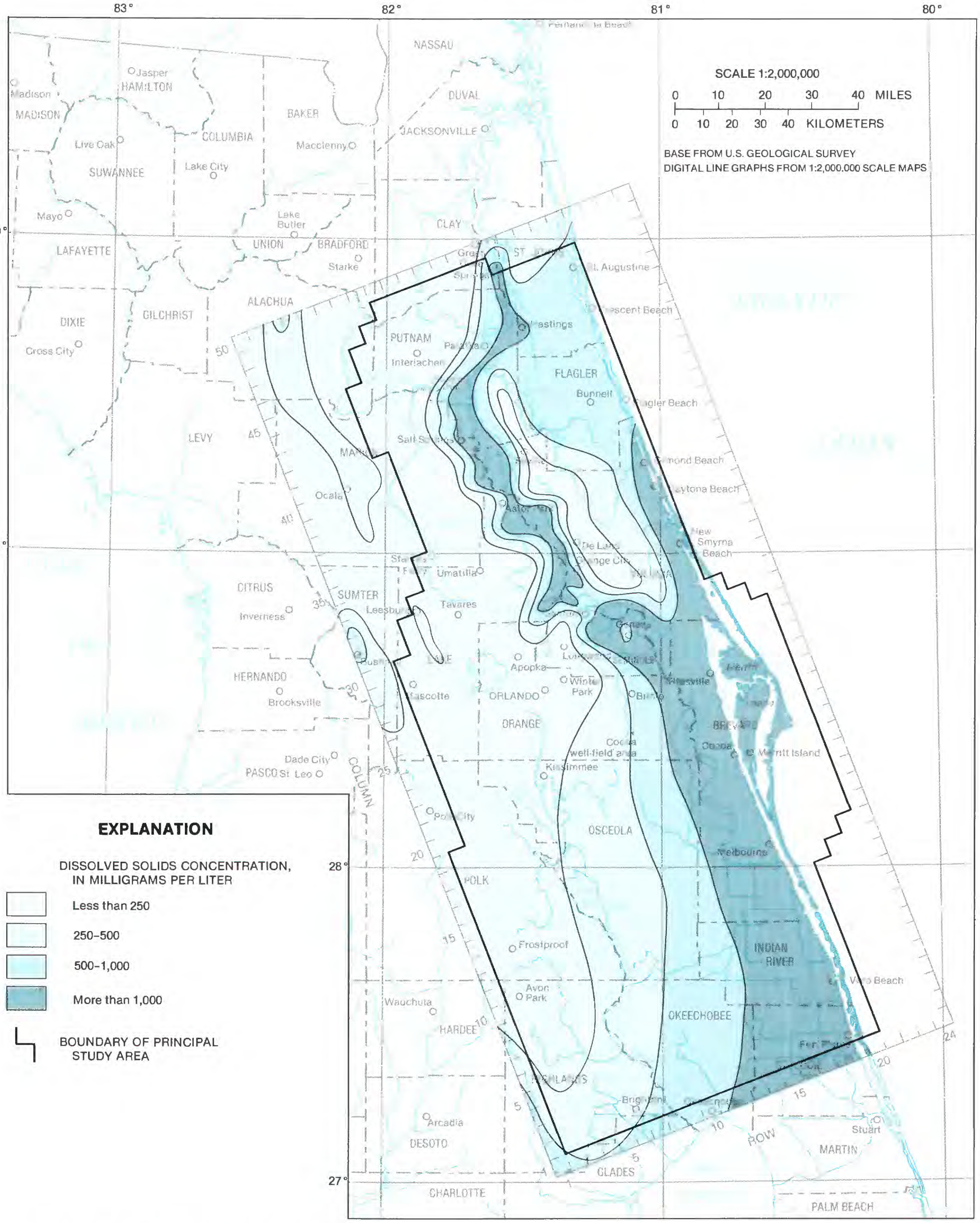


FIGURE 31.—Average dissolved-solids concentration in water in the Upper Floridan aquifer (adapted from Sprinkle, 1982b).

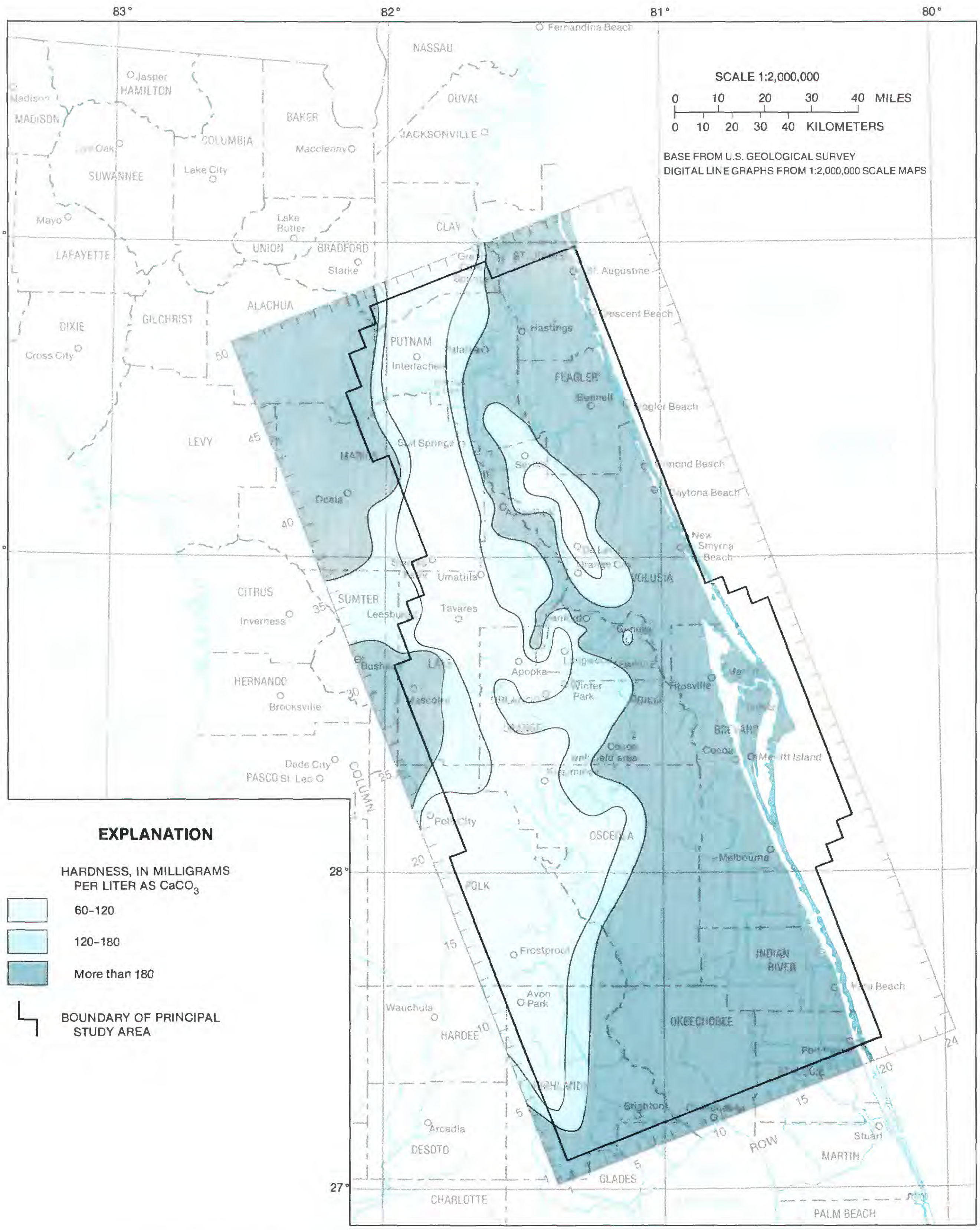


FIGURE 32.—Average hardness of water in the Upper Floridan aquifer (adapted from Sprinkle, 1982d).

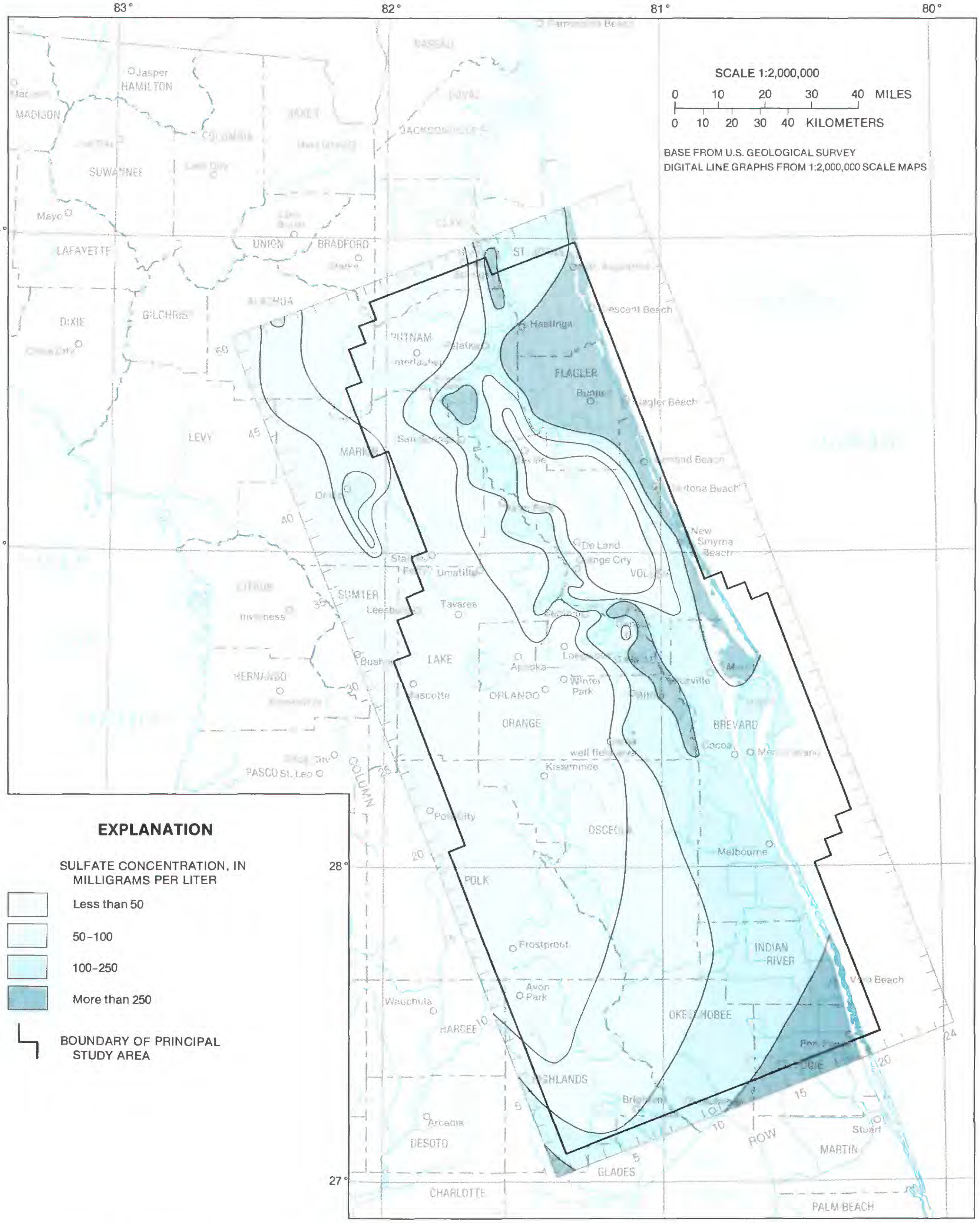


FIGURE 33.—Average sulfate concentration in water in the Upper Floridan aquifer (adapted from Sprinkle, 1982c).

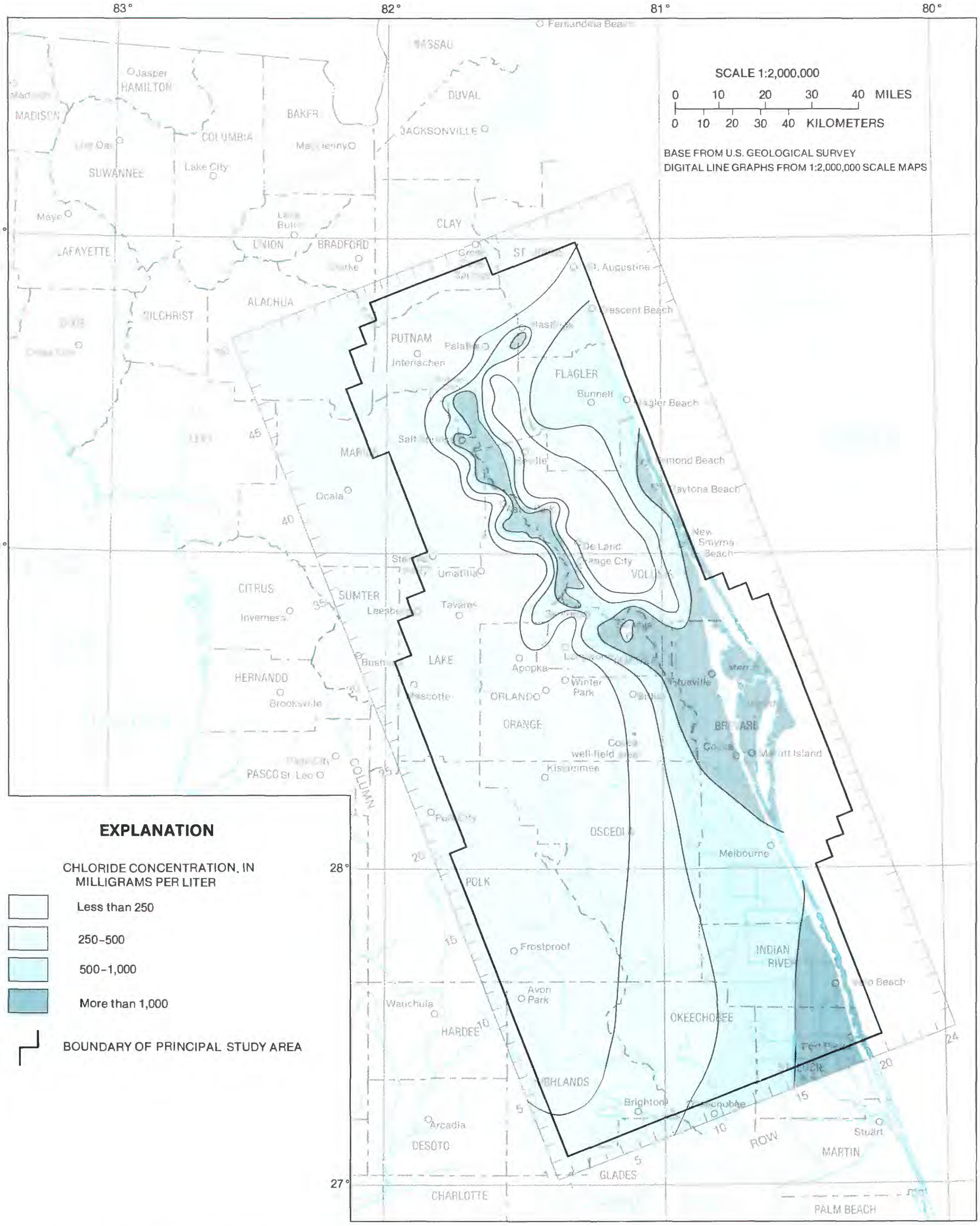


FIGURE 34.—Average chloride concentration in water in the Upper Floridan aquifer (adapted from Sprinkle, 1982a).

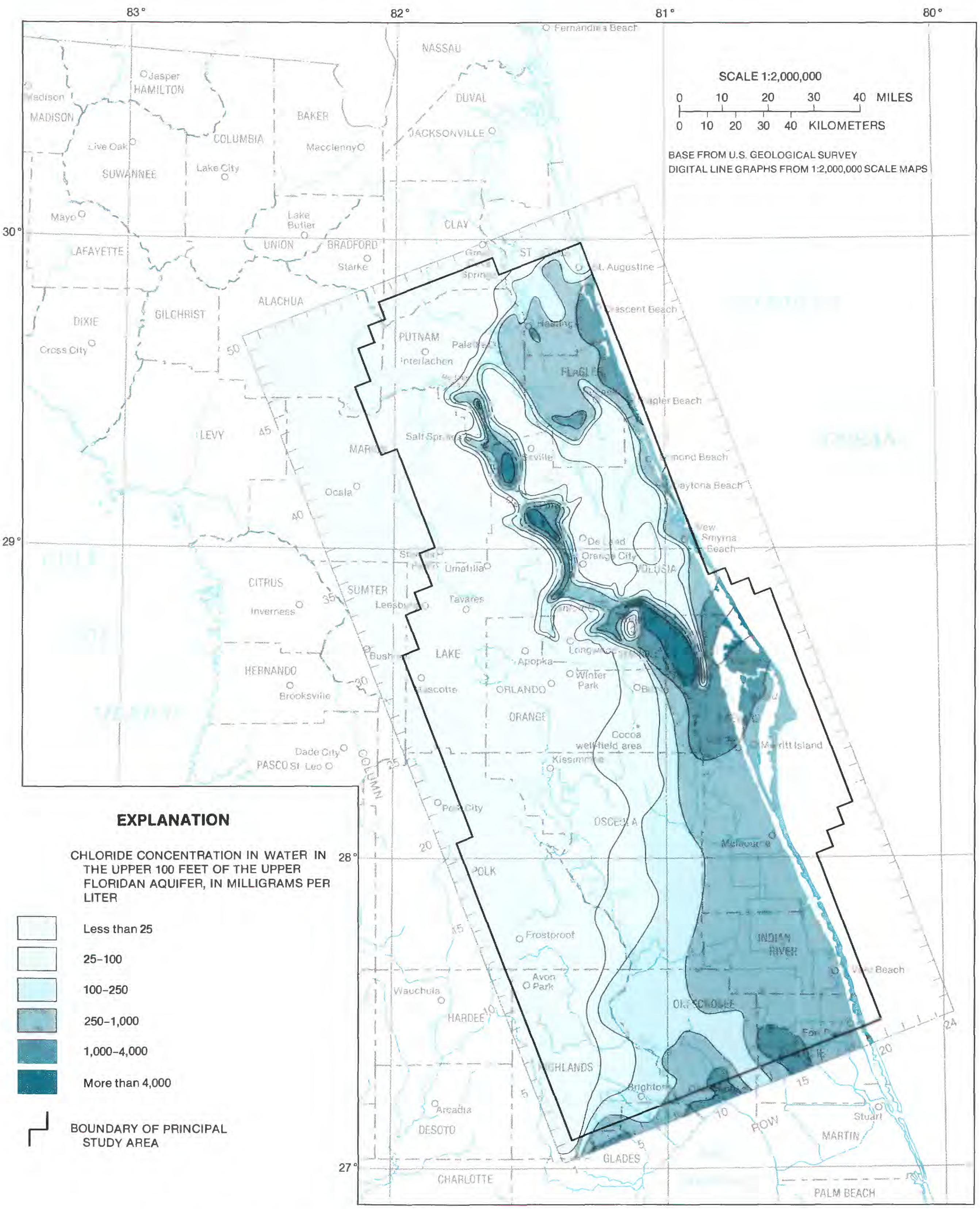


FIGURE 35.—Chloride concentration in water in the upper 100 feet of the Upper Floridan aquifer.

shows the chloride concentration of water in the upper 100 ft of the Upper Floridan. Of the four chemical constituents discussed (dissolved solids, hardness, sulfate, and chloride), chloride is the constituent that, in its higher concentrations, is least tolerated by humans, animals, and plants. Because the upper 100 ft of the Upper Floridan aquifer is most likely to be tapped by most ground-water users, the chloride concentration there is mapped and shown in figure 35.

Though the upper limit of chloride concentration recommended for public water supplies in Florida is 250 mg/L (Florida Department of Environmental Regulation, 1982), most people cannot detect a salty taste in water below concentrations of, say, 400 mg/L. In most of the area, the chloride concentration in the Upper Floridan is less than 250 mg/L (figs. 34, 35). Concentrations generally are more than 1,000 mg/L in the Upper Floridan along most of the course of the St. Johns River and along the Atlantic Coast from about Cocoa north to about St. Augustine. Measurements showed several occurrences of high-chloride water along the St. Johns River: (1) a well near the northeast shore of Lake Harney (south Volusia County) had water with a chloride concentration of about 9,000 mg/L, as did (2) a well near the southeast shore of Lake George (north Volusia County), and (3) a well near the north shore of Lake Poinsett (central Brevard County) had water with a chloride concentration of about 12,000 mg/L.

Along the Atlantic Coast, the highest chloride concentrations occurred in water from wells on the west shore of the Indian River near Titusville (13,000 mg/L) and on the southwest and northeast shores of Indian River near the north end of Merritt Island (12,000 mg/L).

In a few areas beneath the topographically high relict beach ridges of south Brevard and Indian River Counties, the uppermost part of the Upper Floridan aquifer contains water fresher than the water below or water immediately to the east or west. These freshwater areas are oriented parallel to the coast and are relatively long and narrow. The chloride concentration data there are very scattered and for that reason are not shown in figures 34 and 35. The source of the fresher water is not lateral flow because more brackish water is present upgradient from the fresher area. The fresher water cannot be the result of ongoing downward leakage or recharge from the surficial aquifer because the fresher water is in an Upper Floridan aquifer discharge area where heads in the Upper Floridan are above the water table and the land surface. The most probable explanation for the occurrence of the fresher waters is that sometime in the geologic past, the surficial aquifer system recharged the Upper Floridan and the fresher water in the Upper Floridan is the residual. Such an episode could have occurred when the sea stood at a much lower level. At that time, the potentiometric surface of the Upper Floridan would also have stood at a lower level, especially near the coast. If the potentiometric surface was below the water table, then downward leakage or recharge could have occurred. Lower stands of the sea occurred during the Pleistocene Epoch. The following discussion is taken from Stringfield (1966):

> The outstanding feature of Pleistocene time was the extensive continental glaciation in the northern hemisphere. Although this glaciation did not extend to the South Atlantic States, worldwide changes of sea level were caused by removal of water from the sea to form the continental glaciers. At times when the glaciers melted, as described by Cooke (1939), water returned to the sea, causing a rise in sea level.

Cooke (1939, figs. 12–16) and Stringfield (1966, figs. 16–20) describe shorelines that result from sea-level altitudes that range between 270 ft above the present level to 300 ft below the present level (fig. 36). Zellmer (1979, fig. 17) estimated sea-level altitudes as low as 300 ft below present level during at least eight periods in the last million years (fig. 37).

Thus, just as it is possible that the brackish water present in the Upper Floridan is water that entered the aquifer during a higher stand of the sea, it is possible that the isolated pockets of freshwater in what are now discharge areas could be the result of freshwater that was recharged during a lower stand of the sea. This freshwater is being flushed out at an extremely low rate and is, thus, essentially "trapped."

The lateral transition from freshwater to brackish water in the Upper Floridan in east-central Florida occurs over distances of one-half mile to several tens of miles (figs. 31–35).

The vertical transition from freshwater to brackish water occurs over intervals as small as a few tens of feet. The additional vertical transition of slightly brackish water to water that is, say, half as brackish as seawater (chloride concentration of about 10,000 mg/L) occurs over distances of a few tens of feet to several hundred feet.

Few wells, other than oil test wells, have penetrated the full thickness of freshwater in recharge areas. The drillers' logs of the oil test wells generally do not include information that defines the depth to which freshwater extends. Therefore, the few wells drilled specifically for hydrologic purposes provide the little information available. Figure 38 shows the estimated depth to water having a chloride concentration greater than 10,000 mg/L. Some wells shown in figure 38 did not extend to depths at which the chloride concentration was as high as 10,000 mg/L because drilling was generally terminated soon after brackish water was detected. Test wells drilled as part of this study, well 47 at Geneva (northeast Seminole County, fig. 39), well 55 near Blue Spring (southwest Volusia County, fig. 40), and wells 14 and 17 at Polk City (north Polk County, fig. 41), are examples of

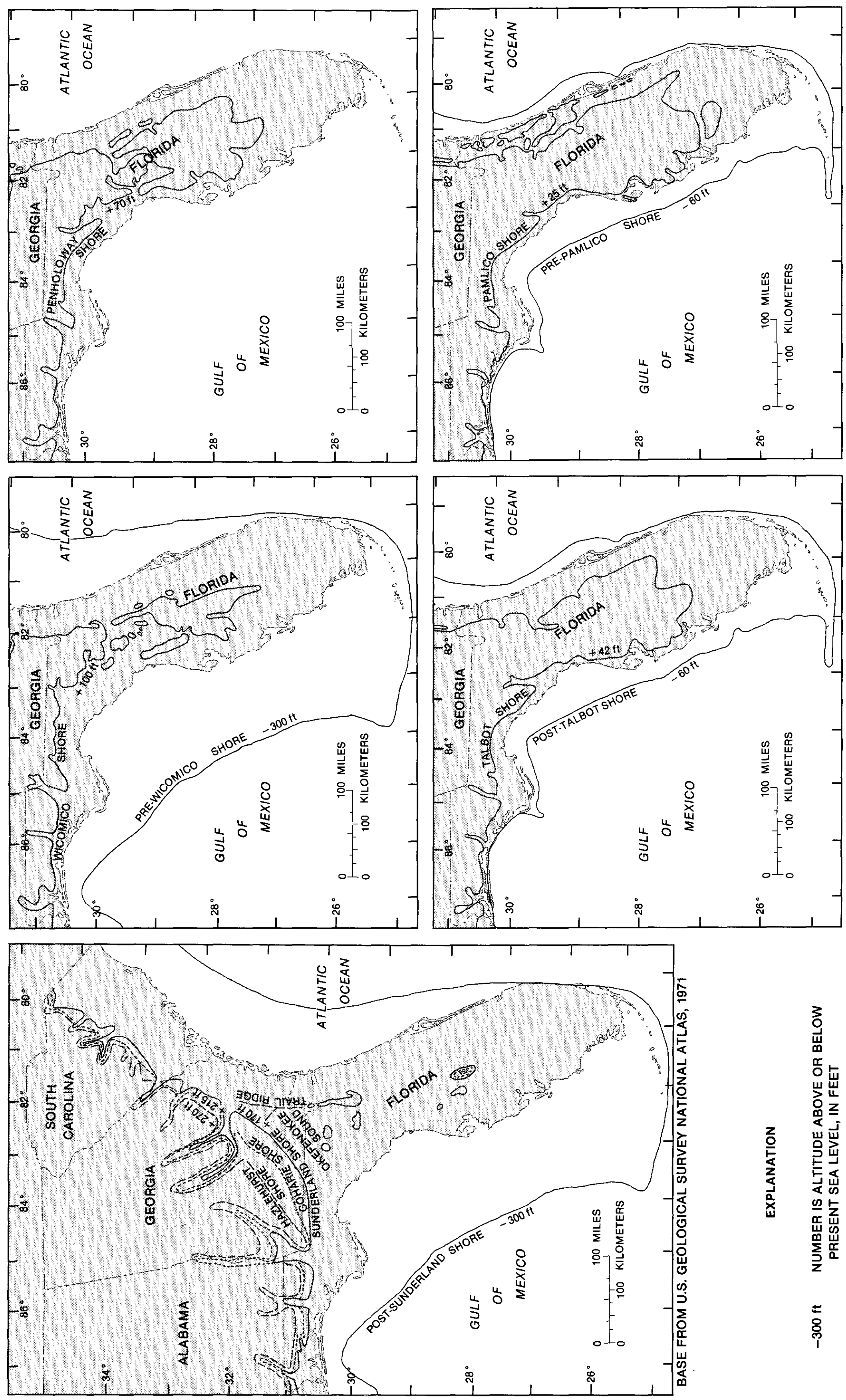


FIGURE 36.—Pleistocene shorelines, much generalized (after Cooke, 1939, figs. 12–16).

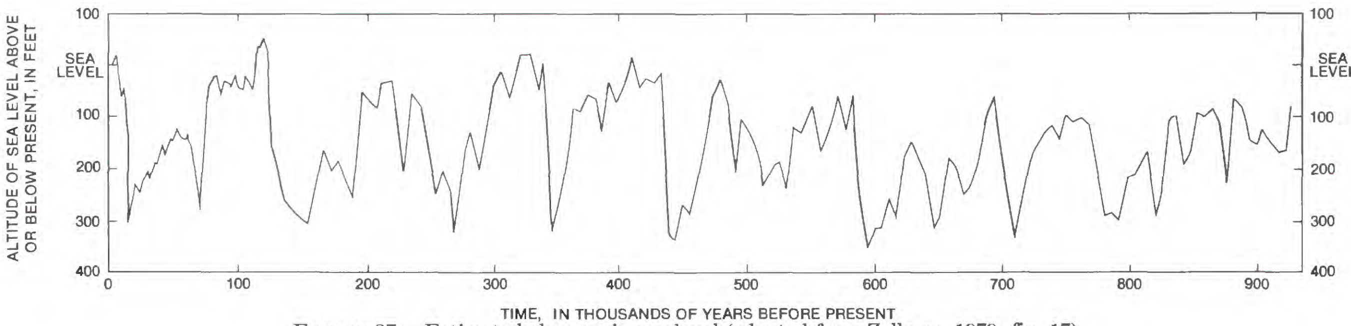


FIGURE 37.—Estimated changes in sea level (adapted from Zellmer, 1979, fig. 17).

wells drilled specifically to collect information on depth of freshwater.

The test well in the Geneva area (fig. 39) tapped brackish water at a depth of about 380 ft. The test well near Blue Spring yielded brackish water through its entire depth, but the sharpest change in chloride concentration occurred at a depth of about 425 ft. From 425 to 442 ft the chloride concentration rose from about 4,000 to about 9,000 mg/L.

The Geneva test well was drilled to help define the vertical extent of an "island" of freshwater in the Upper Floridan in a good recharge area in Seminole County (fig. 21). The Upper Floridan in northeast Seminole County contains brackish water except in the Geneva area (figs. 31–35). This condition was first recognized by Stringfield (1936a), was verified by Barraclough (1962), and was further investigated by Tibbals (1977) and by G.G. Phelps (U.S. Geological Survey, written commun., 1984).

The test well near Blue Spring (fig. 40) was drilled to help determine if an active zone of fresher water was circulating beneath a relatively sluggish zone in the uppermost part of the Upper Floridan near Blue Spring. The results were not conclusive because drilling was stopped when very brackish water was found at a relatively shallow depth. However, it is believed unlikely that a zone of fresher water exists at depth.

In Polk City, north Polk County, a corehole (well 17) was drilled to a depth of about 2,000 ft (Navoy, 1986). Though brackish water as defined by chloride concentration (table 2) was not found during drilling, the water became brackish with depth in terms of concentrations of dissolved solids, hardness, and sulfate (fig. 41). Though not shown in figure 41, the chloride concentration did not exceed 11 mg/L. The relatively low concentration of chloride and relatively high concentrations of dissolved solids, hardness, and sulfate indicate that any seawater that had been present in the aquifer has been flushed out, at least to a depth of about 2,000 ft. The increase in mineralization that starts at about 900 ft is caused by a sluggish flow system that allows prolonged contact of the water with soluble rock minerals.

In 1976 and early 1977 a test well (well 32, fig. 38) was drilled at the Sand Lake Road wastewater treatment facility near Orlando, Orange County, to determine the feasibility of injecting treated wastewater into saline water zones that underlie the Lower Floridan aquifer (Geraghty and Miller, Inc., 1977). Test results determined that freshwater there extended to a depth of about 2,400 ft. Below that depth the dissolved-solids concentration of the water sharply increased from about 200 to about 110,000 mg/L, approximately three times that of seawater. Water that is mineralized to that degree is referred to as "brine." As drilling progressed toward the final well depth of 6,193 ft, the dissolved-solids concentration rose to about 150,000 mg/L and the chloride concentration rose to about 85,000 mg/L. Aquifer testing showed that the brine zone had extremely low permeability (Geraghty and Miller, Inc., 1977). Extremely low permeability in rocks below the Lower Floridan aquifer was also reported in a deep test well in Alachua County, southwest of Gainesville, at the Kanapaha Lakes sewage treatment plant (CH2M Hill, Inc., Gainesville, Fla., written commun., 1977).

Brines probably exist at some depth throughout east-central Florida. Low permeability of the brine zones may be the single most important factor that tends to limit, or at least to minimize, upconing of salty water in response to pumping of freshwater from the Floridan aquifer system.

From Lake Harney northward along the St. Johns River, the brackish water in the Upper Floridan aquifer (figs. 31–35) is virtually stagnant. The relatively small amounts of brackish water discharged are believed to be continually replenished by upward movement of brackish water that occurs at depth. For example, if the 1980 potentiometric surface map (fig. 21) is superimposed on the maps of chloride concentration (figs. 34, 35) it is apparent that the more highly mineralized waters in the Upper Floridan north of Lake Harney are present near

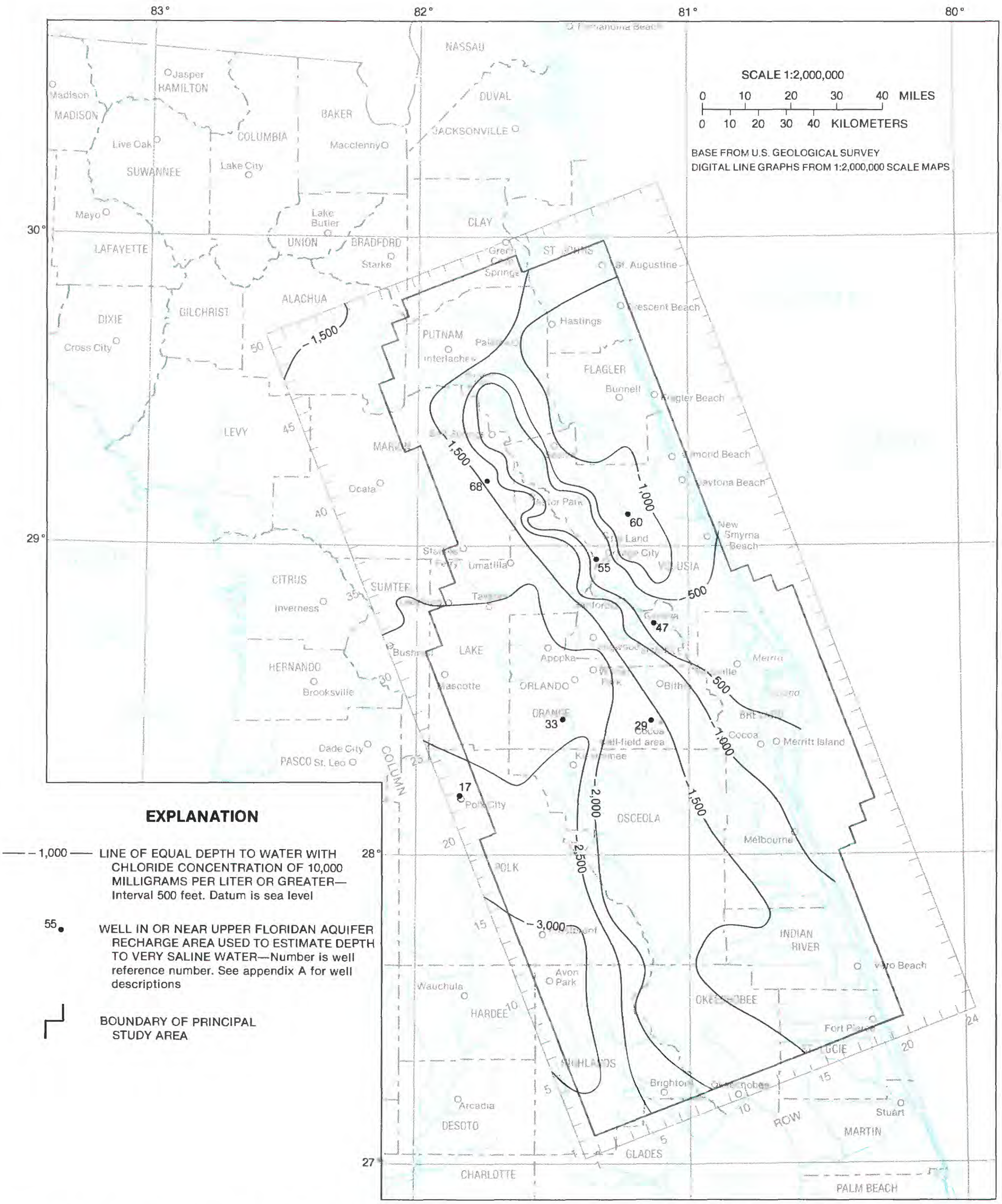


FIGURE 38.—Estimated depth to water having chloride concentration greater than 10,000 milligrams per liter (adapted from C.L. Sprinkle, written commun., 1982).

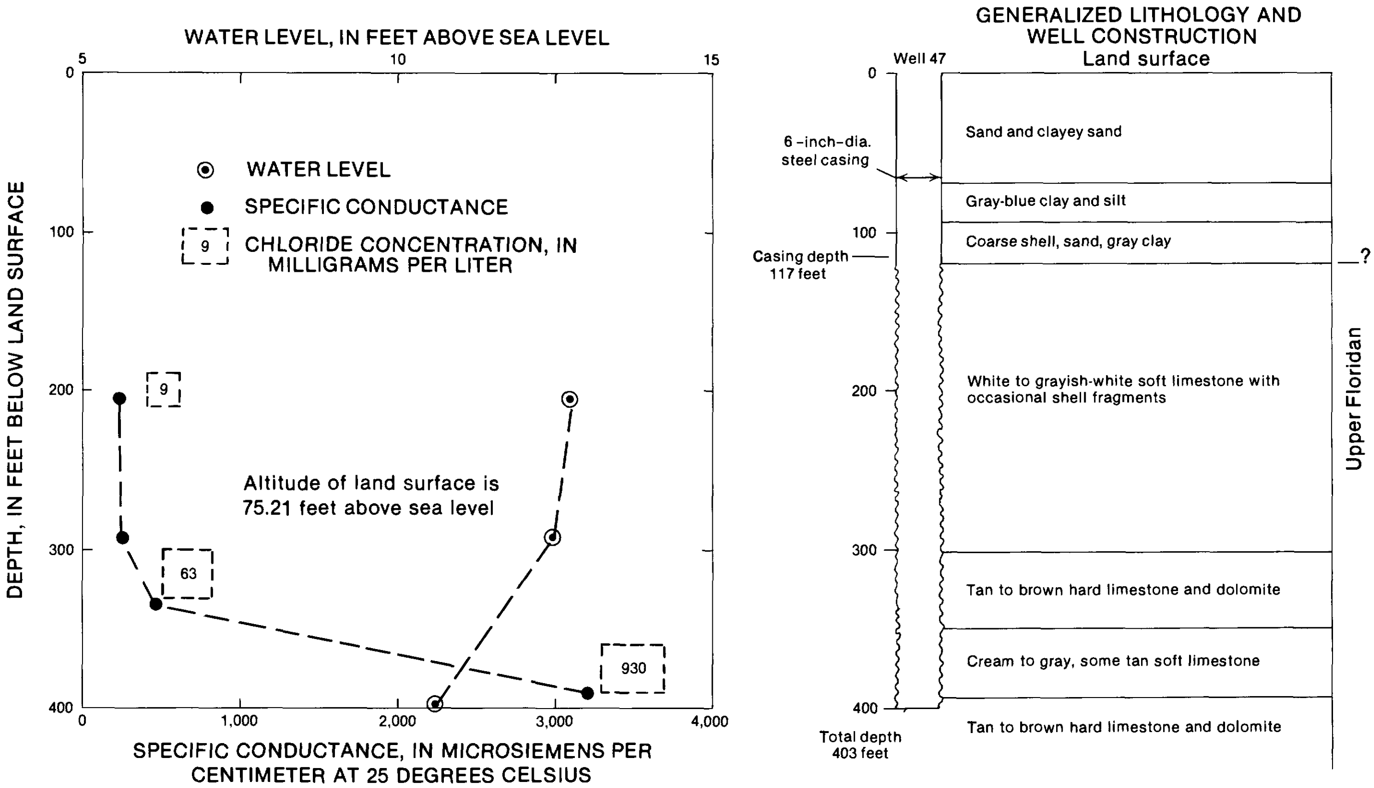


FIGURE 39.—Specific conductance, chloride concentration, water levels, and generalized lithology in well 47, at Geneva, Seminole County, August 1981.

areas where the Upper Floridan is discharging through springs. The springs discharge water that enters the aquifer in the upgradient direction within their ground-water basins (fig. 21). The larger springs and groups of smaller springs capture virtually all the water in their flow fields. In the direction opposite the predominant flow fields there is little hydraulic gradient and flow in the aquifer is extremely sluggish. Therefore, though the flushing of brackish water in the predominant flow fields is complete, the sluggish nature of the opposite flow fields has not allowed flushing to be complete.

The aquifer system along the St. Johns River from Lake Harney northward is, perhaps, as flushed as it will ever be. For example, the Blue Spring ground-water basin (fig. 21) is about 330 mi^2 in area. If it is assumed that the average thickness of freshwater in the Floridan system in the Blue Spring ground-water basin is about 700 ft (area around well 55, fig. 38) and the porosity of the aquifer materials is about 25 percent, then the volume (V) of freshwater in the aquifer is computed as

$$V = 330 \text{ mi}^2 \ (5{,}280 \text{ ft/mi})^2 \ (700 \text{ ft}) \ (0.25)$$
$$= 1.6 \times 10^{12} \text{ ft}^3$$

The approximate period of time (t) that it would take for Blue Spring to discharge that total volume of water is calculated by dividing the spring's discharge rate into the total volume of water in the basin:

$$t = \frac{1.6 \times 10^{12} \text{ ft}^3}{160 \text{ ft}^3\text{/s } (3.1536 \times 10^7 \text{ s/yr})} = 320 \text{ yr.}$$

These calculations are not meant to imply that it took only 320 yr to completely flush the brackish water from the basin. It may have taken many tens of such flushing cycles for the water in the Upper Floridan to have reached its present chemical composition.

It is estimated that if parts of the Floridan aquifer system were filled with brackish water or seawater during a previous high stand of the sea (fig. 36), then the most recent such event would have ended no sooner than 120,000 yr ago (fig. 37). In the Blue Spring basin and in several other selected basins (table 3), enough time has passed for many flushing cycles to have occurred. Of the five spring basins analyzed, the two basins having the shortest flushing times tended to have springs that discharge water that is the most brackish. Therefore, only a small part of the brackish water being discharged from some of the springs is likely to be moving laterally

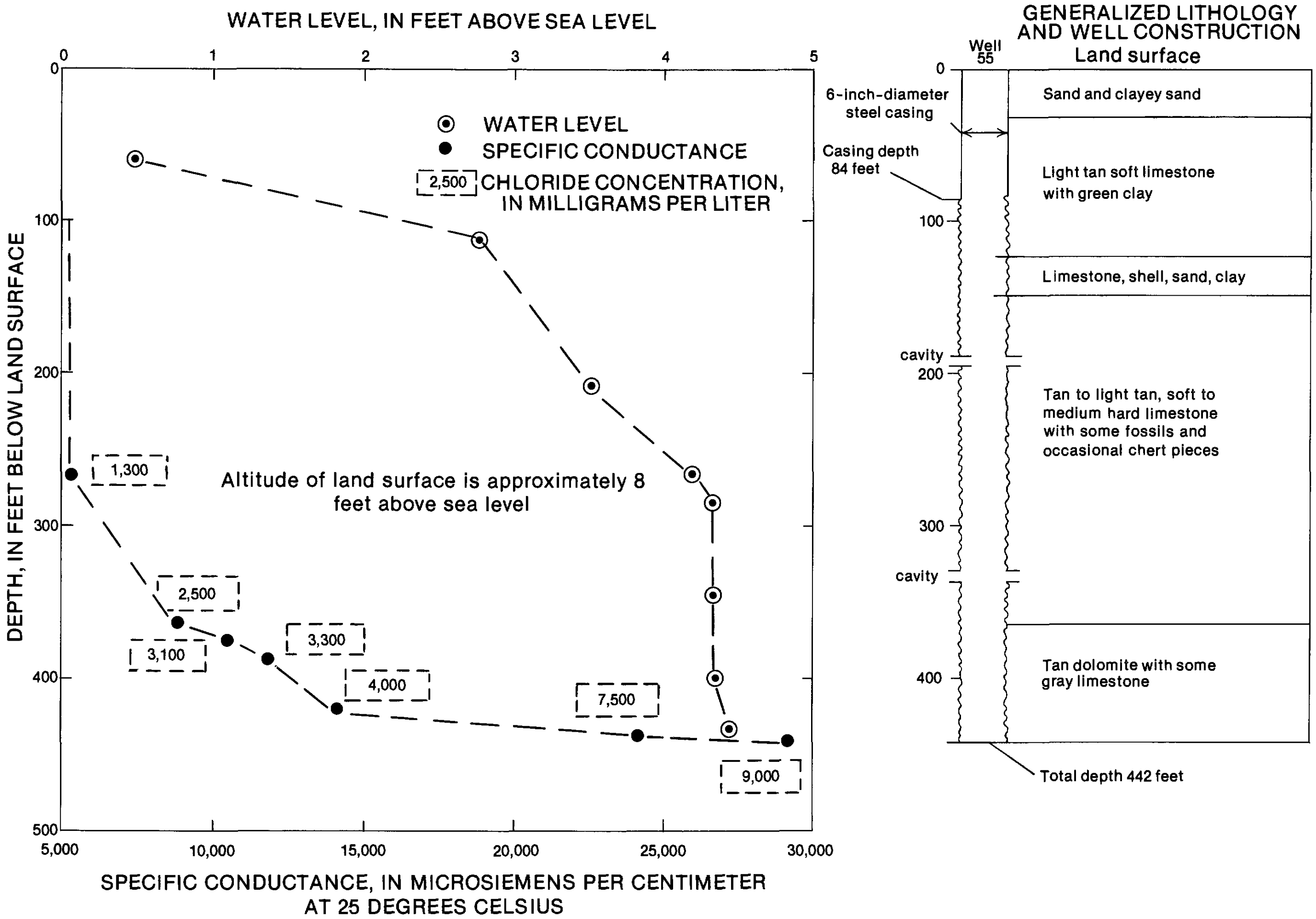


FIGURE 40.—Specific conductance, chloride concentration, water levels, and generalized lithology in well 55, about 0.3 mile southwest of Blue Spring, Volusia County, August 1981.

from areas of relatively stagnant flow. Hence, it is likely that most of the brackish water being discharged is moving upward from depth in the vicinity of the springs. The sharp increase in mineralization of water from well 55 (near Blue Spring) as it was being drilled tends to support this conclusion.

The reader should be aware that the preceding calculations and hypothetical conclusions are based on the

TABLE 3.—*Minimum time to flush brackish ground water from selected spring basins*
[mi^2, square miles; ft, feet; ft^3, cubic feet; ft^3/s, cubic feet per second; mg/L, milligrams per liter]

Spring basin or basins	Approximate basin area (mi^2)	Average thickness of freshwater (ft)	Aquifer porosity	Volume of freshwater (ft^3)	Total known spring discharge (ft^3/s)	Number of years to flush basin	Chloride concentration in: Recharge area (mg/L)	Chloride concentration in: Discharged water (mg/L)
Blue	330	700	0.25	1.6×10^{12}	160	320	75	500
Rock; Wekiva and Miami; Sanlando, Palm, and Starbuck; Seminole and Messant; Apopka; Island	890	2,000	.25	1.2×10^{13}	286	1,300	20	35
Alexander and Alexander Spring Creek	450	1,600	.25	5.0×10^{12}	130	1,200	40	220
Ponce De Leon	150	1,000	.25	1.0×10^{12}	31	1,000	100	150
Juniper and Fern Hammock; Juniper Creek and Sweetwater; Silver Glen; Salt	470	1,000	.25	3.3×10^{12}	294	360	50	812

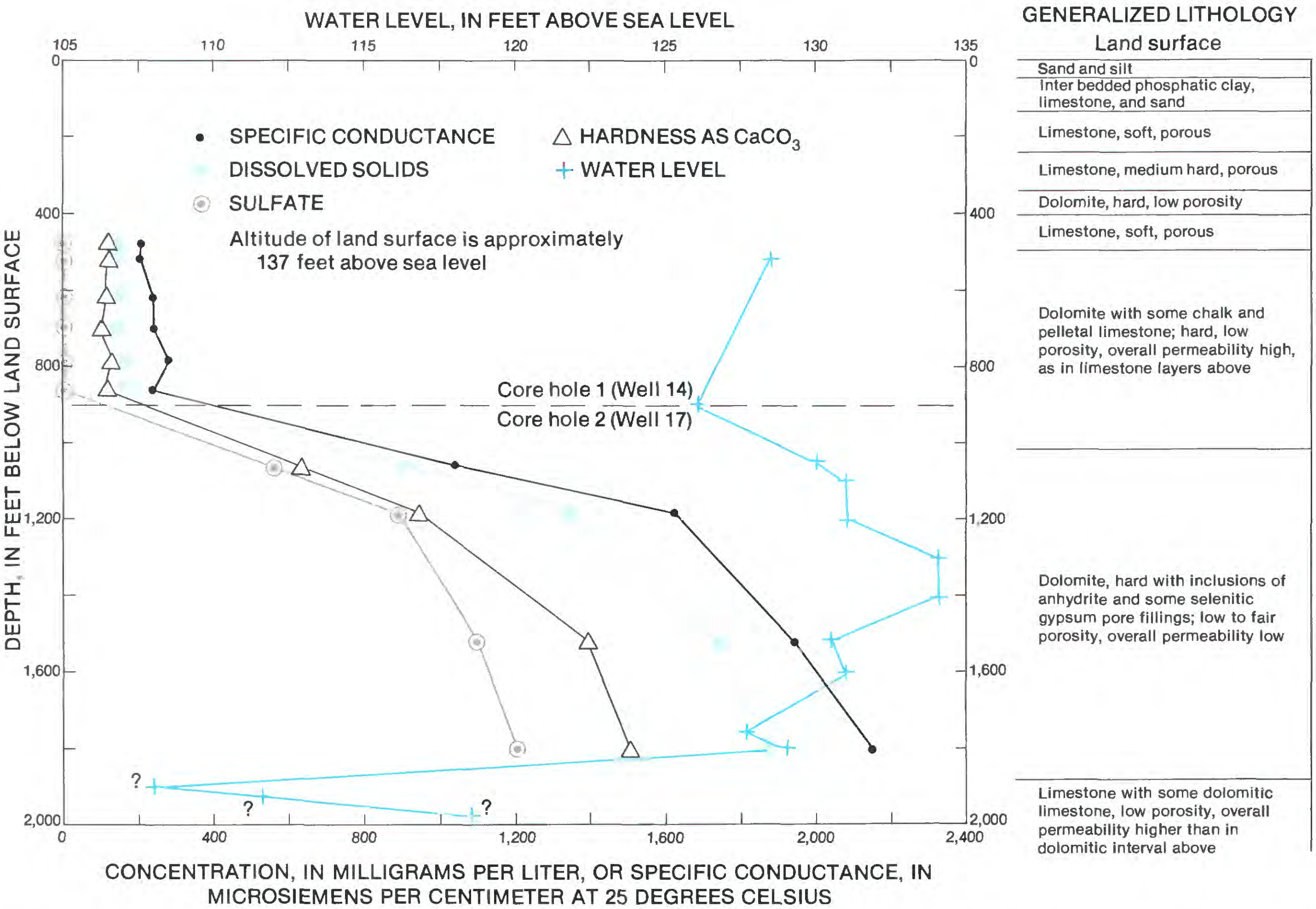


FIGURE 41.—Specific conductance, hardness, dissolved solids, sulfate, water levels, and lithology in core holes 1 and 2 (wells 14, 17) at Polk City, Polk County, 1979–80.

assumptions that (1) the ground-water basins of the springs have remained essentially the same size over the past 120,000 yr as they are now, and (2) the springs' discharges have remained about the same during the flushing period.

The faults that are believed to be present along the St. Johns River (fig. 11) could provide an avenue for substantial upward movement of brackish water to replace that which is discharged either by springs or by diffuse upward leakage. However, even if faults are absent, brackish water can be discharged and still be continually replenished by brackish water from depth. The natural upward hydraulic gradient that is present near springs provides the hydraulic potential to move brackish water upward. For example, as well 55 near Blue Spring was drilled the water level in the well rose about 4 ft (fig. 40). This indicates that as the well was drilled, it tapped zones of increasingly higher head.

DIGITAL COMPUTER MODEL

A digital computer model was used to simulate both predevelopment and present-day (1978) flow conditions in the Floridan aquifer system in east-central Florida. Features and assumptions of the model are described in a previous RASA report by Tibbals (1981). The reader is referred to that report for discussions of the steady-state model calibration, boundary conditions, methods used to simulate spring flow, and derivation of confining-unit leakage coefficients. Model simulations described in this report use the same basic model framework except as follows:

- Some very minor revisions to boundary flow coefficients on the Atlantic Coast were made.
- Croaker Hole Spring and Island Spring were added.
- The fixed boundary head matrix in the vicinity of the lower reaches of the Oklawaha River was changed to

reflect the rise in head caused by the impoundment that created Lake Oklawaha, or Rodman Reservoir.

- Storage coefficients for the Upper and Lower Floridan aquifer were input to simulate transient flow rather than steady-state flow.
- Matrices for 1978 pumping from the Upper and Lower Floridan were added. These matrices also include the effects of recharge by drainage wells in the Orlando area (fig. 23) and of cross-boundary flow to the west to simulate model outflow to adjacent pumping centers.

Except for those changes or additions, the model is identical to that described by Tibbals (1981). Further discussion of the model is limited to the following:

- Discussion of figure 8, which shows reconciliation of the more complex geologic units with a simplified conceptualization of the hydrogeologic units and their equivalent layers as simulated by the model,
- Description of the model grid (fig. 42),
- Portrayal of the conceptualization model input data (fig. 43),
- Brief discussion of the results of the predevelopment steady-state simulation (Tibbals, 1981), and
- Discussion of the method of calibration of the transient model used for simulations described in this chapter.

The computer source code is adapted from the three-dimensional ground-water flow model developed by Trescott (1975) and Trescott and Larson (1976). Steven Larson and James Tracy, U.S. Geological Survey (written commun., September 1979), modified the model to include the head-controlled flux boundary condition that also is used to simulate spring flow. The model was further modified by the writer to facilitate data handling, error analysis, and output manipulation, and by Anthony Navoy, U.S. Geological Survey, to plot hydraulic cross sections.

The model is structured to simulate a three-layered system with the layers separated by confining units (fig. 8). Vertical resistance to flow between layers is simulated by areally variable leakage coefficients that characterize the vertical hydraulic conductivity and thickness of the confining units.

The model area is subdivided into a finite-difference grid of 24 rows and 50 columns (fig. 42). Each of the 1,200 grid blocks, or nodes, is 4 mi on a side and 16 mi^2 in area. Because of the configuration of the model boundaries, only 857 model nodes are active. These 857 nodes represent a surface area of about 13,700 mi^2.

At each of the active nodes, values of starting head, transmissivity, and storage coefficient are input for each aquifer layer. Pumping values are also input at each node for the Upper and Lower Floridan. The Upper Floridan also has input data for boundary heads and boundary flow coefficients at selected nodes. Confining units have leakage coefficients input at each node. The model input data can be conceptualized as a "sandwich" of data, as shown in figure 43.

The Lower Floridan aquifer is modeled as having no-flow boundaries around its sides and an impermeable base (fig. 8). This means that all flow into or out of the Lower Floridan (except for pumping) must ultimately flow through the Upper Floridan.

Though three aquifer layers are simulated (surficial aquifer and Upper and Lower Floridan aquifers), only the Upper Floridan is considered calibrated. The overlying surficial aquifer is treated as a constant-head (though areally variable) source-sink layer for leakage to and from the Upper Floridan. The Lower Floridan aquifer flow system is simulated but is not considered calibrated because of the lack of head data for the Lower Floridan. In essence, then, the Lower Floridan aquifer and the middle semiconfining unit act as a leaky basal boundary condition for the Upper Floridan.

STEADY-STATE PREDEVELOPMENT SIMULATION

Model results indicate that under predevelopment conditions, about 1,930 ft^3/s (1.91 in/yr) is recharged by downward leakage to the Upper Floridan (table 4) aquifer. Areally, the highest rate of recharge from the surficial aquifer to the Upper Floridan in the approximately 6,550 mi^2 in which recharge occurs (figs. 21, 22) is about 14 in/yr, in southeast Marion County. The recharge areas that have the lowest rates are in southeast Orange County, southeast Volusia County, most of northeast Okeechobee County, and the north-south length of the central parts of Osceola, St. Johns, and Flagler Counties. In those areas, recharge rates are typically 1 in/yr or less.

Lateral inflow to the Upper Floridan is about 21 ft^3/s (0.02 in/yr) and occurs chiefly along the east part of the north boundary (fig. 20).

As simulated, net flow between the Upper and Lower Floridan aquifers is zero. That is because water that leaks downward from the Upper Floridan and recharges the Lower Floridan in some areas ultimately leaks upward and returns to the Upper Floridan in other areas. The amount of water that circulates between the two aquifers is about 290 ft^3/s (0.25 in/yr). In the model nodes that discharge to the Upper Floridan from the Lower Floridan, the flow rate averages about 0.6 in/yr. The maximum rate for all nodes except that of the Blue Spring area (row 13, column 31) is about 3 in/yr.

In the node that contains Blue Spring, the Upper Floridan is recharged by the Lower Floridan at a rate of about 41 ft^3/s. The leakage coefficient at that node was set very high to hydraulically simulate a geologic fault

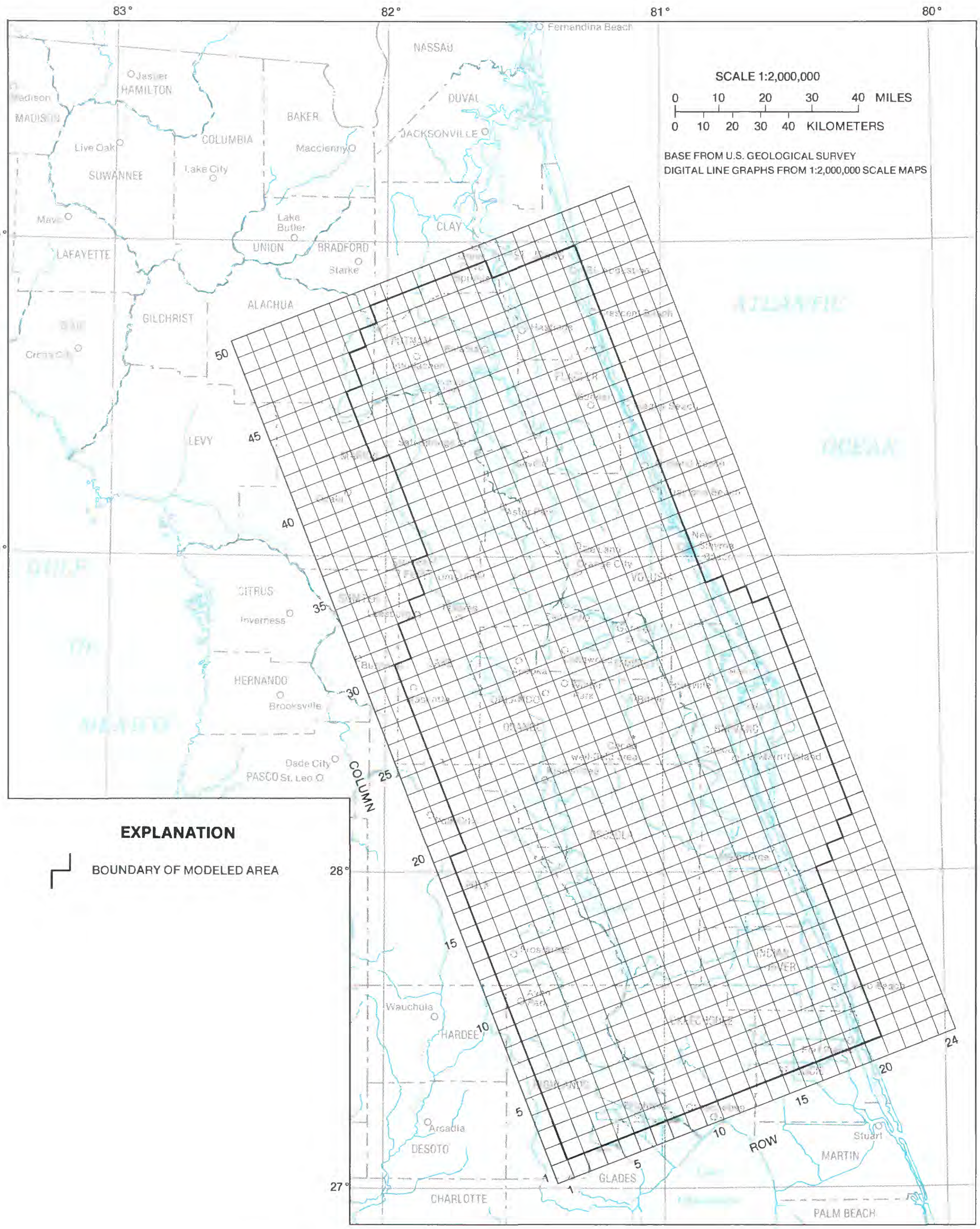


FIGURE 42.—Finite-difference grid superimposed on modeled area.

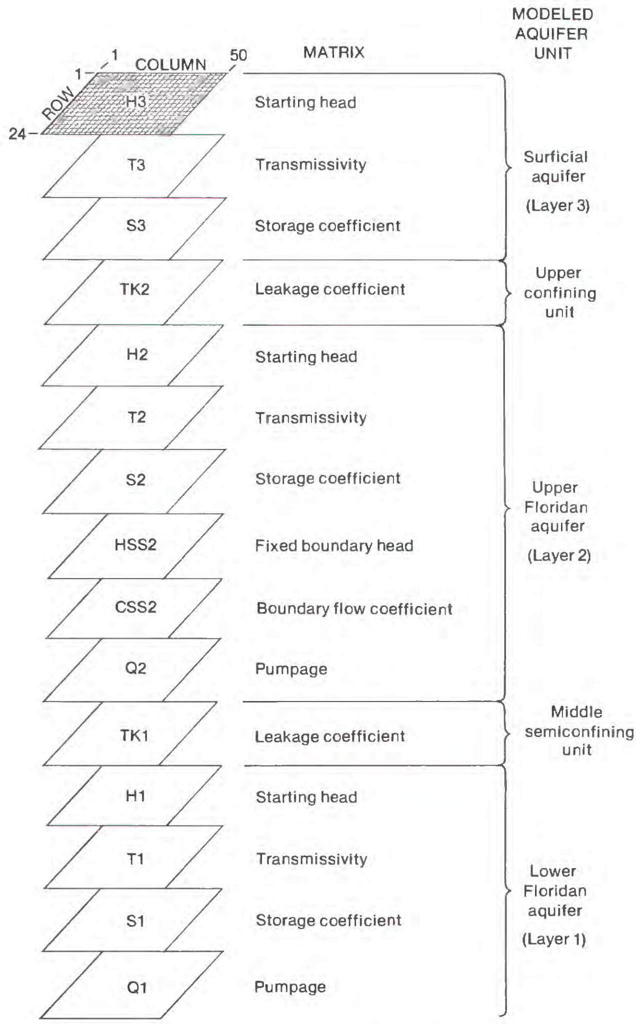


FIGURE 43.—Conceptualized model input data.

(figs. 11, 26) that is believed to provide a very good hydraulic connection between the Upper and Lower Floridan.

The Upper Floridan aquifer, as simulated under predevelopment conditions, discharges water by springs, by diffuse downward leakage to the Lower Floridan in some areas, by diffuse upward leakage to the surficial aquifer in discharge areas (fig. 21), and by lateral outflow along parts of the model boundaries.

Total simulated spring flow is about 1,330 ft^3/s (table 4) and includes about 1,020 ft^3/s of discharge from known springs ("key springs" used in steady-state calibration) for which discharge data are available. About 190 ft^3/s discharge into rivers where Upper Floridan spring flow has been indirectly determined by streamflow and water-quality measurements. About 120 ft^3/s is estimated to discharge in areas where depressions in the Upper Floridan potentiometric surface strongly suggest spring discharge.

Total discharge from the Upper Floridan as diffuse upward leakage to the surficial aquifer is simulated as about 530 ft^3/s (0.53 in/yr) (table 4). The average discharge rate in the approximately 7,150 mi^2 that are discharge areas (figs. 21, 22) is about 1 in/yr. The maximum rates are about 7 in/yr in west-central Flagler County and 6 in/yr in the Lake Kissimmee area. The lowest rates of diffuse upward leakage occur in south Brevard County, Indian River County, and north St. Lucie County. In those areas, leakage rates are generally 0.5 in/yr or less.

Discharge from the Upper Floridan by lateral boundary flow is about 90 ft^3/s (table 4) and occurs chiefly along the east and southwest model boundaries (fig. 20).

Based on the predevelopment steady-state model, the essential features of the predevelopment flow system are described as follows:

- The highest rates of recharge to the Upper Floridan are in four areas: the west flank of the Volusia County potentiometric surface "high" (figs. 20, 21); the Putnam-Alachua County potentiometric surface "high"; the topographically high ridge areas of mid-Polk and Highlands Counties (fig. 3); and the northeast flank of the central Florida potentiometric surface "high" in Lake and Orange Counties and extending into east Marion County.
- About 68 percent of the discharge from the Upper Floridan is in the form of point discharge to springs and streams located within 25 mi of recharge areas.
- The highest rates of diffuse upward leakage from the Upper Floridan (about 27 percent of the total discharge) occur near areas where downward leakage rates are also high. Thus, it is inferred that thin or permeable confining units are common to the areas of high upward leakage and to the nearby areas of high downward leakage.
- Lateral boundary outflow from the Upper Floridan aquifer (mostly along the Atlantic Coast) is relatively small and consists of about 4 percent of the total discharge. Lateral flow to the south is about 1 percent of the total discharge.
- Interchange between the Upper and Lower Floridan aquifers is relatively small (290 ft^3/s) compared with the flow within the Upper Floridan (about 1,950 ft^3/s).
- The model-derived transmissivities of the Upper Floridan are considered to have more regional significance than transmissivity values derived from individual aquifer tests.

In summary, the hydraulics of the Floridan aquifer system under predevelopment conditions are characterized by recharge to the Upper Floridan (by way of leakage from the surficial aquifer), lateral movement through the Upper Floridan for short distances, and discharge by way of springs and diffuse upward leakage. Relatively small amounts of discharge occur along the coast, and small amounts move into and out of the underlying Lower Floridan. The ground-water flow system is relatively vigorous in the Upper Floridan and, except in west Orange County and southeast Lake County, is relatively sluggish in the Lower Floridan.

TRANSIENT SIMULATION WITH MODERN-DAY (1978) PUMPING

The purpose of the transient simulation is to determine how pumping affects the Floridan aquifer flow system. The transient simulation requires input of data on the storage characteristics of the Floridan and on the amount and areal distribution of pumping.

CALIBRATION

To calibrate the transient model, computed drawdown due to pumping is matched to observed drawdown. The ideal method of matching computed and observed drawdown would be to run the model through a series of year-long (or shorter) simulation periods that, together, constitute the length of the observed long-term record of water levels (appendix B). The appropriate values for pumping would be input at each simulation period. Then, after adjusting the storage coefficients areally, the best match between computed and observed long-term water levels would be achieved. At least four problems are associated with this method of calibration:

1. The model does not compensate for climatic changes that affect recharge from simulation period to simulation period (and would not even if those data could be obtained). Climatic considerations make it difficult to compare computed and observed water levels except where the amount of water being recharged is small compared with that being pumped.
2. Long-term pumping data, except for large municipal supply systems, are sparse.
3. Short-term and long-term pumping data are poor for the categories of rural domestic supplies, privately owned public supplies, irrigation, industrial and institutional supplies, and thermoelectric cooling.
4. Data on the areal distribution of pumping are poor.

The pumping data used in this study are best estimates of the amounts and areal distribution of ground-water withdrawals in the study area.

In east-central Florida, the only time of year in which changes in recharge rates are small with respect to discharge by pumping is during the last 2 weeks in March, all of April, and, usually, the first 1 or 2 weeks in May—about 60 days altogether. The timing of the "dry period" varies from place to place. During the dry period, pumping is at a maximum rate for the year. It is this 60-day period that was chosen for comparison of observed and computed changes in ground-water levels in response to pumping and thus for calibration of the transient model. Table 5 gives estimated rates of pumping for selected categories of ground-water use in the study area, and of outflow to pumping centers west of the model area.

Transient-model calibration is accomplished by comparing observed and computed declines in water levels for the 60-day-long dry period in 1978 at 39 sites in the model area (fig. 44). The computed water-level declines are simulated by running the model for two pumping periods (fig. 45). The first period, 210 days, simulates a run to the almost steady-state conditions that might have occurred near the end of March 1978; the pumping rate input at each node is the average annual rate for 1978. The second pumping period has "dry period" pumping rates and does not run to steady state but is terminated at the end of 60 days. "Dry period" pumping rates were also run for a period of only 45 days in order to compute heads for comparison with water levels measured during mid-May for an area-wide potentiometric surface map.

The degree to which transient calibration is accomplished and the effects of using different storage coefficients are shown by example in figures 46–48. Figure 46 is an example of a "good" match of slope and magnitude of drawdown using aquifer storage coefficients of 1×10^{-3} for both the Upper and Lower Floridan aquifers. Figures 47 and 48 are examples of "fair" and "poor" matches of slope and magnitude of drawdown, respectively, also using storage coefficients of 1×10^{-3} for both the Upper and Lower Floridan aquifer. Better matches could have been obtained at the latter two sites (figs. 47, 48) by changing the storage coefficients, but this writer believes that most of the error is caused by errors in estimating the rates and areal distribution of pumping. With all other aquifer parameters being equal, the water level in an aquifer is more sensitive to a change in pumping rate than to the same percentage change in storage coefficient. On a model-wide basis, storage coefficients of 1×10^{-3} gave the best calibration at most sites (fig. 44).

The average absolute error in estimating the magnitude of the "dry period" drawdown at sites shown in figure 44 is about 27 percent. Average absolute error is the average of the errors without regard to mathematical sign. The algebraic average of the errors is about -1 percent. This means that about as much error occurs on the plus side as on the minus side. Therefore, on a model-wide basis, there is a slight tendency toward underestimating computed drawdown.

TABLE 4.—*Simulated rates of recharge and*
[ft³/s, cubic feet per second; in/yr,

Pumping period no.	Simulation	Recharge							
		Vertical				Lateral			
		Downward leakage[1]		Drainage wells		Head-controlled flux		Constant flux	
		(ft^3/s)	(in/yr)	(ft^3/s)	(in/yr)	(ft^3/s)	(in/yr)	(ft^3/s)	(in/yr)
0	Predevelopment, steady-state (revised from Tibbals, 1981)								
	Upper Floridan..................	1,927	(1.91)	------	------	21	0.02	------	------
	Lower Floridan..................	290	(0.29)	------	------	0	0	------	------
1	At end of 210 days pumping at average 1978 pumping rates								
	Upper Floridan..................	2,445	(2.42)	51	(0.05)	38	(0.04)	4	(0.00)
	Lower Floridan..................	367	(0.36)	0	(0)	0	(0)	0	(0)
2	At end of additional 45 days pumping at estimated dry period pumping rates								
	Upper Floridan..................	3,043	(3.01)	0	(0)	59	(0.06)	9	(0.01)
	Lower Floridan..................	310	(0.31)	0	(0)	0	(0)	0	(0)
2A	At end of additional 15 days pumping at estimated dry period pumping rates								
	Upper Floridan..................	3,080	(3.05)	0	(0)	63	(0.06)	9	(0.01)
	Lower Floridan..................	325	(0.32)	0	(0)	0	(0)	0	(0)

[1] From aquifer above.
[2] To aquifer above.

A second check on the calibration of the model is to compare an Upper Floridan aquifer potentiometric surface map based on model-derived heads with a map based on measured heads (fig. 49). In general, the potentiometric contours drawn from model-derived heads are within 10 ft of those drawn from measured heads and the configuration of the computed map is very similar to the map constructed from observed data. Overall, the transient-model calibration (and the estimates of pumping) are considered to be fair to good. Therefore, the calibrated transient model probably simulates the effects of pumping well enough to allow further analysis of the flow system.

HYDROLOGIC EFFECTS OF 1978 PUMPING

The areal distribution of pumping at average annual 1978 rates and the corresponding drawdown of heads in the Upper Floridan aquifer are shown in figure 50. The largest drawdowns are in areas where pumping rates are highest: in the Palatka area of Putnam County (10 ft); in the Ormond Beach-Daytona Beach-New Smyrna Beach area of east Volusia County (6 ft); in northwest Seminole County (6 ft); in the Cocoa well-field area of southeast Orange County (8 ft); in the Orlando-Winter Park area of Orange County (6 ft); and in central Polk and Highlands Counties (8 ft).

Drawdown in the Upper Floridan aquifer in the Orlando-Winter Park area is not as great as might be expected considering that about 68 to 70 Mgal/d is pumped from the Floridan aquifer system there. Drawdown in the Upper Floridan is minimized because

- Of the 68 to 70 Mgal/d pumped, all but about 3 to 4 Mgal/d is pumped from the Lower Floridan,
- The Upper Floridan aquifer is recharged by drainage wells at an estimated average rate of about 33 Mgal/d, and
- Both the Upper and Lower Floridan aquifers are highly transmissive and, thus, can be pumped at relatively high rates and cause relatively small drawdown.

Table 4 shows computed rates of upward and downward leakage, lateral inflow and outflow, spring flow, pumpage, recharge through drainage wells, water released from aquifer storage, and changes in average model-wide drawdown. Table 6 summarizes the changes in computed rates of upward and downward leakage, spring flow, net lateral boundary outflow, and water released from aquifer storage caused by pumping for 210 days at the average 1978 pumping rates and an additional 45 days at "dry period" rates.

In 1978, the average rate of pumping was 555 Mgal/d, boundary outflow toward adjacent pumping centers was about 41 Mgal/d, and recharge through drainage wells was about 33 Mgal/d. Therefore, the total net withdrawal from the aquifer system was 563 Mgal/d. The effects of this withdrawal on the predevelopment Floridan aquifer system are shown in figure 51 and tables 4 and 6 and are summarized as follows:

discharge for steady-state and transient conditions
inches per year; ft, feet]

Discharge													
Vertical						Lateral				Plus or minus change in storage		Area drawdown since previous pumping period	
Pumping wells		Upward leakage[2]		Springs		Head-controlled flux		Constant flux				Average	Maximum
(ft^3/s)	(in/yr)	(ft^3/s)	(in/yr)	(ft^3/s)	(in/yr)	(ft^3/s)	(in/yr)	(ft^3/s)	(in/yr)	(ft^3/s)	(in/yr)	(ft)	(ft)
------	------	532	(0.53)	1,326	(1.30)	90	(0.09)	------	------	0	(0)	------	------
------	------	290	(0.29)	0	(0)	0	(0)	------	------	0	(0)	------	------
753	(0.75)	377	(0.37)	1,236	(1.22)	58	(0.06)	68	(0.07)	−59	(−0.06)	3.7	150.0
105	(0.10)	292	(0.29)	0	(0)	0	(0)	0	(0)			4.0	20.0
1,705	(1.69)	278	(0.28)	1,164	(1.15)	42	(0.04)	137	(0.14)	−354	(−0.35)	2.9	6.1
139	(0.14)	375	(0.37)	0	(0)	0	(0)	0	(0)			2.3	9.2
1,705	(1.69)	265	(0.26)	1,159	(1.15)	41	(0.04)	137	(0.14)	−293	(−0.29)	0.4	0.5
139	(0.14)	358	(0.35)	0	(0)	0	(0)	0	(0)			0.6	0.8

- Average areal drawdown in the Upper Floridan is about 4 ft.
- Downward leakage to the Upper Floridan from the overlying surficial aquifer increased 518 ft^3/s, from 1,927 to 2,445 ft^3/s, an increase of about 27 percent.
- Upward leakage from the Upper Floridan to the surficial aquifer decreased 155 ft^3/s, from 532 to 377 ft^3/s, a decrease of about 29 percent.
- Spring flow decreased 90 ft^3/s, from 1,326 to 1,236 ft^3/s (selected springs shown in fig. 51), a decrease of about 7 percent.
- Net lateral flow at boundaries increased 14 ft^3/s, from 69 ft^3/s outflow to 83 ft^3/s, an increase of about 20 percent.

The drawdown due to pumping at average 1978 rates had not reached equilibrium at the end of the 210-day simulation. At the end of the period, heads were still declining and loss from aquifer storage was still occurring at a rate of 58 ft^3/s. Therefore, steady-state conditions had not been reached. A 210-day pumping period rather than a simple steady-state pumping simulation was chosen for this simulation because (1) variations in pumping and recharge and natural discharge rates make it impossible for the aquifer system to reach a truly steady-state condition, and (2) 210 days is about the longest period of time during the year in which pumping, recharge, and natural discharge rates are reasonably constant at about-average rates. A steady-state simulation with the same pumping rates showed drawdowns that were about 10 percent greater than that of the 210-day simulation. Therefore, steady-state conditions are nearly reached with a 210-day simulation.

Table 7 lists the selected categories and 1978 average rates of pumping from the Floridan aquifer system. Also listed are the average drawdowns in the Upper Floridan aquifer attributed to each category of pumping.

Pumping for municipal supplies in 1978 was about 156 Mgal/d (table 7), about 28 percent of the total pumpage. Municipal pumpage is the most accurately documented pumping category in terms of both rates and areal distribution (fig. 52). The average areal drawdown in the Upper Floridan caused by municipal pumpage was about 0.8 ft (table 7), with the greatest drawdowns occurring in the Orlando-Winter Park area (4 ft), the Cocoa well field

TABLE 5.—*Average 1978 pumping rates and "dry period" pumping rates, by pumping category*

[Qavg, average annual pumping rate in 1978; Qdry, "Dry period" pumping rate in 1978; X, ratio of dry period pumping rate to average annual pumping rate in 1978; Mgal/d, million gallons per day. Negative number indicates recharge]

Pumping category	Qavg (Mgal/d)	X	Qdry (Mgal/d)
Municipal supplies	156	1.34	209
Domestic and private public supplies	47	1.34	63
Industrial and institutional supplies and for thermoelectric cooling	94	1.0–1.2	95
Irrigation	258	2.0–4.0	825
Drainage-well recharge	−33	0.0	0
Outflow to adjacent pumping centers	41	2.0	82
Total	563		1,274
Total pumped in model area	555		1,192

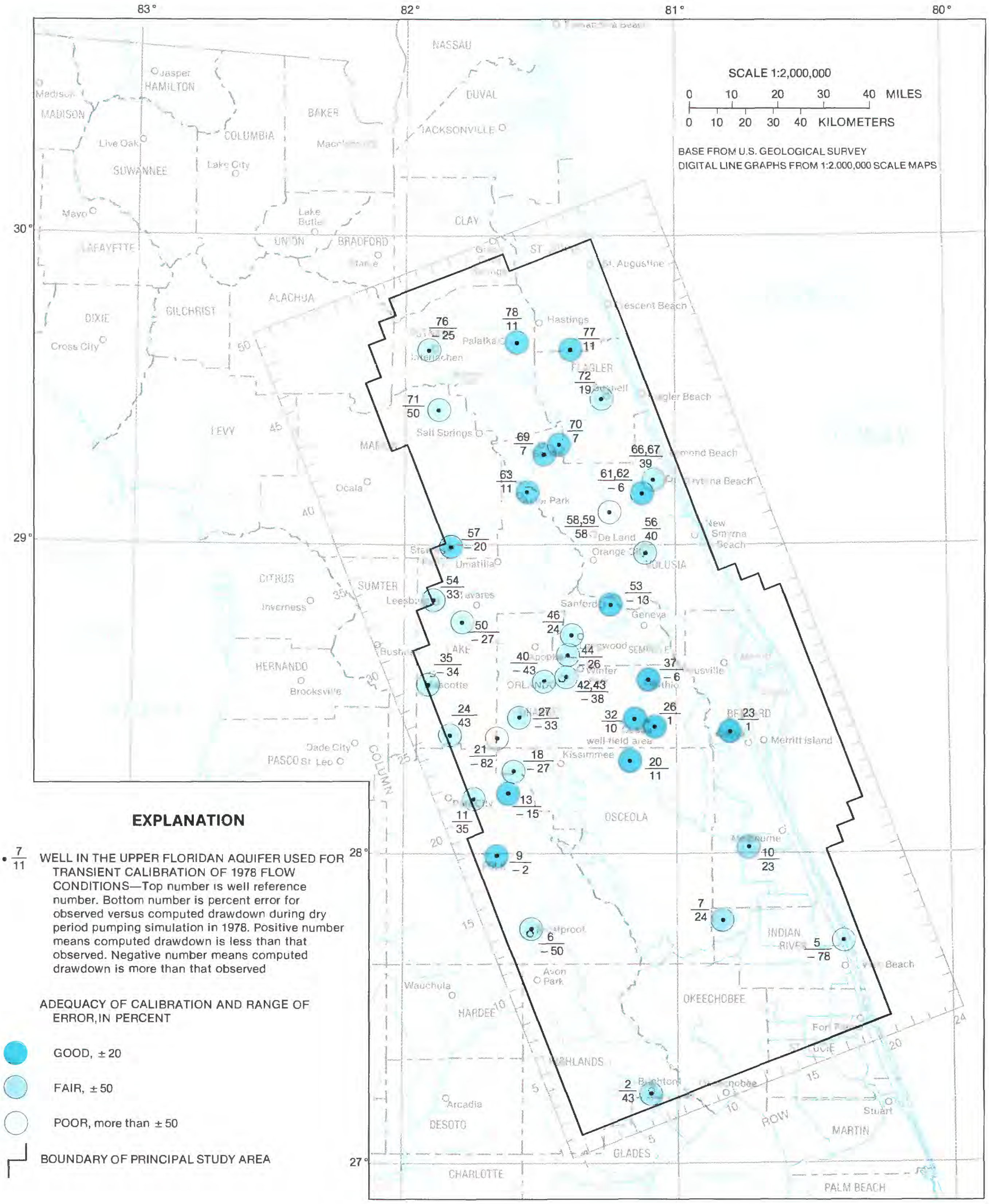


FIGURE 44.—Results of transient model calibration.

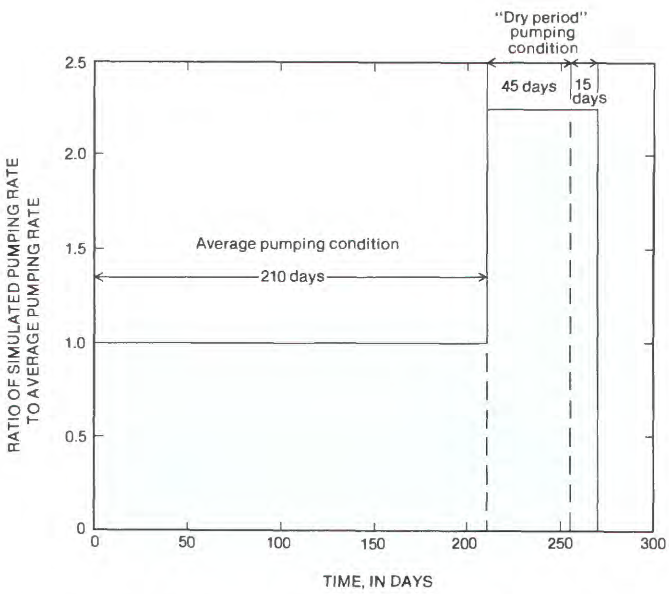


FIGURE 45.—Conceptualized pumping periods for transient model calibration.

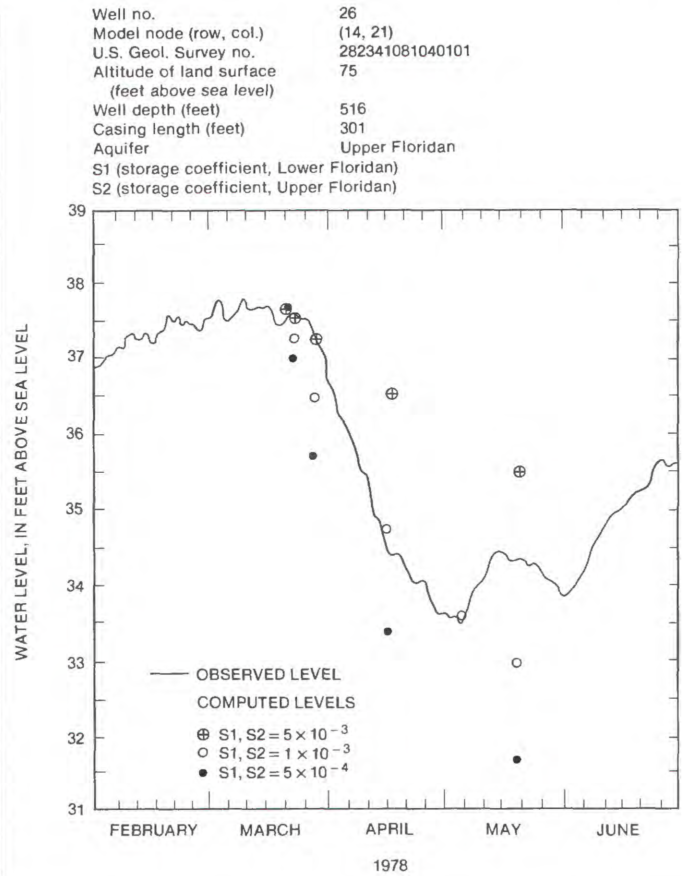


FIGURE 46.—Computed versus observed water levels in well 26 (southeast Orange County) for selected values of storage coefficient.

in southeast Orange County (6 ft), and the Daytona Beach well field in east Volusia County (6 ft). Drawdown in the Lower Floridan aquifer was computed only for the Orange County area, where about 65 Mgal/d were pumped from the Lower Floridan for municipal supply by the cities of Orlando and Winter Park. The computed drawdown in the Lower Floridan in the Orlando-Winter Park area was about 14 ft.

Pumpage for rural domestic and privately owned public supplies in 1978 was about 47 Mgal/d (table 7), about 8 percent of the total pumpage. Data for this category of pumping are not as reliable as those for municipal supples in terms of either rates or areal distribution (fig. 53). Average areal drawdown in the Upper Floridan aquifer caused by pumping for rural domestic and private public supplies is about 0.3 ft.

Pumping for major self-supplied industries and institutions and for thermoelectric condenser cooling in 1978 was about 94 Mgal/d (table 7), about 17 percent of the

TABLE 6.—*Change in Upper Floridan aquifer predevelopment ground-water flow rates caused by pumping*
[Cubic feet per second]

Pumping period no.	Simulation	Net[1] pumping rate (change)[2]	Downward leakage (change)	Upward leakage (change)	Springflow (change)	Net boundary outflow (change)	Change in storage
0	Predevelopment steady-state (revised from Tibbals, 1981)	0	1,927	532	1,326	69	0
		------	------	------	------	------	------
1	At end of 210 days pumping at average 1978 pumping rates	807	2,445	377	1,236	84	−59
		(807)	(518)	(−155)	(−90)	(14)	(−59)
2	At end of additional 45 days pumping at estimated "dry period" pumping rates	1,844	3,043	278	1,164	111	−354
		(1,844)	(1,116)	(−254)	(−162)	(42)	(−354)

[1] Net pumping is equal to amount pumped from Upper and Lower Floridan aquifer minus the amount recharged through drainage wells.
[2] Change from predevelopment conditions.

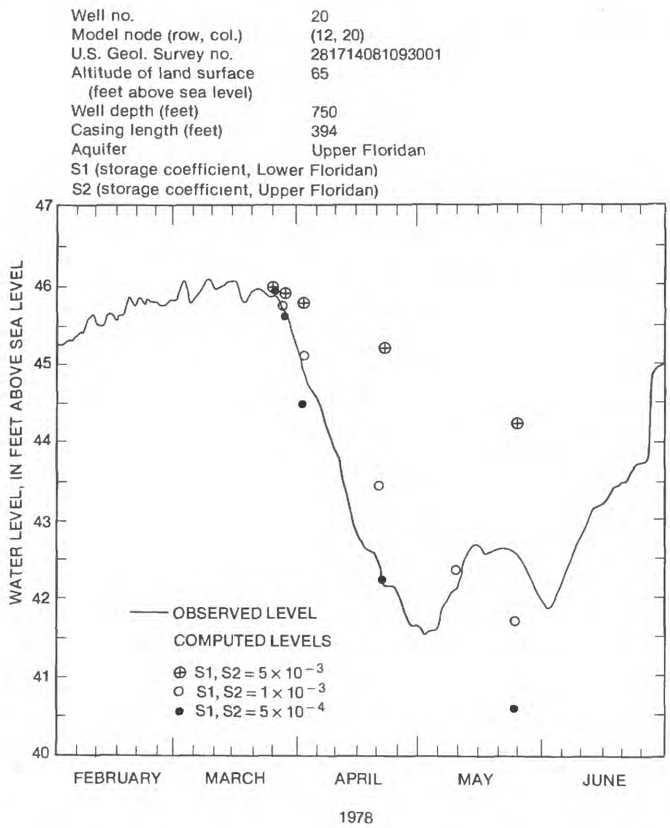


FIGURE 47.—Computed versus observed water levels in well 20 (north Osceola County) for selected values of storage coefficient.

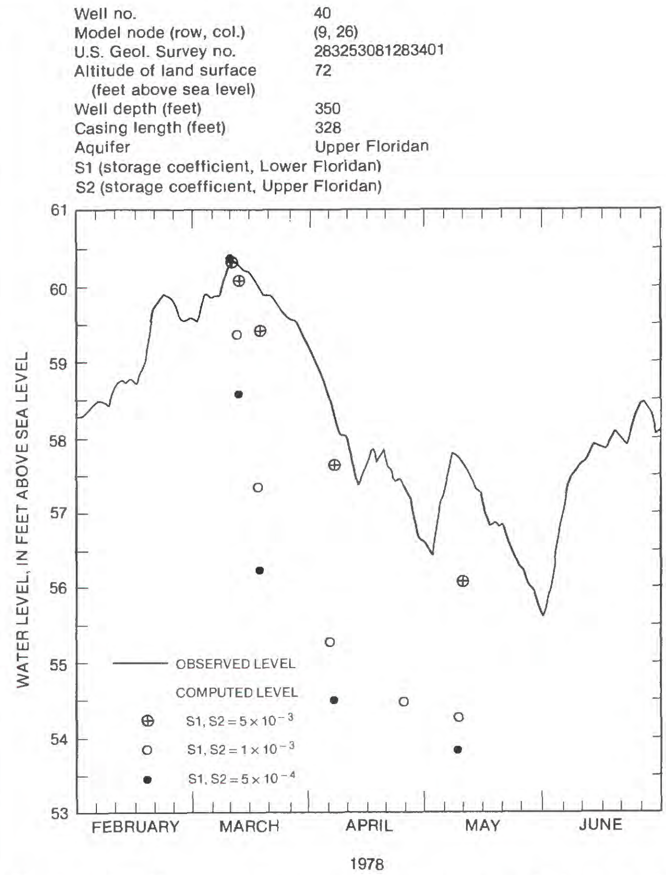


FIGURE 48.—Computed versus observed water levels in well 40 (west-central Orange County) for selected values of storage coefficient.

TABLE 7.—*Average 1978 pumpage in Upper and Lower Floridan aquifer and average drawdown in the Upper Floridan attributable to each category of pumping*

[Mgal/d, million gallons per day; ft, feet]

Pumping category	Average 1978 pumping rate (Mgal/d) Upper Floridan	Lower Floridan	Total	Average areal drawdown in the Upper Floridan aquifer (ft)
Municipal supply...	92	64	156	0.78
Rural domestic and private public supplies........	47	0	47	0.28
Industrial, institutional, and recreational supplies...........	90	4	94	0.37
Irrigation.........	258	0	258	1.97
Recharge (drainage) wells......	−33	0	−33	−0.22
Boundary outflow (net)...........	41	0	41	0.27
Total........	495	68	563	[1]3.58

[1] The drawdowns for the individual pumping categories do not sum to the drawdown resulting from the total of all pumping stresses because of random errors inherent in the model's computational process.

total pumpage. About 4 Mgal/d were pumped from the Lower Floridan aquifer. The distribution of pumping and its drawdown effects are shown in figure 54. Average areal drawdown in the Upper Floridan caused by this category of pumping is about 0.4 ft.

Water pumped for irrigation is the largest single ground-water use in the study area; however, the rate and areal distribution of this pumpage is poorly defined. Water pumped for irrigation in 1978 is estimated at 258 Mgal/d (table 7), about 46 percent of the total pumpage. The areal distribution of irrigation and the estimated drawdowns (fig. 55) are qualitative rather than quantitative. Average areal drawdown caused by irrigation pumpage is about 2 ft.

Rates of recharge through drainage wells in the Orlando area are not accurately known, but estimates are as high as 50 Mgal/d (Kimrey, 1978, p. 15). A lower rate of 33 Mgal/d (table 7) was used in the simulation in this study. The rationale for using the lower rate is given in a later section. Recharge through drainage wells and the resultant buildup of the potentiometric surface of the Upper Floridan is mainly in the Orlando area (fig. 56).

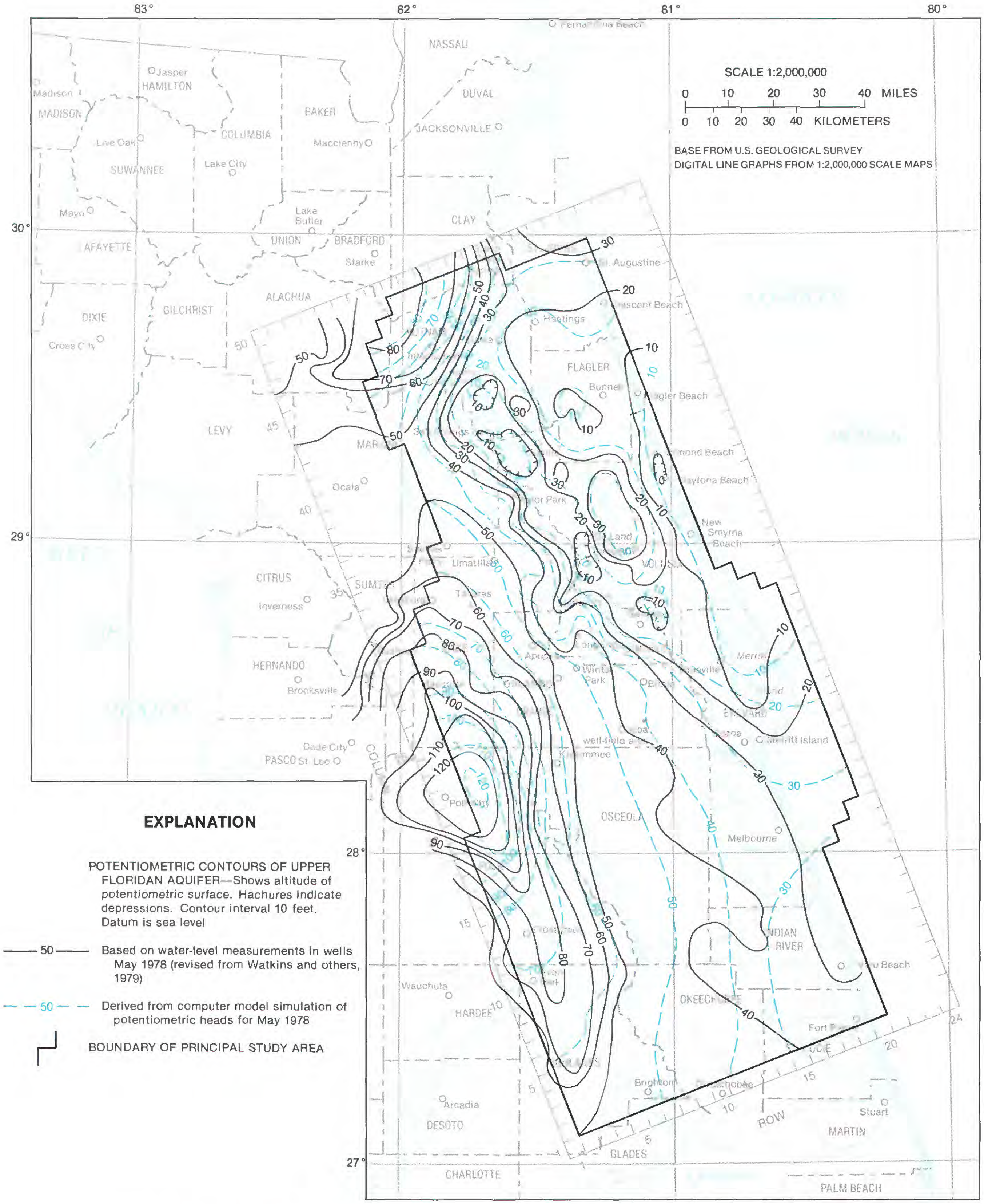


FIGURE 49.—Observed versus computed potentiometric surface of the Upper Floridan aquifer, May 1978.

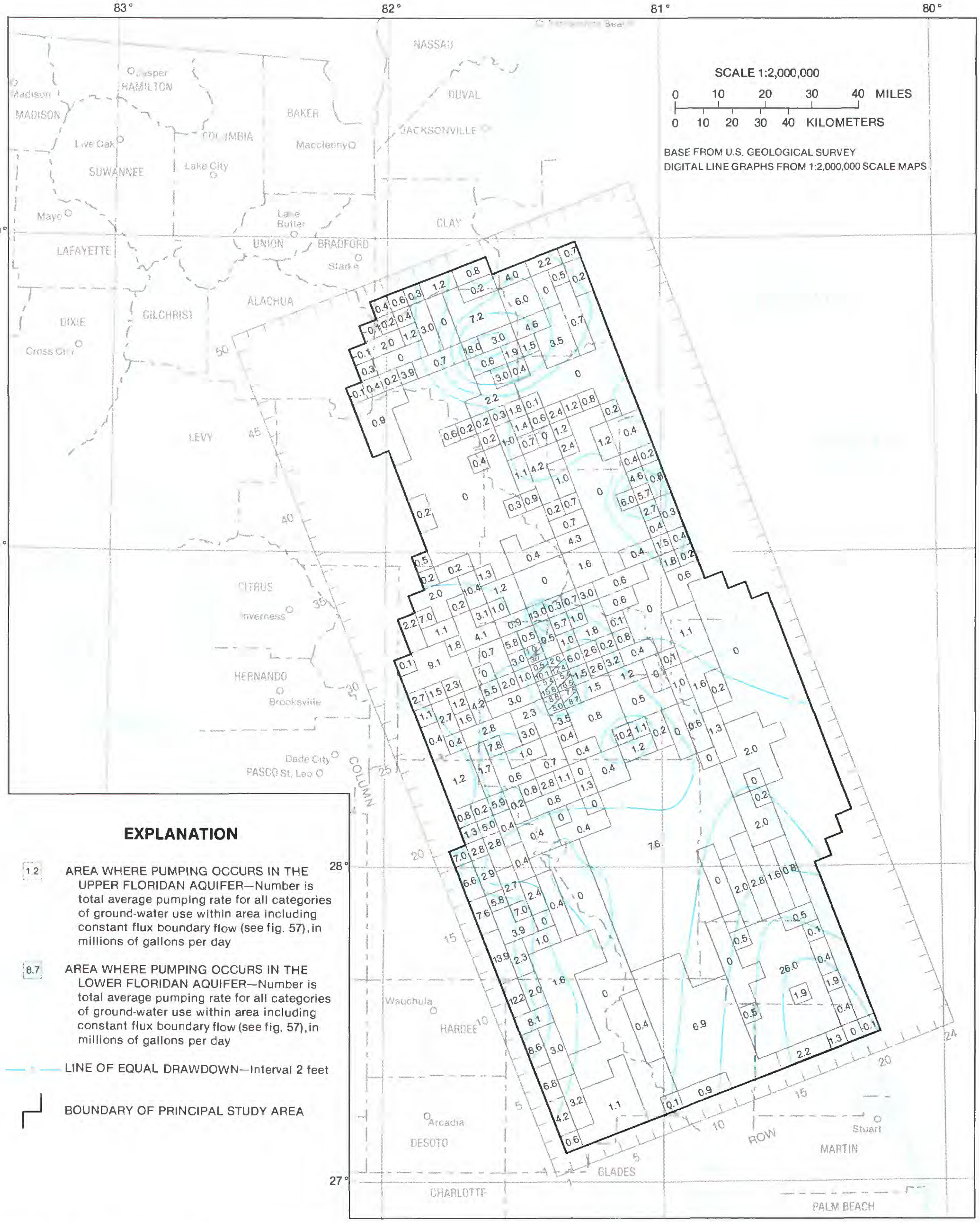


FIGURE 50.—Drawdown of potentiometric surface of Upper Floridan aquifer caused by average 1978 pumping, drainage wells, and boundary flow to adjacent pumping centers.

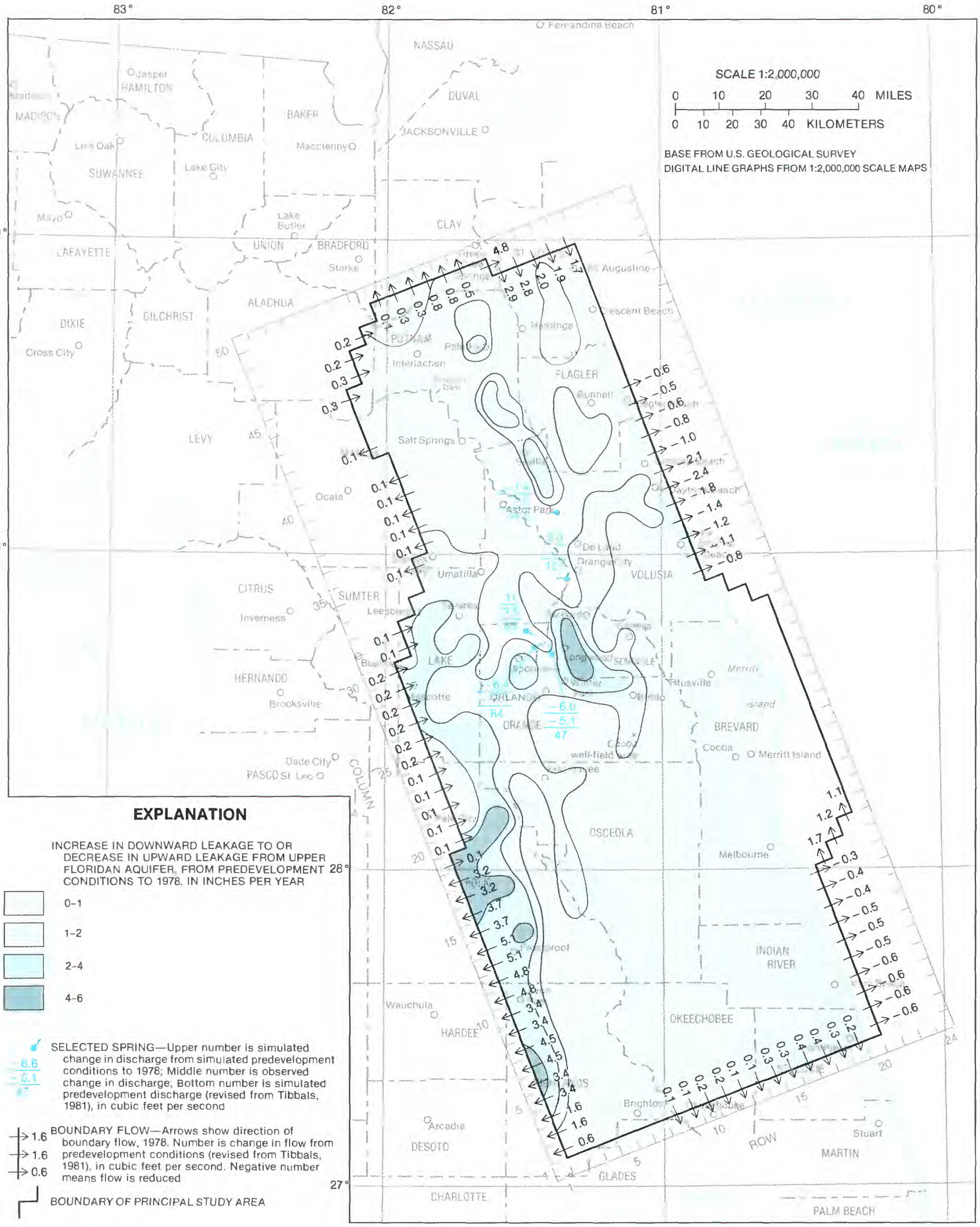


FIGURE 51.—Effects of 1978 pumping on downward and upward leakage rates to and from the Upper Floridan aquifer, flow of selected springs, and flow at boundaries.

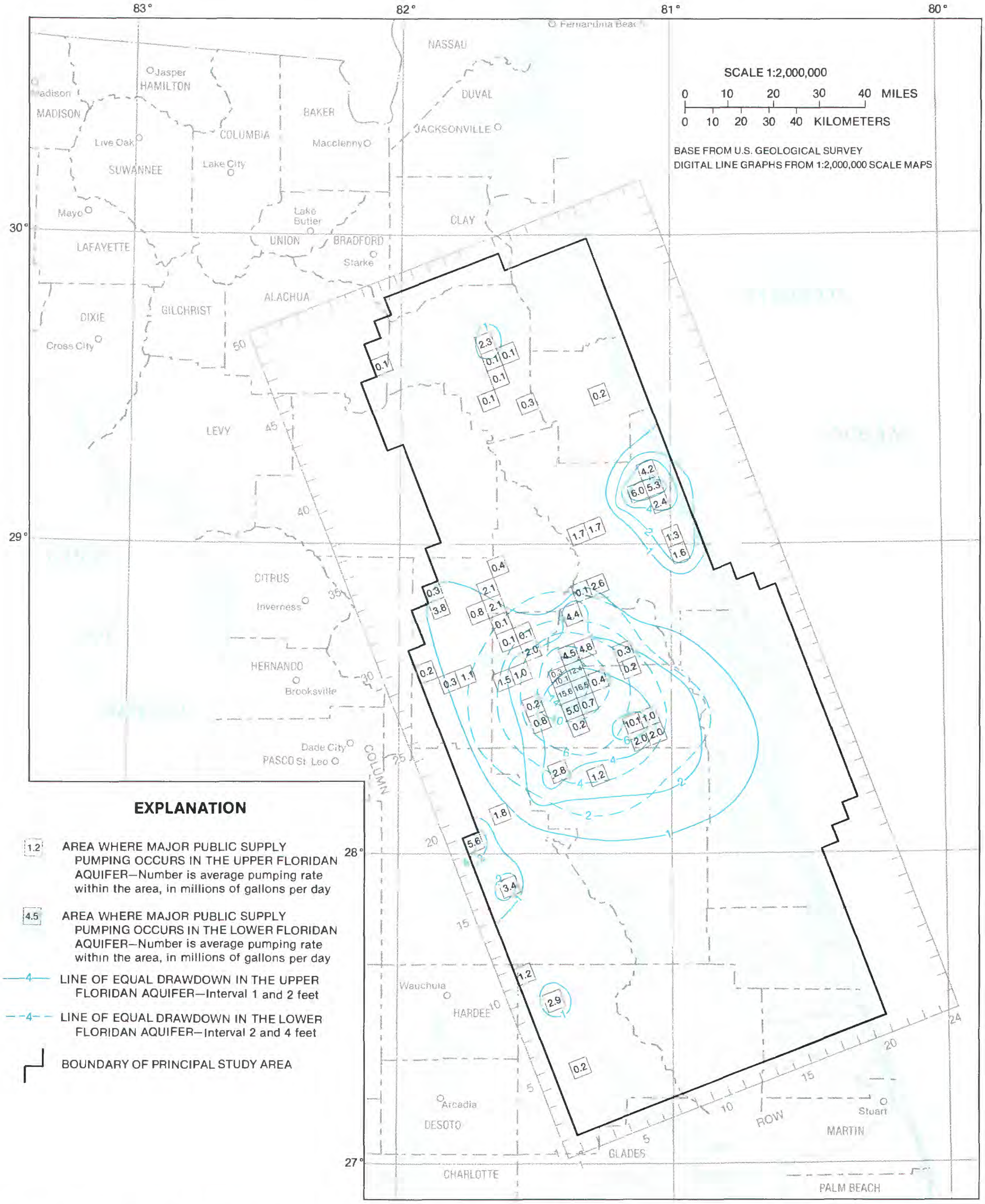


FIGURE 52.—Drawdown of potentiometric surface of Upper Floridan and Lower Floridan aquifers caused by pumping for municipal supplies, 1978.

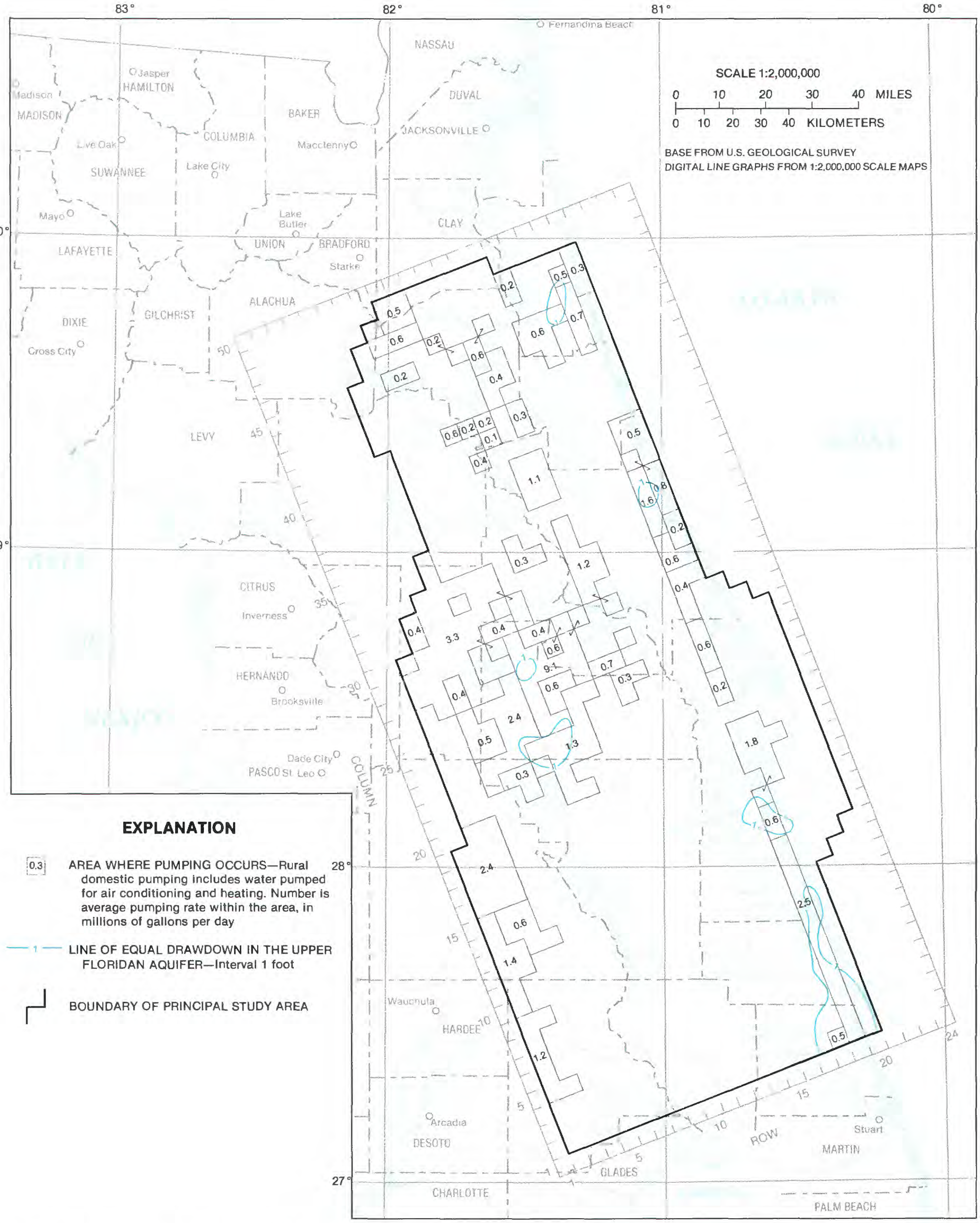


FIGURE 53.—Drawdown of potentiometric surface of Upper Floridan aquifer caused by pumping for rural domestic and privately owned public supplies, 1978.

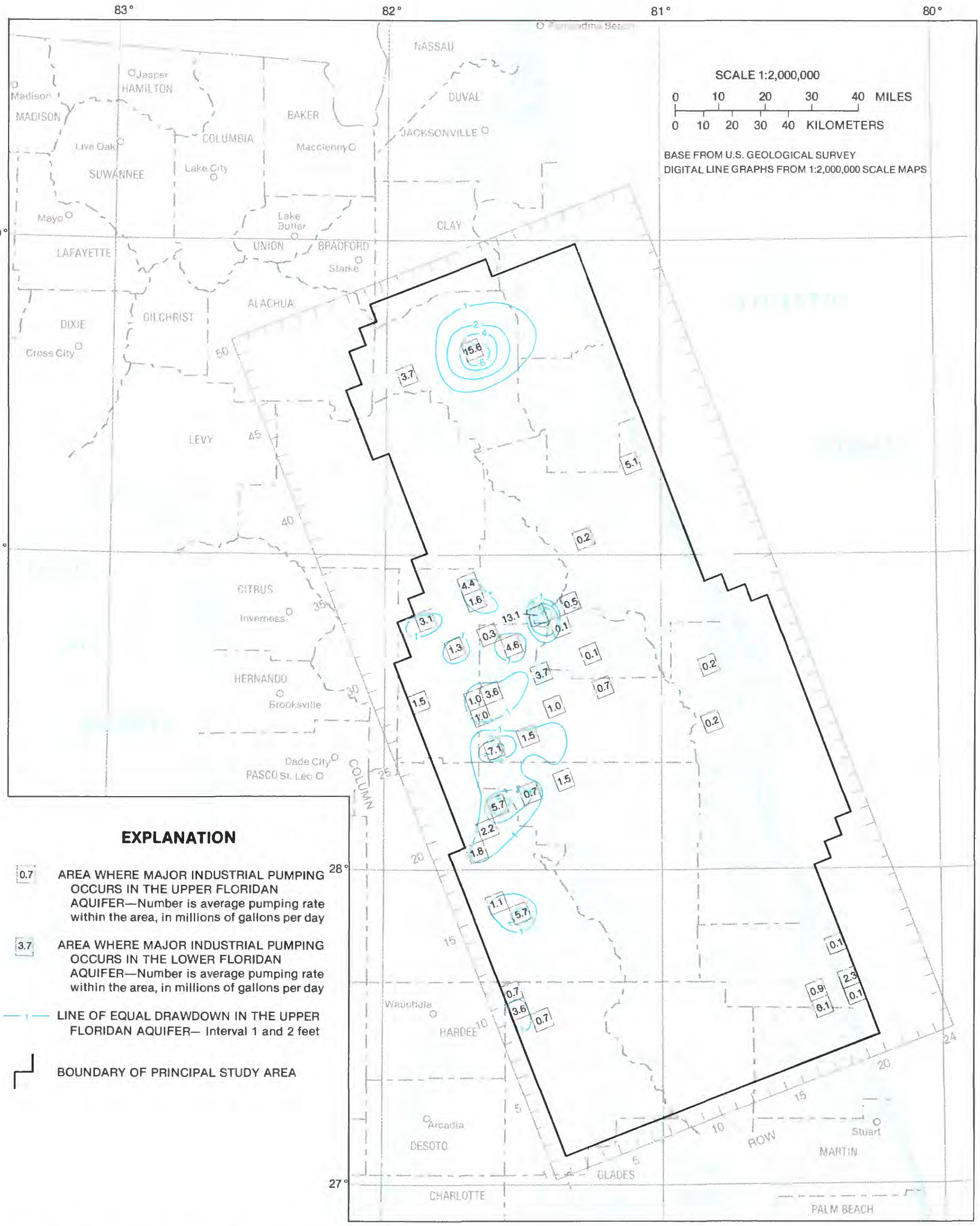


FIGURE 54.—Drawdown of potentiometric surface of Upper Floridan aquifer caused by pumping by major industries, by institutions, and for thermoelectric condenser cooling, 1978.

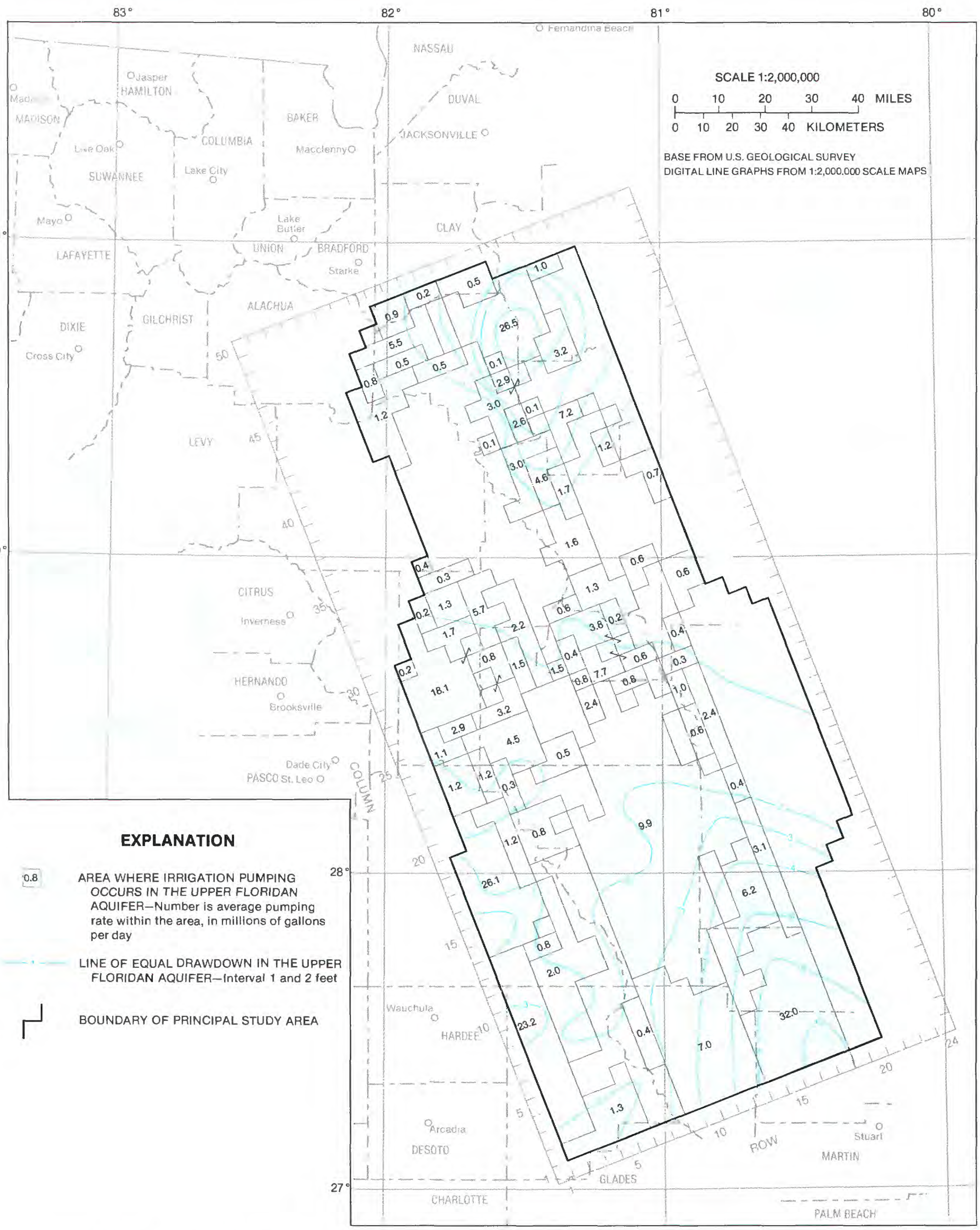


FIGURE 55.—Drawdown of potentiometric surface of Upper Floridan aquifer caused by pumping for irrigation, 1978.

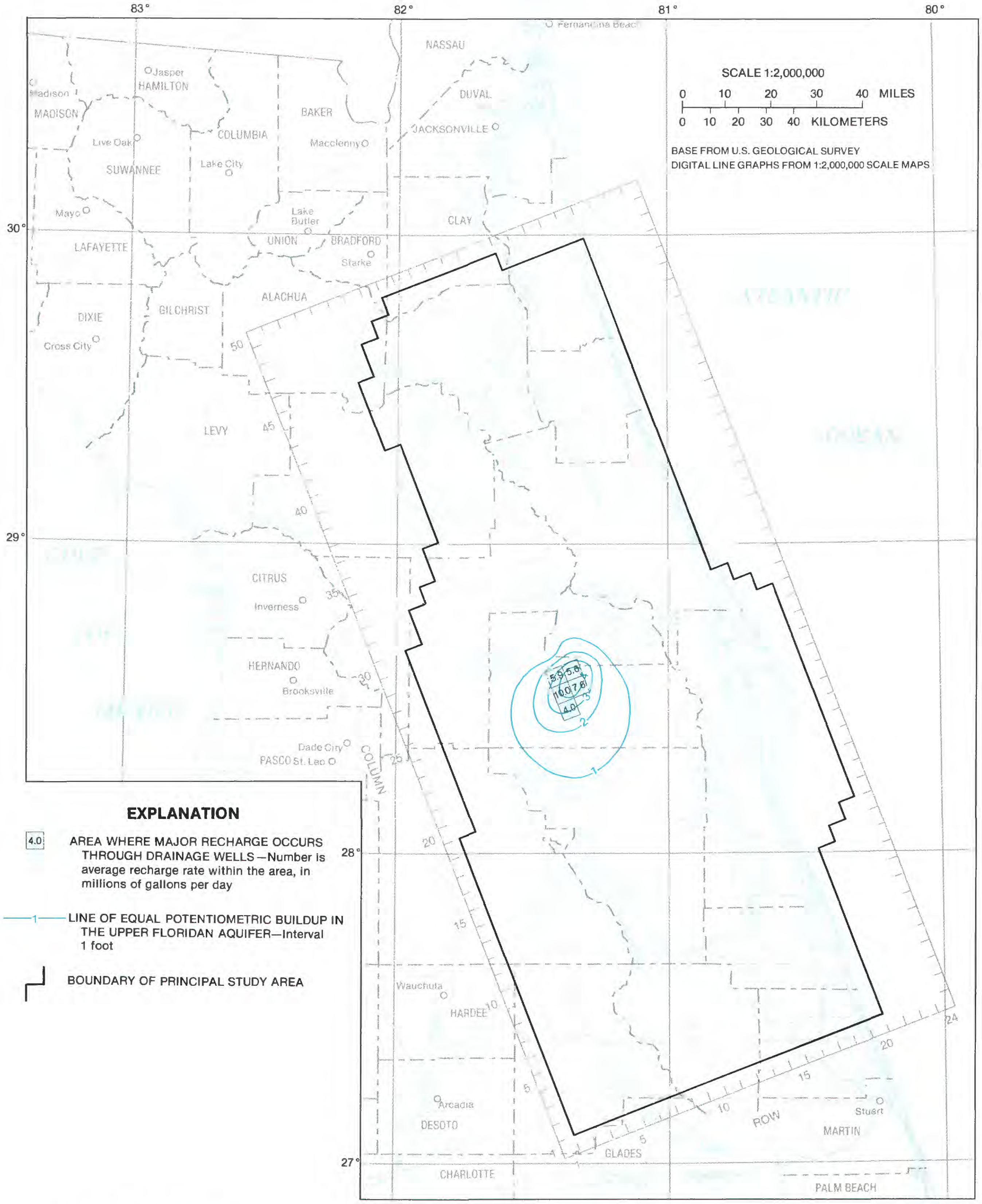


FIGURE 56.—Buildup of potentiometric surface of Upper Floridan aquifer caused by recharge through drainage wells, 1978.

The 0.2-ft average areal buildup is insignificant (table 7). Maximum buildup is about 4 ft and occurs in the immediate Orlando area.

In the transient simulation, cross-boundary flow is simulated in two ways:

1. As flow through head-controlled flux boundaries (as described by Tibbals, 1981) (flow that varies in response to pumping stresses inside the model area), and
2. As outflow through constant-flux boundaries (table 7) (outflow that is the result of pumping stresses in areas adjacent to the model, primarily to the west and north).

The boundary flows shown in figure 57 were obtained by determining internodal flows from a coarser grid regional model (see Professional Paper 1403–C; Bush and Johnson, in press) under pumping conditions along rows or columns that correspond to the boundaries of this subregional model. Where a constant-flux boundary node corresponds with a head-controlled flux boundary node, the internodal constant flows were adjusted so that only one flow was considered.

Most of the constant-flux cross-boundary outflow occurs along the south end of the west boundary and is the result of heavy pumping by phosphate mines, citrus processing plants, and irrigation west of the model area (see Professional Paper 1403–F). Net constant-flux cross-boundary flow is simulated as 41 ft^3/s. Maximum drawdown is about 8 ft and occurs in Polk County. The areal distribution of cross-boundary flow and its drawdown effects in the model area are shown in figure 57.

LONG-TERM EFFECTS OF PUMPING— DOUBLE-MASS CURVE ANALYSES

The model described in this report cannot adequately simulate the year-to-year hydraulic effects of pumping from predevelopment conditions to 1978. However, an attempt is made to show some general trends in spring flow and water levels at selected sites. Several individual springs, a group of springs, a stream whose base flow is almost entirely spring flow, and well 40 are selected for long-term-trend analyses. Hydrographs of average annual discharge at the springs and river sites (fig. 58) and average annual water levels in well 40 (fig. 69 in appendix B) show trends, but the fluctuations in the records are caused by at least two factors: variations in rainfall and nearby pumping. To separate the effects of pumping and rainfall, double-mass analyses were done for Blue Spring near Orange City versus rainfall at De Land (fig. 59), for the Wekiva River near Sanford versus rainfall at Orlando (fig. 60), and for water levels in well 40 near Orlando (see fig. 2) versus rainfall at Orlando (fig. 61).

A double-mass curve analysis consists of plotting the cumulative data of one variable versus the cumulative data of a related variable. The resulting graph plots as a straight line if the relation between the variables remains unchanged as the data accumulate. For example, a double-mass graph of cumulative annual rainfall on a drainage basin versus cumulative annual runoff from the basin would plot as a straight line if other hydrologic conditions remained unchanged. If part of the runoff were diverted to another drainage basin and thus were not measured as discharge from the parent basin, the double-mass curve would show a change in slope (change in the rainfall-runoff relation) beginning at the time of the diversion. However, an apparent change in relation suggested by a change in slope can also reflect changes in the way data were collected at either of the two sites, such as changes in location of the rain gage or in the way stream records are computed. The data upon which the following analyses are based are considered representative of the hydrologic conditions.

About 10 Mgal/d (15 ft^3/s) are pumped from the Floridan aquifer system in the Blue Spring ground-water basin (figs. 21, 50). That amount is relatively small compared with the approximately 97 Mgal/d (150 ft^3/s) modern-day average discharge of Blue Spring. A double-mass analysis of discharge of Blue Spring versus rainfall at De Land (fig. 59) shows that for the 50-year period 1932–82 the graph is essentially a straight line. Thus, the relation between rainfall and the discharge of Blue Spring has remained virtually unchanged. This is as expected because of the relatively small pumpage in the Blue Spring ground-water basin. Also, some of the ground water pumped eventually recharges the aquifer system by percolation from septic tanks and lawn and crop irrigation.

The base flow of the Wekiva River during dry periods is about 190 to 210 ft^3/s and is derived almost entirely from spring flow. The base flow is derived from Wekiva Springs (73 ft^3/s), Rock Springs (57 ft^3/s), Miami Spring (5 ft^3/s), Witherington Spring (4 ft^3/s), Sanlando, Palm, and Starbuck Springs (37 ft^3/s), and a few smaller springs, plus discharge from flowing wells 51 and 52 (see fig. 2; only since 1974 and probably less than 25 ft^3/s) and about 10 ft^3/s inflow from the Little Wekiva River.

The double-mass curve of flow of the Wekiva River versus rainfall at Orlando shows that the average annual flow of the Wekiva River has increased about 64 ft^3/s since about 1960 (fig. 60). Of the 189-mi^2 topographic drainage basin of the Wekiva River, about 40 mi^2 contributes surface runoff to the river. Of that 40 mi^2, most is drained by the Little Wekiva River, a tributary of the Wekiva. In the remaining 149 mi^2 the surface drainage

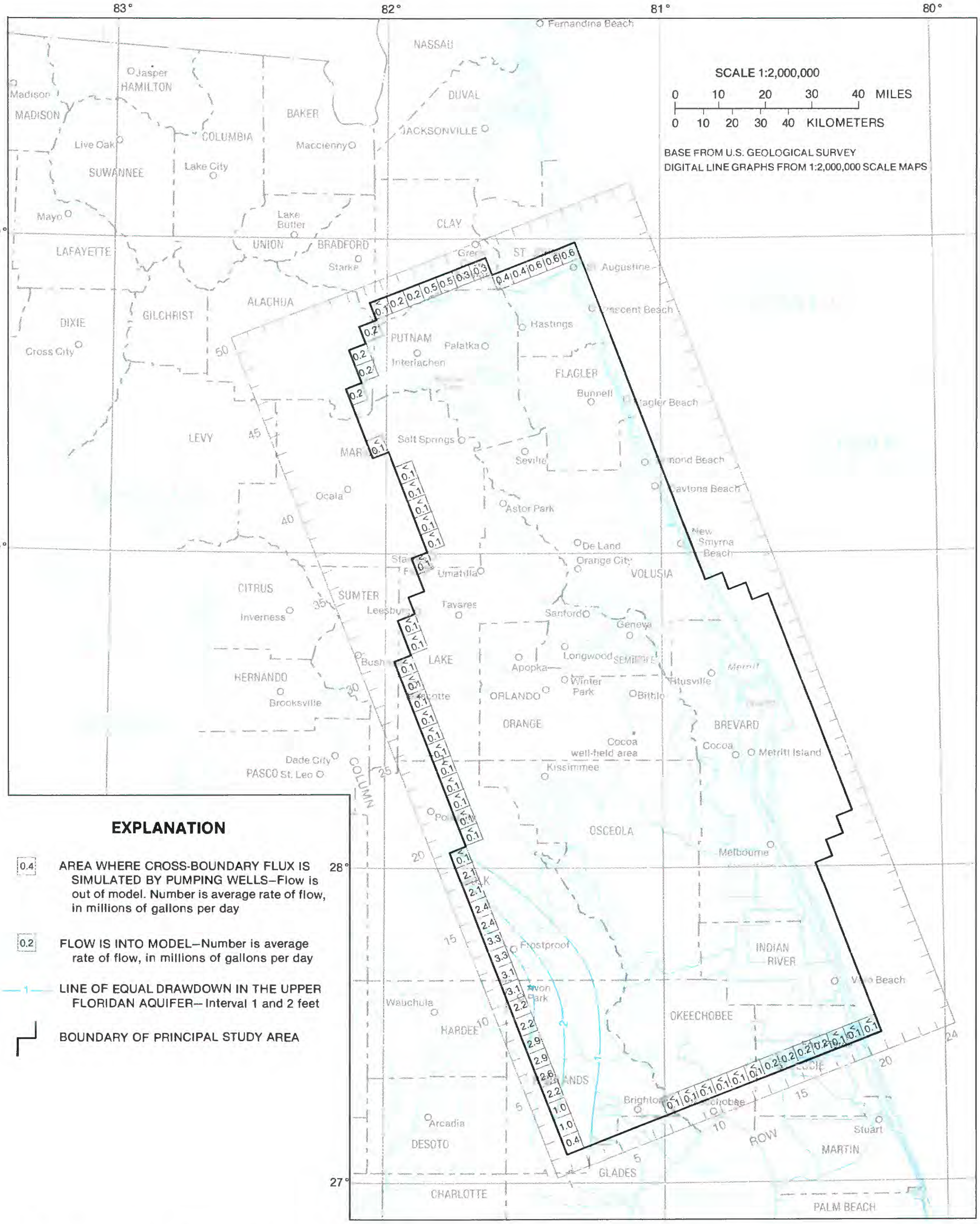


FIGURE 57.—Drawdown of potentiometric surface of Upper Floridan aquifer caused by net boundary flows to or from adjacent pumping centers, 1978.

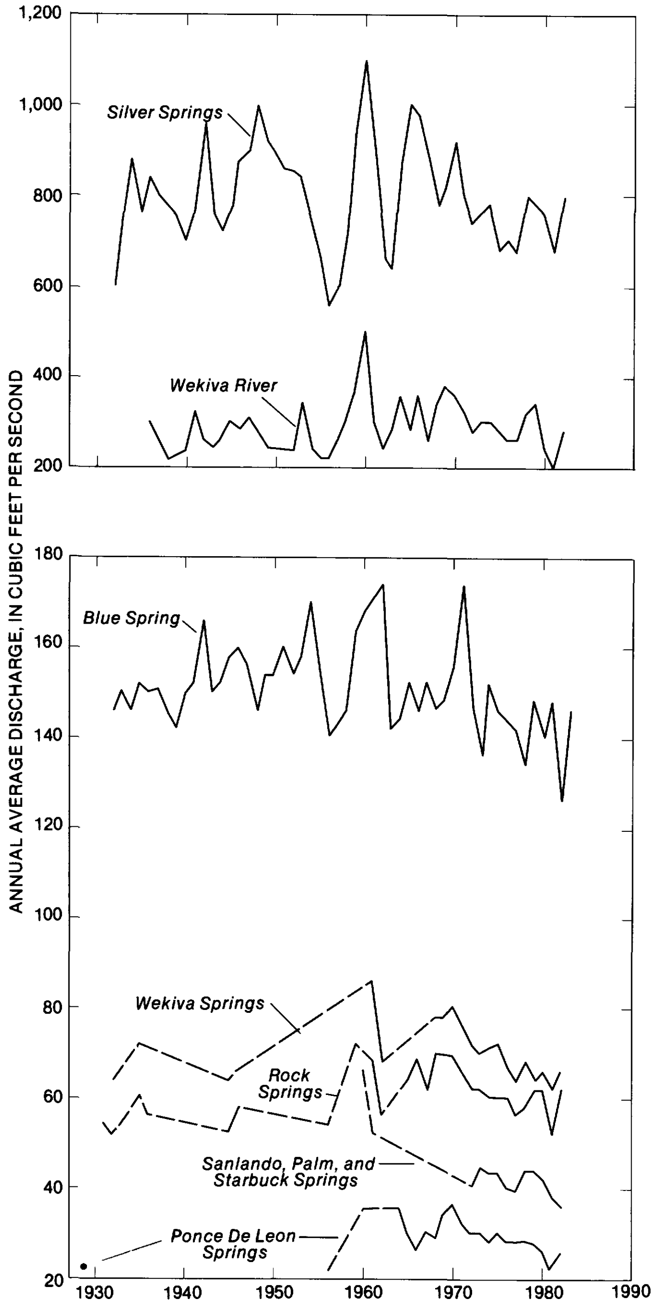


FIGURE 58.—Annual average discharge of Silver Springs near Ocala, Blue Spring near Orange City, Wekiva River near Sanford, Wekiva Springs near Apopka, Rock Springs near Apopka, Ponce De Leon Springs near De Land, and Sanlando, Palm, and Starbuck Springs near Longwood, 1929–82.

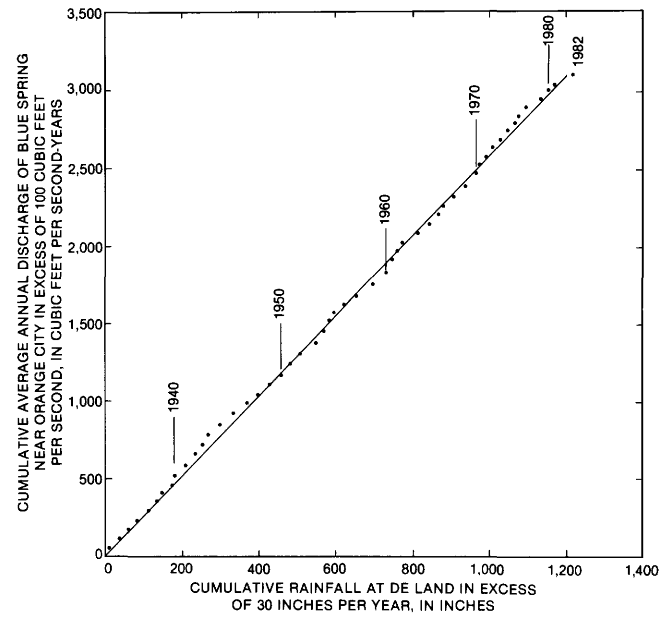


FIGURE 59.—Double-mass curve of discharge of Blue Spring near Orange City versus rainfall at De Land, 1932–82.

system is very poorly developed and the terrain is internally drained by recharge to the Upper Floridan aquifer through diffuse, downward leakage (Lichtler and others, 1968, fig. 54). The average flow of the Little Wekiva River since 1972 (beginning of record) is about 33 ft^3/s. Therefore, of the 64 ft^3/s increase in average annual flow of the Wekiva River since 1960, it is probable that no more than half is due to increased surface runoff from the Little Wekiva River basin. The other half of the increase is probably due to increased ground-water discharge by springs. Inflow from wells 51 and 52 began in 1974. Their combined flow has not been measured, and it is not known if they continuously flow at full capacity. The flow of well 52 was measured at about 20 ft^3/s in July 1975, under conditions of full flow. Because the slope of the double-mass curve from 1974 to 1982 is essentially the same as from 1960 to 1974, it is presumed that the flow from wells 51 and 52 reduced other nearby natural Floridan discharge to the Wekiva River.

Since about 1960, the flow of Wekiva Springs and Rock Springs has tended to be higher than in the period before 1960 (fig. 58) despite below-normal rainfall and increased ground-water pumping. One possible explanation for increased spring flow is that the springs' vents were flushed of silt and debris during the period of record high flows in 1960 (fig. 58). Such flushing could improve the conveyance of the spring vents and therefore increase spring discharge. The increase in spring flow would tend to lower the Upper Floridan potentiometric surface. As

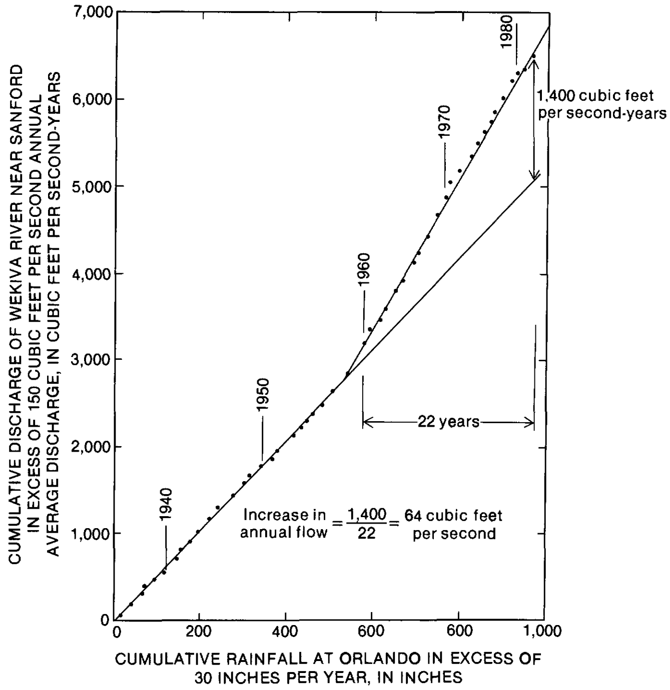


FIGURE 60.—Double-mass curve of discharge of Wekiva River near Sanford versus rainfall at Orlando, 1935–82.

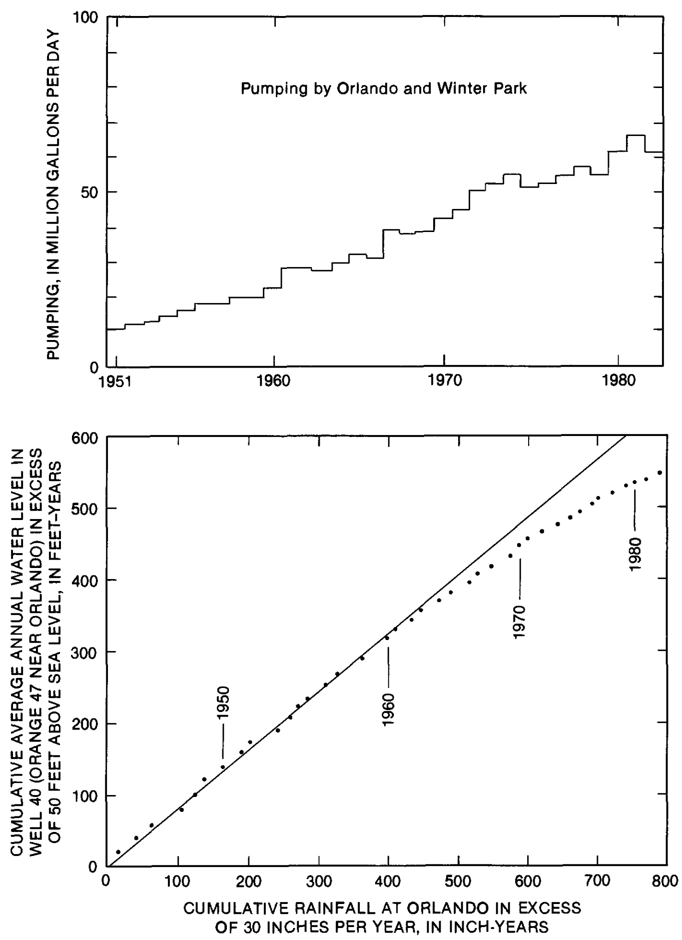


FIGURE 61.—Double-mass curve of water level in well 40 (Orange 47 near Orlando) versus rainfall at Orlando, 1944–82, and pumping by cities of Orlando and Winter Park, 1951–82.

a result, there would be increased head difference between the surficial aquifer and the Floridan, and thus more downward leakage, or recharge, would be induced. Unfortunately, there are no long-term ground-water records in the ground-water basins of the springs that discharge to the Wekiva River. Therefore, the effects of increased spring flow on ground-water levels cannot be verified. The phenomenon of an apparent increase in spring flow was also observed at Weekiwachee Springs in Hernando County (Tibbals and others, 1980). A double-mass analysis of flow of Weekiwachee Springs versus rainfall at St. Leo, Pasco County, showed an increase in spring flow beginning in about 1950–53 following a period of record high spring flows in west peninsular Florida.

Double-mass curve analysis of water levels in well 40 versus rainfall at Orlando (fig. 61) shows that, beginning in about 1961, there has been a decline in water levels that cannot be attributed solely to deficient rainfall. The break in slope of the double-mass curve is not sharp and the graph of the line after 1961 is not straight. This indicates that the change in relation between water levels and rainfall is gradual and suggests a gradual lowering of water levels caused by year-to-year increases in ground-water pumping. The Orlando-Winter Park area began a period of sustained growth in the early 1960's. Ground-water use increased during the 1960's and 1970's and is continuing to increase into the early 1980's (fig. 61). If the break in slope of the double-mass curve of figure 61 is due entirely to pumping in the Orlando-Winter Park area, it is possible that the break occurred as late as 1961 because, prior to that time, pumping was mostly offset by recharge through drainage wells in that area (fig. 23). If so, then recharge through the drainage wells must be about equal to the pre-1960 pumpage by the cities of Orlando and Winter Park plus nearby industrial, rural domestic, and irrigation pumpage. During the period 1956–61, average pumpage by Orlando and Winter Park was about 20 Mgal/d. Pumpage by all other users in the area is estimated at about 10 to 15 Mgal/d. Therefore, if drainage-well recharge equals area pumpage in 1956–61, the amount of recharge that occurs through drainage wells is, on the average, about 30 to 35 Mgal/d.

TABLE 8.—*Changes in Floridan ground-water flow rates caused by selected manmade changes in the hydrologic regimen*
[Cubic feet per second]

Simulation features	Net pumping rate	Downward leakage	Upward leakage	Springflow	Net boundary outflow	Rate of change in storage at end of simulation period
Predevelopment steady state (revised from Tibbals, 1981)	0 ------	1,927 ------	532 ------	1,326 ------	69 ------	0 ------
Doubled the 1978 municipal pumpage (all other categories of pumping remain at 1978 level)	[1]1,054 [2](1,054) [3][247]	2,618 (691) [173]	352 (−180) [−25]	1,202 (−124) [−34]	78 (9) [−6]	−68 (−68) [−9]
Seven spring pools raised 10 feet, no pumping[4]	0 ------	1,877 (−50)	540 (8)	1,266 (−60)	70 (1)	1 (1)
Water table in surficial aquifer lowered 5 feet; no pumping	0 ------	1,704 (−223)	623 (91)	1,087 (−239)	32 (−33)	−38 (−38)

[1] Net pumping is equal to amount pumped from Upper and Lower Floridan aquifer minus the amount recharged through drainage wells.
[2] Change from predevelopment conditions.
[3] Change from transient 1978 pumping conditions after 210 days pumping (table 6).
[4] Wekiva Springs, Rock Springs, Miami Spring, Sanlando Springs, Palm Springs, Starbuck Spring, and Witherington Spring.

It is possible that some of the break in slope of the double-mass curve after 1961 is attributable to the distant effects of the previously discussed increased spring discharge in the Wekiva, Rock, Sanlando, Palm, and Starbuck Springs ground-water-basin. A ground-water-basin divide can shift in response to hydrologic stresses in an adjacent basin and thus cause changes in the potentiometric surface in both basins.

SIMULATED EFFECTS OF SELECTED HYPOTHETICAL MANMADE CHANGES ON THE FLORIDAN FLOW SYSTEM

The computer model described in this report cannot be used to evaluate small-scale or localized stresses on the Floridan aquifer system because

1. The grid size is coarse (4×4 mi) and, therefore, provides poor resolution of drawdown effects;
2. The model cannot compensate for the effects of variations in rainfall and recharge;
3. Data on pumping and its geographic distribution are poorly defined except for municipal pumpage; and
4. Data on the Lower Floridan aquifer are sparse and results of simulations involving the Lower Floridan are debatable.

The model can, however, be used to simulate the effects of large-scale or widespread hypothetical stresses placed on the aquifer system. Three hypothetical conditions were evaluated:

1. Doubling municipal pumpage and holding all other categories of water use at 1978 levels (fig. 62, table 8);
2. Raising the levels of selected spring pools in the Orlando area (fig. 63, table 8);
3. Lowering the water table in the surficial aquifer throughout the model area (fig. 64, table 8).

HYDROLOGIC EFFECTS OF DOUBLING 1978 MUNICIPAL PUMPAGE

Municipalities in east-central Florida can be expected to grow and, consequently, to increase their pumpage. To simulate the effects of increased municipal pumpage, the model was run with municipal pumpage arbitrarily doubled and with all other categories of water use at average 1978 rates. For the municipalities of Orlando, Winter Park, Daytona Beach, Ormond Beach, New Smyrna Beach, and Cocoa, the hypothetical increase in pumpage was areally distributed in nodes adjacent to nodes that contain the existing well fields.

Increased pumpage in the Orlando-Winter Park area was distributed in the Lower Floridan aquifer around the periphery of the present centers of pumping. The increases for Daytona Beach, Ormond Beach, and New Smyrna Beach were distributed in the Upper Floridan mostly westward of their existing well fields. Increased pumpage by the Cocoa well field in east Orange County was distributed in the Upper Floridan west and south of the existing well field.

The coastal areas in the vicinity of St. Augustine (St. Johns County), Bunnell (Flagler County), Titusville (Brevard County), Vero Beach (Indian River County), and Fort Pierce (St. Lucie County) tap the surficial aquifer for municipal supplies, so increased Floridan pumpage is not simulated. Melbourne (Brevard County) uses surface water for supply (Lake Washington in the St. Johns River).

Figure 62 shows the drawdown from predevelopment conditions that results from the simulation of hypotheti-

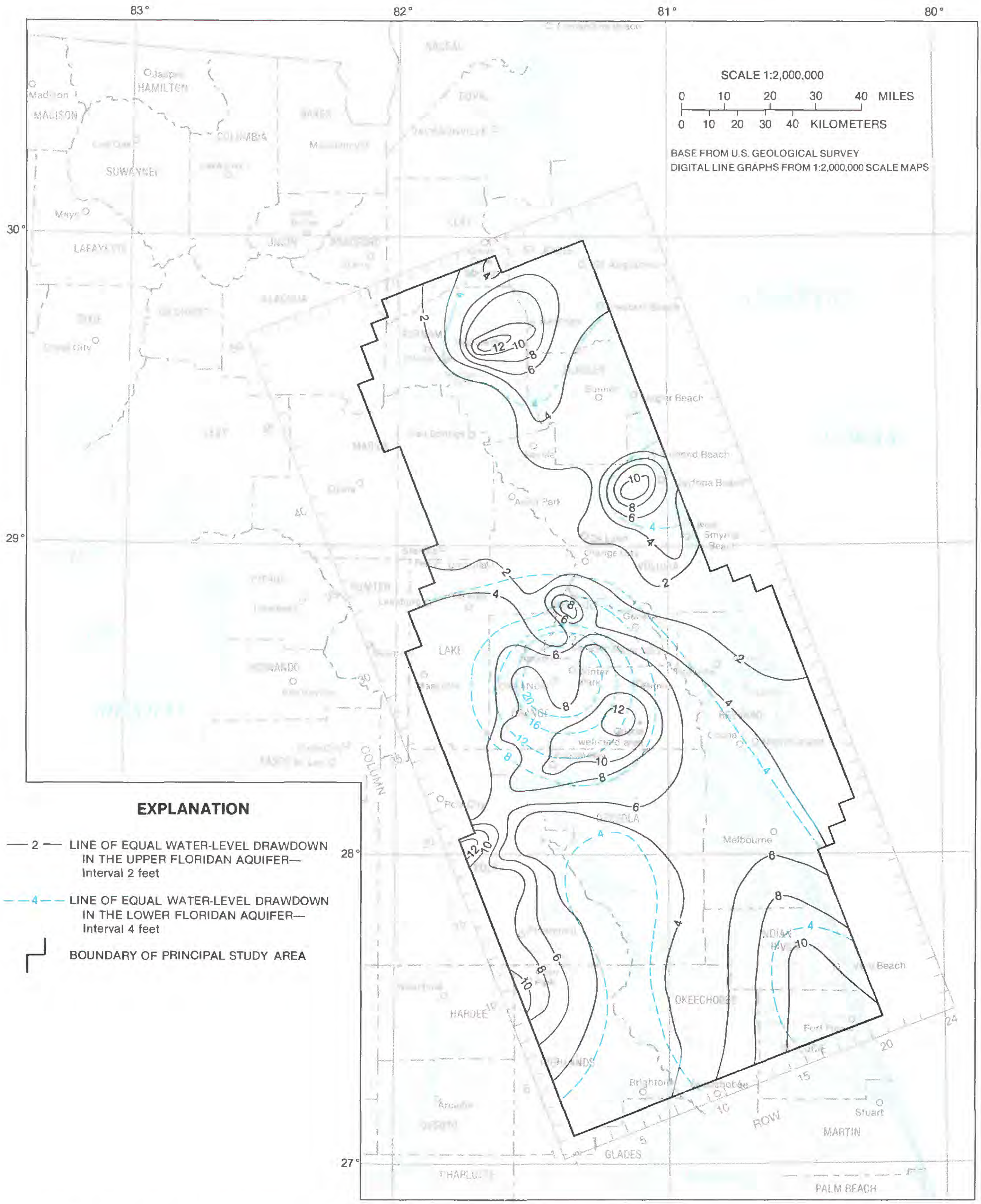


FIGURE 62.—Drawdown of potentiometric surface of Upper Floridan and Lower Floridan aquifers caused by hypothetical doubling of pumping for municipal supplies; all other categories of pumping at average 1978 rates.

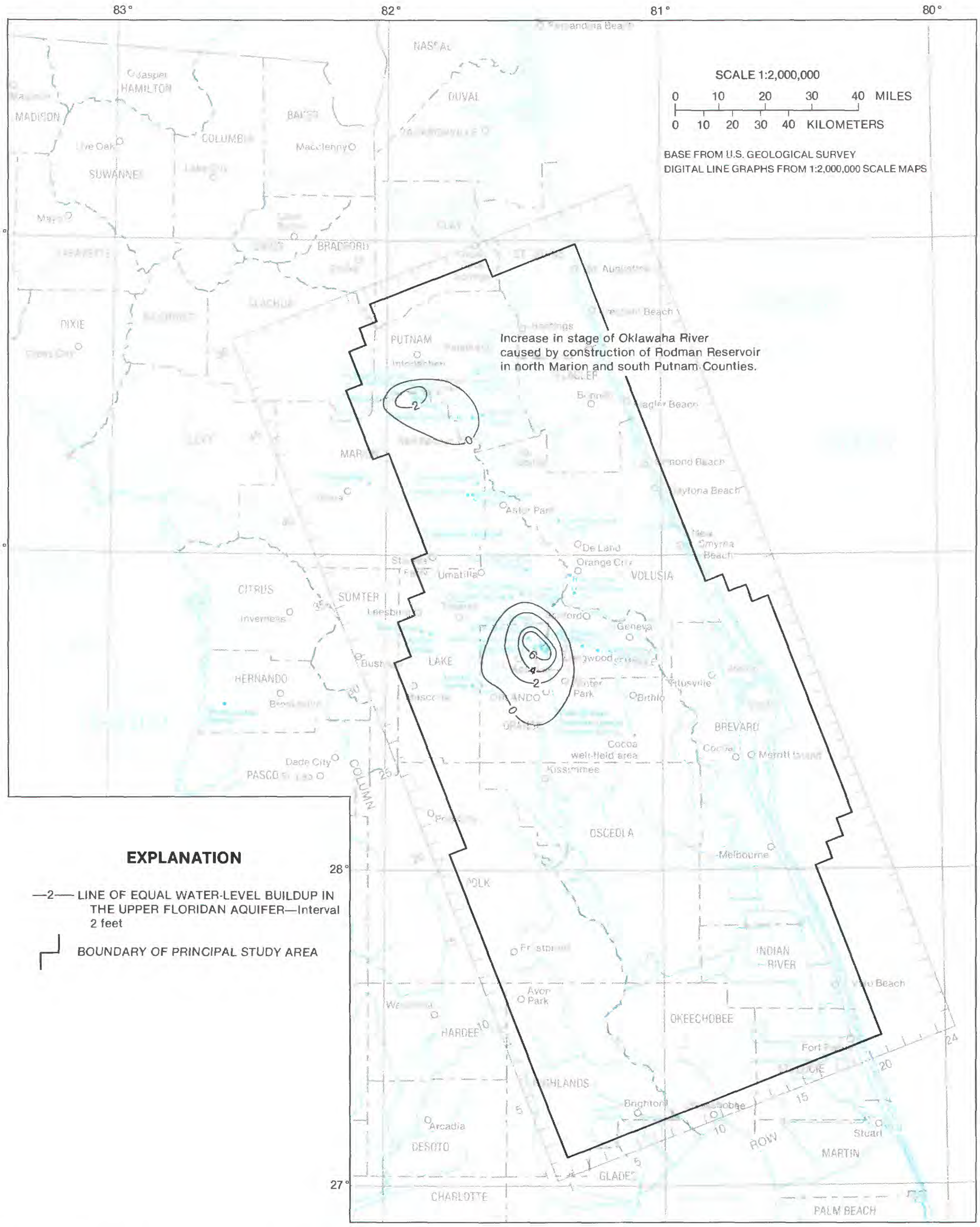


FIGURE 63.—Buildup of potentiometric surface of Upper Floridan aquifer caused by hypothetical raising of selected spring pools by 10 feet and by actual construction of Rodman Reservoir.

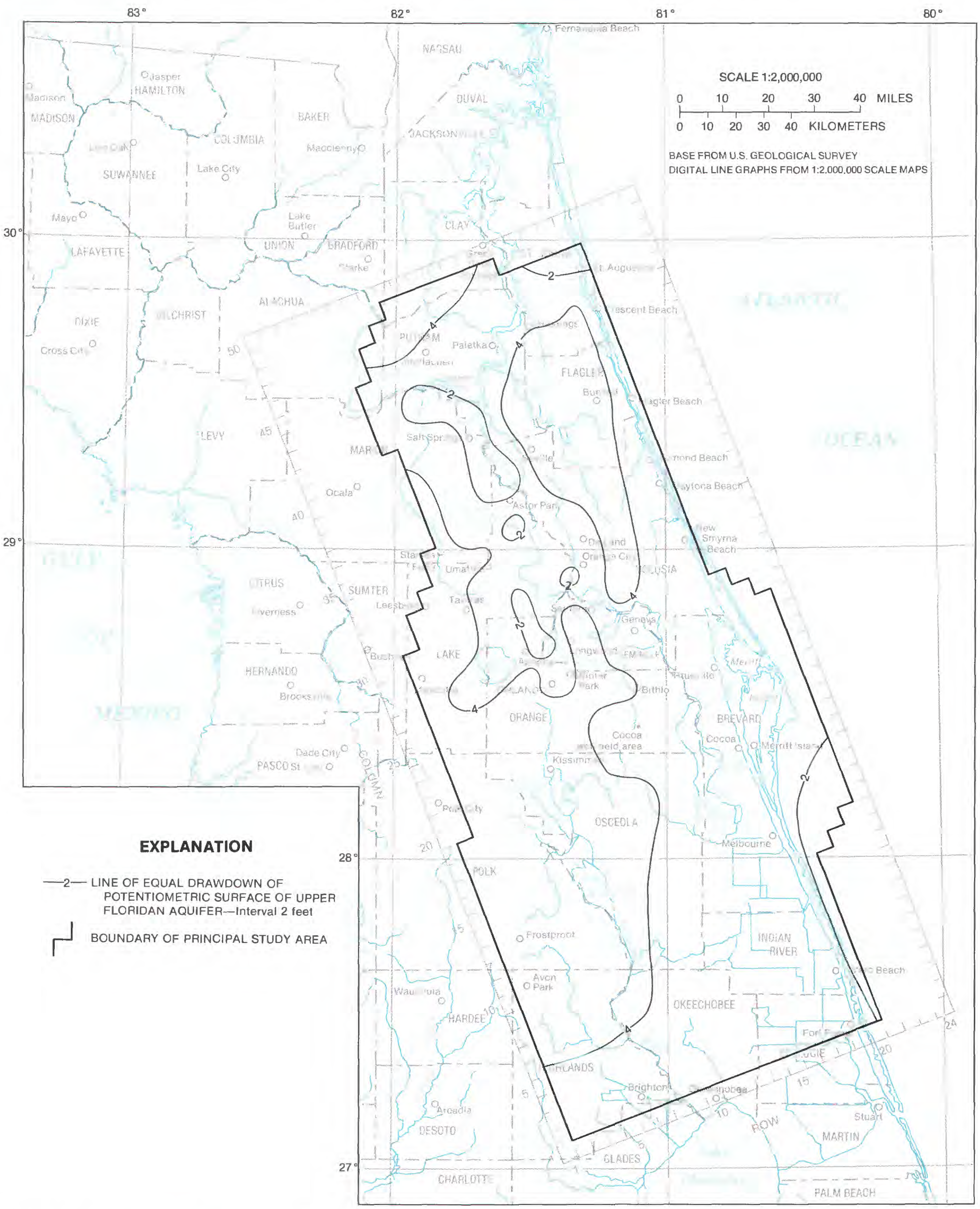


FIGURE 64.—Drawdown of potentiometric surface of Upper Floridan aquifer caused by hypothetical lowering of water table in surficial aquifer by 5 feet.

cal doubling of 1978 municipal pumpage. Table 8 describes the attendant changes in downward leakage, upward leakage, spring flows, and boundary flows. In general, the drawdown effects of doubling the 1978 municipal pumpage are greatest near the larger municipalities, and the effects extend to outlying areas. Of the approximately 247 ft^3/s (160 Mgal/d) simulated increase in municipal pumping from 1978 rates, about 70 percent is derived from increased downward leakage (from 1978 rates) from the surficial aquifer, about 10 percent is from decreased upward leakage, about 14 percent is from decreased spring flow, about 2 percent is from decreased boundary outflow, and, because steady-state conditions had not been reached at the end of the 210-day simulation period, about 4 percent is from storage (table 8).

HYDROLOGIC EFFECTS OF RAISING LEVELS OF SELECTED SPRING POOLS

Occasionally it is suggested that, in order to conserve the ground-water resource, the Floridan aquifer system springs be plugged or dammed to halt their flow. The feasibility of plugging a spring is problematical because the spring might develop new vents or orifices. If the plugging were successful, undesirable side effects would include loss of recreational value and diminished base flow in the receiving stream. A compromise solution would be to build a low-head (say, 10-ft-high) cofferdam around the spring to raise the spring pool. The increase in head or back pressure would temporarily reduce spring flow until the back pressure effects were distributed throughout the spring basin (assuming new vents or orifices did not break open as a result of the increase in pressure) and the hydraulic gradient reestablished toward the spring. At that time, the discharge of the spring would be almost as great as before the cofferdams were built and the potentiometric surface would be higher throughout the spring basin. An analogous condition was imposed by the construction of Rodman Dam on the lower reaches of the Oklawaha River. The lake that resulted from the impoundment by the dam is called Rodman Reservoir, or Lake Oklawaha. The Upper Floridan aquifer, under predevelopment conditions, discharged approximately 150 ft^3/s into the lower reaches of the Oklawaha River. About 89 ft^3/s of discharge by springs (nodes (8,43) and (9,44)) in the area of Rodman Reservoir are simulated. The predevelopment simulated spring pool heads in these nodes were 15 and 13 ft above sea level, respectively.

The model was run without pumping but with the spring pools of seven springs in the Orlando area elevated 10 ft and the pool level of Rodman Reservior set at 18 ft above sea level. The springs involved are Wekiva Springs, Rock Springs, Miami Spring, Sanlando Springs, Palm Springs, Starbuck Spring, and Witherington Spring. The average combined (simulated) discharge of these springs under predevelopment conditions is about 196 ft^3/s (table 1). Their simulated total discharge after their spring pools were raised 10 ft is about 141 ft^3/s—a decrease of 55 ft^3/s from predevelopment conditions. The accompanying buildup in Upper Floridan head caused the discharge of some neighboring springs to increase by about 6 ft^3/s. The head buildup in the area of the seven springs reached a maximum of about 6 ft and extended about 15 to 20 mi (fig. 63).

Along with the simulated raising of the spring pools, the effects of Rodman Reservior (Lake Oklawaha) were also simulated. The increase in pool elevation caused by Rodman Dam reduced Upper Floridan aquifer discharge from 89 ft^3/s to about 75 ft^3/s—a decline of about 14 ft^3/s. The accompanying buildup of Upper Floridan potentiometric head caused some neighboring springs to increase their discharge by about 4 ft^3/s. The Upper Floridan head buildup in the area of Rodman Reservoir reached a maximum of about 2 ft and extended about 10 to 15 mi (fig. 63).

HYDROLOGIC EFFECTS OF LOWERING OF WATER TABLE

Water managers are concerned about the effect that pumping from the Floridan aquifer system has had on water levels in the surficial aquifer system. Though the surficial aquifer system is not a major source of water supply except in some coastal communities, the water level (or water table) in the surficial aquifer system has important implications with regard to water levels in lakes and streams throughout the area. The described computer model has a model layer that represents the surficial aquifer system; however, the surficial is not an active layer. Rather, it is simulated as a constant-head (constant in time though variable in head from place to place) source-sink bed. In Floridan aquifer system recharge areas (fig. 21), the surficial aquifer system leaks water into the Floridan and, in Floridan aquifer system discharge areas, accepts upward leakage from the Floridan. The model cannot directly evaluate the effect of Floridan pumping on the water table. It can, however, give some insight into the degree of interaction between the surficial aquifer system and the Upper Floridan aquifer. To simulate this interaction the model was run with the water-table simulated as being 5 ft lower than originally simulated. Starting heads for the Upper and Lower Floridan aquifers were left unchanged. Though arbitrary, this hypothetically imposed stress is hydrologically reasonable because during an extended drought, the water table and some lake and stream levels commonly decline by as much as 5 ft. The results of the model simulation are shown in figure 64 and table 8.

Lowering the water table 5 ft caused the potentiometric surface of the Upper Floridan aquifer to decline as much as 4 ft in good recharge areas (figs. 21, 64) and also in discharge areas where the higher rates of diffuse upward leakage occur (fig. 22). In good recharge areas and high-rate discharge areas, the confining beds that overlie the Floridan tend to be thin or permeable and there is an intimate hydraulic connection between the Upper Floridan aquifer and the surficial aquifer system. Therefore it can be assumed that, in good recharge areas and high-rate discharge areas, the water table will be most affected by pumping from the Upper Floridan aquifer. The drawdown of the Upper Floridan potentiometric surface caused by pumping in good recharge areas will induce more water to leak downward from the surficial aquifer system and thereby lower the water table in the surficial. Similarly, the lowering of the Upper Floridian potentiometric surface in the high-rate discharge areas will tend to capture some of the water that would have leaked upward to recharge the surficial aquifer system.

SUMMARY AND CONCLUSIONS

The fresh-ground-water flow system of east-central Florida consists of a thin surficial sand aquifer underlain by the thick, highly productive carbonate rocks of the Floridan aquifer system. On the basis of permeability, this system is divided into the Upper and Lower Floridan aquifers which are separated by a less permeable limestone sequence referred to as the "middle semiconfining unit." The transmissivity of the Upper Floridan ranges from about 10,000 to about 400,000 ft^2/d based on aquifer tests, but simulation suggests an average value of 120,000 ft^2/d. In general, however, the aquifer test values for transmissivity of the Upper Floridan are within the range of values determined by computer simulation. The transmissivity of the Lower Floridan is less well known, but the range of transmissivities determined by simulation was from about 30,000 to about 130,000 ft^2/d. Storage coefficients of both the Upper and Lower aquifer are about 1×10^{-3}. Leakage coefficients of the confining bed that overlies the Upper Floridan range from about 1×10^{-6} to about 6×10^{-4} per day. The leakage coefficient of the middle semiconfining unit is about 5×10^{-5} per day.

The chemical quality of the water in the Upper Floridan aquifer varies according to proximity to recharge and discharge areas. Low concentrations of dissolved solids (less than 250 mg/L) generally occur in recharge areas. However, in the discharge areas along the Atlantic Coast and along the St. Johns River, the dissolved-solids concentration is generally more than 1,000 mg/L, and in places exceeds 25,000 mg/L. The quality of water in the Lower Floridan is not well defined, but in east-central Florida, water in the Lower Floridan is probably more mineralized than water in the Upper Floridan.

Most discharge from the Upper Floridan occurs at springs and along streams. Many discharge rates are known from field measurements. Rates of recharge and areal discharge (diffuse upward leakage) are estimated using digital computer simulation.

The essential features of the predevelopment steady-state flow system are as follows:

- The highest rates of recharge to the Floridan are in four areas: the west flank of the Volusia County potentiometric surface "high"; the Putnam County-Alachua County potentiometric surface "high"; the topographically high ridge areas of mid-Polk and Highlands Counties; and the northeast flank of the central Florida potentiometric surface "high" in Lake and Orange Counties and extending into east Marion County.
- Most discharge from the Upper Floridan (about 68 percent of the total) is in the form of point discharge to springs and streams located within 25 mi of recharge areas.
- The highest rates of diffuse upward leakage from the Upper Floridan (about 27 percent of the total discharge) occur near areas where the downward leakage rates are also high. Thus, it is inferred that thin or very leaky confining beds are common to the areas of high upward leakage and to the nearby areas of high downward leakage.
- Lateral boundary outflow from the Upper Floridan aquifer (principally occurring along the Atlantic Coast) is about 4 percent of the total discharge. Lateral flow to the south is about 1 percent of the total discharge.
- Interchange between the Upper and Lower Floridan aquifers is relatively small (about 290 ft^3/s) compared with the flow within the Upper Floridan (about 1,950 ft^3/s).
- The model-derived transmissivities are considered to have more regional significance than transmissivity values derived from individual aquifer tests. In general, however, the aquifer test values for transmissivity of the Upper Floridan are within the range of values determined by computer simulation.

The hydraulics of the Floridan aquifer system under predevelopment conditions involve mostly recharge to the Upper Floridan (by way of leakage from the surficial aquifer), lateral movement through the Upper Floridan for short distances, and discharge by way of springs and seepage to streams. Relatively small amounts of discharge occur along the coast, and small amounts move into and out of the underlying Lower Floridan. Thus, there is a vigorous flow system locally in the Upper Floridan and, except in west Orange County and southeast Lake County, a relatively sluggish flow system in the Lower Floridan.

The imposition of pumping has altered the flow system, but not to a great degree. The simulated effects of 1978 pumpage (about 560 Mgal/d) on the predevelopment Floridan aquifer system flow regime are summarized as follows:

- An average areal drawdown of about 4 ft has occurred in the Upper Floridan aquifer.
- Downward leakage to the Floridan from the overlying surficial aquifer has increased by about 600 ft^3/s (from about 1,900 to about 2,500 ft^3/s).
- Upward leakage from the Floridan to the surficial aquifer has decreased about 150 ft^3/s (from about 530 to about 380 ft^3/s).
- Spring flow has decreased about 90 ft^3/s (from about 1,330 to about 1,240 ft^3/s).
- A slight net increase in lateral flow at boundaries has occurred (about 15 ft^3/s).

Simulation was used to investigate the effects of hypothetical development; the effects are summarized below:

- Doubling the 1978 municipal pumpage would cause relatively small increases in drawdown, with 10 ft or more increase only near the centers of pumping and 20 ft or more only near Orlando.
- Raising elevations of spring pools would cause Upper Floridan head buildup near springs and some decline in spring discharge when steady-state conditions are reached.
- Floridan pumpage tends to induce leakage from the overlying surficial aquifer and to reduce upward discharge to it, thereby lowering the water table.
- Hydrologic analysis of Floridan aquifer system discharge led to the discovery and measurement of two hitherto undocumented springs.

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APPENDIX A: INDEX TO WELLS, OTHER THAN DRAINAGE WELLS, USED IN THIS STUDY

[Aquifer codes: s, surficial aquifer; c, secondary artesian aquifer in confining bed overlying Floridan aquifer system; u, Upper Floridan aquifer; m, middle semiconfining unit; l, Lower Floridan aquifer; um, Upper Floridan aquifer and middle semiconfining unit; uml, Upper Floridan aquifer, middle semiconfining unit, and Lower Floridan aquifer. Well depths and cased depths are referenced to land surface except where noted]

Map location no. (See fig. 2)	Identification no.	County	Local name or number	Model row	Model column	Total depth (ft)	Cased depth (ft)	Aquifer	Date record begins
1	270730081240001	Highlands	Humble, Carlton Estate (oil test)	1	3	12,685	2,430	-----	Jan. 1946
2	271150081054401	Glades	Gl 155 near Brighton	6	2	600	------	u	Dec. 1971
3	272010080221501	St. Lucie	Amerada, Cowles Magazines (oil test)	------	------	[1]5,147	------	------	July 1957
4	272225080573001	Okeechobee	Amerada, Marie Swenson (oil test)	9	4	[1]10,796	4,045	------	Sep. 1955
5	274206080225501	Indian River	Johns Island well near Vero Beach	19	6	2,020	424	uml	June 1977
6	274440081314801	Polk	Coley Well at Frostproof	3	13	319	208	u	Nov. 1949
7	274607080493001	Indian River	IR 189 near Blue Cypress Lake	13	10	630	------	u	Nov. 1951
8	274800080593001	Osceola	Humble, W.P. Hayman (oil test)	10	12	[1]8,730	3,882	------	Dec. 1946
9	275840081391101	Polk	Rodgers Well near Waverly	3	17	612	91	u	Nov. 1958
10	275955080434601	Brevard	Platt well near Melbourne	16	13	447	125	u	Aug. 1934
11	281008081441801	Polk	Lake Alfred deep well	3	21	425	102	u	July 1959
12	281008081441802	do.	Lake Alfred shallow well	3	21	9	6	s	Oct. 1959
13	281058081364201	do.	P44 P.E. Williams well near Davenport	5	21	195	85	u	Dec. 1946
14	281058081495001	do.	USGS core hole 1 at Polk City	1	22	908	350	um	Dec. 1979
15	281058081495002	do.	USGS inner monitor at Polk City	1	22	908	840	m	
16	281058081495003	do.	USGS annular monitor at Polk City	1	22	------	350	------	
17	281058081495004	do.	USGS core hole 2 at Polk City	1	22	1,996	900	1	Sep. 1980
18	281532081345001	do.	Loughman deep well	5	22	250	85	u	Aug. 1960
19	281532081345002	do.	Loughman shallow well	5	22	32	29	s	Jan. 1964
20	281714081093001	Osceola	Lake Joel well near Ashton	12	20	750	394	u	Nov. 1969
21	282202081384601	Orange	Lake Oliver deep	5	24	318	103	u	Feb. 1959
22	282202081384602	do.	Lake Oliver shallow	5	24	30	13	s	Jan. 1961
23	282245080471601	Brevard	USGS observation well at Cocoa	18	20	129	114	u	Aug. 1955
24	282245081492601	Lake	Eva deep well near Eva	3	25	192	100	u	Jan. 1959
25	282245081492602	do.	Eva shallow well near Eva	3	25	23	18	s	Jan. 1959
26	282341081040101	Orange	Cocoa A, SE. Orange County	14	21	516	301	u	Mar. 1960
27	282528081340901	do.	Bay Lake deep well near Windermere	7	25	223	104	u	Mar. 1966
28	282528081340902	do.	Bay Lake shallow well near Windermere	7	25	18	13	s	Mar. 1966
29	282533081082202	do.	Salinity monitor Cocoa C zone 1	13	22	1,357	1,351	l	Dec. 1965
30	282533081082204	do.	Salinity monitor Cocoa C zone 3	13	22	1,224	1,218	m	Feb. 1966
31	282533081082205	do.	Salinity monitor Cocoa C zone 4	13	22	1,050	1,044	m	Feb. 1966
32	282533081082206	do.	Salinity monitor Cocoa C zone 5	13	22	1,004	248	u	Feb. 1966
33	282650081262501	do.	Sand Lake Road injection test well	8	24	[1]6,040	2,442	------	Mar. 1977
34	282800081131501	do.	Warren, George Terry, Sr. (oil test)	13	22	[1]6,524	3,256	------	Sep. 1955
34A	282730081023001	do.	Texaco, Desert Farms (oil test)	22	15	[1]7,050	------	------	Oct. 1970
35	283204081544901	Lake	Mascotte deep well near Mascotte	3	28	160	63	u	Jan. 1959
36	283204081544902	do.	Mascotte shallow well	3	28	30	17	s	Jan. 1959
37	283249081053201	Orange	Bithlo 1 deep well at Bithlo	14	24	492	151	u	Oct. 1960
38	283249081053202	do.	Bithlo 2 secondary artesian at Bithlo	14	24	75	65	c	Oct. 1960
39	283249081053203	do.	Bithlo 3 shallow well at Bithlo	14	24	15	12	s	Oct. 1960
40	283253081283401	do.	Orange 47 near Orlando	9	26	350	328	u	July 1930
41	283253081283402	do.	Orange 47b shallow near Orlando	9	26	20	17	s	Sep. 1948
42	283333081233501	do.	Lake Adair 9 at Orlando	10	26	1,281	601	l	Jan. 1961
43	283333081233502	do.	Lake Adair 10 at Orlando	10	26	400	105	u	Nov. 1962
44	283816081225501	do.	Lake Charity well near Maitland	11	27	374	325	u	May 1961
45	284122081330501	do.	Plymouth Citrus Corp. well	9	29	[1]995	218	uml	Dec. 1956
46	284147081220201	Seminole	Seminole 125 near Longwood	11	28	158	63	u	Oct. 1951
47	284428081072601	do.	USGS Avenue C test hole at Geneva	15	27	403	117	u	July 1981
48	284428081072602	do.	USGS Avenue C 1.25″ inner monitor	15	27	393	388	u	July 1982
49	284428081072603	do.	USGS Avenue C 6″ annular monitor	15	27	353	117	u	Sep. 1981

Footnote at end of table.

APPENDIX A.—CONTINUED

[Aquifer codes: s, surficial aquifer; c, secondary artesian aquifer in confining bed overlying Floridan aquifer system; u, Upper Floridan aquifer; m, middle semiconfining unit; l, Lower Floridan aquifer; um, Upper Floridan aquifer and middle semiconfining unit; uml, Upper Floridan aquifer, middle semiconfining unit, and Lower Floridan aquifer. Well depths and cased depths are referenced to land surface except where noted]

Map location no. (See fig. 2)	Identification no.	County	Local name or number	Model row	Model column	Total depth (ft)	Cased depth (ft)	Aquifer	Date record begins
50	284445081462101	Lake	Lake Yale Groves well near Tavares	6	31	200	112	u	Oct. 1963
51	284740081251701	do.	Wekiva Falls, Inc. 14″-diameter well	11	30	107	58	u	Feb. 1973
52	284740081251702	do.	Wekiva Falls, Inc. 24″-diameter well	11	30	120	80	u	Feb. 1973
53	284750081132301	Seminole	Seminole 257 near Sanford	14	29	206	------	u	Dec. 1951
54	284842081533001	Lake	College Street well at Leesburg	5	33	245	90	u	Sep. 1973
55	285638081203101	Volusia	USGS well 0.3 mi SW. of Blue Spring	13	31	442	84	u	Aug. 1981
56	285745081054001	do.	USGS well at Alamana	17	31	121	113	u	May 1936
57	285920081490501	Marion	Marion 48, Starkes Ferry near Oklawaha	7	35	152	------	u	Mar. 1936
58	290541081132902	Volusia	USGS 04 deep test near De Land 6″ Csg	16	34	575	94	u	May 1955
59	290541081132903	do.	USGS 05 deep test near De Land 4″ Csg	16	34	1,200	639	m	Sep. 1969
60	290541081132904	do.	USGS 06 deep test near De Land 1″ Csg	16	34	1,290	1,275	l	Sep. 1969
61	290920081063001	do.	USGS 6″ observation well near Daytona Beach	18	34	235	102	u	Feb. 1955
62	290920081063002	do.	USGS 2″ observation well near Daytona Beach	18	34	496	480	m	June 1955
63	290950081315501	Lake	Astor Park well at Astor Park	12	36	254	------	u	Feb. 1936
64	291025081050201	Volusia	I–95 well at Daytona Beach	19	34	498	152	um	May 1955
65	291115081592501	Marion	Marion 5, Sharpes Ferry at Silver Springs	6	39	135	135	u	Jan. 1933
66	291133081040601	Volusia	GE plant 6″ well near Daytona Beach	19	34	235	115	u	May 1955
67	291133081040602	do.	GE plant 2″ well near Daytona Beach	19	34	500	483	m	May 1955
68	291254081450001	Marion	Amoco, USA unit 6–4 (oil test)	9	38	[1]4,020	2,699	------	Aug. 1975
69	291715081281801	Volusia	J.C. Mew well at Seville	14	38	180	------	u	Mar. 1936
70	291905081251001	do.	R. Noland well near Seville	14	38	138	------	u	Feb. 1936
71	292546081513301	Marion	USGS well CE 67 near Salt Springs	9	43	340	307	u	Sep. 1964
72	292750081152001	Flagler	Flagler 14 at Bunnell	18	40	417	------	u	Mar. 1936
73	293045081431501	Putnam	Sun, H.E. Westbury (oil test)	12	43	[1]3,872	1,758	------	Jan. 1949
74	293115082251501	Alachua	Texaco, A.M. Creighton (oil test)	7	48	[1]3,457	1,062	------	Aug. 1955
75	293310081284001	Flagler	Humble, J.W. Campbell (oil test)	15	43	[1]4,601	2,962	------	Feb. 1947
76	293720081534501	Putnam	Interlachen city well	10	46	303	300	u	Apr. 1934
77	293729081221201	St. Johns	Florida dot well near Hastings 93712201	17	43	622	142	u	Nov. 1958
78	293933081342801	Putnam	SJRWMD well p–172 at East Palatka	14	45	547	113	u	Nov. 1977
79	294207082163201	Alachua	Sperry Rand well at Gainesville	5	49	447	175	u	June 1957
80	294210082094501	do.	Tidewater, J.A. Phifer (oil test)	2	47	[1]3,116	1,377	------	Apr. 1947

[1] Depth referenced to sea level.

APPENDIX B: LONG-TERM HYDROGRAPHS

Figures 65–73 are long-term hydrographs of water levels in selected wells in the east-central Florida area. The hydrographs were selected on the basis of the longest term record available in each part of the study area. In the central and north-central parts, several well records begin in the early 1930's, when Stringfield (1933) began collecting ground-water data. The longest record, for well 40 near Orlando (fig. 69), begins in 1930. Long-term record is scarce in the Kissimmee River basin and in the area north and west of Lake Okeechobee.

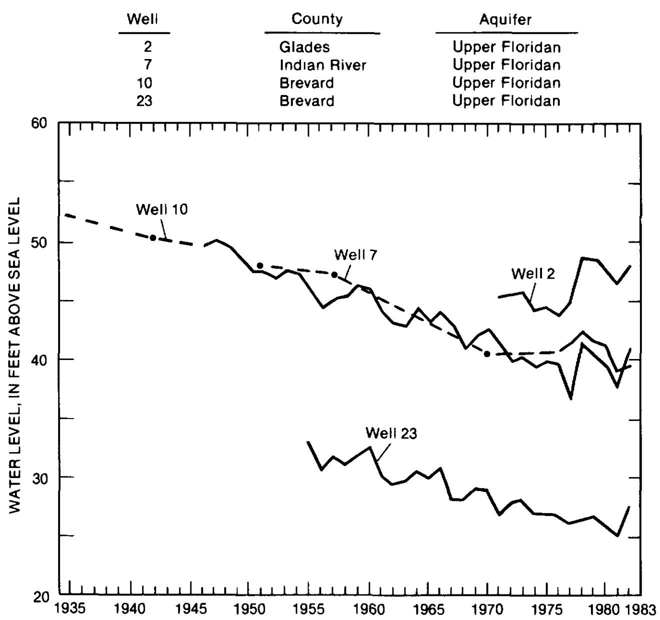


FIGURE 65.—Water levels in well 2 near Brighton; well 7, about 30 miles northwest of Vero Beach; well 10, about 10 miles southwest of Melbourne; and well 23 at Cocoa.

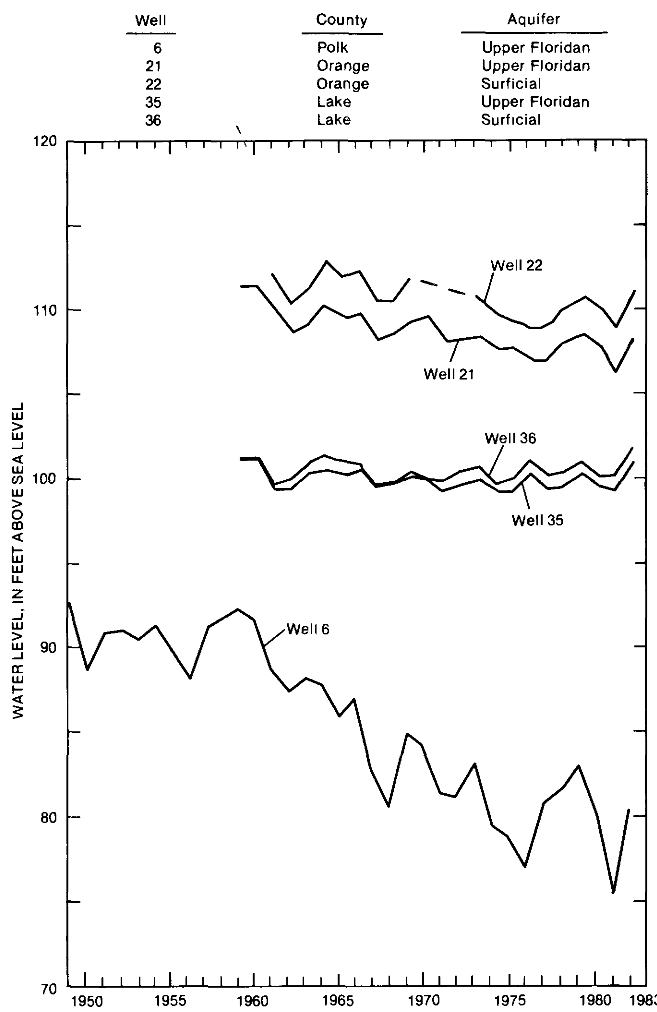


FIGURE 66.—Water levels in well 6 near Frostproof; wells 21 and 22, about 25 miles southwest of Orlando; and wells 35 and 36 near Mascotte.

Well	County	Aquifer or unit
26	Orange	Upper Floridan
29	Orange	Lower Floridan
30	Orange	Middle semiconfining unit
32	Orange	Upper Floridan

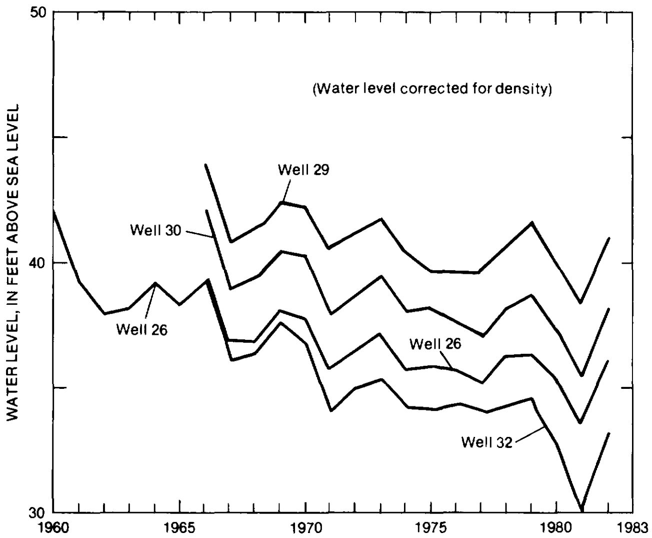


FIGURE 67.—Water levels in well 26, about 22 miles southeast of Orlando, and in wells 29, 30, and 32 (three zones of salinity monitor well, Cocoa well field), about 18 miles southeast of Orlando.

Well	County	Aquifer or unit
37	Orange	Upper Floridan
38	Orange	Upper confining unit
39	Orange	Surficial

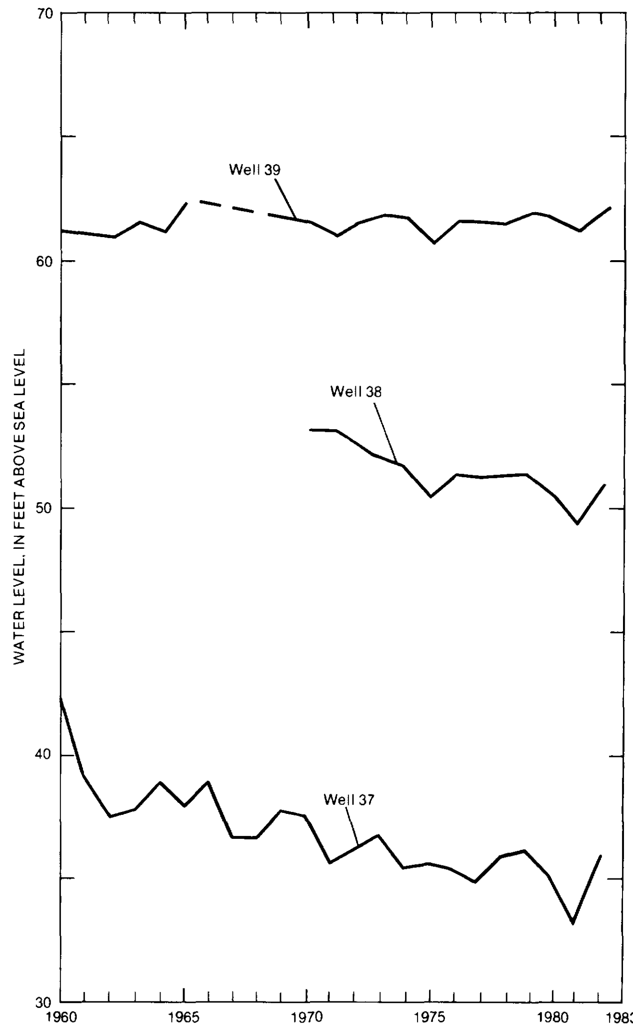


FIGURE 68.—Water levels in wells 37, 38, and 39 at Bithlo.

Well	County	Aquifer
40	Orange	Upper Floridan
41	Orange	Surficial
42	Orange	Lower Floridan
43	Orange	Upper Floridan

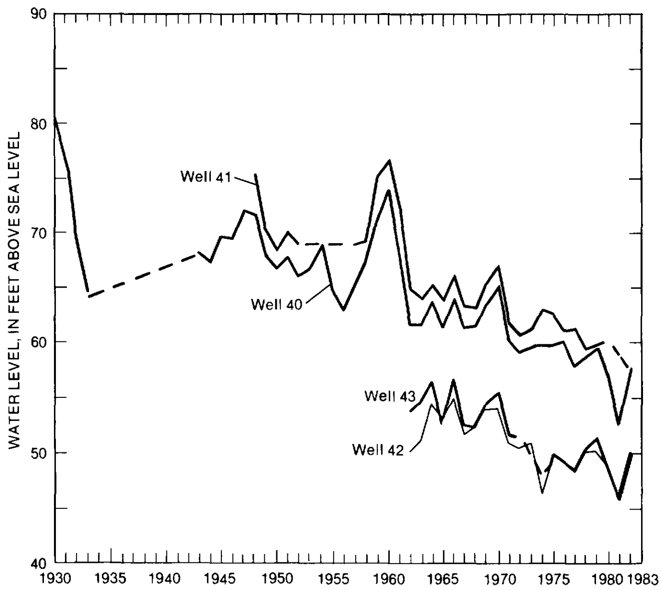


FIGURE 69.—Water levels in wells 40 and 41, about 6 miles west of Orlando, and in wells 42 and 43 at Orlando.

Well	County	Aquifer
46	Seminole	Upper Floridan
50	Lake	Upper Floridan
53	Seminole	Upper Floridan
54	Lake	Upper Floridan
56	Volusia	Upper Floridan

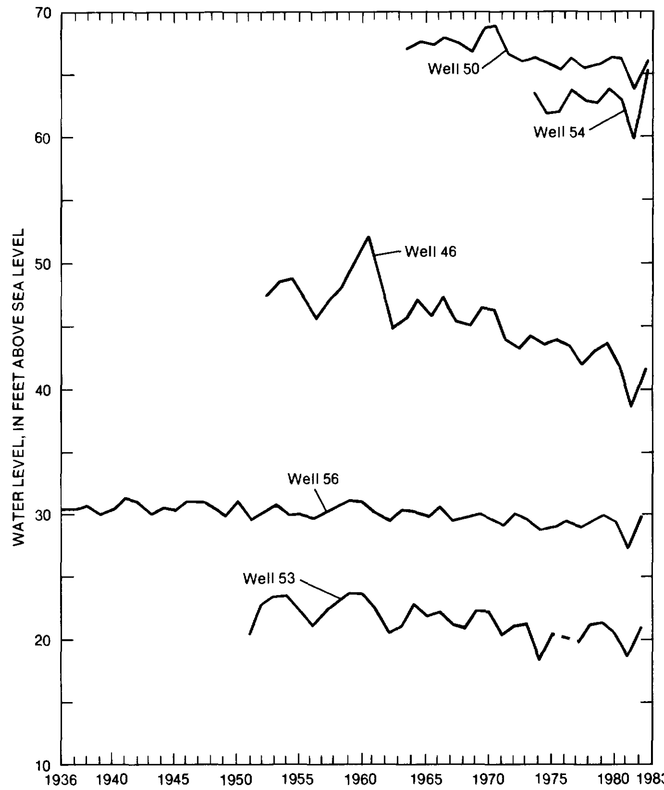


FIGURE 70.—Water levels in well 46 near Longwood; well 50 near Tavares; well 53 near Sanford; well 54 at Leesburg; and well 56, about 13 miles southwest of New Smyrna Beach.

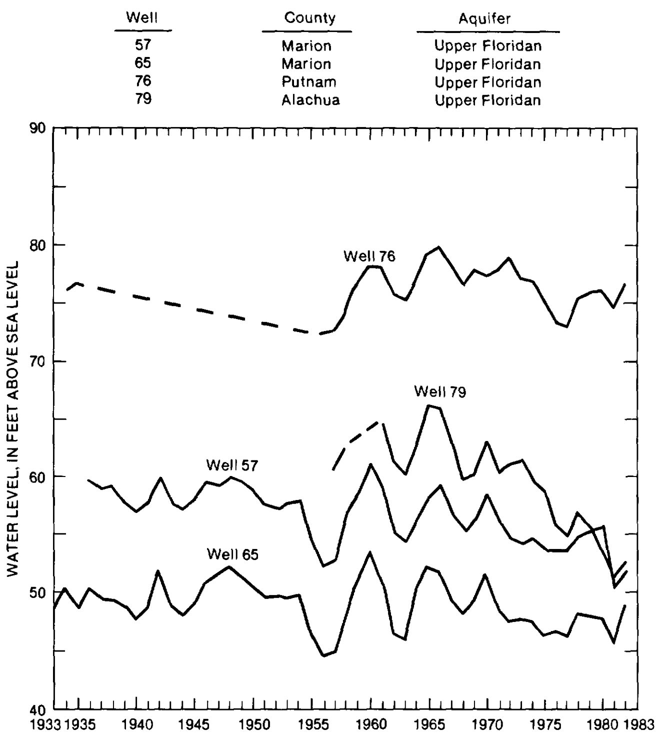


FIGURE 71.—Water levels in well 57 near Starkes Ferry; well 65 near Silver Springs; well 76 at Interlachen; and well 79 at Gainesville.

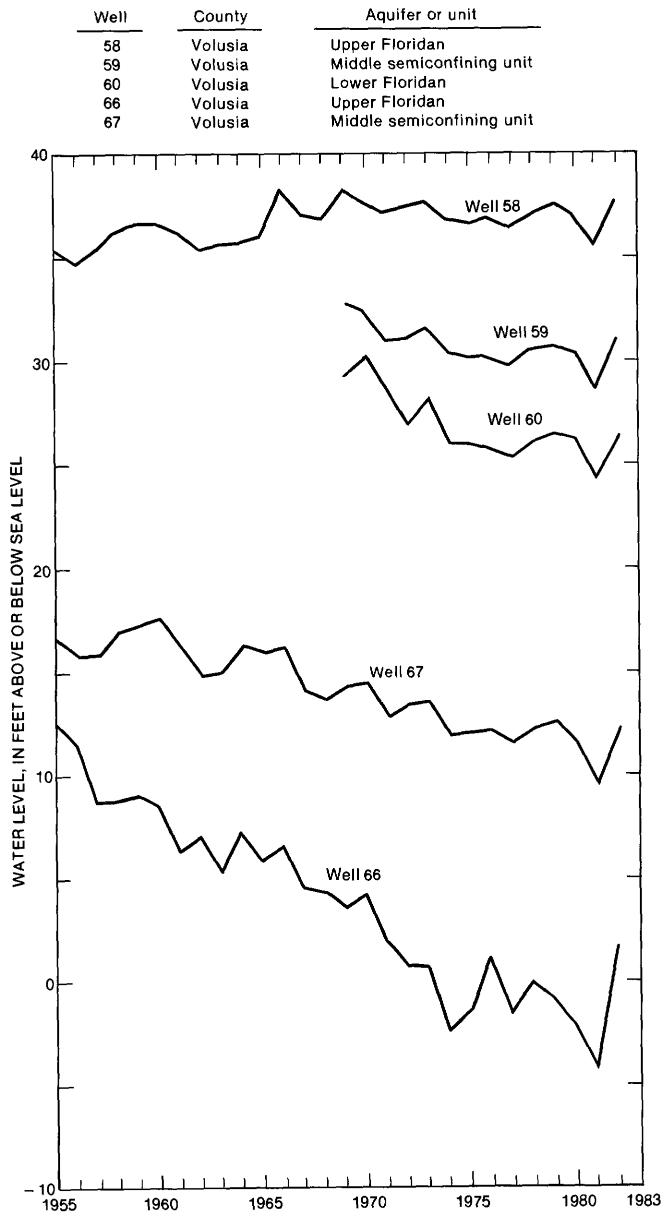


FIGURE 72.—Water levels in wells 58, 59, and 60 (salinity monitor wells, central Volusia County), 7 miles northeast of De Land, and in wells 66 and 67, about 8 miles southwest of Daytona Beach.

Well	County	Aquifer
63	Lake	Upper Floridan
69	Volusia	Upper Floridan
71	Marion	Upper Floridan
72	Flagler	Upper Floridan
77	St. Johns	Upper Floridan

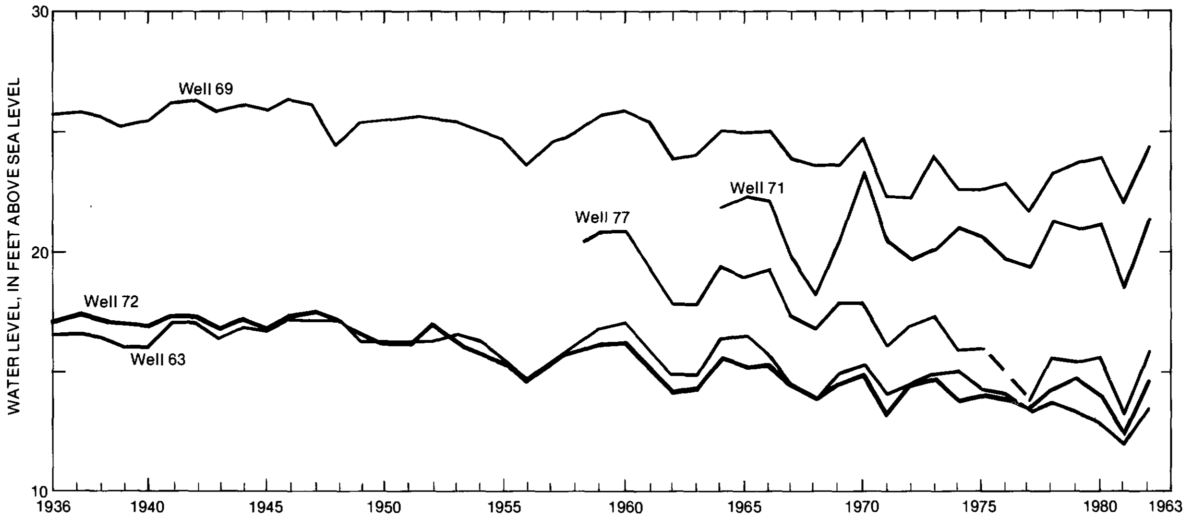


FIGURE 73.—Water levels in well 63 at Astor Park; well 69 at Seville; well 71, about 10 miles northwest of Salt Springs; well 72 at Bunnell; and well 77, about 10 miles southeast of Hastings.

APPENDIX C: INVESTIGATIONS OF UPPER FLORIDAN AQUIFER DISCHARGE TO SPRINGS, RIVERS, AND LAKES

The low-flow measurements shown in figures 74, 75, and 78 were made during periods of deficient rainfall and were preceded by several months of deficient rainfall. There was no surface inflow; therefore, any increase in flow between sites on a stream represents only ground-water inflow. Some of the measurement sites were at known springs that had not been previously or recently measured. Island Spring (fig. 76) and Croaker Hole Spring (fig. 77) were not known to exist prior to this study. These springs are discussed in greater detail later in this section.

Apparently there is about 15 ft^3/s of increase in flow between Salt Springs and the mouth of Salt Springs Run (fig. 74). Some Upper Floridan aquifer discharge definitely occurs in this reach because a spring was observed flowing about 50 ft downstream from the measurement site at Salt Springs. This spring was in an area where the spring run was so wide that a measurement could not be made that included the spring's measured flow with that of Salt Springs. The water-quality data obtained at Salt Springs are representative of the spring, but the water samples taken at the mouth of Salt Springs Run may include fresher water blown upstream from Lake George by a very strong breeze that persisted prior to and during the sampling. Overall flow was definitely downstream, but it was very sluggish at the water surface.

Along Juniper Creek from Juniper and Fern Hammock Springs to Cypress Landing (fig. 74) there is an increase in flow of about 33 ft^3/s and a slight increase in mineralization of the water. From Cypress Landing downstream to State Highway 19 there is an additional 37 ft^3/s increase, of which 12 ft^3/s is due to inflow from Sweetwater Spring. Streamflow measurements were not made on Juniper Creek downstream from State Highway 19, but there is inflow of at least 13 ft^3/s of Upper Floridan aquifer water into Juniper Creek that had been previously discharged by springs into Mormon Branch and into an unnamed stream that empties into Juniper Creek downstream from the confluence of Juniper Creek with Mormon Branch.

Low-flow measurements along Alexander Spring Creek (fig. 75) showed an increase in flow of about 33 ft^3/s from Alexander Springs downstream to State Highway S–445. There was no surface inflow along that reach of the spring run. The chloride concentration and hardness of water in the spring run did not appreciably change along the reach; thus, the 33 ft^3/s of ground water that discharged into the reach was of the same quality as that discharged by Alexander Springs. From State Highway S–445 downstream to the last measurement site on Alexander Spring Creek, there is little, if any, increase in inflow due to discharge from the Upper Floridan aquifer.

Along Blackwater Creek (fig. 75) from Lake Tracy to just above the Wekiva River, there is about 10 to 20 ft^3/s of Upper Floridan aquifer inflow that cannot be attributed to known springs. Most of the inflow occurs between Lake Norris and State Highway 44A.

Along Rock Springs Run, the Little Wekiva River, and the Wekiva River downstream to State Highway 46, most Upper Floridan aquifer inflow can be attributed to known springs and to two large free-flowing wells. The free-flowing wells (wells 51, 52) are near the west bank of the Wekiva River just upstream from State Highway 46 and are 14 and 24 inches in diameter, respectively. The discharge from these wells was not measured at the time of the low-flow measurements, but measurements of the discharge of the 24-in-diameter well were made July 8, 9, and 11, 1975, and averaged about 20 ft^3/s (about 13 Mgal/d). The combined discharge of the two wells is probably greater than 20 ft^3/s but probably does not exceed 25 ft^3/s. Both wells are equipped with valves that can regulate the wells' discharge. The valves are set to allow continuous flow, but it is not known if the wells are flowing at full capacity.

Based on stream-gaging measurements from State Highway 46 downstream to the St. Johns River made April 6 and 7, 1981, the Wekiva River picked up about 66 ft^3/s of inflow from Blackwater Creek, almost all of which is Upper Floridan aquifer discharge (fig. 75). No increase in flow was measured between State Highway 46 and a site just upstream from Blackwater Creek. However, the specific conductance of the water greatly increased about 0.5 mi downstream from State Highway 46. An underwater investigation was made on May 7, 1982. A small, completely submerged spring, hereinafter referred to as "Island Spring," was found near the middle of the Wekiva River (fig. 76). No boil was visible at the surface. About 6 ft^3/s was measured at the spring's orifice. It is possible that Island Spring discharged more than 6 ft^3/s prior to the installation of free-flowing wells 51 and 52 in 1972, approximately 2 mi to the south. Discharge of water from wells 51 and 52 may have caused a reduction in flow of Island Spring. A water sample shows that the spring is discharging water that is more highly mineralized than any of the known springs in the vicinity (fig. 76). Parts of the vertical sidewalls of the spring vent are grooved. The grooves are vertical, fairly smooth, about 0.25 in deep, and spaced fairly uniformly at about 0.5 in. The origin of the grooves is unknown.

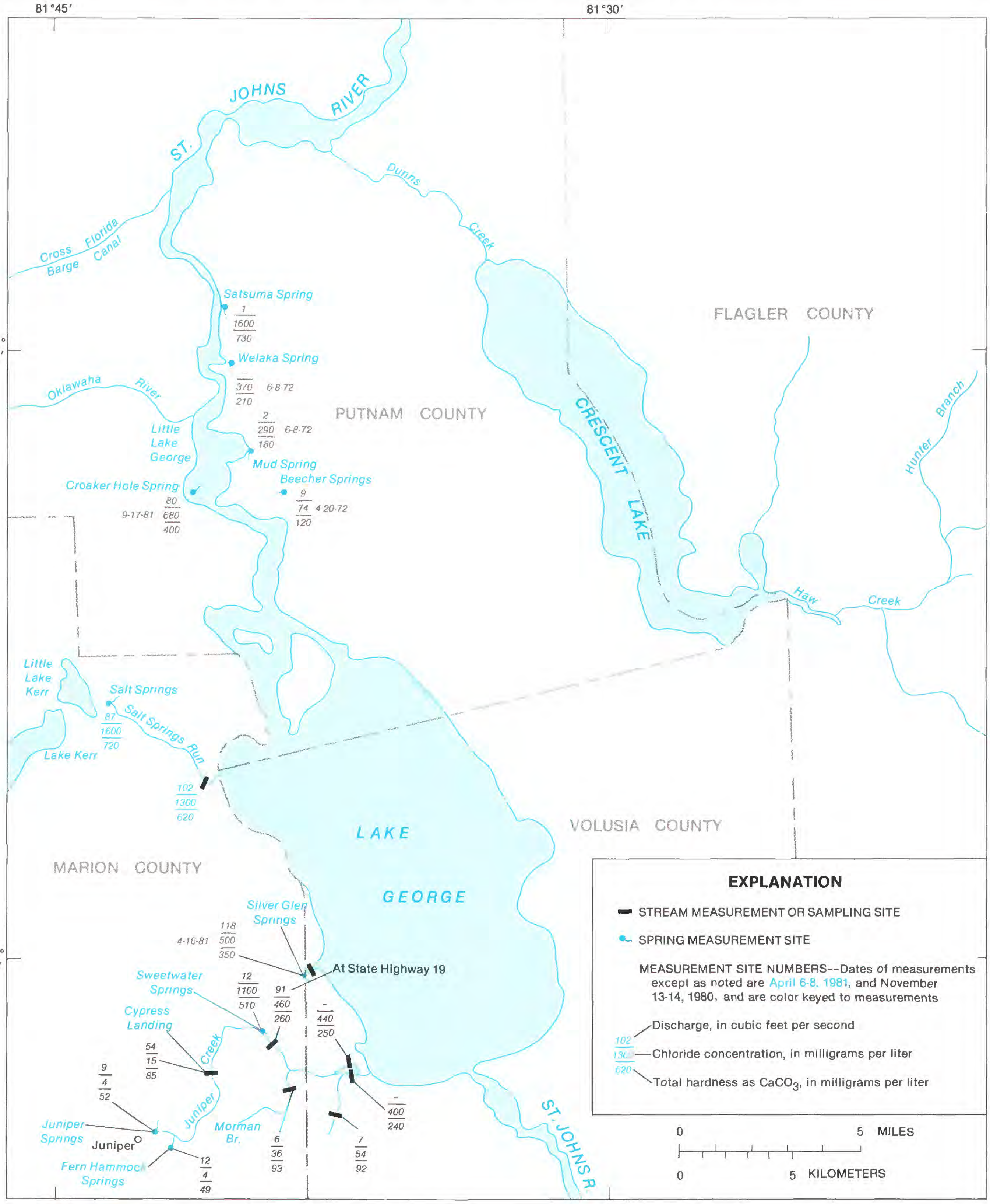


FIGURE 74.—Results of low-flow measurements, Lake George area.

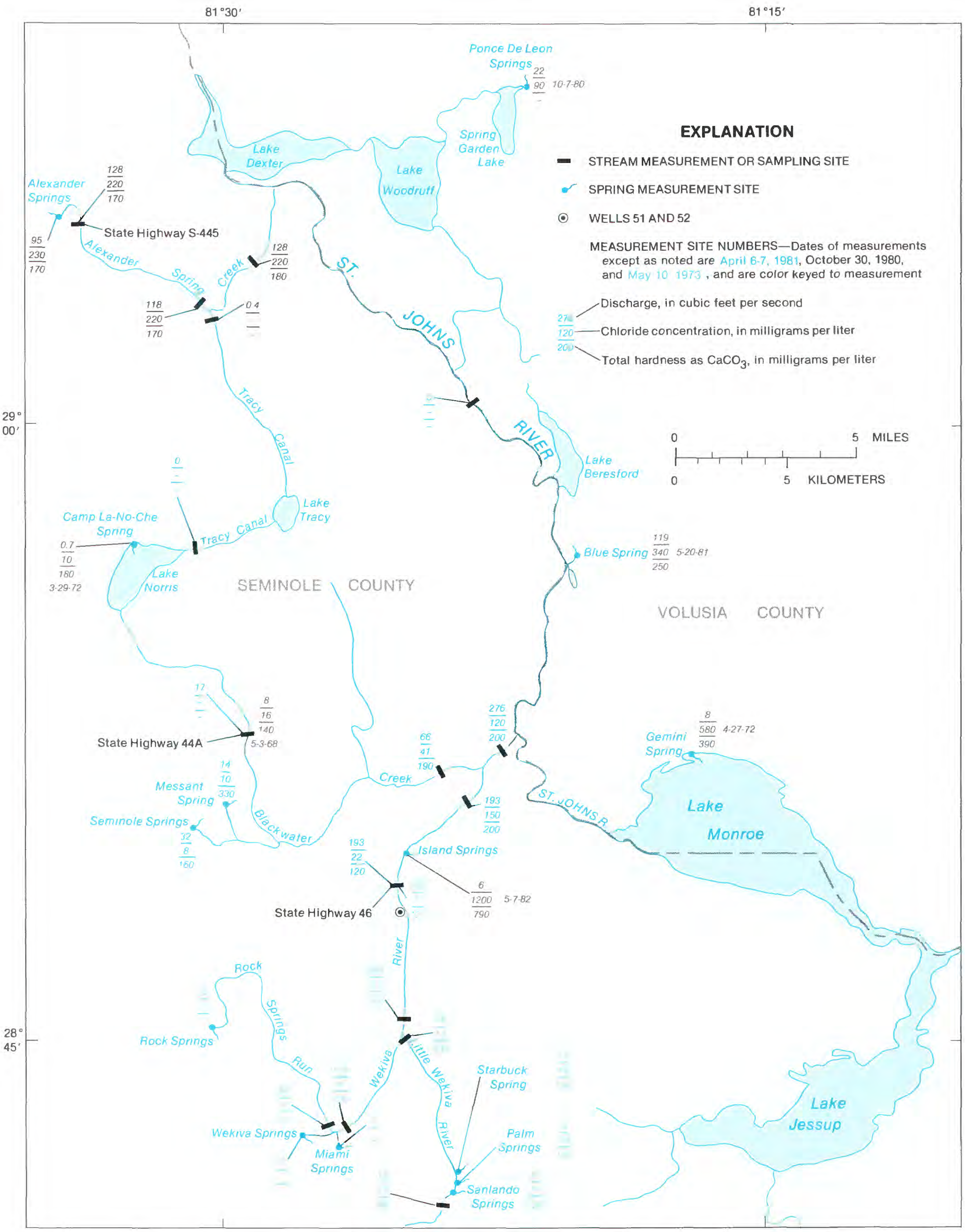
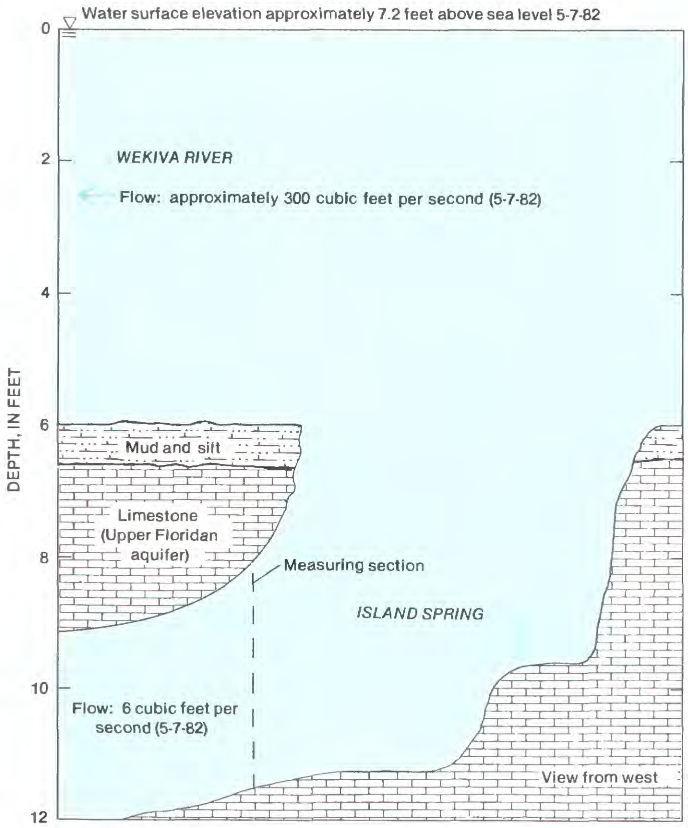
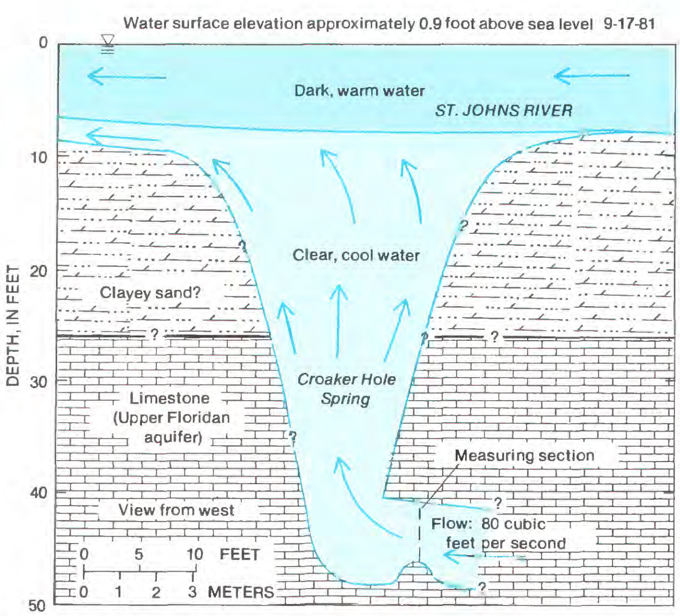


FIGURE 75.—Results of low-flow measurements, Wekiva River–Alexander Spring Creek area.



	Island Spring	*Wekiva River*
Station number	284922-081250300	0223500
Date	5-7-82	4-7-81
Discharge (cubic feet per second)	6	193
Temperature (degrees Celsius)	24.0	21.0
Color (platinum-cobalt units)	10	7
Dissolved solids (milligrams per liter)	2,680	187
Chloride (milligrams per liter)	1,200	22
Sulfate (milligrams per liter)	350	24
Hardness as $CaCO_3$ (milligrams per liter)	790	120
Specific conductance (microsiemens at 25 degrees Celsius)	4,500	296
pH	7.5	7.8

FIGURE 76.—Sketch of Island Spring near Sanford.



	Croaker Hole Spring	*St. Johns River* 50 feet above Croaker Hole
Station number	292618-081412100	292617-081412100
Date	9-17-81	9-19-81
Discharge (cubic feet per second)	80	-
Temperature (degrees Celsius)	23.0	25.0
Color (platinum-cobalt units)	1	38
Dissolved solids (milligrams per liter)	1,430	680
Chloride (milligrams per liter)	680	280
Sulfate (milligrams per liter)	160	84
Hardness as $CaCO_3$ (milligrams per liter)	400	310
Specific conductance (microsiemens at 25 degrees Celsius)	3,000	1,200

Note: River is tidal and had reverse flow daily during September 17-19, 1981. River water may have mixed with water from Croaker Hole Spring.

FIGURE 77.—Sketch of Croaker Hole Spring near Welaka.

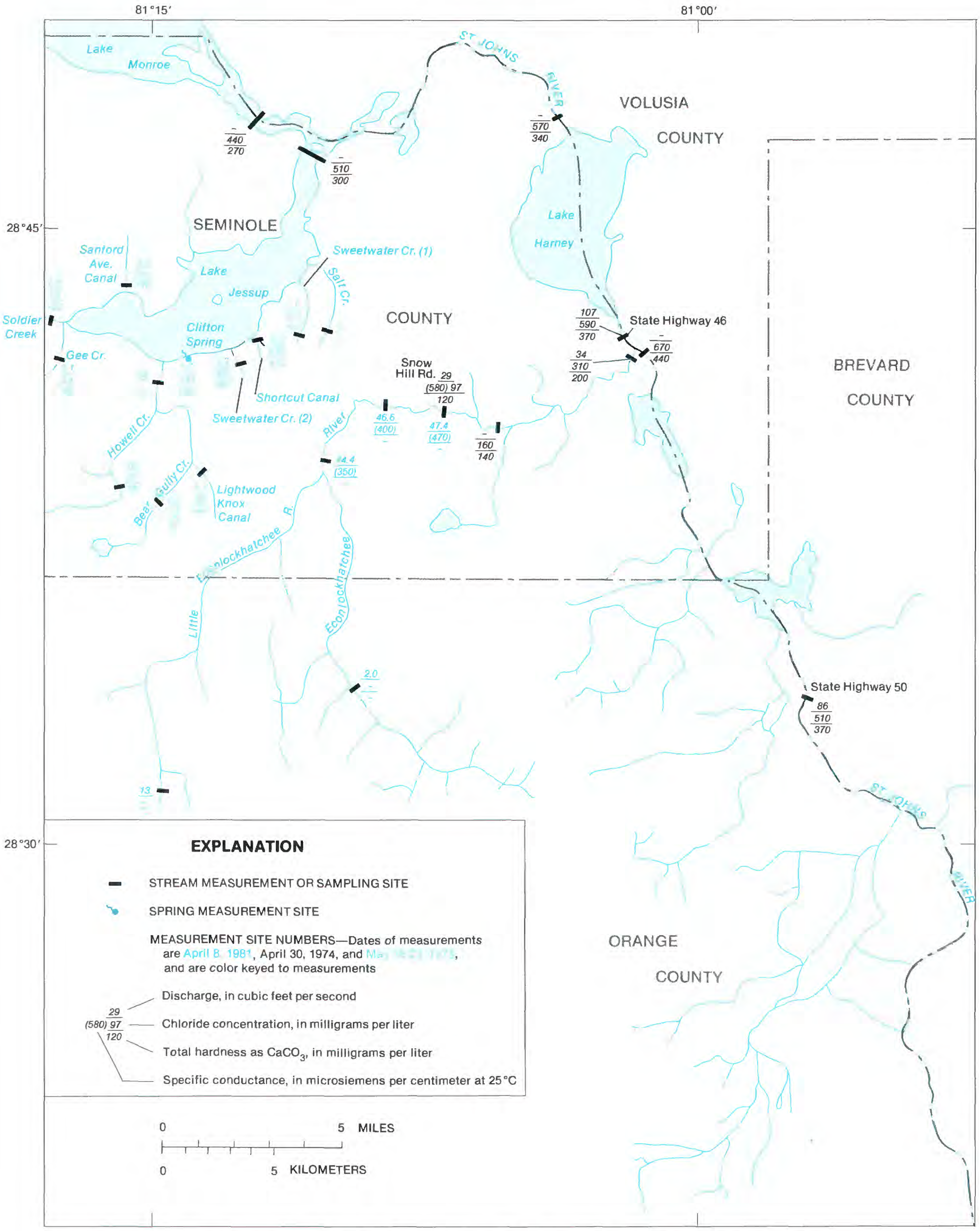


FIGURE 78.—Results of low-flow measurements, Lake Jessup–Econlockhatchee River area.

The depression in the Upper Floridan aquifer potentiometric surface north of Lake George and south of the mouth of the Oklawaha River (figs. 20, 21) is due in part to Upper Floridan discharge upstream from the mouth of the Oklawaha. However, the cone of depression is centered near the southwest quadrant of Little Lake George (St. Johns River) in an area shown as Croaker Hole Cove on U.S. Geological Survey 7½-minute topographic quadrangle maps. Croaker Hole Cove was named by fishermen after Croaker Hole, a relatively deep, small-diameter hole in the bottom of the river and lake. Little Lake George is about 5 to 9 ft deep except in the immediate vicinity of Croaker Hole, where it plunges to a depth of about 48 ft.

On September 17, 1981, U.S. Geological Survey divers and Breck Johnson, Umatilla, Fla., descended into Croaker Hole, took water samples, and measured the discharge at the bottom near the mouth of Croaker Hole Spring (fig. 77). The divers reported that, to a depth of about 7 to 10 ft, the water was turbid and dark brown, the same as that of the river. Below about 10 ft the water became very clear. Strong artificial lights were needed because the dark and turbid water near the surface allowed little natural light to penetrate to the depth at which the divers were working. No spring boil was visible at the surface.

The discharge of Croaker Hole Spring was measured at about 80 ft^3/s. The temperature and dissolved-solids concentration of the spring water were 23 °C and 1,430 mg/L, respectively. The temperature and dissolved-solids concentration of the river water immediately upstream from the spring were 25 °C and 680 mg/L, respectively. The spring water in September was colder, more mineralized, and thus denser than the river water. The denser spring water probably flowed up the spring bore and moved downstream along the bottom of the river. This is probably why no boil was observed at the surface. During the late winter months, when the river water is colder than the spring water, the warmer spring water would tend to rise to the surface and perhaps would cause a noticeable boil.

Though underwater lighting equipment was used, visibility at the bottom of Croaker Hole was limited to only a few feet. Therefore, the sketch of Croaker Hole Spring (fig. 77) should be considered only a crude representation of the configuration of Croaker Hole.

Low-flow stream-gaging measurements made May 16–23, 1973, on streams and springs tributary to Lake Jessup (fig. 78) total about 44 ft^3/s. About 21 ft^3/s is from sewage treatment plants that discharge into Howell Creek above Bear Gully Creek (16 ft^3/s) and into Gee Creek (5.1 ft^3/s). Approximately 21 ft^3/s is from irrigation return flow into Bear Gully Creek above Lightwood Knox Canal (1.2 ft^3/s), Lightwood Knox Canal (8.1 ft^3/s), Sweetwater Creek (3.3 ft^3/s), Shortcut Canal (6.5 ft^3/s), Salt Creek (1.6 ft^3/s), and Clifton Spring (1.3 ft^3/s). All the streams and canals have a seepage component of flow derived from the surficial aquifer, but the total of these seepage components to the Lake Jessup tributaries was probably less than 3 ft^3/s.

An increase of about 5 ft^3/s of Upper Floridan aquifer water was found along the lower reaches of the Econlockhatchee River from Snow Hill Road to the river mouth, April 30, 1974 (fig. 78). However, some increase may be due to irrigation return flow.

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